Division of Compensation Analysis and Support	Document Number: Battelle-TBD-6000 Appendix BB Effective Date: 05/26/2016 Revision No. 02
Site Profiles for Atomic Weapons Employers that Worked Uranium Metals **Appendix BB – General Steel Industries**	Page 1 of 42

Document Owner: David Allen

Approval: Signature on file Date: 05/26/2016 Supersedes: Appendix BB
J.W. Neton, Associate Director for Science Revision 01

TABLE OF CONTENTS

RECORD OF ISSUE/REVISIONS

ISSUE AUTHORIZATION DATE	**EFFECTIVE DATE**	**REV. NO.**	**DESCRIPTION**
6/25/2007	6/25/2007	0	Appendix to Battelle-TBD-6000 describing the use of the TBD for claims at General Steel Industries
6/4/2014	6/4/2014	1	Revised to incorporate resolution of issues raised by the Advisory Board on Radiation Worker Health.
4/28/2016	5/26/2016	2	Revised to incorporate resolution of issues raised by the Advisory Board on Radiation Worker Health in the review of revision 1.

BB.1 Introduction

This document serves as an appendix to Battelle-TBD-6000, *Site Profiles for Atomic Weapons Employers that Worked Uranium Metals*. This appendix describes the results of document research specific to this site. Where specific information is lacking, research into similar facilities described in the body of this Site Profile is used.

BB.2 Site Description

General Steel Industries (GSI) performed quality control work for the Atomic Energy Commission (AEC) from October 1952 until June 1966. Utilizing two 25 MeV betatron machines, it performed x-rays on uranium metal of various forms including uranium ingots and betatron slices to detect metallurgical flaws for the Mallinckrodt Chemical Company (DOE Web Site). The x-ray films were processed, but not interpreted, at General Steel Industries. The facility is located at 1417 State Street in southwest Granite City, Illinois, northeast of St. Louis, Missouri, east of the Mississippi River. The use of the facility for these services was on an as-needed basis controlled by purchase orders with limits and estimates but no indication of actual frequency or duration (ORNL 1990).

BB.2.1 Site Activities

From October 1952 to June 1966, General Steel Industries used betatrons to x-ray uranium metal. Purchase orders were issued by the Uranium Division, Mallinckrodt Chemical Works, from February 1958 through June 1966, first to General Steel Castings Corporation and later (July 14, 1961 and after) to General Steel Industries, Inc., at the same address. The uranium to be x-rayed was owned by the AEC and provided by Mallinckrodt (DOE 1991).

BB.2.2 Frequency of uranium X-rays

General Steel Industries work with uranium was performed under purchase orders with Mallinckrodt Chemical Works starting in March of 1958. These purchases orders cover the time period March 1, 1958 through June 30, 1966 (Mallinckrodt 1958-1965). These purchase orders indicate that the work was to “X-ray material as requested by Mallinckrodt…”. They also contained “Betatron labor charges, including operation and maintenance and all overhead shall be billed at $16.00 per hour.” The last purchase order covering the period of July 1, 1965 to June 30, 1966 indicated a billing rate of $35.00 per hour. The purchase orders also included an estimate or limit of the cost. The first purchase order, covering the period March 1, 1958 to June 30, 1958 stipulated a monthly estimate of $500. That purchase order was extended to October 31, 1958 and added $1800 to the total estimate (an additional $450 per month). A new purchase order covered the period November 1, 1958 to June 30, 1959 and stipulated a monthly estimate of $450 and a total estimate of $3600 (equal to $450 per month). The next purchase order covered July 1, 1959 to June 30, 1960 and stipulated a monthly estimate of $450 with a total estimate of $7200. It should be noted that the total estimate does not add up to 12 months at the monthly estimate. This is the only purchase order with this conflict. Since these are estimates, the most limiting of the two values will be used in this appendix which is consistent with purchase orders written both before and after this one.

From that point on, the purchases orders were written annually covering a period of July 1 to June 30 of the next year. All but the last order stipulated a billing rate of $16 per hour. The purchase order starting in 1960 stipulated no total estimate. Only a monthly estimate of $450 per month was specified. After that, only a total limit was specified. These limits were $7000 for the purchase order starting in 1961, $2000 for the purchase order starting in 1962, and $450 for each of the remaining purchase orders.

From this information, it is possible to determine the maximum hours per month that General Steel Industries spent on operations, maintenance and overhead associated with x-raying uranium for Mallinckrodt Chemical Works. A summary of that information is contained in Table 1.

Table 1 – Summary of Mallinckrodt Purchase Orders

Start Date	End Date	# of months	Monthly ($)	Total ($)	Charge rate ($/hour)	Max hours/month
3/1/1958	6/30/1958	4	500		16	31.25
6/30/1958	10/31/1958	4	450		16	28.13
11/1/1958	6/30/1959	8	450		16	28.13
7/1/1959	6/30/1960	12	450		16	28.13
7/1/1960	6/30/1961	12	450		16	28.13
7/1/1961	6/30/1962	12		7000	16	36.46
7/1/1962	6/30/1963	12		2000	16	10.42
7/1/1963	6/30/1964	12		450	16	2.34
7/1/1964	6/30/1965	12		450	16	2.34
7/1/1965	6/30/1966	12		450	35	1.07

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 estimates initially but never raised them as experience was gained. Also, the last few years were stated as a limit. There is no indication how much of the available funds were actually used. Also the cost was to include maintenance down time and overhead as well as the cost of film.

For the remainder of the year, it is assumed that various alloys of steel were x-rayed. The operators reported that overtime was very frequent. Operators indicated that an 8 hour work day was “not the norm”. They indicated overtime was frequent (Simmons Cooper 2006). During one meeting, workers estimated that they worked an average of 65 hours per week (Minutes 2007). This document will assume workers spent 65 hours per week on average for 50 weeks per year for a total of 3250 hours per year. This equates to an average of 406.25 eight hour shifts per year. From the information contained in Table 1 the number of hours for each calendar year can be calculated and expressed as a number of shifts per year GSI employees worked with uranium and steel. The covered period for GSI starts 10/1/1952 while the first purchase order found starts on 3/1/1958. The time period prior to March 1958 is considered to be equal to the highest monthly rate in Table 1. Table 2 lists the uranium work hours and the total number of eight hour shifts per year associated with uranium or steel.

Table 2 – Uranium Work Hours by Year

Year	Uranium work (hours/yr)	Uranium work (shifts/yr)	Steel work (shifts/yr)	Total work (shifts/yr)
1952[a]	109	13.7	87.9	101.56
1953	438	54.7	352	406.25
1954	438	54.7	352	406.25
1955	438	54.7	352	406.25
1956	438	54.7	352	406.25
1957	438	54.7	352	406.25
1958	367	45.8	360	406.25
1959	338	42.2	364	406.25
1960	338	42.2	364	406.25
1961	388	48.4	358	406.25
1962	281	35.2	371	406.25
1963	76.6	9.57	397	406.25
1964	28.1	3.52	403	406.25
1965	20.5	2.56	404	406.25
1966[b]	6.43	0.80	202	203.13

a – 1952 only covers 3 month of contract period at the site starting 10/1/1952
b – 1966 only covers 6 months of contract period at the site ending 6/30/1966. The remainder of 1966 is covered as a residual contamination period.

BB.3 Occupational Medical Dose

No detailed information regarding occupational medical dose was found in any of the site research or telephone interviews. Information to be used in dose reconstructions, for which no specific information is available, is provided in ORAUT-OTIB-0006, the technical information bulletin covering diagnostic x-ray procedures.

BB.4 Occupational External Dose

Sources of external radiation exposure at GSI included betatron x-ray machines, sealed sources (Ra-226, Co-60, Ir-192), 250 kvp portable x-ray machines and uranium metal. Except for the uranium, all these sources were used for x-ray inspections. This process requires the operator to know the intensity of the radiation source at the material being x-rayed, as well as the thickness of the material in order to determine the length of time necessary to produce a clear x-ray image. Additional concomitant sources of radiation would interfere with the process and it is therefore assumed that workers are only exposed to one source of radiation at a time.

In estimating the external dose at GSI, the dose was estimated for a variety of exposure scenarios for the primary sources of external radiation. The limiting dose estimate for each scenario and job category will be used to estimate an individual's external dose. For some scenarios, no numerical dose estimate was made because an analysis of the scenario compared to other numerical estimates was sufficient to eliminate it as a limiting scenario. This could be done by analyzing parameters that would be used in a numerical estimate for example determining less exposure time with all other parameters being equal.

Doses will be assigned based on one of two job categories. The administrative category consists of people that spent most of their time in an office environment and did not routinely access the operating areas of the plant. The operator category consists of everyone that does not fit the administrative category. It is expected that the majority of workers will fall into this category.

BB.4.1 Betatrons

GSI had two betatron x-ray machines. The machines produced high energy x-rays (up to 25 MeV) by accelerating electrons in a circular orbit then causing them to collide with a platinum target. The x-ray beam was measured by an ion chamber attached to the machine and the beam was "flattened" by an aluminum compensator designed to shield the high intensity center of the beam more than the lesser intense edges. This produced a usable area of relatively uniform intensity.

While the head of the betatron can be moved throughout the shooting room, the betatron units were not mobile. They consisted of various components housed in a specially designed shielded building. The shooting room was surrounded by 10 foot thick walls consisting of 8 feet of sand sandwiched between 2 one foot thick concrete walls. The "old betatron" was built in 1952 and stood alone separated from other buildings on site. The "new betatron" was built in 1962 and was attached to building 10 by an equipment tunnel. Figures 1 and 2 provide drawings of the old and new betatron buildings, respectively.

The intensity of the x-rays from the new betatron was reported to be 250 R/min at 3 feet from the platinum target with the aluminum compensator removed. The compensator reportedly reduced the intensity by a third (Schuetz 2007). The intensity of the old betatron was reported to be less. However, to avoid trying to place workers in one betatron versus the other, this appendix will use 250 R/min at 3 feet for all calculations. Betatron x-rays are of sufficient energy to produce nuclear interactions in material being x-rayed causing some atoms to become radioactive. That material then creates an additional source of external radiation. The external exposure scenarios explored for betatron operations include a scenario for the betatron operators and the layout man. The layout man is a person assigned the duty of marking the casting to determine what portions of the casting need to be x-rayed again, as well as marking any defects found in the previous shots. Several scenarios of workers working outside the betatron building were also evaluated, including working on the roof of the betatron building but were found not be the limiting dose estimate due to limited exposure time or limited dose rates (DCAS GSI web page).

This document will refer to the process of x-raying metal as shooting the metal or taking a shot. This is the vernacular used by former radiographers and avoids confusing an x-ray exposure with worker exposure to x-ray radiation. The betatron operator shooting scenarios consisted of a shooting scenario for uranium and a separate one for steel castings. The scenario for the steel castings includes two different durations and distances, which were based on interviews with former workers at GSI (SC&A 2008).

The uranium shots took 60 minutes for the actual shot as well as 15 minutes between shots to allow for setting up the next shot. The shots were taken at a distance of six feet from the betatron target to the material. This scenario would allow for an average of 6.4 shots per 8 hours shift of continuous uranium operations. It also results in the betatron being energized 80% of the time while uranium is being x-rayed.

The steel casting scenario consists of two types of shots. The first type (short shot) is 3 minutes in duration with 12 minutes between shots. These shots are taken at a distance of nine feet between the betatron target and the material. With one short every 15 minutes (3 minute shot plus 12 minutes between), an average of 32 shots can be taken during an 8 hour shift.

The second type of shot was the long shot. Just like the uranium shots, these shots were taken at six feet and lasted 60 minutes with 15 minutes between. Long shots were assumed to account for 10% of the steel casting shots while short shots accounted for the other 90%. This combined with the shot scenarios results in an average of 20.57 short shots and 2.29 long shots per 8 hours shift. It also results in the betatron being energized 41.43% of the time while x-raying steel.

Figure 1 – Drawing of the Old Betatron Building

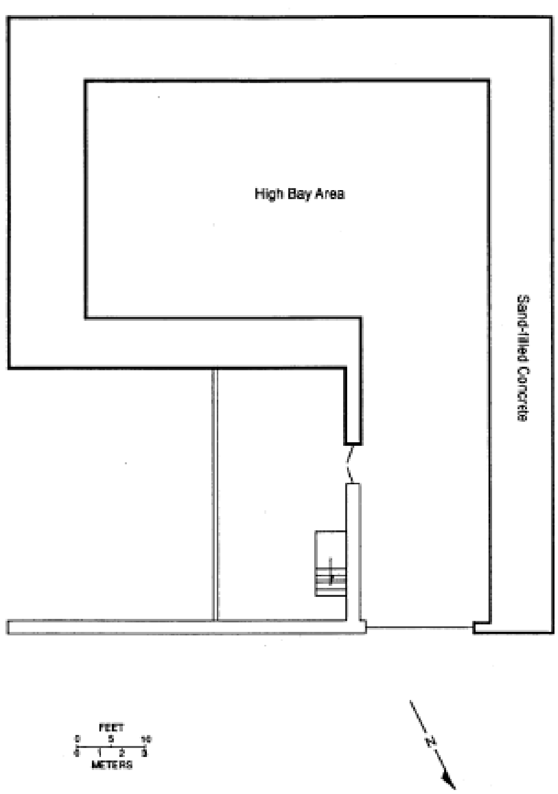
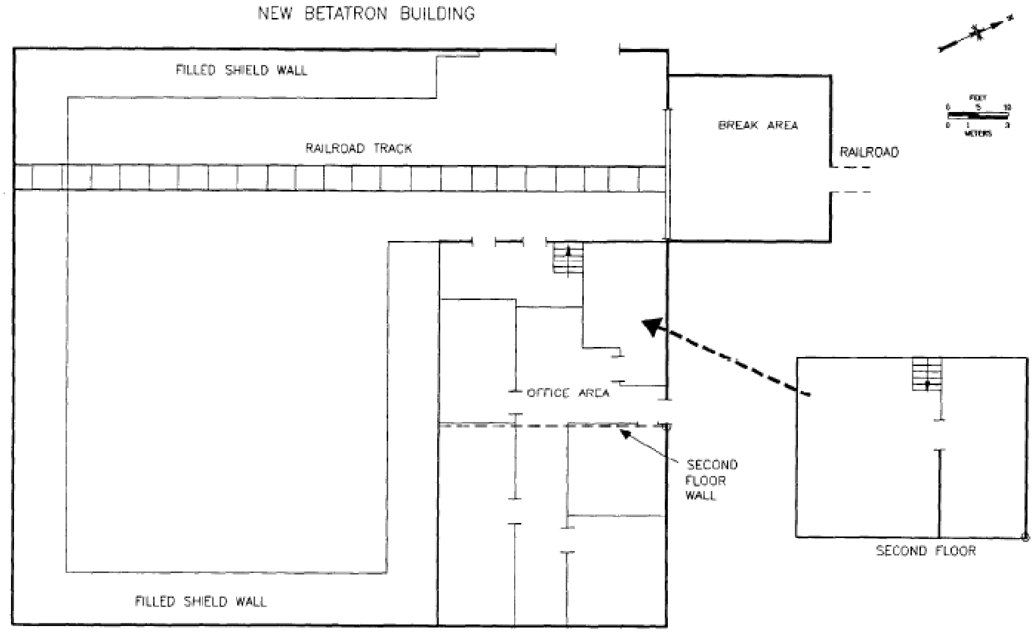


Figure 2 – Drawing of the New Betatron Building



As previously stated, the layout man is a person assigned the duty of marking the casting to determine what portions of the casting need to be x-rayed again, as well as marking any defects found in the previous shots. This is a limiting exposure scenario because the layout man can be working in close proximity to freshly x-rayed castings. While the layout man is a duty performed by radiographers, other classes of employees can also be working in close proximity to these freshly x-rayed castings. This is due to the fact that defects found during radiography are often repaired (for example, grinding out the defect and adding good metal back in by welding). Also, betatron operators were radiographers but others were also associated with the betatron operators and could receive the same type of exposure. For example, riggers may be used to move the castings in and out of the betatron building as soon as the x-ray is done. Therefore, the dose estimate for betatron operators and for the layout man is applied to essentially everyone working at the site. The exception is administrative personnel.

Betatron operators are modeled as being in the betatron control room during the shots and near the freshly x-rayed material between the shots starting 5 second after the end of the x-ray to allow travel time to the material.

During x-rays, the layout man is assumed to be in the #10 building near the railroad tracks used to move castings into and out of the new betatron building. The layout man is not assumed to be in the middle of the doorway since that would not be a credible location for a casting. That would block the path to and from the betatron building. Instead, he is assumed to be 10 feet to the side of the railroad tracks. Both sides were modeled and the higher dose rate side was used in the estimate. This scenario for the layout man would only be applicable after 1962 when the new betatron was built. A similar location for the old betatron would be outdoors and it is unlikely this work routinely occurred there year around. It is much more likely the work was done in another building then the casting transported to the old betatron building. This would result in a considerably lower dose to the layout man before 1963. However, Ra-

226 radiography resulted in an exposure estimate higher than the new betatron layout man estimate so the lower exposure scenario was not explored further.

BB.4.2 Betatron Building Model

Documents obtained from AEC license applications contained building dimensions and other details for the new betatron building (Figures 3 through 5). The documents also included a survey of the new betatron building with an 80 curie cobalt-60 source exposed that was conducted on January 29, 1971. The survey, which included measurements taken at various points around the building, is reproduced in Table 3. The letters in parentheses correspond to the locations identified in Figures 3 through 5.

The building design information contained in the AEC license application was used to modify a previously constructed MCNP model of the new betatron building. MCNP is a general purpose Monte Carlo radiation transport computer code designed to track many particle types over a broad range of energies. It was developed at Los Alamos National Laboratory with new versions released periodically. MCNP calculations for this document were performed using MCNPX versions 2.6 and 2.7 (MCNPX) as well as MCNP6 (MCNP6.1). This document will refer them generically as MCNP.

The 80 curie Co-60 source was purchased in 1968. An application to modify the AEC license was sent on January 18, 1968 and the license was modified on February 14, 1968 (AEC 1968). The purchase of the source would have been after that date. Therefore, the 80 curie source would have decayed for approximately 3 years before the survey making the source strength 54 curies. Once the model of the new betatron building was modified, a 54 curie Co-60 source was added at the position labeled as an X within a circle in Figure 3. Radiation levels were determined, using MCNP, at many of the same locations surveyed by GSI in 1971. Table 3 provides a comparison between the actual survey results and the modeled results.

Figure 3 – New Betatron Building Drawing with Dimensions

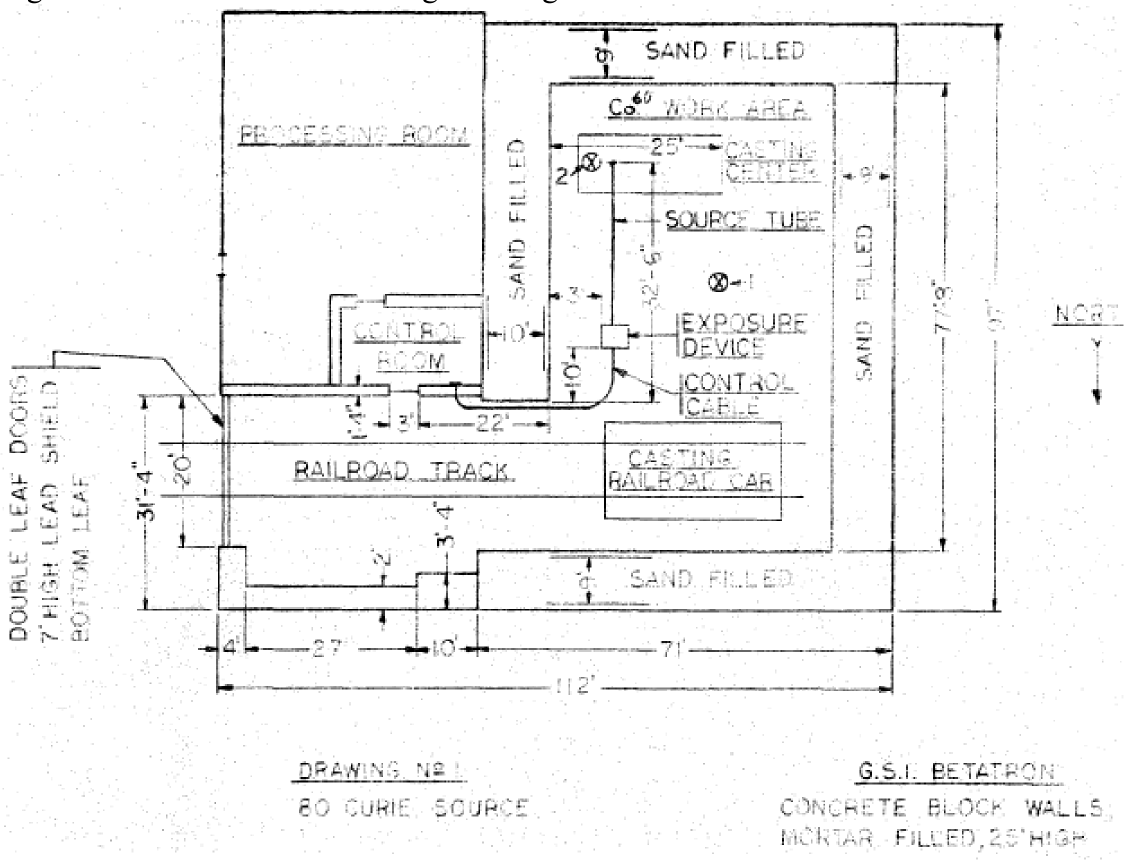


Figure 4 – Drawing of New Betatron Building with Nearby Buildings

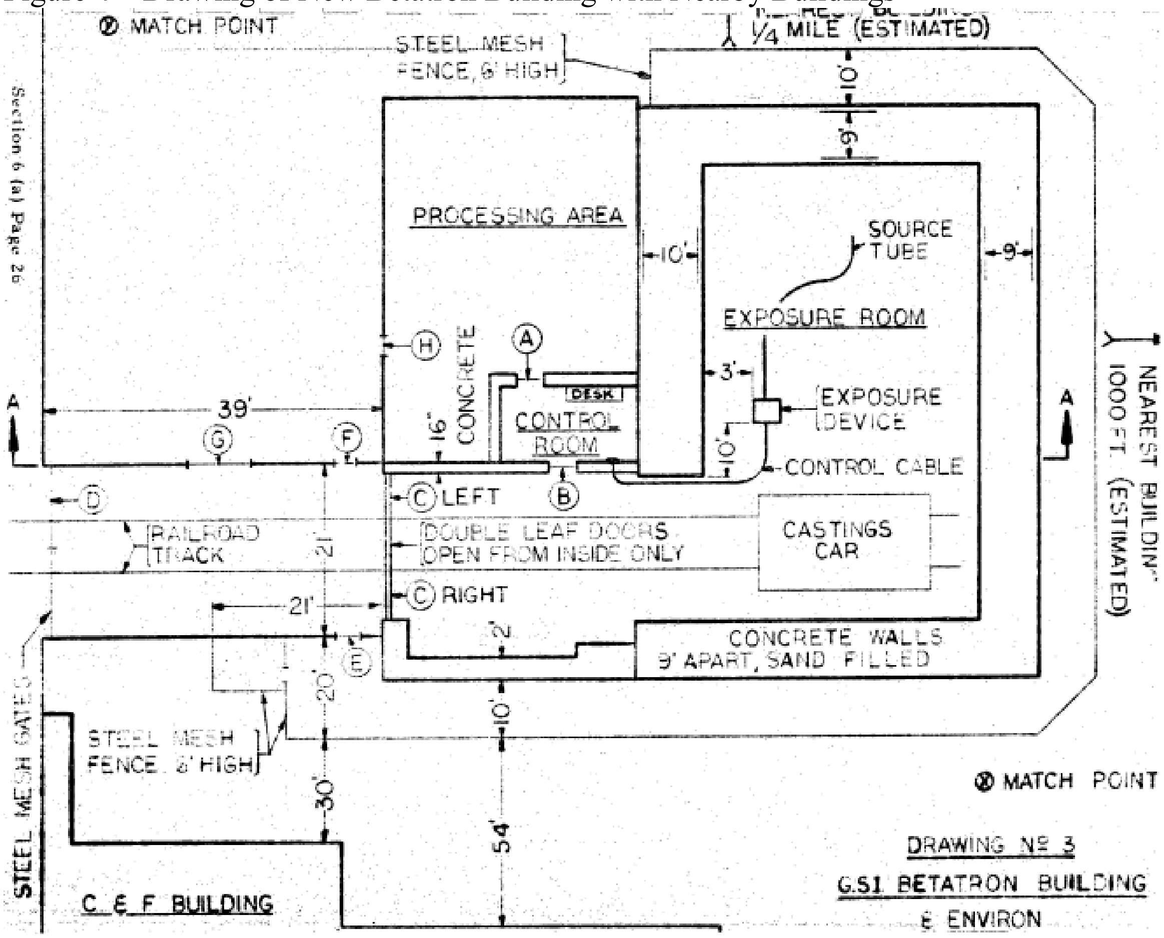


Figure 5 – Drawing of New Betatron Building Elevations

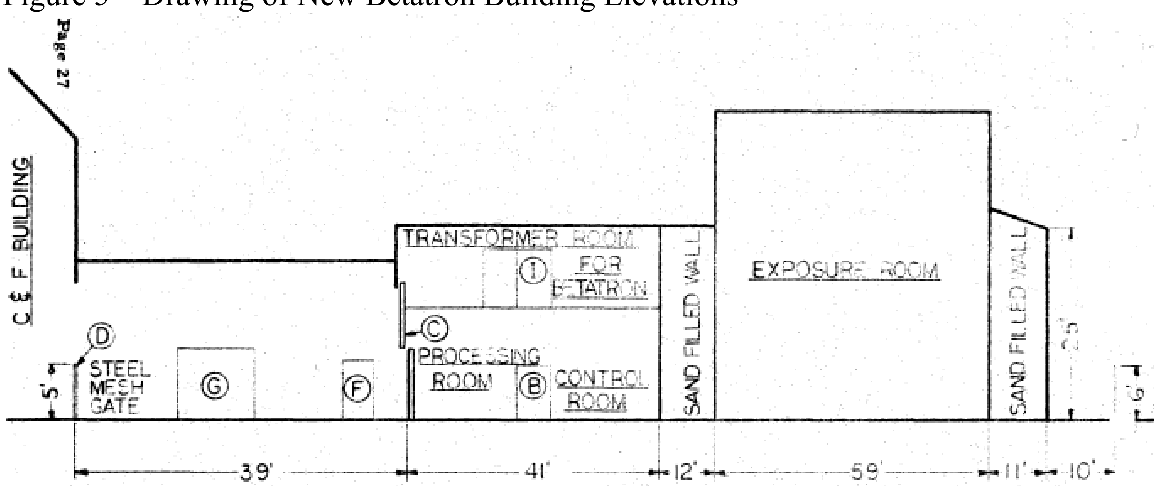


Table 3 – Comparison of Modeled Radiation Levels to 1971 Survey

Location	1971 Radiation Level (mRr/hr)	Modeled Radiation Levels (mR/hr)	
Control Room	3.0	1.7	Meter held against door joint (B)
Control Room	0.6	0.7	2' from door
Control Room	0.1	0.2	At control desk
Outside Surface of Double Leaf Door (C)	0.3	0.2	Left side 5' high
	1.8	1.6	Left side at horizontal door joint 10' high
	2.5	1.5	Left side 2' above horizontal joint at 12' height
	0.2	1.4	Left side 10' from door 12' high
	0.4	0.4	Right side 5' high
	3.4	2.8	Right side at horizontal door joint 10' high
	4.4	2.7	Right side 2' above horizontal joint at 12' height
	1.8	1.6	Right side 10' from door 12' high
Corner at Door E	0.4	0.4	Taken against exterior surface of wall
Corner at Door F	0.2	0.4	Taken against exterior surface of wall

The modeled values were found to be in reasonable agreement with the measured values. All but three were within 50%. However, those three had measured values of 0.2 mR/hr or less and the measurements were recorded in 0.1 mR/hr increments. One of those values did show a significant difference between measured and modeled values. It was a point located 10 feet from the double leaf door, 12 feet high. Inspection of the other survey results near that door revealed that all other measured results, 10 feet or more above the floor, are at least 1.8 mR/hr. The survey measurement at that point, however, is 0.2 mR/hr. The difference between the model and the measured results could be a typographical error or an error in reading the instrument (such as the wrong scale). Since the scales on instruments are typically factors of 10, it is very possible the actual reading was 2.0 mR/hr. The other possibility is that there could be some piece of equipment mounted there (such as a door motor) creating additional shielding that is not depicted in the model. Either way, the values 5 feet above the floor are more representative of the location of workers and for those values the modeled exposure rates are within 0.1 mR/hr of the measured exposure rate. As a check, the relative error of each measurement was calculated and those values averaged. The outlier mentioned above as removed from the data set. The average of the relative errors was found to be 2%. Since the average relative error is near zero, the modeled values appear to be in reasonable agreement with the measured values.

The reasonable agreement between the modeled and measured exposure values indicates that the building model provides a realistic representation of the shielding presented by the new betatron building. This model was used later to estimate dose rates from various shooting scenarios in the new betatron building with one notable exception. The survey description in the AEC license application indicates the double leaf door contained lead in the bottom 7 feet of the door. The MCNP model of the building included this lead and it explains the significant difference between the measurements taken 5 feet above the floor compared to 10 and 12 feet above the floor. However, it was reported that the lead in the door did not exist prior to the 1971 survey or years later. With the conflict between verbal and written reports, the lead was removed from the model for estimates made in this appendix.

BB.4.3 Betatron Operations External Dose Estimate

Neutron and Gamma Dose from Scattered Radiation

The neutron dose rates during radiography were evaluated using MCNP and the model of the new betatron building at several locations, including the control room and the location of the layout man. While shooting steel, the betatron was assumed to always be shooting a large steel object on a railcar. This angle produced the highest dose rate for the layout man location from several credible orientations. The neutron dose rate in the control room and the layout man location were determined and applied for 41.43% of an 8 hour shift to determine the dose per shift while x-raying steel. For uranium x-rays, the neutron dose rate in the control room was determined by assuming the uranium was near the center of the shooting area and the betatron oriented away from the control room. Only the dose rate in the control room was calculated and adjusted to a dose per 8 hour shift of uranium operations. The dose rate for the layout man location was not determined for uranium shots since for this exposure scenario it was more favorable to assume steel was always x-rayed. While that may appear to be inconsistent, it is actually a credible scenario since with two betatrons in operation, it is possible uranium was x-rayed in the old betatron building while steel was being x-rayed in the new betatron building.

Gamma dose rates during radiography for the layout man location were determined in the same manner as the neutron. This model resulted in a dose rate of 6.67 mR/hr at the layout man location while the shot was in progress. The layout man is assumed to be working 100% of the time in that area and it is assumed that steel is always being shot.

Gamma Dose to Betatron Operator

For the betatron operator, gamma dose rates were determined using film badge data. Workers reported that radiographers always wore film badges in the betatron building but with a few exceptions, detailed records of the film badge readings could not be located prior to 1964. The detailed records recovered from 1964 through 1973 (Landauer 1964 through 1973) indicated badges were exchanged weekly and 99.7% of them were recorded as “M” which means the measured exposure was less than 10 mrem. It is possible for a relatively small discrete source of radiation to exist after a shot from either the material being x-rayed or even from activation of betatron components themselves. Because of that, it may be credible that an operator could be working with his back to the primary gamma source in the area. In order to account for this, correction factors contained in ICRP publication 74 (ICRP 1996) were used. This publication calculates dose to various organs per unit air kerma for several orientations. One of the organs listed in ICRP 74 is the breast which would be a reasonable surrogate for a film badge worn on the chest.

Dividing the 10 mrem/week value by the PA breast dose conversion factor (DCF) gives us the dose delivered to the back (PA) that would produce the 10 mrem reading on a film badge. This value varies with photon energy and the values for various energy photons are listed in Table 4. The most limiting energy in Table 4 is the 30 kev photons producing 204.5 mrem/week or 10.225 rem/yr. Therefore, this estimate will assume each betatron operator was exposed to 10.225 rem/yr of 30 kev photons from the PA geometry. Since the ICRP 74 DCF values are in units of dose per air kerma, the calculated PA entrance dose is in units of air kerma. The organ dose therefore should be calculated using the <30 kev kerma to organ dose DCFs in OCAS-IG-001.

Table 4 – Dose for Film Badge Reading at Various Energies

Energy (kev)	PA Breast DCF	PA entrance dose (mrad – air kerma)
30	0.0489	204.5
40	0.181	55.2
50	0.328	30.5
60	0.439	22.8
70	0.511	19.6
80	0.545	18.3
100	0.574	17.4
150	0.6	16.7
200	0.625	16.0
300	0.663	15.1

Neutron and Gamma Dose from Freshly Exposed Material

Along with the exposure during an x-ray shot, layout men and betatron operators could also receive neutron and gamma radiation from freshly x-rayed material. Gamma exposure to the betatron operator is accounted for with the film badge readings. Neutron dose from freshly exposed steel is negligible; however, neutron dose from freshly exposed uranium must be accounted for to estimate the betatron operator's dose. Also, gamma dose from freshly exposed steel must be accounted for in estimating the layout man's gamma dose.

For the neutron dose to the betatron operator, the uranium is assumed to be exposed to x-rays for 60 minutes with the operator's exposure to the uranium starting 5 seconds after the shot and continuing until 15 minutes after the shot. The operators are modeled to be standing one foot from the uranium half of the time and one meter the remaining time. MCNP, which was used to calculate the neutron dose rate from the exposed uranium, found that the neutron dose rate decreases rapidly to essentially zero within 7 minutes following exposure. Since the shots lasted one hour, no buildup of neutron dose would occur from multiple shots. Using these assumptions, the dose from a single shot was estimated to be 0.138 mrem. With each cycle taking 75 minutes (60 minutes per shot plus 15 minutes between shots) an average of 6.4 shots could be taken in one 8 hour shift. The dose per shift would then be 0.882 mrem while x-raying uranium. This value was then multiplied by the number of shifts per year that uranium was x-rayed to estimate the annual neutron dose to the operators from this source of radiation. It was added to the annual neutron dose received in the control room during uranium x-rays and the annual neutron dose received during steel x-rays. The total annual neutron dose varies by year due to differing amounts of steel and uranium work in each year. Table 5 provides the results.

Next, the gamma dose to the layout man from freshly x-rayed steel was determined. The gamma dose rate from irradiated steel decreases quickly but does not decrease to zero in minutes. Therefore, a buildup of radiation could occur with repeated shots causing a higher dose rate than would occur after only one shot. To account for this, a bounding scenario was assumed which includes prior shots on castings.

It was reported by a former supervisor that the layout man would typically spend a full shift marking up a large casting. However, he might have been interrupted to mark up a high priority casting that had just been x-rayed. The first task was modeled as short shots on steel, repeated 532 times ending just before the layout man's shift (SCA 2014). The 532 prior exposures are intended to be a bounding estimate. Additional analysis shows it is not a significant overestimate because the decreasing dose rates cause the recent shots to have a much larger affect than the previous shots (SCA 2008). The layout man is then assumed to work on this casting for a full 8 hour shift. Since marking up the steel requires close contact with the casting, it is assumed that the layout man is within one foot of the casting 90% of the time and one meter from the casting the remaining 10% of the time.

To account for the times when the layout man is interrupted to mark up a freshly x-rayed casting, a model was developed consisting of long shots on steel. It is assumed the steel was x-rayed 400 times prior to being moved to the layout man. Again, this is a bounding value that does not significantly affect the results. The layout man is further assumed to mark up the casting for one long shot cycle (75 minutes) starting 15 minutes after the shots ended (time to move the casting out of the betatron building). After this 75 minute exposure, it is assumed that another freshly x-rayed casting (shot 400 times) is moved to the layout man position and he works on that one for another 75 minutes. This cycle repeats continuously for the full 8 hour shift so it could be repeated an average of 6.4 times per shift. As with the other scenario, it is also assumed he spend 90% of this time within 1 foot of the casting and 10% of the time 1 meter from the casting.

Since it was reported that the layout man would normally spend the whole shift on one large casting, the first scenario is assumed to account for 90% of his time and the repetitive scenario is assumed to account for 10% of his time.

Beta Dose

Lastly, beta dose was evaluated for both the layout man and the betatron operator. The source of beta dose includes the beta dose intrinsically associated with uranium metal as well as beta dose from freshly x-rayed steel. The uranium metal x-rayed at GSI was cast at Mallinckrodt Chemical Works. During recasting, decay products of uranium (notably Th-234 and Pa-234m), can concentrate in the outer surfaces of the cast metal. This effect has been reported to increase the beta dose by a factor of 10 to 15 (Putzier 1982 pp. 74-75). This effect is accounted for by assuming the Th-234 and Pa-234m activity is 15 times higher than what would be present at equilibrium. However, the top of the castings were normally cut off (called a top crop) so the metal sent to GSI is assumed to have been cropped and only the sides would have the concentrated decay products. The concentration on the top and bottom is assumed to be at an equilibrium concentration.

MCNP was used to model an 18 inch diameter ingot. The dose rates at one centimeter, one foot and one meter from the surface were calculated. These dose rates were calculated both as a distance from the top and a distance from the side. It was assumed that the operator was equally likely to be in front of the top or the side of the ingot. Therefore, the two dose rates at each distance were averaged. The betatron operator is assumed to spend half of his time one foot from the uranium and the remaining time at a distance of one meter. While the operator is within one foot, his hands and forearms are assumed to be one centimeter from the uranium (essentially in contact).

Based on the shot scenario for uranium, an average of 6.4 shots per 8 hour shift could be performed. Exposure time near the uranium would be 20% of the time (15 minutes out of 75 minutes). Therefore the betatron operator average beta dose from uranium operations is estimated at 32.4 mrad per shift to the whole body and 506 mrad per shift to the hands and forearms.

In considering beta dose from freshly x-rayed steel castings, it is important to realize shots were overlapped in order to get full coverage of the casting. Also, defects were repaired and reshot. It was reported that the same casting could be returned to the betatron building 5 to 10 times before leaving the site. Therefore, it is possible for the same location to be x-rayed multiple times.

In order to calculate the beta dose from freshly x-rayed steel, the chemical composition of HY-80 steel was modeled with MCNP in order to calculate the production rate of residual nuclides in the steel. From the list of nuclides produced, those that were not radioactive and those that do not emit a beta particle were eliminated.

This production rate was used to calculate the average concentration throughout the depth of the steel of each residual nuclide based on that nuclides half-life and the shot duration. However, the intensity of the betatron beam would decrease with its depth in the steel causing the highest concentrations to be near the surface. Averaging the nuclide concentration over a thick target would dilute the surface concentration. To avoid this, the surface activity concentration was determined for each nuclide using the mass attenuation coefficient for HY-80 steel corresponding to the maximum photon energy from the betatron. This surface activity was the initial surface activity at the time the shot ended. Since some nuclides could decay quickly during the time the operators would be exposed, the nuclides with the highest initial activity may not produce the highest integrated dose. To account for this, the integrated activity from zero to 15 minutes after the shot was then calculated to provide an indication of the integrated dose. Several shot times were analyzed between 1 sec and 30 hours. Six nuclides produced over 99% of the total time-integrated activity for each shot time analyzed so these six were used for the remainder of the analysis.

During radiography operations in the betatron building, materials will be x-rayed and then the beam shut off while the next shot is set up. While radioactive nuclides can be produced in steel while the betatron beam is on, those nuclides continue to decay while the beam is off. This has the effect of reducing the maximum dose rate that can be reached when compared to a continuous x-ray. The maximum dose occurs when the radioactive nuclides reach a maximum concentration (an equilibrium concentration where the rate of decay equals the rate of production). This concentration can be expressed as:

$$C = \frac{P}{\lambda}\ (1 - e^{-\lambda\, t_1})/(1 - e^{-\lambda\, tc_1})$$

Equation 1

Where:
C = the equilibrium concentration
λ = the decay constant
t1 = the shot time
tc1 = the full cycle time

Using Equation 1, the maximum (equilibrium) surface activity of each of the six nuclides was calculated for each of the shot scenarios. This surface activity was then assumed to be consistent throughout the entire depth of a thin HY-80 steel object. MCNP was then used to calculate the initial beta dose rate at 1 centimeter, 1 foot and 1 meter from the object. These dose rates were then integrated between 5 seconds and 15 minutes for the long shots and 5 seconds and 12 minutes for the short shots. The time-integrated dose for each nuclide was then summed to calculate the total beta dose per shot at these distances.

Lastly, the betatron operator was assumed to be 1 foot from the object for half of the time he was exposed and 1 meter from the object for the remainder of the time. His hands and forearms are assumed to be 1 centimeter half the time and 1 meter the remaining time. Also, the operators could participate in an average of 32 short shots in one 8 hour shift or an average of 6.4 long shots. The short shots accounted for 90% of the shots, which would mean 36% of the time the operators were working on long shots and 64% of the time they were working on short shots. This information was combined to calculate a beta dose per 8 hour shift to the whole body and separately to the hands and forearms. That dose was multiplied by the number of shifts per year an operator was working with steel. The resulting annual doses are shown in Table 5.

For the layout man, the same process was used but the scenario was altered. The scenario assumes the layout man is working on a single large casting for the full 8 hour shift but is interrupted from time to time for a priority casting. To account for this, the dose for each scenario (single casting vs. interrupting casting and long shot vs. short shot) is calculated as if only that scenario occurs for an entire 8 hour shift. After that, a fraction of time applicable to each scenario is applied and the individual scenario doses added.

In both the single large casting scenario and the interrupting casting scenario, two castings are assumed to alternate between the betatron building and the layout man. The single large casting is assumed to be x-rayed repeatedly over a 24 hour period and then moved to the layout man position for 24 hours. A second casting is assumed to follow the same routine being in the betatron building when the first casting is at the layout man position and the castings are swapped every 24 hours. The layout man is assumed to start working on the casting 15 minutes after the end of the last x-ray. This alternating of two castings is assumed to occur long enough for the two castings to reach their maximum radioactive nuclide activity.

For the interrupting casting, two castings are assumed to be passed back and forth from the betatron building to the layout man after only one x-ray examination. These castings are alternated from betatron building to layout man long enough to reach the maximum activity in both castings. The castings are assumed to reach the layout man 15 minutes after the end of the x-ray.

For the interrupting casting, Equation 1 is used to calculate the maximum activity for each isotope. Since two castings are cycled back and forth and the one shot cycle time is 15 minutes, for short shots, the shot time is 3 minutes and the full cycle time is 30 minutes. For long shots, the shot time is 60 minutes and the full cycle time is 150 minutes.

For the single large casting, there are two intermittent exposure periods. The first being shot time followed by setup time for the next shot. The second period is the 24 hours it is in the betatron building being repeatedly x-rayed followed by 24 hours at the layout man station. This situation requires the expansion of Equation 1 to account for both cycles. Equation 2 can be used to describe this situation.

$$C = \frac{P}{\lambda}\,(1-e^{-\lambda t_1})/(1-e^{-\lambda tc_1}) * (1-e^{-\lambda t_2})/(1-e^{-\lambda tc_2})$$

Equation 2

Where:
C = the equilibrium concentration
λ = the decay constant
t1 = the shot time
tc1 = the full cycle time
t2 = exposure time for second cycle (24 hours)
tc2 = the full cycle time for second cycle (48 hours)

For the first cycle, the shot time (T1) is 3 minutes while the cycle time (TC1) is 15 minutes for short shots and 60 minutes and 75 minutes respectively for the long shots. The second cycle exposure time (T2) is the 24 hours the casting is in the betatron building. The cycle time (TC2) is the full 48 hours for the casting to complete the 24 hours betatron time and the 24 hours layout man time. These values are the same for both short and long shots.

Using Equations 1 and 2 and the parameters discussed above, the maximum surface activity for each of the six isotopes can be calculated for each scenario. Utilizing the same MCNP calculations used for the betatron operator beta dose, the initial dose rate from each of the isotopes can be calculated. After that, the dose rate was integrated from 15 minutes after the last shot to the appropriate end time for each scenario. Once the dose from all six isotopes are added, the result is the dose per shot. For the single large castings, only one casting is work per shift so no additional calculation is necessary. For the interrupting casting, the dose per shot must be multiplied the number of cycles per shift to get the dose per shift. For the long shots, the layout man could work on an average of 6.4 interrupting castings in an 8 hour shift. For the short shots, an average of 32 freshly exposed castings could be worked on in an 8 hour shift.

It was reported that the layout man would normally work on a single large casting the entire shift and occasionally be interrupted by a freshly shot priority casting. This estimate will assume this interruption accounts for 10% of the layout man’s time.

Based on worker recollections, it was estimated earlier that 10% of the shots in the betatron building were long shots. However, part of the layout man's work on freshly exposed castings is to mark defects. The number of defects in a casting are at least to some extent related to the thickness of the casting with thicker castings expected to have more defects. Therefore, the layout man's work marking castings could be biased toward long shots. This estimate will use a value of 25% to represent the time the layout man is working on long shot castings.

Lastly, since the work involves marking the castings, it is expected that the layout man is in close proximity to the casting a large fraction of the time. This estimate assumes the layout man is 1 foot from the casting 90% of the time and 1 meter the remaining 10% of the time. The layout man's hands and forearms are assumed to be within one centimeter of the castings when his body is within one foot (90% of the time).

Table 5 and 6 include the annual dose estimates from all sources for the betatron operator and the layout man respectively.

Table 5 – Dose Estimate to Betatron Operator

Year	Neutron dose while x-raying steel (mrem/yr)	Neutron dose while x-raying Uranium (mrem/yr)	Neutron dose from irradiated Uranium (mrem/yr)	Total Neutron dose (mrem/yr)	Gamma (mrem/yr)	Beta dose skin of the whole body (rad/yr)	Beta dose hand and forearm (rad/yr)
1952	76	20	12	108	10225	0.71	7.31
1953	303	81	48	432	10225	2.86	29.25
1954	303	81	48	432	10225	2.86	29.25
1955	303	81	48	432	10225	2.86	29.25
1956	303	81	48	432	10225	2.86	29.25
1957	303	81	48	432	10225	2.86	29.25
1958	311	68	40	419	10225	2.60	24.81
1959	314	62	37	413	10225	2.49	22.98
1960	314	62	37	413	10225	2.49	22.98
1961	309	72	43	423	10225	2.67	26.12
1962	320	52	31	403	10225	2.28	19.46
1963	342	14	8	365	10225	1.53	6.63
1964	347	5	3	356	10225	1.35	3.59
1965	348	4	2	354	10225	1.32	3.11
1966	174	1	1	176	10225	0.65	1.32

Table 6 – Dose Estimate to Layout Man

Year	Neutron dose while x-raying steel (mrem/yr)	Gamma while x-raying steel (mR/yr)	Gamma from irradiated Steel (mR/yr)	Total Gamma (mR/yr)	Beta dose skin of the whole body (mrad/yr)	Beta dose hand and forearm (mrad/yr)
All years (a)	751	8982	19.8	9002	226	408

(a) Not applicable before 1963, 1966 dose should be prorated to half these values.

BB.4.4 External Dose Estimate for Isotope source Operations

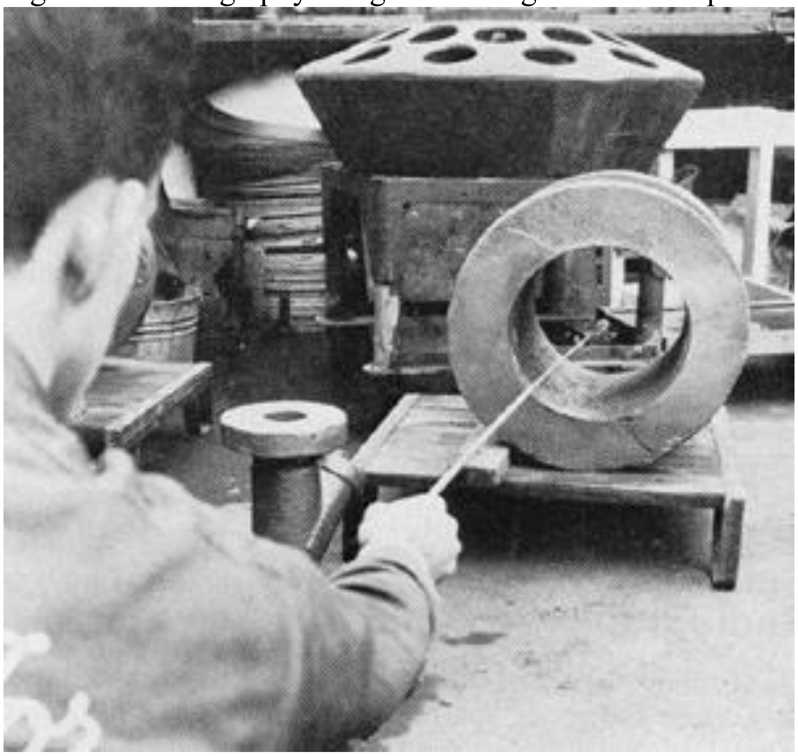
Radium-226 Radiography

Prior to 1963, GSI used two Ra-226 sources for radiography. These sources were 500 mg (500 mCi) each (AEC 1962, pg. 9). The sources were reported to have been held in a container that looked like a plumb bob (see figure 6 for an example of such a container). According to GSI's AEC license application in 1962, the Ra-226 sources were used with the "fishing pole" technique. This technique involves attaching the source to the end of a string and attaching the other end of the string to the end of a pole in a configuration that resembles a fishing pole (figure 7). A former operator indicated the shot was set up so that the film was in place and a small cup was positioned where the source was to be placed. The operator then moved the source from a shielded container to the cup using the fishing pole where it was placed for the duration of the shot. When the desired exposure time was achieved, the process was reversed to remove and store the source. The operator reported that the pole was 4 to 6 feet long and it took 12 to 15 seconds to place the source (DCAS 2011). Assuming the midpoint distance of 5 feet and the midpoint time of 13.5 seconds the exposure to the operator for placing the source would be 0.67 mR. He would receive the same exposure again when removing the source so his total exposure per shot would be 1.33 mR.

Figure 6 – Example of a Common Radium Industrial Radiography Source

ORAU Collection

Figure 7 – Radiography using the Fishing Pole Technique

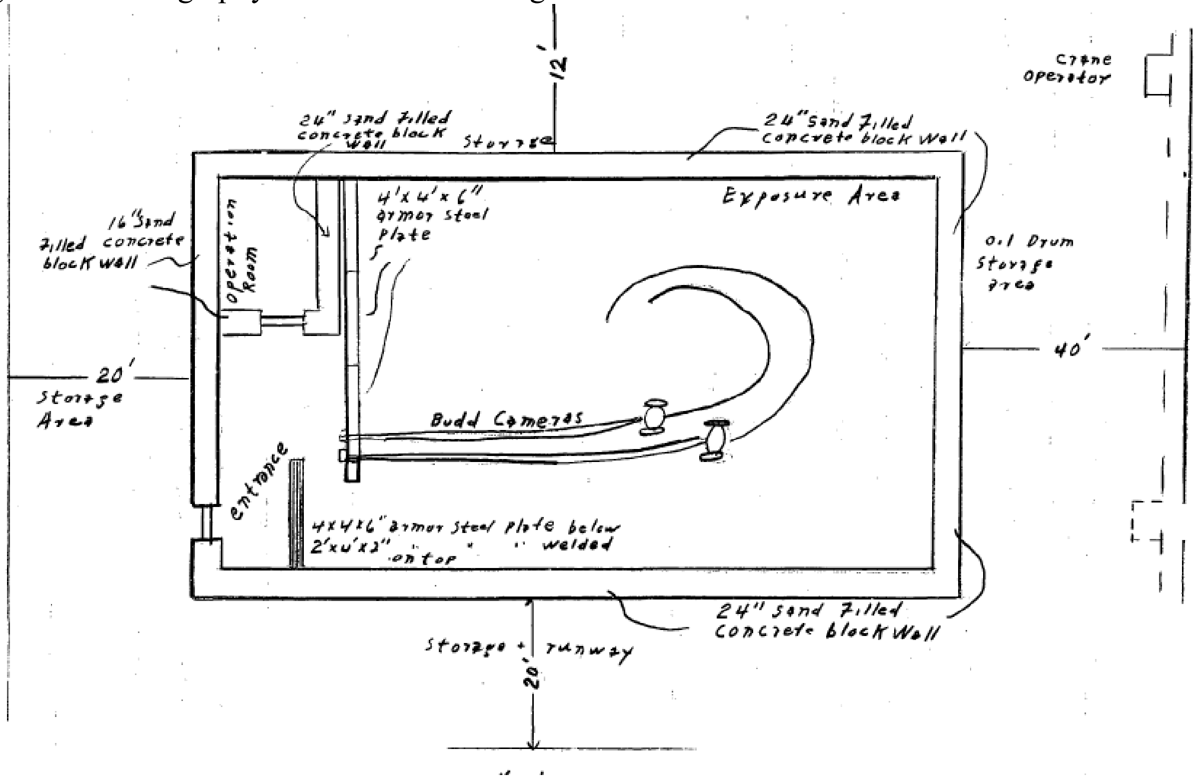


ORAU Collection

A special radiography room was built within the #6 building. The room measured 22 feet by 60 feet and contained a separate room for the operators as well as armor steel plates for shielding (AEC 1962 pg 8 & 9). The walls of the room were constructed with 24" thick sand filled concrete blocks. The top of the room was open to allow an overhead crane to lower items into the room. Figure 8 provides a drawing of this room. The figure was repeated in later license renewal applications. One of the earliest included a notation indicating additional shielding was added in June and July of 1962.

Former workers at GSI also reported that the sources were sometimes used outside of the radiography room. They reported that, when that occurred, they would rope off an area 1.5 times the required distance. Additionally, it was reported that the radiographers would leave the area unattended at times and other people would then ignore the boundary and walk through the area (Transcript 2009; pg 137).

Figure 8 – Radiography Room in #6 Building



In addition to receiving a radiation dose while placing and removing the source, when working outside the radiography room, radiographers would also receive a dose while waiting at the boundary. A boundary was reportedly set up at 1.5 times the required distance. The required distance would be the point where the radiation levels fell below 2 mR/hr. One and a half times this distance would set the boundary at a dose rate of 0.89 mR/hr. Assuming the radiographer stayed at the boundary for the duration of the shot, an additional dose would be received. To estimate that dose, it is first necessary to determine how many shots were taken and the total duration of those shots.

No direct records were found as to how often the radium sources were utilized at GSI (such as a shot log), however, some indirect information does exist. In 1962, GSI transitioned from using two 500 mg Ra-226 source to using two small Co-60 sources. The stated purpose for the transition was a State of Illinois request that GSI stop using the radium sources (Kleber 1962). Some key dates associated with the transition are:

- 3/7/1962 Applied for an AEC source license (Kleber 1962)
- 4/18/1962 License granted by the AEC (AEC 1962 pg 2)
- 5/21/1962 Purchased two Co-60 sources (AEC 1962a, pg 3)
- 6/24/1962 survey of radiography room with 2 Co-60 sources exposed (NCC 1962)
- 8/1/1962 survey of radiography room with 2 Co-60 sources exposed (NCC 1962)
- 11/6/1962 inspected by the AEC (AEC 1962a)

The frequency of the radiographic examinations at GSI was driven by the rate at which products were produced. There is no reason to believe that this production rate would change due to the purchase of the Co-60 sources. The purpose of the source change was to discontinue the use of radium, not change the testing program. Also, the date of the AEC inspection is less than six months after the Co-60 sources were purchased. This makes the inspection contemporaneous with the use of radium sources since they would have been used at least until the Co-60 sources were purchased. Therefore, the frequency of radiographic examinations discussed in the 11/6/1962 AEC inspection is considered the same frequency that the radium sources were used.

The AEC inspection, conducted on 11/6/1962 indicated that approximately 10 radiographic examinations were conducted per work shift and these examinations varied from one minute to 70 minutes in duration (AEC 1962a, pg 3). Another report indicated a maximum of 30% of each shift is used for actual examinations. That report also indicated exams ranged from 1 or 2 minutes up to 1.5 hours (AEC 1962 pg 12). The examination durations in the two reports are reasonable consistent. The first report gives no indication of the total duration per shift while the second report indicates 30% of an 8 hour shift (144 minutes). Therefore, it will be assumed that Ra-226 and Co-60 radiography consisted of 10 shots per shift for a total duration of 144 minutes.

An estimate of the radiographer exposure during Ra-226 radiography can then be made by assuming 1.33 mR/shot (from placing and retrieving the source) times 10 shots per shift times 406.25 shifts per year for an annual exposure of 5411.25 mR. Added to that is the boundary exposure rate of 0.89 mR/hr times 144 minutes per shift times 406.25 shifts per year for an annual exposure of 868 mR. This results in a total annual exposure of 6279 mR.

That estimate is very dependent on time and distance associated with placing and retrieving the source. Those parameters are not well known. While the recollection of the former radiographer is likely to be accurate for his own experience, it is not necessary accurate for others. Therefore, an additional estimate using worst case time and distance from the worker's recollection was calculated. Using the same technique as before but substituting 4 feet and 15 seconds for placing and retrieving the source, a new estimate of 9.40 R/yr can be calculated for placing and retrieving the sources.

In addition, it was reported that the majority of radiography occurred in the radiography room of the number 6 building. Other reports indicated the room was not built until 1955. Those reporting the majority of work occurred within the room started working at GSI after 1955 so the two reports are not conflicting. Rather, this estimate will assume the room did not exist until after 1955. Also, the report that a boundary was set up at 1.5 times the required distance is not documented anywhere. If a boundary exposure rate of 2 mR/hr is assumed, a boundary exposure of 1950 mR/yr can be an estimated using the 144 minutes per shift and 406.25 shifts per year. This boundary exposure would only apply through 1955. For years after 1955, an MCNP model was constructed of the room and used to estimate an exposure rate of 0.303 mR/hr in the operation room. The radiographer was reported to spend most of his time during the shot in this operation room. The model was based on a drawing from the AEC license application (figure 8). Using the results of this model and the source utilization time of 144 minutes per shift, the annual exposure received during the shots can be calculated to be 295 mR/yr.

Combining the boundary exposure with the dose from placing and retrieving the source results in an annual exposure estimate of 11.345 R/yr through 1955 and 9.69 R/yr after 1955.

Also, while dosimetry data for this time frame could not be located (with the exception of a few examples), there were indications that a dosimetry program did exist. The application for an AEC license indicated that using this technique, no one had ever exceeded the annual limit applicable at the time and the average was always below 25% of the limit (AEC 1963 pg 27). The dose limit from 1952 through 1960 was 15 rem per year. After that, the limit was changed to a lifetime limit not to exceed 3 rem per calendar quarter which equates to no more than 12 rem per year.

A former employee provided a report summarizing his radiation dose while the radium sources were still in use. The record indicated that at GSI, he received 9.1 rem in 18 calendar quarters or 2.022 rem per year on average. An interview with the employee indicated he only worked with the sources on a part time basis and estimated he did so 80% to 90% of the weekends for one or two shifts per weekend. This would amount to between 40 and 90 shifts per year (SC&A 2011). Receiving 2.022 rem in 90 shifts is equivalent to 0.0225 rem/shift. This would result in an estimate of 9.12 rem per year to a full time radiographer.

To account for the variation in these estimates, a triangular distribution will be used as the exposure estimate for radium radiography. The minimum values will be the 6.279 R/year. The most likely value will be 11.345 R/yr through 1955 and 9.69 R/yr after 1955. The maximum will be the AEC limit (15 rem/yr or 12 rem/yr depending on the year) (AEC 1960, NBS 1949). It should be noted that this is consistent with the GSI statement in the AEC License application indicating the applicable limit has never been exceeded. It is also consistent with the dose received by the former employee discussed above.

Cobalt-60 Radiography

By 1963 the use of radium for radiography at GSI had ended and the sources were replaced with two Co-60 sources. The Co-60 sources were purchased in 1962 and a survey was conducted of the number 6 building radiography room on 6/24/1962 and 8/1/1962. It is likely the Co-60 sources had begun being used soon after and the Ra-226 sources retired. However, since an exact date is unknown, this estimate uses the favorable assumption that the Ra-226 sources continued to be used through the end of 1962.

It was reported that the majority of Co-60 radiography occurred in the radiography room of number 6 building. Some may have been done outside of that room but it appears to have been infrequent. The surveys conducted on 6/24/1962 and 8/1/1962 showed a maximum dose rate on the exterior of the radiography room of 1.2 mR/hr. The maximum dose rate in the operation room was 1.15 mR/hr (NCC 1962). While the operators were reported to spend most of the time during the shot in the operation room, it is also possible they left the building and could have been in the 1.2 mR/hr area. Since the difference is small, this estimate assumes the operators spend 100% of the time the sources were exposed, outside the room near the wall where the reading was 1.2 mR/hr. Multiplying this by 144 minutes of exposure per shift and 406.25 shifts per year gives an annual exposure of 1170 mR.

Iridium-192 Radiography
An Ir-192 source was also reported to have been used on site. No Ir-192 source was ever added to GSI's AEC license or requested to be added. A former worker for a local company, St. Louis Testing, reported that he was contracted at times to bring sources (including an Ir-192 source and a Co-60 source) on site to perform radiography. He later reported that this did not occur before 1963 and that St. Louis Testing personnel would perform the operation without GSI personnel. He also reported a boundary would be set up and guarded by St. Louis Testing during the shot. The boundary was setup at a distance that would result in an exposure rate of 2 mR/hr. Even if St. Louis Testing used a source full time and a GSI employee stood at the boundary full time, the annual gamma dose would be less than that of the layout man estimate. Therefore, dose estimate of these sources would not be the limiting estimate and thus will not be included in the GSI estimate.

BB.4.5 External Dose Estimate for portable x-ray machines
The existence of a portable 250 kvp x-ray machine was reported at GSI. It was also reported that more than one of these machines had existed. As with other sources of radiation, the purpose of these was to produce a radiograph of metal for quality control purposes. In order to produce a clear radiograph, the film cannot be exposed to stray sources of radiation so these machines would not have been used in the same vicinity at the same time. Nor would they have been used near other sources of radiation.

Details about the use of these machines are limited. A few former radiographers recall using the machines but they were reported to be used rarely. The x-ray beam is not of sufficient energy to activate nuclides in the material being x-rayed,so no source of exposure from freshly x-rayed material would exist. The maximum x-ray energy of a 250 kvp x-ray machine would be 0.25 MeV. This x-ray beam would have considerably less penetrating power than the betatron or the Co-60 sources. As such, it would only be used to x-ray relatively thin metal and such an x-ray would be short in duration. With the reported limited use and short durations when it was used, the annual dose to a worker from using this machine would be less than that estimated for the Ra-226 sources or working as a layout man. Therefore, dose estimate of this machine would not be the limiting estimate and thus will not be included in the GSI estimate.

BB.4.6 External Dose Estimate for Administrative Personnel.
The dose estimate for administrative personnel is based on the reported practice of performing radiography in the main buildings outside of the #6 building radiography room. It is not clear how frequently this occurred. It is also unclear if the reported practice of making a boundary at the point 1.5 times the required distance was always done. Therefore, this estimate assumes the boundary was set at the required distance (2 mR/hr). It was also reported that the boundary was not always respected. People would at times cross the boundary and walk through the area if the boundary was unattended.

As indicated previously, the sources are estimated to be in use an average of 144 minutes per 8 hour shift. As a favorable assumption, it is assumed that every administrative person walked through the area twice (one round trip) every shift.

The Ra-226 sources would produce a gamma exposure rate of 4440 mR/hr at one foot. A distance of 47.1 feet would be required to reduce the exposure rate to 2 mR/hr. It should be noted that the presence of castings and other materials in the area would likely reduce this distance in one or more directions.

However, assuming no shielding is favorable for this calculation. Since the purpose of traveling through the area would presumably be to take a shortcut through the restricted area, it is assumed that the person could have traveled through the area at any distance from the source within the restricted boundary. Therefore, the exposure for traveling through the area was calculated assuming the path took the person within 1 foot of the source (see Attachment A). The same calculation was performed assuming the person came within 2 feet, 3 feet, etc. of the source until all possibilities were calculated (in 1 foot increments). The average of these exposures was calculated, multiplied by 2 trips per shift and then multiplied by 406.25 shifts per year to arrive at an annual exposure of 84 mR.

It is also possible an administrative person stood at the boundary during the radiography. Since this estimate is intended for people that did not spend their entire work day in the production areas, assuming 100% occupancy would be unrealistic. A favorable estimate of 25% is therefore assumed. This is considered favorable because it does not imply they only spend 25% of their time in the production area, it only implies they spend 25% of their time next to a radiography boundary. The remaining time could have been elsewhere in the production area or outside of the production area in their normal work area. Since the sources were exposed an average of 144 minutes per shift and the exposure rate at the boundary was 2 mR/hr, the person could have received 487.5 mR per year during the 406.25 shifts per year. Combining this with the 84 mR received traveling through the area results in an exposure estimate of 571.5 mR per year.

BB.4.7 External Dose Estimate Summary

The limiting external dose estimates depend on the worker category as well as the year in which they worked and the organ of interest for dose reconstruction. The estimates derived above were derived with the intent to choose the highest single estimate for operators because it was assumed individual workers could not be placed in one particular operation or another. Radium radiography was the limiting estimate for most workers prior to 1963. However it was realized that the radium radiography examinations only took approximately 30% of the time during a shift and the remaining time could have been spent working in the betatron building (the next highest estimate). The 30% value represents the actual time the film was exposed and does not include the time to set up the shot or to travel to the location. If it is assumed at least 10 minutes is necessary for setting up and removing the film and other tasks associated with radium radiography to would total 100 minutes per shift. Combined with the 144 minutes of shot time, the radium radiography would account for approximately 50% of the shift. This estimate will assume that during one shift, a radiographer could perform all the radium radiography plus spend 50% of the shift in the betatron building performing radiography there. Therefore, the scenario of 100% radium radiography dose plus 50% of the betatron operator dose will be included as a possible scenario from which the limiting dose estimates are chosen. The limiting scenarios are summarized below.

Administrative Workers

This exposure estimate is to be assigned for all years of AEC operations (October 1952 through June 1966). The years 1952 and 1966 are prorated for the partial year of operations. Partial years of employment within this time period should be prorated for each case. The dose should be assigned as 30 to 250 keV photons as a constant distribution. This estimate is assigned to Administrative Workers which are defined as anyone normally working in an office environment not routinely entering the production areas. All other employees will be assigned the dose estimate for Operators.

Table 7 – Administrative Worker Exposure Estimate

Year	Gamma (mR/yr)
All years	571.5

Operators

For Operators, the bounding estimate from the estimates derived above is used. Tables 8 and 9 provide those estimates. The bounding estimate in the early years at GSI is the exposure estimate to the Ra-226 radiographers. After 1962, the bounding estimate is the layout man dose estimate for most cases. In the case of the skin to the hands or forearms, the betatron operator dose estimate is limiting. This is due to the much larger beta dose estimate for handling uranium. For a case of multiple cancers, if one or more but not all of the cancers include the skin of the hands or forearms, the dose estimate should be from only one of the tables below. That is, it should not be assumed that the skin received the betatron operator dose while the other organs received the layout man dose. Both tables should be used to estimate the dose to each organ and the more favorable overall estimate used.

Table 8 – Operator Dose Estimate for Organs Other Than Skin of the Hands and Forearms (H&F)

Year	Gamma Dose (R/yr)	Neutron Dose (mrem/yr)	Beta Dose (mrad/yr)	Source of Estimate
1952	15/ 11.345/ 6.279 (a) plus 5.112 (b)	54	357	Radium source + 50% of betatron
1953	15/ 11.345/ 6.279 (a) plus 5.112 (b)	216	1428	Radium source + 50% of betatron
1954	15/ 11.345/ 6.279 (a) plus 5.112 (b)	216	1428	Radium source + 50% of betatron
1955	15/ 11.345/ 6.279 (a) plus 5.112 (b)	216	1428	Radium source + 50% of betatron
1956	15/ 9.69/ 6.279 (a) plus 5.112 (b)	216	1428	Radium source + 50% of betatron
1957	15/ 9.69/ 6.279 (a) plus 5.112 (b)	216	1428	Radium source + 50% of betatron
1958	15/ 9.69/ 6.279 (a) plus 5.112 (b)	209	1298	Radium source + 50% of betatron
1959	15/ 9.69/ 6.279 (a) plus 5.112 (b)	207	1244	Radium source + 50% of betatron
1960	15/ 9.69/ 6.279 (a) plus 5.112 (b)	207	1244	Radium source + 50% of betatron
1961	12/ 9.69/ 6.279 (a) plus 5.112 (b)	211	1336	Radium source + 50% of betatron
1962	12/ 9.69/ 6.279 (a) plus 5.112 (b)	201	1141	Radium source + 50% of betatron

1963	9.002	751	226	Layout man
1964	9.002	751	226	Layout man
1965	9.002	751	226	Layout man
1966	4.501	376	113	Layout man

(a) Triangular distribution maximum/most likely/minimum
(b) 5.112 dose is actually rad/yr rather than R/yr and represent a constant distribution, PA geometry, <30 kev photons

Table 9 – Operator Dose Estimate for the Skin of the Hands and Forearms (H&F)

Year	Gamma Dose (R/yr) (a)	Neutron Dose (mrem/yr)	Beta Dose (mrad/yr)	Source of Estimate
1952	10.225	108	7312	Betatron Operator
1953	10.225	432	29249	Betatron Operator
1954	10.225	432	29249	Betatron Operator
1955	10.225	432	29249	Betatron Operator
1956	10.225	432	29249	Betatron Operator
1957	10.225	432	29249	Betatron Operator
1958	10.225	419	24810	Betatron Operator
1959	10.225	413	22982	Betatron Operator
1960	10.225	413	22982	Betatron Operator
1961	10.225	423	26115	Betatron Operator
1962	10.225	403	19456	Betatron Operator
1963	10.225	365	6627	Betatron Operator
1964	9.002	751	408	Layout man
1965	9.002	751	408	Layout man
1966	4.501	376	204	Layout man

(a) 1952 to 1963 readings are actually rad/yr rather than R/yr and represent a constant distribution, PA geometry, <30 kev photons

Except for triangular distributions described in Table 8, all doses should be assigned as a constant distribution. Gamma doses should be assigned as 30 to 250 keV photons except for the 10.225 rad/yr doses from betatron operations. That should be used with the <30 kev DCF for air kerma in the PA geometry. Neutron doses should be assigned as 100 keV to 2 MeV neutrons and beta doses should be assigned as >15 keV electrons.

BB.5 Occupational Internal Dose

The primary source of internal dose at GSI is handling uranium metal. No data was found related to occupational internal dose during AEC work at GSI. In addition, no records of air monitoring were found in the site research database. Since no intentional cutting, machining, or abrading of uranium was involved, there was a low potential for producing elevated air concentrations of uranium. Another source of potential internal dose is the grinding of steel castings soon after being x-rayed in the betatron. The betatron photons are of sufficient energy to interact with materials and cause the creation of radionuclides.

BB.5.1 Intakes from handling uranium metal

Unlike many Atomic Weapons Employers (AWE) the AEC contracted work at GSI did not involve forming or shaping of uranium metal through processes such as rolling, machining, cutting, or straightening. The work at GSI consisted solely of taking x-rays of uranium metal that were used to evaluate the integrity of the cast uranium metal manufactured at Mallinckrodt Chemical Works. Thus, the only potential for generation of airborne uranium at GSI would be from the movement of the metal into position for the examination.

No air samples were found at GSI so data from the movement of uranium metal at other sites was compiled. Samples that may have been interfered with by other operations in the vicinity or associated with the movement of heated uranium metal were avoided since they would not be representative.

Twenty-five samples from three different sites were found to be representative of the airborne activity associated with the movement of cold (i.e., unheated) uranium metal. The samples represent several shapes and sizes of metal varying from one inch diameter by eight inch long slugs weighing a little over 4 pounds to 18 inch diameter by 18 inch long dingots weighing over 3000 pounds. An analysis of the airborne caused by moving these different forms found that the size and shape did not significantly affect the airborne concentration created by moving the metal (Attachment B).

The data reasonably fit a lognormal distribution with a geometric mean of 17.5 dpm/m^3 and a geometric standard deviation of 2.29. This distribution has a 95th percentile of 68.7 dpm/m^3. The 95th percentile will be used in this estimate and applied as a constant.

BB.5.2 Intakes from Fission Products

Intakes of fission products must also be considered. Because there are many different isotopes produced as fission products, it makes it difficult to estimate internal dose from this process. Internal dose from uranium is caused by a low dose-rate delivered over years. Many fission products on the other hand have a relatively short half-life so they do not deliver a dose for a long period of time.

An analysis conducted for revision 0 of this document determined that increasing the uranium airborne activity by 1% would be a favorable method of accounting for uranium fission and activation products. An independent review of this assessment agreed with NIOSH's conclusion (SC&A 2008). Therefore, this revision will increase the uranium airborne activity by 1% in all calculations.

BB.5.3 Intakes from Activation products in Steel

The purpose of x-raying steel castings was to detect internal flaws. Once found, they could be ground out and repaired. This implied the steel could be ground out soon after the x-ray while it is still radioactive, which would cause radioactive dust to be inhaled by the person grinding the casing. To estimate this intake pathway the layout man's work scenario was utilized. It was assumed that someone was grinding on the freshly x-rayed casting the entire time and that the airborne activity produced during the grinding was 4 mg/m^3. The 4 mg/m^3 was derived from Table 7.5 of TBD-6000 which lists uranium airborne concentrations from uranium machining operations. Of the three grinding operations, centerless grinding had the highest results of 4000 to 5000 dpm/m^3. This equates to a mass concentration 3.571 mg/ m^3 to 4.286 mg/ m^3.

The steel was assumed to be x-rayed with the betatron for 30 continuous hours prior to the layout man working on the casting. MCNP was used to determine the production rate of radionuclides in HY-80 steel and the specific activity of each radionuclide in the steel was determined. The activity was allowed to decay after the shot. It was assumed 4 mg/m3 of steel was always in the air from the casting and inhaled. This intake resulted in an annual internal dose less than one mrem for all organs. Therefore, no internal dose will be assigned from the inhalation of steel.

BB.5.4 Summary of Intakes of Radioactive Material

Based on worker input, x-ray shots of uranium took 60 minutes each with 15 minutes between them. Furthermore, it was reported that 4 shots were taken on each piece of uranium. This implies the uranium was being moved only about 5% of the time the uranium was in the building (15 minutes out of 300 minutes). Since the uranium had to be properly positioned in the betatron building and not just moved, it may be reasonable to think that the manipulation of the uranium in the betatron building took more time than moving the same uranium to and from the building. That would imply the time involved in moving uranium around the site would be less than 5% of the time it was in the betatron building.

However, there are several possibilities that could change that assumption. First, it is possible the handling inside the betatron building was more efficient than outside even if inside work involved proper placement and not just movement. Second, it is possible the uranium was moved from conveyance to conveyance within the site (fork truck, rail car, crane, etc.) thus representing multiple episodes of handling rather than once in each direction. It should however be noted that it is unlikely this occurred in one area. More likely, the uranium would be moved some distance with each conveyance before being transferred to another conveyance and airborne activity would thus not accumulate in a single area. Lastly, it is possible that while the uranium is being moved on a conveyance, additional airborne activity could be produced by vibrations. Again however, this would not occur in a single area but rather all along the path.

With these uncertainties in mind, this estimate will assume workers are exposed to uranium airborne contamination as if the uranium were handled 100% of the uranium contract time. The uranium contract times vary by year as described in Table 2. The airborne concentration is assumed to be the 95th percentile of the uranium handling airborne distribution discussed in section BB.5.1. That value was increased by 1% to account for fission product activity (section BB.5.2). The annual intake was divided by 365 days per year to derive an intake rate per calendar day. The intake values are presented in Table 10.

In between uranium work episodes, it is still possible to create uranium airborne contamination by resuspending any uranium surface contamination left behind by the uranium handling. Intakes from this scenario were calculated by first estimating the surface contamination by assuming the uranium airborne was deposited at a rate of 0.00075 m/s for 30 days. A resuspension factor of 1E-5 m^{-1} was then used to calculate the airborne concentration due to resuspension. This concentration was assumed to be inhaled 100% of the time during the operational period. The value was converted to dpm per calendar day and is presented in Table 10.

Intakes due to ingesting uranium contamination were also calculated. The ingestion intake was calculated using OCAS-TIB-009. The airborne value used in that calculation was the average airborne activity to which an operator was exposed. That is, the highest inhalation rate calculated (114.22 dpm/day) was converted to the equivalent airborne activity that would produce that intake rate if inhaled full time. The ingestion rate based on the highest inhalation rate is used for each year. These values are included in Table 10.

Table 10 – Intake Estimate

Start Date	End Date	Uranium work hrs/yr	Metal handling Inhalation (dpm/day)	Resuspension inhalation (dpm/day)	Total inhalation (dpm/day)	Ingestion (dpm/day)
10/1/1952	12/31/1957	437.5	99.80	14.41	114.22	2.38
1/1/1958	12/31/1958	366.7	83.64	14.41	98.06	2.38
1/1/1959	12/31/1959	337.5	76.99	14.41	91.40	2.38
1/1/1960	12/31/1960	337.5	76.99	14.41	91.40	2.38
1/1/1961	12/31/1961	387.5	88.40	14.41	102.81	2.38
1/1/1962	12/31/1962	281.3	64.16	14.41	78.57	2.38
1/1/1963	12/31/1963	76.6	17.47	14.41	31.88	2.38
1/1/1964	12/31/1964	28.1	6.42	14.41	20.83	2.38
1/1/1965	12/31/1965	20.5	4.67	14.41	19.09	2.38
1/1/1966	6/30/1966	6.4	2.96	14.41	17.37	2.38

BB.6 Residual Contamination

After uranium operations ended at GSI, uranium contamination may have been left behind on surfaces. This residual contamination would cause external and internal doses to be received by workers even after the uranium work ended. In 1989 the old betatron building was surveyed to check for residual contamination (ORNL 1990). Later the new betatron building was surveyed and in 1993, a short decontamination effort removed any detectable contamination (DOE 1994). A residual contamination period for GSI is designated from 7/1/1966 to 12/31/1993 (DOE web site).

The internal dose estimate for the operational period included inhalation and ingestion intakes from surface contamination. With no indication of a decontamination effort or a cleanup, it is assumed that these levels of inhalation and ingestion continued into the residual period. This level is assumed from 7/1/1966 to 12/31/1967. After that, the level is assumed to decrease at a rate of 0.00067 per day in accordance with ORAUT-OTIB-0070. The calculated values by year are included in Table 11.

Using contamination levels derived in section BB.5.4 and the conversation factor contained in Battelle-TBD-6000, an annual photon and beta dose can be calculated to be 0.173 mR/yr and 16.7 mrad/yr respectively. However, a 1989 survey of the old betatron also included a dose rate survey of the building. While most measurements were consistent with background levels of radiation, a vacuum cleaner in one corner measured 90 uR/hr on contact. This represents a radiation dose higher than that from the surface contamination levels calculated above. It is possible some uranium was vacuumed and thus concentrated in this localized area causing a localized dose rate higher than what would be expected if the contamination were distributed. Also, in that scenario, the depletion factor from ORAUT-OTIB-0070 would not be applicable. In order to account for this possibility, this estimate assumes someone is in contact with this vacuum cleaner for 3250 hours per year, resulting in an annual dose of 292.5 mR. This value will be assigned to each year of exposure during the residual contamination period as a constant distribution. The energy should be assumed to be 50% greater than 250 keV and 50% 30 to 250 keV. Since in this scenario the vacuum cleaner would stop beta particles the beta dose rate is considered zero in the residual period. It should be noted that this dose is more favorable than the combined photon and beta dose calculated from a distributed source.

Since both internal and external estimates are based on bounding scenarios, doses calculated will be entered into IREP as a constant.

Table 11 – Residual Period Dose Estimate

Start Date	End Date	Inhalation (dpm/day)	Ingestion (dpm/day)	External Photon (mR/yr)
7/1/1966	12/31/1967	14.41	2.38	292.5
1/1/1968	12/31/1968	11.29	1.86	292.5
1/1/1969	12/31/1969	8.84	1.46	292.5
1/1/1970	12/31/1970	6.92	1.14	292.5
1/1/1971	12/31/1971	5.42	0.89	292.5
1/1/1972	12/31/1972	4.24	0.70	292.5
1/1/1973	12/31/1973	3.32	0.55	292.5
1/1/1974	12/31/1974	2.60	0.43	292.5
1/1/1975	12/31/1975	2.04	0.34	292.5
1/1/1976	12/31/1976	1.60	0.26	292.5
1/1/1977	12/31/1977	1.25	0.21	292.5
1/1/1978	12/31/1978	0.98	0.16	292.5
1/1/1979	12/31/1979	0.77	0.13	292.5
1/1/1980	12/31/1980	0.60	0.10	292.5
1/1/1981	12/31/1981	0.47	0.08	292.5
1/1/1982	12/31/1982	0.37	0.06	292.5
1/1/1983	12/31/1983	0.29	0.05	292.5
1/1/1984	12/31/1984	0.23	0.04	292.5
1/1/1985	12/31/1985	0.18	0.03	292.5
1/1/1986	12/31/1986	0.14	0.02	292.5
1/1/1987	12/31/1987	0.11	0.02	292.5
1/1/1988	12/31/1988	0.08	0.01	292.5
1/1/1989	12/31/1989	0.07	0.01	292.5
1/1/1990	12/31/1990	0.05	0.01	292.5
1/1/1991	12/31/1991	0.04	0.01	292.5
1/1/1992	12/31/1992	0.03	0.01	292.5
1/1/1993	12/31/1993	0.02	0.00	292.5

BB.7 References

AEC 1960, Atomic Energy Commission, Title 10 – Atomic Energy; Chapter 1 – Atomic Energy Commission: Part 20 – Standards for Protection against Radiation. *Federal Register*, 22(19), 548-554.

AEC 1962, Atomic Energy Commission, *Application for Byproduct Material License with Attachments*, ML093431334, SRDB 102269, March 7, 1962.

AEC 1962a, Atomic Energy Commission, *Compliance Inspection Report,* General Steel Industries, License number 12-8271-1, ML093431295, SRDB 102258, November 21, 1962.

AEC 1963, Atomic Energy Commission, *Application for Byproduct Material License*, Amendment No. 5, ML093451452, SRDB 102283, February 14, 1968.

AEC 1968, Atomic Energy Commission, *Byproduct Material License*, ML093451491, SRDB 102284, February 15, 1963.

DCAS 2011, Division of Compensation Analysis and Support, *Battelle-TBD-6000 Appendix BB General Steel Industries, Dose Estimates for Portable Radiography Sources*, August 2011, http://www.cdc.gov/niosh/ocas/pdfs/dps/dc-gsidpradsrc0811.pdf

DCAS GSI web page, Division of Compensation Analysis and Support web page providing various white papers pertaining to GSI. http://www.cdc.gov/niosh/ocas/gsi.html

DOE 1991, U.S. Department of Energy, Office of Environmental Restoration, *Designation Summary for the Granite City Steel Division in Granite City, Illinois*, SRDB 10441, September 1991

DOE 1994, Department of Energy, *Certification Docket for the Remedial Action Performed at the Granite City Site in Granite City, Illinois, June 1993*, SRDB 10451, September 1994

DOE Web Site, DOE Office of Health, Safety and Security, EEOICPA web site. http://www.hss.energy.gov/healthsafety/fwsp/advocacy/faclist/findfacility.cfm

ICRP 1996, International Commission on Radiological Protection . "Conversion Coefficients for use in Radiological Protection against External Radiation," ICRP Publication 74. *Annals of the ICRP*, *26* (3/4). Tarrytown, NY: Elsevier Science, Inc.

Kleber 1962, *Letter from L.A. Kleber to James Mason*, ML093431291, SRDB 102254, March 7, 1962

Landauer 1964, 1964 Landauer film badge reports for GSI, SRDB 41708, 1964

Landauer 1965, 1965 Landauer film badge reports for GSI, SRDB 41662, 1965

Landauer 1966, 1966 Landauer film badge reports for GSI, SRDB 41663, 1966

Landauer 1967, 1967 Landauer film badge reports for GSI, SRDB 41664, 1967

Landauer 1968, 1968 Landauer film badge reports for GSI, SRDB 41665, 1968

Landauer 1969, 1969 Landauer film badge reports for GSI, SRDB 41666, 1969

Landauer 1970, 1970 Landauer film badge reports for GSI, SRDB 41667, 1970

Landauer 1971, 1971 Landauer film badge reports for GSI, SRDB 41668, 1971

Landauer 1972, 1972 Landauer film badge reports for GSI, SRDB 41669, 1972

Landauer 1973, 1973 Landauer film badge reports for GSI, SRDB 41670, 1973

Mallinckrodt 1958-1965, Mallinckrodt Chemical Works, Various Purchase Orders. U-52538-C, U-57809-M, U-55125-M, U-00045-M, U-00211-M, U-00339-M, U-00399-M, U-00497-M, 00623-L, SRDB 10443, 45104, 45106, 45108, 45110, 45124, 45125, 45126, 45127, 1958 through 1965.

Minutes 2007, Meeting Minutes, *Dr. Robert Anigstein of Sanford Cohen & Associates (SC&A) Interviewing Former Employees of General Steel Industries (GSI)*, SRDB 47970, October 9, 2007

NBS 1949, National Bureau of Standards (NBS), Department of Commerce (U.S.), *Medical X-ray Protection up to Two Million Volts: Handbook 41*, 1949

NCC 1962, Nuclear Consultants Corp., *Area Radiation Survey of the Radiographic Exposure Facility at General Steel Industries*, ML093431294, SRDB 102257, August 14, 1962

ORAU Collection, Oak Ridge Associated Universities (ORAU), Radium Industrial Radiography Source (ca. 1940s), Oak Ridge Health Physics Historical Instrumentation Museum Collection, last updated May 10, 2011, http://www.orau.org/ptp/collection/Sources/radiumradiog.htm

ORNL 1990, Oak Ridge National Laboratory, *Results of the Radiological Survey at the Granite City Steel Facility, Granite City, Illinois. ORNL/RASA-89/10*, SRDB 10425, July 1990

Putzier 1982, Putzier, E. A., *The Past 30 Years at Rocky Flats: A Summary of Experiences and Observations at Rocky Flats Plant Over the Past 30 Years with Emphasis on Health and Safety*, Rockwell International Energy Systems Group, Rocky Flats Plant, SRDB 4632, 1982.

SC&A 2008, Sanford Cohen & Associates, *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*, April 2008

SC&A 2011, Sanford Cohen & Associates, *Update on the Use of Sealed Radioactive Sources at General Steel Industries*, October 2011

SC&A 2014, Sanford Cohen & Associates, *Update of Doses from External Exposure at General Steel Industries*, January 12, 2014

Schuetz 2007, Jack G. Schuetz, *Correspondence with Dr. Samuel Glover*, SRDB 34933, May 2007

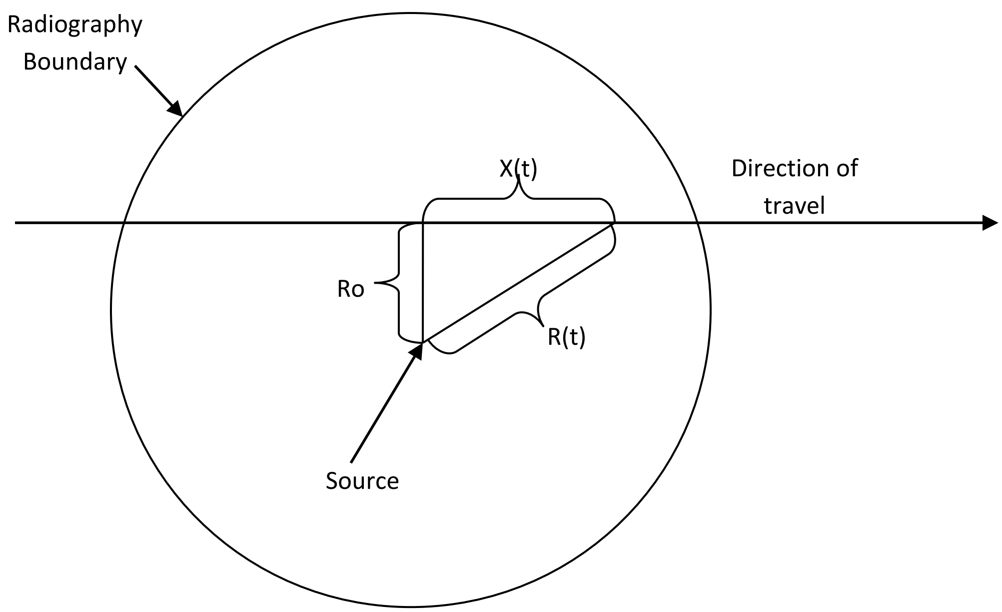
Simmons Cooper 2006, LLC, *GSI Affidavit Testimony*, SRDB 47972, July 7, 2006

MCNP6.1, T. Goorley, et al., Initial MCNP6 Release Overview, Nuclear Technology, 180, pp 298-315 (Dec 2012)

MCNPX, D.B. Pelowitz, Ed., MCNPX Users Manual version 2.7.0 LA-UR-03-1987 (2003).

Transcript 2009, Transcript of the TBD-6000/6001 Work Group of the Advisory Board on Radiation and Worker Health, SRDB 124168, October 14, 2009

ATTACHMENT A – Dose Estimate for Walking Through Radiography Area



The dose received by an individual walking through a radiography area can be calculated using the diagram provided above. The source is represented by the center of the circle while the circle represents the delineated boundary of the radiography area. The horizontal arrow represents the path taken by the individual through the delineated area. The closest distance the person come to the source is indicated as Ro and the distance from the source at any time t is R(t).

The distance between the individual and the source can then be expressed as:

$R^2(t) = Ro^2 + X^2(t)$

Or

$R^2(t) = Ro^2 + V^2 * t^2$

Where V is the velocity at which the person is walking.

The dose rate at any time, DR(t), can be expressed as:

$DR(t) = DRo * Ro^2 / R^2(t)$

or

$DR(t) = DRo * Ro^2 / (Ro^2 + V^2*t^2)$

The dose received by walking through the area is then:

$$\text{Dose} = 2 \int_0^t \text{DRo} * \text{Ro}^2 / (\text{Ro}^2 + \text{V}^2 * \text{t}^2)\, dt$$

With t = 0 at the time the person is closest to the source and t = t when the boundary of the radiography area is reached.

This equation can be approximated as:

$$Dose = \frac{2 * DRo * Ro^2}{\sqrt{Ro^2 * V^2}} * ATAN(\frac{t * \sqrt{Ro^2 * V^2}}{Ro^2})$$

The time t required to walk through the area varies as Ro changes. That is, it depends whether the person is walking through the middle of the area or cutting through the outer edge. Since DRo is the dose rate at the closest point, this too varies as Ro changes. The equations for both are:

$$t = \frac{\sqrt{R'^2 - Ro^2}}{V}$$

$$DRo = DR' * (\frac{1}{Ro})^2 \div 3600$$

Where R' is the radius of the delineated area and DR' is the dose rate at 1 foot from the source.

Substituting these two equations into the equation for dose and simplifying yields:

$$Dose = \frac{2 * DR'}{\sqrt{Ro^2 * V^2}} * ATAN(\frac{\sqrt{R'^2 - Ro^2}}{Ro})$$

ATTACHMENT B – Surrogate Air Data for Handling Uranium Metal

Battelle-TBD-6000 contains an analysis of surrogate air sample data for a number of common tasks associated with uranium metal. One task not covered is the handling and movement of cold uranium metal. To fill this void, NIOSH reviewed air sample data for a number of sites and combined them into this analysis.

Most active manipulation of uranium metal requires the metal to be heated. Typically uranium in these processes is heated to well over 1000 degrees Fahrenheit. At these high temperatures, the uranium metal oxidizes readily forming a loose oxide layer that can easily create airborne contamination. An exception to heating uranium metal during operations is machining. When uranium metal is machined or cut, it is not normally preheated. Rather, the area being cut is cooled with machine oil, water or some other coolant. This not only reduces the release of airborne activity, but also cools the metal to prevent fuming.

In all cases, however, the metal is moved by various means to the furnace or equipment prior to working. The movement of cold uranium metal presents such a low potential for airborne uranium that very few air samples were ever taken. Those that were, are often taken while other operations are also occurring causing the air in the vicinity to be contaminated by the nearby operations. Therefore, samples intended to be representative of the operation at GSI must consider not only the type of operation but the potential interferences in the vicinity.

The data set used in listed in Table B.1. The samples include data collected at several facilities and cover operations involving three forms of uranium metal: slugs, billets and dingots.

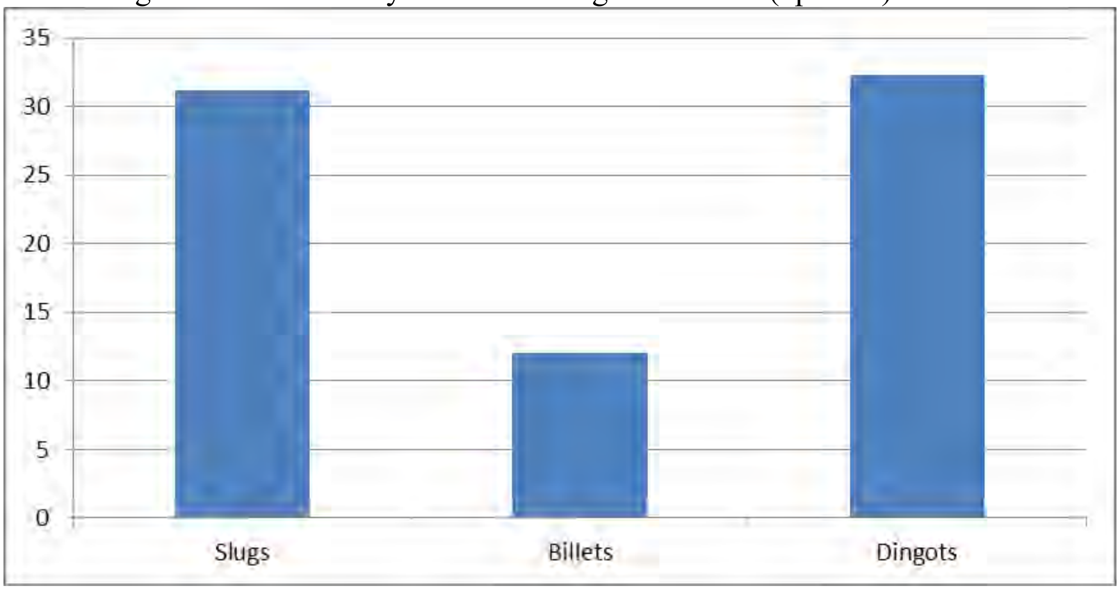
Slugs were typically 8 inches long and approximately 1 inch diameter weighing approximately 4 pounds. They were intended to be used as fuel in plutonium production reactors. Operations associated with the selected samples primarily involved moving slugs into or out of a container.

A billet is a generic metallurgical term used to describe a semi-finished piece of metal. In uranium fuel fabrication, it is a piece of uranium metal that was originally cast into an ingot and rolled into a smaller dimension using a blooming mill. The billet would later be further rolled to a finished product using a rolling mill. The billets associated with the data found for this report were approximately 7 inches in diameter and 20 inches long. This would result in a billet weighing approximately 525 pounds.

A dingot (direct ingot) is a term used at Mallinckrodt to describe an ingot made directly from the metal reduction process. The alternative procedure was to remelt several derbies and cast them into ingots. The dingot is approximately 18 inches in diameter and 18 inches long weighing approximately 3300 pounds.

Figure 1 graphically depicts the average airborne value associated with handling each form of uranium found in Table B.1.

Figure B.1 – Average Airborne Activity while Handling Cold Metal (dpm/m^3)



The figure is arranged from left to right by the weight associated with each form of metal. No specific pattern can be seen that would indicate one form of metal creates higher airborne activity than another. Based on the data reviewed, however, the levels of airborne activity are relatively low and can be represented by a fairly consistent quantity regardless of the form of the metal. Therefore, to establish the range of exposures associated with the movement of cold uranium metal, all the data in Table B.1 were combined into a single distribution of airborne activity.

Table B.1 contains the results for the samples utilized in this report. The attachment includes the Site Research Database document number and page number where the sample was located. It also includes the site from which the samples were collected as well as the type of metal and the date the sample was collected. A few of the values are listed as “nd” which represents a “none detectable” sample.

The samples were analyzed assuming they can be represented as a lognormal distribution. The resulting distribution has a geometric mean of 17.5 dpm/m^3 with a geometric standard deviation of 2.29. This distribution results in a 95th percentile value of 68.7 dpm/m^3. This is the value NIOSH intends to use for the assessment of inhalation exposure to uranium at GSI.

Table B.1 – Airborne Activity Samples

SRDB#	Pg#	Activity (dpm/m^3)	Site	type	Date
10634	11	9	Leblond	billets	8/22/1961
10634	11	Nd	Leblond	billets	8/22/1961
10634	11	Nd	Leblond	billets	8/22/1961
10634	11	15	Leblond	billets	8/22/1961
10634	11	Nd	Leblond	billets	8/22/1961
10634	11	Nd	Leblond	billets	8/22/1961
98533	129	53	Tocco	slugs	2/16/1968
98533	129	22	Tocco	slugs	2/16/1968
98533	124	9.44(1)	Tocco	slugs	6/6/1968
98533	124	69.83(1)	Tocco	slugs	6/6/1968
98533	124	9.44(1)	Tocco	slugs	6/6/1968
98533	124	45.3(1)	Tocco	slugs	6/6/1968
98533	124	Nd	Tocco	slugs	6/6/1968
98533	124	35.86(1)	Tocco	slugs	6/6/1968
12363	78	24	Weldon Spring	dingots	11/14/1960
12363	78	21	Weldon Spring	dingots	11/14/1960
12363	22	66.6 (2)(3)	Weldon Spring	dingots	7/26/1961
12363	22	46.62 (2)(3)	Weldon Spring	dingots	7/26/1961
14956	4	25	Weldon Spring	slugs	3/30/1960
14956	4	25	Weldon Spring	slugs	3/30/1960
14956	4	25	Weldon Spring	slugs	3/30/1960
14956	4	23	Weldon Spring	slugs	3/30/1960
17254	6	11.8	Weldon Spring	dingots	12/10/1956
17254	6	Nd	Weldon Spring	dingots	12/10/1956
17254	6	23.7	Weldon Spring	dingots	12/10/1956

(1) Actual values for depleted uranium increased by a factor of 1.887 to adjust to normal uranium equivalent
(2) Values listed as maximum, minimum used as two different samples
(3) Values back calculated using conversion factors at the bottom of summary report