SC&A S. Cohen & Associates
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April 21, 2008

Mr. David Staudt
Center for Disease Control and Prevention
Acquisition and Assistance Field Branch
Post Office Box 18070
626 Cochrans Mill Road – B-140
Pittsburgh, PA 15236-0295

Re: Contract No. 200-2004-03805, Task Order 1: Transmittal of Draft Document No. SCA-TR-TASK1-0024, *Review of "Site Profiles for Atomic Weapons Employers That Worked Uranium and Thorium Metals - Appendix BB: General Steel Industries,"Battelle-TBD-6000, Appendix BB, Rev. 0.*

Dear Mr. Staudt:

SC&A is pleased to submit to NIOSH and the Advisory Board its draft report, *Review of "Site Profiles for Atomic Weapons Employers That Worked Uranium and Thorium Metals – Appendix BB: General Steel Industries,"Battelle-TBD-6000, Appendix BB, Rev. 0.*, SCA-TR-TASK1-0024, dated April 21, 2008. This document has been reviewed for Privacy Act information, edited accordingly, and is cleared for unrestricted distribution. Additional editorial changes were made to the original report which was submitted on March 17 (two replacement pages were transmitted on March 19). These changes are intended to clarify some of the discussion and do not represent any changes to our results and conclusions.

We began our review by performing an independent assessment of the radiation exposures at the GSI foundry in Granite City, based on our own research on exposure conditions at this facility. This research included extensive interviews with former workers and other site experts, such as a former employee of Allis-Chalmers, the company that manufactured the betatron radiography units at GSI, who supervised the installation and maintenance of these instruments, and who prepared a report under contract to NIOSH. Based on these interviews and follow-up correspondence, we obtained an understanding of procedures and work practices involving industrial radiography at GSI that differed in several significant aspects from the descriptions in Appendix BB. We also constructed what we believe are more detailed models of the betatrons and of the surrounding structures, and employed the latest release of the computer code MCNPX to perform our calculations. Some of our significant findings were:

- According to Appendix BB, betatron operators, who had the limiting exposures of all GSI workers, spent 2 h/shift at a distance of 6 ft from the activated betatron apparatus and in the vicinity of irradiated steel. Our finding is that they spent over 4 h/shift at distances of 3–6 ft from the betatron, during which time they were exposed to the irradiated steel. As a result, their external doses per 8-hour shift were more than 4 times as high as those calculated in Appendix BB.

- The recollection of a group of former workers was that overtime work was the norm, and that 65 hours/week was a reasonable estimate of their work hours. We therefore conclude that

they worked approximately 3,250 h/y, as opposed to the 2,400 h/y assumed in Appendix BB. This would result in an additional 35% increase in their radiation exposures.

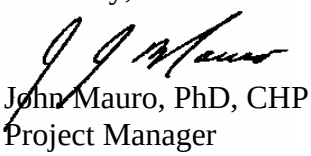
- We identified several errors in the calculations of external dose rates from irradiated uranium that were furnished to us by OCAS. As a result, we found that the dose rates were overestimated by a factor of 16. According to our models, the daily external dose rates from the radiography of steel and of uranium were about equal. Therefore, we found that the annual external dose rates were relatively constant from year to year, rather than varying with the amount of uranium radiographed each year.

- We estimated annual external exposures of the betatron operators of about 12 R/y for 1952–1963, when only the 24-MeV betatron was in operation, and about 14 R/y for 1964–1966, after the 25-MeV betatron was installed. (One half the annual dose was received in 1966, since the contract ended on June 30.) These exposures are 2–6 times the external exposures listed in Appendix BB.

- According to Appendix BB, workers who did not perform betatron radiography or handle the metal within 2 hours of irradiation are to be assigned exposures of 0.72 mR/h. Our analysis identified locations on the foundry floor, to which such workers had unrestricted access, that had exposure rates as high as 50 mR/h while the betatron was in operation. Locations on the roof, accessible to maintenance workers servicing ventilation equipment, had exposure rates of up to 1,000 mR/h. Contrary to the assertion in Appendix BB, radiography employing ^{60}Co sources could produce higher dose rates than the betatron radiography. In the absence of detailed information on the locations of their work stations and the time spent on various tasks, we were not able to arrive at bounding estimates of external exposures of workers maintaining ventilation equipment, nor of those in the vicinity of ^{60}Co radiography sources.

If you have any comments or questions, please contact me at 732-530-0104.

Sincerely,



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ADVISORY BOARD ON

RADIATION AND WORKER HEALTH

National Institute for Occupational Safety and Health

Review of "Site Profiles for Atomic Weapons Employers that Worked Uranium and Thorium Metals - Appendix BB: General Steel Industries," Battelle-TBD-6000, Appendix BB, Rev. 0.

Contract No. 200-2004-03805
Task Order No. 1
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April 2008

Disclaimer

S. COHEN & ASSOCIATES: ***Technical Support for the Advisory Board on Radiation & Worker Health Review of NIOSH Dose Reconstruction Program***	Document No. SCA-TR-TASK1-0024 Effective Date: Draft —April 21, 2008
Draft Review of "Site Profiles for Atomic Weapons Employers that Worked Uranium and Thorium Metals - Appendix BB: General Steel Industries," Battelle-TBD-6000, Appendix BB, Rev. 0	Revision No. 1 – (Draft)
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EXECUTIVE SUMMARY

Introduction

During Meeting 48 of the Advisory Board on Radiation and Worker Health, held in Richland, WA, on July 17–19, 2007, the Board directed SC&A to perform a review of "Site Profiles for Atomic Weapons Employers that Worked Uranium and Thorium Metals," Battelle-TBD-6000 (Scherpelz 2006), as well as "Appendix BB: General Steel Industries" (Allen and Glover 2007) to that report. SC&A reviewed the main report (Scherpelz 2006) and delivered a working draft of our report to the Board on September 14, 2007. At the same time, we commenced work on our review of Appendix BB. According to the Appendix:[1]

> This document serves as an appendix to Battelle-TBD-6000, Site Profiles for Atomic Weapons Employers that Worked Uranium and Thorium Metals. This appendix describes the results of document research specific to this site.

The site in question, located in Granite City, IL, was originally the Commonwealth Division of the General Steel Castings Corporation, later known as the Castings Division of General Steel Industries, Inc. (GSI). This facility performed betatron radiography of uranium for the Uranium Division of the Mallinckrodt Chemical Works in St. Charles, MO, which was under contract to the U.S. Atomic Energy Commission. This activity resulted in potential radiation exposures of some workers at this site. However, the facility also performed radiography of steel castings, its principal product, during the contract period. The radiological assessments of workers exposed to radiation from the weapons-related activities therefore encompass these other sources of radiation exposure.

Analysis of Radiation Exposures

We began by performing an independent assessment of the radiation exposures at the GSI foundry in Granite City, based on our own research on exposure conditions at this facility. In addition to examining available documents related to the operation of the site, we interviewed a group of former workers and other experts who were knowledgeable about the site and especially about the radiographic procedures and work practices.

The analyses utilized the latest release of Los Alamos computer code MCNPX version 26e, which was made available to approved users on November 17, 2007. We first constructed detailed models of the betatron apparatus, the metal objects being radiographed, and the betatron buildings and surrounding structures. We utilized the code to assess exposures to stray radiation in potentially occupied locations both inside and outside the betatron buildings while the betatron was in operation. We also used the code to assess external exposures to direct penetrating radiation from metal that had become radioactive due to photonuclear interactions

[1] In the Executive Summary, the term "Appendix" refers to "Site Profiles for Atomic Weapons Employers that Worked Uranium and Thorium Metals - Appendix BB: General Steel Industries" (Allen and Glover 2007).

during betatron radiography. The metal objects comprised slices of uranium ingots produced at Mallinckrodt as well as various steel castings. These assessments also addressed doses to the skin from beta radiation from the irradiated metal objects, including the contribution from short-lived progeny of ^{238}U found in aged natural uranium. We also assessed intakes of activated metallic dust and skin doses from beta radiation from activated metals. Finally, we estimated radiation exposures to the activated betatron apparatus shortly after radiography.

The most detailed assessment was of the betatron operators, both because they were among the workers likely to have received the highest exposures, and because of the large amount of information regarding their exposure conditions that was obtained in the course of our research. The following table summarizes the annual exposures of these workers.

Estimated Annual External Exposures of Betatron Operators

Years	External exposure	Neutron dose	Skin dose	
			Hands & forearms	Other skin
	(R/y)	(mrem/y)	(rads/y)	
1952-1957	12.4	470	27.2	2.5
1958	12.4	470	25.9	2.4
1959-1960	12.4	470	24.7	2.4
1961	12.4	470	28.1	2.6
1962	12.4	470	20.9	2.2
1963	12.4	470	7.0	1.4
1964	13.6	735	3.8	1.2
1965	13.6	735	3.3	1.2
1966[a]	13.6	735	2.3	1.2

[a] Annual rate during contract period, June 1–June 30.

The annual dose rates listed in the above table are up to 10 times higher than the corresponding doses listed in the Appendix. In addition, we calculated dose rates of approximately 20–200 mrem/h at locations accessible to other workers while the "new" betatron (installed at the end of 1963) was operating, such as a restroom used by workers from nearby buildings. This is far higher than the maximum dose rate of 0.72 mrem/h outside the shooting area of the betatron building reported in the Appendix. Furthermore, we found that dose rates during radiography with an 80-Ci ^{60}Co source used at GSI could reach approximately 1,000 mrem/h in a location on the roof that was accessible to maintenance workers—even higher dose rates could have been received by a radiographer during an incident when he had to manipulate a source that had not properly retracted into its shield. We did not perform a complete assessment of these other workers, due to lack of information on the frequency and duration of their exposures, and on the radiation levels at their various work stations and other locations occupied during their tours of duty.

We found that the photoactivation of steel and uranium did not lead to any significant internal exposures of the GSI workers. The maximum intakes of activated steel dust led to doses on the order of 0.1 mrem/y. The intake of activated uranium did not lead to any significant increase in dose over the intake of the same amount of natural uranium. We did not perform a quantitative assessment of the intakes of uranium dust, but did review the assessment in the Appendix, as discussed later in this executive summary.

Findings

In addition to the general observations discussed above, our review of the Appendix produced a number of specific findings.

Finding 1: Completeness of Data Sources

The authors of the Appendix have not utilized some key information on the GSI Granite City site. For example, they failed to note the presence of two betatrons, housed in two different buildings, as indicated in the reports by Murray and Uziel (1992), and Murray and Brown (1994), and as was brought out at the General Steel Industries Worker Outreach Meeting on August 21, 2006. Other examples of incomplete utilization of available data are presented in the context of other findings discussed below.

Finding 2: Period of Covered Employment

The Appendix states that the covered activities took place in 1953–1966. It is plausible and claimant favorable to assume that this work began in 1952. We base this assumption on Atomic Energy Commission "Correspondence Reference Form," with a hand-corrected date of December 5, 1952, that has a summary titled: "Regarding ingots of uranium metal furnished to General Steel Castings Co. for betatron testing." Since the Army installed the first betatron in Granite City in January 1952, an event that was reported in a local newspaper, it is seems likely that Mallinckrodt would have taken advantage of this facility at an early date.

Finding 3: Underestimate of Betatron Beam Intensity

The authors assume a betatron beam intensity of 100 R/min (without the aluminum beam-flattening compensator) at a distance of 3 ft from the target. They cite an interview with Jack Schuetz as the source of information that the betatron beam had a "design maximum" output of 100 R/min.[2] This value is inconsistent with the material furnished by Schuetz (2007), which lists outputs of up to 282 R/min. It is also inconsistent with the Allis-Chalmers acceptance criteria for the betatron tubes, which required a minimum output of 220 R/min at 25 MeV. We find that assigning an uncompensated intensity of 250 R/min at 3 ft is reasonable and claimant favorable.

[2] Mr. Schuetz was under contract to NIOSH/OCAS to provide information on Allis-Chalmers betatrons.

Finding 4: Underestimate of Stray Radiation from Betatron

The Appendix understates the stray radiation during the operation of the betatrons. Our calculations show higher dose rates in the control rooms than the 0.72 mrem/h cited in the Appendix. We calculated effective dose rates of 208 mrem/h on the roof, which was occasionally occupied by maintenance workers, 22 mrem/h in a restroom, and up to 51 mrem/h in other areas accessible to workers while the betatron was in operation. The Appendix ignores neutrons generated in the betatron target, which make a minor but potentially significant contribution to the effective doses.

Finding 5: Failure to Assess Other Radiography Sources

The authors acknowledge the use of other radiography sources, notably ^{60}Co, but dismiss the doses from these sources, stating that the doses from the betatron would be more limiting. As shown in our analysis, an 80-Ci ^{60}Co source produced a dose rate of up to 960 mrem/h on the roof of the New Betatron Building, and rates of 12–16 mrem/h in other locations outside the building. Furthermore, stray radiation from a 250-mCi ^{60}Co source that was used in a lightly shielded structure produced dose rates in accessible areas of 9–17 mrem/h. These rates are one to three orders of magnitude higher than the stray radiation cited in the Appendix.

Finding 6: Neglect of Skin Dose from Activated Steel

The Appendix ignores the skin dose from beta radiation from activated steel. Our analysis yielded doses of about 2 rads/y to bare skin from beta radiation from irradiated steel.

Finding 7: Underestimate of Exposure to Activated Betatron Apparatus

The Appendix assigns an initial exposure rate of the betatron operator of 15 mR/h from activation products in the betatron apparatus, based on a measurement reported by Schuetz (2007) at 6 ft (183 cm) from the betatron target. This exposure rate would apply only if the operator were located 6 ft from the betatron during the setup period. Such an assumption is inconsistent with the calculation of dose rates from the handling of irradiated steel or uranium, which assumes that the betatron operator spent one half of the setup time at a distance of 1 ft (30 cm) from the metal and the rest at 1 m. Assuming, as we did, that his distance from the betatron target ranged uniformly from 3 to 6 ft (61–183 cm) would double his exposure rate.

Finding 8: Underestimate of Work Hours

The authors assume that the GSI employees worked an average of 2,400 h/y. This estimate is contrary to the recollection of the workers, who remember working 50–80 h/week. The consensus estimate was 65 h/week, or 3,250 h/y. Such a value is reasonable and claimant favorable, and should be adopted as a default value for dose reconstruction.

Finding 9: Mischaracterization of Steel Work Practices

According to the Appendix: "The overall estimate for Betatron x-ray of steel is: 30 minutes setup with no dose; one hour Betatron x-ray exposure due to skyshine at 0.72 mR/hr; and, 30 minutes takedown . . . ." Such a description is at variance with a report prepared by former GSI workers (2007) that indicates repeated exposures of the same casting, with 12–15 minutes between exposures. Since both the steel and the betatron were activated from previous exposures, there was no setup period with no dose. Furthermore, most exposures were of a few minutes' duration, which reduced the time in the control room, where the exposure rates were relatively low, and increased the number of times during the day that the operators were exposed to the steel and the betatron.

Finding 10: Errors in Calculating Dose Rates from Uranium

We have found errors in calculations that lead to a significant overstatement of the dose rates from uranium presented in the Appendix. The Appendix lists a dose of 21.7 mrem during the first 30 min following irradiation. Our model yields a dose of 1.4 mrem, using the same assumptions regarding the duration of the radiographic exposure, the duration of the worker's exposure, and his distances from the metal. Since the dose rates in the Appendix are not scientifically correct, they should not be used as the basis of dose reconstructions of exposed workers.

Finding 11: Underestimate of Doses to Other Workers

The Appendix states that workers who did not work in the betatron building and did not routinely handle steel or uranium within 2 h following the x-ray exposure should be assigned a "dose" rate of 0.72 mR/h. As discussed under Finding 4, there were many situations in which these other workers could have been exposed to much higher radiation levels.

Finding 12: Incorrect Calculation of Residual Surface Contamination and Resuspension

The Appendix uses the same methods of calculating surface contamination and resuspension as were used in the main report (Scherpelz 2006). In SC&A's review of that report, we pointed out that calculating surface contamination on the basis of a settling velocity of 5 µm AMAD aerosol particles ignores the sloughing off of much larger flakes of uranium oxide that fall directly onto the floor. We also showed that a resuspension factor of 10^{-6} m^{-1} might understate the airborne concentrations by one or more orders of magnitude.

Finding 13: Use of Incorrect Units

The Appendix switches erratically between units of mrem and mR. The results of the skyshine calculations are stated as 0.72 mrem/h in Section BB.4.2, then as 0.72 mR/h in later sections. Dose rates are incorrectly stated in units of mR/h, which is an exposure rate. Uranium dose rates are stated in mrem, whereas our review of the output files from the Appendix BB analysis shows

that the calculations were of air kerma, which is expressed in mrads. A notable misuse of units appears in the table in Section BB.4.5, where the dose to the skin from beta radiation is expressed as "R/yr." Beta radiation should not be expressed in roentgens, which only apply to photons.

Responses to Comments

NIOSH/OCAS has received comments on Appendix BB from two advocates for claimants. We were asked to respond to these comments. Issues that are relevant to dose reconstruction are addressed in our radiological assessments of GSI workers. Other comments deal with the completeness and accuracy of the Appendix. We find that, in the interest of a more comprehensive report, some of these comments should be addressed in a future revision of the Appendix. Some other comments arise from a misunderstanding of the nature of dose reconstruction under EEOICPA.

References for Executive Summary

Allen, D., and S. Glover. 2007. "Site Profiles for Atomic Weapons Employers that Worked Uranium and Thorium Metals - Appendix BB: General Steel Industries," Battelle-TBD-6000, Appendix BB, Rev. 0. http://www.cdc.gov/niosh/ocas/pdfs/tbd/b-6000-apbb-r0.pdf

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Scherpelz, R. 2006. "Site Profile for Atomic Worker Employers that Worked Uranium and Thorium Metals," Battelle-TBD-6000 Rev. F0.
http://www.cdc.gov/niosh/ocas/pdfs/tbd/bat-6000-r0.pdf

Schuetz, J. G. 2007. Letter report to Samuel Glover, NIOSH/OCAS, May 1, 2007.

PREFACE

During Meeting 48 of the Advisory Board on Radiation and Worker Health, held in Richland, WA, on July 17–19, 2007, the Board directed SC&A to perform a review of "Site Profiles for Atomic Weapons Employers that Worked Uranium and Thorium Metals," Battelle-TBD-6000 (Scherpelz 2006), as well as "Appendix BB: General Steel Industries" (Allen and Glover 2007) to that report. SC&A reviewed the main report (Scherpelz 2006) and delivered a working draft of our report to the Board on September 14, 2007. At the same time, we commenced work on our review of Appendix BB.

Following the Board meeting, two sets of public comments on Appendix BB were submitted to Larry Elliot, Director of OCAS. The Board asked SC&A to respond to these comments.

On October 9, 2007, Robert Anigstein of SC&A met with a group of former employees of General Steel Industries who had worked at the Castings Division in Granite City, IL, as well as with other site experts. This meeting was held at the Holiday Inn in Collinsville, IL, and was not open to the public. Two members of the NIOSH/OCAS staff attended as observers but did not participate in the discussions. Also in attendance was a staff member of Advanced Technologies and Laboratories (ATL) International, Inc., a NIOSH support contractor, who made a voice recording of the proceedings. The meeting lasted from approximately 4:00 until 6:45 PM, and was chaired by Dr. Anigstein. During the course of the meeting, the site experts shared their recollections of activities at the site, answered questions, prepared sketches of the layout, and provided written documentation to Dr. Anigstein.

Further communications with some of the attendees as well as other site experts were held during October 2007–February 2008 by telephone, e-mail, and regular mail. The purpose of these contacts was to elicit more details about the layout of the site, the operation of the equipment, and general work practices that helped us to perform an independent assessment of the radiation exposures of GSI workers and to evaluate Appendix BB.

The authors wish to express their appreciation to advocates for GSI workers who have assembled an invaluable trove of reference material on the GSI Castings Division, as well as on Allis-Chalmers betatrons and related topics. One advocate was instrumental in assembling the GSI workers and other site experts for the meeting in Collinsville. We wish to thank everyone who took the time to attend the meeting and share his experiences and information. We further want to express our appreciation to everyone who responded to our telephone calls and e-mail messages, and furnished additional information. Our special thanks go to Jack Schuetz, a former employee of Allis-Chalmers, who shared invaluable information on betatrons,[1] and to Keith Eckerman, a member of the Life Sciences Division of the Oak Ridge National Laboratory, who calculated dose coefficients for some short-lived nuclides.

[1] Mr. Schuetz had been under contract to NIOSH/OCAS to provide information on Allis-Chalmers betatrons.

Chapter 1

INTRODUCTION

The General Steel Castings Corporation, which later became General Steel Industries, Inc., performed betatron radiography of uranium at its Granite City site for the Uranium Division of the Mallinckrodt Chemical Works in St. Charles, MO, which was under contract to the U.S. Atomic Energy Commission. This activity resulted in potential radiation exposures of some workers at this site. This chapter presents a brief history of the corporation and of its radiographic facilities.

1.1 Historical Background of General Steel Industries, Inc.

The General Steel Castings Corporation was organized in Delaware in December 1928, and was originally owned by the Baldwin Locomotive Works, the American Locomotive Company, and American Steel Foundries. A minority interest was later acquired by the Pullman-Standard Company. A bond issue was floated on June 21, 1929 to enable the company to build a plant in Eddystone, PA and to acquire the Commonwealth Steel Corporation in Granite City, IL. Commonwealth, which was chartered in 1901, was consolidated with General Steel Castings in November 1929, becoming the Commonwealth Division of General Steel Castings. The Commonwealth Division was unionized in 1937, with four separate unions representing various industrial workers.[1]

In 1955, General Steel Castings acquired National Roll and Foundry Company, which made iron and steel rolls for the steel industry. In 1956, the company offered its common stock for sale to the public. In 1960, the company acquired the St. Louis Car Company, which made light rail and railroad cars. To reflect its expanded activities, General Steel Castings formally changed its name to General Steel Industries, Inc., also known as GSI, on May 1, 1961. GSI shut down the Eddystone foundry sometime in 1963 and moved the remaining operations to the Granite City location. An aerial view of the General Steel's Castings Division in Granite City is shown in Figure 1.

The Granite City operation continued until 1973, when the plant closed. The land and buildings occupied by the foundry, but not its business, equipment, or processes, were acquired by the Granite City Steel Division of National Steel Corporation in 1974.

1.2 Betatrons at GSI

General Steel Castings produced tank armor for the U.S. Army during the Korean War. To enable the company to inspect the castings for defects, the Army built betatron radiographic facilities for General Steel at both the Eddystone and Granite City foundries. The two

[1] Most of the historical information in this section is from the *New York Times* Archive, 1851–1980, accessed at www.nytimes.com.

Figure 1. Aerial View of General Steel Castings Division in Granite City (GSI n.d.)

radiographic facilities went into operation in November 1951 and January 1952, respectively. The betatron at Granite City was housed in a building that was separate from the rest of the facility. When GSI shut down the Eddystone foundry in 1963, that betatron was moved to the Granite City location. This betatron was housed in a new building that was adjacent to the production facilities. Because this second machine was installed in Granite City 12 years after the first betatron, it is referred to as the "new" betatron, while the original machine is called the "old" betatron. Figure 2 shows the New Betatron Building under construction. The two betatron buildings are shown in the foreground on the left side of Figure 1; an enlarged view of these buildings is shown in Figure 3. Figure 4 shows a recent closeup view of the New Betatron Building and surrounding structures.

Both betatrons were originally designed to operate at 22 MeV. However, by the time it was installed, the original Granite City betatron had been upgraded to 24 MeV ("General Steel Unveiling Giant X-Ray Machine Here" 1952). When the Eddystone betatron was transferred to Granite City, it was refurbished by Allis-Chalmers and upgraded to 25 MeV.

1.3 Radiography of Uranium at GSI

The documentation of the radiography of uranium castings at the Granite City foundry is incomplete. Copies of purchase orders issued by Mallinckrodt to General Steel Castings for this work span the period of March 1, 1958 to June 30, 1966. However, there is indication that the work may have started as early as 1952. Attached to a memorandum regarding a review of the FUSRAP determination of the Granite City site (Williams 1991) is an Atomic Energy Commission "Correspondence Reference Form", with a hand-corrected date of December 5, 1952, that has a summary titled: "Regarding ingots of uranium metal furnished to General Steel Castings Co. for betatron testing." Although the "Authority Review for Granite City Steel Site

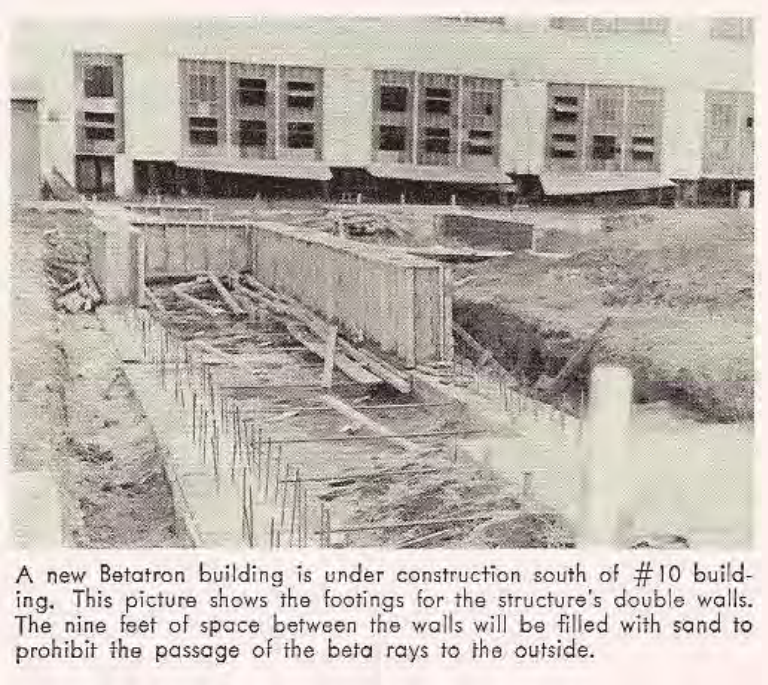

Figure 2. New Betatron Building Under Construction at GSI Foundry in Granite City (GSI 1963)

in Granite City, Illinois," attached to Williams 1991, refers to historical data regarding the Mallinckrodt contracts beginning in December 1953, it would appear that the 1953 date typed on the correspondence reference form was a typographical error, since the "3" was changed to a "2." We therefore infer that such activity was already in progress in 1952. An invoice submitted in February 1958 by General Steel Castings refers to a previous contract, but does not mention the date of the contract.

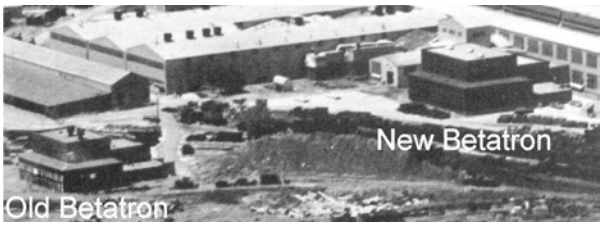

Figure 3. Enlarged Aerial View Showing Two Betatron Buildings (GSI n.d.)

Figure 4. Aerial View of New Betatron Building (Google 2007)

Chapter 2

ANALYSIS OF POTENTIAL RADIATION EXPOSURES OF GSI WORKERS

SC&A has performed an independent assessment of potential worker exposures to radiation at the Castings Division of General Steel Industries. The assessment addressed a variety of exposure scenarios, including:

- Exposure to direct and scattered radiation during the operation of the betatrons at locations accessible to workers;
- Exposure to direct radiation from induced radioactivity in the betatrons themselves and in metals that have been radiographed;
- Exposure to beta radiation from steel following betatron radiography and from uranium metal;
- Internal exposure to metallic dust generated during the grinding and welding of steel castings and to dust from the oxidation of uranium metal, following betatron radiography.

2.1 MCNPX Computer Code

The analyses utilized the latest release of Los Alamos computer code MCNPX version 26e, which was made available to approved users on November 17, 2007. We used this version of the code because of its advanced capabilities, notably the ability to model delayed gamma rays and delayed neutrons following photonuclear reactions resulting from the interaction of high-energy photons, such as those generated by a betatron, with material in a target. In addition, the code lists an inventory of nuclides produced by such photonuclear reactions. However, we note the following:

> *Warning! The new delayed gamma emission capability and delayed neutron capability is preliminary and not covered by the MCNPX cash awards program. It has been included in MCNPX 26E because of user and sponsor demand.* (Hendricks et al. 2007)

Despite this caution, we used this version of MCNPX since it is the only code capable of modeling the complex phenomena associated with betatron radiography. The long experience and high repute of the Los Alamos MCNP development group give us confidence that even this preliminary version produces reasonable results.

2.1.1 Model of Betatron

We constructed a simplified geometrical model of the betatron for use with the MCNPX code, based on drawings and descriptive material furnished by Schuetz (2007).[1] Figure 5 shows an

[1] Mr. Schuetz was under contract to NIOSH/OCAS to provide information on Allis-Chalmers betatrons.

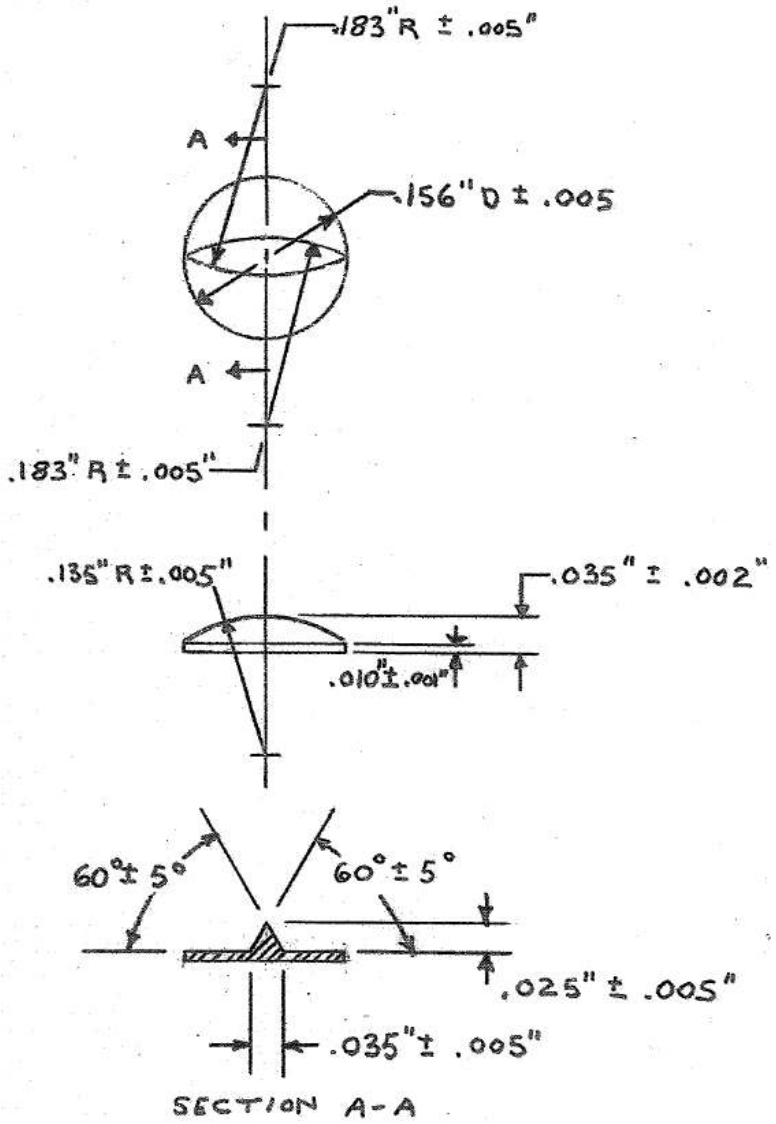

Figure 5. Engineering Drawing of Platinum Target (Schuetz 2007)

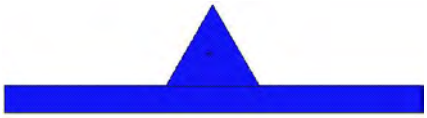

Figure 6. Transverse Cross-Section of Platinum Target

Figure 7. Horizontal Cross-Section of Platinum Target

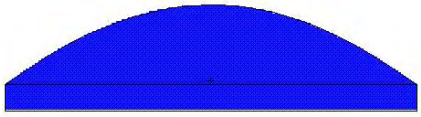

Figure 8. Longitudinal Section of Platinum Target

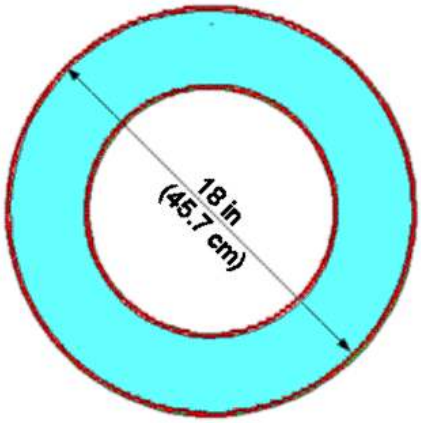

Figure 9. Horizontal Cross-Section of Betatron Doughnut

engineering drawing of the betatron target, which is made of platinum. Its shape can be described as the intersection of two overlapping cones (with vertical axes) and a horizontal plane. This form is mounted on top of a horizontal disk with a diameter of 0.156 in (3.96 mm). Figure 6 shows a transverse cross-section of the target in a vertical plane, as modeled in MCNPX. The electron beam is incident on the target near the tip of the triangular cross-section, perpendicular to the plane of the diagram. Figure 7 shows a cross-section in a horizontal plane just above the circular disk at the base of the target, while Figure 8 shows a longitudinal cross-section in a vertical plane, perpendicular to the plane of Figure 6. The beam is directed horizontally, in the plane of Figure 8.

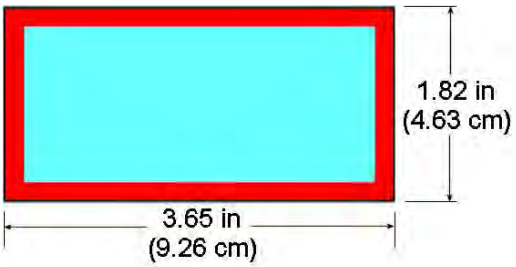

Figure 10. Vertical Cross-Section of Betatron Doughnut

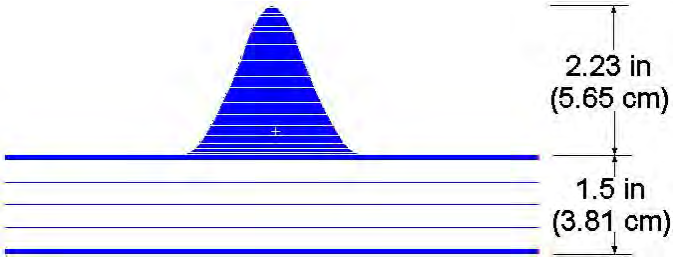

Figure 11. Cross-Section of Aluminum Compensator and Ionization Chamber

The target is located inside the sealed and evacuated betatron tube, which is constructed of porcelain with a ⅜-in (2.22-cm) thick wall. Its actual shape is a circular torus with an elliptical cross-section and is commonly referred to as the doughnut. We initially constructed an MCNPX model with such a shape. However, its complexity complicated the execution of the code, so we replaced it with a hollow cylindrical ring with the same dimensions. Figure 9 shows a horizontal cross-section of the MCNPX model of the doughnut, while Figure 10 shows an enlarged view of the vertical cross-section of the hollow ring. The light blue areas depict the evacuated region.

The beam of x rays emerges through the wall of the doughnut and passes through an ionization chamber, which is housed in a rectangular aluminum box that contains three thin aluminum plates. These plates collect the ionization current that measures the intensity of the beam. The current is also directed to a counter or "clicker," which measures the elapsed exposure in increments of 10 R. The exposure terminates after the accumulation of a preset number of clicks. Since the counter can be set to a maximum of 250 clicks, the maximum single exposure is 2,500 R. Although the ionization chamber is centered about 50 cm from the target, it is calibrated to read the exposure at a distance of 3 ft (~91 cm) from the target, the standard reference point specified by Allis-Chalmers (1951) for betatron exposures.

An aluminum compensator is attached to the ionization chamber. This device, in the shape of a cone with varying taper, serves to flatten the x-ray beam in order to produce a uniform exposure across the cross-section of the beam. In the process, the intensity of the beam along the center line is reduced by about 35%. Figure 11 shows a cross-sectional view of the ionization chamber and the compensator.

2.1.2 Models of Betatron Buildings

Figure 12 shows a floor plan of the New Betatron Building, excerpted from Murray and Uziel (1992, Fig. 3). Figure 13 is a detail from the "Plant Layout" drawing (GSCC 1969), showing the New Betatron Building and adjacent structures. The small building southwest of the betatron building that abuts the No. 10 Finishing Building was identified by former workers as a sheet-metal shed that housed a restroom used by the betatron operators, workers in Nos. 9 and 10 Buildings, and possibly workers in other buildings.

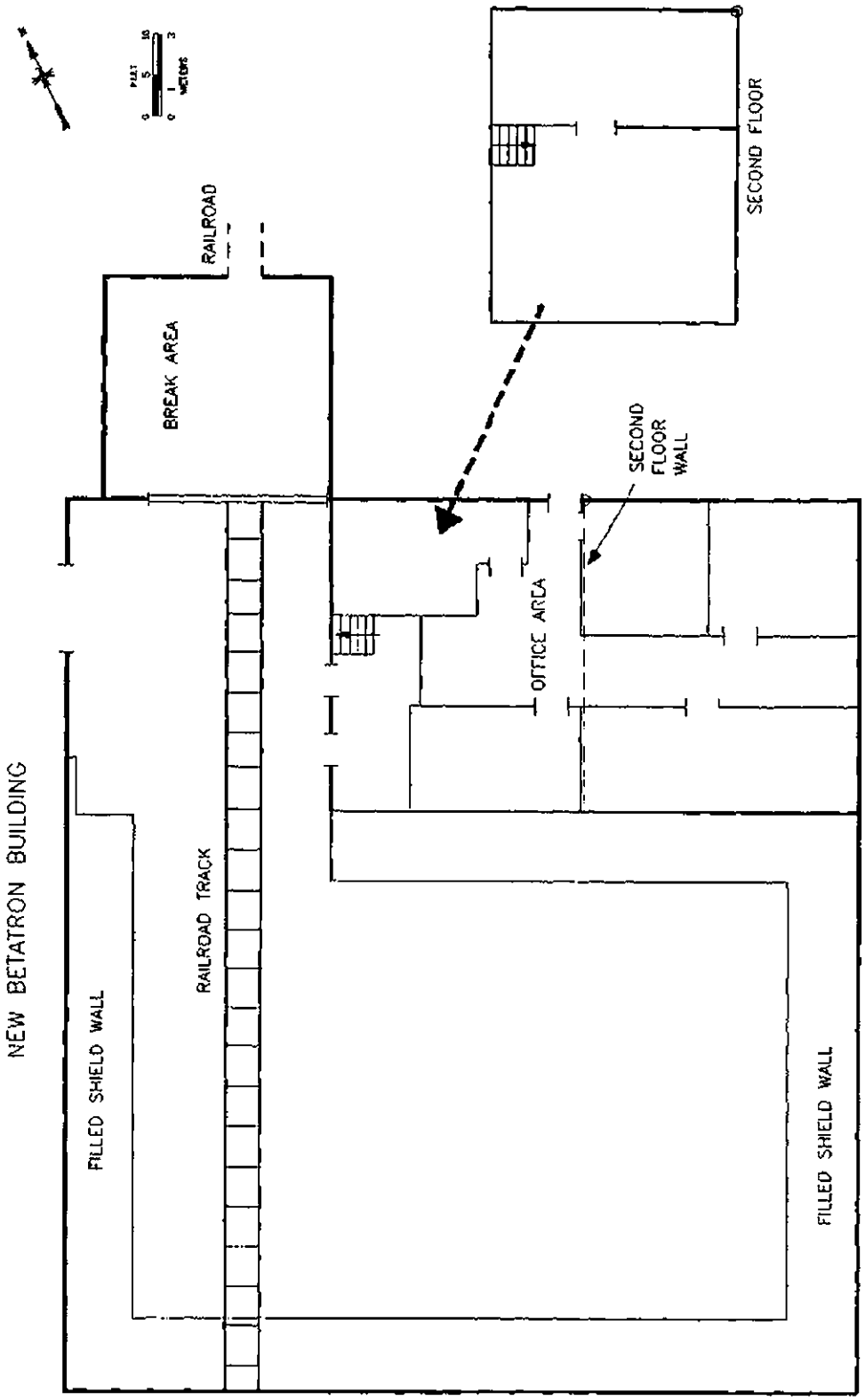

Figure 12. Floor Plan of New Betatron Building (Murray and Uziel 1992, Fig. 3)

Figure 13. Detail from Plant Layout, Showing New Betatron Building (GSCC 1969)

Figure 14 shows a horizontal cross-section of our model of the building. The drawing is a superposition of two horizontal planes, one at 1 m above the floor that contains the dose points, and another at a height of 2.5 m that passes through the center of the betatron and the steel casting being radiographed. Dotted lines indicate the outlines of the shed housing the restroom, and of the No. 10 Finishing Building. (The walls of these structures are not incorporated in our model.) Figure 15 shows a vertical east-west cross-section in the plane of the betatron, which is positioned to radiograph a hollow cylindrical casting. Figure 16 depicts a vertical north-south cross-section in the plane of

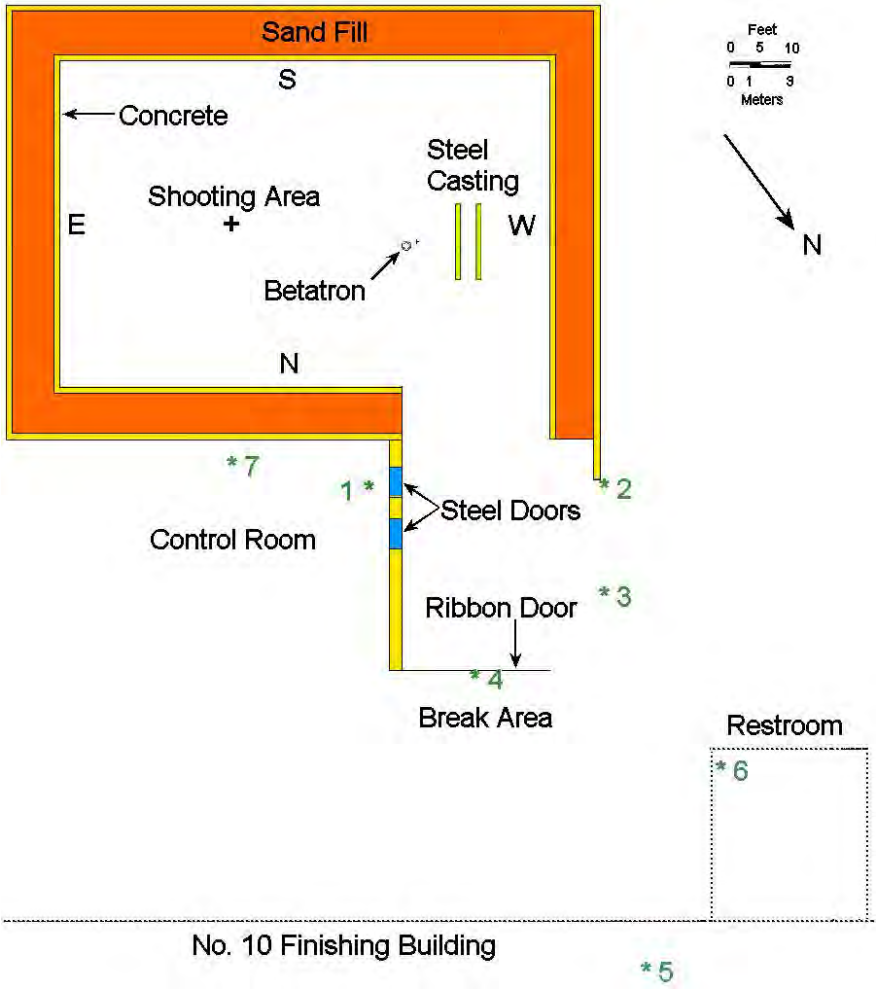

Figure 14. Horizontal Cross-Section of New Betatron Building

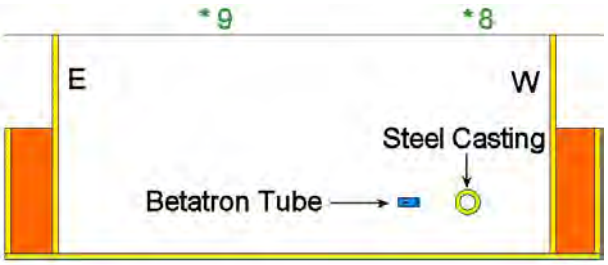

Figure 15. East-West Cross-Section of New Betatron Building

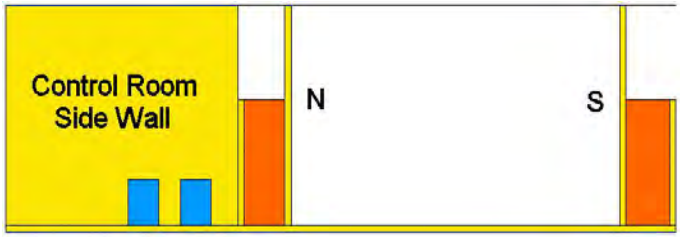

Figure 16. North-South Section of New Betatron Building

the side wall of the control room, showing the two doors which lead to the betatron shooting area. All three figures are drawn to the same scale.

As described by our model, the shield walls that surround the shooting area consist of two 1-ft (30.48-cm) thick walls of solid concrete, with the interior space filled with sand to a height of 20 ft (6.1 m) above the floor. The overall thickness varies from 248 to 274 cm. The interior concrete walls extend another 15 ft (4.6 m) above the sand fill. The wall separating the control room from the corridor leading to the shooting area is 2 ft (61 cm) thick, and is made of hollow concrete blocks with a bulk density of 0.92 g/cm^3. This wall is penetrated by two hollow steel doors, each comprising two layers of steel, $\frac{1}{16}$-inch (1.6-mm) thick. A railroad track, shown in Figure 12 but not part of the model, runs along the center of the corridor outside the control room, terminating at the south wall. A ribbon door, consisting of $\frac{1}{16}$-inch-thick steel, is lowered over the railroad track when the betatron is on. A break area is on the other side of the ribbon door. The shooting area has a tin roof approximately 35 ft (10.7 m) above the floor. The open area in the northwest portion of the building, shown in Figure 14, is believed to be a wall of some light material and is modeled as an open doorway.

Figure 17 shows a floor plan of the Old Betatron Building, based on a drawing from Murray and Brown (1994, Fig. 1). Figure 18 shows a horizontal cross-section of our model of this building. The overall thickness of the shield walls of the Old Betatron Building varies from 179 to 327 cm, as scaled from Figure 17. The wall separating the control room from the corridor leading to the shooting area is assumed to be 66 cm thick and is penetrated by two steel doors. The shooting area is covered by a ¾-inch (1.9 cm) thick plywood roof that is approximately 39 ft (11.9 m) above the floor. Otherwise, our model of the old building is similar to that of the new. Unlike the New Betatron Building, the old building is relatively isolated from the main plant: there is no adjacent break area or restroom, nor other areas that would be occupied for extensive periods of time. According to a former GSI worker, the building was surrounded by a fence to restrict access to the area.[2]

[2] Personal communication with Robert Anigstein, SC&A, Inc., January 21, 2008.

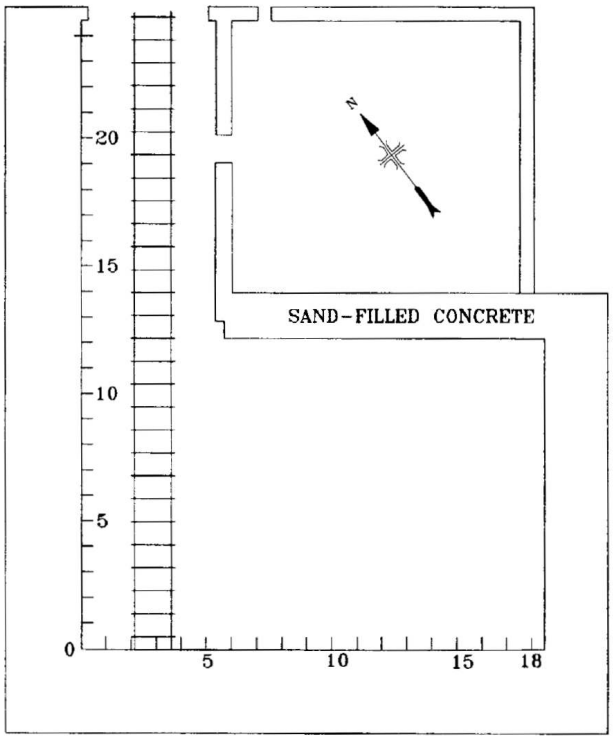

Figure 17. Plan of Old Betatron Building (Murray and Brown 1994)

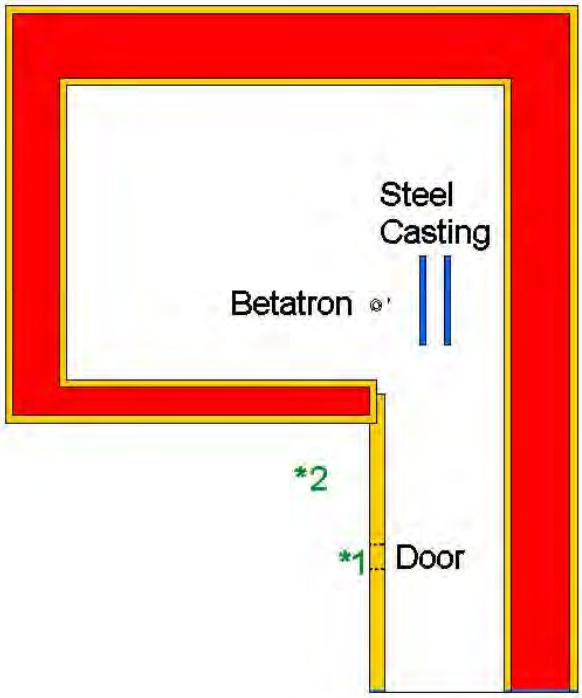

Figure 18. Horizontal Cross-Section of Old Betatron Building

2.1.3 Method of Analysis

The results produced by the MCNPX analyses are normalized to one source particle. In most of the present analyses, the source is an electron striking the betatron target. Consequently, in order to scale the results to the actual exposure conditions, we first needed to determine the intensity of the electron beam.

Schuetz (2007) lists the x-ray outputs of the last seven betatron tubes purchased by GSI, which are reproduced in Table 1. At a beam energy of 25 MeV, the output varied from 260 to 282 R/min. According to Schuetz, the levels shown in Table 1 were only obtainable in his laboratory at Allis-Chalmers, where the betatron operated under optimum conditions. We therefore assume, for the purpose of the present analysis, that the 25-MeV machine had a nominal output of 250 R/min along the centerline at a distance of 3 ft (91.44 cm) from the target, with the aluminum compensator removed. The compensator reduces the beam by about 35%, resulting in an intensity of 162.5 R/min. This is consistent with the recollection of a former worker, who recounted that the typical output was 160 R/min.

In order to simulate the calibration conditions specified in the betatron manual (Allis-Chalmers 1951), we calculated the air kerma per source electron at 6 ft (182.88 cm) from the target, with the aluminum compensator removed. We used the inverse square law and the conversion factors

discussed later in this section to convert this value to exposure at 3 ft from the target.[3] Based on the results of the MCNP analysis and the assumed intensity of the x-ray beam, we determined the beam current of the 25-MeV betatron to be 2.02×10^{12} electrons/s, or 0.323 µA. We assume the same beam current for the 24 MeV machine.

Table 1. Output of Betatron Tubes Purchased by GSI

Date shipped	Output (R/min)	
	22 MeV	25 MeV
12/29/69	205	265
3/2/71	180	260
3/18/71	240	280
3/22/71	196	275
4/9/73	200	280
5/9/73	200	282
5/31/73	195	262
Average	202.3	272.0

Source: Schuetz 2007

We then used MCNPX to model the scenarios described later in this chapter. All simulations were performed with the beam passing through the aluminum compensator. The effective dose was calculated from the photon flux by combining the conversion coefficients for air kerma per unit fluence (ICRP 1997, Table A.1) with the coefficients for effective dose per unit air kerma in the anteroposterior (AP) exposure geometry (ICRP 1997, Table A.17). However, these tables do not include data for photon energies greater than 10 MeV. For these higher-energy photons, we used the fluence-to-effective dose conversion coefficients for the AP geometry listed by Pelliccioni (2000, Table A1.1). In similar fashion, neutron dose rates were calculated by applying the coefficients for effective dose per unit fluence in the AP exposure geometry (ICRP 1997, Table A.41) to the neutron flux.

The exposure was calculated from the air kerma, using the following relationship:

$$1\ \mathrm{R} = 2.58 \times 10^{-4}\ \mathrm{C/kg}\ \text{(definition of roentgen in SI units)}$$

$$E_{ip} = \text{average energy per ion pair from fast electrons in air}$$
$$= 33.8\ \mathrm{eV} = 33.8\ \mathrm{J/C}\ \text{(Knoll 2000)}$$

$$1\ \mathrm{R} = 2.58 \times 10^{-4} \times 33.8 = 8.72 \times 10^{-3}\ \mathrm{Gy}$$

The photon flux was converted to air kerma, using the conversion coefficients from ICRP 1997, Table A.1, for photons ≤10 MeV. We derived conversion coefficients in the range of

[3] The Allis-Chalmers calibration procedure specifies that exposure be measured at 6 ft using a 25-R Victoreen thimble ionization chamber. The chamber is then read on a Victoreen R meter, using a 100-R scale, effectively multiplying the measurement by 4.

10–25 MeV by fitting a curve to the coefficients in the range of 3–10 MeV, deriving a linear function with a correlation coefficient $R^2 = 0.9999$. We used this function to calculate coefficients above 10 MeV and used these coefficients to calculate the air kerma over this extended energy range.[4]

2.1.4 Calculation of Exposure to Residual Radiation

Photoactivation, photofission, and neutron activation can induce residual radioactivity in the materials exposed to the betatron beam. We utilized the delayed gamma/delayed neutron capability of MCNPX 26e to model the dose and exposure rates from photons and neutrons emitted from the metal following betatron radiography. The code calculates the particle flux (photons or neutrons) in user-specified time bins after the initiating event (i.e., an electron striking the platinum target). The value in each time bin (or step) is the flux accumulated since the end of the previous step. This flux can be converted to dose or exposure (in the case of photons), as described in the previous section.

After the metal has been irradiated for a period of time, the dose rate from the metal is the sum of contributions from the activation and subsequent decay of nuclides that were created during the period of exposure. To calculate the dose rate at a time after the end of the exposure, we performed a numerical integration over the doses in the individual time bins, as shown below:

$$R_j = \sum_{i=j}^{n} \frac{\delta_i n_i}{t_i - t_{i-1}} = J_e \sum_{i=j}^{n} \delta_i$$

R_j = dose rate at time t_j after exposure (pSv/s)

t_n = $t_j + t_x$ (s)
t_x = duration of betatron exposure (s)

δ_i = incremental dose per electron during time interval $[t_{i-1},t_i]$ (pSv/e^-)

n_i = number of electrons during time interval $[t_{i-1},t_i]$
= $J_e(t_i - t_{i-1})$
J_e = electron flux (e^-/s)

The first of the two equations above states that the dose rate is the sum of the contributions from different time increments during the period of irradiation. The dose rate during the time interval $[t_i,t_{i-1}]$ is the incremental dose per electron, δ_i, as calculated by MCNPX, divided by the length of the time interval, $t_i - t_{i-1}$, and multiplied by n_i, the number of electrons striking the platinum

[4] It should be noted that, strictly speaking, exposure is not defined above a photon energy of 3 MeV. We have extended the concept to higher energies in order to permit calculations of doses to specific organs using the "External Dose Reconstruction Implementation Guideline," OCAS-IG-001 (Taulbee 2002).

target during that interval. However, n_i is the beam current, J_e, multiplied by the length of the time interval. In the second equation, we substitute the expression $J_e(t_i - t_{i-1})$ for n_i. The summation is carried out over the period of betatron exposure, t_x. The dose to an individual during a given time following the betatron exposure is calculated by integrating R_j over the period of time the individual is exposed to the irradiated material:

$$D_{km} = \int_{t_k}^{t_m} R_j \, dt = J_e \int_{t_k}^{t_m} \sum_{i=j}^{n} \delta_i \, dt$$

D_{km} = absorbed dose during time interval $[t_k,t_m]$ (pSv)

The dose is multiplied by 10^{-7} to convert to units of mrem. Exposure, in units of mR, is calculated in an analogous manner.

2.2 Calculation of External Exposure

2.2.1 Exposure to Stray Radiation During Betatron Radiography of Heavy Steel Castings

25-MeV Betatron

Our analysis of radiation exposures to betatron radiography is bounded by the 25-MeV betatron which was housed in the New Betatron Building, both because of its higher beam energy and because of its closer proximity to other occupied areas of the foundry. We therefore emphasized the exposures from this instrument in our analysis, which are discussed first. The exposures to stray radiation from the 24-MeV machine are discussed later in this section.

We calculated the effective dose rates and exposure rates in several potentially occupied locations during the radiography of a heavy casting, using the exposure geometry shown in Figure 15. Figure 19 is a photograph of the casting—the axle of a power shovel—on a flatbed trailer in the center of the shooting room. This axle is also illustrated and described in Figure 20, taken from a GSI publication (House 1964). According to a former worker, at least one of the four axles produced by GSI was radiographed while mounted on a flat car on the railroad track in the Betatron Building. While this was not a general practice, heavy castings were occasionally radiographed on the railroad track in the interest of saving time and allowing the casting to stay hot, thus facilitating any rework required if flaws were discovered during the radiography.[5] Since some of the highest radiation fields in locations outside the shooting area would result from the object's being radiographed in this position, we used this scenario to simulate claimant-favorable dose rates from scattered radiation during betatron radiography.

[5] Personal communication with Robert Anigstein, SC&A, Inc., November 2007.

Figure 19. Betatron Radiography of the Axle of a Power Shovel Cast at GSI

Seven locations that had the potential for significant exposures to GSI workers were selected as dose points for this simulation. Six of these locations, numbered 1–6, are indicated by green asterisks in Figure 14. Location 1 is in the control room, behind a steel door that provided access to the shooting area. Locations 2–3 are just outside the minimally shielded portion of the west wall. Location 4 is in the break area, just outside the ribbon door. Location 5 is inside the No. 10 finishing building, at a point 2 m from the wall facing the Betatron Building. Location 6 is in the restroom which abuts the No. 10 building. All six dose points are 1 m above the floor. Location 8, shown in Figure 15, is 1 m above the roof, directly above the steel casting. This location was included because a former GSI worker interviewed during the meeting with site experts stated that he periodically serviced the rooftop ventilator on that building. Since he said he did not notify the control room of his presence on the roof, we assume that the betatron could

Cast Steel Axle for World's Largest Power Shovel

The first of four mammoth axle castings for a giant power shovel was shipped recently from the Granite City plant. The heaviest casting ever produced at this location, (about 184,000 pounds shipping weight) the axle is shown here ready for shipment to Marion Power Shovel Company where the huge machine will be built. Of additional interest to GSI people is that the 125-ton flat car upon which the axle is loaded is built with one-piece cast steel underframe and six-wheel heavy duty trucks of General Steel design and manufacture.

The new power shovel, the largest land machine ever built anywhere, has been purchased by Peabody Coal Company. To be known as the Marion type 6360, the big stripping shovel will be able to strip 200 cubic yards of earth at a bite. It will be powered by electric motors with 33,000 horsepower, will weigh 13,000 tons and will stand as high as a 21-story building.

Figure 20. View of Axle for Power Shovel (House 1964)

have been operating while he was performing the maintenance work. Similarly, there were no limitations on access to the other six locations during betatron operations.

We also analyzed a second, more typical exposure scenario. The model utilized the same casting at the same elevation above the floor. However, the casting was located in the center of the shooting area, with the axis of the cylinder aligned in an east-west direction, parallel to the walls. The betatron was positioned with the platinum target 6 ft (~182 cm) from the casting and the beam aimed horizontally in the direction of the south wall. The second analysis examined three of the locations—Nos. 1, 2, and 6—addressed by the first scenario. The results of both analyses, which include the contributions of both photons and neutrons, are presented in Table 2. These contributions include radiation that penetrates the shielding walls, is scattered off walls and other objects, and is scattered by the air (skyshine).

24-MeV Betatron

A more limited stray radiation analysis was performed of the 24-MeV betatron housed in the Old Betatron Building. The structure nearest to this building is a pattern-storage building, the closest point of which is 250 ft (76 m) away. Since there is no indication that any areas near the Old Betatron Building were commonly occupied during betatron operations, the analysis was limited

to calculating doses and exposures at two locations inside the control room: at the likely position of the operator at the betatron control console and near the door leading from the control room to the shooting area. These locations are identified by green asterisks in Figure 18. The object being radiographed was the same steel axle used in the 25-MeV betatron analysis, mounted on a transfer car on the railroad track. The results of the analysis are presented in Table 3.

Table 2. Exposure to Stray Radiation from 25-MeV Betatron During Radiography

Location		Dose rate (mrem/h)						Exposure (mR/h)	
		RR track[a]			Center[a]				
Number	Description	Photon	Neutron	Total	Photon	Neutron	Total	RR track	Center
1	Control room	2.0	0.6	2.6	0.4	0.3	0.7	1.9	0.3
2	Outside 1	3.5	0.5	4.0	2.4	1.1	3.5	3.4	2.4
3	Outside 2	49.7	1.5	51.1				55.8	
4	Break area	23.0	1.3	24.3				24.8	
5	#10 Bldg	8.2	0.4	8.6				9.0	
6	Restroom	21.1	0.5	21.6	1.6	0.3	1.9	23.8	1.5
8	Roof 1	192.1	16.2	208.2				208.5	

[a] Position of casting

Table 3. Exposure to Stray Radiation from 24-MeV Betatron During Radiography

Location		Dose rate (mrem/h)			Exposure (mR/h)
Number	Description	Photon	Neutron	Total	
1	Control room door	1.7	0.5	2.2	1.6
2	Control console	0.5	0.2	0.7	0.5

2.2.2 Exposure to Stray Radiation During ^{60}Co Radiography of Steel Castings

In addition to the two betatrons, GSI utilized several other radiography sources, including two ^{60}Co sources and an x-ray machine that was leased from another steel company. The 80-Ci ^{60}Co source was primarily used to radiograph hollow steel castings, such as torpedo tubes for submarines and nuclear reactor vessels. The radiography was performed in the shooting area of one of the two betatron buildings. The shielded source was placed inside the steel vessel and the source was extracted from its shield by means of a mechanical remote control cable that snaked from the source apparatus through a hole in the side wall of the control room.

We analyzed two exposure scenarios involving the use of a large ^{60}Co source to radiograph steel castings in the New Betatron Building. In the first scenario, the source was inside a casting modeled after a nuclear reactor vessel. The casting was in the shape of a hollow cylinder closed at one end, with the open end facing up. The inside of the cylinder was 5 ft (~152 cm) high and 6 ft (~183 cm) in diameter. The walls and the bottom were 5 inches (~13 cm) thick. The ^{60}Co was modeled as a point source at the center of the cylindrical cavity. The casting was in the

center of the shooting area of the New Betatron Building, 3 ft (~91 cm) above the floor. Because the castings varied in thickness and had openings for the passage of pipes, etc., we analyzed a second, bounding scenario with the source in the same position with respect to the room, but with no casting to attenuate the radiation.

Dose and exposure rates were calculated for four of the locations (Nos. 1–3 and 6) used for the analysis of scattered radiation from the 25-MeV betatron, as described in Section 2.2.1 and illustrated in Figure 14. We added two new locations: No. 7 was in the control room, opposite the source and 1 m from the north shield wall, 1 m above the floor, while No. 9 was directly above the source, 1 m above the roof. The results of the analysis are presented in Table 4.

Table 4. Exposure to Stray Radiation from 80-Ci ^{60}Co Source During Radiography

Location	Description	Dose rate (mrem/h)		Exposure (mR/h)	
		Steel	No steel	Steel	No steel
1	Control room—near door	0.35	1.26	0.32	1.19
2	Outside 1	0.69	16.3	0.68	17.9
3	Outside 2	1.51	12.5	1.51	13.4
6	Restroom	0.77	4.6	0.75	4.78
7	Control room—near wall	0.32	0.53	0.30	0.48
9	Roof 2	924	960	1053	1086

We also analyzed a scenario involving a smaller ^{60}Co source that was used in radiographing steel castings. This activity took place in a small, roofless structure inside the No. 6 Building, which is about 1,250 ft (38 m) from the New Betatron Building. On the basis of descriptions by former workers, we modeled the structure as being 7 ft (~213 cm) high, 15 × 20 ft (~457 × 610 cm) wide, with hollow cinder block walls 8 inches (~20 cm) thick, and a 3-ft (91-cm) wide steel door near one corner. We calculated dose and exposure rates in three locations: 1 m outside the steel door and 1 m and 2 m from the center of the long, 20-ft wall, all locations being 1 m above a concrete floor. The radiation was from a bare 250-mCi ^{60}Co source in the center of this room. The results are presented in Table 5.

Table 5. Exposure to Stray Radiation from 250-mCi ^{60}Co Source During Radiography

Location	Description	Dose rate (mrem/h)	Exposure (mR/h)
1	Near door	17	19
2	1 m from long wall	16	18
3	2 m from long wall	9.2	10

In addition to the use of on-site sources, radiography of steel castings was performed by the St. Louis Testing Laboratory at the GSI Granite City site. The radiography was performed outdoors and involved a 10-Ci ^{60}Co source, as well as an ^{192}Ir source of undetermined activity. A former employee of St. Louis Testing, who was interviewed at the meeting of site experts, reported that

he used a survey meter to establish a 2-mR/h isodose perimeter around the source. The area was roped off and access was restricted to St. Louis Testing personnel. Assuming the procedure was properly executed and enforced, no GSI workers would have been exposed to a radiation field that was greater than 2 mR/h.

2.2.3 Exposure to Delayed Gamma Rays from Betatron Apparatus

The betatron instruction manual (Allis-Chalmers 1951) warns users not to touch the betatron doughnut for at least 15 min after the machine is turned off, stating that the tube becomes "intensely radioactive" while generating x rays. (There are no warnings about approaching the apparatus.) Schuetz (2007) measured the exposure rate from residual activity in the betatron apparatus after the beam was turned off. He reported an initial exposure rate of 15 mR/h at beam centerline 6 ft (183 cm) from the target, which dropped to "near zero" within 15 min. Schuetz explained that he performed the measurement to determine when it was safe for him to make adjustments to the machine following an exposure. He estimated that the betatron had been operating for 10–15 min, and that initial reading was taken within 5–10 s after the beam was turned off. These measurements were taken on a medical betatron, whose operating characteristics are similar to those of an industrial unit. The initial measurements were taken in the 1960s and were repeated over the years to ensure that later machines did not produce significantly greater residual radiation levels. However, no written records of these measurements are known to exist.[6]

We attempted to model the dose rates from photons and neutrons from induced radioactivity in the betatron apparatus, using the delayed gamma/delayed neutron capability of MCNPX 26e. We modified our model of the betatron doughnut by adding a palladium coating on the inner surface, which was used to create a conducting surface and prevent the buildup of an electrical charge from electrons in the beam that strike the wall of the tube. Kerst (1951) stated that the palladium coating was "a few millionths of an inch" thick. To maximize the possible radiation yield from the palladium, we specified the thickness to be 1×10^{-5} in (2.54×10^{-5} cm). The results showed no significant photon or neutron radiation in any time step more than one second after an electron struck the platinum target.

There are several possible explanations for this result:

- The residual radiation, although attributed by Schuetz to the platinum target and by Allis-Chalmers (1951) to the betatron tube, may in fact have originated in other parts of the apparatus, such as the magnets, which were not included in our MCNPX model. Such radiation could have been due to photoactivation of the surrounding betatron structure, or neutron capture in these structures from photoneutrons produced in the platinum target.

[6] Jack Schuetz, former Allis-Chalmers maintenance supervisor, personal communication with Robert Anigstein, SC&A, Inc., December 2007.

- The MCNPX analysis utilized models, developed from theories of nuclear structure, to predict photoactivation and photofission in the betatron apparatus. Certain stable isotopes in the materials of the apparatus may have cross-sections in the energy range in question that deviate significantly from the model predictions.

- MCNPX does not model the direct electron-nuclear interaction, which is similar to the photonuclear interaction, albeit with reaction cross-sections about 100 times smaller than for a gamma ray of the same energy as an electron (Segrè 1977). Although we could not identify any likely reaction products that would account for the reported radiation levels, such interactions cannot be conclusively ruled out.

We calculated the radiation exposure of the betatron operators on the basis of Schuetz's reported measurements. Schuetz used a survey meter with multiple scales; during a recent discussion of his measurements, he assumed that the reading at the end of the 15-min period would have been on the lowest scale. He agreed that 15 µR/h would be a reasonable assumed value of the exposure rate at the end of this time period (this assumption is based on typical background readings of 5–10 µR/h). These initial and final values correspond to a decay constant of $\lambda = 0.46\ \text{min}^{-1}$. We note that these readings were taken at a distance of 6 ft (183 cm) from the betatron target. During the setup of metal objects for radiography, the distance of the operator from the betatron would vary. To determine the exposure rate if the distance of the operator were uniformly distributed over a range, we utilize the inverse square law:

$$A_o = R_o x_o^2$$

$$R_{o12} = \frac{A_o \int_{x_1}^{x_2} \frac{dr}{r^2}}{x_2 - x_1} = \frac{\frac{A_o}{r}\Big|_{x_1}^{x_2}}{x_2 - x_1}$$

A_o = source strength at t = 0
= 540 mR·ft^2/h = 50.17 mR·m^2/h

R_o = exposure rate at x_o, t = 0
= 15 mR/h

x_o = 6 ft = 182.9 cm

R_{o12} = average exposure rate over interval $[x_1, x_2]$ at t = 0

We next calculate the integrated exposure during the time interval [0,t]:

$$X(t) = \frac{R_o}{60} \int_o^t e^{-\lambda\tau}\, d\tau = \frac{R_o\left(1 - e^{-\lambda t}\right)}{60\ \lambda}$$

X(t) = integrated exposure during time interval [0,t]

λ = 0.46 min^{-1}

t = exposure time (min)

2.2.4 Exposure to Delayed Radiation from Steel

We used MCNPX to calculate the dose rates from external exposure to steel that had been radiographed with the 25-MeV betatron, using the methodology described above. In this scenario, we modeled the exposure of a massive steel plate, 12 ft × 12 ft × 20 inches thick (366 × 366 × 50.8 cm), at distances of 6 ft (183 cm) or 9 ft (274 cm) from the betatron target.[7] The analysis addressed HY-80, one of the steel alloys cast at GSI. Because this alloy comprises many different elemental components, it has the potential of forming a variety of radioactive isotopes, as discussed later in this chapter. Another alloy cast at GSI, HY-100, has the same elemental composition. The elemental compositions of the alloys included in the analysis are listed in Table 6.

The effective dose rates from delayed photon radiation following an instantaneous exposure to the betatron x-ray beam of plates of HY-80 steel, high-manganese steel, and a slice cut from an ingot of natural uranium are displayed in Figure 21. The dose rates from each metal are normalized to the maximum rate from that metal during the time span displayed in the graph. As shown in this graph, the dose rate from HY-80 steel is relatively constant during the first 2 min. The fluctuations are due to the Monte Carlo sampling, which produces sparse statistics during the short initial time steps. After 2 min, the rate decreases steadily until 2 h after exposure. It then remains steady at about 0.1% of the maximum rate until 16 h, after which it continues to decline.

Because of the variability of radiography practices at GSI, we modeled several versions of this scenario. In the first, we assume that the various portions of the plate are each exposed for a period of one hour, with a 15-min setup period between shots. In these "long shots," the casting is 6 ft from the betatron target.[8] We assume that the betatron operator and his assistant were in

[7] The actual distance used in the MCNPX simulation was 235 cm. The calculated doses were adjusted for the 6-ft distance using the inverse-square law. In reality, almost the entire photon flux is incident on the steel plate at either distance. However, the photoactivation products are distributed over a larger area of the plate at the greater distance, so some correction to the dose rates at points near the plate is required. Because the beam is strongly peaked at the center and tapers off towards the edges, the applied correction gives conservatively high dose rates, and is thus claimant favorable. No correction was applied in the scenarios where the steel plate was 9 ft (274 cm) from the target.

[8] The long shots modeled in this scenario represented about 10% of the actual radiographs at GSI (Former GSI Workers 2007).

the control room during the shot, and estimate that it would take them a minimum of 5 s after the radiographic exposure to reach the vicinity of the metal object. We derived this value by estimating, on the basis of the floor plan, that the distance from the control room door to the center of the shooting room was about 50 ft (~15 m). At a fast walking pace of 5 mph (~2.2 m/s), it would have taken ~7 s to cover this distance, which does not include the time to open the door and perform other movements. Therefore, assuming an elapsed time of 5 s from the time the beam is shut off to the beginning of the worker's exposure is claimant favorable.

Table 6. Composition of Materials in MCNPX Analyses

Element	Porcelain	Concrete	Sand	HY-80	Mn steel	1020[a]	Lead alloy[b]	Uranium[c]
H		0.56%						0.00025%
C				0.16%	1%	0.2%		0.003%
N								0.001%
O	47.96%	49.85%	53.26%					
Na		1.72%						
Mg		0.24%						0.0005%
Al	13.95%	4.59%						0.0015%
Si	28.06%	31.57%	46.74%	0.25%				0.0105%
P				0.01%				
S				0.01%				
K	10.03%	1.92%						
Ca		8.32%						
Ti				0.01%				
V				0.02%				
Cr				1.40%				0.0005%
Mn				0.25%	15%	0.7%		0.0005%
Fe		1.23%		94.87%	86%	99.1%		0.015%
Ni				2.63%				0.01%
Cu								0.0004%
Mo				0.40%				
Sb							4%	
Pb							96%	0.0003%
U								99.96%
Density (g/cm^3)	2.4	2.3	1.59	7.83	7.83	7.86	11.03	19.0

[a] SAE 1020 steel alloy

[b] Typical alloy used for shielding

[c] Weakley 1963

Since the maximum film size was 14 × 17 inches (36 × 43 cm), and there was an overlap of 3–4 inches (~8–10 cm) for adjacent exposures, a 12 × 12 ft (366 × 366 cm) slab of steel would

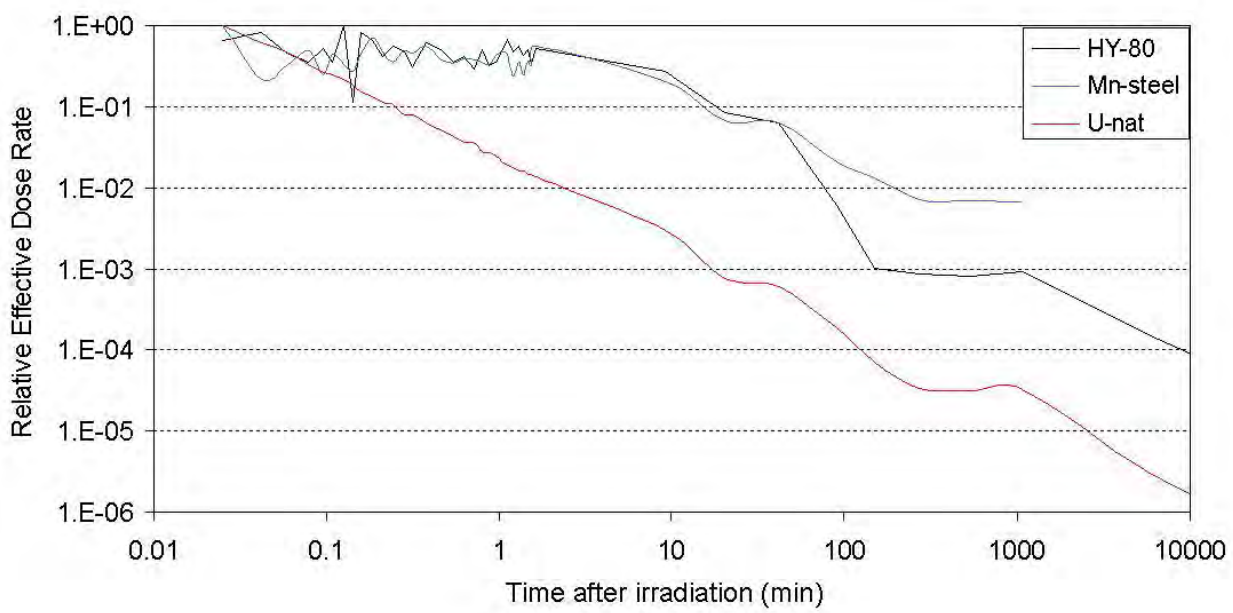

Figure 21. Relative Dose Rates from Various Metals After Irradiation With 25-MeV Betatron

require about 140 films for the initial radiography. Since each film would require 75 min (60 min of exposure and 15 min setup), about six exposures could be performed during an 8-hour shift, which included a 20-minute paid lunch. However, according to former GSI workers, the casting might be returned to the betatron room 5–10 times for additional radiography as flaws are found and repaired, with the entire process taking 2–3 weeks. In the interest of a bounding analysis, we assume that the casting had been subjected to 400 radiographic exposures prior to the shift in question. The betatron operator and his assistant would thus be exposed to the delayed gamma radiation from these previous exposures, as well as from the radiation from exposures during their own shift.

The actual position of the operator with respect to the steel plate cannot be precisely determined. Furthermore, the contributions to the dose rate at a given location from the various portions of the plate that had been exposed at different times would depend on the sequence of the exposures. We made the simplifying assumption that all the exposures were of the central portion of the plate—i.e., that the betatron remained stationary with respect to the plate, and the same portion of the plate was exposed repeatedly—and calculated the dose rate in front of the center of the plate. This is claimant favorable because all the activation products were assumed to be in the region of the plate nearest to the worker, rather than being distributed over the entire plate as was actually the case, and thus produced a higher dose.

In order to assess the effects of the bounding assumptions—that the casting had been in the betatron room continuously, and had been subjected to 400 one-hour exposures with 15 min between shots—we also analyzed a less bounding version of the scenario, assuming that the casting had been subjected to only 12 such exposures in the two preceding shifts.

The long shots described above were used for steel castings 6–18 inches (15–46 cm) thick. Thinner castings, which made up about 90% of the exposures, were radiographed at a distance of 9 ft (274 cm) from the internal betatron target. In modeling this scenario, we assume a typical exposure time of 3 min, a setup time of 11 min, with an additional minute between shots spent going to and from the control room, initiating the exposure, etc. Thirty-two such exposures can be made in a single 8-hour shift (Former GSI Workers 2007). Again, the dose rates were derived from the same portion of the steel plate being exposed repeatedly. In this scenario, we assume 500 such exposures prior to the shift in question.

Lead markers were used to identify the location and orientation of each exposed film. Because the same markers were used over and over, there was a potential for external exposure to any residual radioactivity from photoactivation or photofission of the lead alloy. We simulated the markers with a lead plate, ¼-in (0.635-cm) thick, with an area of 4 in^2 (25.8 cm^2), positioned just in front of the steel casting. The exposure of the betatron operator from this lead plate was modeled in the same manner as for the "long" (one-hour) exposures of the HY-80 steel plate, except that the lead was assumed to have been exposed 4,000 times prior to the beginning of the shift in question.

In another set of scenarios, the exposed individual was the layout man who marked the casting following the radiography. He would typically start work as soon as the film was developed in the Kodak X-omat —this took 8–10 min—and read by the film reader. He was unlikely to start work on the casting until 15 min after the last betatron exposure. Depending on the number of exposures, his work could last from a few minutes to the entire shift. We modeled two versions of this scenario. In one version, castings were processed through the betatron every 75 min, and the layout man spent 75 min marking the casting. This is admittedly a very aggressive schedule, and would allow only one long (60-min) radiographic exposure per casting. We assume 400 prior exposures. A more moderate schedule assumes a new casting every 8 h. In this case, the layout man spent 8 h marking up the casting, which had been exposed for one hour.

The other alloy included in the analysis was austenitic manganese steel, which was reported to contain 15% Mn. Such a manganese concentration is within the range of currently available alloys, which contain up to 32% Mn. It was included in our analysis because manganese has the potential for forming radioactive isotopes with significant half-lives. This alloy was used to make jaws for ore crushers used in the taconite fields in Minnesota. Unlike other castings made at GSI, there was no requirement to radiograph these parts. However, occasional radiographs were taken for foundry control purposes: to verify the effects of changes in foundry practices on the integrity of the castings. As shown in Figure 21, the relative dose rate from manganese steel parallels the dose rate from HY-80 steel for about the first 40 min. After that time, the dose rate declines more slowly, most likely due to the presence of ^{56}Mn, which has a 2.6-h half-life. The formation of this nuclide by the reaction $^{55}Mn(n,\gamma)^{56}Mn$ is predicted by MCNPX.

The manganese steel castings were in and out of the betatron room in about 4 hours.[9] We modeled the exposure of the betatron operator to the irradiated manganese steel assuming four successive one-hour exposures, with a 15-min setup and takedown period after each shot. No prior exposures of the metal were assumed. Since no repairs were performed, a layout man was not exposed to the irradiated casting.

The results of the analysis are listed in Table 7. The effective dose and exposure for each scenario are calculated for an 8-hour shift. Separate calculations are performed for distances of either 1 ft (30.48 cm) or 1 m from the irradiated metal. The radiography of manganese steel comprised four one-hour shots with 15 min between shots, for a total of 5 h. In order to produce comparable results, these were prorated to an 8-h period by multiplying the calculated values by $\frac{8}{5} = 1.6$.

Table 7. Dose and Exposure to Delayed Radiation from Steel and Lead

Worker	Metal	Number of shots[a]		Duration of shot (min)	Exposure duration[b] (min)	Delay time	Effective dose (mrem/shift)		Exposure (mR/shift)	
		Prior to shift	During shift				1 ft	1 m	1 ft	1 m
Betatron operator	HY-80	12	6	60	15	5 s	0.79	0.15	0.83	0.15
		400	6	60	15	5 s	1.04	0.21	1.09	0.22
		500	32	3	11	5 s	0.55	0.10	0.58	0.11
	Mn steel[c]	0	4	60	15	5 s	0.99	0.20	1.06	0.21
	Lead	4000	6	60	15	5 s	7.1e-04	8.9e-05		
Layout	HY-80	400	6	60	75	15 min	2.23	0.50	2.40	0.56
		500	32	3	15	15 min	0.32	0.08	0.37	0.09

[a] "Shot" is the workers' term for radiographic exposure

[b] Exposure of worker to irradiated metal following each shot

[c] Results prorated to an 8-hour shift

2.2.5 Exposure to Delayed Gamma Rays and Delayed Neutrons from Uranium

As described in Chapter 1, GSI radiographed uranium slices under contract with the Mallinckrodt Chemical Works. The maximum thickness of uranium that could be radiographed with the 25-MeV betatron is about 4 inches (~10 cm). The slices were cut from uranium ingots or "dingots" (direct ingots), the largest of which was 18 inches (~46 cm) in diameter. We thus modeled the uranium object as a right circular cylinder, 18 inches in diameter and 4 inches high (45.72 × 10.16 cm). Unlike the dose rates from the steel alloys, the dose rates from uranium following instantaneous irradiation, shown in Figure 21, decrease steadily, reaching 0.1% of the maximum value in 20 min, and continuing to decline for another 4 h. They then level off for the next 12 h before continuing to decrease.

[9] Former GSI employee, personal communication with Robert Anigstein, SC&A, Inc., December 2007.

Because the object was larger than the largest x-ray film—14 × 17 inches (36 × 43 cm)—as many as four exposures were required to encompass the entire film. Because of the thickness of the uranium, each exposure is assumed to take one hour. We model the radiation exposures of the betatron operator assuming that the four shots were performed in succession, with a 15-min setup period between shots and a 5-s interval from the end of the exposure until the operator reached the irradiated object. Because of the induced photofission as well as photoactivation, both delayed gamma rays and delayed neutrons contributed to the radiation dose. (Exposure is defined only for photons.) Doses and exposures are listed in Table 8.

Table 8. Exposure of Betatron Operator to Delayed Radiation from Uranium—per shift

Number of shots	Duration of shot (min)	Exposure duration (min)	Delay time	Effective dose (mrem)						Exposure (mR)	
				1 ft			1 m			1 ft	1 m
				γ	n	Total	γ	n	Total		
4	60	15	5 s	10	1.2	11	1.2	0.14	1.4	11	1.4

Note: Results are prorated to an 8-hour shift.

See notes to Table 7.

The doses from the delayed radiation following betatron radiography are added to the doses from gamma rays, characteristic x rays, and beta-bremsstrahlung x rays from the natural uranium slice that had aged for 100 days, that are listed in Table 9.

Table 9. Exposure of Betatron Operator to Radiation from Aged Natural Uranium—per shift

Effective dose (mrem)						Exposure (mR)					
1 ft			1 m			1 ft			1 m		
γ + x rays	Brem[a]	Total	γ + x rays	Brem	Total	γ + x rays	Brem	Total	γ + x rays	Brem	Total
0.29	0.28	0.56	0.04	0.04	0.07	0.33	0.31	0.64	0.040	0.04	0.079

Note: Results are prorated to an 8-hour shift.

[a] Bremsstrahlung

2.2.6 Exposure to Beta Radiation from Residual Nuclides in Steel

As stated in Section 2.1, MCNPX can model the emission of delayed gamma rays and delayed neutrons following photonuclear interactions. Although it does not directly calculate the emission of beta particles from the residual nuclides produced by such interactions, the code can calculate the creation of such nuclides. We utilized this capability to estimate the concentration of residual nuclides in steel, both in order to estimate the dose to the skin and other superficial organs from strong beta emitters, and to estimate the internal dose from the intake of dust from the irradiated metals. The external dose from beta rays is discussed later in this section of the report, while internal exposure is discussed in Section 2.3.

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. As stated earlier, 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 assume that the HY-80 steel had been exposed for 30 h (4 × 7.5 × 1 h = 30 h). Because repeated radiographic examinations of the austenitic manganese steel castings were unlikely, we assume that this steel had been exposed for 4 h.

MCNPX, when used in the physics-models-only mode, lists two generations of residual nuclides: the nuclide produced by the original interaction and its initial progeny (daughter products). It does not automatically list later progenies (grand-daughters, etc.) With the aforementioned exception, it lists residual nuclides in all materials specified in the problem, including the platinum target in the betatron, the porcelain doughnut, the aluminum ionization chamber and beam-flattening compensator, the metal being radiographed, and the surrounding air. We determined which nuclides were generating in steel by examining the entire list and eliminating those nuclides that most likely resulted from photonuclear interactions with the elemental constituents of materials other than the steel. We also examined the decay chains of the significant beta emitters and determined that no important daughters of these nuclides had been omitted.

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 list of residual nuclides and their specific activities immediately after the radiography of HY-80 steel is presented in Table 10. Since MCNPX does not distinguish between isomeric (metastable) and ground states of the residual nuclides, we chose the state that would result in the highest dose. MCNPX lists the number of atoms, not the activity, of each residual nuclide. The activity of a given isomer is inversely proportional to its half-life; therefore, in most cases, the shorter-lived isomer would produce the higher dose.

The worker that was most likely to receive the highest external exposure to beta radiation was the betatron operator, because he was exposed to the activated steel as soon as 5 s after the end of the radiographic exposure, and because he spent time in proximity to the steel. Combining the short and long shots for HY-80 steel castings (see discussion in Section 2.2.4), we estimate he spent an average of 11.4 min setting up for the next shot. We therefore ranked the 42 radionuclides listed in Table 10 in descending order of activity integrated over the period of 5 s to 11.4 min following irradiation. After eliminating three nuclides that produce no beta radiation, we selected the six nuclides listed in Table 11 from the first nine nuclides listed in rank order.

Table 10. Residual Radionuclides in HY-80 Steel and Worker Exposure by Inhalation

Nuclide	Half-life	Sp. act. Bq/g	Intake Bq	DCF Sv/Bq	Dose rate Sv/h
C-11	20.39 m	5.18e-03	4.78e-06	3.20e-12	1.53e-17
P-30	2.50 m	6.73e-02	5.88e-09	3.64e-12	2.14e-20
P-32	14.26 d	2.80e-04	1.68e-06	3.20e-09	5.37e-15
S-35	87.32 d	1.46e-04	8.73e-07	1.30e-09	1.14e-15
Cl-36	301,000 y	8.99e-10	5.40e-12	6.90e-09	3.72e-20
Sc-47	3.35 d	7.55e-03	4.49e-05	7.30e-10	3.28e-14
Ti-45	184.80 m	2.65e-02	1.27e-04	1.50e-10	1.91e-14
Ti-51	5.76 m	3.82e-02	8.57e-07	4.50e-08	3.86e-14
V-49	330.00 d	7.49e-03	4.49e-05	3.20e-11	1.44e-15
V-52	3.74 m	3.12e-01	6.51e-07	5.20e-12	3.38e-18
V-53	1.61 m	2.40e-02	1.37e-11	2.19e-12	3.00e-23
Cr-49	42.30 m	1.80e+00	4.19e-03	5.90e-11	2.48e-13
Cr-51	27.70 d	2.59e+00	1.55e-02	3.60e-11	5.58e-13
Cr-55	3.50 m	3.80e-03	5.01e-09	4.04e-12	2.03e-20
Mn-52	5.59 d	2.26e-03	1.35e-05	1.80e-09	2.43e-14
Mn-53	3,700,000 y	2.64e-07	1.59e-09	5.20e-11	8.25e-20
Mn-54	312.30 d	5.39e-02	3.23e-04	1.50e-09	4.85e-13
Mn-56	2.58 h	5.01e+00	2.30e-02	2.00e-10	4.61e-12
Mn-57	85.40 s	8.07e-02	7.49e-12	1.70e-12	1.27e-23
Fe-53	8.51 m	1.07e+02	1.13e-02	1.08e-11	1.22e-13
Fe-55	2.73 y	4.33e+00	2.60e-02	9.20e-10	2.39e-11
Fe-59	44.50 d	1.40e-01	8.37e-04	3.50e-09	2.93e-12
Co-56	77.27 d	1.84e-04	1.11e-06	6.30e-09	6.97e-15
Co-57	271.79 d	1.15e-01	6.90e-04	9.40e-10	6.48e-13
Co-58	70.86 d	1.12e-04	6.71e-07	2.00e-09	1.34e-15
Co-60	5.27 y	8.21e-05	4.92e-07	2.90e-08	1.43e-14
Co-61	1.65 h	5.51e-02	2.19e-04	7.50e-11	1.64e-14
Ni-57	35.60 h	7.44e+00	4.38e-02	7.60e-10	3.33e-11
Ni-59	76,000 y	1.44e-06	8.64e-09	2.20e-10	1.90e-18
Ni-63	100.10 y	3.99e-05	2.40e-07	5.20e-10	1.25e-16
Zr-88	83.40 d	4.84e-05	2.90e-07	4.10e-09	1.19e-15
Nb-91	60.86 d	1.23e-01	7.40e-04	1.84e-09	1.36e-12
Nb-92	10.15 d	3.39e-04	2.03e-06	2.71e-08	5.50e-14
Nb-93	16.13 y	9.03e-06	5.42e-08	1.60e-09	8.67e-17
Nb-94	6.26 m	1.05e-01	3.42e-06	4.50e-08	1.54e-13
Nb-95	34.98 d	3.36e-04	2.02e-06	1.60e-09	3.23e-15
Nb-96	23.35 h	1.84e-02	1.07e-04	1.00e-09	1.07e-13
Nb-97	72.10 m	3.79e-02	1.29e-04	7.20e-11	9.32e-15
Mo-91	15.49 m	1.17e+01	6.35e-03	1.99e-11	1.26e-13
Mo-93	6.85 h	1.58e+01	8.56e-02	2.20e-09	1.88e-10
Mo-99	65.94 h	4.34e+00	2.58e-02	1.10e-09	2.84e-11
Mo-101	14.61 m	1.59e+00	7.59e-04	4.50e-11	3.41e-14
Total					2.85e-10

Table 11. Residual Nuclides in Steel: Sources of External Exposure to Beta Radiation

Nuclide	Half-life	Peak energy[a] (MeV)	$\mu_{\epsilon t}$[b] (cm^2/g)		Sp. act.[c] (Bq/g)		Time-integrated sp. act.[d] (Bq·h/g)	
			HY-80	Mn steel	HY-80	Mn steel	HY-80	Mn steel
Fe-53	8.51 m	19.65	0.0321	0.0323	187.97	227.31	23.11	32.58
Mo-91	15.49 m	16.04	0.0311		20.16		2.99	
Ni-57	35.60 h	17.89	0.0316		12.97		2.46	
Mn-56	2.58 h	19.65	0.0321	0.0323	8.80	16.71	1.63	4.04
Mo-99	65.94 h	15.86	0.0310		7.50		1.42	
Cr-49	42.30 m	19.82	0.0322		3.16		0.55	

[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

As discussed in Section 2.2.4, the radiography of manganese steel involved only long shots. Because fewer elements were included in our analysis of manganese steel, the list of significant beta-emitting residual nuclides was reduced to two: ^{53}Fe and ^{56}Mn.

The specific activities listed in Table 10 represent the average activity concentrations in the 5-cm-thick slice of HY-80 steel. However, the beta rays that would contribute to external exposure originate near the surface of the metal. We therefore needed to calculate the specific activities near the surface. We note that the x-ray flux, and hence the photonuclear interactions, decrease exponentially with increasing depth in the steel. We calculated the specific activities at the surface of the metal as follows:

$$A_{io} = \frac{\overline{A_{ix}}\ \mu_{\epsilon t}\ \rho\ x}{1 - e^{-\mu_{\epsilon t}\rho x}}$$

A_{io} = specific activity of nuclide *i* at surface of irradiated metal (Bq/g)

$\overline{A_{ix}}$ = specific activity of nuclide *i* averaged over thickness *x* of irradiated metal (Bq/g)

$\mu_{\epsilon t}$ = total absorption coefficient for photons of energy ϵ in steel alloy (cm^2/g)

ρ = density of steel alloys
= 7.83 g/cm^3

x = thickness of steel
= 5 cm

Since the total absorption cross-section depends on the photon energy, we needed to determine the energy corresponding to the peak photonuclear cross-section for the production of each of

these nuclides. Five of the nuclides listed in Table 11 are produced by a (γ,n) reaction, such as $^{54}Fe(\gamma,n)^{53}Fe$. (The exception is ^{56}Mn, which is produced by an n-capture reaction: $^{55}Mn(n,\gamma)^{56}Mn$.) Plots of the photonuclear cross-sections for the five target nuclei, generated by MCNPX, are displayed in Figure 22. We digitized these plots and determined the peak energy of each nuclide, as listed in Table 11.

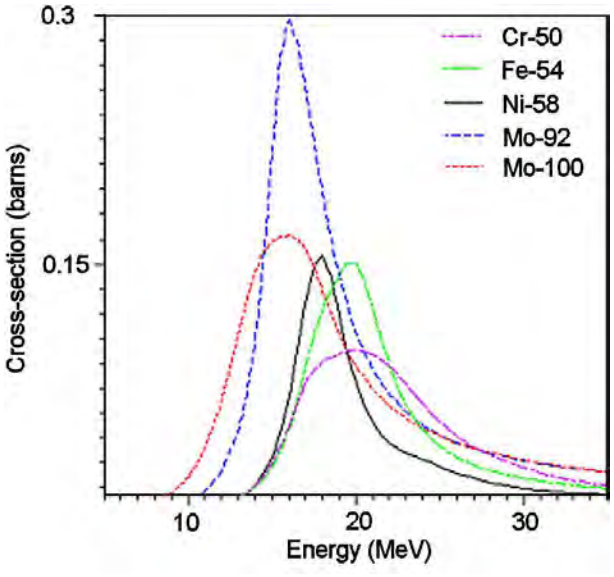

Figure 22. Photonuclear Cross-Sections Used in Calculating Formation of Residual Nuclides

Table 11 lists the specific activities at the surface of the steel. The last two columns list the specific activity integrated over the time the betatron operator is assumed to be exposed to the steel. The six nuclides listed in this table account for over 98% of the time-integrated activity of all of the beta-emitting radionuclides in HY-80 steel listed in Table 10. The two nuclides in manganese steel account for 99.5% of the time-integrated activity in that metal.

We then used MCNP to calculate the dose to the skin and to other superficial organs from the beta radiation (including β^+) from each of the six nuclides in Table 11. The beta spectra of all the nuclides except ^{53}Fe have been compiled by the Tokai Research Establishment, JAERI (2001). The spectrum of ^{53}Fe, which is not listed by JAERI, was derived by digitizing a graphical representation of the spectrum displayed in the "WWW Table of Radioactive Isotopes" (Chu et al. 1999).

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, cloth-covered skin 1 ft (30.48 cm) from the metal, and other organs 1 ft from the metal with an intervening layer of cloth. The characteristics of the cloth were based on data on several different fabrics presented by Sarkar (2004, Table 1) which are listed in Table 12, below.

Table 12. Characteristics of Several Fabrics

Fabric	Weight (g/m^2)	Thickness (cm)	Thread count (per inch)
Plain weave	120	0.035	205
Twill weave	258	0.069	81
Sateen weave	235	0.061	106

Source: Sarkar (2004, Table 1)

We adopted the plain weave, which is similar to the fabric cited by Sarkar (n.d.): "The fabric used was a bleached cotton T-shirt fabric (Weight 124 g/m^2; Testfabrics, Inc.)." We assigned the cloth a thickness of 0.035 cm (as shown in Table 12), and a density of 0.34 g/cm^3, which was calculated by dividing the fabric weight (0.012 g/cm^2) by the thickness.

In each instance, the beta particle flux at the given location was calculated using MCNPX. Organ doses were calculated by applying the coefficients for effective dose per unit fluence in the AP exposure geometry (ICRP 1997, Table A.43). The results of the calculations are presented in Section 2.5.

2.2.7 Exposure to Beta Radiation from Residual Nuclides in Uranium

We determined the residual nuclides following the radiography of slices of natural uranium in a manner similar to the analysis of residual nuclides in steel. For the purpose of this analysis, the uranium slice was modeled as a right circular cylinder with a radius of 22.86 cm (9 in) and a height of 0.5 cm. The thickness was selected to encompass a large fraction of the photonuclear interactions.

The only significant beta-emitting residual nuclides are ^{237}U and ^{239}U. The former is produced by the reaction ^{238}U(γ,n)^{237}U, while the latter is produced by ^{238}U(n,γ)^{239}U. The peak of the total photonuclear cross-section for ^{238}U is centered on 13.1 MeV. The specific activity of each nuclide at the surface of the uranium slice was calculated from the average specific activity in the entire volume in the same manner as discussed in Section 2.2.6. The results are listed in Table 13. The time-integrated specific activities of these two nuclides account for 99.98% of the time-integrated activity of all residual nuclides in uranium.

Table 13. Residual Nuclides in Uranium: Sources of External Exposure to Beta Radiation

Nuclide	Half-life	Peak energy[a] (MeV)	μ_{et}[b] (cm^2/g)	Sp. act.[c] (Bq/g)	Time-integrated sp. act.[d] (Bq·h/g)
U-237	6.75 d	13.1	0.0559	642	160
U-239	23.45 m			2462	496

[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

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

For a preliminary estimate of the relative contribution of the two uranium isotopes listed in Table 13 to the beta radiation from the uranium slices, let us compare their activities to the short-lived beta-emitting progeny of ^{238}U. In aged natural uranium, ^{234}Th and ^{234m}Pa each have a specific activity of 12,347 Bq/g. The time-integrated specific activity of each of these nuclides over the 15-min exposure time of the betatron operator is 3,087 Bq·h/g. Since this is about

5 times the total time-integrated specific activity of ^{237}U and ^{239}U, the beta radiation from uranium metal is dominated by the beta-emitting progeny of ^{238}U.

There is another effect that needs to be considered in this assessment. Putzier (1982) reported measurements of increased beta activities on the surface of freshly cast uranium. He attributed this to the tendency of ^{234}Th, in equilibrium with its ^{234m}Pa daughter, to migrate to the surface as well as to the interface between the molten metal and the mold. Whereas the beta radiation at the surface of uranium metal in secular equilibrium with its short-lived progeny produced dose rates of about 200 mrad/h, the fresh castings had rates of 2,000–3,000 mrad/h. This effect would be manifest for a limited time after the uranium was melted and cast into an ingot. In about 100 days, the ^{234}Th (with a half-life of 24.1 days) that had migrated to the surface would have almost completely decayed, to be replaced by ^{234}Th that had grown in from the decay of ^{238}U. By this time, ^{234}Th would essentially be in secular equilibrium with its ^{238}U parent. Since ^{234m}Pa has a half-life of 1.17 min, it will always be in secular equilibrium with its ^{234}Th parent over the time scales of the present analysis.

Westbrook and Bloom (2007), however, present a picture which is the reverse of the observation reported by Putzier:

> The billet (ingot) was initially low in beta activity because during the melting in the vacuum furnace (i.e., in vacuo), the dross and slag floated to the top of the crucible and the beta-emitting UX1 and UX2 (Th-234 and Pa-234) sublimed and cooled on the underside of the furnace lid . . . .

These seemingly contradictory accounts refer to different methods of producing uranium ingots, but actually indicate the same phenomenon. In both cases, thorium migrated out of the molten uranium. In the process observed by Putzier, the thorium stayed on the surface of the uranium as the ingot cooled and solidified, while in the process cited by Westbrook and Bloom, it separated completely and condensed on the oven. Since it is uncertain which behavior would be manifest in dingot production, we will make the claimant-favorable assumption that the uranium slices radiographed at GSI had enhanced surficial concentrations of ^{234}Th.

If we assume that, in order to obtain representative samples of the metal, the slices were cut from the interior sections of the ingot, only the sides (i.e., the radial surfaces of the cylinders) would contain the enhanced beta activity characteristic of the surface of the cast ingot. On the other hand, because only the front face of the slice was exposed to the betatron beam, the two uranium isotopes listed in Table 13 would largely be confined to a layer just beneath the front surface.

The betatron operator would have been exposed to both the front and the side of the uranium slice. We therefore calculated the beta dose separately from each surface. We used MCNPX to calculate doses to the skin and to superficial organs, using the methodology described in Section 2.2.6. Doses to the skin were assessed for four situations: bare skin in contact with the surface of the metal, skin covered with one layer of cloth adjacent to the metal, and at distances

of 1 ft (30.48 cm) and 1 m, with an intervening layer of cloth. Doses to three other superficial organs were calculated at distances of 1 ft and 1 m, with an intervening layer of cloth.

To characterize the radiation from the front face of the uranium cylinder, we combined the beta spectra of the nuclides in 100-day-old natural uranium with those of the two principal residual nuclides, weighted by the specific activities at the surface of the uranium slice. The doses from the side (radial) surface of the cylinder were calculated using only the combined beta spectra of ^{234}Th and ^{234m}Pa. Because Putzier reported dose rates at the surface of the freshly cast ingots that were 10–15 times higher than those for old uranium castings, we assume that the specific activities of these nuclides near this peripheral surface were 12.5 times their equilibrium values. Since the betatron operator would have been exposed to both the front and the side of the uranium cylinder at different times during the setup period, we averaged the dose rates at the front and sides for each organ and each distance. The results are listed in Table 14.

Table 14. Dose Rates from External Exposure to Beta Radiation from Uranium Slice (mrad/h)

Location	Orientation	Organ			
		Skin	Testes	Bone marrow	Female breast
Contact	Front	94.6	–	–	–
	Side	1347.9	–	–	–
	Average	721.3	–	–	–
Cloth	Front	73.0	–	–	–
	Side	1032.6	–	–	–
	Average	552.8	–	–	–
1 ft	Front	16.8	0.3	0.1	1.3
	Side	58.3	1.0	0.4	4.2
	Average	37.5	0.6	0.3	2.7
1 m	Front	2.0	0.0	0.0	0.1
	Side	8.7	0.1	0.0	0.5
	Average	5.3	0.1	0.0	0.3

The doses listed in Table 14 embody two assumptions:

1. The ingot had been recently cast, so that no significant decay of the enhanced ^{234}Th activity at the radial surface has taken place. The only information regarding the timetable of uranium shipments from MCW to GSI is furnished by Westbrook and Bloom (2007). The following excerpt is from their description of operations at Plant 4 (also known as the Pilot Plant):

> Aged metal billets were stored on the floor beside the operator's desk and were left there until the lead operator or the engineer examined and approved them, a period of one to three days. The operator spent four to six hours sawing "betatron slices" (samples to be sent to Granite City Steel [sic] (aka General Steel Castings) in Granite City, Illinois for testing) because the shape of the slices required the operator to spend

several minutes setting the metal on the saw. The slices were stored on a table in a storeroom until enough had accumulated for shipment, a period of three to four weeks. When enough slices had accumulated, the operator would examine each closely to determine the weight and lot number stamped on it, which took a total of 30 to 45 minutes.

It is not clear what is meant by "aged metal billets." Since there is no reason the billets would be deliberately allowed to sit, we assume that they were not more than a few days old. Since they were accumulated for a period of 3–4 weeks, we assume that a typical slice arriving at GSI had been cast about two weeks prior to being radiographed. During this time, the enhanced ^{234}Th activity on the surface would have decreased by about 33%. However, since this delay time may not have applied to all uranium shipped from MCW or Weldon Spring, we use the claimant-favorable assumption that the shipments occurred shortly after the uranium was cast.

2. The natural uranium that was used as the raw material for the production of the melt was at least 100 days old.

In one process used to produce uranium ingots at Mallinckrodt, nitric acid was used to leach uranium from the ore concentrate. The resulting uranyl nitrate was purified by means of a double ether extraction process, which separated the uranium from thorium and protactinium. Several more steps were required to produce UF_4, which was placed in a "bomb" and reduced by powdered magnesium, resulting in molten uranium metal and MgF_2. Thus, it was possible that the ingots were made from freshly purified uranium, in which case there would have been little ingrowth of ^{234}Th and ^{234m}Pa. In such a case, our calculations would overstate the beta doses from the uranium slice. If, however, the ether extraction had taken place many days before the metal was produced, or if the ingot was made by remelting uranium metal scrap, or if the UF_4 had been produced at another facility and later shipped to the Mallinckrodt facility in St. Louis or to Weldon Springs, then significant ingrowth may have taken place. Since the time line for the production of the uranium ingots is uncertain, our analysis yields doses that are reasonable and claimant favorable.

2.3 Calculation of Internal Exposure

2.3.1 Internal Exposure from Inhalation of Dust from HY-80 Steel Castings

As discussed in Section 2.2.6, MCNPX was used to calculate the concentration of residual nuclides resulting from photonuclear interactions in steel and uranium. These radionuclides constitute a source of internal exposure of workers such as chippers, grinders, burners, and welders who repaired defects in steel castings that were identified by the betatron radiography. The repair activity is assumed to take place 30 min after the betatron exposure and to continue for one hour.

Table 10 lists the significant radionuclides, their specific activities immediately after the irradiation, and their intake by inhalation, assuming a respiration rate of 1.2 m^3/h and dust

loading of 5 mg/m^3. This dust loading is an upper-end value of the time-weighted average (TWA), and was set equal to the OSHA permissible exposure limit (PEL) for respirable nuisance dust. Although such a value could be exceeded on occasion, it is unlikely that workers would be subjected to an annual-average concentration that is higher than this value. No adjustment was made for the probable oxidation of the steel dust. If the dust loading corresponded to the oxide rather than to the metal, the metal would constitute only a fraction of the dust, the remainder being the oxygen in the compound. Since the specific activities of the residual nuclides are stated in terms of the metal, a lower concentration of metal would lead to a lower intake of radionuclides. The effective dose coefficients listed in Table 10 were taken from ICRP 1995; each nuclide was assigned the particle size (1 µm or 5 µm AMAD) and lung absorption type that would result in the highest effective dose. Dose coefficients for a few short-lived nuclides not listed by ICRP were calculated by Keith Eckerman, a member of the Life Sciences Division of the Oak Ridge National Laboratory (Eckerman 2007). No dose coefficient was available for ^{51}Ti; this nuclide was assigned the highest dose coefficient of all the nuclides in our list.

The total hourly dose listed in Table 10 is equal to about 2.8×10^{-5} mrem, or about 0.09 mrem per year, assuming an exposure of 65 h per week, 50 weeks per year (see discussion of work hours in Section 2.6). This assessment utilizes several highly conservative assumptions, both to ensure a claimant-favorable analysis and to simplify the calculations:

- The same portion of the steel had been exposed for 30 h, without interruption.
- The specific activity was averaged over a 5-cm-thick cylindrical region, with a radius of 8.255 cm (3.25 in), that lay just under the surface of the steel plate facing the betatron, and was centered on the beam. In reality, much of the repair involved deeper regions of the casting, with lower specific activities.
- The worker spent one hour repairing the defect in the center of the exposed area, and then immediately proceeded to work on another recently exposed casting.
- The maximum permissible dust loading (OSHA PEL) prevailed for the entire shift.
- The hours per week corresponded to the period of peak work at GSI.

We conclude that inhalation of dust from activated steel did not constitute a significant exposure pathway.

2.3.2 Internal Exposure from Inhalation of Dust from Irradiated Uranium

There was no processing of the uranium metal following betatron radiography at GSI. However, there was some residual uranium contamination, most likely due to the oxidation of the uranium metal and the subsequent sloughing off of the oxide layer. To estimate the effect of the irradiation of uranium on the internal exposure of workers from the inhalation of the uranium dust, we calculated the specific activities of the residual radionuclides created by photofission

and photoactivation. We then calculated the dose per milligram of uranium dust inhaled during the first 24 h following the betatron irradiation.

The results of the analysis are shown in Table 15. This table lists the 12 radionuclides that account for 99% of the dose from the inhalation of residual radionuclides in irradiated uranium—the complete list includes several hundred stable and radioactive nuclides, most of which make no significant contribution to the dose from inhalation. As shown, the dose from the inhalation of these 12 nuclides is about 9.3×10^{-5} mrem per milligram of uranium metal inhaled. This is compared to a dose of about 20 mrem per milligram from the isotopes of natural uranium. Clearly, the irradiation of the uranium slices has no significant effect on the internal dose from inhalation.

Table 15. Exposure of Workers to Inhalation of Uranium Dust

Nuclide	Half-life	Sp. act. Bq/g	Intake Bq/mg	DCF Sv/Bq	Dose Sv/mg
Fission and activation products[a]					
Zr-97	16.91 h	4.70e+00	2.99e-03	1.40e-09	4.19e-12
Sn-127	2.10 h	3.89e+01	4.91e-03	2.00e-10	9.83e-13
Sb-127	3.85 d	8.65e-01	7.92e-04	1.70e-09	1.35e-12
Sb-128	9.01 h	1.01e+01	4.62e-03	6.70e-10	3.09e-12
Sb-129	4.40 h	4.31e+01	1.11e-02	3.50e-10	3.90e-12
Te-132	3.20 d	6.81e+00	6.12e-03	3.00e-09	1.84e-11
I-131	8.02 d	3.26e-01	3.12e-04	1.10e-08	3.44e-12
I-133	20.80 h	1.52e+01	1.05e-02	2.10e-09	2.20e-11
I-135	6.57 h	9.58e+01	3.48e-02	4.60e-10	1.60e-11
Ba-140	12.75 d	6.94e-01	6.76e-04	1.60e-09	1.08e-12
U-237	6.75 d	4.98e+02	4.73e-01	1.80e-09	8.52e-10
U-239	23.45 m	1.91e+03	4.49e-02	3.50e-11	1.57e-12
Total					9.28e-10
Natural uranium					
U-234	2.46e+05 y	1.24e+04	1.24e+01	8.50e-06	1.06e-04
U-235	7.04e+08 y	5.68e+02	5.68e-01	7.70e-06	4.38e-06
U-238	4.47e+09 y	1.23e+04	1.23e+01	7.30e-06	9.01e-05
Total					2.00e-04

[a] Based on average specific activities during first 24 h following irradiation

2.3.3 Internal Exposure from Inadvertent Ingestion

We did not perform separate assessments of internal exposure from inadvertent ingestion of residually radioactive materials. The maximum dose coefficients for ingestion of the significant beta-gamma emitters in these materials are comparable (within a factor of two) to the maximum coefficients for the inhalation pathway—they are lower for alpha emitters. The reasonable

maximum intake by inadvertent ingestion is 50 mg per day (EPA 1997), which is essentially the same as the intake by inhalation in the steel casting scenario, which assumes a dust loading of 5 mg/m^3 and a respiration rate of 1.2 m^3/h during an 8-hour day (5 × 1.2 × 8 = 48 mg/d). Consequently, the dose from inadvertent ingestion would be comparable to that from inhalation. Since the dose from inhalation is approximately 0.1 mrem/y, the ingestion dose would not make a significant contribution to the total dose from the radionuclides produced by photoactivation and photofission in irradiated materials.

2.4 External Exposures of Individual Workers to Direct Penetrating Radiation

Exposure assessments were performed for three categories of workers: betatron operators, layout men, and workers who repaired defective castings (chippers, grinders, burners, and welders).

2.4.1 Betatron Operator

Table 16 lists the external exposures and neutron doses to 25-MeV-betatron operators from direct penetrating radiation during three types of operations included in our analysis: short and long radiographic exposures of HY-80 steel plates, and radiography of uranium slices. Three radiation sources are listed for each exposure scenario: stray radiation in the control room during betatron radiography, radioactive activation and fission products in the metal following irradiation, and residual radioactivity of the betatron doughnut (or perhaps some other portion of the apparatus) following radiography. Because the radiation from the activated betatron apparatus was reported as an exposure rate rather than a dose rate, we list exposures but not photon doses for these three scenarios. We do list neutron doses, since these are separate from exposures, which are only derived from photons.

As discussed in Section 2.2.1, we modeled two exposure geometries in calculating the exposures in the control room—one in which the metal object was on the railroad tracks, another assuming it was in the center of the shooting area, with the betatron pointed away from the control room. However, many other geometries were possible. Therefore, although radiographing castings on the railroad tracks was not the typical practice, we assume that this scenario yielded a reasonable upper bound to the exposure in the control room and used these results to arrive at a claimant favorable assessment. The exposures and neutron doses in the control room were calculated by multiplying the rates listed in Table 2 for the railroad track scenario by the total duration of betatron exposures during an 8-hour shift exclusively devoted to one of these three tasks. The duration for the short shots is 96 min (3 min/shot × 32 shots), while that for the long shots is 6 h (1 h/shot × 6 shots).

During the setup time between betatron exposures, the operators are assumed to spend half the time at a distance of 1 ft (30.48 cm) from the metal casting and the other half at a distance of 1 m. Therefore, the exposures from external radiation from the irradiated HY-80 steel casting are the averages of the exposures at 1 ft and 1 m listed in Table 7, while the exposures and doses from the uranium metal are the averages at the two distances listed in Tables 8 and 9. The

duration of these exposures is listed for reference; however, the actual exposures and doses are calculated according to the method described in Section 2.1.4.

Table 16. External Exposure of Betatron Operators to Direct Penetrating Radiation

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	3.1	0.9
				Metal	5.9	0.3	
				Doughnut	5.9	34.5	
				Total		38.0	0.9
	Long	6	36%	Control room	6.0	11.7	3.4
				Metal	1.5	0.7	
				Doughnut	1.5	13.0	
				Total		25.3	3.4
	Composite		100%			33.5	1.8
Uranium	Long	6		Control room	6.0	11.7	3.4
				Metal	1.5	6.8	0.7
				Doughnut	1.5	13.0	
				Total		31.5	4.1
				24 MeV			
HY-80	Short	32	64%	Control room	1.6	1.7	0.6
				Metal	5.9	0.3	
				Doughnut	5.9	34.5	
				Total		36.5	0.6
	Long	6	36%	Control room	6.0	6.3	2.2
				Metal	1.5	0.7	
				Doughnut	1.5	13.0	
				Total		20.0	2.2
	Composite		100%			30.6	1.2
Uranium	Long	6		Control room	6.0	6.3	2.2
				Metal	1.5	6.8	0.7
				Doughnut	1.5	13.0	
				Total		26.1	2.9

The exposure to the residual radioactivity of the betatron apparatus was calculated using the methodology discussed in Section 2.2.3. During the short shots, in which the casting was 9 ft (274 cm) from the betatron target, the operator's distance is assumed to vary uniformly from 3 to 6 ft (91–137 cm). During the long shots, the casting was 6 ft from the target, giving the operator less range of movement. We assume that the operator was at a fixed distance of 3 ft from the target during that operation.

As stated in footnote 8 (page 20), about 10% of the radiographs of steel castings were long shots, while the remainder were short shots. As discussed in Section 2.2.4, 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. The exposures during a shift comprising a composite of short and long shots are shown in Table 16. We note that the average exposure from radiographing steel is higher than the exposure from radiographing uranium. However, radiography of uranium results in a higher neutron dose.

Exposures of the 24-MeV-betatron operators were calculated in a similar manner. The exposures and neutron doses in the control room were based on the average of the values at the two locations presented in Table 3. The radiation exposures to other sources were the same as those of the 25-MeV-betatron operators. The assessment of the 24-MeV-betatron operators is simplified, in that the time in the control room and the number of exposures per shift were not adjusted for the longer exposure duration due to the lower beam intensity. Since these factors reduced the time the operators were exposed to the residually radioactive betatron apparatus, the principal source of radiation exposure, the assessment of these workers is claimant favorable.

2.4.2 Layout Man

The layout man was not a distinct labor category—this work assignment was drawn by members of the betatron radiography team. That team normally consisted of three workers: betatron operator, assistant, and film cassette handler. Since the assignment was not uniformly distributed among the betatron crew, it is difficult to apportion the exposures. We therefore treat this as a separate job category for the purpose of comparing the exposures to those of other workers.

The layout man marked up the steel after all shots were completed; therefore, the duration of his exposure to steel that had been subjected to long shots and short shots is not the same as that of the betatron operator. According to a former GSI worker, the layout man would typically spend a full shift of 8 h marking up a large casting. However, he might sometimes be interrupted to mark up a casting that has just been radiographed and is close to being shipped (footnote 9, page 23). We characterized that scenario as involving long (one-hour) shots, as described in Table 7. We assume that 10% of his shift consisted of such activity, while 90% was devoted to marking up a single large casting that had been subjected to multiple short shots, also described in Table 7. Because marking the steel requires continuous close contact with the metal, we assume that he was at a distance of 1 ft (30.48 cm) 90% of the time and at 1 m the remaining 10%.

We assume that the work took place in a location in the No. 10 Building that had a high potential exposure to stray radiation from the betatron, which is described in Section 2.2.1. We assume that he was on break for one half hour per shift, and we used the dose rates in the restroom adjacent to the No. 10 Building to characterize his exposure during that time. We derived the

betatron duty cycle by noting that, as calculated in Section 2.4.1, a combination of one long shot and nine short shots took a total of 210 min. The actual exposures during this time were 60 min for the long shot and 27 min (9 × 3 = 27) for the short shots. Thus, the betatron was operating for 87 out of 210 min, or about 41%. This does not include time the machine might be shut down for maintenance.

The results of the analysis are presented in Table 17. We see that the doses to the layout man are slightly less than to the betatron operator. This is despite the worst-case assumption that his entire shift was spent in a location that would receive one of the highest exposures to stray radiation from the betatron of any work station in the foundry. This result, combined with the fact that layout was not a permanent full-time assignment, indicates that the external exposure of the betatron operator to direct penetrating radiation would be the limiting exposure of any member of the betatron team.

Table 17. External Exposure of Layout Men to Direct Penetrating Radiation

Source of radiation		Betatron duty cycle	Duration (h/shift)	Exposure (mR/shift)	Neutron dose (mrem/shift)
Steel	Short shots–90%	—	6.75	0.3	
	Long shots–10%	—	0.75	0.2	
#10 Building		41%	7.5	27.9	1.3
Restroom			0.5	4.9	0.1
Total				33.3	1.4

2.4.3 Other Workers

Another external exposure scenario which we modeled was the use of ^{60}Co for radiography. The dose rates in the control room, shown in Table 4, are bounded by the doses in this location during the betatron radiography of a steel casting on the railroad tracks, shown in Table 2. Furthermore, according to a former worker (footnote 2, page 9), the radiographer left the control room once the radiographic exposure began and stayed in an office remote from the shooting area, thus reducing his personal radiation exposure. Therefore, the exposure of the radiographer to the 80-Ci ^{60}Co source during normal operations was bounded by the radiation exposure of the 25-MeV-betatron operator. However, this does not account for instances when the sources could not be retracted into the shield using the remote control cable. There was at least one incident in which a worker was exposed to the unshielded source while trying to get it back into the shield. The exposure rate from an unshielded 80 Ci ^{60}Co source at a distance of 1 m is about 100 R/h. Extremely high doses could be received during such an occurrence.

There were also reported incidents of a worker remaining inside a steel casting while it was exposed to the betatron. The beam would have been substantially attenuated by the steel; nevertheless, we cannot rule out high doses from such an occurrence.

Bounding estimates of external exposures of other workers also cannot be readily calculated. As shown in Table 2, dose rates greater than 200 mrem/h were calculated for a location on the roof of the New Betatron Building during betatron radiography. Further, as listed in Table 4, dose rates during ^{60}Co radiography were approximately 1,000 mrem/h at a nearby location. A former worker reported spending one half hour every 6 months in this location; he could have received a dose of approximately 1 rem/y in the unlikely event that the 80-Ci ^{60}Co source was in use each time he was on the roof (see Section 2.2.1). However, he and other workers performed maintenance on the roof of the No. 10 Finishing Building for undetermined periods of time. As shown in Figures 1 and 3, the roof of the No. 10 Building is higher than the shield wall of the New Betatron Building. Workers on or near the roof could therefore have been exposed to scattered radiation and perhaps direct radiation from the ^{60}Co source, if it were in use at the time, as well as to radiation from the betatron, if it were aimed upwards at a sufficiently large angle, as might be necessary in radiographing the underside of the steel axle illustrated in Figure 19.

Potentially significant external exposures may also have resulted from radiography using the 250-mCi ^{60}Co source. At first blush, it would appear that radiation from this source would be dwarfed by that from the 80-Ci source. However, because of the light shielding afforded by the 8-inch (20-cm) thick wall made of hollow cinder blocks, the exposure rates outside the room were as high as 19 mR/h, as shown in Table 5. We have no information on how frequently this source was used, nor on the exposure time or the typical occupancy of the area outside the room. If, as is not unlikely, the radiographer remained just outside the door during the exposures, he could have been exposed to as much as 100 mR per shift, assuming about 5 h of exposure per shift. Workers not directly involved in this operation mentioned jumping up or standing on tiptoe to look over the wall out of curiosity. Again, we cannot reliably estimate how often this occurred, or for what period of time.

There was an incident in which a worker took home the 250-mCi ^{60}Co source, apparently mistaking it for a plumb bob or a fishing sinker—it was returned a few days later. A lead shield that would reduce the exposure rate to about 6 mR/h—considered to be a safe level of radiation in the 1950s—at 1 m from the source would have been 8 cm thick. Assuming a spherical configuration—the most compact shape possible—the shield would weigh over 50 lb (~24 kg). Therefore, it is unlikely that the source was adequately shielded at the time it was removed. Furthermore, it was reported that GSI used an airplane equipped with radiation detectors to survey the area, locating the source in the worker's home. This would also indicate that the source was not well shielded. Thus, we can conclude that this worker received a significant radiation dose from this incident. It also indicates lax security involving this source, raising the possibility of other, unreported, radiation exposure incidents.

Another instance of potentially significant external exposures would have been occupancy of the break area in the rail tunnel leading into the New Betatron Building. As listed in Table 2, the exposure rates during betatron operation could be about 25 mR/h. Assuming a 41% duty cycle for the betatron, the average exposure rate could be about 10 mR/h. Assuming an occupancy of one hour per shift, a worker could have an exposure of 10 mR/shift, in addition to any other exposures during his workday. A similar exposure would occur in the restroom, where the

exposure rate during betatron radiography was calculated to be about 24 mR/h. According to former workers, some workers used this as a break area or a place to evade their supervisors. This location could also contribute an exposure of 10 mR/shift. Table 2 lists a still higher exposure rate—56 mR/h—in a location outside the New Betatron Building. Applying the same duty cycle, this results in an average exposure rate of ~23 mR/h. This again could make a significant contribution to worker exposures if this area was occupied for any significant length of time. We have no information about the occupancy of this location.

2.5 External Exposure to Beta Radiation

The calculation of dose rates from beta radiation from irradiated steel is described in Section 2.2.6. Table 18 lists doses to two hypothetical workers—a betatron operator and a layout man—that were calculated using this methodology. The exposures of the betatron operator are based on the average time spent in the proximity of the steel during the setup for short and long shots, and on the assumption that for one half of the time, parts of the skin were in contact with the steel while other parts of the skin and the superficial organs were at a distance of 1 ft (30.48 cm). The rest of the time he was further away, receiving a relatively small beta dose. To calculate the exposure of the layout man, we simplified the scenario described in Section 2.2.4 and made the claimant-favorable assumption that he was exposed to the steel 15 min after the last irradiation and was in contact with the casting 90% of the time for 75 min. The exposures of both workers were prorated to an 8-hour shift. Since there is no layout operation following the radiography of manganese steel, we only calculated the doses to the betatron operator from that source.

Table 18. Dose Rates from External Exposure to Beta Radiation from Steel (mrad/shift)

Organ	Distance	Shield	HY-80 steel		Mn steel
			Betatron operator	Layout man	Betatron operator
Skin	Contact	None	4.6	2.1	1.6
	Contact	Cloth	3.9	1.7	1.3
	1 ft	Cloth	2.8	1.2	1.0
Testes	1 ft	Cloth	0.10	0.047	0.027
Bone marrow			0.035	0.016	0.010
Female breast			0.31	0.14	0.09
Thyroid			0.005	0.003	3.9e-04

As shown in Table 18, doses to the skin from external exposure to beta radiation are a potentially significant fraction of the exposures of the betatron operator and the layout man. The doses to the other organs are two orders of magnitude less than the exposures to direct penetrating radiation and therefore need not be considered.[10] We also note that the beta doses to the betatron

[10] For the sake of this discussion, we use the approximation 1 mR = 1 mrad. This is not an accurate relationship; unless explicitly stated it is not used elsewhere in the present analysis.

operator are higher than to the layout man, confirming that the radiation exposure of the former is limiting. Finally, we note that the beta doses from Mn steel are lower than from HY-80 steel.

Table 19 presents the dose rates to a betatron operator resulting from his handling of a uranium metal slice while performing betatron radiography. We assume that bare skin on the hands and forearms was in contact with the uranium during one half of the setup period, and that the operator was 1 m from the slice the rest of the time. The portion of the skin covered with clothing was 1 ft (30.48 cm) from the metal during one half of this time, and at 1 m the rest of the time. Each value is based on the average of the dose rates from the front face and the side of the uranium slice, as discussed in Section 2.2.7.

Table 19. Dose Rates to Betatron Operator from Beta Radiation from Uranium Slice

Organ		Dose (mrad/shift)
Skin	Hands & forearms	544.9
	Clothed	32.1
Testes		0.5
Bone marrow		0.2
Female breast		2.3

As was the case for activated steel, the beta rays make a significant contribution to the dose to the skin, but only a minor contribution to the dose to other organs. Unlike the case of external exposure to direct penetrating radiation, for which there was little difference in the average doses to the betatron operator from radiographing steel or uranium, the dose to the skin is significantly higher from the handling of uranium than from activated steel.

2.6 Estimates of Annual Doses

The estimate of the annual exposures of GSI workers depends on the hours they worked each year. Former workers estimated that, during peak years, the work week ranged from 50 to 80 h. They agreed that 65 hours per week was a reasonable average. Therefore, we adopted a value of 3,250 h (65 × 50) per year, or approximately 406 8-hour shifts, as a reasonable, claimant-favorable assumption.

The radiation exposures of a betatron operator bound the exposures of the other workers—a layout man and a radiographer using an 80-Ci ^{60}Co source—for whom we performed detailed exposure assessments.[11] These exposures also bound the exposures of the chainmen who attached hooks and chains to hoist the casting onto a transfer car after the radiography was completed, and who transported the casting out of the betatron building. Their exposures would have been less than those of the betatron operator because they were exposed to the casting, and possibly to the betatron apparatus, at a later time after the radiography, when the radiation levels

[11] Radiographers may have experienced higher exposures as a result of incidents involving a mechanical malfunction of the radiographic apparatus.

were reduced by radioactive decay. The exposures of the layout man, in turn, bound the exposures of the chippers, grinders, burners, and welders to both penetrating and non-penetrating radiation. These workers began to repair the castings after the layout man finished marking up the metal. Since most of the external exposure was due to short-lived radionuclides, the radiation levels of the metal would be significantly lower by the time these workers began their tasks.

2.6.1 Annual Doses from External Exposure to Direct Penetrating Radiation

For the years 1964–1966, we base the limiting exposure to direct penetrating radiation on the composite exposure of the operator of the 25-MeV betatron while radiographing steel. As listed in Table 16, the exposure is calculated to be 33.5 mR per shift, while the neutron dose is 1.8 mrem/shift. Based on 406 shifts per year, we obtain an annual exposure of approximately 13.6 R, as well as a neutron dose of 735 mrem from the radiography of steel. We estimate a higher neutron dose from the radiography of uranium, but this is offset by a lower estimated exposure, leading to approximately the same total dose per shift (see footnote 10 on page 41).

For the years 1952–1963, only the 24-MeV betatron was operating at the GSI Granite City plant. Using the corresponding exposures from that machine listed in Table 16, we calculate an annual exposure of 12.4 R and a neutron dose of 470 mrem from the radiography of steel. We again calculate a higher neutron dose from the radiography of uranium, but this is more than offset by a lower exposure.

2.6.2 Annual Doses from External Exposure to Beta Radiation

Skin doses from beta radiation would have been primarily from handling of the uranium slices. Therefore, these doses would have varied from year to year, depending on the time spent radiographing uranium each year. These time estimates are based on purchase orders issued by the Mallinckrodt Chemical Works, which are summarized in Table 20.

Table 20. Summary of Mallinckrodt Purchase Orders

Date issued	Dates covered	Hourly rate ($)	Monthly estimate ($)	Annual limit ($)	Estimated monthly hours
3/6/58	3/1/58 – 6/30/58	16	500	—	31.3
6/12/58	7/1/58 – 10/31/58	16	450	—	28.1
10/13/58	11/1/58 – 6/30/59	16	450	—	28.1
6/26/59	7/1/59 – 6/30/60	16	450	—	28.1
6/17/60	7/1/60 – 6/30/61	16	450	—	28.1
7/14/61	7/1/61 – 6/30/62	16	—	7000	36.5
7/16/62	7/1/62 – 6/30/63	16	—	2000	10.4
5/9/63	7/1/63 – 6/30/64	16	—	450	2.3
5/20/64	7/1/64 – 6/30/65	16	—	450	2.3
7/7/65	7/1/65 – 6/30/66	35	—	450	1.1

The earliest purchase order available to us is dated March 6, 1958. However, as discussed in Section 1.3, we assume that the Granite City facility may have been radiographing uranium for Mallinckrodt as early as 1952. We note that prior to the purchase order issued July 14, 1961, the total and/or monthly amount was listed as an estimate; therefore, it is possible that the actual work done could have exceeded this estimate if authorized by the responsible Mallinckrodt employee. Starting July 14, 1961, each purchase order listed a "not to exceed" amount, so we assume that these amounts represented firm fixed limits. We calculated the estimated hours devoted to radiographing the uranium each month by dividing the monthly estimate by the hourly rate for the first five purchase orders. For the last five purchase orders, we divided the annual limit by 12 to get the average monthly amount, then divided that amount by the hourly rate to obtain the average monthly hours.

To estimate the skin dose from beta radiation, we calculated the number of 8-hour shifts per year devoted to radiographing uranium, based on the monthly hours listed in Table 20. We subtracted this number from the total number of shifts per year worked by a betatron operator to obtain the number of shifts spent radiographing steel. Since the Mallinckrodt purchase orders specified that the work was to be performed on the day shift Monday through Friday, we assume that the same operator could have performed all the uranium radiography during a given year. We then calculated the annual doses to the skin from irradiated uranium and steel, based on the skin dose per shift listed in Tables 18 and 19. The results are listed in Table 21.

Table 21. Annual Doses to Skin of Betatron Operators from Beta Radiation (rads)

Year	Number of shifts		Hands and forearms			Other skin		
	Uranium	Steel	Uranium	Steel	Total	Uranium	Steel	Total
1952-1957	46.9	359.4	25.5	1.7	27.2	1.5	1.0	2.5
1958	44.5	361.7	24.3	1.7	25.9	1.4	1.0	2.4
1959-1960	42.2	364.1	23.0	1.7	24.7	1.4	1.0	2.4
1961	48.4	357.8	26.4	1.7	28.1	1.6	1.0	2.6
1962	35.2	371.1	19.2	1.7	20.9	1.1	1.0	2.2
1963	9.6	396.7	5.2	1.8	7.0	0.3	1.1	1.4
1964	3.5	402.7	1.9	1.9	3.8	0.1	1.1	1.2
1965	2.6	403.7	1.4	1.9	3.3	0.1	1.1	1.2
1966[a]	0.8	405.4	0.4	1.9	2.3	0.03	1.1	1.2

[a] Annual rate during contract period January 1–June 30

As shown in Table 21, the annual skin doses are relatively constant during the years 1952–1961. The doses decrease between 1962 and 1966, when the purchase orders for uranium radiography steadily declined, ending on June 30, 1966.

2.7 Conclusions

We have analyzed a few exposure scenarios involving GSI workers, primarily members of the betatron radiography teams. We selected those scenarios for which we had adequate information

and which were likely to lead to the maximum reasonable exposures of the workers. We have presented additional information about exposures of maintenance workers servicing equipment on the roofs of the betatron buildings and adjacent structures, but did not have enough detailed information to quantify these exposures. Likewise, we could not quantify the exposures to the ^{60}Co radiography source used in the No. 6 Building.

We analyzed two possible orientations of the betatron and the steel casting in the New Betatron Building, and one such geometry in the Old Betatron Building. Obviously, many more geometries were possible, and would have resulted in both smaller and larger doses at the 11 locations included in the analyses. These locations were selected on the basis of our professional judgment. It is possible that individuals in other locations could have experienced higher exposures.

In order to perform these analyses within a reasonable time and level of effort, we made certain simplifying assumptions, all of which were claimant favorable. We therefore believe that these analyses provide a reasonable upper bound to the exposures of the betatron radiography teams, the layout men, and the workers assigned to the repair of the castings.

We cannot bound the exposures of workers maintaining ventilation and other equipment on the roofs of buildings above or near the betatrons, nor of workers exposed to radioactive sources used for radiography. The cinder-block structure used to house the 250 mCi ^{60}Co source appears to have afforded inadequate shielding. The actual activity of the source is uncertain: it has been variously described as ¼ curie and "less than one curie." Furthermore, the date of acquisition is unknown, so the source may have significantly decayed from its original activity prior to the covered period (when GSI was radiographing uranium).

We conclude that internal exposures to either particulate matter generated during the repair of radiographed steel castings or to any residual radionuclides generated during the radiography of uranium would make a negligible contribution to the total radiation exposures of GSI workers.

2.8 Recommendations for Further Studies

NIOSH/OCAS has recently acquired film badge dosimetery records for a number of former GSI workers from Landauer, Inc. We would be interested in examining copies of these records. However, one must bear in mind some inherent limitations of these records:

- It is our understanding that these records go back only to 1964, leaving much of the period uncovered.

- It is likely that only workers directly involved with radiation sources—members of the betatron teams and the "isotope workers" (radiographers utilizing ^{60}Co sources)—were monitored. Other workers at the plant, whose radiation exposures are more uncertain, were most likely not issued film badge dosimeters.

- Monitored workers reported that they sometimes left their badges behind so as not to record radiation exposures that might cause them to be reassigned to other work.

A major source of uncertainty in the exposure assessment of the betatron operators is the residual radiation from the betatron itself after it is de-energized. Our only sources of information are Schuetz (2007) and further communications with that author. Given the lack of written documentation and the fact that the reported radiation field could not be confirmed by our calculational model, it might be useful to repeat those measurements on one of the three Allis-Chalmers 25-MeV betatrons still operating in the United States. However, such measurements would not resolve the uncertainty regarding the exposures of other workers.

Chapter 3

REVIEW OF "APPENDIX BB: GENERAL STEEL INDUSTRIES"

We have reviewed Appendix BB to "Site Profiles for Atomic Weapons Employers that Worked Uranium and Thorium Metals" (Allen and Glover 2007), describing the General Steel Industries (GSI) site in Granite City, IL, and have identified a number of key issues, which are presented below. These issues are discussed in greater detail in Section 3.2, where we present further observations and comments.

3.1 Key Issues

Issue 1: Completeness of Data Sources

The authors of the Appendix[1] have not utilized some key information on the GSI Granite City site. They failed to note the presence of two betatrons, housed in two different buildings, as indicated in the reports by Murray and Uziel (1992), and Murray and Brown (1994), and as was brought out at the General Steel Industries Worker Outreach Meeting on August 21, 2006. Other observations in the Appendix, e.g., that no information was available about the roof of the betatron building, also indicate that the authors did not review the minutes of the outreach meetings, at which one former worker described the construction of the roofs of both buildings. Other examples of incomplete utilization of available data are presented in the context of other issues discussed below.

Issue 2: Period of Covered Employment

The Appendix states that the covered activities took place in 1953–1966. As we point out in Section 1.3 of the present review, it is plausible and claimant favorable to assume that this work began in 1952. We base this assumption on Atomic Energy Commission "Correspondence Reference Form," with a hand-corrected date of December 5, 1952, that has a summary titled: "Regarding ingots of uranium metal furnished to General Steel Castings Co. for betatron testing." Since the Army installed the first betatron in Granite City in January 1952, an event that was reported in a local newspaper, it seems likely that Mallinckrodt would have taken advantage of this facility at an early date.

Issue 3: Underestimate of Betatron Beam Intensity

The authors assume a betatron beam intensity of 100 R/min (without the aluminum beam-flattening compensator) at a distance of 3 ft from the target. They cite an interview with Jack Schuetz as the source of information that the betatron beam had a "design maximum" output of 100 R/min. This value is inconsistent with the material furnished by Schuetz (2007), which lists

[1] In Chapters 3 and 4 of this review, the term "Appendix" refers to "Site Profiles for Atomic Weapons Employers that Worked Uranium and Thorium Metals - Appendix BB: General Steel Industries" (Allen and Glover 2007).

outputs of up to 282 R/min. It is also inconsistent with the Allis-Chalmers acceptance criteria for the betatron tubes, which required a minimum output of 220 R/min at 25 MeV. Furthermore, a former worker recalled an intensity of 160 R/min with the compensator. He stated that this was a "middle-of-the-road" value which was sometimes exceeded. Schuetz agreed that this was a reasonable value for field operations.[2] Since the compensator attenuates the beam by about 35%, this value corresponds to an uncompensated intensity of 246 R/min. We therefore find that assigning an uncompensated intensity of 250 R/min at 3 ft is reasonable and claimant favorable. A more detailed discussion of this issue is presented in Section 3.2.7.

Issue 4: Underestimate of Stray Radiation from Betatron

The Appendix understates the stray radiation during the operation of the betatrons. Our calculations show higher dose rates in the control rooms than the 0.72 mrem/h cited in the Appendix. We calculated effective dose rates of 208 mrem/h on the roof, which was occasionally occupied by maintenance workers, 22 mrem/h in a restroom, and up to 51 mrem/h in other areas accessible to workers while the betatron was in operation. The Appendix ignores neutrons generated in the betatron target, which make a minor but potentially significant contribution to the effective doses.

Issue 5: Failure to Assess Other Radiography Sources

The authors acknowledge the use of other radiography sources, notably ^{60}Co, but dismiss the doses from these sources, stating that the doses from the betatron would be more limiting. As shown in our analysis, an 80-Ci ^{60}Co source produced a dose rate of up to 960 mrem/h on the roof of the New Betatron Building, and rates of 12–16 mrem/h in other locations outside the building. Furthermore, stray radiation from a 250-mCi ^{60}Co source that was used in a lightly shielded structure produced dose rates in accessible areas of 9–17 mrem/h. These rates are one to three orders of magnitude higher than the stray radiation cited in the Appendix.

Issue 6: Errors in Calculation of Dose Rates from Activated Steel

The authors limit their calculation of external exposure from activated steel to a single nuclide, ^{53}Fe, in the erroneous belief that this results in the highest dose rates. This assumption leads to understating the dose from external exposure to direct penetrating radiation from steel during the first 30 minutes after irradiation, because this nuclide, with a half-life of 8.51 min, undergoes significant decay during this time. Whereas the Appendix lists an integrated "dose" of 0.0529 mR during this period, our calculations of the integrated exposure following the irradiation of HY-80 steel (an alloy commonly produced at GSI), using the same time and distance as specified in the Appendix, yield a value of 0.098 mR. The higher value is from the contribution of longer-lived activation products of other elemental constituents of HY-80 steel.

[2] Jack Schuetz, former maintenance supervisor, Allis-Chalmers, personal communication with Robert Anigstein, SC&A, Inc., November 24, 2007.

Issue 7: Neglect of Skin Dose from Activated Steel

The Appendix ignores the skin dose from beta radiation from activated steel. Our analysis yielded doses of about 2 rads/y to bare skin from beta radiation from irradiated steel.

Issue 8: Underestimate of Exposure to Activated Betatron Apparatus

The Appendix assigns an initial exposure rate of the betatron operator of 15 mR/h from activation products in the betatron apparatus, based on a measurement reported by Schuetz (2007) at 6 ft (183 cm) from the betatron target. This exposure rate would apply only if the operator were located 6 ft from the betatron during the setup period. Such an assumption is inconsistent with the calculation of dose rates from the handling of irradiated steel or uranium, which assumes that the betatron operator spent one half of the setup time at a distance of 1 ft (30 cm) from the metal and the rest at 1 m. During the setup of thick steel castings and uranium slices that were positioned 6 ft from the target, the operator would have been between the metal and the betatron. Assuming, as we did, that his distance from the betatron target ranged uniformly from 3 to 6 ft (61–183 cm) would double his exposure rate.

Issue 9: Underestimate of Work Hours

The authors assume that the GSI employees worked an average of 2,400 h/y. This estimate is contrary to the recollection of the workers, who remember working 50–80 h/week. The consensus estimate was 65 h/week, or 3,250 h/y. Such a value is reasonable and claimant favorable, and should be adopted as a default value for dose reconstruction.

Issue 10: Mischaracterization of Steel Work Practices

According to the Appendix: "The overall estimate for Betatron x-ray of steel is: 30 minutes setup with no dose; one hour Betatron x-ray exposure due to skyshine at 0.72 mR/hr; and, 30 minutes takedown . . . ." Such a description is at variance with a report prepared by former GSI workers (2007) that indicates repeated exposures of the same casting, with 12–15 minutes between exposures. Since both the steel and the betatron were activated from previous exposures, there was no setup period with no dose. Furthermore, most exposures were of a few minutes' duration, which reduced the time in the control room, where the exposure rates were relatively low, and increased the number of times during the day that the operators were exposed to the steel and the betatron.

Issue 11: Errors in Calculating Dose Rates from Uranium

We have found errors in calculations that lead to a significant overstatement of the dose rates from uranium presented in the Appendix. The Appendix lists a dose of 21.7 mrem during the first 30 min following irradiation. Our model, which is based on the latest release of MCNPX, yields a dose of 1.4 mrem, using the same assumptions regarding the duration of the radiographic exposure, the duration of the worker's exposure, and his distances from the metal. Since the

dose rates in the Appendix are not scientifically correct, they should not be used as the basis of dose reconstructions of exposed workers.

Issue 12: Underestimate of Doses to Other Workers

The Appendix states that workers who did not work in the betatron building and did not routinely handle steel or uranium within 2 h following the x-ray exposure should be assigned a "dose" rate of 0.72 mR/h. As discussed under Issue 4, there were many situations in which these other workers could be exposed to much higher radiation levels.

Issue 13: Incorrect Calculation of Residual Surface Contamination and Resuspension

The Appendix uses the same methods of calculating surface contamination and resuspension as were used in the main report (Scherpelz 2006). In SC&A's review of that report, we pointed out that calculating surface contamination on the basis of a settling velocity of 5 µm AMAD aerosol particles ignores the sloughing off of much larger flakes of uranium oxide that fall directly onto the floor. We also showed that a resuspension factor of 10^{-6} m^{-1} understates the airborne concentrations by one or more orders of magnitude.

Issue 14: Use of Incorrect Units

The Appendix switches erratically between units of mrem and mR. The results of the skyshine calculations are stated as 0.72 mrem/h in Section BB.4.2, then as 0.72 mR/h in later sections. Dose rates are incorrectly stated in units of mR/h, which is an exposure rate. Uranium dose rates are stated in mrem, whereas our review of the output files from the Appendix BB analysis shows that the calculations were of air kerma, which is expressed in mrads. A notable misuse of units appears in the table in Section BB.4.5, where the dose to the skin from beta radiation is expressed as "R/yr." Beta radiation should not be expressed in roentgens, which only apply to photons.

3.2 Detailed Comments and Observations

The following comments and observations are keyed to specific sections of the Appendix. They supplement but, for the most part, do not duplicate the issues raised in the previous section.

3.2.1 Review Comments on Section BB.2: Site Description

The first sentence of Section BB.2 states: "General Steel Industries performed quality control work for the Atomic Energy Commission (AEC) from 1953-1966." Since the betatron was furnished by the Army and installed in January 1952, it is entirely likely that Mallinckrodt would have soon taken advantage of this nearby facility to radiograph their uranium metal products. This was a period of heightened activity at Mallinckrodt. According to Westbrook and Bloom (2007):

> In late 1950 or 1951, in order to increase production, Plant 6E was placed in six-day, three-shift operation as quickly as new crews could be trained . . . while Plant 7 was designed to operate on a six-day, three-shift schedule.

The next sentence in Section BB.2 states: "Utilizing a 25 MeV betatron machine, it performed x-rays on uranium ingots and betatron slices to detect metallurgical flaws for the Mallinckrodt Chemical Company." In fact, as discussed in Section 1.2 of this review, there were two betatrons at GSI, housed in two separate buildings. The "old" betatron was originally a 22-MeV machine that was later upgraded to 24 MeV. The "new" machine, transferred to the Granite City site from the GSI plant in Eddystone, PA in late 1963, was upgraded to 25 MeV. Furthermore, although some correspondence refers to ingots, the former GSI betatron operators described radiographing slices of ingots. Since the maximum penetration of the x rays generated by the 25-MeV betatron is about 4 inches (~10 cm) of uranium, it is highly unlikely that whole ingots were delivered for radiography. According to Elliot (1956), ". . . the maximum section of uranium which can be radiographed satisfactorily is about 3.5 to 4 inches."

3.2.2 Review Comments on Section BB.2.1: Site Activities

Section BB.2.1 states: "During the late 1950s and early 1960s, General Steel Industries was the custodian of a government-owned betatron used to x-ray uranium ingots for the AEC under purchase orders issued by Mallinckrodt Chemical Works." This statement is inconsistent with the assertion in the previous section that uranium work began in 1953. The authors then state that the purchase orders from 1958 to 1960 were issued to General Steel Castings Corporation and later to General Steel Industries "at the same address," which suggests that these were two different entities. In fact, the General Steel Castings Corporation formally changed its name to General Steel Industries on May 1, 1961, as explained in Section 1.1 of this review. This should be mentioned in the Appendix, since it could be relevant to determining the prior employment status of claimants.

Further on, Section BB.2.1 states: "The ingots were in the form of cylinders 18 to 20 inches in diameter, approximately 18 inches long, and weighing up to 3000 pounds." This statement is from Murray and Uziel (1992), who cite a 1988 letter from J. J. Fiore of DOE. Radiographing an ingot of that size is physically impossible. The reference is undoubtedly to ingots produced at Mallinckrodt, which then cut the betatron slices for radiographic examination at GSI. This statement should be corrected.

3.2.3 Review Comments on Section BB.2.2: Frequency of Uranium X-rays

In Section BB.2.2, the authors describe the use of purchase orders issued by Mallinckrodt to determine the time spent radiographing uranium at GSI. However, the purchase orders issued in 1958–1960 are incorrectly cited as requiring "that the work not to exceed a set cost." Further in this section, it is stated:

> These estimated hours are considered the maximum hours that could have been spent x-raying uranium. These are considered maximum because the purchase orders set these costs as a limit.

In fact, as we observe in Section 2.6.2, the monthly and annual costs are listed as estimates on the purchase orders dated 1958–1960. Only the 1961–1965 purchase orders list a "not to exceed" annual limit. Although we agree that the estimated costs are a reasonable basis for estimating the labor hours for radiographing the uranium, it is incorrect to characterize them as limits that could not be exceeded,

As the authors correctly state: "The first purchase order, covering the period March 1, 1958 to June 30, 1958 stipulated a monthly limit of $500." However, they then ignore this *estimate* (not limit) in calculating the time spent on uranium radiography. It is more reasonable and claimant favorable to assume that the $500 per month represented the costs during the period prior to this purchase order as well, and to assign 31.25 hours/month, or 375 h/y, as the time spent radiographing uranium prior to March 1, 1958.

The last paragraph discusses the work hours at the GSI plant, and concludes: ". . . it will be assumed that the operators worked 2400 hours per year . . . ." As discussed in Section 2.6 of this review, former GSI workers believe that 65 hours a week represented a reasonable estimate of their work hours, which is equivalent to 3,250 h/y. They also maintained that the pay rate was considerably less than the $3.80/h cited in the Appendix. The calculation of the hours corresponding to a hypothetical paycheck of $500 overlooks the deductions for income and social security taxes and other miscellaneous deductions that would have substantially lowered the hourly take-home pay. The last paragraph of Section BB.2.2 should be deleted and replaced with the higher work-hour estimate, which is based on worker testimony and is more claimant favorable.

3.2.4 Review Comments on Section BB.4: Occupation External Dose

As we state in Section 3.2.2, there is some understandable confusion regarding the configuration of the uranium metal handled at GSI. The collective opinion of the former betatron operators is that the uranium was in the shape of round disks that had been cut from cylindrical ingots. Allen and Glover model the external exposure as being from rectangular uranium ingots, which is not technically accurate but is claimant favorable.

3.2.5 Review Comments on Section BB.4.1: Exposure Time

The discussion of time spent on the various tasks involved in betatron radiography in Section BB.4.1 does not accurately describe the work practices at GSI. First, the authors assume that a casting was radiographed only once, and that 30 min was spent on setup and a longer time on takedown. In fact, large castings required hundreds of exposures. Each shot took 10–15 min to set up (Former GSI Workers 2007). The film was developed and read while further radiographs were in progress. The emphasis was on speed, efficiency, and throughput.

Takedown, as discussed in Section BB.4.1, applied to removing the casting after all exposures were made, and was therefore much less frequent than the setup between shots.

Uranium slices required fewer exposures. However, since at least some of the circular slices were larger than the largest film, they were radiographed one quadrant at a time, each slice thus requiring four exposures.

3.2.6 Review Comments on Section BB.4.2: Skyshine

The description of the skyshine calculation describes the betatron building as being "constructed with 10 foot thick wall[s]," but does not specify the material. Cottrell and Carrier (1990) describe the walls of the Old Betatron Building as being 10-ft (3.05-m) thick concrete. However, Murray and Brown (1994) and Bechtel (1994, Exhibit I, Figures I-2/5) label the walls of this building as "sand-filled concrete." Furthermore, Murray and Brown (1994, Figure 1) indicate that the wall separating the control room from the betatron in the Old Betatron Building was only 6 ft (183 cm) thick. Other walls in both betatron buildings, especially the wall between the control room and the rail tunnel or corridor leading into the betatron shooting area, were also substantially less than 10 ft thick.

The description of the walls as being "one story high" is too vague to allow confirmation of the model used by Allen and Glover to model skyshine. Although none of the available references specific to GSI indicate the height of the walls, the floor plans of the betatron buildings appear to conform to the design presented by Allis-Chalmers (1951), which also specifies 20 ft (6.1 m) as the height of the shield walls, and 35 ft (10.1 m) as the overall height of the inside of the betatron room. The portion of the wall above the shield wall is 12 inches (30 cm) thick. Furthermore, Bechtel (1994, Figure I-3) includes a floor plan of the second floor, which shows the shield walls extending to this elevation. The description in Section BB.4.2 states that the model was based on a drawing but does not specify the source of the drawing, or whether it was based on the Old or New Betatron Building. The description should include the actual dimensions and materials used in the model, as well as the specific sources of the information.

We recommend that the analysis be replaced by more detailed, realistic analyses of several exposure scenarios, or a single bounding analysis of the worst case scenario. A metal casting, which contributes to scattered radiation in locations and directions shielded from the primary beam, should be included in such an analysis. We also note that, according to our analysis, neutrons emitted by the betatron target contribute up to 50% to the effective dose rate. This source of radiation needs to be addressed in the Appendix.

3.2.7 Review Comments on Section BB.4.3: Steel Dose Rates

As stated in Section BB.4.3:

> In an interview with Jack Schuetz, who worked with Betatrons for Allis Chalmers, it was learned that the output of the machine was variable and that the 100 R/min was the design

maximum value, but that was only achievable in his laboratory when the compensator (or filter) [was] removed.

As stated in the discussion of Issue 3, this information is at variance with data furnished by Schuetz (2007) that are reproduced in Table 1 of the present review. This tabulation of laboratory test results on the last seven tubes purchased by GSI shows outputs that range from 260 R/min to 282 R/min at 25 MeV, with an average of 272 R/min.

The authors state that the most significant activation product generated during the betatron radiography of steel is ^{53}Fe and limit their analysis to that single radionuclide. Our own analysis indicates that significant activities of 42 nuclides (listed in Table 10) are produced during the irradiation of HY-80 steel, a common alloy produced at GSI. Immediately after a one-hour irradiation, ^{53}Fe accounts for about 86% of the total activity. However, during the second hour following irradiation, this nuclide accounts for only about 4% of the time-integrated activity. It is thus incorrect to assume that pure iron, which would produce a higher concentration of ^{53}Fe, would yield the highest radiological impact. Nuclides produced from other components of HY-80 steel listed in Table 6 that are prominent during the second hour and are strong gamma-emitters include ^{51}Cr, ^{56}Mn, ^{57}Ni, and ^{99}Mo. Restricting the analysis to ^{53}Fe also ignores the buildup of activation products during repeated exposures of the same piece of metal.

On a technical note, the correct characterization of the interaction of high-energy photons with matter is a *photonuclear* reaction rather than *photo-neutron*, as stated in the text. Although (γ,n) is frequently the first reaction, (γ,α) and (γ,p) reactions are also possible, as well as photofission of the heavier elements. More important, subsequent activation of other nuclei by the (n,γ) reaction creates nuclides that would not be predicted if (γ,n) were the only reaction.

Another scientific error is found in the statement: "[^{53}Fe] decays by electron capture. This results in the emission of two 511 keV annihilation photons." In fact, about 98% of the decays are by positron (β^+) emission, the remainder being by electron capture. Only positrons can generate annihilation photons, which result from the interaction of a positron with an electron.

The authors report integrated doses from the steel during the first 30 min following a 60-min irradiation as being 0.0934 mR at 1 ft (30.48 cm) and 0.0125 mR at 1 m, for an average exposure of 0.0529 mR. Using the same time periods, we obtain exposures of 0.165 and 0.0312 mR, respectively, at these two distances. The differences are partly due to the authors' neglecting nuclides with half-lives longer than ^{53}Fe. It is not clear if the authors are referring to effective doses, which should be expressed in mrem, or exposures, which are stated in mR. The two quantities seem to be used interchangeably, which is confusing and scientifically incorrect.

The longer-lived nuclides would build up over the course of repeated irradiations of the same piece of steel, as discussed in Section 2.2.4. The scenario described in the Appendix, of a one-hour irradiation preceded and followed by 30 min each of setup and takedown, would be repeated about four times during an 8-hour shift. The average 30-min exposure of 0.0529 mR would thus yield a daily exposure of about 0.21 mR. This can be contrasted to the exposure of

0.65 mR/shift of the betatron operator, which we calculated for the purpose of this comparison by taking the average of the 1-ft and 1-m exposures listed in Table 7 for the scenario yielding the maximum exposure. The layout man, who spends more time in proximity to the steel, would experience an exposure of about 1.5 mR/shift, calculated by averaging the exposures at the two distances from the maximum exposure scenario for this worker.

In conclusion, the authors significantly underestimated the exposures to the activated steel.

On a technical note, the authors' conclusion that the radiation is due to the activation of the aluminum compensator is not supported by our MCNPX analysis. The small buildup of ^{28}Al would produce exposures of less than 1 µR/h, which is indiscernible over background. Furthermore, since the compensator was removed during the calibration of the betatron beam, it would have been obvious to Schuetz if the aluminum cone were the source of the radiation, which he firmly stated was not the case. Finally, the betatron manual (Allis-Chalmers 1951) warns of the activation of the doughnut, not the compensator.

The authors conclude that the average exposure of the betatron operator was 0.792 mR/h while x-raying steel, which is equivalent to 6.3 mR during an 8-hour shift. Our calculations, presented in Table 16, are based on a composite of radiographic exposures of long (60-min) and short (3-min) duration; they yield an exposure of 33.5 mR/shift, more than five times greater than the value derived from the Appendix. The major difference is the exposure duration and distance from the betatron doughnut. We also calculated a neutron dose of 1.8 mrem/shift which, as stated earlier, is not addressed by the Appendix.

3.2.8 Review Comments on Section BB.4.4: Uranium Dose Rates

The discussion in Section BB.4.4 is not sufficient to explain the calculation of dose rates from the products of photofission in uranium. We learned from one of the authors that they used MCNPX to calculate the photofission density as a function of position in the uranium ingot irradiated with the beam of x-rays from the betatron.[3] They then used the photon spectrum of uranium fission products from other data sources to calculate a photon source distribution in the uranium, and used MCNP again to calculate the dose rates from this distribution. According to the Appendix, the average of the dose rates at 1 ft (30.48 cm) and 1 m from the uranium, integrated over the first 30 min following irradiation, yielded a dose reported as 21.7 mrem. However, since the MCNPX output file which we examined incorporated the air kerma to unit fluence conversion coefficients, the correct units are mrads. According to the Appendix, this dose was repeated once every 2 h during the radiography of uranium, which would yield a dose of 86.8 mrads during an 8-hour shift.

Our calculations, which utilized the delayed gamma/delayed neutron capabilities of MCNPX 2.6e, yield an effective dose of 6.8 mrem/shift from the fission/activation products in irradiated uranium, including the photon radiation from aged natural uranium. As discussed in

[3] Sam Glover, NIOSH/OCAS, personal communication with Robert Anigstein, SC&A, Inc., October 2007.

Section 2.2.5, this dose was based on the operator's being exposed to the uranium slice for 15 min after each of four cumulative one-hour exposures, scaled up to an 8-hour shift, and was averaged over distances of 1 ft and 1m.

The differences between the two exposure scenarios do not allow a direct comparison with the result in Section BB.4.4. In order to facilitate such a comparison, we used our MCNPX results to replicate the exposure scenario in the Appendix. We calculated the effective dose during the period 1 s–30 min following a single one-hour exposure (starting at zero time after exposure would include the contribution from the primary beam, producing unrealistic results), averaged over the two distances from the uranium metal. Our calculation yielded an effective dose of 1.4 mrem, approximately 16 times less than the Section BB.4.4 result. Upon reviewing the NIOSH/OCAS calculations, including the MCNPX output files and the Excel spreadsheets used to evaluate the MCNPX results,[3] we found an error in their calculation of the photofission density. The atom density had been specified as 1 instead of the correct value of 0.048 atoms/(barn·cm), resulting in an overestimate of the fission density by a factor of 21. This error partially explains the differences in the results.

Other differences in the models include the shape and size of the primary beam and the assumptions regarding the beam intensity, discussed in Section 3.2.7.

We were not able to verify the calculations of doses at various times after the irradiation of the uranium slab. However, we are puzzled that Allen and Glover would use times of 0, 2 h, 9 h, and 23 h post-irradiation, since their aim was to calculate the dose during the first 30 min. A curve fit over such a wide range of delay times would not be expected to yield good results for such a short initial period. Furthermore, we question the time-dependence of the dose rates expressed by the two equations in Section BB.4.4. These equations indicate that the induced activities undergo exponential decay with half-lives of over one hour. For example, if we evaluate $D_{30}(t)$ (dose rate at 30 cm) and $D_{100}(t)$ (dose rate at 100 cm), at t = 1 min and t = 10 min, we find that both dose rates decrease ~9% during this time. As shown in Figure 21, however, our MCNPX model shows an almost 10-fold reduction in activity during this time. We believe that the faster decay rate more accurately represents the actual behavior of the irradiated uranium.

Although the authors used an ingenious approach to calculate dose rates from photon-induced fission in uranium, the complexity of their method and errors in its application produced results that are not scientifically correct.

The discussion of the non-penetrating dose to the skin incorrectly states the results in units of R/y. A roentgen is a unit of exposure, which is defined as the formation of a given electrical charge in a mass of air. These units should not be used to express doses to the skin from beta radiation.

3.2.9 Review Comments on Section BB.4.5: External Dose Summary

Section BB.4.5 displays a table described as summarizing the external photon dose to betatron operators. However, the table also lists doses to the skin, not further specified, and to the skin of the hands and forearms. The heading in the table states the units as R/y (see discussion of units in Sections 3.2.7 and 3.2.8, above).

We first discuss the external doses from photons. According to the table, these "doses" for the years 1953–1966 range from 6.3 R/y in 1961 to 1.025 R/y in 1966.[4] These values are significantly lower than the exposures which we derived in Section 2.6.1, which are 12.9 R/y for 1952–1963 and 13.6 R/y for 1964–1966. The neutron effective doses are 470 mrem/y and 735 mrem/y, respectively, for these two time periods. Since we calculated a slightly higher exposure per shift for the radiography of steel than of uranium, the frequency of uranium radiography does not affect the maximum annual exposure, which we assumed to be that of an operator on the evening or night shift, when no uranium radiography was supposed to take place.

The discussion of doses to the skin is hard to understand. According to Section BB.4.4:

> Using the methodology in section 6.3 of this Technical Basis Document [Scherpelz 2006], the non-penetrating dose to the skin of the forearms and hands can be calculated to be 5.75 R/yr. The non-penetrating dose to the skin of the rest of the body can be calculated to be 0.52 R/yr.

There is no explanation of how the values of dose rates to the skin of various workers listed by Scherpelz (2006, Table 6.3) are used to derive the skin doses cited above. Furthermore, the skin doses cited in Section BB.4.4 seem to bear no relationship to the doses listed in the table in Section BB.4.5. The doses to the skin on the hands and forearms for the years 1953–1966 range from 22.3 to 0.37 "R/yr" (presumably rads), while those to the rest of the skin range from 2.0 to 0.034. The doses in the table appear to be based on the number of hours of uranium radiography per year but are otherwise not explicable.

The doses to the skin of the hands and forearms, which we calculated using MCNP and the actual uranium configuration at GSI, that are listed in Table 21, are 26%–34% higher than those listed in Section BB.4.5 for the years 1953–1962, while our doses to the rest of the skin are 27%–48% higher. This is primarily due to our including the enhanced concentration of ^{237}Th and ^{234m}Pa on the peripheries of the uranium slices. The doses to the skin of the hands and forearms for 1963–1966 are 60%–500% higher than those in Appendix BB, while the doses to the rest of the skin are 4–30 times higher. The reason is that the authors omit the contribution of the beta-emitting nuclides in activated steel, which are the major contributors to the skin doses in later years, when fewer uranium slices were radiographed. The largest contributor to the skin dose

[4] The radiation field from the activation of the betatron apparatus is reported by Schuetz (2007) in mR/h. The skyshine and the radiation from the induced uranium were stated in mrem, while values for steel were expressed in mR. It is not clear if the values in different units were simply added together.

from activated steel is ^{53}Fe, which emits positrons with end-point energies of 2.3–2.7 MeV. The authors base the dose from external exposure to direct penetrating radiation on this nuclide, but fail to consider it as a source of non-penetrating radiation to the skin.

No doses from either penetrating or non-penetrating radiation are assigned for 1952. As stated earlier, it is both plausible and claimant favorable to assume that uranium radiography began in 1952.

The Appendix states that the external doses to betatron operators should be assigned only "to radiographers and anyone else that was routinely handling the steel or uranium within 2 hours following the x-ray exposure." Other employees are to be assigned a "dose" rate of 0.72 mR/h or 1.73 R/y.

As discussed in Section 2.4.3, there are several scenarios which could lead to radiation exposures of other workers that were greater than 0.72 mR/h. As displayed in Table 2, the exposure rates in several locations outside the New Betatron Building ranged from 24 to 209 mR/h when a casting was radiographed on the railroad tracks. The average daily exposure rates should take into account the duty cycle of the betatron which we estimate to be 41%. For example, if a worker were to spend one hour per shift in the restroom (as some workers were reported to do in order to evade their duties), he would receive an exposure of about 9.8 mR/shift. Even if such a worker worked only the normal 250 shifts/y, he would have an exposure of 2.46 R/y from this scenario alone. If he worked 406 shifts, as was assumed for the betatron operators, his annual exposure would be about 4 R. We also note that the exposure rate in the break area just outside the shooting area of the New Betatron Building was even higher than in the restroom, and the rate at one location ("Outside 2") outside the building was over twice as high, so even if the worker spent less than one hour per shift in the restroom, he might have been in other areas with elevated exposure rates.

Other workers that could have experienced higher exposures than assigned by the Appendix are those that maintained the ventilation equipment on the roofs of the betatron buildings and other buildings near the New Betatron Building. Their exposures would have been particularly high when the 80-Ci ^{60}Co source was used to perform radiography in the New Betatron Building. Another group of workers with potentially elevated exposures were those in the No. 6 Building who worked with or near the 250-mCi ^{60}Co source. Although we do not have any information on the frequency of these radiographs nor of the whereabouts of the radiographers during the exposures, their potential exposures could be higher than those of the betatron operators.

Finally, the radiography performed outdoors by the St. Louis Testing Laboratory subjected nearby GSI workers to exposures of up to 2 mR/h, assuming that the safety precautions were properly administered and enforced.

Except for the radiography with radioactive sources and the maintenance of the ventilation equipment on the roof of the Old Betatron Building, there were fewer opportunities for exposure

to stray radiation during the years 1952–1963, before the installation of the "new" betatron at the Granite City site.

3.2.10 Review Comments on Section BB.5: Occupation Internal Dose

Our analyses of intakes of activation and fission products produced by the radiography of steel and uranium, discussed in Section 2.3, indicate that the internal exposure from these sources would be negligible. We therefore concur with the conclusions regarding such exposures stated in Section BB.5. We also concur with the assignment of inhaled intakes of uranium during the handling of uranium metal by the betatron operators, except that, as stated earlier, we believe that the covered period should be extended to the beginning of 1952, and that the hours from 1952 to June 30, 1958, should be increased, as discussed in Section 3.2.3 of this review.

We note some erroneous citations of data in the main report. Section BB.5.2 states:

> Table 7.5 of this Technical Basis Document lists air concentrations for uranium machining operations. Of the three grinding operations, centerless grinding had the highest results of 4000 to 5000 dpm/m^3.

In fact, the value listed in Table 7.5 is 5000–6000 dpm/m^3. We also note that the reference in Section BB.5.3 to an air concentration of 198 dpm/m^3 is incorrectly attributed to Table 7.8 of the main report—the correct reference is Table 7.6.

We do not agree with the methodology used to calculate the airborne concentrations of uranium in the betatron building during activities not involving uranium radiography. In our review of the main report (Scherpelz 2006), SC&A took issue with the use of the settling velocity of 5 µm AMAD aerosols to determine surface contamination levels, since that approach neglected the sloughing off of large flakes of uranium oxide that fall directly onto the floor and that would make a significant contribution to the uranium contamination. The same concerns apply to the Appendix. The observation in Section BB.5.3 that the surface contamination level of 1,170 dpm/100 cm^2 is ". . . reasonably close to the maximum value of 540 dpm/100 cm^2 measured in a 1989 survey" does not support the calculated value. The GSI facility in Granite City continued to operate for another 7 years after the cessation of uranium handling activities. It would be expected that normal housekeeping activities during this time, as well as additional attrition between 1973 and 1989, when the site was controlled by the Granite City Steel Division of National Steel Corporation, would have caused more than a 2-fold reduction in the surface contamination levels.

An example of such housekeeping activities is the contaminated vacuum cleaner that was present in the Old Betatron Building at the time of the 1989 ORNL survey (Cottrell and Carrier 1990). According to Wallo (1989), this vacuum cleaner was used in cleaning the betatron building. Uranium residues were found in the vacuum cleaner by the survey team. Since the vacuum cleaner was most likely emptied periodically during the period of operations, considerable amounts of uranium residue could have been removed during this time. We therefore assume

that significantly more uranium residue was initially present on the floor than estimated by the authors of the Appendix.

As discussed in the SC&A review of the main report, we disagree with the use of a resuspension factor of 10^{-6} m^{-1} employed in the Appendix. The resuspension in the shooting areas of the betatron building, with both pedestrian and vehicular traffic, was most likely higher by one or more orders of magnitude.

Because the uranium slices that were brought into the betatron building were most likely transported through other buildings on their way into and out of the GSI facility, workers other than the betatron operators could have experienced intakes of uranium dust. It would be reasonable and claimant favorable to assign the same intakes that were experienced by the operators to any workers that might have handled or been near the uranium metal.

3.2.11 Review Comments on Section BB.6: Residual Contamination

The same comments that were made in Section 3.2.10, above, regarding surface contamination and resuspension during the intervals between uranium handling operations, apply to the dose assessments during the residual contamination period discussed in Section BB.6.

Chapter 4

RESPONSES TO COMMENTS ON APPENDIX BB

NIOSH/OCAS received two sets of comments on Appendix BB from advocates for claimants who were former GSI employees, or their survivors. The Board asked SC&A to respond to these comments. We limited our responses to comments that have a direct bearing on reconstruction of doses to GSI employees. We base our responses on our analyses, findings, and observations in Chapters 1–3 of this review. Since the claimant advocates inserted their comments into the text of the Appendix, we keyed our responses to the individual sections of the Appendix in which their comments appear.

4.1 Comments by Advocate #1

We begin by responding to comments prepared by a team of advocates whom we will refer to as Advocate #1 ("Comment and Reply Re: Appendix BB . . . ." 2007).

4.1.1 Advocate #1 Comments on Section BB.1: Introduction

The advocates call attention to a 1956 report of the Los Alamos National Laboratory (Tenney 1956) that describes inter alia the use of a 22-MeV Allis-Chalmers betatron at LANL for the radiography of metal objects, including uranium. We examined the redacted version of this report; however, we found that the relevant information in this report was largely supplanted by information from other sources. These included interviews with former GSI employees and with Jack Schuetz, a former employee of Allis-Chalmers, as well as literature furnished by Schuetz (2007) and by the advocates. Our use of the information in the LANL report was limited to the reference by Elliot (1956) to the maximum thickness of uranium—4 inches (~10 cm)—that could be radiographed using this instrument. This information corroborated our own estimate, based on information from other sources, and was used in establishing the limiting thickness of the uranium slices which we modeled in our radiological assessment of GSI workers. Allen and Glover (2007) used a 20-in (51-cm) thick uranium block to calculate dose rates from the irradiated uranium. Since a negligible fraction of the primary x-ray beam would have penetrated more than 4 inches of uranium, the additional thickness has no effect on the results.

4.1.2 Advocate #1 Comments on Section BB.2: Site Description

The advocates call attention to the two betatrons that were in use at the GSI facility in Granite City in 1964–1966 (1966 marks the end of AEC-related activities at GSI), as well as to radioactive sources and an x-ray machine used for radiography. They also call attention to the configuration of the New Betatron Building and its location with respect to other structures, notably the No. 10 Finishing Building. We agree that both betatron buildings need to be included in the analysis because of the differences in their locations and configurations. As we mention on page 58 et seq., because of the isolated location of the Old Betatron Building, there were fewer opportunities for exposure to stray radiation prior to the installation of the “new”

betatron at the end of 1963. However, because the two buildings are about 400 ft apart, the stray radiation from the two betatrons is not additive. The highest dose rate outside one building would have been at a location so far away from the other building that the contribution from the second betatron would have been negligible.

We also agree that some of the radioactive sources need to be included in the site description and addressed by the analysis. As shown in Tables 2–5 of our review, there were some locations where the potential doses from ^{60}Co radiography sources were higher than from stray radiation from a betatron.

The ^{192}Ir sources, however, were brought on site by the St. Louis Testing Laboratory and were not handled by GSI employees. Any incidental exposures they may have received would have been subsumed by the exposures from ^{60}Co sources also used by St. Louis Testing, which established a 2-mR/h exclusion zone around their sources. The 250 kVp x-ray machine was used inside the betatron buildings. The shielding in those buildings would have rendered any exposures from this machine completely insignificant. Therefore, these sources, while worthy of being mentioned, do not need to be explicitly included in the analysis.

4.1.3 Advocate #1 Comments on Section BB.2.1: Site Activities

The advocates commented on the years of the AEC-related activities at GSI. Despite some inconsistencies in the discussion in the text, the radiation exposures listed in the Appendix spanned the period from 1953 to mid-1966, the contract period cited by the advocates. However, we found that the activities may have started in 1952 and therefore believe that the covered period should be 1952–1966.

They also commented on the sizes and shapes of the uranium metal objects radiographed at GSI. Since slices of dingots were the objects primarily radiographed at GSI, the relevant dimensions are the diameter and thickness of this slice. If the dingot was 18 inches long and weighed between 3,000 and 3,300 lb, the diameter would be about 18 inches. This size is confirmed by Weakly (1963). Other, thinner ingots were also produced at Mallinckrodt. Thus, the size of the uranium objects varied. The analysis of dose rates from irradiated uranium reported in the Appendix was based on a rectangular block 20 × 18 × 18 inches thick. Since this was larger than the actual objects radiographed at GSI, the results of such an analysis would be limiting, notwithstanding other factors that affected the analysis.

4.1.4 Advocate #1 Comments on Section BB.2.2: Frequency of Uranium X-rays

The advocates commented on the incomplete records of Mallinckrodt purchase orders and other documents related to the 1953–1958 period. This is a common circumstance at DOE and AWE facilities, and is a frequent challenge to the administration of the Energy Employees Occupational Illness Compensation Program Act (EEOICPA). With reference to the Mallinckrodt memo cited by the advocates, dated February 20, 1958, which requests payment of General Steel Castings Invoice #M216, we note that the request was reissued on July 10, 1958,

in the amount of $48. Based on the $16/h rate in effect at the time, this invoice represents 3 hours of work by General Steel. This work appears to have been performed at a time that there was no purchase order in place, and does not represent an "add-on" to the total, as claimed in the comments.

They also call attention to the alloyed dingots produced by Mallinckrodt. In most cases, the term "alloyed" refers to a metal that has several deliberately blended components, such as the numerous alloys of steel. In the present instance, however, the "alloyed" dingots are actually purer than ordinary uranium ingots. According to Weakly (1963), the dingots had less than 30 ppm carbon, compared to 400–500 ppm in ordinary uranium ingots. These dingots did contain trace amounts of aluminum and copper, which are not listed as constituents of ordinary uranium ingots.

Leaders et al. (1953) report on small-scale experimental castings of various uranium alloys. They also mention three zirconium alloy ingots being radiographed with a betatron, presumably at GSI. These uranium alloy ingots would have no significant effect on the radiation exposures of GSI workers. First, they were small objects, which would involve shorter exposures. Second, they were few in number; the fact that special mention was made of three ingots being radiographed suggests that this was not a routine procedure. Third, the external exposure to direct penetrating radiation from radiographed uranium is dominated by uranium fission products. The presence of lighter metals would tend to reduce concentration of fission products and thereby reduce the radiation doses.

Other comments on this section are on the frequency of uranium x rays. We agree that there is no documentation regarding the frequency of radiographic testing of uranium prior to March 1958. However, given the fairly constant estimates of monthly costs during 1958–1962, projecting the estimate for the March 1–June 30, 1958 period backward to 1952 is reasonable. The fact that General Steel submitted a separate invoice for $48 for a period not covered by a purchase order would not indicate a high level of activity. We do not agree with the hypothesis that 100% of the uranium produced at Mallinckrodt was radiographed at GSI. The uranium slices, that were up to 4 inches thick, were samples cut from the 18-inch-long dingots. These slices could not be used in the production of uranium fuel rods, but would have to be remelted and cast into billets or ingots. Consequently, the uranium radiography was in fact a destructive process, and could only be applied to a representative sample of the uranium produced at Mallinckrodt.

Our analysis showed that the external exposure to direct penetrating radiation associated with the radiography of uranium was slightly lower than that associated with the radiography of steel. This was because uranium required longer exposures, so betatron operators spent more time in the control room, where the exposure rates were relatively low. During the radiography of steel castings, they spent more time exposed to the residually radioactive betatron apparatus and to the activated steel. Therefore, increasing the frequency of uranium x rays would not increase the dose from external exposure to direct penetrating radiation. There would, however, be an increase to the dose to the skin of the betatron operators, since the dose rates from beta radiation

from uranium are higher than those from radiographed steel (see further discussion at the end of this section).

Another comment concerns the repeated exposures of the same piece of uranium metal. The need for four exposures was due to the diameter of the slice, which was greater than the largest x-ray film, not to the thickness. (Repeated exposures do not increase the ability of the betatron x-ray beam to penetrate the metal, which, as stated earlier, is limited to a thickness of about 4 inches). Our analysis accounted for the partial overlap of four exposures by modeling a simplified and claimant-favorable scenario in which the entire slice was subjected to four successive exposures. We can estimate the magnitude of this effect by considering two different scenarios. In one, the betatron operator is exposed for 15 min to a uranium slice that had been radiographed for one hour. This happens four times in succession, with a new slice being radiographed each time. In the second scenario, the same slice is radiographed four times—the operator handles the uranium slice after a one-hour exposure, then, 1¼ h later, he handles it again after a second one-hour exposure, then later after a third, and finally after a fourth. In this second scenario, his total dose is 15% higher than in the first scenario. Thus, accounting for the multiple exposures has a small effect on the dose, which should however be addressed in the interest of a comprehensive analysis.

Another comment addresses the different steel alloys produced and radiographed at GSI. The most common alloy was carbon steel, such as SAE 1020, which is 99% iron. There is insufficient information to determine the actual mix of alloys that were produced and radiographed at GSI; furthermore, the mix most likely varied from year to year, depending on orders from their customers. Even if such information were available and we analyzed each individual alloy, we do not believe that there would be any significant change in the estimated exposures of the workers.

We agree that, from a purely technical standpoint, calculating dose rates from irradiated steel on the basis of pure iron can underestimate the time-integrated dose following the radiographic exposure, as discussed in Section 3.2.7. Our analysis addressed two alloys—HY-80 and high-manganese steel—which, because of the concentrations and variety of constituents, we believe to be bounding examples of GSI products. Subsequent to performing our analyses, we learned that high-manganese steel was used for jaws for ore crushers which were not routinely radiographed. As shown in Table 16, the combined exposures of the 25-MeV betatron operators to activated HY-80 steel from short and long shots were about 1 mR/shift, compared to their average total exposure of 33.5 mR/shift. Although our calculated exposure rate is much higher than the rate estimated in the Appendix (see Issue 6 in Chapter 3), exposure to the metal represents only about 3% of the total exposure. The annual dose to the skin of the hands and forearms from the activated steel, shown in Table 21, is higher, but is still less than 2 rads/y. This needs to be compared to an annual external exposure to direct penetrating radiation of 12–14 R/y. Thus, the inclusion of the various alloys in the exposure assessments is unlikely to substantially change the total radiation exposures of GSI workers.

4.1.5 Advocate #1 Comments on Section BB.4: Occupation External Dose

The advocates repeated their earlier critique of the size and shape of the uranium ingots. As discussed in Section 4.1.3, a more detailed description of the sizes and shapes of the uranium objects would not lead to a more claimant-favorable analysis.

4.1.6 Advocate #1 Comments on Section BB.4.1: Exposure Time

The advocates asked for details on the size, shape, and chemical composition of the uranium metal radiographed at GSI. While these are legitimate questions, the answers would not substantially affect the assessment of radiation exposures related to the uranium radiography at GSI. As we stated in Section 4.1.4, the exact chemical composition of the uranium, which might contain trace quantities of other elements, would have no significant effect on the exposure to the irradiated metal, which is primarily due to uranium fission products.

4.1.7 Advocate #1 Comments on Section BB.4.2: Skyshine

The advocates urged that the actual configuration of the betatron buildings at GSI be used in the calculations of doses from stray radiation during the operation of the betatrons. We agree that the skyshine calculations should be based on the actual configurations of the betatron buildings and surrounding areas that were accessible to workers. A number of their other comments on this section are addressed in Section 3.2.6 of this review.

4.1.8 Advocate #1 Comments on Section BB.4.3: Steel Dose Rates

The advocates pointed out the operating characteristics of the two betatrons. We note that their description of the "new" betatron included an editorial error: they stated that it operated "up to 250 MeV"—we believe they meant "250 R/min." The maximum energy of the electron beam was 25 MeV, while the maximum beam intensity in a field installation such as GSI was about 250 R/min. They also observe that the description of the MCNPX results ". . . is too general and very misleading." Although we do not necessarily agree with this characterization, we agree that a more detailed description of the analysis should be presented in the Appendix, and that a discussion of steel alloys should be included. However, as noted on page 64, our own analyses indicate that the radiation from irradiated steel makes a minor contribution to the total doses.

4.1.9 Advocate #1 Comments on Section BB.4.4: Uranium Dose Rates

The advocates observed that "This section needs to be discussed in much greater detail. A review by SC&A and other experts would appear fitting." Our review of Section BB.4.4 is found in Sections 2.2.5, 2.2.7, and 3.2.8.

4.1.10 Advocate #1 Comments on Section BB.4.5: External Dose Summary

The advocates observed ". . . that the Betatron Buildings were like 'Grand Central Station'." We agree that workers performing other duties had ready access to locations in or near the New Betatron Building and could have been exposed to significant levels of stray radiation from the operation of the betatron. We do not believe that this was the case with the Old Betatron Building, since it was located well away from the main part of the plant, was surrounded by a fence that limited access to the building, and carried placards warning individuals to stay away from the building. We note that other tradesmen, such as electricians, might have worked in the Old Betatron Building in areas such as the capacitor banks on the second floor. These areas were further from the shooting area than was the control room, so the exposures of these workers would be bounded by the exposures of the betatron operators.

4.1.11 Advocate #1 Comments on Section BB.5.3:Summary of Intakes of Radioactive Material

The advocates stated: "Some residual uranium contamination may have been present that could become airborne and cause additional intakes." Allen and Glover (2007) modeled the resuspension of uranium contamination, both during the periods in between the times uranium was being handled in the betatron building, and after the cessation of AEC-related activities—the so-called "residual period." As discussed in Section 3.2.10, we find that the intakes during these periods were underestimated.

4.1.12 Advocate #1 Comments on Section BB.6: Residual Contamination

The advocates observe that "Coming into an industrial site about 30 years after the contract period ended and trying to recreate the past is impossible." Although Allen and Glover (2007) did not directly use the results of the ORNL surveys of the Old Betatron Building (Cottrell and Carrier 1990) to estimate the contamination levels during the residual period—the time after the cessation of AEC-related activities—they did cite these results as a validation of their model. We have taken issue with their model, as discussed in Section 3.2.10, and of their use of the survey results.

4.2 Comments by Advocate #2

We next respond to comments prepared by Advocate #2, and submitted to Larry Elliot, Director of OCAS, in July 2007 ("Critique to NIOSH of Appendix BB . . . ." 2007).

4.2.1 Advocate #2 Comments on Section BB.2: Site Description

The advocate presents a detailed comment on information on the GSI site that is not cited in the Appendix. We have already commented on most of these issues in our responses to comments from Advocate #1 and/or have addressed them explicitly in our review of the Appendix in Chapter 3 of the present report. The issue of the two betatrons is discussed in Section 4.1.2. The

issue of the composition of the uranium objects is discussed in Section 4.1.4. The advocate is correct in stating that "The overall radiation exposure by the Betatron and from activation products in the industrial/military castings dwarfed the total exposure of the workforce from MCW-UR uranium." However, he errs in stating ". . . the omission of these data is most serious" since the radiation exposures of the betatron operators from the radiography of steel were addressed in the Appendix—the authors assumed that the betatron was used for radiographing steel whenever it was not used for uranium. His comment about ^{60}Co sources is addressed in Section 4.1.2.

4.2.2 Advocate #2 Comments on Section BB.2.1: Site Activities

The advocate correctly observes that the Mallinckrodt purchase orders for uranium radiography at GSI, starting with March 1, 1958, were most likely for material produced at Weldon Spring, since all regular operations at the MCW St. Louis downtown site ceased in 1958. There is therefore some question whether the volume of work, based on purchase orders for the radiography of uranium metal produced at Weldon Spring, is representative of the years 1952–1957, when the metal was produced at the St. Louis downtown location. A reasonable guess is that the volume would have been smaller, since the uranium receipts at Weldon Spring ranged from 8 to 19 Gg (8,000–19,000 metric tons) during the 1958–1966 period (Little and McDowell-Boyer 2005, Table 2-7). Westbrook and Bloom (2007) do not indicate the actual production rates at MCW during 1952–1957. However, according to these authors, processing, receipts, and production during earlier years are stated in hundreds of tons annually, compared to thousands of tons at Weldon Spring. As we observed in Section 4.1.4, the volume of uranium radiography has little impact on the annual doses to GSI workers.

The advocate describes the various possible types of uranium objects that might have been radiographed at GSI. Again, as discussed in Section 4.1.4, the detailed descriptions of these objects would not significantly affect the results of the analysis.

We could not substantiate the advocate's claims about enriched uranium being processed at MCW or Weldon Spring. According to Westbrook and Bloom (2007): "In 1955, very low enrichment uranium [1% enrichment] (probably only a small amount) as UF_4 was processed at Plant 7, and in August 1956, about 5.5 kg of 20%-enriched uranium was processed, presumably in Plant 7." These authors further state:

> Also, . . . [Goldsmith et al.] (1981) stated that in . . . [their] pre-survey review of the site, including interviews with Mallinckrodt old-timers, no indications were found that there had ever been any process conducted under AEC contracts involving the purification or working of Th-232, highly enriched uranium, fission products, or byproduct material. Thus it is assumed that no recycled uranium or any of the materials listed by . . . [Goldsmith et al.] (1981) was handled at Mallinckrodt's St. Louis facilities as part of AEC work.

It is thus unlikely that any enriched uranium had been cast into ingots at MCW and radiographed at GSI. Furthermore, according to Little and McDowell-Boyer (2005), Weldon Spring received

about 442 tonnes of "slightly enriched" uranium (defined as ≤ 1% ^{235}U) in 1965, the peak year for receipts of this material, which is a small fraction of the over 11,000 tonnes of natural uranium received the same year. We therefore conclude that little if any of even low-enriched uranium was radiographed at GSI.

4.2.3 Advocate #2 Comments on Section BB.2.2: Frequency of Uranium X-rays

The advocate's comments deal with the missing purchase orders for the years prior to 1958, as well as with the other types of radiography performed at GSI during the covered period. We discuss these topics in Section 4.1.4. He objects to the description of the purchase orders as "limits and not estimates." He is correct with respect to purchase orders issued prior to 1961. As we observed in Section 3.2.3, these purchase orders did in fact list the costs as "estimates." Thus, these estimates could have been exceeded upon request from the Mallinckrodt officials authorized to order this work. However, the amounts listed in the purchase orders from July 1961 onward were specified as "not to exceed." Thus, these were limits. We disagree with the advocate's contention that the limits may have been changed during the period covered by a given purchase order. The purchase orders in the NIOSH/OCAS file appear to be complete for the period from March 1958 to 1966. They cover the entire period of March 1,1958– June 30, 1966, with no gaps. They also include such non-monetary changes as the authorization to use different sizes of x-ray film and the inclusion of additional personnel authorized to approve the work orders, and even an order for a piston rod fabricated by GSI. Thus, since there are no records of changes to the annual estimates or limits during any period covered by these purchase orders, we doubt that any such changes were made.

He cites the fact that each uranium slice required several exposures as proof that the time devoted to uranium radiography in any given year was longer than estimated by Allen and Glover. Mallinckrodt paid GSI by the hour, not by the piece, so the hours spent radiographing uranium were independent of the duration of any given exposure. Assuming longer exposures would simply imply that fewer uranium slices could be radiographed during the time period covered by a given purchase order.

The advocate further questioned if the purchase order limits were actually adhered to. Each purchase order, whether for an estimated amount or a fixed limit, was signed by an authorized representative of the U.S. Atomic Energy Commission. It is implausible that GSI and Mallinckrodt could casually flaunt the terms of the purchase orders and expect to be reimbursed for their costs: GSI by Mallinckrodt and Mallinckrodt by the federal government.

The advocate raises several issues related to radiography of steel, which we discuss in Section 4.1.4.

4.2.4 Advocate #2 Comments on Section BB.4: Occupation External Dose

The advocate observes that Landauer has film badge dosimetry data on some former GSI employees for part of the covered period. We agree that such data are of interest, and address this issue in Section 2.8 of this review. We also note the limitation of such data.

The advocate questions the size and shape of uranium objects that are the basis of the analysis of external exposure to the irradiated uranium. As discussed in Section 4.1.3, the assumptions in the Appendix regarding the sizes and shapes of the uranium objects yield a bounding estimate of doses from irradiated uranium.

4.2.5 Advocate #2 Comments on Section BB.4.1: Exposure Time

The advocate refers to the lack of a cool-down period from the time the betatron exposure ended to the time the operator and his assistant entered the shooting area. Allen and Glover (2007) take no credit for the cooling down of either the betatron apparatus or the irradiated metal.

The advocate further mentions the close contact of the workers with the irradiated steel. This is accounted for in the Appendix BB analysis, which assumes that during one half of the time that the worker spends in the shooting area after the radiographic exposure he is at a distance of 1 ft (30 cm) from the casting, while the rest of the time he is at 1 m. These distances are to the center of the worker's torso. Since the torso of Standard Man—the model that has been adopted by the U.S. and international radiation protection community for calculating radiation doses from external exposure—is 20 cm thick (8 inches) in the anteroposterior direction, a distance of 1 ft assumes that there is an 8-inch space between the torso and the metal. This is a reasonable minimum distance for marking the casting. The 1-m distance assumes the worker is moving about, adjusting the position of the betatron, etc., and not in intimate contact with the casting.

According to the advocate:

> It should be realized there was usually no time gap between the takedown phase of one Betatron shot and the setup period for the next shot. In addition, the large castings and the MCW uranium ingots required many shots. Thus, during the setup phase the workers were often in direct contact with a highly activated casting or uranium ingot.

The lack of a time gap is inherent in the Appendix BB analysis. Multiple exposures of the same piece of metal are discussed in Section 4.1.4 of this review.

The advocate questions the assumption of one-hour exposures in the Appendix. We agree that there was a range of exposure times, which depended on the thickness of the metal, the distance, and the output of the betatron. Using a mix of long and short exposures, as we did in our analysis, would produce a more realistic and claimant-favorable exposure assessment.

The advocate further states:

> One would have to have exact specifications of the geometries and shapes or [*sic*] the uranium and of the industrial castings to plug into simulation programs such as MCNP-5. A 3-D CAD program front end to MCNP5 as employed in the literature would have to be used [to] accurately model the external doses, including activation, from both types of targets.

First, MCNP5 does not simulate the delayed radiation from photoactivation and photofission—only the recently released MCNPX Version 2.6e has that capability. Second, a CAD front end is a labor-saving device—it does not yield a more accurate analysis. SC&A staff members have extensive experience in creating the MCNP input geometries and have constructed detailed models of the betatron, the surrounding structures, and the object being radiographed, without the use of such a program (see Figures 6–11, 14–16, and 18 of this review). Third, an exact reconstruction of the geometry of every object that was radiographed at GSI during the covered period is impossible because such information is not available. Furthermore, an exact dose calculation would require knowledge of the precise location of each exposed individual at every moment of every day. Again, this information does not exist. Finally, such exact calculations are not required by EEOICPA. What are required are reasonable and claimant-favorable estimates of *annual* radiation exposures.

Annual exposures are based on average exposure conditions and can thus be estimated more easily and more precisely than exposures at any given moment. The Mallinckrodt purchase orders provide a reasonable basis for estimating the annual duration of the uranium exposures.

4.2.6 Advocate #2 Comments on Section BB.4.2: Skyshine

The advocate points out details of the construction of the betatron buildings, based on diagrams, presumably from the ORNL reports (Cottrel and Carrier 1990, Murray and Uziel 1992, and Murray and Brown 1994). We agree that the analysis should include detailed models of both betatron buildings, as we discuss in Section 4.1.7.

The advocate also refers to the warning signs outside the Old Betatron Building. These signs—along with a security fence surrounding the building—seem to represent sensible precautions on the part of GSI; they do not prove that the radiation or the skyshine produced measured radiation fields that were considered hazardous. Since the nearest structure—a pattern-storage building—was 250 ft (76 m) from the Old Betatron Building, there was little opportunity for the radiation exposure of workers not directly involved in the operations, such as the betatron radiography team, the chainmen transporting the irradiated castings, or workers performing maintenance in the building. He also reiterates his comment regarding film-badge dosimetry data, which we discuss in Section 4.2.4.

The advocate points out the need for calculation of neutron doses. We agree that neutron doses should be included in order to produce a more comprehensive analysis, and addressed them in our analysis. However, we found only a few locations, with low total dose rates, where the neutrons made a significant contribution. Neutron doses constituted less than 10% of the annual

exposures of the betatron operators. Neutron radiation was a greater problem for hospital betatron facilities, which primarily relied on lead for radiation shielding. Lead provides good protection from photon radiation, but is relatively ineffective in shielding against neutrons. GSI, as well as other industrial facilities, relied on concrete and sand, which provides better protection from neutrons.

The advocate questions the use of the Attila computer program; we agree that the use of this program should be better documented. He suggests that a preliminary analysis which SC&A performed of the delayed radiation from the photofission and photoactivation of uranium following betatron radiography, using MCNPX Version 2.6c, be utilized by NIOSH. That calculation is superceded by the analyses reported in the present review.

The advocate urges that both betatron buildings should be modeled. We discuss this issue in Section 4.1.2. He also mentions the construction of the roofs, and the presence of workers on the roofs. Although a more precise analysis may well include the construction of the roofs (as was done in our assessment), we doubt that this would have any significant impact on the results. We agree that the possible presence of workers on the roofs should be addressed, as noted in our analysis. He further mentions the presence of electricians at the capacitor banks on the second floor, which we discuss in Section 4.1.10. He requests more details on the calculations of scattered radiation in the Appendix. We agree that a more detailed discussion of the skyshine results should be included.

4.2.7 Advocate #2 Comments on Section BB.4.3: Steel Dose Rates

The advocate concludes that, based on his discussion with Jack Schuetz: "the 100 [R/min] figure is on the low side and is not claimant favorable." We agree with this observation and discuss it in Section 3.2.7.

The advocate reiterates his comment about a 3-D CAD front end, to which we respond in Section 4.2.5. He also criticizes MCNP5, which was not used in the Appendix BB analysis. He mistakenly refers to ^{53}Fe as an activation product of uranium. We agree that this nuclide is not the only activation product of steel, although it is the largest contributor to the external dose in the first few minutes after the betatron exposure (see Section 3.2.7). Other nuclides make significant relative contributions to the external doses from irradiated steel. However, as discussed on page 64, our own analyses indicate that the radiation from irradiated steel makes a minor contribution to the exposures of GSI workers. Therefore, the actual dimensions of the steel and its actual composition would not have a significant effect on the results. We agree with the need for assessing radiographic sources other than the betatrons, as discussed in Section 4.1.2.

The advocate criticizes Appendix BB for not utilizing the work of Kuttemperoor (1974, 1975). MCNPX Version 2.6e, released in November 2007, incorporates data on activation cross-sections based on the most recent experimental data and theoretical measurements. These data incorporate and/or supercede Dr. Kuttemperoor's results.

Contrary to the advocate's assertion, it is not necessary to "model the large variety of GSI military and industrial castings" to produce a bounding estimate of the doses from irradiated steel which, as discussed on page 64, make only a minor contribution to the exposures of GSI workers.

4.2.8 Advocate #2 Comments on Section BB.4.4: Uranium Dose Rates

The advocate requests better documentation for the assertion in the Appendix that photoactivation of uranium results in dose rates that are negligible compared with those from the uranium metal. Although we agree with this conclusion in the Appendix, we also agree that this assertion should be better documented in the report, as should the analysis of photo-induced fission products, which we discuss in Section 3.2.8. The advocate refers to modeling different geometries of uranium, which we discuss in Section 4.1.3. He questions the conclusions that uranium fission occurs in the first few centimeters of the surface being exposed. Although we agree with this conclusion, we also agree that an illustration of the fission density within the metal would enhance the presentation of these results in the Appendix and make them more comprehensible to a layman.

The advocate also requests a more detailed presentation of the activation and fission products. Given the approach chosen by Allen and Glover, in which they first calculate the fission rate in the metal, then characterize the photon spectrum based on the ORIGEN code, then calculate the dose rates from these fission products, we agree that a more detailed discussion of these steps would be appropriate. He again cites the Kuttemperoor (1974, 1975) papers, as well as papers by Schmitt and Sugarman (1953) and Schmitt and Duffield (1957) (whom he erroneously refers to as Sugarman and Duffield). While we commend the advocate and his associates for the depth of their research on this subject, they should be aware that the data bases utilized by Allen and Glover (as well as data utilized by the SC&A staff members who prepared this review) have been compiled by physicists who continually review and evaluate reports on experimental and theoretical research in their respective specialties. Therefore, the papers cited by the advocate, as well as much more recent data, are already reflected in these data bases.

The advocate repeats his earlier comment about the distance from the metal, which is discussed in Section 4.2.5. He also refers to each uranium slice being exposed four times. We agree that there were multiple *overlapping* exposures, which we discuss in Section 4.1.4. He then presents a summary of his comments, all of which we have addressed in the preceding sections of this chapter. His next comment addresses the exposure of workers other than betatron operators or workers handling steel within 2 h of the radiographic exposures. We discuss the exposures of workers to radioactive sources in Section 4.1.2, while the exposures of other workers are discussed in Section 4.1.10.

4.2.9 Advocate #2 Comments on Section BB.5.3:Summary of Intakes of Radioactive Material

The advocate refers to extensive contamination with uranium dust. We cannot confirm that this was the case, but we discuss the issue of uranium contamination on page 66 of this review. He also questions the estimates of "aerosolized" (also known as "resuspended") uranium dust. We also have concerns about the resuspension model presented in the Appendix, which are also discussed on page 66. The advocate states that the fission and activation products in uranium are not characterized. Although Allen and Glover are correct in concluding that these nuclides make a very small contribution to the internal dose, we concur with the advocate that their results should be presented in a more quantitative manner.

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