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ADVISORY BOARD ON

RADIATION AND WORKER HEALTH

National Institute for Occupational Safety and Health

Focused Review of Appendix C to TBD-6000 – Dow Chemical Company (Madison Site)

Contract No. 200-2009-28555

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EXECUTIVE SUMMARY

The Advisory Board on Radiation and Worker Health (Advisory Board) requested that SC&A conduct a focused review of Appendix C, Dow Chemical Co. (Madison Site), a supplement to Battelle-TBD-6000 (Battelle 2006). Appendix C provides site-specific dose reconstruction guidance to support the generic guidance included in TBD-6000. In its reviews of the Special Exposure Cohort (SEC) Petition Evaluation Report for SEC-00079, including Addendums 1 and 2, NIOSH had determined that the operating period for Atomic Weapons Employer (AWE) work at Dow extended from January 1, 1957, through December 31, 1960, and included exposures to both uranium and thorium. NIOSH had also determined that the residual period for uranium extended from January 1, 1961, through July 31, 2000, and through November 30, 2007, for thorium.

SC&A had previously reviewed the site profiles, SEC petitions, and evaluation reports pertaining to what is referred to as the operations period (i.e., 1957 through 1960) and the residual period (post-1960) at the Dow Madison facility. Subsequent to those SC&A reviews, NIOSH published Appendix C to TBD-6000, which provides updated information and guidance pertaining to the Dow facility. During a conference call of the Advisory Board Work Group on SEC issues held on July 24, 2009, the work group requested that SC&A review Appendix C to determine if there is any new information contained in that report that should be brought to their attention.

Appendix C tabulates and consolidates data and guidance that can be used to calculate internal (inhalation and ingestion) and external doses from uranium exposures during both the operating and residual periods. Appendix C also provides data that can be used to calculate external thorium exposures during the operating period, and both external and internal (inhalation, ingestion, and thoron) exposures during the residual period. NIOSH had determined that it was not possible to reconstruct internal thorium doses during the operating period, and NIOSH recommended that SEC status be granted for AWE workers during that period. However, NIOSH concluded that thorium exposures during the residual period could be reconstructed by using the limited data available for the operations and residual period, along with bounding, but plausible, dose reconstruction models.

SC&A's findings from its review of Appendix C are as follows:

Finding 1: NIOSH has proposed the use of geometric mean data to calculate internal uranium exposures during the operating period. The geometric mean is based on only two measurements and, since NIOSH's stated goal is to estimate maximum doses, we believe that use of the 95th percentile is a more appropriate metric for this situation.

Finding 2: The resuspension factor used by NIOSH for estimating uranium dust concentrations in air could be low by 1 to 2 orders of magnitude. NIOSH should revisit the use of a value of 1×10^{-6}/m.

Finding 3: NIOSH should consider developing an exponential decay function for uranium removal during the residual period, based on guidance in ORAUT-OTIB-0070.

Finding 4: There appear to be data entry errors in Table C.2 for the residual period.

Finding 5: NIOSH should focus additional attention on insuring the transparency of the dose reconstruction guidance.

1.0 INTRODUCTION

SC&A had previously performed two investigations pertaining to the Dow Madison facility. These include the following:

- *A Focused Review of Operations and Thorium Exposures at the Dow Chemical Company Madison Plant*, August 2007 (SC&A 2007a). This report presents SC&A's review of NIOSH's Evaluation Report for SEC-00079 (April 13, 2007), which is concerned with the reconstruction of doses to workers at the Dow Madison facility during the uranium operations performed from 1957 through 1960.

- *A Focused Review of Addendum 2 to the Dow Chemical-Madison Plant SEC Petition Evaluation Report* (SEC-00079), September 2008 (SC&A 2008a). This report presents SC&A's review of NIOSH Addendum 2 to its evaluation report, which deals with the reconstruction of thorium doses during the residual period.

During the July 24 teleconference of the Advisory Board's Work Group on SEC issues, SC&A was requested to conduct a focused review of Appendix C, Dow Chemical Co. (Madison Site), of Battelle-TBD-6000 (Battelle 2006). As described by the work group, the primary intent of the review is to determine if Appendix C contains any new material that is relevant to the work group's consideration of exposures at Dow. This request was confirmed during the July 27–29 meeting of the Advisory Board in Cincinnati, Ohio. This report is provided in response to that request.

1.1 SYNOPSIS OF SITE PROFILE AND SEC ISSUES

During 1957 and 1958, Dow Madison performed uranium extrusion work related to the Atomic Energy Commission (AEC) atomic weapons program under contract from Mallinckrodt Chemical Company. Subsequently, in 1959 and 1960, again under contract to Mallinckrodt, Dow performed uranium rod straightening for the weapons program. These activities established the operating period for uranium dose reconstruction as 1957 through 1960. During this period, the major activity at Dow Madison was the production of magnesium alloys, many of which contained thorium. These alloys were sold commercially for use in applications involving missiles and spacecraft, for example. Workers at Dow were subject to radiation exposures from both thorium and uranium during the operating period and the residual period.

The following was noted by NIOSH in its SEC Petition Evaluation Report, Petition SEC-00079 (NIOSH 2007a):

For dose reconstructions under EEOICPA, all sources of radiation exposure must be considered in the assessment of dose received during AWE operational periods. However, exposures due to non-AEC radioactive materials are not included in the assessment of dose received during an AWE residual radiation period if they can be distinguished from exposures resulting from AEC residual contamination. [See 42 U.S.C. 7384 n (c)(4)(b)].

Thus, exposures to both Th and U must be considered during the operating period, but thorium exposures can be excluded during the residual period, if they can be separated from uranium exposures. With regard to reconstructing doses from thorium exposures during the operating period, NIOSH concluded the following (NIOSH 2007a):

NIOSH has documented herein that it cannot complete the dose reconstructions related to this petition where doses resulted from exposure to thorium-containing materials. The basis of this finding is specified in this report, which demonstrates that NIOSH does not have access to sufficient information to estimate with sufficient accuracy either the maximum radiation dose incurred by any member of the class or to estimate such radiation doses more precisely than a maximum dose estimate. Members of this class at the Dow Chemical Company site in Madison, Illinois, may have received unmonitored internal and external radiological exposures from thorium radionuclides at the plant. NIOSH lacks sufficient information, which includes sufficient personnel and workplace monitoring data and radiological source term information, to allow NIOSH to estimate the potential total internal thorium exposures to which the proposed class may have been exposed.

With the data currently available to NIOSH, it is feasible to reconstruct with sufficient accuracy the external and internal doses resulting from exposure to uranium metal during the Dow Madison AWE operational period (January 1, 1957 through December 31, 1960), and during the residual radiation period (January 1, 1961 through December 31, 1998). NIOSH also considers the reconstruction of medical dose for Dow Madison workers to be feasible.

NIOSH determined that workers exposed to thorium during the period January 1, 1957, through December 31, 1960, should be defined as an SEC. Uranium exposures could be estimated using tools such as NIOSH guidance document, *Estimating the Maximum Plausible Dose to Workers at Atomic Weapons Employer Facilities*, ORAUT-OTIB-0004 (ORAUT 2006). However, no estimates of uranium exposures were reported by NIOSH until Appendix C of TBD-6000 was published in September 2008.

At about the time that the initial petition evaluation report was published, NIOSH received 676 pages of additional documentation from Dow. Results of the NIOSH review of this additional material were presented in Addendum 1 to SEC-00079 (NIOSH 2007b). The new material did not alter NIOSH's conclusion about the inability to reconstruct internal thorium doses during the operating period. However, NIOSH did observe that bounding of external thorium doses was possible. The Addendum 1 report states the following (NIOSH 2007b, p. 3):

> *NIOSH has reviewed the additional documentation provided by Dow and concluded that the documentation does not provide sufficient additional information regarding potential internal thorium dose to workers at the Madison site during the covered period of the SEC, which would result in a change to the initial conclusion that it is not feasible to reconstruct those doses. The additional documentation does include sufficient information to provide a bounding reconstruction of external dose resulting from thorium.*

It was subsequently learned by NIOSH that some Mg-Th alloys sold to AEC contractors (i.e., Mallinckrodt) by Dow may have been used in nuclear weapons (DOE 2008). This new information means that exposure to thorium must also be considered during the residual period. Prior to the availability of the information in DOE 2008, consideration of thorium exposures during the residual period was excluded from consideration. In response to this new requirement, NIOSH prepared Addendum 2 to SEC-00079, in which the feasibility of reconstructing thorium doses during the residual period was presented (NIOSH 2008a). NIOSH concluded that "…potential radiation doses received from exposure to residual thorium at Dow Madison from January 1, 1961 through October 31, 2006 can be reconstructed with sufficient accuracy."

SC&A's review of Appendix C is presented in the next section.

2.0 REVIEW OF APPENDIX C – DOW (MADISON SITE)

In September 2008, NIOSH published Appendix C to TBD-6000. The purpose of Appendix C was to provide site-specific dose reconstruction information to supplement the generic information provided in TBD-6000. Key topics addressed in Appendix C include the following:

- Occupational internal dose from uranium
- Occupational external dose from thorium and uranium
- Dose from residual contamination by thorium and uranium

Since Dow Madison AWE employees who worked with thorium during the occupational period are part of an SEC, no dose reconstruction is required for any of these workers who develop one of the 22 types of cancer specified in Energy Employees Occupational Illness Compensation Program Act (EEOICPA), and who worked for at least 250 days during the period from January 1, 1957, through December 31, 1960. In all probability, workers who handled uranium also handled thorium. Consequently, uranium dose reconstruction during the operational period would not be required, unless one needed to consider probability of causation for a cancer that was not one of the 22 types specified in EEOICPA. For claimants with non-specified cancers, a partial dose reconstruction would be performed that would include occupational internal and external doses from uranium and medical doses.

Subsequent sections of this review discuss the exposure modeling guidance in Appendix C in greater detail.

2.1 URANIUM EXPOSURES

SC&A's report dated August 24, 2007 (SC&A 2007a), does not include a review of NIOSH's dose reconstruction protocol for uranium. However, we concurred with NIOSH's conclusion that such doses could be reconstructed, because of the vast amount of data available characterizing exposures to workers at uranium handing facilities. Our August 24, 2007, report concluded the following:

> *We have reviewed numerous reports addressing these types of operations, including the reports by Harris and Kingsley (1959), Adley et al. (AEC 1952), and documentation in support of the Site Profile for Simonds Saw and Steel ORAUT-TKBS-0032 (ORAUT 2005) and the recently issued Site Profiles for Atomic Weapons Employers that Worked Uranium and Thorium Metals (Battelle-TBD-6000 2006). We believe that these reports, taken in combination, are comprehensive in describing the range of operations and the range of exposures that workers might have experienced during uranium metal-working operations at DOE/AWE facilities during the early years. We believe that the material contained in these reports can be used to place plausible upper bounds on the uranium exposures experienced by workers at the Dow Madison facility.*

Hence, the comments and findings contained in this report are new and identify issues regarding how NIOSH is using the available models and surrogate data to reconstruct uranium doses at Dow.

2.1.1 Uranium Exposures during the Operating Period

2.1.1.1 External Uranium Exposures

NIOSH assumed that workers involved in uranium extrusion were exposed 168 hours in each year for 1957 and 1958. This assumption was based on the fact that the AEC contract called for 12 monthly cycles of 28-hours each for the extrusion work, including clean-up (Appendix C, Section C.2.1.2,a). Similarly, workers involved with uranium rod straightening were assumed by NIOSH to spend 168 hours in each year for 1959 and 1960. Purchase orders have been discovered covering two monthly periods of rod straightening work in 1959 and 1960. SC&A believes that these estimates of exposure duration are reasonable, based on the available information.

Using an annual exposure of 168 hr/yr and dose rate parameters obtained from TBD-6000, appropriate exposures and/or doses were calculated by NIOSH. For example, the external dose to an extrusion operator is listed in Table C.2 of Appendix C as 176 mR/yr. This is based on a photon dose rate for that job category of 5.7 mrem/calendar-day[1] from Table 6.4 of TBD-6000 plus small contributions from contaminated floor exposure and air submersion. (Making the assumption that the whole-body dose of 5.7 mrem/day results from a photon exposure of 5.7 mR/day[2], then 5.7 mR/calendar-day × 365 calendar days/2,000 work hours × 168 work-hours/yr = 175 mR/yr).

While the traceability of the Table C.2 data in Appendix C to the data in Table 6.4 of TBD-6000 is apparent, the provenance of the data in Table 6.4 is less clear. Table 6.2 of TBD-6000 lists the daily whole-body photon dose (30 to 250 keV) to an operator standing near a bare uranium metal shape as 5.7 mrem/d based on a 40-hr work week, which can be converted to 1.04 mrem/hr (5.7 mrem/calendar-day × 365 calendar-days/250 work-days × 1 work-day/8hr). TBD-6000 further assumes that an operator spends 50% of his time 1 foot (30.48 cm) from a uranium metal slab. From Table 6.1, we see that the dose (photon plus bremsstrahlung) 1 foot from a rectangular uranium ingot is 2.08 mrem/hr, or based on exposure 50% of the time, equals a dose of 1.04 mrem/hr. Of the several uranium shapes listed in Table 6.1, the rectangular ingot[3] generates the highest dose, so the selection of this geometry is claimant favorable.

2.1.1.2 Internal Uranium Exposures

Internal uranium exposures are summarized in Table C.1 of Appendix C. To calculate internal exposures, air monitoring data were selected from Table 7.2 of TBD-6000 for extrusion operations and from Table 7.7 for rod straightening operations. In Table 7.2, geometric mean values for the daily-weighted average (DWA) are presented for several extrusion-related activities. NIOSH selected the maximum DWA from within this group of activities; 992 dpm/m^3 for the [redacted]. This was converted in Table C.1 to an inhalation exposure of 551 dpm/calendar-day based on a breathing rate of 1.2 m^3/hr (992 dpm/m^3 × 1.2 m^3/hr × 168 hr/yr × 1 yr/365 calendar-days). General extrusion laborers were assumed to be exposed to air containing 147 dpm/m^3 based on the geometric mean DWA for a "weigh man." Supervisor and clerical exposures were assumed to be 50% and 10% of the general laborer, respectively (Battelle 2006, p. 44).

Geometric mean air concentrations experienced by operators during rod straightening were assumed to be 1,690 dpm/m^3, while exposures to laborers were 50% of operators, supervisors were 50% of laborers, and clerical personnel were 10% of supervisors (Battelle 2006, p. 47).

It is important to note that the geometric mean values for the operators in Tables 7.2 and 7.7 of TBD-6000 are calculated from min/max values (i.e., two values) reported by the original authors and not from a multi-value population (TBD-6000, p. 44):

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[1] This is the geometric mean for a lognormal distribution with an assumed GSD of 5.

[2] This assumption is slightly non-conservative, based on a conversion factor of 1 mR/0.877 mrem.

[3] The dimensions of the slab are 40.64 cm wide × 60.96 cm long × 10.16 cm thick (Anderson and Hertel 2005).

If the value was presented as a two-value range, the two values were assumed to be set about the geometric mean such that the geometric mean is equal to the square root of the product of the two values; this lognormal distribution is also assumed to have a GSD=5.

Given the very limited data used to calculate the geometric mean and the fact that the geometric mean is substantially less than the expected value of the lognormal distribution, we do not believe that the geometric mean is a claimant-favorable metric for calculating inhalation doses. We believe that, given the uncertainty in the data, the 95th percentile value is a more appropriate metric under these circumstances. We note that in its SEC-0079 Petition Evaluation Report (NIOSH 2007a), NIOSH specifically cited its ability to estimate **maximum doses**:

NIOSH has access to sufficient information to estimate the maximum radiation dose that could have been incurred from exposure to uranium. Potential internal doses received from exposure to uranium during AEC-related uranium metal operations can be reconstructed using assumptions and methods such as those provided in the NIOSH guidance document, "Estimating the Maximum Plausible Dose to Workers at Atomic Weapons Employer Facilities" (ORAUT-OTIB-0004).

We do not believe that the approach taken in Appendix C is representative of a maximum dose estimate or one that is claimant favorable for all workers. We question the use of "maximum dose," since this is only appropriate in denial of claims. The stated approach should be to develop plausible bounding doses based on sound scientific principles.

Finding 1: NIOSH has proposed use of geometric mean data to calculate internal uranium exposures during the operating period. The geometric mean is based on only two measurements and, since the stated goal is to estimate maximum doses, we believe that use of the 95th percentile is a more appropriate metric in this situation.

Ingestion exposures are also presented in Table C.1 of Appendix C. These exposures are calculated based on OCAS-TIB-009 (NIOSH 2004). Based on the methodology in OCAS-TIB-009, the daily ingested activity is assumed to equal 0.2 times the airborne activity. This is adjusted to a calendar-day basis in Table C.1. For example, the DWA for the extrusion operator of 992 dpm/m^3 is converted to an ingestion exposure of 136 dpm/calendar-day (992 dpm/m^3 × 0.2 × 250 work-days/365 calendar-days = 136 dpm/calendar-day). Notwithstanding some of our previously cited concerns with OCAS-TIB-009, the ingestion exposures as derived for this application appear to be upper bounds, because the implicit assumption is that cleanup did not occur after the extrusion and rod straightening campaigns, and ingestion occurred throughout the year.

2.1.2 Uranium Exposures during the Residual Period

2.1.2.1 Internal Uranium Exposures

Guidance for estimating internal uranium doses during the residual period is presented in Table C.1. The only additional information provided in Appendix C is that the estimates assume resuspension of uranium deposited during 1960. If one assumes a uranium air concentration in 1960 of 1,690 dpm/m^3 (TBD-6000, Table 7.7), a terminal settling velocity of 0.00075 m/s, and a settling time of 168 hours, the uranium surface concentration is 0.767 × 10^{-6} dpm/m^2 at the beginning of the residual period, which can be converted to an air concentration of 0.767 dpm/m^3 in subsequent years, based on a resuspension factor of 1 × 10^{-6}/m. The resulting inhalation rate is 5.0 dpm/calendar-day, based on a breathing rate of 9.6 m^3/work-day (0.767 dpm/m^3 × 9.6 m^3/work-day × 250 work-days/365 calendar-days). This value is similar to the value of 5.5 dpm/calendar-day cited in Table C.1.

There are two issues that should be addressed relative to this approach—the resuspension factor and the assumption of a time-independent air concentration during the residual period. SC&A had previously questioned the use of a resuspension factor of 1 × 10^{-6}/m (SC&A 2007b, Section 7.1). In our review of TBD-6000, we noted the following:

> *Resuspension factors are highly uncertain and variable in time and location, and that the resuspension factor adopted in the TBD might be too low by at least 1 order of magnitude, especially if it is to be used to place a plausible upper bound on exposures*.

SC&A also provided a comprehensive review of ORAUT-OTIB-0070 (ORAUT 2008), where similar concerns about the use of a resuspension factor of 1 × 10^{-6}/m were raised (SC&A 2008b). These concerns were summarized in Finding No. 13 from SC&A 2008b:

> *Finding #13: NIOSH's Recommended Resuspension Factor of 10^{-6} m^{-1} is Inappropriate.*
>
> *Indoor resuspension factors cited in the* ***scientific literature*** *that involve substantial industrial activities (as would be expected in an AWE facility that may continue to operate* ***after*** *operations were performed for the MED or AEC) may experience air concentrations corresponding to RF values of 10^{-4} m^{-1} to 10-3 m^{-1}.*
>
> *The recommended RF value of 1 × 10^{-6} m^{-1} by the NRC is limited to facilities that have previously been subjected to extensive decontamination efforts in anticipation of license termination. A principal objective of such decontamination efforts is to minimize any removable surface contamination that would contribute to the resuspension of surface contaminant. NRC's criteria that include the recommended RF value of 10^{-6} m^{-1} have only recently been established, and have limited relevance to AWE facilities that operated decades*

ago and were never subjected to the stringent D&D criteria that separated the AWE's operational period from its post-operational period.

The second concern is the use of a time-invariant uranium air concentration during the residual period. While this approach is claimant favorable and will, in part, offset a low resuspension factor, it is inconsistent with the guidance in ORAUT-OTIB-0070 (ORAUT-2008), where an exponential decay function is recommended. It is also inconsistent with the exponential decay approach taken for thorium air concentrations during the residual period, as discussed subsequently in Section 2.2.2.1.1.

Finding 2: The resuspension factor used by NIOSH for estimating uranium dust concentrations in air could be low by 1 to 2 orders of magnitude. NIOSH should revisit the use of a value of 1×10^{-6}/m.

Finding 3: NIOSH should consider developing an exponential decay function for uranium removal during the residual period based on guidance in ORAUT-OTIB-0070.

2.1.2.2 External Uranium Exposures

Guidance on estimating doses from external pathways during the residual period is presented in Table C.2. Appendix C does not provide any information as to how the external exposures and doses were calculated, except to state that they are based on "Contamination Only" from Table 6.4 of TBD-6000. We note that the data entries on the last line of columns 4, 5, and 6 in Table C.2 are the same as those on the last line of columns 4, 5, and 6 in Table C.1. We believe that typographical errors exist in Table C.2, since we have been able to reproduce the data in Table C.1. If we assume that the "Contamination Only" exposure from Table 6.4 of TBD-6000 is 1.384×10^{-3} mR/calendar-day (geometric mean), then the annual exposure would be 0.505 mR, not 5.5 mR, as reported in Table C.2.

Finding 4: There appear to be data entry errors in Table C.2 for the residual period.

2.2 THORIUM EXPOSURES

2.2.1 Thorium External Exposures during the Operating Period

Consistent with the position developed in Addendum 1 to the petition evaluation report for SEC-00079 (NIOSH 2007b), NIOSH does not attempt to reconstruct internal thorium doses during the operating period, but they do develop bounding external doses based on data received after the initial petition evaluation report was published on April 13, 2007.

Before describing the NIOSH approach to external thorium dose reconstruction during the operating period, it is useful to review the available data. This review is presented in the following paragraphs.

Silverstein (1957c) observed that, based on a film badge survey, the average weekly external exposure to workers involved in a variety of production operations, including foundry activities, inspection, and shipping, was less than 10 mR, with the maximum exposure being about 30 mR. The film badge survey data, which were taken at the Dow Bay City Plant, where operations similar to those at Dow Madison Plant were performed, are summarized in Table 1 (Silverstein 1957b). The data are based on exposures for 13 working days.

Table 1. Film Badge Survey of HK31 Casting Production during 13 Working Days

Job	Exposure (mR)
Pour Off #1	10
Pour Off #2	75
Pour Off #3	10
Knockout #1	10
Knockout #2	<10
Sandblast #1	10
Sandblast #2	<10
Bandsaw #1	10
Bandsaw #2	50
Chipper #1	<10
Chipper #2	10
Machine Trim	10
Inspection (Rough)	10
Pickler	<10
Rotary File #1	50
Rotary File #2	10
Buffer	10
Heat Treat	10
Wheelabrator	<10
Pickler	<10
Inspection (Final)	10
Touchup	<10
X-ray	<10
Fixture	<10
Shipping	50
Metal Reclamation	10

External radiation exposure had been measured by Dow for a stack of Mg-3.5% Th alloy (HK31A) slabs.[4] The β/γ dose at the surface was 4.2 mR/hr, 1.8 mR/hr at 1 foot, and declined to 0 at a distance of 7 ft from the alloy stack. Dow estimated that a worker with his hands in contact with the alloy stack and his body 1 foot from the stack would receive an exposure to the hands of 168 mR/week and exposure to the body of 72 mR/week, based on a 40-hr week (Silverstein 1956c).

[4] This was a 9-ft high stack of slabs with dimensions of 10 in × 26 in × 76 in (Dow 1956).

Exposure to thorium pellets measured 35 mR/hr on contact and Dow estimated that at the normal working distance from the pellets, the worker's exposure was less than 1 mR/hr (Silverstein 1956a).

In addition, Dow estimated that a single worker handling all the thorium pellets required for a 100,000 lb run of Alloy HK31 would receive an external exposure of 53 mR (Levy 1957). Based on 2 to 3 such runs per year, the annual exposure would be 0.10–0.16 R. Companion estimates using 26% Th hardener yielded values of 0.25–0.38 R/yr. A worker who continuously handled HK31 for 40 hours per week would receive a weekly whole-body dose of 0.07R (Levy 1957).

Stein (1982) reported on external exposure measurements made during the casting of Alloy HK21A by CONALCO (a successor operator of the Madison Plant). While these measurements were made during the residual period, they should be representative of external exposures during the operating period. Other than exposures to thorium hardener, the highest exposure reported by Stein (1982) was 0.7 mR/hr measured at a distance of 1 foot from HM scrap slabs. Extrapolating this measurement to a full year results in an exposure of 1,400 mrem. Most of the other measurements reported by Stein (1982), except those involving hardener exposures, were at least an order of magnitude lower. Exposures to a barrel of thorium hardener (38% Th) were 15–20 mR/hr, values similar to those reported by Silverstein (1956a) for Th pellets.

These various thorium external exposure estimates are summarized in Table 2.

Table 2. Annual Estimates of External Thorium Exposures

Activity	Annual Exposure (mR/yr)	Reference
Alloying with 26% Th hardener	250–380	Levy 1957
Alloying with Th pellets	100–160	Levy 1957
Casting HK31 at Bay City	<500–1,450	Silverstein 1957b
Continuously handling HK31	3,500	Levy 1957
Continuously handling Th pellets (at worker's normal distance from Th)	<2000	Silverstein 1956a
Standing one foot from a stack of HK31A alloy slabs	3,600	Silverstein 1956c
Standing one foot from HM alloy scrap slabs	1,400	Stein 1982

It should be emphasized that all the annual exposure estimates in Table 2 except casting of alloy HK31 at Bay City are based on meter readings, not time-integrated measurements.

NIOSH used the film badge data in Table 1 of this report to develop external photon exposures for thorium. They developed a lognormal distribution for the data and assumed that operators' exposures would be defined by the 95th percentile exposure of 1,095 mR/yr. Laborers' exposures were set at half of the value for operators (548 mR/yr). Supervisors' exposures were set at half the laborers' exposures, and clerical and other workers' exposures were set at the 5th percentile. NIOSH assumed that beta doses were the same as photon doses at all distances. SC&A checked the NIOSH analysis but, as can be seen from Table 1, all but three of the photon exposure measurements are 10 mR (or less). This results in a poor fit to a lognormal distribution and creates considerable uncertainty as to the 95th percentile value. By fitting the data points to a regression line for a lognormal distribution, SC&A calculated that the 95th percentile was 788 mR/yr. However, fitting the data to an empirical cumulative distribution function resulted in a value of about 1,000 mR/yr for the 95th percentile. This is in reasonable agreement with the value of 1,095 mR/yr cited by NIOSH.

2.2.2 Thorium Exposures during the Residual Period

The beginning date for the residual period was fixed as January 1, 1961. The end date for thorium exposures during the residual period was fixed at November 30, 2007, since the final shipments of thorium-contaminated material were made during November 2007 (Pangea 2008).

2.2.2.1 Internal Exposures

Inhalation Exposures

The approach used to bound thorium exposures during the residual period was originally presented in Addendum 2 to SEC-00079 Petition Evaluation Report (NIOSH 2008a). The same approach was adopted for use in Appendix C of TBD-6000. As a starting point for the internal exposure analysis, it is assumed that the airborne thorium concentration at the beginning of the residual period was 8.44 pCi/m^3. This value is based on the highest value (actually the highest minimum detectable concentration) of any general area air sample taken between 1957 and 1959 at Dow Madison. Process and breathing zone samples were excluded, based on the premise that general area samples would be representative of resuspension and dispersion processes. SC&A agrees with this basic approach for this type of problem.

The limiting sample was cited by Dow as <0.076 mg/m^3 of Th, which was converted to 8.44 pCi/m^3. When annualized using a breathing rate of 9.6 m^3/day, the resulting exposure is 20,256 pCi/yr. In its focused review of Addendum 2 (SC&A 2008a), SC&A raised questions regarding the definition of the sample population from which the maximum value of <0.076 mg Th /m^3 was selected. Although these questions have not been answered, their resolution will probably not change the bounding value significantly.

To establish the rate at which this initial (1961) concentration would decay, NIOSH selected data obtained during clean-up operations conducted by Pangea in 2006 (Pangea 2008). Pangea measured airborne Th concentrations of 9.94% of the derived air concentration for Class Y Th-232 in perimeter monitoring stations. (The DAC for Class Y Th-232 is 1 pCi/m^3 per 10 CFR 20, Appendix B, Table 1.) The initial air concentration and the 2006 air concentration were then fitted to an exponential decay function based on guidance provided in ORAU-OTIB-0070 (ORAUT 2008), and year-by-year air concentrations were calculated. The annual inhalation intakes in pCi/yr of Th-232 from Table 3-2 of Addendum 2 to the SEC-00079 Petition Evaluation Report were converted to units of dpm/calendar-day in Table C.3 of Appendix C. For example, for 1961, 20,256 pCi/yr × 2.22 dpm/pCi × 1 yr/365 calendar-days = 123 dpm/calendar-day. The calculations in the two documents are clear and correct. The approach of using air concentrations made during clean-up is clearly a bounding approach.

NIOSH notes that the values in Table C.3 should be used for Th-232, Th-228, and Ra-228, and that twice the Table C.3 values should be used for Th-230. The basis for the Th-230 assumption is assays of materials (soil, slag, and debris) removed during decontamination of the Dow Madison facility in 1992. A total of 100,614 tons containing 11.4 Ci of Th-230 and 5.7 Ci of Th-232 was shipped to Envirocare in Utah for disposal (Baker 1992, p. 3-1). SC&A believes that, at a facility such as this, it would be unlikely that Th-230 exposures would be greater than Th-232 exposures. However, the approach taken by NIOSH is certainly bounding.

Thoron Exposures

In Addendum 2 to the SEC-00079 Petition Evaluation Report, NIOSH analyzed thoron (Rn-220) measurements made in December 1959 during the melting and casting of HK31 alloy. From the selected dataset, NIOSH calculated that the 95th percentile thoron concentration was 0.182 pCi/L. When SC&A reviewed Addendum 2, we determined that the correct value for the 95th percentile was 0.247 pCi/L (SC&A 2008a). NIOSH used the corrected value of 0.247 pCi/L in Appendix C of TBD-6000 as the beginning thoron concentration for the residual period. The thoron concentration was then allowed to decay at the same exponential rate as was used for thorium in air (see Section 2.2.2.1.1). NIOSH also reported thoron exposures in WLM, although they did not define the units of measurement (presumably WLM per year), nor how units of pCi/L were converted to WL. We note in UNSCEAR 2000 (Annex B, p. 103) that for thoron, 1 Bq/m^3 equals 3.64 mWL (0.135 WL per pCi/L) at equilibrium. NIOSH cites essentially the same value (0.133 WL per pCi/L) in OCAS-TIB-0011 (NIOSH 2008b).

It appears, although not so stated, that NIOSH made the claimant-favorable assumption of equilibrium between Rn-220 and its progeny. DOE cites a default value for the thoron progeny equilibrium factor of 0.04 (DOE 1999, Table 4), while UNSCEAR cites a somewhat higher value of 0.1 (UNSCEAR 1993, Annex A, Para. 120). Both values are well below the equilibrium factor apparently assumed by NIOSH.

Ingestion Exposures

Estimates of thorium ingestion during the residual period are provided in Table C.3 of Appendix C. Thorium ingestion rates were calculated based on the concepts provided in OCAS-TIB-0009 (NIOSH 2004). Assuming a thorium air concentration of 8.44 pCi/m^3 in 1960, the ingestion rate in 1961 was 2.57 dpm/calendar per Table C.3 (8.44 pC/m^3 × 2.22 dpm/pCi × 0.2 × 250 work-days/365 calendar days. Ingestion exposures followed the same exponential decay rate as inhalation exposures. As discussed above for uranium, this approach appears to be claimant favorable.

3.0 TRANSPARENCY OF MODELING APPROACH

Numerous instances are included in the above discussion regarding how the dose reconstruction guidance was developed. It is often difficult to trace the assumptions to their source or to understand how the cited assumptions were actually implemented. In some cases, units of measurement are not clear. With minimal effort, NIOSH could significantly enhance the transparency of the dose reconstruction guidance.

Finding 5: NIOSH should focus additional attention on insuring the transparency of the dose reconstruction guidance.

4.0 REFERENCES

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