DRAFT

WHITE PAPER FOR GSI APPENDIX BB REVIEW

For Discussion Purposes Only

Background

The NIOSH dose estimate for General Steel Industries (GSI) employees is described in Appendix BB to Battelle 6000, approved on June 25, 2007. This dose estimate was reviewed by SC&A and documented in a report dated March 17, 2008. The report was subsequently reviewed and made available on the OCAS website in April 2008. Neither report had the advantage of using film badge data later retrieved from Landauer Inc. This white paper describes the film badge data as well as analyzes the film badge results. It also identifies several inconsistencies in the SC&A report and the effect of correcting them. Lastly, the white paper will examine the effect of the film badge results on these corrected values.

Analysis of Film Badge Data

<u>Data</u>

The oldest data received from Landauer covers the week beginning January 1, 1964 (a Tuesday). The next oldest data covers the week beginning January 6, 1964 (a Sunday) followed by the week beginning January 13, 1964. The data continues to cover every week with the last week covered being the week beginning December 10, 1973.

The data provides the last name of the person to which the badge was assigned. It also provides the results of the badge processing. An "M" was recorded for readings that were less than the recording level of 10 mr. The current reading as well as the cumulative dose for the calendar quarter and year was included. The report also included a cumulative dose for the individuals' entire employment at the site. However, it is important to realize the beginning of this tabulation is the day that person started wearing a film badge, not the day the individual actually began employment. Lastly, the report indicates the number of times the person was monitored by film badge and the first week he was monitored. The early reports indicate 17 people were monitored beginning on November 6, 1963. However, the weekly reports prior to January 1, 1964 were not recovered. A spot check of these values indicates several people were often missing from the report in late December and would show up again in January. The cumulative number of badges was not increased while the names were missing. This likely indicates vacation time was accounted for in this total.

A total of one-hundred eight different names were recorded between 1964 and 1973. There were never that many names assigned a badge at any one time. Through June 1966, a total of 6999 badge readings were recorded for individuals. Of these, 22 were recorded at or greater than the 10 mr recording level. For the full amount of data, from 1964 through 1973, a total of 16292 individual badge readings were recorded with a total of 49 recorded greater than 10 mr. Also, there were 114 badges recorded as "Betatron

CTL" for the Betatron Control room. The last was the week of February 6, 1966. All 114 readings were less than 10 mr.

Representativeness of Data

Individuals that clearly identified themselves as being associated with radiography (Radiographer, Radiographer Helper, Film Processor, etc) during worker outreach meetings (a total of five people) were checked against the film badge data. The names of all five appear in the records. Also, an article from a company publication named 11 people that had passed a 32-hour course in Health Physics. The article indicated the course was to "qualify them as radiographers in handling radioactive isotopes". All 11 names were checked against the dosimetry reports and all 11 appear in the records.

With all 17 people known to be associated with radiography included in the records, it appears that the all the employees directly associated with radiographers were assigned a film badge at GSI between 1964 and 1973. It also appears these radiographers were indeed the ones who performed the source radiography. The betatron buildings were described as a very busy place. With only 108 names appearing over the entire time span, it appears equally clear that ancillary workers (those working to move or repair castings, maintenance personnel, etc.) that were not directly involved with the radiography were not issued film badges.

The question of how representative these readings are for years prior to 1964 must be asked. Only one betatron existed at the site prior to 1963. During 1963, a new betatron building was built and a betatron was moved from the Eddystone, PA site to the Granite City site. The "new betatron" as it was called was reportedly upgraded when it was moved to Granite City. Operators indicated that the new betatron had a higher output than the old betatron.

More importantly, a supervisor for the betatrons described work prior to 1963 as much slower paced. He indicated prior to 1963 the radiography was essentially a quality control function that checked a sampling of castings. In 1963 the role of radiography at GSI changed from "two people who worked there part time to, as these guys have said, seven days a week, 24 hours a day and we were 500 percent overscheduled". Another worker indicated that 1963 to 1966 was the peak production period.

It appears after 1963 the radiography at GSI occurred much more often and included a higher output machine. This indicates the film badge readings starting in 1964 would not necessarily be representative of the pre-1963 dose but it should be higher and thus bounding.

Analysis

From 1964 through the end of the contract period (June 1966) only 22 of the 6999 film badges processed resulted in a reading greater than 10 mr. With 99.7% of the readings being below the recording level, statistical analysis is limited. The rank-file 95th percentile is obviously less than 10 mr. If a lognormal distribution is assumed, the distribution results in a geometric mean of 2.06×10^{-5} mr/badge reading. The geometric standard deviation of this distribution would be 100. This results in a 95^{th} percentile of 0.04 mr/badge reading. While there is no standard value considered too high for a geometric standard deviation, a value of 100 is very high. If a normal distribution is assumed, the mean is 0.46 mr/badge reading with a standard deviation of 29.8 mr. This results in a 95^{th} percentile of 49.4 mr. Since a normal distribution is symmetrical about the mean, this distribution implies 49.3% of the values of this distribution are less than zero. Obviously it is impossible for the true radiation dose to be less than zero. While a small percent of negative values may still represent a distribution that is an acceptable approximation of the true distribution, nearly half the values being negative is clearly not a good approximation.

Next, the average badge reading for each individual was determined. The individuals were monitored for different periods and lengths of time. Therefore, to normalize the values an average weekly reading was determined for each individual. That is, each person's recorded dose was divided by the total number of badges he was assigned. A distribution of these averages was then determined. Sixty-seven of the eighty-nine individuals (approximately 75%) had no dose recorded at or above the recording level of 10 mr. The average of these values was 0.371 mr with a standard deviation of 2.76 mr. Again, this results in a normal distribution with a large fraction of the values (44.6%) being less than zero. If a lognormal distribution is assumed, the geometric mean is 0.0065 mr with a geometric standard deviation of 16.7. The 95^{th} percentile of this distribution would be 0.673 mr. With the high percentage of censored data and a GSD that is still relatively high, additional distributions were explored.

From the above description, it is clear that no analysis of this data is going to provide a distribution that clearly well represents the data. This is due to the high percentage of censored data. As an alternate approach, the recording level (10 mr) was substituted for each reading recorded below the recording level. As with the last analysis, a weekly average reading for each individual was then determined using these substituted values. A distribution of these values has an average of 10.35 mr with a standard deviation of 2.75 mr. That produces a 95^{th} percentile of 14.87 mr. If a lognormal distribution is assumed, the geometric mean is 10.2 mr with a geometric standard deviation of 1.15 for a 95^{th} percentile of 12.78 mr.

The parameters of both of these distributions are more reasonable than the previously-reported distributions. The normal distribution does not imply a large fraction of the readings have a negative value. The GSD of the lognormal is not exceedingly high and the median and 95^{th} percentiles of both distributions are relatively similar. The substitution is obviously a bounding substitution (replacing those recorded as less than 10 mr with 10 mr). It is equally obvious that with 99.7% of the values replaced with this substitution that the result is a bounding estimate of the recorded dose. However, in order to insure the doses actually recorded are accounted for, the 95^{th} percentile is used. This is essentially the upper bound of a bounding distribution. Therefore, the 14.87 mr per reading (per week) is used for the rest of this white paper.

Inconsistencies in SC&A review of Appendix BB

Betatron Operator Exposure to Apparatus

In the SC&A review of Appendix BB, photon dose from the betatron apparatus was based on two different scenarios. For the "short shot" scenario, the casting was assumed to be 9 feet from the betatron target and the betatron operators' distance from the apparatus was assumed to vary uniformly between 3 feet and 6 feet. The operator is therefore assumed to be at a distance of 3 feet to 6 feet from the casting. However, the photon dose from the casting was based on the assumption that the operator was 1 foot from the casting half of the time and 1 meter (approx. 3.3 feet) from the casting the other half. Combining these two scenarios effectively puts the operator in two places at one time.

Using the same technique described in the review, the dose from the apparatus can be recalculated to be consistent with the other scenarios. That is, the operator is assumed to be 1 foot from the casting half of the time (5 feet from the apparatus for long shots, 8 feet for short shots). The other half of the time, the operator is assumed to be 1 meter from the casting (approximately 2.7 feet from the apparatus for long shots, 5.7 feet for short shots)

The formula on page 19 of the SC&A report were used to calculate dose based on a uniform varying distance. However, since the exposure scenario elsewhere in the report indicates a dose rate from two set distances was used, this formula is not necessary. The inverse square law was used to determine the initial exposure rate at the various distances. These were based on the exposure rate of 15 mr/hr at 6 feet. The initial exposure rates are then 73 mr/hr at 2.7 feet, 16.5 mr/hr at 5.7 feet, 21.6 mr/hr at 5 feet, 15 mr/hr at 6 feet and 8.44 mr/hr at 8 feet.

The formula on page 20 was used to determine the dose over the exposure period taking into account the decay rate. This formula assumes an operator is exposed from the moment the betaton is turned off to the end of the assumed period of time (11 minutes for the short shot scenario, 15 minutes for the long shot scenario). However, when the dose from the uranium metal and steel after the shot was calculated in the report, it was assumed that the operators were not exposed for the first 5 seconds after the shot. This was described as the minimum amount of time it would take to exit the control room and reach the vicinity of the metal object. In order to allow this same assumption for the apparatus dose calculation, the formula on page 20 is adjusted to:

$$X(t) = \frac{R_0}{60}\int_{t1}^{t2} e^{-\lambda t}\,dt = \frac{R_0(e^{-\lambda t_1} - e^{-\lambda t_2})}{60\lambda}$$

In this equation, t1 is the time from the end of the x-ray exposure until the operators reach the betatron (5 seconds). Also, t2 is the time from the end of the x-ray exposure until the operators leave the betatron area (11 minutes for the short shot scenario and 15 minutes for the long shot scenario).

In order to minimize rounding errors, the dose rates in the SC&A document were first recreated. Next, the exposure was calculated as described above and the exposure for the two appropriate distances were averaged. This average was multiplied by the number of "shots" described in Table 16 to arrive at the exposure per shift.

Railroad Shot Exposure Scenario

Dose rates outside the new and old betatron building were modeled based on two scenarios. One was a "center shot" in which the betatron was in the approximate center of the shooting area while an x-ray exposure was occurring. The other was a "railroad shot" in which a casting is assumed to be exposed while sitting on a railroad car straight in from the equipment door. The betatron has limit switches that prevent a shot from occurring in this position but operators indicated they were ordered to defeat these limit switches by "flipping the head" of the betatron and perform shots in this position. The operators went on to indicate that this was not done until the supervisor present in the early 1960s left the company and was replaced by another. This supervisor left the company on 6/30/1966 which is the last day of the uranium work. This information indicates the railroad shots occurred after the covered period. The analysis performed by SC&A summarized photon dose rates based on the railroad shot scenario. However, some dose rate information for the center shot was included in the report.

Table 2 shows that the exposure rate in the control room of the new betatron building is calculated to be 1.9 mr/hr for the railroad shot and 0.3 mr/hr for the center shot. Likewise the neutron dose is calculated to be 0.6 mrem/hr for the railroad shot and 0.3 mrem/hr for the center shot. Table 3 provides two exposure rates for the control room of the old betatron building. These two values were averaged when calculating values for Table 16. The average of the railroad shot photon exposure rate was 1.05 mr/hr. The SC&A report provided no values for a center shot, however, values for the center shot can be calculated similar to those calculated for the new betatron building. This was done using MCNP to find control room values for both neutron and photon doses. The same two points in the control room were used. Only the location and orientation of the betatron and the steel were changed.

250 R/min Exposure Rate from Old Betatron Machine

SC&A used a betatron output of 250 R/min from both the new and old betatron machines. This was based on a letter from a former Allis Chalmers employee. It was also noted that this was consistent with a GSI employee recollection of 160 R/min once a 35% reduction for the beam compensated was factored in. However, the seven tube outputs listed by the Allis Chalmers employee represent shipping dates between 12/29/1969 and 5/31/1973. In the paragraph immediately preceding this table, the employee wrote:

> *Tubes manufactured in the early 1950s produced outputs between 125-150 R/M, the 1960s between 200-275 R/M and by the late 1970s, between 300-375 R/M @ 25 Mv.*

Both betatrons were built in the early 1950s but the new betatron was originally in Eddystone, PA. That betatron was moved to GSI in 1963 and reportedly underwent an upgrade at that time. The statement above from the Allis Chalmers employee indicates the early 1950s model would have an output between 125 and 150 R/min. This is also consistent with GSI employee recollections. During an August 21, 2006 meeting, an operator indicated the output of the new betatron was between 200 and 250 R/min but the old betatron "couldn't do that good". He indicated the old betatron had an output of "probably 100, 110 at maximum". The SC&A report relied on the recollection of a GSI employee that he recalled 160 R/min on the new betatron. The same employee in a meeting held on October 9, 2007 indicated that a 10,000 R shot would have taken 1 hour and 15 minutes (133 R/min) but that the old betatron would have taken longer because it did not have a capacitor bank.

The compensator used to flatten the photon flux causes a reduction of about 1/3 of the beam intensity (35% per the SC&A report). The Allis Chalmers employee was referring to the uncompensated output of the betatron. If the maximum 1950s output is assumed (150 R/min) the compensated beam would have an output of approximately 100 R/min. This is consistent with the GSI employee recollection. Either way, both GSI employees clearly remember the output of the old betatron being lower than the output of the new betatron. Therefore, the rest of this white paper will consider the uncompensated output of the new betatron to be 250 R/min and the uncompensated output of the old betatron to be 150 R/min.

Inconsistent Assumption between Photon and Beta dose

A summary of the annual doses is presented in the SC&A report. Section 2.6.1 describes the photon and neutron doses while Table 21 in section 2.6.2 describes the beta doses. In order to estimate the beta dose, an estimate of the amount of uranium work was performed and a mixture of uranium and steel work was used. However, in order to estimate the photon and neutron doses, no uranium work was assumed. This leads to the inconsistent assumption that employees were working both with and without uranium at the same time. The remainder of this white paper will use the estimated uranium versus steel work time used in the beta dose calculation.

The effect of adjusting for these inconsistencies is shown in the next two tables. The first table is a recreation of Table 16 from the SC&A report. The second table is the same table with the values adjusted as described above. The values in the first table were recreated as best as possible from the SC&A report as well as MCNP output files provided by SC&A. The recreation produced some differences between this table and Table 16 in the SC&A report due primarily to different rounding errors. One value, the photon exposure from uranium metal in the new betatron building, was incorrectly reported in the original SC&A report as 0.66 mr/shift and later corrected to 6.8 mr/shift. However, the recreation below resulted in a value of 6.56 mr/shift. This represents the largest difference in attempting to recreate this table. The 6.56 mr/shift was recreated starting with values from tables 8 and 9 from the SC&A report. While round-off error may explain some of the difference, it can not explain it all.

Recreation of Table 16 from SC&A review of Appendix BB

Metal	Type of shot	Number per shift	Fraction	Source of radiation	Duration (h/shift)	Exposure (mR/shift)	Neutron dose (mrem/shift)
25 MeV							
HY-80	Short	32	64%	Control room	1.6	3.11	0.92
				Metal	5.87	0.35	
				Doughnut	5.87	34.56	
				Total		38.02	0.92
	Long	6	36%	Control room	6.0	11.66	3.44
				Metal	1.5	0.66	
				Doughnut	1.5	13.03	
				Total		25.35	3.44
	Composite		100%			33.46	1.82
Uranium	Long	6		Control room	6.0	11.66	3.44
				Metal	1.5	6.56	0.67
				Doughnut	1.5	13.03	
				Total		31.25	4.11
24 MeV							
HY-80	Short	32	64%	Control room	1.6	1.68	0.59
				Metal	5.87	0.35	
				Doughnut	5.87	34.56	
				Total		36.58	0.59
	Long	6	36%	Control room	6.0	6.29	2.20
				Metal	1.5	0.66	
				Doughnut	1.5	13.03	
				Total		19.97	2.20
	Composite		100%			30.60	1.17
Uranium	Long	6		Control room	6.0	6.29	2.20
				Metal	1.5	6.56	0.67
				Doughnut	1.5	13.03	
				Total		25.88	2.87

Adjusted Table 16 from SC&A review of Appendix BB

Metal	Type of shot	Number per shift	Fraction	Source of radiation	Duration (h/shift)	Exposure (mR/shift)	Neutron dose (mrem/shift)
25 MeV							
HY-80	Short	32	64%	Control room	1.6	0.50	0.52
				Metal	5.87	0.35	
				Doughnut	5.87	14.37	
				Total		15.21	0.52
	Long	6	36%	Control room	6.0	1.86	1.96
				Metal	1.5	0.66	
				Doughnut	1.5	10.28	
				Total		12.79	1.96
	Composite		100%			14.34	1.04
Uranium	Long	6		Control room	6.0	1.86	1.96
				Metal	1.5	6.56	0.67
				Doughnut	1.5	10.28	
				Total		18.70	2.63
24 MeV							
HY-80	Short	32	64%	Control room	1.6	0.07	0.22
				Metal	5.87	0.21	
				Doughnut	5.87	8.62	
				Total		8.90	0.22
	Long	6	36%	Control room	6.0	0.27	0.84
				Metal	1.5	0.39	
				Doughnut	1.5	6.17	
				Total		6.83	0.84
	Composite		100%			8.16	0.45
Uranium	Long	6		Control room	6.0	0.27	0.84
				Metal	1.5	4.08	0.40
				Doughnut	1.5	6.17	
				Total		10.52	1.24

Application of Film Badge Data

With an analysis of the film badge data and the adjustments to the SC&A model in place, it is possible to put the information together. A briefing of the model was previously given to a working group of the Advisory Board by SC&A. An overview of the dose was provided in a table format during that briefing. The table is a recreated below.

Estimated Annual External Exposures of Betatron Operators

Years	External exposure (R/y)		Neutron dose (mrem/y)	Skin dose (rads/y)			
				Hand & forearms		Other skin	
	SC&A	NIOSH	SC&A[a]	SC&A	NIOSH	SC&A	NIOSH
1952-1957[b]	12.4	5.8	470	27.2	19.4	2.5	1.8
1958	12.4	5.8	470	25.9	19.4	2.4	1.8
1959-1960	12.4	5.8	470	24.7	19.4	2.4	1.8
1961	12.4	6.3	470	28.1	22.3	2.6	2.0
1962	12.4	5.1	470	20.9	16.2	2.2	1.65
1963	12.4	2.8	470	7.0	4.4	1.4	0.4
1964	13.6	2.2	735	3.8	1.6	1.2	0.15
1965	13.6	2.1	735	3.3	1.2	1.2	0.11
1966[c]	6.8	1.0	368	1.4	0.37	0.6	0.034

[a] Neutron doses not assessed by NIOSH

[b] NIOSH assumed covered period began 1953

[c] Total during covered period: January 1 – June 30

The photon dose of 14.87 mr/week from the film badge data can be multiplied by a 50 week work year resulting in an annual exposure of 743.6 mr/yr. The values in the table above were recreated and then adjusted for the inconsistencies described earlier. After that, a value of 743.6 mr/yr was substituted for the photon exposure and the neutron and skin dose was adjusted proportionately. The resulting dose is shown in the table below.

Adjusted Annual External Exposures of Betatron Operators

Years	External exposure (R/y)	Neutron dose (mrem/y)	Skin dose (rads/y)	
			Hand & forearms	Other skin
1952-1957	0.7436	41	6.733	0.536
1958	0.7436	41	6.369	0.514
1959-1960	0.7436	41	6.009	0.493
1961	0.7436	41	0.550	6.978
1962	0.7436	41	0.431	4.959
1963	0.7436	41	0.224	1.450
1964	0.7436	41	0.160	0.485
1965	0.7436	54	0.156	0.418
1966	0.3718	54	0.076	0.175