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TO: Advisory Board on Radiation and Worker Health, Work Group on TBD-6000
FROM: Robert Anigstein and John Mauro, SC&A
SUBJECT: Review of NIOSH Response Paper: July 10, 2015
DATE: September 11, 2015

Review of "Responses to Sanford Cohen & Associates Review of Battelle-TBD-6000 Appendix BB (General Steel Industries, Rev. 1)," Response Paper

Background

On June 23, 2014, David Allen (NIOSH/OCAS) issued a revision of Appendix BB to TBD-6000 (Allen 2014). On December 10, 2014, SC&A issued a review of the revised appendix that included nine findings (Anigstein and Mauro 2014). Allen (2015a, 2015b) issued two papers responding to our findings. We subsequently replied to Allen's response papers (Anigstein and Mauro 2015a, 2015b). In the process of preparing our replies, we found another issue, which became Finding 10.

On February 5, 2015, the Work Group on TBD-6000 met by teleconference. Based on NIOSH responses to the SC&A findings, the work group members unanimously agreed that NIOSH had agreed to resolve the issues reflected in Findings 1, 3, 4, 7, 8, and 9, and that these findings can therefore be closed. On July 10, 2015, Allen (2015c) issued a Response Paper that was intended to address the four SC&A findings on Appendix BB, Rev. 1, that remained unresolved. The present memo is our reply to this Response Paper. The findings are discussed in the order in which they were presented by Allen—the titles are those used by Allen.

Finding 2: Betatron Operator Beta Doses

Skin Doses from Uranium

Allen (2015c) began the discussion of doses to the skin of betatron operators from β rays emitted by uranium, using the year 1953 as an example, by citing our previous values for the years 1952–1957 (Anigstein and Mauro 2013, 2014). In reviewing the calculations that led to these skin doses, we observed that the dose rate from the side of the uranium metal (i.e., the curved surface of the cylindrical slab) had been calculated using a ß spectrum that comprised contributions from the short-lived progenies of natural uranium—^{234}Th, ^{234m}Pa, ^{237}Pa, and ^{231}Th—as well as the photoactivation products ^{237}U and ^{239}U. This led to an overestimate, since the concentrations of these uranium isotopes would decrease exponentially over the 4-in thickness of the slab, and would further fall off at the edge. Consequently, we repeated the MCNPX simulations, using a β spectrum comprising only the short-lived progenies of natural uranium in secular equilibrium with their parents. The results of the simulations of the dose rates at the surface of the uranium ingot were increased to account for the Putzier Effect—a 10–15-fold increase in the short-lived progenies. Although we had previously used a multiplier of 12.5—the midpoint of the 10–15 range cited by Putzier (1982)—we increased the multiplier to 15 to be consistent with the NIOSH analysis, which produced higher, more claimant-favorable results.

We also reviewed the calculated β dose rate from the face of the uranium slice, which did include contributions from ^{237}U and ^{239}U. Since each uranium slice was assumed to be exposed four times to the betatron beam (to account for four overlapping shots, as reported by the former GSI betatron operators), the slice had been assumed to be irradiated continuously for 4 hours prior to being handled by the operators. To be consistent with the intermittent irradiations developed by Allen (2015b) for assessing the dose rates from irradiated steel, we averaged the concentrations of ^{237}U and ^{239}U over the four 15-min setup periods following each of the four 1-h radiographic exposures. We also took this opportunity to perform a new simulation of the rate of creation of these photoactivation products. Instead of a 6.5-in diameter, 5-mm-thick uranium disk that was used in the previous analysis to improve MCNPX scoring efficiency and to bias the concentrations of the photoactivation products by confining the metal to the center of the betatron beam, we performed a more realistic analysis, using an 18-in diameter uranium slice with a thickness of 1 mm. Because the high-energy photons that constitute the betatron beam would undergo <10% attenuation over this depth, the production of the photoactivation products would be relatively uniform in this layer, thus eliminating the need to extrapolate the surface concentration using an assumed exponential profile. The calculated, time-weighted-average specific activities of the photoactivation products at the front surface of the uranium slab are listed in Table 1.

Table 1. Residual Nuclides in Uranium: Sources of External Exposure to Beta Radiation

Nuclide	Half-life	TWA sp. act.[a] (Bq/g)
U-237	6.75 d	3.3
U-239	23.45 m	1077.5

[a] Time-weighted average: specific activity averaged over exposure duration of betatron operator

The simulation of skin doses from the front face of the uranium slice utilized a combined β spectrum comprising the short-lived uranium progenies as well as the β spectra of ^{237}U and ^{239}U. The relative intensities of the β emissions from the latter isotopes were derived from the time-weighted-average specific activities listed in Table 1. The calculated skin doses from exposure to a uranium slice are presented in Table 2.

Skin Doses from Irradiated Steel

Allen (2015c) calculated the doses to the skin of the betatron operator from ß rays emitted from irradiated steel using the exposure scenario we had proposed earlier (Anigstein and Mauro 2014) but modified the activity concentrations of the photoactivation products by modeling intermittent exposures to the betatron beam. The "long" shots lasted 1-h, with 15-min intervals between exposures. The "short" shots consisted of 3-min exposures with 12 min in between. The shots were repeated until the activation products were in complete equilibrium, which essentially constituted an infinite number of shots. Except for accounting for the intervals between shots, the scenario is even less realistic than the original bounding scenario proposed by SC&A, in which the steel was irradiated continuously for 30 h. According to the NIOSH scenario, the casting would never leave the betatron shooting room. Nevertheless, we accept this scenario as being bounding and claimant favorable.

Table 2. Dose Rates to Skin from External Exposure to Beta Radiation from Uranium Slice

Location	Orientation	Dose Rates to Skin (mrad/h)
Contact	Front	81.1
	Side	1,173.7
	Average	627.4
Cloth	Front	65.2
	Side	919.7
	Average	492.4
1 ft	Front	15.7
	Side	55.5
	Average	35.6
1 m	Front	1.7
	Side	8.2
	Average	5.0
Average for bare skin		316.2
Average for other skin		20.3

We previously verified NIOSH's mathematical derivation of the intermittent exposure algorithm (Anigstein and Mauro 2015a). We now independently applied the algorithm to the betatron operator's skin dose from irradiated steel and found that Allen's (2015c) values are either the same or higher by <1%, mostly due to different assumptions about the betatron beam intensity. These differences are trivial and claimant favorable. We consequently agree with Allen's results for doses to the skin of the betatron operator from irradiated steel, which are based on an amalgam of SC&A's original MCNPX calculations and derivations of activity concentrations, and NIOSH's intermittent exposure algorithm.

Skin Doses from Uranium and Steel

Our earlier analyses of skin doses from uranium assumed a total of six uranium radiographs per shift. Since each radiograph took 75 min—a 15-min setup time and a 60-min exposure—six shots took 7.5 h. As pointed out by Allen (2015c), this is inconsistent with the steel radiography scenarios, which are assumed to consume the entire 8 h of the shift. We consequently increased the duration of the uranium scenarios to 8 h/shift. The final results of the updated skin dose assessment are listed in Table 3.

Comparing these doses to Allen (2015c, Table 1), we note that the SC&A doses are lower, primarily due to our revised calculations of doses from uranium: the annual doses to the hands and forearms are 7%–18% lower, while the doses to the skin on the rest of the body are 1%–12%

lower. Although Allen's results are claimant favorable, NIOSH may wish to adopt the more realistic values listed in Table 3.

Table 3. Annual Doses to Skin of Betatron Operators from Beta Radiation (rads)

Year	Annual number of shifts		Hands and forearms			Other skin		
	Uranium	Steel	Uranium	Steel	Total	Uranium	Steel	Total
1952[a]–1957	54.7	351.6	27.67	1.53	29.20	1.77	1.05	2.82
1958	45.8	360.4	23.19	1.57	24.76	1.49	1.07	2.56
1959-1960	42.2	364.1	21.34	1.59	22.93	1.37	1.08	2.45
1961	48.4	357.8	24.50	1.56	26.06	1.57	1.07	2.64
1962	35.2	371.1	17.79	1.62	19.40	1.14	1.10	2.25
1963	9.6	396.7	4.84	1.73	6.57	0.31	1.18	1.49
1964	3.5	402.7	1.78	1.75	3.53	0.11	1.20	1.31
1965	2.6	403.7	1.30	1.76	3.05	0.08	1.20	1.29
1966[b]	0.8	202.3	0.41	0.88	1.29	0.03	0.60	0.63

[a] Doses for 1952 must be prorated to reflect start of covered operations: October 1, 1952

[b] During contract period January 1–June 30

Finding 10: Betatron Operator Gamma Dose

Finding 10 (Anigstein and Mauro 2015a) stated:

> Allen (2014 Table 9) lists dose estimates for the skin of the hands and forearms of the betatron operator during 1952–1963 as 1,300 mrem/y. This value is based on the hypothetical 30-keV residual photon radiation from the betatron apparatus after shutdown and was calculated in terms of effective dose rates, which are incompatible with the dose conversion factors listed in OCAS-IG-001 (OCAS 2007).

In response to this finding, Allen (2015c) pointed out that Appendix BB, Rev. 1, uses the betatron operator photon exposure scenario only to calculate limiting doses to the skin of the hands and forearms, which appears to be the case. He accepted our proposed limiting value of 204.5 mrad/week air kerma in the PA orientation (Anigstein and Mauro 2015a), which corresponds to an MDL of the film badge dosimeters of 10 mrem/week, accounting for the shielding of the film by the worker's torso. Allen proposed to use this air kerma rate, together with the maximum air-kerma-to-skin-dose conversion factor for photons, E_γ <30 keV (0.654 rem/rad [OCAS 2007]) to calculate the dose to the skin on the back and sides. However, he assigned only one-half of this dose to the skin on the hands and forearms, since he assumed that the worker's hands were at the side of the body only one-half of the time and in front of the body the rest of the time. He assigned an additional dose of one-half the MDL of the film badge—5 mrem/week or 0.25 rem/y—to account for the time the hands were in front of the body. The skin on the anterior portion of the body, other than the skin of the hands and forearms, would be assigned a dose of 0.5 rem/y.

Although we agree that the worker would not always have his hands at his sides, we do not agree that his hands and forearms would have been completely shielded by his torso during one-half of the time he was working. That would only happen if his hands and forearms were held close together, which cannot be assumed to occur during one-half of his activities. For example, Figure 1, reproduced from SC&A (2008, Figure 19), shows a betatron operator (on the left in the photograph) positioning the betatron, holding his left hand and forearm above his shoulders and his right arm at the side of his body. Although some shielding of the hands and forearms by the torso may have occurred during some unknown portion of the setup period, in the absence of more specific information, we recommend that NIOSH assigns bounding doses to the skin of the hands and forearms of 6.687 rem/y (10.225 rad × 0.654 rem/rad = 6.687 rem). We agree with the assignment of 0.5 rem/y to the skin on the anterior portion of the body, other than the hands and forearms, since the dose to that skin would be approximately the same as the dose recorded by the film badge dosimeters.

Finding 5: Adding Betatron Operator Dose to Radium Radiography Dose

Finding 5 (Anigstein and Mauro 2015a) pointed out that radiographers during the Radium Era (1952–1962) utilized the betatron as well as ^{226}Ra sources to perform radiography, and that workers should be assigned some fraction of the β and neutron doses calculated for betatron operators in addition to the photon doses from radiography utilizing radium sources. Since GSI reported that "a *maximum* of 30% of each shift is used for actual exposure [to sealed sources] [NRC 2009a, p. 12, italics added]," the radium exposures may have taken less than 30% of the time on some shifts, allowing the radiographers more time to work on the betatron. We originally recommended that NIOSH should make the bounding assumption that a radium radiographer spent 70% of each shift in the Old Betatron Building during 1952–1962.

Allen (2015c) responded that radiography using radium would require 15 minutes setup time between shots, the same that was assumed for the "long" shots using the betatron. Assuming 10 exposures per shift, this would add 150 min (2.5 h) to the exposure time. Since the exposures are assumed to take up 30% of each shift, or 2.4 h, this would leave only 3.1 h (8 − 2.4 − 2.5 = 3.1), or 38.75% of an 8-h shift, available for work in the betatron.

We disagree with this assumption for several reasons. The most important evidence, and the only available evidence that has a direct bearing on this issue, is the interview with [redacted], a former radiographer—the only source of first-hand information on radium radiography at GSI—in which he reported that he spent 50%–60% of each shift during which he worked as a radiographer in the betatron building. His film dosimetry records—the only available records from GSI during the Radium Era—prorated to account for his part-time work as a radiographer, are consistent with the agreed-upon estimates of external exposures of a worker performing full-time radiography during this era. Consequently, we recommend that the upper end of the reported range, 60%, be used as a plausible upper bound to the occupancy of the betatron building.

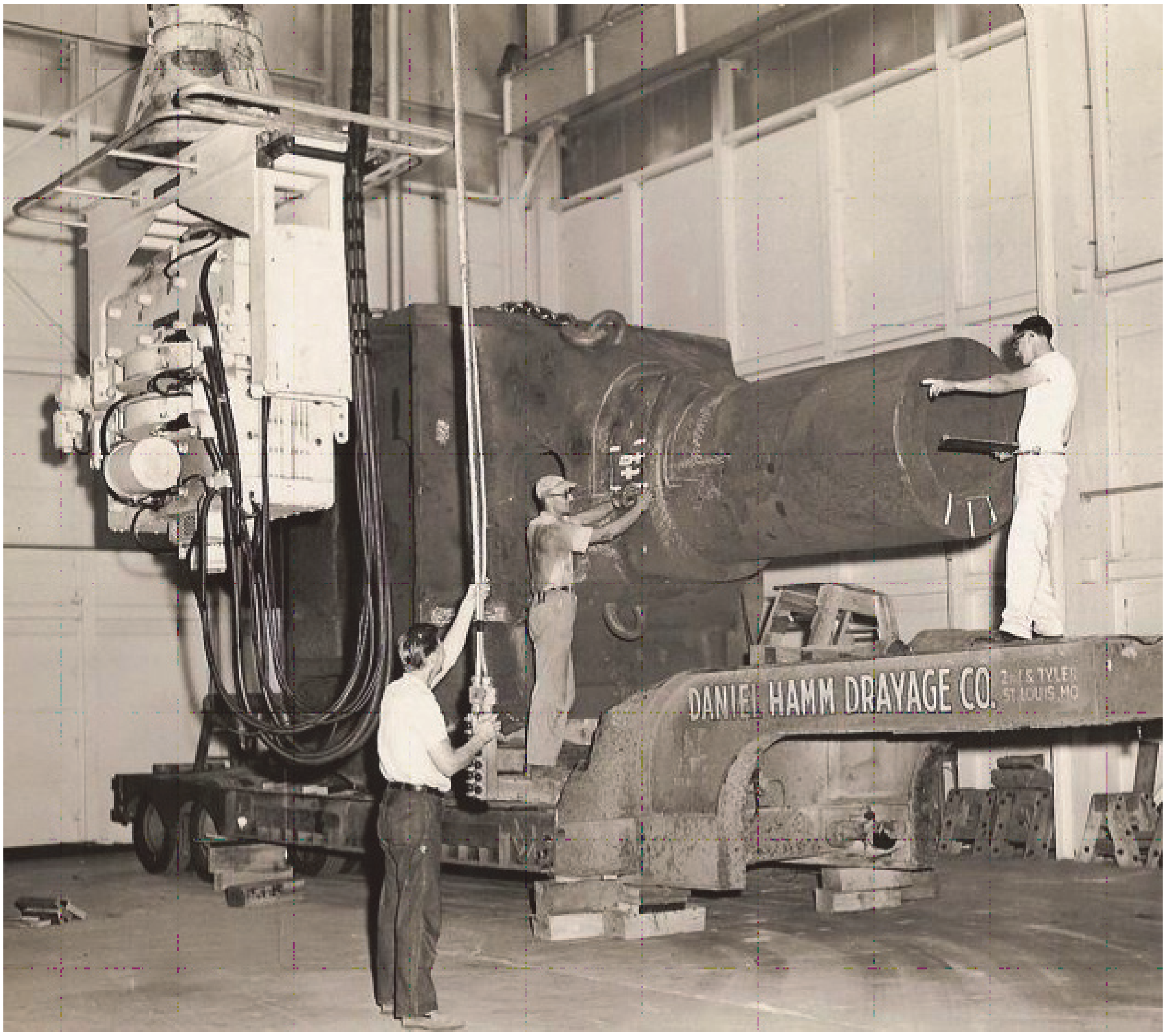

Figure 1. Betatron Radiography of the Axle of a Power Shovel Cast at GSI
(Courtesy of [redacted])

There are no relevant data that would support the assumption of 15 min between shots. Mr. [redacted] reported taking 12–15 s to transport the radium source from the lead pig, which was kept inside the radiography room, and position it for the exposure. It would not have taken much longer to position and remove the films, which would have been also stored nearby. It was not necessary to develop each film prior to exposing the next one. According to the Atomic Energy Commission's (AEC) "Compliance Inspection Report" (NRC 2009b), [redacted], the GSI [redacted] reported that the exposures ranged from 1 to 70 min. Assuming 2.4 h of exposure and 10 shots per shift, the average shot took 0.24 h ([8 × 0.3] ÷ 10 = 0.24) or ~14 min. The longer shots provided ample time to develop the previously exposed films, which could be processed in batches. Since a typical casting was larger than one x-ray film, it took several exposures to radiograph one casting. There was no need to transport the casting between shots—repeat shots could have been taken in quick succession: position the film, position the radium source, wait for the exposure to finish. This procedure bears no relationship to betatron radiography, which involved using electrical controls to move and aim the betatron apparatus and retiring to the control room to set the controls for the next shot. GSI workers have reported that the castings radiographed with the betatron tended to be large and complex, requiring a significant setup time. The very reason that the betatron was installed at GSI was to radiograph hulls of Army tanks and other castings that were too large for the isotope sources (^{226}Ra and later ^{60}Co).

Allen (2015c) disagreed with our assumption that the radiographer working with radium should be assumed to have participated in all the betatron radiography of uranium during a given year. Our reason is the same as the reason for assuming that a single worker was involved in all the uranium radiography in the first place. Since GSI workers worked in shifts, one could argue that the same worker did not necessarily participate in all the uranium work. Nevertheless, since one worker *could* have been involved in all this work, it has been agreed that the GSI dose assessments would assume that one worker did, in fact, participate in all the uranium radiography. This assumption is equally valid if such a worker were absent from the betatron building working with radium for perhaps 40% of the time. This assumption is thus plausible, claimant favorable, and consistent with the rest of the agreed-upon dose assessment methodology.

The triangular distributions of external photon doses during the Radium Era that have been adopted by the Work Group on TBD-6000, NIOSH, and SC&A are derived from the calculated exposures to ^{226}Ra sources and the AEC exposure limits. Since these did not incorporate the exposures to the hypothetical residual radiation from the betatron, we agree with Allen's (2015c) recommendation that photon doses to the skin from such radiation, discussed in Finding 10, should be added to the radium radiographer's skin dose in proportion to the time he spent in the betatron building.

Finding 6: Layout Man Beta Dose

Perhaps the most complex of the remaining dose reconstruction issues for GSI workers is the assessment of doses to the skin of the layout man from irradiated steel. This is partly due to the variable nature of the work of the layout man and to the varied description of that work by former GSI workers. The most recent SC&A analysis (Anigstein and Mauro 2014) used a simplified scenario which assumed 30 h of continuous irradiation of the steel that ended 15 min prior to the exposure of the layout man. The layout man received a new casting every 75 min and worked on it continuously until the next casting arrived. Long and short shots were differentiated by the steel being irradiated at either 6 or 9 ft, respectively. The ratio of long:short shots was approximately 36:64, the same as the ratio of irradiation times devoted to the two types of shots.

Allen (2015b) proposed a scenario based the layout man's exposure to photon radiation from irradiated steel, first described by SC&A (2008, Section 2.1.4). He assumed that the layout man spent his entire shift marking up one casting, except for being interrupted to spend 15 min marking up a freshly irradiated casting. He assumed that such an activity occupied 10% of his shift. In both the single-casting and interrupting-casting scenarios, he assumed that 90% of the time was devoted to castings that had been exposed to short shots and 10% to long shots.

As we stated earlier:

> At that time [2008], our intent was to describe and calculate a set of scenarios, based on available information, to present examples of calculations of doses from irradiated steel. . . Since the exposures of the layout man to direct penetrating radiation from irradiated steel were trivial compared to direct exposure to the penumbra of the betatron x-ray beam and radiation scattered from the casting being radiographed in the New Betatron Building, we did not attempt to refine this calculation. . . Unlike the case for γ rays, the β radiation from irradiated steel made a potentially significant contribution to the dose to the skin of the layout man. (Anigstein and Mauro 2015a)

Since NIOSH chose to adopt our 2008 photon exposure scenario to model the β dose to the layout man, we re-examined our earlier assumptions as to how they would affect the present analysis. In principle, we agree that Allen's (2015b) approach is a reasonable alternative to calculating the β doses to the skin of the layout man. Although the description of a single casting being continuously shuttled back and forth between the betatron and the layout man is not realistic, it could be used in a bounding calculation. We agree with the application of Allen's intermittent exposure algorithm to model the buildup and decay of photoactivation products in steel. However, we do not agree with one of the parameters used in Allen's calculations.

Allen (2015b) assumed that it took the layout man the same amount of time to mark up the defects from long and short shots. The reason we believe that the long shots took longer is that the steel was much thicker. If the same size film was used for both types of shots, the film from long shots represented a greater mass, hence a greater likelihood of defects. This was confirmed by Don Piper, who participated in the February 5, 2015, work group meeting. As Allen correctly reported, Mr. Piper said that submarine missile tubes had fewer defects. However, Allen mistakenly described the tubes as being thick. According to a declaration filed by the late [redacted] (2006), a former GSI worker, the missile tubes were produced for Polaris submarines. When John Harrop, an SC&A Associate, who served as an engineering officer on Polaris submarines, was asked if the tubes were at the lower end of the range of 5–18 in cited by Mr. Piper, CDR Harrop explained that the function of the tubes was to launch the missiles using compressed air.[1] The rocket propellant did not ignite until the missile was 100 ft in the air; consequently, there was no need for a thick-walled tube. He said the missile tubes were definitely less than 5 in thick, which qualifies them as thin metal. Mr. Piper also said "the bigger the casting . . . had [sic] more defects."

This conclusion is further buttressed AFS (n/d):

[1] CDR John K. Harrop, U.S. Navy (retired), private communication with Robert Anigstein, SC&A, Inc., September 10, 2015.

> Below are descriptions of defect types and their correct terminology. . .
>
> 6. Upon x-ray, you observe a cavity in the middle of your casting. Defect: Axial Shrinkage—All metal shrinks as it solidifies. Axial (or centerline) shrinkage, most often plate-like in shape, occurs when the metal at the center of the casting takes longer to freeze than the metal surrounding it. The defect is partly a function of the section thickness designed into the casting.

It is finally confirmed by our colleague William C. Thurber, an experienced metallurgist, who wrote: "I think, in general, the larger and more complex the casting the greater will be the probability for some of these . . . defects to occur" (Thurber 2015).

It is difficult to quantify the relative time spent on short and long shots. The lowest ratio would be 1:1—no difference between the short and long shots, as assumed by Allen (2015c). The upper end of the range might be the relative duration of long:short shots, including setup time, which is 75:15 min, or 5:1, since that is the ratio of the production rate of the individual shots. A reasonable estimate would be the average of these two ratios, or 3:1. If we assume that there were n long shots during a given time period and $9n$ short shots, but that the long shots took 3 times as long to mark up, then the fraction of time spend on the long shots would be $\frac{3n}{3n + 9n} = 0.25$ or 25%, the remaining 75% being spent on short shots.

We compared the β skin doses to the layout man using the various proposed scenarios. First, we recalculated the doses from the scenario first described by Anigstein and Mauro (2014), applying the intermittent exposure algorithm. The resulting does are lower than from the continuous irradiation in our original calculation, but higher than those obtained by Allen (2015b). We then applied the scenarios described by Allen, but assumed that the layout man spent 25% of his time on long shots, the remainder on short shots. The results are listed in Table 4.

Table 4. Annual Doses to Skin of Layout Man from Beta Rays Emitted by Irradiated Steel

Skin on:	Dose (rad/y)				
	SC&A-1[a]	SC&A-2[b]	NIOSH-1[c]	NIOSH-2[d]	New[e]
Hands and forearms	1.89	0.278	0.807	0.264	0.405
Rest of body	1.14	0.178	0.463	0.147	0.224

[a] Scenario described by Anigstein and Mauro (2014)

[b] SC&A-1, recalculated using intermittent exposure algorithm

[c] Scenario proposed by Allen (2014)

[d] Scenario proposed by Allen (2015b)

[e] NIOSH-2 recalculated by SC&A, using betatron beam intensity based on MCNPX simulations and assuming 25% of time spent marking up long shots

We recommend that NIOSH adopt the "New" values, which are based on a plausible interpretation of the betatron operations at GSI and on metallurgical knowledge, and are claimant favorable. We note that these doses are significantly less than the β skin doses to the layout man listed in Appendix BB, Rev. 1 (Allen 2014).

Conclusion

We conclude that NIOSH has achieved a reasonable resolution of the issues involving Finding 6, with the only outstanding difference being the relative amount of time that the layout man spent marking up long vs. short shots.[2] We note that our recommended β dose to the skin on hands and forearms of the layout man represents about 4% of his total skin dose, while our value of the β dose to the skin on the rest of the body represents about 2%. Thus, this issue plays a relatively minor role in the overall reconstruction of doses to the skin from this exposure scenario.

[2] As pointed out by [redacted] (2015), Allen (2015c, p. 6) transposed the distances for long and short shots. This is an editorial error—the correct distances were used in the NIOSH analyses.

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