DEPARTMENT OF HEALTH & HUMAN SERVICES

Memorandum

Date January 10, 2007

From Lewis Wade, DFO

Subject Draft SC&A Report on Blockson Chemical

To The File

"" The attached Draft Letter Report, Blockson SEC Petition Review Issues, was issued on January 10, 2007. As stated in the Executive Summary, "This report presents SC&A's initial review of the Blockson Chemical Company Special Exposure Cohort (SEC) petition, Technical Basis Document (TBD), Evaluation Report, and selected supporting documentation….".

On January 8, 2007 Larry Elliott of NIOSH informed the Advisory Board that , "…NIOSH OCAS has decided to withdraw the SEC Petition Evaluation Report and the Blockson TBD for further evaluation and possible revision based on a determination of what radiation exposures must be included in dose reconstructions for former Blockson Chemical Workers." It is anticipated that once NIOSH releases an updated Petition Evaluation Report and TBD, the Advisory Board will ask SC&A to update its Draft Letter Report based on a review of the updated documents. At that time the SC&A updated report will be made public.

The Draft Letter Report dated January 10, 2007 is being made available to ensure complete public disclosure of the Advisory Board's activities. ""

Draft Letter Report

REPORT TO THE ADVISORY BOARD ON RADIATION AND WORKER HEALTH

National Institute for Occupational Safety and Health

FOCUSED REVIEW OF THE NIOSH EVALUATION REPORT FOR THE BLOCKSON CHEMICAL COMPANY SEC PETITION

Contract No. 200-2004-03805
Task Order No. 5

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Disclaimer

This document is made available in accordance with the unanimous desire of the Advisory Board on Radiation and Worker Health (ABRWH) to maintain all possible openness in its deliberations. However, the ABRWH and its contractor, SC&A, caution the reader that at the time of its release, this report is pre-decisional and has not been reviewed by the Board for factual accuracy or applicability within the requirements of 42 CFR 82 and 42 CFR 83. This implies that once reviewed by the ABRWH, the Board's position may differ from the report's conclusions. Thus, the reader should be cautioned that this report is for information only and that premature interpretations regarding its conclusions are unwarranted.

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EXECUTIVE SUMMARY

This report presents SC&A's initial review of the Blockson Chemical Company Special Exposure Cohort (SEC) petition, Technical Basis Document (TBD), Evaluation Report, and selected supporting documentation, including ORAUT-OTIB-0043 (ORAU 2006), which describes National Institute for Occupational Safety and Health's (NIOSH's) generic default methods for reconstructing exposures to radon and its short-lived progeny for Atomic Energy Commission (AEC) contract workers involved in the recovery of uranium from phosphate materials. This report is limited to the identification of potential issues, especially those that might be considered SEC-related issues. It does not contain a detailed analysis of the issues, and is intended solely for use by the designated working group for Blockson Chemical Company.

SC&A has identified the following seven findings.

***Finding No. 1*:** The default upper-bound uranium inhalation rate of 82 pCi/day of Type M uranium, which was derived based on bioassay data and which is used in the TBD as the upper-bound intake rate for all production workers at Blockson, would result in a large underestimate of the doses to some organs if the uranium at the site behaved more as Type S than as Type M. It is not apparent from our review of the TBD that exposures to uranium at Blockson consisted entirely of Absorption Type M. If there are uncertainties regarding this matter, NIOSH should consider adopting the strategy used in the exposure matrix for Chapman Valve, where the dose reconstructor would use the form of uranium (i.e., Type M or Type S) that results in the highest dose to the organ of concern.

***Finding No. 2*:** Since the ratio of the concentration of U-238 to Th-232 in phosphoric acid is reported to be as high as about 10:1, NIOSH should consider adopting a high-end default intake rate for Th-232 and Th-228 of about 8.2 pCi/day instead of 1.1 pCi/day. NIOSH adopted an intake rate of 1.1 pCi/day for Th-232 and Th-228 based on the ratio of U-238 to Th-232 observed in phosphate ore concentrate, which, on face value, would appear to be an appropriate approach. However, based on a report by Guimond et al. (1977), it appears that Th-232 might be more efficiently partitioned to the phosphoric acid stream than uranium, resulting in an enrichment of Th-232 relative to that of U-238.

***Finding No. 3*:** The TBD should explicitly include Th-230 in the exposure matrix. The TBD seems to have overlooked the possibility that Th-230 also partitioned to the phosphoric acid stream along with uranium. If this occurred, Th-230 would not have been detected by the bioassay program, but could have contributed significantly to the internal doses; hence, the possibility of an important missed dose.

***Finding No. 4*:** The TBD should address whether a separate waste stream containing thorium raffinates might have been produced during the processing of the uranium and, if such a stream was produced, there is a need to develop a method for reconstructing the doses associated with exposures to the raffinates.

***Finding No. 5*:** It is not apparent that 0.036 WLM/yr, which is adopted in the TBD for deriving upper-bound internal doses to Blockson workers from radon and its short-lived progeny, is a

plausible and bounding exposure rate as applied to Blockson. The TBD based its default value by selecting the best estimate of a vast amount of data gathered at phosphate mining and processing facilities in Florida, as reported in ORAU 2006. ORAU 2006 makes an effort to select data that might be applicable to facilities such as Blockson (i.e., facilities contracted by the AEC to separate uranium from phosphate ores). However, additional information is needed regarding the location, size, and characteristics of the tailings piles, which contain the radium, at Blockson and at the Florida facilities in order to support the default value adopted in the TBD.

***Finding No. 6*:** If the tailings produced during routine phosphate ore processing operations at Blockson were used as construction fill or in the actual construction of Building 55, the levels of radon and its short-lived progeny in Building 55 might have been higher than the values adopted in the TBD. SC&A's review of data gathered during the radiological survey performed at the site in 1978 as part of the Formerly Utilized Site Remedial Action Program (FUSRAP) (DOE 1978) seems to indicate that tailings were not used in such a manner. Nevertheless, a review of historical records regarding the construction of Building 55 and a review of the radiological surveys performed in support of the FUSRAP investigations might help to answer this question.

***Finding No. 7*:** The TBD should explicitly address the amounts of Ra-226 and its short-lived progeny that may have partitioned into the phosphoric acid stream, the various byproducts associated with uranium separation and purification, and in the final uranium product. Even if only a small fraction of the Ra-226 in ore partitioned to the phosphoric acid stream, it has the potential to contribute significantly to the external exposures experienced by workers, due to the relatively high-photon flux from its short-lived progeny, especially Bi-214.

In the opinion of SC&A, among these findings, Finding 4 has the greatest potential to represent an SEC issue because, if determined to be valid, it is not immediately apparent how this issue can be resolved.

1.0 INTRODUCTION AND SCOPE

During the meeting of the Advisory Board on Radiation and Worker Health (the Board) held in Naperville, Illinois, on December 11–13, 2006, SC&A was directed to perform a focused review of the Special Exposure Cohort (SEC) petition and the National Institute for Occupational Safety and Health's (NIOSH's) evaluation of the petition for Blockson Chemical Company. This report presents the results of SC&A's review. This report is designed to be used by the Board as part of the basis for determining whether radiation doses can be estimated with sufficient accuracy based on the following criteria:

> *Radiation doses can be estimated with sufficient accuracy if NIOSH has established that it has access to sufficient information to estimate the maximum radiation dose, for every type of cancer for which radiation doses are reconstructed, that could have been incurred in plausible circumstances by any member of the class, or if NIOSH has established that it has access to sufficient information to estimate the radiation doses of members of the class more precisely than an estimate of the maximum radiation dose* [42 CFR 83.13(c)(1)].

The scope of this report consists of a technical review of the latest version of the site profile (OCAS 2006) (also referred to as the Technical Basis Document (TBD)), the petition (Petition SEC-00058 and -00045), the evaluation report (NIOSH 2006), and applicable technical information bulletins (specifically ORAU 2006), and selected other references as judged to be pertinent to the identification of potential SEC issues. Specific attention is given to the radon model proposed by NIOSH and related radon exposure issues. To the extent feasible, this report identifies those issues that, in the opinion of SC&A, might rise to the level of an SEC issue, including a brief description of our rationale for raising these issues. SC&A was specifically directed not to perform a full SEC petition review at this time, as described in our draft SEC petition review procedures (SC&A 2006). As such, this report does not present an in-depth analysis of any of the issues, nor does the work performed by SC&A in support of this report include SC&A interviews with any claimants or petitioners.

This report includes 2 attachments that address two issues in some detail that are especially important to this review. Attachment 1 addresses Th-230, which is a radionuclide that is not addressed in the TBD but could be an important contributor to the radiation exposures experienced by AEC contract workers at Blockson. Attachment 2 addresses in some detail potential exposures of AEC contract workers to radon and its progeny. Attachment 2 includes an aerial photograph of the facility, which helps in understanding the proximity of Building 55 to the phosphogypsum storage pile (i.e., the principal source of exposure to radon and its progeny).

2.0 BACKGROUND INFORMATION

On August 9, 2006, SEC-00058 was qualified by the Department of Health and Human Services (Federal Register Vol. 71, No.159, August 17, 2006). On September 9, 2006, NIOSH issued its SEC Evaluation Report for Petition SEC-00058. The petitioner's class definition is as follows:

> *All Atomic Weapons Employer [AEC] employees, contractors, and subcontractors, who worked in Building 55 at the Blockson Chemical Company (also known as Olin Matheson) from January 1, 1951 to December 21, 1962.*

NIOSH's proposed class definition is slightly different than the petitioner's definition, as follows:

> *All Atomic Weapons Employer personnel who worked on uranium recovery pilot studies and/or in Building 55 of the Blockson Chemical Company, Joliet, Illinois, from January 1, 1951 through December 31, 1962.*

The main differences between the two definitions are that NIOSH excluded subcontractors from the definition, as required by Statute for AWE facilities, but expanded the scope of the class by including workers that were involved in the pilot studies, which preceded AEC operations in Building 55 under contract to the Atomic Energy Commission (AEC).

In the evaluation report, NIOSH concludes that "it has access to sufficient information to (1) estimate the maximum radiation dose incurred by any member of the class; or (2) estimate radiation doses more precisely than a maximum dose estimate." NIOSH states that the basis for this conclusion is information available from the site profile and additional resources. Section 7.4 of the evaluation report explicitly addresses each of the issues raised in the petition, and provides NIOSH's rationale for its determination that, notwithstanding the issues raised in the petition, doses can be reconstructed with sufficient accuracy. In the sections that follow, SC&A presents a brief description of the various possible exposure scenarios for AEC contract workers at Blockson and the data, methods, and assumptions used by NIOSH in the site profile and evaluation report for reconstructing worker doses. Each description is followed by a review of the methods adopted by NIOSH for reconstructing doses, including potential SEC-related issues. An issue is considered "SEC-related" if it raises a question that doses may not be able to be reconstructed with sufficient accuracy.

3.0 OVERVIEW OF BLOCKSON AEC OPERATIONS, SOURCES OF EXPOSURE TO RADIOACTIVE MATERIALS, AND EXPOSURE SCENARIOS

A letter from E.B Lopker, Director of Engineering at Blockson Chemical Company, to Sheldon Wimpfen of the Atomic Energy Commission, dated July 31, 1951, describes the process for recovering uranium from phosphate rock.[1] In addition, a report by Emil M. Stoltz (Stoltz 1953) presents a detailed description of the chemical processes used to recover uranium from phosphate rock. These documents present the various research activities and pilot studies performed by Blockson, and the methods adopted by Blockson to efficiently and economically recover uranium from phosphate rock on a commercial scale. These reports explain that Blockson Chemical Company was one of several companies actively engaged in the commercial processing of phosphate rock.

Blockson received phosphate ore concentrates from Florida mining operations and produced technical grades of sodium phosphate, which met strict purity specifications. Blockson differed from many other phosphate ore processing companies because most other companies produced triple phosphates, for which the purity requirements were not nearly as stringent. This distinction is being pointed out because Blockson had to carefully research a number of different strategies in order to continue to produce technical grades of sodium phosphate, and also cost-effectively separate the uranium contained in the ore. Based on our review of the literature, it appears that, in order to produce a high level of purity in its phosphate product and also meet AEC requirements to extract uranium from the phosphate ore, some changes had to be made to the overall chemical operations at Blockson. For example, it appears that the calcining process and perhaps some of the steps in the treatment of phosphoric acid to produce sodium phosphate were also modified.

This point is being made because the evaluation report and site profile describe the AEC operations as a simple add-on to ongoing operations, where the phosphoric acid was processed using the procedures described in Figure 2 of the TBD to produce sodium phosphate, and the filtrate was then processed to recover the uranium contained therein. It appears that many of the steps may have been modified in order to accommodate the AEC portion of the operations. This brings us to our first observation. In addition to the exposures associated with the AEC operations, NIOSH should describe the changes in the overall operations in order to fully disclose and characterize how these changes may have impacted the radiation exposures experienced by workers involved in both AEC and non-AEC operations at the facility.

Without going into the details, as provided in Stoltz (1953), the overall process used by Blockson to produce their primary product, technical grade sodium phosphate, required that, prior to being shipped from the mine in Florida, the ore was processed to ore concentrates, which were then shipped to Blockson. Table 1 summarizes the radiological characteristics of typical Florida phosphate mine products.

[1] On October 10, 1951, a contract was executed between the Atomic Energy Commission and Blockson Chemical Company for the scope of services described in the letter from E.B. Lopker (Contract No. AT-(49-1)-611).

Table 1: Natural Radioactivity Concentrations in Florida Phosphate Mine Products and Wastes
(pCi/gm) (from Guimond et al. 1977)

Material	Ra-226	U-238	Th-230	Th-232
Marketable Rock	42	41	42.3	0.44
Slimes	45	44	48	1.4
Sand Tailings	7.5	5.3	4.2	.89

As may be noted, the marketable rock contained U-238 series radionuclides in equilibrium, and typical background concentrations of Th-232.

At Blockson, the ore concentrates were heated (calcined) to destroy organic matter. In order to optimize the oxidation of the uranium in the ore concentrates in a manner that was able to increase the efficiency in the recovery of uranium, special calcining procedures were developed (Stoltz 1953). This is one of the fundamental changes made to its ore processing procedures in order to accommodate uranium recovery, and which could have impacted non-AEC contract workers.

The calcined ore concentrates were then pulverized to the required degree of fineness. Sulfuric acid was then added to the pulverized ore concentrates, creating calcium sulfate and phosphoric acid. The calcium sulfate (gypsum or phosphogypsum) produced in this reaction was separated from the phosphoric acid using conventional methods. The phosphogypsum was then sent to the phosphogypsum storage pile (tailings) as a slurry, creating a large phosphogypsum pile (see Figure 2-1 in Attachment 2). Because of the chemical similarity of radium and calcium, the majority of the radium partitioned with the gypsum and was transported to the phosphogypsum pile. However, about 1% of the Ra-226 (by activity) remained with the phosphoric acid (Guimond et al. 1977; Roessler et al. 1979).

The tailings, which were stored on site, represented a source of exposure of all workers to Ra-226 and radon and its progeny, and also to lower concentrations of uranium and thorium. These tailings and their associated exposures to radioactive material occurred as a byproduct of the production of sodium phosphate, and not specifically as a result of AEC contract operations. Hence, exposures that were part of the standard phosphate production operations at such facilities are not of concern to this report. However, exposures to the radium and radon in the tailings of workers that were onsite specifically in support of AEC contract operations are appropriately included in the dose reconstruction. NIOSH addresses these sources of worker exposure in its site profile and evaluation report, and these exposure scenarios are included in our review of those documents.

The phosphoric acid produced in the reaction of sulfuric acid with the ore concentrate contained numerous impurities, including calcium, iron, aluminum, sulfate, fluorine, and fluorosilicate. Among these impurities are uranium, chromium, vanadium, magnesium, and manganese. In addition, the Th-232 and Th-230 contained in, or associated with, the original ore stayed primarily with the phosphoric acid (Guimond et al. 1977; DOE 1978). The various chemical and physical operations performed on the phosphoric acid and the resulting production of sodium

phosphate, and also the production and storage of the uranium product, constitute the AEC contract operations that took place at Blockson. Figure 2 of the TBD presents the flow diagram for the production of sodium phosphate and uranium from the phosphoric acid. The steps in this process were developed by Blockson to produce both high quality sodium phosphate and purified uranium. It is our understanding, based on Blockson (1951), that this process was tailored to meet both needs, and was different than the original process employed by Blockson when its primary product was sodium phosphate. Hence, this is another example where it appears that the overall process was modified to accommodate the AEC contract.

The processing of phosphoric acid for the removal and purification of sodium phosphate and uranium involved the following steps:

(1) Chlorination of the phosphoric acid in order to oxidize the uranium

(2) Neutralization of the solution with soda ash (NaOH), which produced monosodium phosphate (that contained the uranium) and the precipitation of iron and aluminum salts for removal

(3) The addition of sodium hydrosulfite to the monosodium phosphate liquor to precipitate out the uranium for filtration (the monosodium phosphate solution was the input stream to sodium phosphate production)

(4) The uranium precipitate was purified by a series of steps involving redisolution and reprecipitation and filtration

The final product was 50% to 60% U_3O_8. The purified uranium was dewatered, dried, and then deposited into 55-gallon storage drums, either by shovel or through the use of a hopper.

The entire process involved processing about 6,000 net tons of phosphate rock per week, which contained an average of 0.014% U_3O_8, and the production of about 50,000 pounds of uranium oxide per year in the form of a dry powder, containing 50% to 60% U_3O_8. The uranium oxide product was deposited into 55-gallon drums, each containing about 1,000 pounds of uranium product. Hence, about 1 drum was produced per week. Exposures experienced by the workers involved in these operations, and also workers that were onsite while these operations took place, are of concern to the petitioners and are the subject of the SEC petition, the site profile, the petition evaluation report, and this report.

In the sections that follow, a description is provided of the data, models, and assumptions used by NIOSH to reconstruct the doses to workers from processing the phosphoric acid, under contract to the AEC, for the purpose of producing a high-quality uranium product for use in the weapons production program. The sections are organized according to the various exposure scenarios. As part of these descriptions, SC&A provides commentary with regard to issues that need to be addressed that may be pertinent to the completeness, scientific robustness, and claimant-favorability of the dose reconstruction methods adopted by NIOSH.

In this report, a distinction is made between "site profile issues" and "SEC-related issues." A site profile issue is one where SC&A raises a concern regarding the completeness, scientific robustness, and/or claimant-favorability of the dose reconstruction methods, and, based on our limited review of the issue, it appears that NIOSH could develop methods to address the issue. An SEC-related issue is one where it is not immediately apparent that sufficient data and/or process knowledge are available to correct the deficiency and, if left uncorrected, could result in the inability to reconstruct doses with sufficient accuracy.

As an aid to the reader, we would like to point out at this time that among the various issues identified in the following sections, it appears that at least one issue, if found to be valid by NIOSH and the Board, might rise to the level of an SEC issue. This issue has to do with internal exposures to Th-230. Our concern regarding Th-230 relates to the fact that NIOSH models do not address exposure to Th-230 and the possibility that Th-230 was produced as a raffinate in the uranium production process. If Th-230 was produced as a raffinate, it could have dried out, become airborne, and resulted in an undetected source of internal exposures.

In our initial review of the TBD, we also had concerns regarding radon exposures, which we believed might be an SEC-related issue. Our concerns had to do with uncertainties regarding the proximity of the phosphogypsum tailings to Building 55, where the AEC contract operations took place, or whether tailings were used as construction fill or construction material in Building 55. If the tailings were used in this manner, the methods adopted by NIOSH to reconstruct doses from the inhalation of radon and its progeny might not be valid, and it was not immediately apparent how such doses can be reconstructed. In order to further explore this potential issue, we reviewed other selected reports, especially the FUSRAP report prepared by the Department of Energy in 1978 (DOE 1978). As discussed in Attachment 2, we determined that the characterization of the site and radiological measurements made in and around Building 55 at that time suggest that the tailings were several hundred yards away from Building 55, and that the radiological condition, at least in 1978, indicate that tailings were not used as construction material. However, this matter requires further investigation, as described below.

Our limited investigations into the remaining issues discussed in the following sections indicate that NIOSH should be able to develop strategies to address these issues using available data and process knowledge. Hence, at this point in the review process, these other issues do not appear to be SEC issues.

4.0 INTERNAL DOSE FROM URANIUM

Section 3.1 of the TBD presents the data, models, and assumptions used by NIOSH to develop the exposure matrix for deriving internal doses to AEC contract workers from the intake of uranium. The TBD explains that, among the various steps used to extract and produce uranium from phosphoric acid at Blockson, the handling of dried uranium compounds in the packaging area in Building 55 created the greatest potential for internal exposures to uranium. SC&A agrees with this conclusion, as long as a separate dry thorium raffinate stream was not produced during the purification of the uranium (this topic is discussed below in Section 5.3).

The TBD explains that no air-sampling data were collected at Blockson; however, a review of the literature is provided in the TBD that describes the various steps in the production of U_3O_8 (also referred to as yellowcake) **at uranium mills**, and the data characterizing the concentration of airborne and deposited uranium oxide dust at various locations throughout uranium mills. The TBD summarizes the air-sampling data collected before, during, and after yellowcake packaging at these facilities, and found that the **median** airborne concentrations of uranium ranged from 40 to 340 $\mu g/m^3$ (27 to 498 pCi/m^3).

As explained in the TBD, the uranium mill air-sampling data cited in the TBD are considered by NIOSH to be of limited applicability to Blockson because of significant differences in the concentration of uranium in uranium ore as compared to phosphate rock, differences in the production rate of uranium, and differences in the operational practices and design of uranium mills as compared to phosphate production facilities. The TBD explains that Blockson produced about 5 drums of yellowcake per month, each containing about 1,000 pounds of yellowcake, while the production rate of uranium at uranium mills is much greater.

SC&A does not necessarily agree with this conclusion, because, though the total number of exposed workers would differ due to differences in uranium production rates, the high-end exposures to individual workers at both types of facilities may be similar since the uranium packaging operations were likely similar. One could postulate that, at both facilities, the limiting exposure was to those individuals that worked full time at uranium packaging operations, and that the local dust loadings associated with uranium packaging operations were similar at both types of facilities. Under these conditions, the size of the operation wouldn't affect the high-end exposures. However, we acknowledge that, if the uranium packaging operations at Blockson did not require at least 1 full-time operator, while packaging operations at uranium mills required at least 1 full-time operator, then exposures to uranium packaging personnel at uranium mills could have been higher than at the Blockson facility.

The TBD also explains that air-sampling data are not essential in the case of Blockson, because a considerable amount of data are available characterizing the uranium concentrations in urine samples collected from AEC contract workers at Blockson during the time period covered by the petition. SC&A agrees that bioassay samples are preferable to air-sampling data if the bioassay data are adequate to reconstruct doses with sufficient accuracy. This means that sufficient data need to be available to either accurately reconstruct internal doses or place a plausible upper bound on the internal doses experienced by all workers. This section explores the degree to which the bioassay data satisfy this criterion.

The evaluation report states that, "NIOSH obtained results from 122 urine samples collected from 25 different workers between 1954 and 1958." This is as compared to the worker population cited in Blockson (1951) that states that the annual labor costs required to produce 50,000 pounds of yellowcake per year is estimated to be about $84,000. This cost estimate was based on 2 operators per shift, 1 chemist per shift, 2 daymen, 2 mechanics, 1 clerk, 1 developmental chemist, and 1 foreman. Hence, staffing of the operation was estimated by Blockson Chemical Company (1951) to be about 10 workers on site at any given time. Understanding the worker population is important, because it provides the baseline information needed to determine if the bioassay data provide the information needed to judge whether internal doses could be reconstructed with sufficient accuracy.

The TBD states that the first bioassay sample was reported as collected in April 1954 and on nine other occasions, as reported by the AEC Health and Safety Laboratory in February 1958. The TBD also states that 122 sample results are available, with results ranging from 0 to 17 μg U/L of urine. Fluorometric analyses were performed on each sample, yielding the uranium concentration in urine on the date the sample was collected. Using these data, the TBD estimates that the upper 95% uranium inhalation rate for production workers (i.e., the workers with the highest potential for exposure) is 82 pCi/day. The TBD also determined that the most likely form of uranium was Type M.

As an independent check, we downloaded the hand-written bioassay records for Blockson provided on the NIOSH Site Query Database and found the following:

Table 2: Bioassay Results

Person	Date Urine Sent or Received	Urine Bioassay Result (mg U/L)
1	1/18/1956	0.001
	5/31/1956	0.013
	10/18/1956	0.004
	3/28/1957	0.001
	8/15/1957	0.002
	2/20/1958	None reported
2	1/18/1956	0.001
	5/31/1956	0.002
	10/18/1956	0.002
	3/28/1957	0.001
	8/15/1957	None reported
	2/20/1958	0.000
3	1/18/1956	0.002
	5/31/1956	0.008
	10/18/1956	0.004
	3/28/1957	0.005
	8/15/1957	0.003
	2/20/1958	None reported

Table 2: Bioassay Results

Person	Date Urine Sent or Received	Urine Bioassay Result (mg U/L)
4	1/18/1956	0.001
	5/31/1956	0.002
	10/18/1956	None reported
	3/28/1957	None reported
	8/15/1957	None reported
	2/20/1958	None reported
5	1/18/1956	0.007
	5/31/1956	None reported
	10/18/1956	None reported
	3/28/1957	None reported
	8/15/1957	None reported
	2/20/1958	None reported
6	1/18/1956	0.004
	5/31/1956	0.006
	10/18/1956	0.002
	3/28/1957	0.002
	8/15/1957	0.002
	2/20/1958	0.002
7	1/18/1956	0.002
	5/31/1956	0.004
	10/18/1956	0.003
	3/28/1957	None reported
	8/15/1957	None reported
	2/20/1958	None reported
8	1/18/1956	0.001
	5/31/1956	0.000
	10/18/1956	0.002
	3/28/1957	0.001
	8/15/1957	0.004
	2/20/1958	None reported
9	1/18/1956	0.001
	5/31/1956	0.006
	10/18/1956	0.000
	3/28/1957	0.004
	8/15/1957	0.001
	2/20/1958	0.002
10	1/18/1956	0.003
	5/31/1956	0.014
	10/18/1956	0.002
	3/28/1957	0.002
	8/15/1957	0.000

Table 2: Bioassay Results

Person	Date Urine Sent or Received	Urine Bioassay Result (mg U/L)
	2/20/1958	0.000
11	1/18/1956	0.003
	5/31/1956	0.004
	10/18/1956	0.001
	3/28/1957	0.005
	8/15/1957	0.003
	2/20/1958	None reported
12	1/18/1956	0.002
	5/31/1956	None reported
	10/18/1956	None reported
	3/28/1957	None reported
	8/15/1957	None reported
	2/20/1958	None reported
13	1/18/1956	None reported
	5/31/1956	0.002
	10/18/1956	0.002
	3/28/1957	0.002
	8/15/1957	0.001
	2/20/1958	0.000
14	1/18/1956	None reported
	5/31/1956	None reported
	10/18/1956	None reported
	3/28/1957	0.001
	8/15/1957	0.001
	2/20/1958	0.000
15	1/18/1956	None reported
	5/31/1956	None reported
	10/18/1956	None reported
	3/28/1957	0.001
	8/15/1957	None reported
	2/20/1958	None reported
16	1/18/1956	None reported
	5/31/1956	None reported
	10/18/1956	None reported
	3/28/1957	0.001
	8/15/1957	0.005
	2/20/1958	0.000
17	1/18/1956	None reported
	5/31/1956	None reported
	10/18/1956	None reported
	3/28/1957	None reported

Table 2: Bioassay Results

Person	Date Urine Sent or Received	Urine Bioassay Result (mg U/L)
	8/15/1957	0.002
	2/20/1958	None reported
18	1/18/1956	None reported
	5/31/1956	None reported
	10/18/1956	None reported
	3/28/1957	None reported
	8/15/1957	0.001
	2/20/1958	0.002
19	1/18/1956	None reported
	5/31/1956	None reported
	10/18/1956	None reported
	3/28/1957	None reported
	8/15/1957	None reported
	2/20/1958	0.006
20	1/18/1956	None reported
	5/31/1956	None reported
	10/18/1956	None reported
	3/28/1957	None reported
	8/15/1957	None reported
	2/20/1958	0.000
21	1/18/1956	None reported
	5/31/1956	None reported
	10/18/1956	None reported
	3/28/1957	None reported
	8/15/1957	None reported
	2/20/1958	0.002
22	1/18/1956	None reported
	5/31/1956	None reported
	10/18/1956	None reported
	3/28/1957	None reported
	8/15/1957	None reported
	2/20/1958	0.004

As shown, the records available to SC&A for review at this time indicate that 69 bioassays were performed on 22 workers on one or more of the following dates:

January 18, 1956
May 31, 1956
October 18, 1956
March 28, 1957
August 15, 1957
February 20, 1958

Clearly there is some disparity between the time periods and numbers of urine analyses reported in the TBD and that found by SC&A to date. This disparity should be resolved. However, the range of concentrations of uranium in urine, as reported in the TBD and in the above table, is quite similar (i.e., 0–0.014 versus 0–0.017 mg U/L).

Taking the TBD at face value regarding the number of samples, it appears that a relatively large fraction of the workers received multiple bioassays. Specifically, given that 122 urine samples were collected from 25 workers primarily over a 5-year period (1954–1958) as stated in the TBD, an average of 1 bioassay per year was collected from each worker over the 5-year period of AEC contract operations at Blockson when bioassay data were collected. In reality, as evidenced by Table 2, at least some workers received at least three bioassays in 1956 and 1957. Whether or not such a sample is deemed to be sufficiently representative of the exposures experienced by the workers depends on the range of differences in exposures among workers and categories of workers, the range of differences in exposures as a function of time, and whether the uranium inhaled or ingested by workers is rapidly cleared (i.e., whether the uranium was Absorption Type F, M, or S). The latter question is important, because, if the uranium were Type F or Type M, a worker could have experienced a large intake, but a urine analysis could have missed it.

Based on our review of the literature, it is likely that the uranium to which workers were exposed was either Type M or Type S. In either case, it appears that, if a given worker experienced one or more large acute intakes, it is likely that at least one of the samples would have revealed such an intake. **Nevertheless, the TBD would do well to explore this issue and demonstrate that either (1) the bioassay program would have detected a large intake or (2) that the exposure matrix adopted by NIOSH for dose reconstruction is sufficiently conservative to provide a high level of assurance that no workers likely experienced a cumulative intake in excess of the intakes adopted in the exposure matrix.**

SC&A believes that such an analysis can and should be performed, thereby demonstrating that a plausible upper bound can be, and has been, placed on the time-integrated uranium intake experienced by all workers. As a quick check on this issue, SC&A ran IMBA using the default upper-bound chronic uranium inhalation rate adopted in Table 1a of the TBD for use in dose reconstructions for production workers (i.e., 82 pCi/day). Assuming Type M uranium with 5 micron AMAD, the chronic uranium excretion rate associated with a chronic inhalation rate of 82 pCi/day is 5.7 pCi/L. Using a natural uranium specific activity of 683 pCi U/mg, the mass concentration in urine is 0.008 mg/L. Hence, the default uranium intake rate of 82 pCi/day results in a chronic concentration of uranium in urine that is toward the high end of the concentrations observed in workers. The assumption that all production workers have a chronic intake of 82 pCi/day, and therefore a chronic urine concentration of 0.008 mg/L, appears to be bounding, given the actual uranium concentrations observed in the workers. It is important to recognize that, though some workers at some points in time were observed to have uranium concentrations in urine greater than 0.008 mg/L, it appears to be highly conservative to assume that the same worker was chronically exposed for 8 hours per day, 7 days per week, 52 weeks per year for every year he or she worked at Blockson, such that the uranium concentration in urine was chronically at or above 0.008 mg/L for that entire time. For this reason, we believe the exposure matrix in the TBD is bounding **if the uranium was Type M**.

It is important to recognize that the exposure matrix adopted in the TBD assumes that all production workers were exposed to 82 pCi/day every calendar day per year, which translates to 29,930 pCi/yr. The question becomes, is it possible that the bioassay program could have missed a large acute intake that one or more workers might have experienced, where an acute intake comparable to 29,930 pCi would be considered large, because it would double the annual intake?

In order to evaluate the likelihood that such intakes could have occurred and be missed by the bioassay program, Figure 1 presents the uranium concentration in urine as a function of time following an acute intake of 29,930 pCi of Type M uranium. Given that the lower limit of detection is between 0.002 and 0.0038 mg U/L of urine (see Section 7.1.1 of the evaluation report), such an intake would have been detectable for about 150 days following intake. Given that virtually all workers appear to have had at least 1 urine sample per year, it is unlikely that such an exposure could have occurred without being detected. Another consideration related to this scenario is that such an acute exposure would be associated with an 8-hour dust loading of 4.5 mg/m^3. Section 4.1.2 of ORAU 2006 cites a study that found airborne particulate concentrations at a phosphate plant ranged from 10 to 100 mg/m^3; hence, it appears that the potential existed for dust loadings to reach as high as several mg/m^3 at phosphate facilities for short periods of time. The implications are that such an exposure scenario is not out of the question, but if it did occur, it would have been detected by the bioassay program and is, defacto, accommodated by the default uranium intake rates used in the TBD.

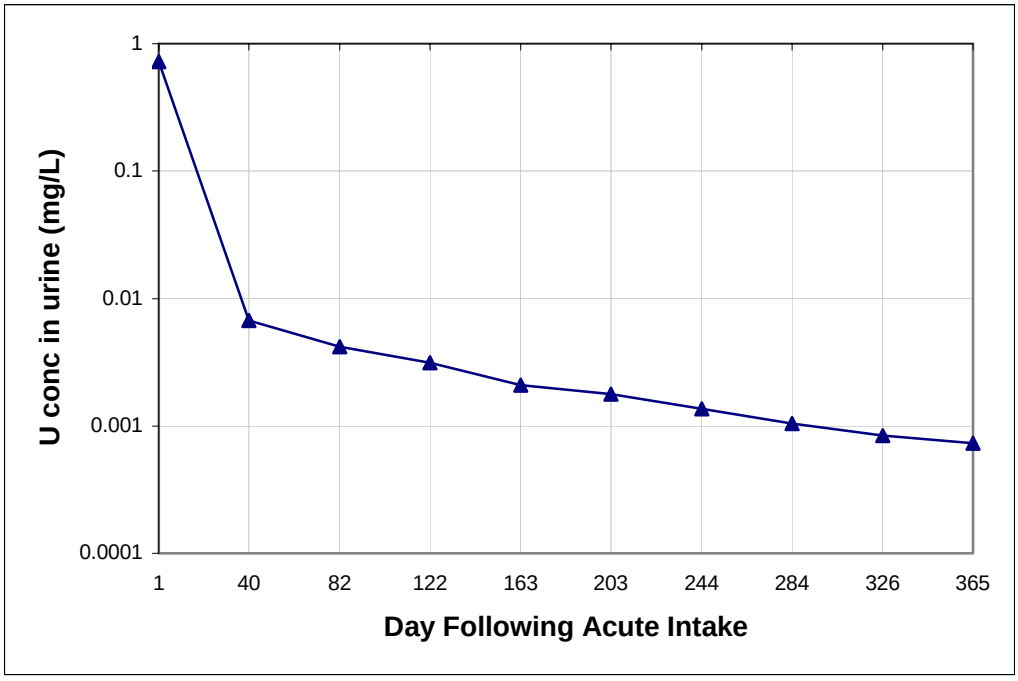

Figure 1: Concentration of Uranium in Urine Following Acute Intake of 2.933E4 pCi Type M

The above conclusions are valid only if the inhaled uranium was Type M, as assumed in the TBD. However, if the inhaled uranium was Type S, a chronic inhalation rate of over 4,000 pCi/day would be required in order to observe a chronic concentration of 0.017 mg U/L in urine (i.e., the upper-bound excretion rate observed among the urine samples collected at

Blockson). The implications of this scoping analysis are that, if the uranium inhaled by AEC contract workers at Blockson were Type S, the inhalation rate could have been much higher than that adopted by NIOSH in the exposure matrix. This would mean that the default assumptions adopted by NIOSH in the TBD for estimating the doses to workers from the inhalation of uranium could result in a significant underestimate of the doses to some organs, particularly the lungs. When one considers that (1) the uranium produced at Blockson was primarily U_3O_8, (2) that an inhalation rate of 4,000 pCi/day is associated with an airborne uranium dust loading of 357 pCi/m^3, and (3) the observed dust loading at uranium mills ranged from 27 to 498 pCi/m^3 (see above discussion), it seems plausible that the uranium at Blockson could have been Type S.

Finding No. 1: The default upper-bound uranium inhalation rate of 82 pCi/day of Type M uranium would result in a large underestimate of the doses to some organs if the uranium at the site behaved more as Type S than as Type M.

In SC&A's opinion, this finding does not appear to be an SEC issue, because if it is found to be a valid concern, NIOSH can modify its exposure matrix to take into consideration the possibility that the uranium was Type S. This strategy was adopted by NIOSH in the exposure matrix for Chapman Valve, and it seems appropriate to adopt a similar strategy here, unless it can be demonstrated with certainty that the chemical form of the uranium at Blockson was, in fact, Type M.

5.0 INHALATION OF THORIUM

Our review of the TBD identified a number of issues associated with the methods adopted by NIOSH for addressing possible exposures to thorium, one of which we consider to be a possible SEC issue. Given its importance, this issue was independently evaluated by SC&A radiochemists, and the results of that evaluation are presented in Attachment 1.

5.1 THORIUM-232 AND THORIUM-228

Table 1a of the TBD assumes that the intake rate of Th-232 and Th-228 for production workers is 1.1 pCi/day. On first inspection, this appears to be reasonable, because the typical concentration of Th-232 in phosphate rock concentrate is reported as 0.44 pCi/g, while the average concentration of U-238 in phosphate rock concentrate is cited as 31.9 pCi/g (see Section 4.1.2 in the TBD). Hence, the ratio of U-238 to Th-232 in typical phosphate rock concentrate is about 72:1. Accordingly, given that the high-end intake rate of uranium is 82 pCi/day, the high-end intake rate for Th-232 (and its progeny Th-228) would be expected to be about 1.1 pCi/day. However, inspection of the U-238 and Th-232 concentration in phosphoric acid, as reported in Guimond et al. 1977, reveals that the ratio is closer to 8:1 to 10:1. The implications are that the Th-232 in phosphate rock concentrate might be more available for partitioning to phosphoric acid than the uranium in phosphate rock concentrate. If this is, in fact, the case, then the default high-end intake rate of Th-232 and Th-228 for production workers at Blockson should be perhaps 8 to 10 times higher than the values adopted in the TBD. It is also noteworthy that Table 1 of DOE 1978 reveals that the ratio of U-238 to Th-232 in the sodium phosphate solution was closer to 40:1. The data, therefore, appear to be somewhat ambiguous regarding this matter and require further investigation.

Finding 2: Since the ratio of the concentration of U-238 to Th-232 in phosphoric acid might be as high as 10:1, consideration should be given to assigning a high-end default intake rate for Th-232 and Th-228 of about 8.2 pCi/day instead of 1.1 pCi/day.

We do not consider this to be an SEC issue, because, if this finding is determined to be correct, the TBD can be easily revised.

5.2 THORIUM-230

The TBD is silent regarding the contribution of Th-230 to the internal doses. According to Guimond et al. (1977), and Table 2 of FIPR 1998, Th-230 was found to be in equilibrium with U-238 in phosphoric acid. The implications are that the activity concentration of Th-230 in the uranium product should be the same as U-238. Hence, the intake rate of Th-230 should be explicitly considered in the TBD, and it should be comparable to that of U-238 if the Th-230 remains with the uranium throughout the process. Th-230 could be an important contributor to internal dose, because the dose conversion factors for the various organs for Th-230 are larger than those for U-238. For example, the inhalation dose conversion factors (expressed in terms of 50-year effective dose commitment) reported in the International Commission on Radiological Protection (ICRP) Publication No. 68 (ICRP 1994) for 5 micron Types M and S uranium are 1.6E-6 and 5.7E-6 Sv/Bq inhaled, respectively. For Th-230, the respective inhalation dose

conversion factors are 2.8E-5 and 7.2E-6 Sv/Bq inhaled; i.e., by not considering Th-230, the effective dose commitment, if limited to only uranium inhalation, might be underestimated by 17.5-fold for Type M or about 1.3-fold for Type S Th-230.

Finding 3: The TBD should explicitly include Th-230 in the exposure matrix.

We do not consider this to be an SEC issue, because, if this finding is determined to be correct **and if the Th-230 remains with the uranium**, the TBD can be easily revised to accommodate this source of exposure.

5.3 POSSIBLE THORIUM-230 RAFFINATES

As discussed above, the TBD is silent regarding the contribution of Th-230 to the internal doses to AEC contract workers; but this issue can be resolved if the Th-230 remains with the U-238 in the same proportion as in the ore. However, it is not apparent that the Th-230 (and the Th-232 and Th-228) remains with the uranium through all the purification steps, up to and including the production of the uranium product. If thorium is separated from the uranium at one of the purification steps, a thorium raffinate might be produced. If this raffinate dries out and becomes airborne, it may not be feasible to reconstruct the internal doses associated with this exposure scenario, since there are no air samples or bioassay data addressing Th-230.

Finding 4: The TBD should address whether a separate waste stream containing thorium raffinates might be produced during the processing of the uranium and, if such a stream was produced, there is a need to develop a method for reconstructing the doses associated with exposures to the raffinates.

This finding might be an SEC issue, because, if thorium raffinates are produced during the purification of the uranium, it is not immediately apparent how the internal doses from exposure to such raffinates can be reconstructed.

6.0 RADON EXPOSURES

Section 5.2 of the TBD provides the exposure matrix for reconstructing doses to AEC contract workers to radon and its progeny. The TBD acknowledges that, though radium and its progeny do not partition to the phosphoric acid solution (i.e., radium predominantly stays with the calcium sulfate and ends up in the phosphogypsum pile), AEC contract workers can still experience exposures to radon and its progeny because of the large quantities of phosphogypsum stored on site (see Figure 2-1 in Attachment 2). The approach used by NIOSH to develop the dose reconstruction protocol to reconstruct doses to AEC contract workers due to exposure to radon and its progeny employed a 2-step process. First, NIOSH used the vast amount of data characterizing the concentration of radon and its progeny at phosphate ore processing facilities in Florida to place a plausible upper bound on the airborne concentration of radon and its progeny that may have been experienced by workers in Building 55 at Blockson. Second, NIOSH derived the doses to respiratory and non-respiratory tissues using well-established methodologies that have been previously reviewed by SC&A and found to be scientifically valid. Hence, this section is limited to a review of the first step in the process; i.e., the data, models, and assumptions used in the TBD to determine the radon and radon progeny concentrations to which AEC contract workers might have been exposed. Specifically, Table 2 of the TBD adopts 0.036 WLM per year as the default upper-bound exposures for all AEC contract workers at Blockson.[2] It is appropriate to point out that this exposure level is comparable to the naturally occurring background levels of radon and its progeny to which everyone is exposed.

As explained in the TBD, NIOSH derived this value from data provided in ORAUT-OTIB-0043 (ORAU 2006). ORAU 2006 presents a review of the vast literature compiled by various organizations and agencies (especially the EPA) characterizing the radiological conditions primarily at phosphate recovery facilities in Florida. As is the case at Blockson, the production of phosphoric acid from phosphate ore generates large volumes of tailings in the form of phosphogypsum. These tailings are stored onsite and contain most of the radium that was originally present in the phosphate ore. The concentration of radium in these tailings range from 12.8 to 42.8 pCi/g, and radon exhalation rates from these piles were observed to be as high as 8,070 pCi/m^2-min, with measured radon fluxes at selected Florida phosphate plants ranging from 26.4 to 2,526 pCi/m^2-min.[3]

As described in the TBD, the Florida Institute of Phosphate Research (FIPR) has evaluated and compiled an enormous amount of data characterizing the radiological conditions at these facilities in Florida, including personnel monitoring data, exposure rates, area monitoring, environmental monitoring, and radon measurements. Samples were collected in the mine area, rock-handling area, phosphoric acid production area, dry production area, shipping area, and services area.

[2] For individuals not familiar with the concept of a WLM (working level month), it is approximately equivalent to being exposed to 100 pCi/L of radon (with short-lived progeny in full equilibrium) for 160 hours per month.

[3] For expediency, these values were taken directly from ORAUT-OTIB-0043 and accepted at face value at this time.

Clearly, there are abundant data characterizing the radiological conditions at Florida phosphate mines and processing facilities. Because Blockson did not make its own radon and radon progeny measurements, the TBD uses these data to place a plausible upper bound on the radon and radon progeny concentrations experienced by AEC contract workers at Blockson. The question is, can the experience at the Florida facilities be used as a surrogate for Blockson, and if so, has NIOSH used these data in a scientifically plausible and claimant-favorable manner? Of particular interest is the adoption of 0.036 WLM/yr as the default exposure rate to radon progeny. These questions are addressed in this section[4] and in more detail in Attachment 2.

ORAU 2006 explains that, although some data exist characterizing the radium and radon exposures at AWE phosphate facilities, it was determined that "the available documentation does not provide enough detail" to characterize the levels of exposures to radium, radon, and radon progeny at AWE facilities. Hence, FIPR data were selected by NIOSH as appropriate surrogates.

Sections 3, 4, and 5, and Attachment B of ORAU 2006 present a detailed description of the sources of the data and summaries of the data characterizing the levels of radon and radon progeny at Florida phosphate mines and processing facilities. ORAU 2006 explains that the phosphate plant operations and activities with the potential for occupational exposure include mining and beneficiation, ore drying and grinding, the wet acid process, maintenance, work in the vicinity of phosphogypsum stacks, and product packaging and handling. As also explained in ORAU 2006, "only the work locations and activities related to the extraction of uranium from phosphate ores should be considered," since the other activities would occur with or without the presence of AEC contract activities.

By selecting those data from Appendix B of ORAU 2006 that were judged by NIOSH to be most applicable to AEC contract workers at Blockson, NIOSH selected the following radon and progeny concentrations and default levels of exposures:

Table 3: Phosphate Plant Worker Radon WL Values
(Taken directly from Table 4-4 of ORAUT-OTIB-0043)

DR Approach	Radon Concentration (pCi/L)	F	WL	WLM/yr	Distribution
Best estimate	0.751	0.4	0.003	0.036	Lognormal, GSD=1.989
Maximizing	2.33	0.4	0.0093	0.112	Constant

In this table, 0.4 is the progeny fractional equilibrium as recommended by the United Nations Scientific Committee on the Effects of Atomic Radiation. Hence, the values of WLM are derived as follows:

$$\text{WLM} = 0.751 \text{ pCi/L} \times 0.01 \text{ WL per pCi/L} \times 0.4 \times 12 \text{ work months/yr} = 0.036 \text{ WLM/yr}$$

[4] Exposure to airborne levels of Ra-226 is not of particular interest, since it is self-evident that exposure to airborne uranium dust (and perhaps Th-230) at Blockson is by far the limiting internal exposure scenario for long-lived airborne particulates at Blockson.

One issue comes to mind with regard to this strategy for developing a surrogate model for Blockson workers. In order for the measurements of radon and radon progeny concentrations at Florida facilities to be used as a surrogate for radon exposures for workers in Building 55 at Blockson, there needs to be a level of assurance that the exposure settings were comparable or bounding; i.e., the size of the piles, their proximity to the radon concentration measurements, and the radon emanation rates at the Florida facilities result in radon concentrations that are high as applied to Building 55 and the location and characteristics of the tailings piles at Blockson. In addition, some consideration of similarities and differences in building ventilation rates and the use of localized ventilation would provide greater assurance of the applicability of the Florida data.

One strategy SC&A used to assess the validity of the default radon progeny exposure level adopted in the TBD was to compare the TBD value to the radon progeny concentrations for Building 55 made in 1978 as part of the FUSRAP program (DOE 1978). The 5 values reported in DOE (1978) range from 0.0014 to 0.0061 WL. The value of 0.003 WL adopted in the TBD falls right in the middle of this range, and is actually comparable to natural background levels. The implication is that the default value is reasonable **if the 1978 data are considered representative of the conditions at the site during uranium production**. For example, we are not quite certain whether the Blockson tailings piles and also the Florida tailings piles were stabilized at the time that the various measurements were made at these sites. It is instructive to note that under EPA regulations (National Emission Standards for Hazardous Air Pollutants (NESHAPs) set forth in 40 CFR Part 61, phosphate facilities that produce fertilizer are required to stabilize their tailings piles to meet the standards, but Blockson, which did not produce fertilizer, was not required to meet the NESHAPs (see Attachment 2 for details). It is also noteworthy that the size of the tailings piles at the Florida facilities were likely much larger than those at Blockson, as discussed in Attachment 2. Hence, there appear to be factors that could argue both for and against the default value for radon progeny exposure adopted in the TBD. It would seem that this issue requires further documentation.

Lacking assurances that the radon measurements made at Florida phosphate facilities represent bounding conditions for Blockson, the values used in the TBD may not be claimant favorable. It may be more appropriate to use the maximizing value of 0.112 WLM/yr as the bounding default value for Blockson, as opposed to the best estimate. However, even if this value were to be adopted, some assurance is needed that the value is bounding as applied to Blockson.

Finding 5: It is not apparent that 0.036 WLM/yr is a plausible and bounding exposure rate for radon progeny as applied to Blockson, especially considering that this exposure rate is associated with naturally occurring levels of radon.

This is not necessarily an SEC-related issue, because with appropriate analysis, NIOSH may be able to demonstrate whether the best estimate of 0.036 WLM/yr or the maximizing exposure rate of 0.112 WLM/yr is bounding as applied to Blockson.

A related issue is the possibility that the phosphogypsum tailings might have been used as construction fill or construction material for Building 55. Under these conditions, it might be difficult to place an upper bound on the radon exposures experienced by the Blockson workers.

However, in light of the radon progeny concentrations reported in DOE 1978 for Building 55, it appears to be unlikely that tailings were used as construction material. In addition, surface soil samples collected in the vicinity of Building 55 in 1978 and reported in Table 5 of DOE 1978 reveal that residual contamination had substantially higher concentrations of uranium as compared to radium. If tailings were used as construction fill, one would have expected at least some of the soil contamination to be higher in radium than uranium (see Attachment 2 for more details).

Finding 6: The TBD should address the possibility that tailings might have been used in the construction of Building 55.

7.0 EXTERNAL EXPOSURES

Section 4.2 of the TBD explains that data are not known to exist that characterize the external exposures experienced by Blockson workers. As a result, the TBD adopts an approach that takes advantage of process knowledge as a means to place a plausible upper bound on the external doses experienced by AEC contract workers at Blockson.

Based on process knowledge, NIOSH assumes that the highest external exposures were experienced by workers involved in the packaging of the finished uranium product. SC&A agrees with this assumption, because the purified uranium product had the greatest localized concentration and quantities of uranium and its short-lived progeny. Hence, the uranium packaging area appears to have had the potential to produce the highest external gamma radiation field among all the activities and locations associated with AEC contract activities at the site.

NIOSH estimated the external photon and beta radiation fields in the vicinity of the yellowcake and 55-gallon drums filled with yellowcake. These calculations were performed assuming that short-lived progeny of U-238 (Th-234, Pa-234 m, Pa-234) were in equilibrium with U-238, and that U-234 and U-235, including its short-lived progeny (Th-231), were present at their natural abundance relative to U-238. NIOSH used conventional methods to derive the external beta and gamma exposure rates and organ dose rates as a function of density of the yellowcake and the workers' distance from the yellowcake and 55-gallon drums. SC&A performed similar calculations in the past and concurs in the external beta and photon exposure rates reported in the TBD.

Though we concur with the external beta and gamma exposure rates derived by NIOSH for uranium and its short-lived progeny, we have one concern related to the exclusion of any Ra-226 and its short-lived progeny. As indicated in the TBD, a small fraction of the Ra-226 contained in the ore partitions to the phosphoric acid (about 1% in terms of activity (Roessler et al. 1979)). Hence, it is possible that for every curie of U-238 in a drum, there might be 0.01 Ci of Ra-226 with its sort-lived progeny. On first inspection, one might consider this negligible; however, the external dose conversion factors for Ra-226 plus its short-lived progeny are much greater than that of natural uranium and its short-lived progeny. For example, Table 4 presents the external photon dose conversion factors as reported in Federal Guidance Report No. 12 (EPA 1993):

Table 4: Comparison of External Dose Conversion Factors*

Radionuclide	Ext DCF (Sv/sec per Bq/m^2)	Abundance	Normalized Ext DCF (Sv/sec per Bq/m^2 of parent radionuclide)
U Series			
U-238	5.51E-19	1	5.51E-19
Th-234	8.32E-18	1	8.32E-18
Pa234m	1.53E-17	1	1.53E-17
Pa234	1.84E-15	.0016	2.94E-18
U-234	7.48E-19	1	7.48E-19
Th-230	7.50E-19	1	7.50E-19
Total			2.87E-17

Table 4: Comparison of External Dose Conversion Factors*

Radionuclide	Ext DCF (Sv/sec per Bq/m^2)	Abundance	Normalized Ext DCF (Sv/sec per Bq/m^2 of parent radionuclide)
Ra-226 Series			
Ra-226	6.44E-18	1	6.44E-18
Rn-222	3.59E-19	1	3.59E-19
Po-218	8.88E-21	0.9998	8.88E-21
At-218	4.18E-18	0.0002	8.36E-22
Bi-214	1.41E-15	1	1.41E-15
Po-214	8.13E-20	0.9998	8.13E-20
Tl-210	NA	0.0002	NA
Pb-210	2.48E-18	1	2.48E-18
Bi-210	1.05E-18	1	1.05E-18
Po-210	8.29E-21	1	8.29E-21
Tl-206	1.99E-18	.0000013	2.59E-24
Total			1.42E-15

* These values were taken from Table III.3 of EPA 1993. The values represent the external effective whole-body dose rate equivalent at 1 meter above an infinite plane.

As may be noted, the external dose rate from Ra-226 in equilibrium with all its progeny is about 50 times higher than that of natural uranium in equilibrium with all its short-lived progeny. Hence, even if only a small fraction of Ra-226 partitioned to the phosphate stream, it could have contributed significantly to the external dose rate of workers relative to that of natural uranium. The literature cited in the TBD indicates that about 1% of the Ra-226 might partition to phosphoric acid. However, a report by the National Academy of Sciences (NAS 1999) implies that as much as 20% of the Ra-226 might partition to phosphoric acid. This is based on page 64 of that report, which states, "About 80% of the Ra-226 in the ore follows the PG" [phosphogypsum]. The implications of that statement are that about 20% of the Ra-226 might partition to phosphoric acid. This statement, though inconsistent with the data cited in the TBD, warrants some follow-up in light of its potential importance to reconstructing external doses associated with AEC contract activities at Blockson. Further, Table 2 of FIPR 1998 indicates that the concentration of Ra-226 in phosphoric acid is about 4% that of U-238. Given these statements, which we uncovered during our review of the partitioning of Ra-226 to phosphoric acid (i.e., 1% versus 4 % versus 20%), there appears to be a degree of uncertainty and variability in the amount of Ra-226 that partitions to phosphoric acid. Hence, NIOSH should evaluate the possible contribution of trace levels of Ra-226 and its short-lived progeny in the phosphoric acid stream to the external dose rate.

Finding 7: The contribution of trace levels of Ra-226 and its short-lived progeny in the phosphoric acid stream and final uranium product to the external gamma field experienced by workers needs to be explicitly considered in the exposure matrix.

SC&A does not consider this finding to be an SEC-related issue, because it appears to be feasible to make adjustments to the exposure matrix to account for this possible source of external exposure.

Once the beta and gamma exposure rates were derived, NIOSH made certain assumptions regarding the time spent by workers in the vicinity of the filled drums of uranium. The median exposure was determined by assuming all workers were working 8 hours per day, 1 day per week at a distance of 1 foot from the drum, which was normalized to 400 hours per work year. The upper 95th percentile exposure time was determined by assuming the worker spent a standard 2,000 work hours a year at 1 foot from the drum.

Intuitively, one could argue that some workers may have spent more than 400 hours per year 1 foot from the drum, or that there may have been more than 1 drum in storage at a given time. However, these assumptions would appear to be reasonable upper bounds for most if not all workers, especially if it is assumed that such exposures occurred over the time period (up to 12 years) that the workers worked at the facility and considering that an average of about only 1 drum per week was produced.

REFERENCES

40 CFR 61. "*National Emission Standards for hazardous Air Pollutants*" Part 61 of Title 40 of the Code of Federal Regulations.

42 CFR 83. 2005. *Procedures for Designating Classes of Employees as Members of the Special Exposure Cohort Under the Energy Employees Occupational Illness Compensation Program Act of 2000*, Final Rule; May 28, 2005.

Blockson Chemical Company, 1951. Letter from E.B. Lopker (approved by Louis Block, President of Blockson Chemical Company) to Sheldon Wimpfen, Atomic Energy Commission, July 31, 1951.

DOE 1978. "Formerly Utilized MED/AEC Sites Remedial Action Program, Radiological Survey of Chemicals Group, Olin Corporation (Formerly Blockson Chemical Company), Joliet, Illinois, March 27-November 28, 1979, DOE/EV-0005/35. Prepared by the Occupational health and Safety Division, Health Physics Section of Argonne National Laboratory, Argonne, Illinois.

EPA 1993. "External Exposure to Radionuclides in Air, Water, and Soil," Federal Guidance Report No. 12, EPA/402-R-93-081, September 1993.

FIPR 1998. "Evaluation of exposures to technologically Enhanced Naturally Occurring Radioactive Materials (TENORM) in the Phosphate Industry," Prepared by Applied Environmental Consulting, Inc. with Environmental Radiation Group and Polk County Public Health Unit under a grant sponsored by the Florida Institute of Phosphate Research, FIPR, Publication No. 05-046-155, July 1998.

Guimond, R. J., Mills, W. A., and Windham, S. T., 1977. "Radiation Exposures in the Florida Phosphate Industry," International Radiation Protection Association Meeting #4, Paris, France, Volume 3, pp.1049-1052.

ICRP (International Commission on Radiological Protection) 1994. "Dose Coefficients for Intakes of Radionuclides by Workers, ICRP Publication 68, ISSN 0146-6453, July 1994.

NAS (National Academy of Sciences) 1999. "Evaluation of Guidelines for Exposure to Technologically Enhanced Naturally Occurring Radioactive Material." Committee on Evaluation of EPA Guidelines for Exposure to Naturally Occurring Radioactive Materials – Board on Radiation Effects Research – National Research Council. National Academy Press, Washington, DC. 1999.

NIOSH (National Institute of Occupational Safety and Health) 2006. SEC Petition Evaluation Report – Petition SEC-00058, Report Rev # 0, 9/5/06.

OCAS (Office of Compensation and Support) 2006. *Technical Basis Document for Atomic Energy Operations at Blockson Chemical Company, Joliet, Illinois*. OCAS-TKBS-0002, September 11, 2006 http://www.cdc.gov/niosh/ocas/pdfs/tbd/ocblocksnr0.pdf.

ORAU 2006. "Characterization of Occupational Exposure to Radium and Radon Progeny During Recovery of Uranium from Phosphate Materials," ORAUT-OTIB-0043, Revision 00, January 6, 2006.

Roessler, C.E., Z.A. Smith, W.E. Bolch, and R.J. Prince, et al. 1979. "Uranium and Radium-226 in Florida Phosphate Materials," Health Physics, Vol. 37(3):269-277.

SC&A 2006. *Board Procedures for Review of Special Exposure Cohort Petitions and Petition Evaluation Reports*, Revision 1 (SCA-TR-TASK5-0002, June 12, 2006) and the *Report to the Working Group on Special Exposure Cohort Petition Review* (Draft January 16, 2006), S. Cohen & Associates, Inc., Vienna, Virginia.

Stoltz, E.M. Jr. 1953. "Uranium Recovery from Wet Process Phosphoric Acid," Blockson Chemical Company, Joliet, Illinois, Research Contract No. AT[49-1]606, RMO-2850. February 23, 1953.

ATTACHMENT 1: PRESENCE AND DISPOSITION OF THORIUM-230 IN URANIUM PRODUCTION FROM PHOSPHORIC ACID

Prepared by Charles Phillips (SC&A, Inc.)

Document OCAS-TKBS-0002 (OCAS 2006) is the TBD for exposures resulting from nuclear weapons-related work at the Blockson Chemical Company. The document summarizes the known radiological processes and source terms, as well as the radiological controls and monitoring practices at Blockson. The document is intended to provide information on conditions and establish the basis for dose reconstruction related to the uranium removal from phosphoric acid that was routinely produced at the plant.

According to OCAS 2006:

> *In the Blockson process, the phosphate rock was calcined and then digested with sulfuric acid resulting in phosphogypsum and phosphoric acid. The phosphogypsum partitions most of the calcium and radium, and the phosphoric acid partitioned about 90% of the uranium. Very little uranium was lost to the phosphogypsum. The phosphoric acid was then converted into monosodium phosphate and other phosphorus derivatives. The uranium byproduct was precipitated from the monosodium phosphate stream. The monosodium phosphate liquor was heated and clarified. Sodium hydrosulfite ($Na_2S_2O_4$) was added to precipitate the uranium. The liquor was filtered and the filtrate returned to the phosphate-processing plant. The precipitate, containing about 5% U_3O_8 was slurried in water in an upgrading step in which the uranium was redissolved. The uranium was then reprecipitated as uranous phosphate. The slurry was filtered and the precipitate, known as yellowcake and containing 40 to 60% U_3O_8, was dried for shipping (Clegg and Foley 1958, McGinley 2002, Wimpfen 2002).*

For Blockson Chemical, only exposures relevant to uranium removal and processing are considered to be applicable to Energy Employees Occupational Illness Compensation Program Act (EEOICPA); therefore, the radionuclides contributing to the dose reconstruction are those available in the phosphoric acid stream serving as the feed material to the uranium recovery processes. Possible exceptions are radon and those radionuclides contained in materials from the phosphoric acid process incorporated into the construction of Building 55.

In OCAS 2006, Section 3.0, it states the following:

> *Workers in Building 55 and related activities were potentially exposed to airborne uranium. Thorium, assumed to follow the uranium in the Blockson process, and radon are also considered to be present in Building 55 and* [are] *included in this document.*

The estimation of internal exposures for Blockson Chemical workers is based on the results of 122 bioassay samples analyzed by the AEC New York Operations Office Health and Safety Laboratory (HASL) using fluorimetry.

Fluorimetry methods only report uranium results and do not include the attendant radionuclides, namely radiothorium. According to OCAS-TKBS-0002, "The presence of associated radionuclides that could be present and contribute to significant internal dose is assumed (ORAU 2006)." OCAS 2006, referring to ORAU 2006, uses the results of phosphate ore analyses reported in Guimond et al. 1977 for estimating Th-228 and Th-232 activity in urine to estimate thorium inhalation rates.

The results are summarized in Table 1a below (OCAS 2006):

Table 1a: Inhalation Rate for Operations

Worker category	Intake rate for Type M material[1]	Distribution
Administrative	25 pCi/day total U	Constant value
Administrative	0.35 pCi/day Th-228[2]	Constant value
Administrative	0.35 pCi/day Th-232[2]	Constant value
Production workers	82 pCi/day M total U	Constant value
Production workers	1.1 pCi/day Th-228[2]	Constant value
Production workers	1.1 pCi/day M Th-232[2]	Constant value

1 – Intake rates are normalized to units of calendar days. The intake period for operations is March 1, 1951, through March 31, 1962.

2 – Thorium intake rates are derived from ratios in ORAU 2006. Solubility types for thorium are based on recommendations in ICRP Report 68 (ICRP 1994b).

Two significant concerns arise from this estimation of thorium inhalation rates. Since the doses to be considered are related to the uranium removal from phosphoric acid, would it not be more appropriate to use the relative concentrations of Th-232 to U-238 in the phosphoric acid, as reported in Guimond et al. 1977, rather than the concentrations in phosphate ore? Phosphoric acid is the feed material to the uranium removal process and not phosphate ore. The use of the ratio of Th-232 to U-238 in phosphoric acid (0.12) as opposed to that in phosphate pebble rock (0.014) for estimating Th-228 and Th-232 inhalation rates would result in over an 8-fold increase in these thorium intake values. This is clearly a more claimant-favorable assumption.

Possibly of greater concern is the omission of Th-230 from the radionuclides, considered to be contributors to doses assigned to Blockson workers. Based on the analyses reported in Guimond et al. 1977, Th-230 is in radioactive equilibrium with U-238 in both phosphate ore and phosphoric acid. If Th-228 and Th-232 are deemed to be relevant radionuclides, then there is no apparent reason to exclude Th-230, particularly since it would be processed in much greater quantities than Th-228 and Th-232. It is not clear why Th-230 is not considered in the contributing radionuclides, but it seems to be a major omission from the Blockson assessment that could potentially result in significant unmonitored exposures.

To properly assign doses attributable to radiothorium to workers in the Blockson uranium processing operations (Building 55), it is necessary to identify the partitioning of the radiothorium into the various products and byproducts of the Blockson uranium recovery process. There are no firm data in the material reviewed by SC&A that identifies the concentrations of radiothorium in the final uranium product (yellowcake) or in process byproducts, such as waste streams, raffinates, and recycled materials. A review of the details of the uranium recovery process by an SC&A senior radiochemist concluded that it was not possible to assess the partitioning of the radiothorium with any degree of certainty using the process descriptive materials available.

References

Clegg, J.W., and Foley, D.D., "Uranium Ore Processing," prepared under contract with the U.S. AEC, Addison-Wesley Publishing Company, Inc., 1958, pp. 375-378.

Guimond, R. J., Mills, W. A., and Windham, S. T., 1977, "Radiation Exposures in the Florida Phosphate Industry," *International Radiation Protection Association Meeting #4, Paris, France*, volume 3, pp. 1049–1052.

ICRP (International Commission for Radiological Protection) 1994b. *Dose Coefficients for Intakes of Radionuclides by Workers*. ICRP Publication No. 68.

McGinley, Frank, Personal Communication, December 2002.

OCAS (Office of Compensation and Support) 2006. *Technical Basis Document for Atomic Energy Operations at Blockson Chemical Company, Joliet, Illinois*. OCAS-TKBS-0002, 9/11/2006 http://www.cdc.gov/niosh/ocas/pdfs/tbd/ocblocksnr0.pdf.

ORAU 2006, "Characterization of Occupational Exposures to Radium and Radon Progeny During Recovery of Uranium from Phosphate Materials, ORAUT-OTIB-0043, Rev 00, January 6, 2006.

Roessler, C.E., Z.A. Smith, W.E. Bolch, and R.J. Prince, et al. 1979. "Uranium and Radium-226 in Florida Phosphate Materials," Health Physics, Vol. 37(3):269-277.

Wimpfen, Sheldon, Personal Communication, November 2002.

ATTACHMENT 2: RADON EXPOSURES AT BLOCKSON CHEMICAL COMPANY

Prepared by William Thurber (SC&A, Inc.)

This attachment considers two issues related to possible radon exposures of uranium recovery workers at Blockson Chemical Company:

- Whether the model developed by NIOSH for uranium extraction workers at phosphate plants (ORAU 2006) is reasonable for use at Blockson Chemical Company

- Whether workers in Building 55 at Blockson might have received incremental radon exposures if phosphogypsum tailings were used in construction of that building

Each of these issues is addressed in the following sections.

Appropriateness of the NIOSH Model for Uranium Extraction Workers

NIOSH notes in ORAU 2006 that very few data were available at the time when Atomic Weapons Employers (AWE) operations for uranium extraction were conducted at phosphate plants. Consequently, NIOSH used data published by the Florida Institute of Phosphate Research (FIPR 1998) to develop worker radon exposures. The relevant FIPR data are from a variety of anonymous sources, including the following:

- Chemical plant radon readings – summary statistics, 1989 to 1994
- Radon measurements summary (chemical plant readings), 1995 to 1996
- Terredex radon measurements – summary statistics, 1982 to 1996
- Chemical plant track-etch radon results, 1993 to 1996
- Phosphate facility radon measurements (electret ion chambers), 1997

The ORAU authors state the following:

> *This was possible because the factors that affect radon concentrations have changed very little over time. No significant changes in the construction of wet process acid plants had occurred since the time of AWE operations (Birky 2005b). While environmental regulations led to decreased overall emissions, the controls had little or no effect on occupational radon levels. In addition, the rate of ore processing has increased over time (Birky 2005b).*

It is easy to understand that, since wet acid plant designs have not changed significantly, radon exposures from plant operations, per se, should be similar today to what they were in the 1950s and 1960s. However, occupational exposures resulting from radon emissions from phosphogypsum stacks could have changed due to new regulations. In 1989, EPA issued Subpart R of 40 CFR Part 61 limiting radon emissions from inactive phosphogypsum stacks to 20 Ci/m^2-sec of Rn-222. Any stacks that were inactive at the time or have since then become inactive might need to be modified to meet the standard. An EPA study conducted prior to

promulgating the standard indicates that, based on surveys of four active stacks in central Florida, the average annual radon flux was at the standard level (Horton et al. 1988). Thus, little remediation should be required for regulatory compliance of these stacks. In contrast, another author has described extensive modifications made to several phosphogypsum stacks in Florida (Morris 2004). Although many of the modifications were made to meet State of Florida requirements rather than the requirements of 40 CFR Part 61, Subpart R, the changes have likely reduced radon emissions. An industry expert from FIPR has commented that even though some phosphogypsum stacks have been closed, including lining and covering, there is always an active stack at each chemical plant (Birky 2005b).

The NIOSH radon exposure modeling of uranium recovery workers, as described in Section 3.2 of OCAS 2006 and Section 4.2 of ORAU 2006, was based on eliminating those operations that were not generally related to phosphoric acid production from the full dataset in FIPR 1998. These included rock tunnel operations, float plant operations, heavy equipment operations, wet rock loading, etc. Peripheral operations involving the burn area, the auto shop, and the main office building were **not** excluded from the dataset. Using this reduced data set of 130 measurements, ORAU calculated that the mean radon exposure was 0.036 WLM/yr and the 95th percentile exposure was 0.112 WLM/yr. While the use of a mean exposure of 0.036 WLM/yr should provide a reasonable estimate for all workers at a phosphoric acid plant, it is not clear that it is appropriate for the more limited cohort of uranium recovery workers in Building 55. For example, that cohort would not have included low-exposure jobs, such as office workers or trailer occupants, which tend to lower the mean dose. While some portion of the dataset in FIPR 1998 could be used to estimate radon exposures at Blockson, it would need to be adjusted to include only those types of jobs relevant to the Building 55 operations.

As described in the Technical Basis Document for Blockson Chemical Company (OCAS 2006), the Company provided, in a pre-operational letter to AEC, cost estimates based on processing 6,000 tons of phosphate rock concentrate per week (or about 300,000 tons per year). Assuming that 6,000 tons per week was the operating capacity of the Blockson wet chemical phosphate process (OCAS 2006, p. 6), and the relevant reaction for the production of phosphoric acid and phosphogypsum from phosphate rock is given by the following equation, Blockson would have produced about 520,000 tons of phosphogypsum annually:

$$3\ H_2SO_4(l) + Ca_3(PO_4)_2(s) + 6\ H_2O(l) \rightleftharpoons 2\ H_3PO_4(s) + 3\ CaSO_4 \cdot 2H_2O(s)$$

By comparison, the phosphate producers in Florida generate about 30 million tons of phosphogypsum per year, and a total of nearly 1 billion tons is stored in 25 phosphogypsum stacks (http://www.fipr.state.fl.us/research-area-chem.htm). Clearly, the scale of operations at Blockson was substantially smaller than the operations in Florida. Therefore, use of an appropriate subset of the data from FIPR 1998, as discussed above, should provide a reasonably conservative basis for modeling radon exposures.

An aerial photograph of the Blockson Chemical Company site is presented in Figure 2-1. Building 55 is easily identifiable in this figure, based on its unique floor plan with a truncated left side (see also Figure 1 in OCAS 2006). From this figure, it can be seen that the tailings ponds are at least 300 yards east or northeast of Building 55. Conceivably, some tailings could

have become airborne and accumulated in and around Building 55, resulting in increased radon exposures. However, no evidence supporting this conjecture has been found. As discussed in the next section, soil samples taken not only around Building 55, but also across the property, do not exhibit significant increases in Ra/U ratios over those expected from the feedstock to the process. Since Ra is concentrated in the tailings along with the Ca from the phosphate rock concentrate, high Ra/U ratios might indicate mobilization and transport of tailings from the storage areas. No such evidence was found by ANL (DOE 1983). For example, two samples were taken from the roof gravels on Building 55—a likely place for any accumulations from airborne mobilization. Samples 4-S1 and 4-S2 had Ra/U ratios of 0.11 and 0.32, respectively. These ratios are less than those for the rock concentrate fed to the process, indicating that tailings mobilization and transport would not be a measurable contributor to the dose of Building 55 workers.

Figure 2-1: Aerial Photo of Blockson Chemical Company Site, Building 55 marked with Arrow

Use of Phophogypsum as Fill

Conceptually, phosphogypsum tailings could have been used as fill or in other construction materials during the construction of Building 55. Based on the limited available evidence, this possibility appears to be remote. According to Wissa (undated), "Phosphogypsum, because of its relatively high solubility, high compressibility and radioactivity is not recommended as structural fill for land reclamation, especially if the land will be used for housing."

In addition, review of soil and building samples taken by ANL in 1978 do not indicate high radium or radon concentrations (DOE 1983). Soil samples 4-S6, 4-S7, and 4-S8 were taken immediately adjacent to Building 55 (see DOE 1983, Figure 10). The 30-cm long sample cores were analyzed for uranium and radium. Based on analysis of the phosphate rock concentrate received at Olin (formerly Blockson Chemical) at the time of the ANL survey, the ratio of radium to uranium in the concentrate was 0.45 (DOE 1983, Table 5, sample 4-S5). If the soil samples were enriched in tailings, the ratio of Ra/U would be substantially greater than 1, since radium is concentrated in the tailings. The Ra/U ratio for soil samples 4-S6, 4-S7, and 4-S8 were 1, 2, and 0.09, respectively, indicating that use of tailings around Building 55 was unlikely. In each case, the calculated ratios are based on the 5-cm surface increment of the 30-cm long cores. For sample 4-S6, the ratio was calculated using the one-sigma values rather than the mean, since use of a zero mean resulted in a useless ratio.

ANL also obtained air samples from Building 55 and used these to determine Rn-222 concentrations and Working Levels. The Working Levels ranged from 0.0014 to 0.0061, which according to ANL, were within the expected background range. These observations provide further support to the contention that use of tailings around Building 55 at the time of its construction is unlikely. Even if tailings were used, the ANL measurements suggest that they would have provided no significant incremental contribution to doses.

References

Birky, B., 2005b. "Phosphate Plant Radon Levels," electronic mail to R. Gard (Oak Ridge Associated Universities Team), September 1, Florida Institute of Phosphate Research, Bartow, Florida.

DOE (U. S. Department of Energy) 1983. *FUSRAP, Radiological Survey of Chemicals Group, Olin Corporation (formerly Blockson Chemical Company, Joliet, Illinois, March 27 – November 28, 1978.* Argonne National Laboratory; DOE/EV-0005/35; ANL-OHS/HP-83-103, May 1983 [SRDB Ref ID 23615].

FIPR (Florida Institute of Phosphate Research) 1998. *Evaluation of Exposure to Technologically Enhanced Naturally Occurring Radioactive Materials (TENORM) in the Phosphate Industry*, Publication 05-046-155, Bartow, Florida. http://www1.fipr.state.fl.us/FIPR/FIPR1.nsf/9bb2fe8f45c4945e85256b58005abaec/deb248481f98842e85256b2f005d7524/$FILE/05-046-155Final.pdf.

Horton, T.R., R.L. Blanchard, and S.T. Windham 1988. *A Long-Term Study of Radon and Airborne Particulates at Phosphogypsum Stacks In Central Florida*. EPA/520/5-88-021. U.S. Environmental Protection Agency, Montgomery, Alabama.

Morris, O. 2004. *Phosphogypsum Stack Systems, Closed and Lined Replacements at Cargill Crop Nutrition*. Presented at 2004 IFA Technical Conference, Beijing, China. http://www.fertilizer.org/ifa/publicat/PDF/2004_tech_beijing_morris.pdf.

OCAS (Office of Compensation and Support) 2006. *Technical Basis Document for Atomic Energy Operations at Blockson Chemical Company, Joliet, Illinois*. OCAS-TKBS-0002, 9/11/2006 http://www.cdc.gov/niosh/ocas/pdfs/tbd/ocblocksnr0.pdf.

ORAU (Oak Ridge Associated Universities) 2006. *Characterization of Occupational Exposure to Radium and Radon Progeny During Recovery of Uranium from Phosphate Materials.* ORAUT-OTIB-0043. 1/06/2006. http://www.cdc.gov/Niosh/ocas/pdfs/tbd/tib/tib43.pdf

Wissa, Anwar E.Z. (undated). *Phosphogypsum and the Environment*. Ardaman & Associates. Inc. http://www.fipr.state.fl.us/pondwatercd/phosphogypsum_disposal.htm