TO: Advisory Board on Radiation and Worker Health Work Group on TBD-6000
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SUBJECT: Review of Skin Doses at GSI
DATE: December 5, 2013

Review of Skin Dose Calculations for General Steel Industries

1 Updated Analysis of Skin Dose

During the ongoing exchange of information between NIOSH and SC&A regarding the assessment of doses to the skin of betatron operators from irradiated steel castings, we reviewed and updated our previous analyses, as discussed below.

We begin with a step-by-step derivation of the doses to the skin from irradiated steel and uranium.

1.1 Original SC&A Skin Dose Model

As stated by SC&A (2008, pp. 25–26),

> In calculating the concentrations of residual nuclides, we note that the same portion of a steel plate could be exposed to the betatron beam several times, both because of overlapping shots and because repeated radiographs were performed as flaws were repaired and checked. . . . The casting could be returned to the betatron room 5–10 times before leaving the plant. Given the possibility of four overlapping shots irradiating the same area and an average of 7½ examinations, we assumed that the HY-80 steel had been exposed for 30 h (4 × 7.5 × 1 h = 30 h). . . .
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> Most of the photonuclear interactions in steel, and hence most of the production of residual nuclides, would be near the surface of the metal and near the center of the betatron x-ray beam. To avoid diluting the activity by averaging over a large volume of metal, most of which would have low levels of activation, we restricted the analysis to a small, relatively thin disk: a right circular cylinder, 5 cm thick, with a radius of 8.255 cm (3.25 in). This radius encompasses the most intense part of the beam. The resulting specific activities are thus characteristic of the central, most highly exposed portion of the steel.

The SC&A (2008) analysis of skin doses from photoactivation products in irradiated steel that was based on the two scenarios—short and long shots—used a hybrid approach. According to SC&A (2008, pp. 37–38),

> About 10% of the radiographs of steel castings were long shots, while the remainder were short shots. . . . The long shots included 15 min of setup and one hour of exposure, while the short shots took a total of 15 min. Thus, 10 average shots included one long shot, which took 75 min, and 9 short shots which took 135 min

(9 × 15 = 135), for a total of 210 min. As a result, about 36% of the time (75 ÷ 210 = 0.36) was spent on long shots and 64% on short shots.

We will first explain how the two distances of the steel from the betatron target—9 ft for short shots and 6 ft for long shots—were addressed in the SC&A (2008) analysis. The exposure geometry in our original MCNPX simulation of photoactivation placed the casting 6 ft from the point the measuring string was attached to the outside of the betatron—this was based on a misunderstanding of the measuring procedure employed at GSI. We later learned from Jack Schuetz (former Allis-Chalmers engineer and a NIOSH consultant) that the string was calibrated to indicate the distance to the internal betatron target, so that the shots described as 6 ft were actually 6 ft (182.88 cm) from the target, not 234.95 cm, as specified in our model. Rather than repeat the MCNPX run, we increased the results by applying the inverse square law. Such a correction factor essentially contracts the radius of the steel disk to match the angular width of the x-ray beam that it intercepts. Since the area and hence the mass (the thickness being held constant) of such an adjusted disk varies with the square of the distance, and since the specific activities of the residual nuclides are inversely proportional to the mass, such an adjustment factor yields a reasonable approximation of the specific activities, the only neglected factor being the different amounts of air attenuation over different distances. To evaluate this last effect, we observe that the peak energies for photoactivation of the nuclides in the skin dose assessments, which are listed in Table 1, are in the range of 15–20 MeV. The linear attenuation coefficient of 17.5 MeV photons (the midpoint of the energy range) in air is ~0.0021 m^{-1}. Their attenuation in 52 cm, the difference between the two distances, is ~0.11%, which is entirely negligible in the present analysis.

We increased the specific activities from the long shots by multiplying the specific activities derived from the MCNPX simulation by the ratio of the square of the distance used in the simulation—234.95 cm—to that of the actual distance—6 ft (182.88 cm); however, in the interest of a conservative assessment, we did not decrease the activities for the short shots, which were at a distance of 9 ft (274.32 cm) from the target. We then derived an average of the specific activities by weighting the activities by the fractions of time devoted to the short and long shots. The exposure duration of the betatron operator to irradiated steel, 11.4 min, was an average of the setup and handling during short shots (11 min) and long shots (15 min), weighted by the relative numbers of short and long shots, 90% and 10%. We assumed that the operator was in the immediate proximity of the steel for only one-half of this time.

1.2 First Revision to Skin Doses from Irradiated Steel

Anigstein and Olsher (2012) repeated the MCNPX simulation of residual nuclides using the MCNPX ver. 2.7.E. We placed the steel disk at a distance of 6 ft (182.88 cm) from the target, obviating the need for any adjustment for long shots, and assumed that all the castings were exposed at this distance, avoiding the complication of interspersing radiographic exposures of different durations and at different distances. Other aspects of the analysis were unchanged. The result was intended to be a bounding, claimant-favorable assessment.

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

Nuclide	Half-life	Peak energy [a] (MeV)	$\mu_{\varepsilon t}$ [b] (cm^2/g)	Sp. act.[c] (Bq/g)		Time-integrated sp. act.[d] (Bq·h/g)	
				Short[e]	Long[e]	Short	Long
Fe-53	8.51 m	19.6	0.0321	304.43	684.96	36.61	98.18
Mo-91	15.49 m	16.0	0.0311	33.55	75.49	4.84	13.70
Ni-57	35.6 h	17.9	0.0316	20.54	46.20	3.76	11.52
Mn-56	2.58 h	19.6	0.0321	18.57	41.77	3.32	10.10
Mo-99	65.94 h	15.9	0.0310	9.55	21.49	1.75	5.37
Cr-49	42.3 m	19.8	0.0322	4.23	9.52	0.71	2.11

[a] Energy of peak photonuclear cross-section for production of given nuclide; assumes photoneutrons from ^{54}Fe produced ^{56}Mn by the reaction $^{55}Mn(n,\gamma)^{56}Mn$

[b] Mass attenuation coefficient corresponding to peak energy for HY-80 steel, interpolated from Storm and Israel (1970)

[c] Specific activity at surface immediately after irradiation

[d] Specific activity integrated over exposure duration of betatron operator

[e] Short and long shots—see text

1.3 Final Revision to Skin Doses to Betatron Operators from Irradiated Steel

Following our review of the NIOSH assessment of doses to the skin of betatron operators from photoactivation products in irradiated steel, we performed a more comprehensive analysis of skin doses from both the long and short shots. We modeled each scenario (i.e., short shots and long shots) separately and apportioned the resulting doses according to the fraction of time taken up by both types of shots.

We began by repeating our simulation of the photoactivation of the HY-80 steel alloy commonly produced at GSI, using MCNPX 2.7.0, the latest publicly released version of the code. This version also had the advantage of an updated library of photonuclear cross-sections, containing an expanded list of nuclides—the input file was modified to explicitly take advantage of these data. We ran the code for 2.147 billion histories, very close to the code maximum, to obtain the optimum precision in the results.

The results of the new analysis listed 37 radionuclides that were produced during the betatron irradiation of HY-80 steel. From this list, we identified 27 nuclides that are significant β emitters. We ranked these 27 radionuclides in descending order of activity integrated over the period from 5 s to 11 min or 15 min following irradiation, depending on the scenario. Since the first six nuclides in this list accounted for ~99.5% of the total integrated activities, we selected these nuclides, which are listed in Table 1, for the assessment of β doses to the skin. These are the same six nuclides identified in our prior analyses.

Employing the same methodology discussed by SC&A (2008, pp. 28–29), we used the total activities in the steel that we derived from the new MCNPX simulation to calculate the specific activities at the surface by adjusting for the exponential decrease of the x-ray beam over the 5-cm thickness of the steel disk, as listed in columns 5–6 in Table 1. The last two columns list the specific activity integrated over the setup time in each scenario. The specific activities for the long shots were calculated directly from the MCNPX results; those for the short shots were scaled by the ratio of the squares of the distances: $6^2 \div 9^2 = 0.444$.

Upon reviewing the MCNPX simulations of doses to the skin from the six nuclides listed in Table 1, performed in January 2008, we observed several areas for improvement that we incorporated in the revised analyses. The more significant of these are described below. The energy spectrum of the β rays from ^{53}Fe had been estimated from a graphical representation of the spectrum— tabulated data were not available to us at that time. Since then, ICRP (2008) has issued a database from which we extracted the spectrum in tabular form. Furthermore, ^{53}Fe and ^{91}Mo were originally modeled as electron emitters (β^-), when in fact they emit positrons (β^+). MCNPX uses the same model for the attenuation of electrons and positrons; however, the annihilation of positrons is accompanied by the emission of two 511-keV γ rays, which generate electrons through photoionization and Compton scatter that can make further contributions to the skin dose. We repeated the analyses for the three nuclides—^{53}Fe, ^{56}Mn, and ^{91}Mo—that together account for 98%–99% (depending on the scenario) of the dose to the skin of the betatron operators. The analyses of all three nuclides utilized the corresponding ICRP (2008) beta spectra.

The NIOSH scenario for the exposure of the betatron operator to irradiated metal specified that the worker was at a distance of 1 ft from the metal for one-half of the exposure time and at a distance of 1 m for the other half. However, previous simulations of skin doses from radionuclides in steel did not include assessments at 1 m. The doses calculated for the skin of hands and forearms in contact with the metal, and for other skin at a distance of 1 ft, were divided by 2, implying that the dose at 1 m was zero. To correct this oversight, we included assessments at 1 m in the new simulations of skin doses from ^{53}Fe, ^{91}Mo, and ^{56}Mn. Based on extrapolations from the analyses at other distances, these nuclides are estimated to contribute ~99% of the dose at 1 m. Given the small contribution of the dose rate at this distance to the overall skin dose assessment, omitting the contribution of the other nuclides has a negligible impact on the overall uncertainty of this assessment.

Dose rates were calculated for bare skin in contact with the metal, skin in contact with the metal but covered by one layer of clothing, and cloth-covered skin at 1 ft (30.48 cm) and at 1 m from the metal. The number of shots during one 8-h shift was calculated by dividing the duration of the shift by the total time for one shot—15 or 75 min. The new analyses took advantage of some MCNPX features that increased the accuracy of the simulations of electron/positron transport, as well as improved geometry that is more representative of the area of exposed skin.

The results of our analyses are presented in Table 2.

Table 2. Dose Rates to Skin of Betatron Operators from Beta Radiation from HY-80 Steel

Distance	Shield	Dose (mrad/shift)		
		Short[a]	Long[a]	Composite
Contact	None	9.35	5.11	7.84
Contact	Cloth	7.98	4.36	6.69
1 ft	Cloth	5.77	3.15	4.83
1 m	Cloth	2.11	1.15	1.76

[a] Short and long shots—see text

The last column in Table 2 lists the composite doses from both scenarios—the time-weighted average of the doses from short and long shots.

1.4 Skin Doses to Betatron Operators from Irradiated Uranium

We next repeated the MCNPX analyses of the generation of residual nuclides from the betatron radiography of uranium slices. The simulation that was the basis of our previous assessments of skin doses from irradiated uranium had originally been performed using MCNPX ver. 2.6.E. In that version of the code, the generation of residual nuclides was not specific to the specific region of interest in the metal being irradiated, requiring the analyst to use his judgement to determine which nuclides were in the metal. The new version of the code identifies the nuclides in the user-specified region (i.e., the uranium slice). In the process, we changed the thickness of the uranium disk from 0.5 cm to 5 cm. A 5-cm thickness of uranium absorbs ~99.5% of 13.1 MeV photons—the center of the peak energy of the total photonuclear cross-section of ^{238}U—as compared to an absorption of ~42% in 0.5 cm of the metal. The greater thickness specified in the simulation represents a more realistic scenario, and also leads to greater efficiency in the MCNPX analysis. Other enhancements were specifying uranium as an electrical conductor, and air as a gas. These lead to minor changes in the interactions of these materials with incident radiation and thus yield a more realistic analysis. As before, we found that the two principal β-emitting radionuclides produced by photoactivation were ^{237}U and ^{239}U. The revised specific activities are presented in Table 3.

We next performed an MCNPX simulation of skin doses from β rays emitted from a uranium slice. The exposures were to the side as well as to the front face of the cylindrical slab. The radiation source in the exposures at the side of the metal comprised the short-lived β-emitting progeny of ^{238}U and ^{235}U, enhanced by the Putzier effect. The β-ray spectrum is thus that of these progenies in secular equilibrium with the parent nuclides, which have the relative abundance of naturally-occurring uranium; however, the results of the assessments are multiplied by a factor of 12.5 to account for the enhancement of these progenies at the surface of the uranium ingot during casting. Because the activities of these β-emitting progenies would far exceed the activities of the photoactivation products, whose concentrations exponentially decreased over the 4-inch thickness of the slab, the latter nuclides were not incorporated in the β spectrum from the cylindrical surface (i.e., at the side of the slice).

Table 3. Residual Nuclides in Uranium: Sources of External Exposure to Beta Radiation

Nuclide	Half-life	Peak energy[a] (MeV)	$\mu_{\varepsilon t}$[b] (cm^2/g)	Sp. act.[c] (Bq/g)	TWA sp. act.[d] (Bq/g)
U-237	6.75 d	13.1	0.0559	19.9	19.9
U-239	23.45 m			9,718	7,830

[a] Energy of peak of total photonuclear cross-section of ^{238}U

[b] Mass attenuation coefficient corresponding to peak energy for uranium, interpolated from Storm and Israel (1970)

[c] Specific activity at surface immediately after irradiation, assuming an exponential profile over a 5-cm thickness

[d] 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 3. The simulation used the same tallies and exposure geometry as the analyses of the β-emitting nuclides in steel, described previously. The calculated skin doses from exposure to a uranium slice are presented in Table 4.

The final results of the skin dose assessment are listed in Table 5. The annual number of shifts devoted to the handling of uranium was based on the revised hours of uranium handling listed by Anigstein and Mauro (2013, Table 1). The remainder of the shifts were assumed to be devoted to the radiography of steel.

2 Conclusions

In the course of the continuing exchange of information between SC&A and NIOSH, most outstanding differences in the calculation of β doses to the skin of betatron operators appear to have been resolved. The latest exchange of spreadsheet calculations shows complete agreement on the methodology of calculating the doses. Assuming that NIOSH adopts or replicates out MCNPX simulations, and that the uranium work hours differences are resolved, SC&A and NIOSH will be in agreement regarding the limiting doses to the skin from β radiation, which are those experienced by a betatron operator.

Table 4. Dose Rates to Skin from External Exposure to Beta Radiation from Uranium Slice

Location	Orientation	Dose Rates to Skin (mrad/h)
Contact	Front	119
	Side	1,428
	Average	774
Cloth	Front	95
	Side	1,094
	Average	594
1 ft	Front	23
	Side	65
	Average	44
1 m	Front	2.5
	Side	8.9
	Average	5.7
Average for bare skin		389.6
Average for other skin		24.8

Table 5. 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
1952-1957	54.7	351.6	31.96	2.76	34.72	2.03	1.70	3.73
1958	46.5	359.8	27.17	2.82	29.99	1.73	1.74	3.46
1959-1960	42.2	364.1	24.66	2.85	27.51	1.57	1.76	3.33
1961	48.4	357.8	28.31	2.80	31.11	1.80	1.73	3.53
1962	35.2	371.1	20.55	2.91	23.45	1.31	1.79	3.10
1963	9.6	396.7	5.59	3.11	8.70	0.36	1.92	2.27
1964	3.5	402.7	2.05	3.16	5.21	0.13	1.95	2.08
1965	2.6	403.7	1.50	3.16	4.66	0.10	1.95	2.05
1966[a]	0.8	202.3	0.47	1.59	2.06	0.03	0.98	1.01

[a] During contract period January 1–June 30

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