BATTELLE-TBD-6000 Appendix BB General Steel Industries
DOSE ESTIMATES FOR BETATRON OPERATIONS
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Background

Numerous documents and information from former workers at General Steel Industries (GSI) have come to light since the original exposure estimate for GSI was written and approved (DCAS 2007). The information contained in these documents, as well as the input from former workers, has proven to be useful in refining the estimates of potential radiation dose to employees of GSI. This white paper is intended to incorporate all information into a model for exposures at GSI that are consistent with all the data. The scenarios developed are intended to represent either realistic or worst case exposure conditions when information is lacking.

This paper starts by adjusting the previous exposure model for the new betatron building to incorporate the newly collected information. The exposure conditions developed in the new model are compared to the survey results obtained when a Co-60 source was exposed. Next the dose rates from various routes of exposure are developed. Lastly, the information is assembled in a manner that is consistent with film badge records. In this paper, the process of exposing x-ray film to radiation in an attempt to produce a radiograph of a piece of equipment is referred to as a "shot". An attempt was made not to refer to the process as "an exposure" to avoid confusion with radiation exposure to a person.

New Betatron Building

Previous exposure models for GSI's new betatron utilized building drawings from a January 1992 report (ORNL 1990) that described an August 1991 FUSRAP survey (see Figure 1). After these models were developed, new information and drawings were obtained that provided additional details of the building. The additional drawings are provided in Figures 2 through 4 (ML093480290). Some of the additional building details included:

- The existence of a concrete shield wall extending beyond the 10 foot thick walls of the equipment tunnel;
- The existence of lead inside the double leaf door at the end of the equipment tunnel; and,
- Various dimensions of the building and its relationship to adjacent buildings.

Figure 1 – New Betatron Building from 1992 FUSRAP report

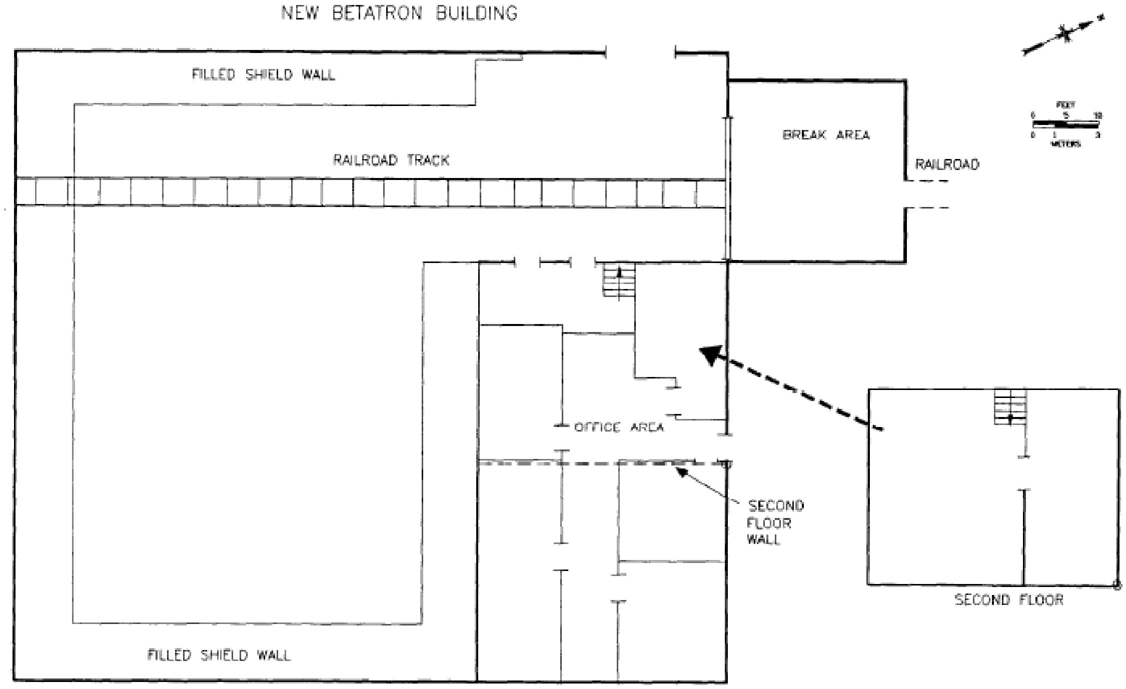


Figure 2 – New Betatron Building from AEC License Application

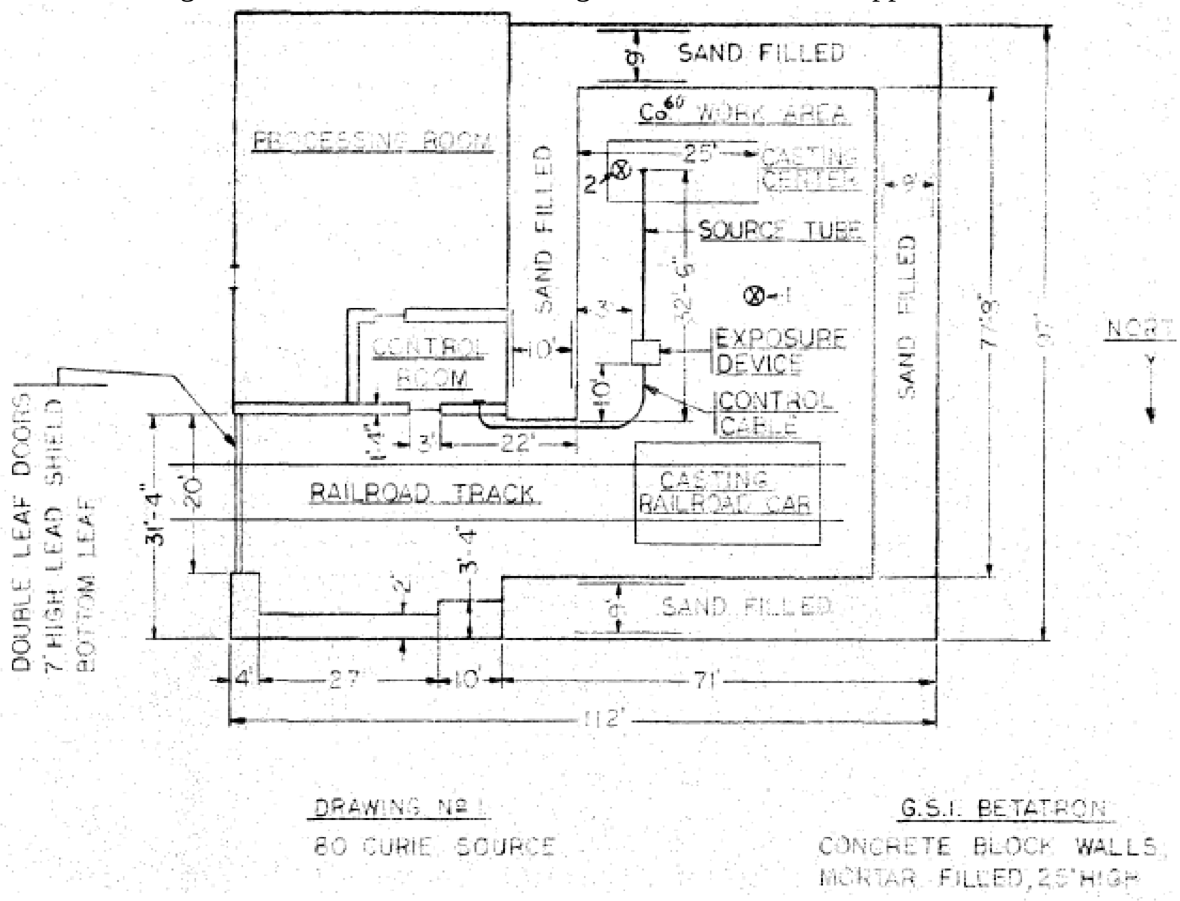


Figure 3 – New Betatron Building with Nearby Buildings

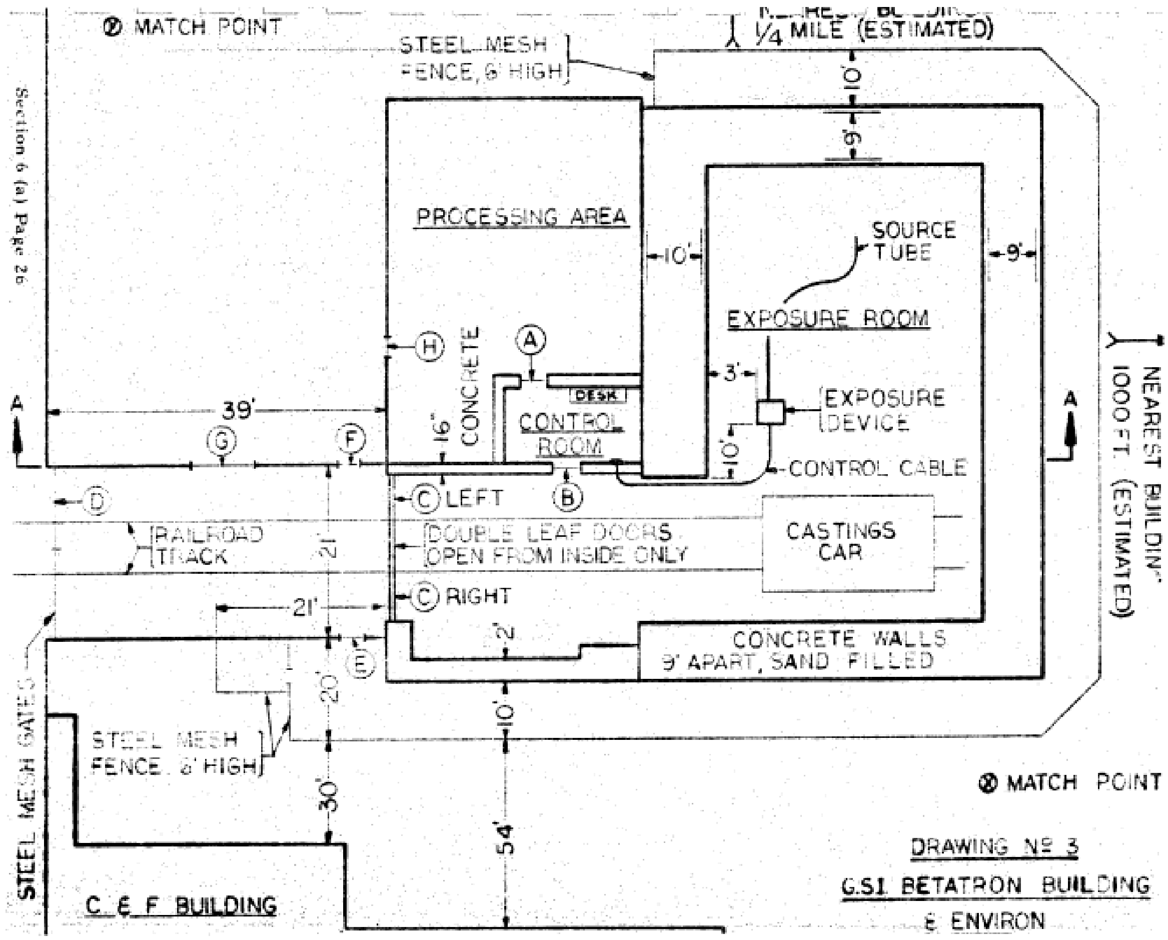
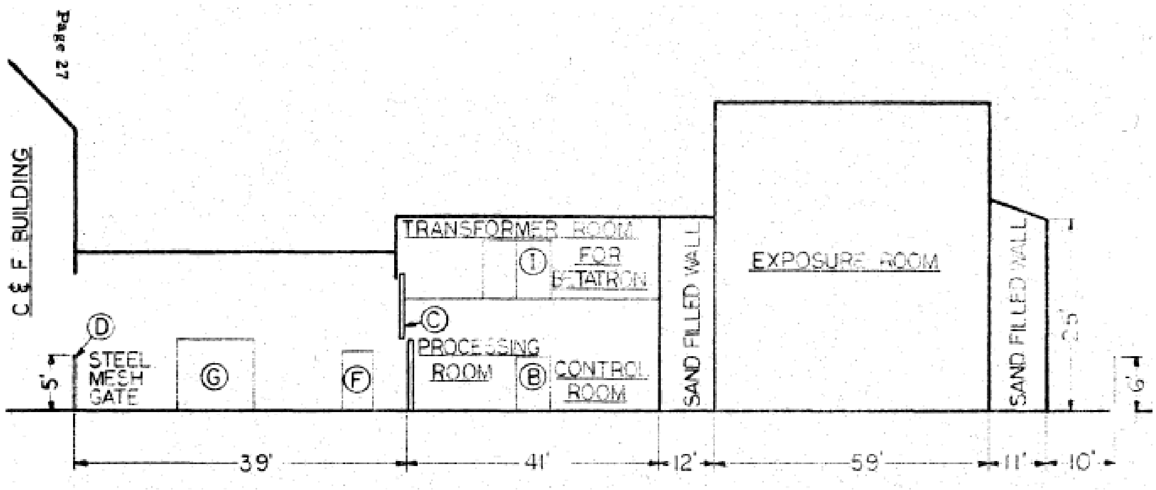


Figure 4 – New Betatron Building Elevations



A survey of the new betatron building with an 80 curie cobalt-60 source exposed was conducted on January 29, 1971 (ML093480290). The survey, which included measurements taken at various points around the building, is reproduced in Table 1. The letters in parentheses correspond to the locations identified in Figures 2 through 4.

Table 1 – 1971 Survey of New Betatron Building with 80 Curie Co-60 Source Exposed

Location	Radiation Level	Remarks
Control Room	3.0 mr/hr	Meter held against door joint (B)
Control Room	0.6 mr/hr	2’ from door
Control Room	0.1 mr/hr	At control desk
Processing Room	0.05 mr/hr	Highest reading in the area against wall
Concrete Exterior Wall	0.05 mr/hr	Highest level, survey meter against wall at 5’ height, entire exterior wall surveyed
Transformer Room	1.5 mr/hr	At meter door (I)
Transformer Room	2.0 mr/hr	At open area in ceiling – wall junction near door (C)
Outside Surface of Double Leaf Door (C)	0.3 mr/hr	Left side 5’ high
	1.8 mr/hr	Left side at horizontal door joint 10’ high

	2.5 mr/hr	Left side 2' above horizontal joint at 12' height
	0.2 mr/hr	Left side 10' from door 12' high
	0.4 mr/hr	Right side 5' high
	3.4 mr/hr	Right side at horizontal door joint 10' high
	4.4 mr/hr	Right side 2' above horizontal joint at 12' height
	1.8 mr/hr	Right side 10' from door 12' high
Corner at Door E	0.4 mr/hr	Taken against exterior surface of wall
Corner at Door F	0.2 mr/hr	Taken against exterior surface of wall

The new information was used to modify the previous model of the new betatron building. An 80 curie Co-60 source was then added to the model at the position labeled as an X within a circle in Figure 2. Radiation levels were determined, using MCNPX, at many of the same locations surveyed by GSI in 1971. Table 2 provides a comparison between the actual survey results and the modeled results.

Table 2 – Comparison of Modeled Radiation Levels to 1971 Survey

Location	1971 Radiation Level (mr/hr)	Modeled Radiation Levels (mr/hr)	
Control Room	3.0	2.5	Meter held against door joint (B)
Control Room	0.6	1.1	2' from door
Control Room	0.1	0.2	At control desk
Outside Surface of Double Leaf Door (C)	0.3	0.4	Left side 5' high
	1.8	2.4	Left side at horizontal door joint 10' high
	2.5	2.2	Left side 2' above horizontal joint at 12' height
	0.2	2.0	Left side 10' from door 12' high
	0.4	0.6	Right side 5' high
	3.4	4.2	Right side at horizontal door joint 10' high

	4.4	4.0	Right side 2’ above horizontal joint at 12’ height
	1.8	2.4	Right side 10’ from door 12’ high
Corner at Door E	0.4	0.6	Taken against exterior surface of wall
Corner at Door F	0.2	0.6	Taken against exterior surface of wall

With one exception, the modeled value was either higher or within 20% of the measured value. The exception was for the location 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 scaled 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 those values differ by no more than 0.2 mr/hr.

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.

Shot scenarios

The betatron could be positioned and aimed in various directions in the shooting area. Limit switches prevented it from being pointed in the direction of the control room, but reports from operators indicated a procedure was sometimes used to defeat these limits. The procedure, referred to as “flipping the head”, was used starting no earlier than 1965.

To explore the effect of various positions of the betatron on exposure conditions, three equipment positions were modeled. In this context, “equipment position” refers to the position in which the equipment being x-rayed was located. The first position is referred to as the “railroad” position. In this position, the equipment is assumed to be on a railroad type cart located in the shooting room. For this configuration, the betatron is assumed to be pointed directly at the equipment, perpendicular to the railroad tracks. Additional scenarios could involve aiming the betatron head 45 degrees to the right and to the left of that position. It should be noted that aiming 45 degrees to the right would be a “flipped head” position. For all three scenarios, the shots were aimed parallel to the floor. For the straight and right scenarios, the shot was also aimed up and down 45 degrees.

The second equipment position is referred to as the “center shot” position. For this, configuration, the equipment is centered in the shooting room near the wall opposite of the control room. The betatron head was aimed directly away from the control room as well as 45 degrees to the right and to the left and was aimed parallel with the floor for all three shots.

The third equipment position is referred to as the “back shot” position. For this position, the equipment is located near the wall in the shooting room opposite the rail road tracks. The aiming scenarios including pointing the betatron head directly away from the rail road tracks, as well as 45 degrees to the right and to the left of that position. In this configuration, 45 degrees to the left would be a “flipped head” position. For all three shots, the head was aimed parallel to the floor. For the 45 degree to the left position, the head was also tilted 45 degrees up and 45 degrees down.

Ten tally locations, listed in Tables 3 and 4, were explored for dose rate modeling. Three locations were in the control room. The first being 2 feet inside the control room door, the second being the approximate center of the control room and the third at the control room desk shown in Figure 4. Location 4 was just behind the double leaf door. Location 5 was just inside #10 building centered with the equipment tunnel. Location 6 was located in the restroom near the new betatron building.

In determining the location of the restroom, it was noted that Figure 3 appears to be a scale drawing for the betatron building and equipment tunnel, but not for the adjacent buildings. This can be seen easily by comparing the 21 feet across the equipment tunnel to the 30 feet from the wire mesh fence to the adjacent building. Therefore, the drawing in Figure 5 was utilized in combination with Figure 3 to estimate the location of the restroom. The restroom was identified on Figure 5 by former workers, so this drawing was considered to be a good representation of the scale (SCA 2008). Dimensions from Figure 3 were then used to scale the drawing and determine the location of the restroom.

Figure 5 – Location of Restroom

Tally locations 7, 8, and 9 are the three vents on the roof of the new betatron building. Their locations were approximated from Figure 6. Location 10 was outside the betatron building. This location was chosen to be in the area of low shielding and at a close distance to the building. The distance to the building was limited due to the wire mesh fence shown in Figure 3.

Tables 3 and 4 provide the modeled photon exposure rates and neutron dose rates respectively for each of the ten locations and for each of the shot scenarios. In Tables 3 and 4, the positions of the betatron orientation are labeled with the abbreviation for the orientation of railroad, center shot or back shot (RR, CS or BS) followed by an abbreviation of whether it is aimed straight, turned to the right or turned to the left (ST, RT or LT) followed by an abbreviation whether is it not tilted (parallel to the floor), tilted up or tilted down (No, Up, or Dn).

Figure 6 – New Betatron Building Vents

Table 3 – Beam-On Photon Exposure Rates from New Betatron

	CR door	CR desk	CR center	Leaf door	#10 Bldg
RR_ST_No	1.42	0.41	0.65	1.48	1.26
RR_ST_Up	1.15	0.38	0.61	1.52	1.93
RR_ST_Dn	1.28	0.29	0.52	1.98	1.38
RR_LT_No	0.55	0.13	0.27	0.38	0.75
RR_RT_No	8.58	2.21	4.38	29.84	17.13
RR_RT_Up	4.13	1.30	2.83	20.95	8.43
RR_RT_Dn	4.96	1.24	2.81	17.49	7.16
CS_ST_No	0.38	0.06	0.08	0.12	0.29
CS_LT_No	0.25	0.06	0.08	0.19	0.32
CS_RT_No	0.37	0.09	0.12	0.22	0.49
BS_ST_No	0.04	0.03	0.06	0.05	0.17
BS_LT_No	0.08	0.01	0.02	0.06	0.22
BS_RT_No	0.04	0.01	0.01	0.09	0.19
BS_LT_Up	0.10	0.07	0.10	0.23	0.85
BS_LT_Dn	0.06	0.02	0.02	0.07	0.20

Values are in mr/hr

Table 3 – Beam-On Photon Exposure Rates from New Betatron (continued)

	Restroom	Roof 1	Roof 2	Roof 3	Outside
RR_ST_No	0.47	43.14	105.68	208.85	1.64
RR_ST_Up	1.16	54.59	151.75	2349.32	2.34
RR_ST_Dn	0.40	43.52	98.07	135.65	1.35
RR_LT_No	0.33	50.87	122.55	236.28	0.58
RR_RT_No	2.89	49.93	113.35	191.59	28.50
RR_RT_Up	2.67	53.69	170.76	1004.45	10.38
RR_RT_Dn	1.20	46.79	103.71	139.95	9.35
CS_ST_No	0.28	100.13	119.08	90.73	0.32
CS_LT_No	0.30	159.14	139.47	66.53	0.35
CS_RT_No	0.41	67.21	178.41	157.50	0.45
BS_ST_No	0.17	177.39	79.83	34.27	0.13
BS_LT_No	0.24	193.18	85.11	38.89	0.17
BS_RT_No	0.19	228.50	100.57	46.17	0.16
BS_LT_Up	0.44	538.93	116.72	44.81	0.47
BS_LT_Dn	0.17	140.15	78.42	35.43	0.15

Values are in mr/hr

Table 4 – Beam-On Neutron Exposure Rates from New Betatron

	CR door	CR desk	CR center	Leaf door	#10 Bldg
RR_ST_No	0.30	0.03	0.08	0.23	0.63
RR_ST_Up	0.03	0.02	0.02	0.43	0.36
RR_ST_Dn	0.27	0.41	0.45	1.38	0.35
RR_LT_No	0.10	0.27	0.17	16.68	0.33
RR_RT_No	1.21	0.98	0.86	0.37	0.37
RR_RT_Up	0.15	0.04	0.05	0.66	0.43
RR_RT_Dn	0.01	0.01	0.01	0.15	0.14
CS_ST_No	0.01	0.17	0.20	0.20	0.15
CS_LT_No	0.13	0.00	0.01	0.08	0.10
CS_RT_No	0.07	0.01	0.02	0.16	0.28
BS_ST_No	0.02	0.10	0.06	0.09	0.19
BS_LT_No	0.24	0.09	0.13	0.12	0.09
BS_RT_No	0.53	0.06	0.13	0.06	0.12
BS_LT_Up	0.20	0.03	0.10	0.03	0.05
BS_LT_Dn	0.02	0.00	0.00	0.03	0.06

Values are in mrem/hr

Table 4 – Beam-On Neutron Exposure Rates from New Betatron (continued)

	Restroom	Roof 1	Roof 2	Roof 3	Outside
RR_ST_No	0.06	9.15	18.81	17.63	0.17
RR_ST_Up	0.32	8.69	13.13	12.25	0.65
RR_ST_Dn	0.14	8.95	26.06	19.20	0.56
RR_LT_No	0.15	9.44	18.32	15.19	0.51
RR_RT_No	0.11	9.33	18.80	15.63	0.21
RR_RT_Up	0.13	7.23	11.27	9.49	0.36
RR_RT_Dn	0.05	6.53	14.28	13.80	0.16
CS_ST_No	0.15	12.02	17.30	11.40	0.23
CS_LT_No	0.08	9.00	17.36	12.32	0.10
CS_RT_No	0.15	13.15	19.95	12.63	0.24
BS_ST_No	0.08	20.44	17.21	8.64	0.12
BS_LT_No	0.05	20.54	17.90	11.62	0.10
BS_RT_No	0.10	18.54	14.71	8.20	0.09
BS_LT_Up	0.03	11.86	12.98	6.21	0.05
BS_LT_Dn	0.04	19.53	11.08	5.35	0.05

Values are in mrem/hr

Residual radiation from uranium

As part of their AEC contract work, GSI x-rayed slices of uranium ingots from Mallinckrodt Chemical Works (SCA 2008). The slices were larger than the largest film GSI used, so up to four shots had to be made on each slice to cover 100% of the object. Each shot was reported to take 60 minutes with 15 minutes between them to remove the film and setup the next shot.

The dose at 1 foot and 1 meter from the uranium object was modeled using MCNPX. The dose was estimated in one minute increments following an irradiation of the uranium object with the betatron. The incremental doses were summed to determine the dose between zero to 15 minutes following a 1 minute irradiation. The doses were then summed to determine the dose between 1 minute and 16 minutes after an irradiation. The process was continued until the full 60 minute irradiation was accounted for. It should be noted that the first 5 seconds after irradiation were eliminated because at least 5 seconds would be necessary for operators to reach the uranium object following an irradiation.

Next, the same process was done for the time frame 75 to 90 minutes following irradiation. This was done to account dose from the previous shot. The process was repeated for time frames 150 to 165 minutes and 225 to 240 minutes after irradiation. When processing a uranium object using 4 shots, the dose from zero to 15 minutes after the shot would be received four times while the dose 75 to 90 minutes after the shot would only be received three times. This is due to the fact that that dose would not exist following the first shot. Likewise, the dose 150 to 165 minute following irradiation would only be received twice and the 225 minute to 240 minute dose once. Summing these doses produces the dose received from the entire 4 shot series.

Approximately 90% of the neutron dose is received in the first minute following irradiation and the dose rate reduces to zero within a few minutes. Therefore the neutron dose received from 4 shots of the uranium object is simply 4 times the dose received from a single shot. The photon and neutron doses for 4 x-rays of the uranium object are shown in Table 5.

Table 5 – Dose from Residual Activity in Uranium

	1 foot from uranium object	1 meter from uranium object
Photon (mr)	4.11	0.49
Neutron (mrem)	1.04	0.13

Doses are for a 4 shot series lasting 300 minutes

The uranium also emits radiation naturally. The dose rate was determined at 1 foot and 1 meter and is provided in Table 6. One hundred day aged uranium was assumed to insure the in-growth of short lived decay products. The photon dose includes both gamma and x-rays from decay and from Bremsstrahlung radiation. These dose rates will be added to the dose rates from residual activity.

The operators would also receive a skin dose from beta radiation when working with uranium. The beta dose comes primarily from the short lived decay products Th-234 and Pa-234m. These isotopes can concentrate near the surface of the uranium ingot when it is cast. The assumptions used in an earlier analysis (SCA 2008) are again used here, resulting in the skin dose rates shown in Table 6.

Table 6 – Dose Rates from Natural Uranium Metal

	Contact with the uranium object	1 foot from uranium object	1 meter from uranium object
Photon (mr/hr)	N/A	1.25	0.16
Beta (mrad/hr)	721.3	37.5	5.3

The effect of the short lived decay products concentrating on the surface of freshly cast uranium has been evaluated previously (Allen 2010). As part of that evaluation, actual film badge data from a facility that cast a large quantity of uranium was examined and found that a 10 to 1 ratio of beta to photon dose would be favorable. The ratio used here is approximately 30 to 1. However, the facility from which the measured ratio was obtained worked with considerably more uranium at any time than GSI. It is possible that for a given worker, nearby uranium metal contributed to photon dose while not contributing to beta dose due to the short range nature of beta radiation. The 10 to 1 ratio therefore may not be representative of GSI since only small amount of uranium was handled at any one time. A more representative ratio would be higher. This lends credibility to the 30 to 1 ratio derived.

Residual radiation from steel

The duration of the x-ray exposures for steel castings vary with the thickness of the steel being examined. Discussions with operators indicated approximately 90% of the examinations were "short shots" and the other 10% were "long shots". The short shots were approximated as being 3 minutes in duration, with the betatron head being 9 feet from the target, and 12 minutes needed between shots to setup the next shot. The long shots are approximated as being 60 minutes in duration at a distance of 6 feet with 15 minutes necessary between shots.

Some radioactive isotopes created during the irradiation have a long half-life, while others have a short half life. The time necessary to reach equilibrium is governed by the half-life of the isotope being created. For example, if an isotope had a 2 minute half-life, half of the activity initially created would decay 2 minutes into a shot. Seven half-lives into the shot, the isotope would reach approximately 99% of its equilibrium activity. Because of this effect, some of isotopes created would reach equilibrium during a 60 minute shot and the activity would not increase after that. Others with a longer half-life would continue to increase while the shot proceeded. This will affect the ratio of short lived isotopes and long lived isotopes depending the duration of the shot.

To address this, MCNPX was used to determine the production rate of radioactive isotopes in HY-80 steel. HY-80 steel was chosen based on the analysis performed in SCA 2008. That production rate was then used to determine the buildup of each isotope based on the length of a shot. This was then used to correct the modeled doses to account for the decay of isotopes during the shot.

There were two primary reasons for performing x-ray examinations. The first consisted of 100% coverage of the casting to check for voids or other flaws. The second was to recheck locations repaired after flaws had been discovered. The 100% coverage examination would result in exposure not only from the location being shot but from any nearby locations previously shot. The nearby locations would contribute less exposure than the current shot due to geometry and decay time. Repairs would normally result in a follow-up shot to verify the repair. This in turn could result in subsequent repairs and additional verification shots. For these shots, the exact same location would be x-rayed repeatedly, building up radioactive isotopes in that area. However, since the repair would take some period of time, the frequency of the shooting would be less than that of the coverage shots.

To account for both types of shots, the dose was modeled assuming repeated shots on the same location. The frequency of the repeated shots is that of the 100% coverage scenario. For the long shots, it is assumed 400 previous shots were accomplished in the same location while for the short shots it is assumed there were 500 previous shots (SCA 2008).

The dose rates at 1 foot and 1 meter at various times following irradiation of the steel were determined. The dose rates were determined in line with the betatron beam. The times following a shot applicable to the operator exposure for a given exposure scenario were added and used to determine a dose to the operator. The decay correction was then applied to account for the decay of the isotopes during the shot. In this fashion, the decay of isotopes during the shot are accounted for with the decay correction, and the decay of isotopes after the shot are accounted for by MCNPX. The modeled results are shown in Table 7.

Table 7 – Photon Dose from Residual Activity in HY-80 Steel

	1 foot (mr/shot)	1 meter (mr/shot)
Short shot	0.017	0.0033
Long shot	0.20	0.038

For this estimate, the operators are assumed to be directly in front of the location just x-rayed. They are further assumed to be at a distance of 1 foot 50% of the time and a distance of 1 meter the remaining 50% of the time. The exposure time is assumed to be from 5 seconds to 12 minutes following the last shot for the short shots and 5 seconds to 15 minutes following the last shot for the long shot scenario. The 5 second time period represents the minimum amount of time necessary to travel between the control room and the casting following a shot. Based on the assumption of 90% of the shots being short shots and 10% being long shots, the weekly exposure to the operators was determined to be 3.94 mr per week assuming a 65 hour work week.

Beta Dose

Beta dose from residual activity in steel was determined using the same techniques described in SCA 2008. The technique involved determining the specific activity of beta emitting isotopes created in HY-80 steel. The specific activity was determined from a relatively small disc of steel (6.5 inch diameter) to insure only the most intense part of the betatron beam was used. The activity was allowed to build up for 30 hours. Next the specific activity on the surface was calculated and applied to a larger relatively thin steel disc (100 cm radius, 0.4 cm thick). From this disc, the dose rate at various distances was determined. The dose from each isotope was then integrated over the appropriate time and summed. The appropriate time is the time after each shot that the individual is working with the casting. The betatron operator time for short or long shots was discussed previously. The appropriate time for the layout worker is discussed later.

Table 8 – Skin Dose from Residual Activity in HY-80 Steel

	Whole Body Skin (mrad/week)	Skin of the hand and forearms (mrad/week)
Betatron Operator	18.4	30.0
Layout Worker	10.8	20.4

Film badges

GSI film badge records covering the period of 1964 through 1973 were obtained from Landauer. The records indicate that these badges were exchanged on a weekly basis starting in November of 1963. From the beginning of this service through February 6, 1966, one badge was designated each week for the betatron control room. This results in 114 badge readings from the control room, all of which indicated exposures of less than 10 mrem/week. While no film badge was designated for the control room after February of 1966, the operators from GSI have repeatedly indicated that film badges were stored in the betatron building whenever they were not working in the betatron building. This would indicate the film badges were always in the betatron building either stored when not in use or on the radiographer. There is some indication the film badges were actually worn outside the betatron building when radiographers were working with isotopic sources, but this was generally done by only a few people at a time. The effect of this on the dose estimate will be discussed later. More than 99.8% of the badge readings indicated exposure of 10 mrem or less. With the badges always in the control room during shots (either stored there or worn by the radiographers) the dose rate in the control room can be determined to be less than 10 mrem per 168 hour week, even after February of 1966.

The dose in the control room can be affected by the dose rate during various types of shots as well as the duration of those shots. For example, if a particular type of shot produces a dose rate of 1 mrem/hr in the control room, that type of shot could not normally be performed for more than 10 hours in a week. Also, assuming that shot occurred for the full 10 hours each week prevents other shots from occurring in the betatron building since they would add to the badge reading and cause the total dose on the badge to exceed 10 mrem in a week. This fact will be used to determine the maximum number of hours each week for each type of shot. That will in turn be used to determine weekly dose rates outside the betatron building.

Residual radiation from the Betatron

It was reported by a former Allis-Chalmers employee that the betatron apparatus itself exhibited residual radiation (Schuetz 2007). He reported:

> *"The donut platinum target becomes radioactive generating on average, around 15 milliroetgens/hour measured at beam centerline 6 ft. from target. This activity will diminish to near zero within 15 minutes. Identical measurements made to rear show approximately 1% of forward readings. Effective beam readings follow the same natural beam shape as 25 Mv x-rays. Instrumentation used was an ionization gamma survey meter, model 247A."*

Attempts to explain this phenomenon have not definitively determined the source of this radiation. Some of the possibilities explored include:

- activation of the platinum target as reported
- activation of the aluminum ion chamber and beam compensator
- activation of some other part of the betatron

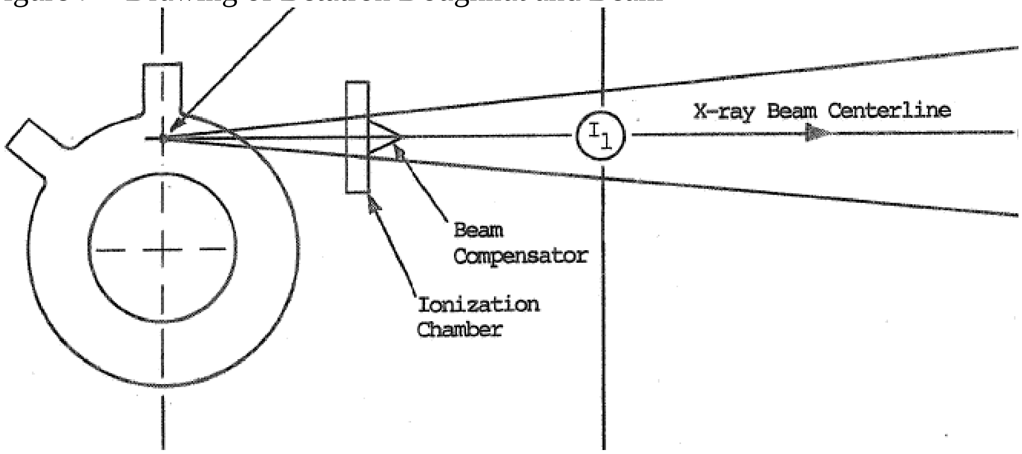
- activation of air in the betatron beam
- activation of a beam dump (or part being x-rayed)
- residual current in the betatron continuing to produce x-rays at a lower intensity
- Magnetic interference with the detector

The first three possibilities involve activation of various parts of the betatron. Figure 7 provides a drawing of a betatron tube with the ion chamber and beam compensator in place (Schuetz 2007). The platinum target is the point inside the doughnut shaped tube where the x-ray beam originates. The tube is sandwiched between two large electromagnets that control the betatron. The beam compensator is essentially a radiation shield that is cone shaped to provide the most shielding at the beam centerline and progressively less shielding away from the centerline. This has the affect of flattening the intensity of the x-rays to provide a more even useful beam. Without it, the film would be highly exposed at the centerline of the beam and much less exposed at the edges.

Radiation originating from activation products would be isotropic in nature. That is, the radiation would be emitted in all directions equally. Radiation originating from inside the betatron tube should therefore be as high in to the rear of the head as it is in front. The exception to this is that the radiation intensity should be lowest in front of the compensator since that would provide some shielding. This is in contrast with the description that indicates the readings to the rear were 1% of the readings in the beam centerline and that the readings showed the same shape as the 25 MeV x-rays. Therefore, this phenomenon does not appear to be consistent with any parts of the betatron being activated with the possible exception of the aluminum compensator.

It may be possible for activation of the compensator to give these indications. Activation products produced in the middle of the compensator could be equally shielded in the forward and reverse directions. With a longer distance from the compensator to the rear of the machine, the readings in the rear would be lower. Also, the compensator is thickest in the centerline of the beam and exposed to the most intense radiation at that point, so there is more material that can be activated resulting in a more intense activation field. However, attempts to demonstrate this effect using the known physical constants of aluminum and the betatron field indicates the activation of the aluminum would not produce a radiation field of this magnitude. Also, the entrance of the compensator is closest to the x-ray beam and should be most highly activated. This implies the most intense radiation would be emitted from the rear of the compensator and that would reduce the difference between the forward and reverse radiation fields. Therefore, it was not possible to recreate induced activity in the aluminum ionization chamber and beam compensator that would produce the described exposure conditions.

Figure 7 – Drawing of Betatron Doughnut and Beam



The betatron is also capable of activating air in the x-ray beam. If the air was stagnant, and the beam on long enough, it could be possible for the activated air to produce a measureable amount of radiation. This source of radiation would produce a more intense radiation field in front of the machine than behind because only the air in front of the machine would be activated. The intensity of the radiation would, however, not follow the shape of the very directional 25 MeV x-ray profile as was reported. The air would provide very little shielding so the activated air in the beam centerline would produce a radiation field for several feet to the sides. The profile would be more like a point source in front of the betatron and it could not be described as following the shape of the 25 MeV x-ray profile. Furthermore, air in an operational radiography room would not be so stagnant as to allow a small volume of air to become activated to a high degree. Instead the air movement would create a much larger source of lower activity and the profile of the radiation when measured with an instrument would be much more consistent throughout the area rather than directional as was reported.

The report of this phenomenon did not discuss what was in front of the beam. Even if the purpose was calibration and testing, rather than x-raying equipment, it is possible the experimental setup used some type of beam dump to shield nearby areas from the beam. If this beam dump became activated, it could produce a radiation field with the highest intensity in the beam centerline and decreasing quickly as the instrument was moved to the side. That could give the illusion of an intensity profile similar to the betatron x-ray profile. Depending on the material used to construct the dump, the half-life of the activation product could be short enough to result in the reduction in dose rate reported. If this was the cause of the phenomenon, this would not have to be accounted for separately at GSI since the activation of the steel being x-rayed is already accounted for separately.

Another possibility explored was the idea that the betatron could exhibit some residual current creating residual radiation in the form of x-rays. This possibility was explored by SC&A and no method of producing residual x-rays near this intensity could be found. (SCA 2010)

The last possibility explored is the effect of magnetic interference on the survey instrument used to measure this dose rate. The instrument was reported to be an ionization gamma survey meter, model 247A. This was likely to be a model 247A portable gamma survey meter manufactured by Victoreen. It is a well know fact that survey meters can be affected by magnetic fields. Figure 8 has been reproduced from a paper that explored the effect of static magnetic fields on survey instruments (Liu 1993). The Figure shows the effect of moving a Victoreen model 450 instrument parallel with the magnetic field. With a field strength of 10 milliTesla, the instrument over responded by a factor of 70 when moved in one direction while in the other direction, it under responded, showing only 20% of the actual radiation intensity. A magnetic field of this strength can be created by a betatron. Kerst constructed a 315 MeV betatron in 1949 that had a magnetic field of 9200 Gauss or 920 milliTelsa (Lee 2004). While that would be the operating strength of the magnetic field, it is credible that a small amount of residual magnetism would exist in the magnet core for a period of time following operation and that the residual magnetism would decay gradually. The strength explored in the paper by Lee is only about 1% of that reported to have been used by Kerst. Furthermore, this paper explored the affect of a static field but clearly it was relative motion in the field that caused the effect (movement of the instrument). A similar effect can be caused by a changing magnetic field which is what would be expected as any residual magnetism or residual current in the magnet coils decay.

It is impossible to predict the indication the instrument would give in this situation. However, it is credible that the survey instrument would be moved towards the front of the machine in one direction and towards the rear of the machine in the opposite direction. Measurements around the machine would likely move perpendicular to that motion and thus be much less affected. So as the instrument is moved around the magnetic field, it would greatly over respond as it was moved in one direction (say near the area of the compensator), have little effect as it was oriented away from this direction and under respond when oriented in the opposite direction as the original measurement (the rear of the machine). This could cause the readings to the rear to be 1% of the readings in the front and produce a profile roughly similar to the 25 MeV x-ray of the betatron.

Figure 8 – Ion Chamber Response to Magnetic Field

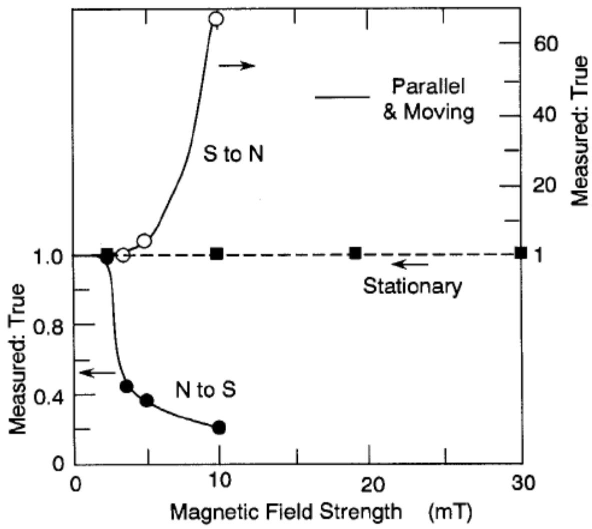


Fig. 4. Response of the Victoreen 450p ion chamber survey meter. True signal is 0.77 $\mu C\ kg^{-1}\ h^{-1}$ (3 $mR\ h^{-1}$).

One last issue to explore is to consider the exposure scenarios. A reasonable scenario of "short shots" and "long shots" was described by SC&A and will be used again in this paper (SCA 2008). This scenario results in approximately 185 shots in a 65 hour work week. Since 99.8% of the film badges recorded a value of 10 mrem or less in a week, it is reasonable to believe the maximum dose that could be achieved per shot is 0.054 mrem (10 mrem/ 185 shots). If a person exposed to a 15 mrem/hr field only receives 0.054 mrem, the half-life associated with the decay would have to be 0.15 seconds. This eliminates virtually any possible activation product of the materials in the betatron, including those in air.

Of the possibilities explored, the idea that a magnetic interference affected the instrument appears to be the most likely. At the least, instruments of this type are known to be unreliable in magnetic fields that are easily produced by a betatron. This fact alone brings into question the reliability of the measurements.

Even if one of the other possibilities occurred, the aluminum, iron, and other materials common to the machine typically produce activation products that emit a 511 keV photon. Photons of this energy would be easily detected by the film badges which means; 1) the half life would have to be so short that no significant dose is received; and, 2) ignoring the effect means in order to receive a dose equal to the sensitivity of the badges, other mechanisms would have to be assumed. Those mechanisms tend to also produce neutron or electron dose which would result in a more claimant favorable dose estimate.

Betatron operator dose estimate

The operators of the betatron can receive radiation dose while in the control room during a shot, as well as from residual activity in the material being x-rayed. Since 99.8% of the film badge readings indicated exposures of 10 mrem/week or less, any scenario of typical exposures must stay within this value. It should be noted that dose received by workers outside of the betatron building laying out shots on recently exposed steel is dealt with separately in the next section. Dose to these workers was dealt with separately because operators reported they did not wear their film badges in the 10 building while performing this task. As such, the operators were either performing radiography or laying out shots in another building, but not both at the same time.

Communications with operators indicated approximately 10% of the shots lasted 60 minutes while the other 90% lasted 3 minutes. The assumptions used in this analysis are that it took 12 minutes between short shots. This would include time for traveling to and from the control room and the casting, setting up and taking down film, orienting the betatron head, and setting controls to initiate the next shot. The assumption for long shots is that it took 15 minutes between shots. Therefore, the total time per shot is 15 minutes per short shot and 75 minutes for long shots. Based on this, an 8 hour shift would be sufficient time to accomplish 32 short shots or 6.4 long shots. If 90% of the shots are short shots, then these values would indicate 64% of the time the betatron was involved in taking short shots and 36% of the time involved long shots. Therefore, the weekly dose in the control room will be based on 430.1 short shots and 48.4 long shots per week. Obviously, a fraction of a shot would not occur but the values are intended to be an average.

These assumptions also indicate that for 69.89 hours of a 168 hour week the beam of the betatron is on. Since the operators were reported to work an average of 65 hours per week, they were not present during all of this time. Prorating the utilization of the betatron to a 65 hour work week, would result in the operators being present for 27.04

hours per week with the betatron on and for the remaining 37.96 hours per week they are exposed to residual radioactivity from the steel. Additionally, the badges are exposed in the control room when the operators are not there and the betatron is on for an additional 42.85 hours per week.

The 114 weekly film badges assigned to the betatron control room all indicated exposures of less than 10 mrem/week. With the betraton assumed to be on 69.89 hours per week, the average dose rate in the betatron control room, while the betatron is on, would be no greater than 0.143 mrem/hr. Assuming the film badges are exposed to 10 mrem/week from the operating betatron does not allow for the accrual of any dose received from exposure to residual activity in the steel castings. This is because the vast majority of the film badges (approx. 99.8%), indicated total exposures of 10 mrem/week or less. Because the dose from residual activity in the steel is based on bounding assumptions which likely over predict that dose, subtracting that dose from the dose received in the control room would possibly under predict the true dose in the control room. This would in turn under predict the doses received by others outside the betatron building. Therefore, this dose estimate will assume the badges receive 10 mrem per week in the control room.

Operators, however, are not exposed to the entire 10 mrem each week. Much of that exposure occurs while the operators are not at work and their badges are stored in the betatron building. The operator exposure is assumed to be 3.87 mrem per week from the operating betatron. This value comes from considering the fact that the operators are present for only 27.04 hours of the 69.89 hours per week the betatron is operating. Combining this 3.87 mrem per week with the 3.94 mrem per week from residual activity in the steel results in a total dose to the operators of 7.81 mrem/week.

This dose assumes the operator is working 65 hours per week, performing radiography on steel. Adjustments to this estimate must be made to account for radiography operations with uranium. Sixty five work hours per week for 50 weeks per year results in an average work year of 3250 hours. The amount of uranium work performed at GSI has been derived from work orders and is described in Appendix BB to TBD 6000 (OCAS 2007). Table 9 shows the assumed number of hours per year of uranium work, along with the fraction of time the work involved uranium (based on 3250 work hours per year).

Table 9 – Hours per Year of Uranium Work at GSI

Years	Hours per year working with uranium	Fraction of work year working with uranium
1953-1960	337.5	0.104
1961	387.5	0.119
1962	281.25	0.087
1963	76.5	0.024
1964	28	0.009
1965	20.5	0.006
1966	13	0.004

The weekly dose from exposure to the uranium metal (intrinsic radiation as well as residual activity) was estimated to be 39.06 mr, based on continuously working with uranium. Since the amount of uranium work was limited, it is possible that any one operator worked with all the uranium. Also, the amount of uranium handled varied from year to year. Therefore, the dose estimate will vary from year to year. The assumption is that any particular operator worked with all the uranium and worked with HY-80 steel the remainder of the time. The fractions of time spent on uranium work are listed in Table 9. Also, the dose estimate while the betatron is on assumes 64% of the shots are short shots, which is not the case for uranium work. Therefore, the dose to the operator while in the control room is adjusted to account for the higher fraction of the time the betatron is on. The weekly dose rate while continuously x-raying uranium is then 39.06 mr/week from the uranium metal plus 7.44 mr/week in the control room for a total of 46.5 mr per week. This weekly dose is assumed for the fraction of time listed in Table 9 with the remaining fraction of the work year assumed to be at the rate of 7.81 mr per week from x-raying steel. The overall annual estimate year by year is listed in Table 11.

The same assumptions are combined with the applicable neutron and skin dose rates to arrive at the annual dose estimates in Table 11.

Workers outside the betatron building

Workers not working in the betatron building may also have been exposed to radiation resulting from betatron operations. This would be caused by scattered radiation (including skyshine) while the betatron is in operation, as well as from residual activity when repairing a recently x-rayed casting.

Dose from scattered radiation depends on the location of the worker. A number of locations outside the betatron building were explored, with several locations of interest discussed below. Dose rates in those locations vary depending on the location and orientation of the betatron head. In general, however, those betatron orientations that resulted in higher dose rates outside the betatron building also resulted in higher dose rates inside the betatron control room. As described earlier, dose received inside the betatron control room would be detected on the film badges.

Dose rates from these locations and shot orientations were described earlier. In order to estimate the weekly dose locations outside the betatron building, Excel's "Solver" function was utilized. Solver allows the user to find the optimal value for a formula. The function was used to find the maximum weekly dose at the number 10 building location. The criteria for Solver were:

- weekly dose at the control room desk equal to 10 mr
- hours per week (of betatron operation) equal to 69.89

The results of the Solver calculation was an assumed 67.46 hrs per week oriented in the back shot, left, up position and 2.42 hours per week oriented in the railroad, right, level position (see discussion on orientations in a previous section). With these assumed hours, the dose rate in the number 10 building is estimated to be 99.2 mr/week from photon and 4.04 mrem/week from neutrons. However, this is based on a 168 hour week. Prorating exposures for a 65 hour work week resulted in an estimated dose of 38.4 mr from photons and 1.56 mrem from neutrons.

With these assumptions in place for the shooting orientation, weekly photon doses at other locations were estimated. Weekly doses for a 65 hour week were estimated to be 14.3 mr in the restroom and 38.9 mr in the outdoor area. However, it is not realistic to believe workers spent 3,250 hours per year in either of these locations. Since the number 10 building dose rate is nearly the same as the dose in the outdoor area (and higher than the restroom) workers will be assumed to be working continuously in the number 10 building.

An additional point of interest is the examination of potential exposures on the roof of the betatron building. One report indicated that a maintenance worker performed periodic work on the fans above the shooting room. The frequency of this operation was reported as being 20 minutes per fan twice per year (Meeting Minutes 2007). There were three fans on the roof of the shooting room. To estimate this dose, the weekly dose at all three fans was determined and averaged. Next this was multiplied by the fraction of a week the person would be at work assuming a 65 hour per week work week. Lastly, this was multiplied by the fraction of the work week the person would be on the roof. This was estimated by assuming 2 hour of maintenance per 3,250 hour year (20 minutes per fan times 3 fans twice per year). This results in an estimated weekly dose of 3.82 mr. The maintenance person could have worked in the number 10 building near the betatron building equipment door, but it is unlikely any maintenance activity would require full time work at one location. More likely the maintenance worker worked all over the plant at various times. Even assuming the maintenance worker worked elsewhere (such as the betatron building roof) 10% of the time would result in a lower dose estimate than if the worker is assumed to work 100% of the time in the number 10 building. Since placing workers in an exact location is usually difficult, no special treatment will be considered for this worker. As with other workers, the maintenance worker will be considered to spend 100% of his work day in the number 10 building.

One additional exposure potential for workers outside the betatron building is the dose to workers from residual activity in steel castings. This is addressed in the next section. The section is based on a radiographer laying out shots on the casting but will also serve as a bounding estimate for anyone working on the freshly x-rayed casting.

Layout Worker

Castings were often prepared for an x-ray by laying out the shots prior to moving them into the betatron building. This minimized the time necessary to set up a shot in the betatron building and allowed the betatron to be operated more efficiently. If the casting had been previously x-rayed, residual activity could cause a dose to be received while laying out another shot. Furthermore, radiographers reported that the company policy was to not wear film badges in this location because hot sparks could burn through them.

Residual activity from steel decreases fairly quickly. Therefore, the highest dose rate to which these workers would be exposed was from a freshly x-rayed casting. The bounding estimate will be based on the same shot scenario used elsewhere. For short shots, the assumption is the shot lasted 3 minutes with an additional 12 minutes to take down the shot and move the casting out of the betatron building. Based on this, the layout worker is exposed to the casting starting 12 minutes after the shot. It is further assumed that this cycle repeats every 15 minutes. Therefore, the layout worker is exposed to a casting from 12 minutes to 27 minutes after a 3 minute shot. It is also possible that the casting was cycled into and out of the betatron repeatedly. While most of the dose would be caused by the latest shot, some additional radiation would be created from the previous shots. Also, if two castings were alternated, it would be possible for the layout worker to always be exposed to a freshly x-rayed casting that had been shot numerous times previously. This scenario was explored by assuming two castings alternated in the short shots. It was further assumed that this continued until the castings had each been shot 250 times.

The layout worker could also be exposed to residual radiation from long shots. In this case, the shot lasts 60 minutes with 15 minutes between shots. So the assumption is that the layout worker is exposed from 15 to 90 minutes following a 60 minute shot. This cycle is repeated every 75 minutes. Again, the scenario was explored in which two castings were alternated until each had been shot 200 times.

When the layout worker is working with the casting, it is assumed he is within one foot of the exposed location of the casting 50% of the time and 1 meter the other 50% of the time. Again, it is assumed 90% of the shots are short shots and the other 10% are long shots. Using these assumptions, the weekly photon dose from a single shot would be 2.05 mr while the multiple shot scenario yields a 2.21 mr/week dose. The reason the difference in the two scenarios is small is because the dose rate from residual activity decreases relatively quickly and the castings can only be x-rayed half as frequently due to the two castings being alternated. Even though the scenario chosen for the multiple shot scenario may be unrealistic, it is only marginally higher than the single shot scenario and the single shot scenario could under estimate the dose in some situations. Therefore, the multiple shot scenario will be used in the dose estimate.

If we assume this work always occurred in the number 10 building near the betatron building, an additional 38.4 mr per week from scattered radiation must be added to that estimate for a total of 40.6 mr/week.

For skin dose, the same technique was used that was used for the betatron operator. The technique included assuming a single 30 hour shot on the casting just prior to the operator being exposed. Therefore this is essentially a multiple shot scenario. The time the layout worker was assumed to be exposed was from 15 minutes to 90 minutes following the x-ray for the long shots and 12 to 27 minutes following the short shots. The short shot exposure was repeated every 15 minutes and the long shot cycled every 75 minutes. 90% of the shots were assumed to be short shots. The resulting weekly skin dose to the layout worker was 20.4 mrad/week to the hands and forearms and 10.8 mrad/week to the skin of the whole body.

The annual doses to the layout worker are shown in Table 10. These doses are to be used for all employees.

Table 10 – Annual Dose to Layout Worker

Year	Photon (mr/yr)	Neutron (mrem/yr)	Skin-WB [a] (rad/yr)	Skin-HF [b] (rad/yr)
1953-1965	2030	78	0.540	1.020
1966 [c]	1015	39	0.270	0.510

a Skin-WB represents the skin of the whole body
b Skin-HF represents the skin of the hands and forearms
c 1966 represents 6 months

Summary

The annual doses to the betatron operators derived in this white paper are summarized in Table 11.

Table 11 – Annual Dose to Betatron Operator

Year	Photon (mr/yr)	Neutron (mrem/yr)	Skin-WB [a] (rad/yr)	Skin-HF [b] (rad/yr)
1953-1960	590	125	2.269	25.867
1961	620	132	2.469	29.477
1962	557	117	2.044	21.806
1963	435	89	1.226	7.023
1964	406	82	1.032	3.522
1965	401	81	1.002	2.980
1966 [c]	199	40	0.972	2.439

a Skin-WB represents the skin of the whole body
b Skin-HF represents the skin of the hands and forearms
c 1966 represents 6 months

Betatron operator dose is intended to apply to anyone working in the betatron building. Because little information is available for the location of most workers, these doses will apply to all workers at GSI. For the same reason, the layout worker dose is intended to apply to all workers. These doses are not intended to be additive. Dose reconstructors will chose the most favorable set of doses for the given case.

In order to reconcile all the available data, the film badge data was used in estimating this dose. Film badge data, however, are only available starting in 1964. The estimate is considered reasonable for years prior to 1964 for two reasons.

First, the time period from approximately 1963 on has been referred to as the busiest time for the betatron. This was stated by betatron operators as well a former supervisor. It is also consistent with a large increase in the number of radiographers. Furthermore, prior to 1963, only one betatron was in operation at this facility. In 1963, an additional betatron from the Eddystone plant was moved to the Granite City plant and upgraded. The original betatron was reported to have a maximum intensity of approximately 100 R/minute while the new betatron (moved from the Eddystone plant) was reported to have a maximum intensity of 250 R/minute (Transcript 2006). Therefore, the years in which film badge data are available are the years for which:

- The maximum betatron throughput was occurring
- Two betatrons were in operation instead of one; and.
- Betatron intensity was increased (100 R/min max prior to 1963)

Lastly, the effect of the lower intensity of the old betatron would be lower doses, even if all other parameters were equal. If it is assumed that similar castings were being x-rayed, it would take longer to expose the film using the old betatron. Indeed, this was reported by operators. That would result in the operators being exposed to scatter radiation for longer durations and thus exposed to residual activity less frequently. The dose rate of the scatter radiation can be approximated as proportionally lower but for a longer duration resulting in the same exposure delivered to the casting and to the operators. Therefore, the overall result would be to reduce the dose estimate slightly, based on workers being exposed to residual activity less frequently. Since all the shot scenarios used in this whitepaper come from workers that were not employed prior to 1963, no detailed estimate was performed. The post 1963 (adjusted for uranium work) is considered bounding on the old betatron and the time period prior to 1964.

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