BATTELLE-TBD-6000 Appendix BB General Steel Industries
DOSE ESTIMATES FOR PORTABLE RADIOGRAPHY SOURCES
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1.0 Background

Numerous documents and information from former workers at GSI have come to light since the original exposure estimate for GSI was approved (DCAS 2007). The information contained in these documents, as well as the input from former workers, has proven to be useful in estimating the potential radiation dose to employees of GSI. This white paper is intended to account for all known sources of radiation dose at GSI that are not associated with the betatron machines. Further, it is intended to gather the known facts about each source and exposure scenario and estimate the dose to worker categories that were potentially exposed. The scenarios developed are intended to represent worst case exposure conditions for the different categories of workers.

In this paper, R (and mR) is used interchangeably with Rem (and mRem).[1] This is a typical practice in most facilities because dose limits are described in Rem while most gamma and x-ray instruments measure R. Field personnel often refer to them interchangeably, making an attempt to distinguish between them impractical. .

Also, 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 an examination or a "shot". An attempt was made not to refer to the process as "an exposure" to avoid confusion with radiation exposure to a person.

[1] Although it is recognized that the Roentgen is a measure of exposure to air and the rem represents dose to the body, for photon x-rays, they are considered to be sufficiently close numerically so that they can be used interchangeably.

2.0 Sources of Radiation

2.1 Isotopic Sources

GSI used two radium-226 (Ra-226) sources until 1962. At that time, they purchased two cobalt-60 (Co-60) sources (ML093431295 pg 3). The Co-60 sources were used instead of, not in addition to, the Ra-226 sources. In 1968 they purchased an additional 80 Ci Co-60 source (ML093451491 pg 3). Since that source was purchased after the AEC contract period (ending in 1966), the source will not be discussed further here. In addition, GSI contracted St. Louis Testing to perform some radiography at the GSI site. St. Louis Testing is reported to have brought a 10 Ci Co-60 source and a 50 Ci iridium-192 (Ir-192) source on site to accomplish this work (Meeting Minutes, October 9, 2007; pg 8).

2.2 X-ray Units

GSI was also reported to have used a portable x-ray unit for radiography. Auction notices for three x-ray units were provided to NIOSH (Attachment A). One unit (Westinghouse) was included on an announcement for dispensary equipment. This is a medical x-ray unit not suitable for industrial radiography. The other two units were an Andrex unit and a General Electric Model OX-250.

3.0 Source Strength

3.1 Isotopic Sources

GSI originally used two 500 mg Radium-226 sources for radiography (ML093431334 pg. 8). Five hundred milligrams of Ra-226 is approximately equivalent to 500 mCi of activity. These sources were replaced with two Co-60 sources in 1962 assayed at 0.26 Ci and 0.28 Ci (ML093431295 pg 3). St. Louis Testing was a contractor that brought their sources to GSI on occasion to perform radiography. They used both a 50 Ci Ir-192 source and a 10 Ci Co-60 source (Meeting Minutes, October 9, 2007; pg 8).

The table below provides the gamma ray constants and exposure rates at 1 foot from each of these sources.

Table 1
Exposure Parameters for Various Sources used at GSI

Isotope	Gamma ray constant ($R\text{-}cm^2/hr\text{-}mCi$)	Dose rate at 1 foot (R/hr)
Ra-226 500 mg (2 sources)	8.25	4.44
Co-60 0.28 Ci	13.2	3.98
Co-60 0.26 Ci	13.2	3.69
Co-60 10 Ci	13.2	142
Ir-192 50 Ci	4.8	258

3.2 X-ray units

The Andrex x-ray unit was reported in the auction notice to have operating specifications of 250 kV and 8 mA. Only the model number for the G.E. unit, which was an OX-250, was given in the auction notice. Another reference (AEC 1963) provided the peak output of the G.E. OX-250 as 250 kV and 10 mA.

The intensity of an x-ray unit is proportional to the current and the square of the accelerating potential (high voltage). Therefore, assuming similar filtration, a reference unit can be used to estimate the intensity of other units using the following equation:

$$Dx = \frac{I_X V_X^2}{I_r V_r^2} D_r$$

The subscripts *X* and *r* represent the parameter for the unit of interest and for the reference unit respectively. Also:

D = Dose rate
I = tube current
V = accelerating voltage

For a reference unit, the G.E. model ISOVOLT 225 M2/0.4-3.0 was used. This model has a tube current of 15 mA and a voltage of 225 kV. The reported dose rate at 1 meter from the focal point is 12.93 Sv/hr (21.55 Rem/min). To verify the equation, another unit, the G.E. model ISOVOLT 225 M2/0.4-1.5, was chosen. This unit has a tube current of 7 mA, a voltage of 225 kV and a reported dose rate at 1 meter of 6.92 Sv/hr (11.53 Rem/min). Using the parameters from the M2/04-3.0 and the tube current and voltage from the M2/0.4-1.5, a dose rate for the second unit was calculated to be 6.96 Sv/hr. This compares well with the reported 6.92 Sv/hr for the machine.

Using the M2/0.4-3.0 as a reference, the dose rate at 1 meter from the Andrex unit and the G.E. OX-250 were calculated to be 16.4 and 20.5 Rem/min respectively.

4.0 Exam Frequency and Scenarios

4.1 Radium

Frequency

No direct record exists as to how often the radium sources were utilized at GSI, 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 (ML093431291). Some key dates associated with the transition are:

- 3/7/1962 Applied for an AEC source license (ML093431291)
- 4/18/1962 License granted by the AEC (ML093431334 pg 2)
- 5/21/1962 Purchased two Co-60 sources (ML093431295 pg 3)
- 6/24/1962 survey of radiography room with 2 Co-60 sources (ML093431294)
- 8/1/1962 survey of radiography room with 2 Co-60 sources (ML093431294)
- 11/6/1962 inspected by the AEC (ML093431295)

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. This frequency is discussed in section 4.2.

Radiographic Examination Scenarios

As part of their application for an AEC license, GSI indicated they had been using radium sources that employed the "fishing pole" technique. The fishing pole technique consists of using a long pole to move the source from a shielded container to the necessary position for the radiographic examination. The pole is again used to move the source back to the shielded container once the examination is completed. The purpose of the pole is to reduce the radiographer's dose by increasing the distance between the source and the worker.

A conversation with a former employee indicated that he started performing radiography with radium sources in 1956. He estimated that the source was 4 to 6 feet away from his body and the time to place the source took no more than 12 to 15 seconds. The process was repeated after the shot to remove the source and place it back into the shielded container (Attachment B).

Control of the test area during Ra-226 radiography was not discussed with the former employee, however, area control for Co-60 sources used outside the radiography room was discussed. It was reported that when sources were used outside of the radiography room, an area was roped off at a distance 1.5 times the required distance (Transcript, October 14, 2009; pg 136). This practice was not mentioned in the AEC license application for the Co-60 sources, so it was apparently a practice adopted by GSI radiographers, rather than being official procedure. Since the practice of performing radiography in various areas of the plant evolved from experience with the Ra-226 sources, it is likely similar precautions were used. Thus it is assumed that when Ra-226 was used to perform radiography, the practice would have been to rope off an area 1.5 times the required distance.

4.2 GSI owned Cobalt-60 sources

Frequency

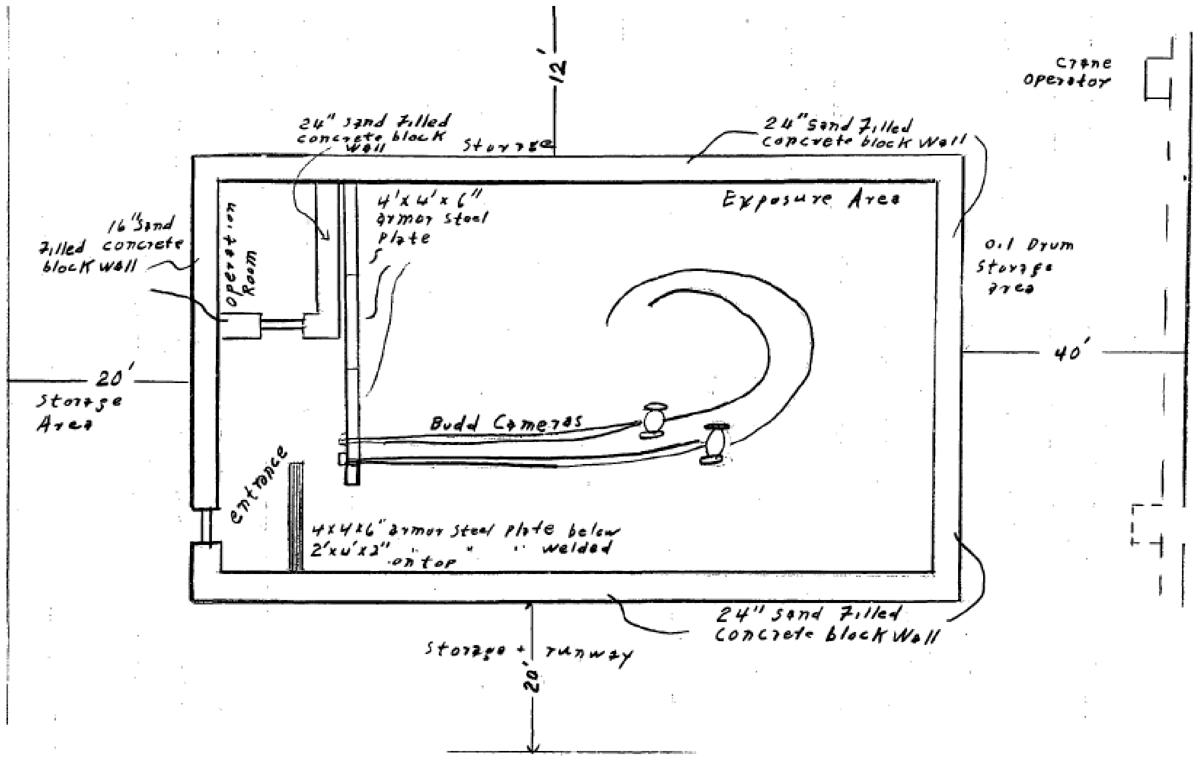
An AEC inspection, conducted on 11/6/1962 indicated that approximately 10 radiographic examinations were conducted per work shift and these examinations varied from one minute to 70 minutes in duration (ML093431295 pg 3). Another report indicated a maximum of 30% of each shift is used for actual examinations. That report also indicated exams ranged from 1 or 2 minutes up to 1.5 hours (ML093431334 pg 12). The examination durations in the two reports are reasonable consistent. The first report gives no indication of the total duration per shift but a range of 100 minutes to 700 minutes could be inferred. It should be noted that 700 minutes exceeds the duration of an 8 hour shift while 30% of an 8 hour shift would be 144 minutes per shift. Since 30% is the only indication of the utilization of the sources, and it does not disagree with the AEC inspection report, 30% will be assumed.

Radiographic Examination Scenarios

The two small Co-60 sources were intended to be used in a specially constructed room 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 (ML093431334 pg 8 & 9). The room was constructed with 24" thick sand filled concrete block walls. The top of the room was open to allow an overhead crane to lower items into the room. Figure 1 provides a drawing of this room.

Former workers at GSI also reported that the Co-60 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, October 14, 2009; pg 136).

Figure 1 – Radiography Room in #6 Building



4.3 St. Louis Testing Sources

Frequency

St. Louis Testing was subcontracted to bring isotopic sources to GSI to perform radiography on some products produced there. The radiographer from St. Louis Testing indicated that he had brought a 10 Ci Co-60 source to GSI to perform radiographs of Westinghouse Castings. He said the radiograph took one week plus a half a day (180 hrs) to perform due to the extra fine grain film used. He further stated that St. Louis Testing brought the cobalt source to GSI ten times over a period of six months (Meeting Minutes, October 9, 2007; pg 8).

St. Louis Testing also brought to the site a 50 Ci Ir-192 source to perform repair shots. The radiographer indicated that this was infrequent and stated that Ir-192 shows more defects than the Betatrons did which meant more rejects. Presumably this statement means the use of Ir-192 was discontinued soon after it began (Meeting Minutes, October 9, 2007; pg 8).

Radiography Examination Scenarios

When the St. Louis Testing Co-60 source was used to radiograph castings, the casting was shot in open air with a distance of 6 feet from source to casting. It was further explained that that distance was used because they wanted to examine the entire casting in one exam. The casting was placed on a rail car and moved to a railroad spur. The area was secured with barricades and roped off with radiation warning signs. The boundary was set at the point that the exposure rate reached 2 mR/hr. Two radiographers working 12 hours shifts kept the area under constant surveillance (Meeting Minutes, Octobers 9, 2007; pg 8).

St. Louis Testing also brought to the site a 50 Ci Ir-192 source to perform repair shots. No detail was given about the procedures used with the Ir-192 source but presumably the same procedures would be used. That is, a boundary would have been setup at the point where the exposure rate was 2 mR/hr.

4.4 Portable X-ray Machines

Frequency

Little information was provided about the frequency of use of the x-ray units. A former supervisor stated that the units were not used much (Meeting Minutes, October 9, 2007; pg 9). Previously, during a worker meeting on August 11, 2006, he explained in more detail:

"[REDACTED]: [REDACTED] and[REDACTED] and I picked it out. It kind of looked like a vacuum cleaner, the tank type vacuum cleaner. And we used it to see would it work.
[REDACTED]: Uh-huh
[REDACTED]: And to my knowledge after that, it was never ever used. It -- it -- it just didn't meet -- it didn't meet what we needed.
[REDACTED]: Uh-huh So- -
[REDACTED]: And I think it was stored in the Betatron. But it wasn't used to my knowledge only when we wanted to - - to make sure it would do a good job. I don't - - I don't even know if we did the - - you known, the plates that come with it to – to make sure that machine is okay. I don't even know if we did that. But we do it for our own purpose to make sure it did a good job in thin sections. But I don't think it was ever used after that.
[REDACTED]: But in other words, it wasn't used routinely to - -
[REDACTED]: No.
[REDACTED]: - - inspect thin sections in quality control or - -
[REDACTED]: No, sir."
(Transcript, August 11, 2006; pg 59)

An exchange with[REDACTED] radiographers about the x-ray units also occurred during a July 7, 2006 meeting:

"[REDACTED]: [REDACTED], the 250 KV was what I remembered it was in the old betatron. The control unit was on the desk on the side wall. And what I distinctly hated about this unit was there was no safeties on it, [REDACTED]. It - - it was something we were very fearful of and had the incidents involved with people being exposed because there was no safeties on it.
[REDACTED]: Tell me about that now. I'm an amateur. What - - when you say - -
[REDACTED]: Any time we would - -
[REDACTED]: - - no safety, what - - what kind of safety could it have been?
[REDACTED]: For instance on the betatrons we had key safeties, we had door interlock safeties. We had none of this on the KVP other than a key on machine itself.
[REDACTED]: Okay
[REDACTED]: And what would happen any time we used a kvp and it was used for small metal - -
[REDACTED]: Uh-huh
[REDACTED]: - - we would have to be in the same shooting room as the betatron of course to set this up.

[REDACTED]: uh-huh

[REDACTED]: and on occasion if we were using the betatron, there was an incident one time of St. Louis Testing coming over, actually triggered the KVP while workmen were out in the betatron shooting room doing work. [REDACTED]of course to do that, but why in the world this person never checked with the operators. [REDACTED] to the machine, triggered the machine while we had people in the shooting room. It was bad setup. Now, the KVP machine was used only on rare occasions for specific small metal users.

[REDACTED]: And was it used just in the betatron building?

[REDACTED]: Yes, sir, as to my knowledge.

[REDACTED]: To both - - both buildings or - -

[REDACTED]: The old building, sir.

[REDACTED]: The old betatron building?

[REDACTED]: It was – it was in the old building

[REDACTED]: All right. That's very important. Anybody else remember that unit ever being used anywhere else in the plant besides - - okay.

[REDACTED]: Yeah. That was the one where [REDACTED] of the workers walked out while it was still going to - - [REDACTED] had taken a shot, and for some reason there was no safety switch or nothing. And somehow [REDACTED] walked out there and set up another shot while the machine was still going. That was [REDACTED].

[REDACTED]: [REDACTED]

[REDACTED]: That was [REDACTED].

[REDACTED]: [REDACTED], yeah.

(Transcript, July 7, 2006; pp. 139-142)

The former Supervisor that doesn't remember the unit being used much left the department near the end of 1964. This is based on the last film badge assigned to him was for the week of [REDACTED]/1964. The [REDACTED] radiographers that remember the machine being used only in the old betatron building left the department later. The last badge assigned to one was the week of [REDACTED]/1966 and the other was [REDACTED]/1969. From these discussions, it appears the portable x-ray unit was used very little until after November 1964 and then normally in the old betatron building. During that time frame, film badges were supplied by Landauer and would be capable of measuring any dose.

Radiography Examination Scenarios

A 250 KVP x-ray machine can produce a maximum photon energy of 250 keV with an average energy of approximately 80 keV. This energy is considerably lower than that of the Co-60 source, the Ra-226 source or the Betatrons. Because the lower energy photons will not penetrate steel as easily as the other sources, this unit would only be useful for examining some of the thinner materials produced at GSI. From the transcript above, it appears if it was routinely used, it was used in the old betatron building and probably after 1964.

5.0 Personnel Exposure Scenarios

5.1 Radium

The radium sources would have been used in various areas of the plant. As indicated in section 4.1, it is assumed the area was roped off at a distance 1.5 times the required distance, which would be the point where the dose rate reached 2 mrem/hr. A point 1.5 times that distance would result in an exposure rate of 0.89 mr/hr. It is also assumed that the radiographers utilized the fishing pole technique to place and remove the source, resulting in radiation exposures close to the source for a short time while positioning and removing the source. In addition, a radiographer could be exposed at the boundary for the duration of the exam.

Other personnel could be working as at or near the boundary. Also, it was reported that even though the boundary was roped off, some people would walk through the area rather than go around it. This would occur when the radiographer left the source unattended. As described in Section 4.1, the source is assumed to be exposure 144 minutes per shift (30% of the time) to perform 10 examination of one to 90 minutes. This implies an average of eight short exposures (one to two minutes) and 2 longer exposures (>15 minutes) per shift. Assuming the short exposures would not provide the radiographer enough time to leave the area and accomplish another task, it can be assumed that the other workers walked through the area only during the longer exposures.

The radiological boundary would be placed to notify people working at floor level that radiography was occurring. At times, however, people worked at other elevations such as the roof or the pulpit of the overhead crane. These workers would not necessarily know the radiography sources were exposed.

Personnel exposure scenarios would then include:

- Radiographers;
- Others working at floor level near the boundary (including walking through the area);

- Workers working on the roof of the building during exposures; and,
- Crane operator in the crane pulpit

5.2 GSI owned Cobalt-60 sources

A special room was constructed within the #6 building at GSI to perform radiography. The room measured 22 feet by 60 feet and contained a separate room for the operators as well as armor steel plates for shielding (ML093431334 pg 8 & 9). The walls of the room were constructed with 24" thick sand filled concrete block walls. The room had no roof so that equipment could be lowered into the room with an overhead crane. The crane could travel the length of the #6 building and was operated from a pulpit attached to the crane. Crane operators were told not to travel over the radiography room while examinations were in progress. Reports from operators indicate that this rule was not always followed. Figure 2 provides a cross-sectional drawing of #6 building including the radiography room. The location of the crane pulpit is designated with the letter "B" on the right hand side of the drawing. Figure 3 provides a map of the site with the location of the radiography room within #6 building depicted.

Figure 2 – Cross-sectional drawing of #6 building

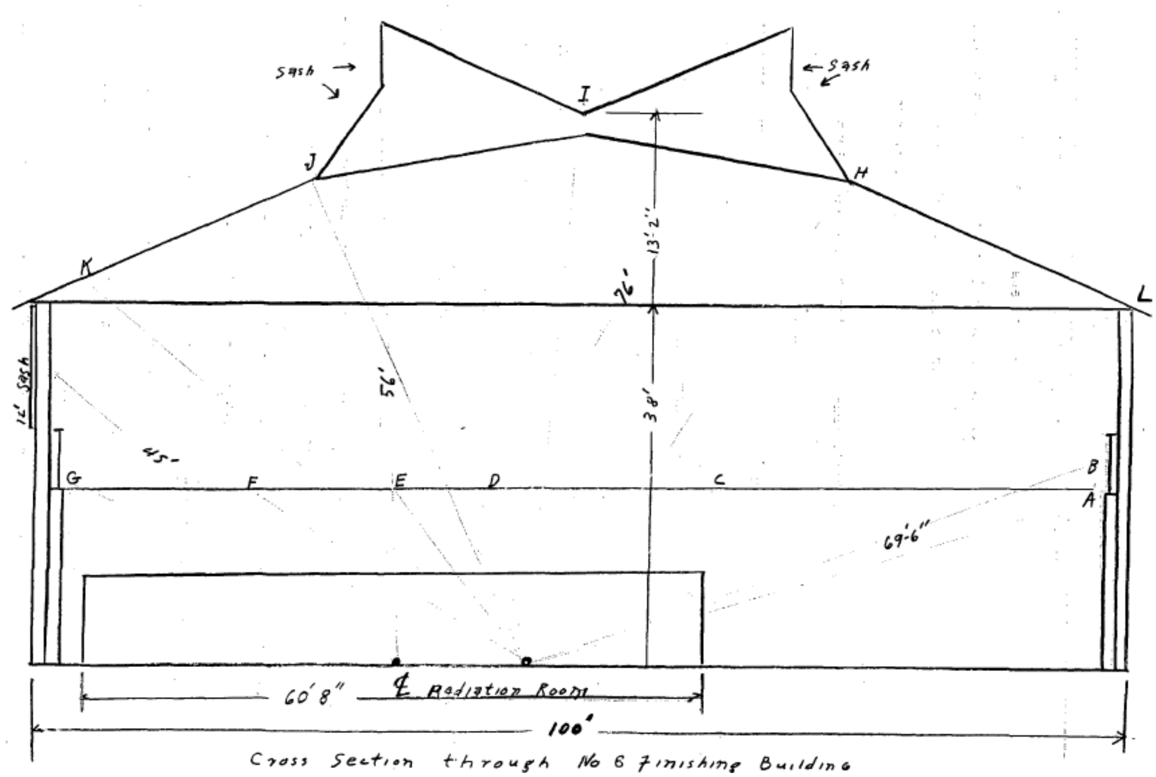
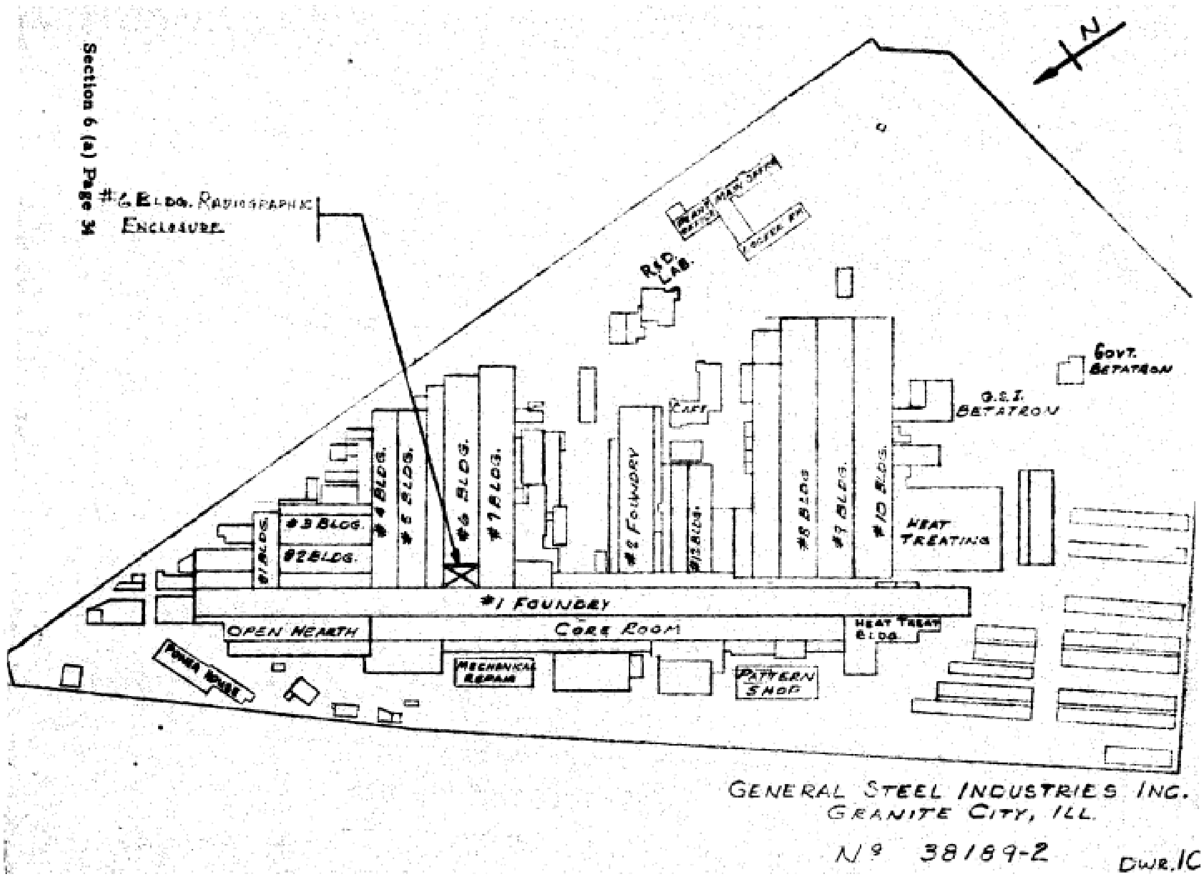


Figure 3 – Site Map of GSI



Other workers were not stopped from walking by or even working next to the radiography room during examinations. Radiographers would have to start and stop the examination from the operator area of the room, but nothing prevented them from leaving and walking around the outside of the room during the examination.

In addition to the radiography room, there were reports that radiography did occur outside the room in various areas of the plant. When this occurred, a boundary was set up at 1.5 times the required distance. Also, there were reports that when the radiographer left the area, people would walk through the boundary rather that around it.

People working above the floor level may not see the boundary and may not be shielded by the walls of the radiography room; therefore, they require special consideration. The two situations when someone can be working above the floor are the overhead crane operator and someone working on the roof of #6 building.

The personnel exposure scenarios for the GSI Co-60 sources are then:

- Radiographer using the radiography room;
- Radiographer using other areas of the plant;
- Others working near the radiography room;
- Others working near the boundary setup outside the radiography room (including walking through the area);
- Others working on the roof of the building for both shooting scenarios; and,
- Crane operator in the pulpit of the crane during both shooting scenarios

5.3 St. Louis Testing Sources

St. Louis Testing performed radiography on the GSI site using their own sources. These exams were done outdoors and a boundary was set up at the 2mR/hr limit. The boundary was continuously watched to prevent personnel from entering the area. In addition, it was reported that GSI personnel assisted the St. Louis Testing personnel during the shots.

The personnel exposure scenarios are then:

- St. Louis Testing Radiographers and any GSI personnel assisting them.
- GSI personnel working near the boundary

5.4 Portable X-ray Machines

GSI purchased a portable X-ray machine to perform some radiography. The voltage of the machines was 250 kV which produced an average photon energy of approximately 80 keV. This energy results in the x-ray units having a lower penetrating ability than Ra-226, Co-60, Ir-191 or the betatrons. As such, its use would have to be limited to thinner items.

No information was provided about the protocols followed when the portable x-ray unit was used.

6.0 Calculated Doses

6.1 Radium

For the radiographic examination scenario using the Ra-226 sources, it is assumed that an area 1.5 times the required distance was roped off around the object to be examined and the source was moved to the area in a shielded container. The film was set up in the appropriate location on the object and the source was moved to the appropriate location for the shot using the fishing pole technique.

The fishing pole technique gives the radiographer an exposure while moving the source that will be similar for every examination, regardless of the length of the shot. In addition, it is assumed that the radiogrpaher waited at the roped off boundary for the entire duration of the shot.

As discussed in section 4.1, the sources are assumed to be exposed 30% of the time, which results in 144 minutes of exposure during an 8 hour shift. A boundary is required to be set up at a location that will not exceed 2 mR/hr. The dose rate at a boundary 1.5 times the required distance would be 0.89 mR/hr. The time the radiographer moved the source to and from the shooting location would not be counted in the 144 minutes of exposure time, however, that time has to be minimized to prevent a blurred or overexposed image. Therefore, the radiographers are assumed to be exposed for 144 minutes per shift at 0.89 mR/hr plus the exposure necessary to place and remove the source. The worker's dose at the boundary is then 2.1 mrem per shift (0.89 mrem/hr * 144 minutes/60 min per hour). The number of shifts per year is assumed to be 406.25 (65 hours per week x 50 weeks per year/8 hours per shift). The annual dose to the radiographer while waiting at the boundary is then 868 mrem/yr.

For the dose received while positioning the source, the distance from the source to the radiographer is assumed to be 5 feet (average of the reported 4 to 6 feet) and the time to place the source is assumed to be 13.5 seconds (average of the reported 12 to 15 seconds). The distance and time to remove the source is assumed to be the same as positioning the source. A 500 mg Ra-226 source will produce a dose rate at 5 feet of 178 mrem/hr. Exposure to this dose rate for 27 seconds (13.5 seconds time 2) produces a dose of 1.33 mrem. This dose will be received for every examination the radiographer places and removed the source regardless of the duration of the examination. From section 4.1, it is assumed 10 examinations were performed with the Ra-226 per shift. This equates to an annual dose of 5411 mrem, if one radiographer performed all the examinations in a year. If this is added to the 868 mrem while waiting at the boundary, the total annual dose would be 6279 mrem.

It is more likely, however, that the duties were shared with other radiographers or radiographer helpers. If only two radiographers shared the duties of placing the source, and both were present at the boundary, the dose from transporting the source would be cut in half, while the dose at the boundary would not. The annual dose would then be 3573 mrem (5411 mrem/2 + 868 mrem).

In 1946, the recommended dose limit used by most organizations was 300 mrem per week (NCRP 1954). In 1958 that same recommendation was in affect with the additional limit of 3000 mrem per calendar quarter(NCRP 1954). At the estimated dose rates above, the single radiographer would receive 42% and 52% of the respective limits while for the two radiographer scenario, each would receive 24% and 30% of the respective limits. In the original application for an AEC license, GSI indicated no one had exceeded the limit and that exposures averaged less than 25% of the limit. This statement appears to correlate reasonably well with the two radiographer scenario.

Based on reports from former workers, it appears likely this dose was tracked using self reading pocket dosimeters (Transcript, July 7, 2006; pg. 54 & 110; Transcript, August 22, 2006; pg. 23). These are often referred to as pencil dosimeters, pocket dosimeters, SRPD's, or just dosimeters. Additional discussion on these devices can be found in section 7.

For other workers working at the floor level, the exposure scenario includes the possibility that the person was working next to the boundary, as well as the possibility that the individual ignored the boundary and walked through the area when the radiographer left it unattended. From section 4.1 and 4.2 it is assumed that the typical radiography schedule resulted in 8 short examinations and 2 longer examinations per shift, which totaled 144 minutes per shift. The short examinations were reported to take one to two minutes while the longer ones could be as much as 90 minutes. It is unreasonable to assume the radiographer left the area during a one or two minute examination. He has to be there in time to remove the source to obtain the appropriate film exposure. Therefore, eight minutes of the 144 minutes per shift are assumed to be used during short examinations with no one walking through the area. For the remaining 136 minutes, it is unrealistic to assume someone paced back and forth within the area the entire time. The purpose was likely to take a short cut, not to receive radiation exposure. Given these conditions, a reasonably bounding value of 10% is used to account for the amount of the available time a person actually walked through the area. That equates to 13.6 minutes per shift.

A person working at floor level, not associated with the radiography, is then assumed to be exposed while walking through the area for 13.6 minutes per shift. That person is further assumed to be exposed at the boundary of the area for the remaining 130.4 minutes per shift.

Using the technique described in Attachment C, the average dose rate while walking through the area is estimated to be 6.16 mrem/hr. At 13.6 minutes per shift and 406.25 shifts per year, this results in an annual dose of 567 mrem from walking through the area. Additionally, the worker is assumed to be at the boundary the remaining 130.4 minutes per shift. At 0.89 mrem/hr for 406.25 shifts per year, this results in an additional dose of 786 mrem per year or a total annual dose of 1353 mrem.

The overhead crane in the #6 building was operated from a pulpit on the crane. The pulpit was approximately 25 feet above the floor of #6 building (ML093431335 pg 15). The dose rate from the unshielded source at this point would be 7.1 mrem/hr. However, the crane was in constant use and it is unrealistic to assume the pulpit was directly above the radiography every minute of every shot. Since the crane could operate the entire length of the building, it is more accurate to assume all locations in the build had equal probabilities. Therefore, the average dose rate in the pulpit would be the most appropriate estimate. To estimate the average dose rate in the pulpit, the length of the building was first determined. Figure 2 shows the width of #6 building to be 100 feet. Figure 3 shows a map of the site. Taking measurements from this map, and equating them to the building being 100 feet wide, results in an estimated length of 610 feet for #6 building. With the pulpit 25 feet above the floor the distance between the source and the pulpit could be anywhere from 25 feet to 610 feet. Assuming equal possibilities for all locations of the crane, the average distance would be:

$$R_{avg} = \frac{1}{X_{max}} \int_0^{X_{max}} \sqrt{H^2 + X^2}\, dx$$

Where:

R_{avg} = the distance from the source to the pulpit

H = the height of the pulpit above the floor

X = the horizontal distance between the source and the pulpit

X_{max} = the length of the building

Although the pulpit is located on one side of the building, we will assume the worst case scenario that the source is always used on the same side of the building as the pulpit. Also, we will assume the source is centered in the building (lengthwise) resulting in the smallest maximum distance of 305 feet (610 feet/2). The resulting average distance from source to pulpit is 156 feet. The dose rate from the source at this distance is 0.18 mrem/hr. Exposure to this dose rate for 144 minutes per shift and 406.25 shifts per year equals 177 mrem per year.

For workers located on the roof, it can be seen from figure 2 that at its lowest point (the edge of the roof) the height of the roof above the floor of the building is 38 feet. While it is possible that an individual could have worked directly above the exposed source on occasion, it is unrealistic to assume that person worked directly above the exposed source every minute of every examination. Therefore, it is assumed that all locations along the length of the roof are equally probably for the workers location. Using the same technique as used for the crane pulpit, the average distance from the source to an individual on the roof can be estimated as 165.5 feet. This results in an annual exposure of 158 mrem.

6.2 GSI owned Cobalt-60 sources

6.2.1 Radiography Room

A radiation survey of the #6 building radiography room was conducted on 6/24/1962 and 8/1/1962 (ML093431294). This survey included the outside of the room as well as normally occupied areas inside the room.

The maximum dose rate found on the exterior wall of the room was 1.2 mR/hr, while the average reading was reported as 0.15 mR/hr one meter above the floor and 0.23 mR/hr two meters above the floor. The operator area within the room was also surveyed. One meter above the floor a maximum reading of 1.15 mR/hr was found while the average reading was 0.26 mR/hr. At two meters above the floor, the maximum was 0.85 mR/hr with an average of 0.33 mR/hr.

Using the maximum reading of 1.2 mR/hr, 144 minutes of source usage per shift and 406.25 shifts per year results in a maximum annual dose to the radiographers of 1170 mR. Since this maximum dose rate is outside the room and nothing prevents other individuals from working next to the wall, 1170 mR is also the maximum annual exposure for other workers at floor level.

On 1/19/1963 an additional survey was conducted above the radiography room (ML093451452 pp 11-16). This survey was conducted on the catwalk and cab of the overhead crane servicing the building. The surveys were conducted with both Co-60 sources exposed. Several configurations were explored both with and without castings present. Table 2 provides the results of the 1/19/1963 survey above the radiography room. The locations are designated by letters corresponding to the letters in Figure 2. The dose rates for positions H through L were calculated from the surveys at points A through G and the distances to the remaining points.

Table 2 – Dose Rates above the Radiography Room.

Location	Description	Exposure rate with source in casting (mR/hr)	Exposure rate without casting (mR/hr)
A	Seat of the crane operator	0.5	1
B	Catwalk on top of crane	1	1.5
C	Catwalk immediately above wall	1	3
D	Catwalk immediately above sources	3.5	7
E	Catwalk about half-way between sources and operator's position	1.5	2.5
F	Catwalk immediately above operator's position	1	1.5
G	Catwalk immediately above end wall of room	0.5	1
H	Platform inside building used to work on window controls 60' from sources (used measured field at C for calculation)		0.52
I	Ridge area on top of roof 52' from sources (used measured field at D for calculation)		0.85
J	A second platform inside building used to work on window controls 56' from sources (used measured field at E for calculation)		0.45
K	Edge of building 62 feet from sources (used measured field at F for calculation)		0.4
L	Area between two buildings 68' from sources (use measured field at C for calculation)		0.4

It is possible for the overhead crane to move over the top of the radiography room. Since the pulpit is on one side of the building and the radiography room does not extend all the way to that side, the pulpit cannot move directly over the sources. Figure 2 lists a distance of 69 feet 6 inches; however, it is possible for the distance to be less if the sources are moved as close as possible within the radiography room. At the closest location, the crane pulpit is approximately 40 feet from the wall of the radiography room and 25 feet above the floor. This results in a straight line distance of approximately 47 feet. Since the crane is constantly in use, it will not stay in one position for long. Assuming equal possibility for the crane to be in any location within the building, the same equation used in section 6.1 can be used. In this case, 47 feet is used for “H” to represent the closest distance. However, since the radiography room is on one end of the building, the maximum distance in that direction is approximately 610 feet, resulting in an average distance between source and crane pulpit of 314 feet. The dose rate at this distance from the Co-60 source would be 0.04 mrem/hr. Exposure to this dose rate for 144 minutes per shift and 406.25 shifts per year results in an annual dose to the crane operator of 39 mrem.

An individual working on the roof would be higher above the sources than the crane operator but could move laterally closer so that he is directly above the sources. Using the distances from points “H” though “L” in table 2, the shortest distance from source to roof was 52 feet at location “I”. Using 52 feet as the closest distance and again using the same equation and other parameters as above, the annual dose to someone on the roof would be 38 mrem.

6.2.2 Co-60 Sources Outside the Radiography Room

It was reported that on occasion, the Co-60 sources were used outside of the radiography room. It was further reported that on these occasion a boundary was set up at the point 1.5 times the required distance. The required distance was the point where the dose rate reached 2 mrem/hr. A distance 1.5 times that would result in a dose rate of 0.89 mrem/hr.

The Co-60 sources were used in a Budd model 110AB “camera”. The camera allows the operator to secure one end of a tube to the desired location and the other end to the camera. Then by turning a remote crank, the source is moved from the camera to the desired location. This allows the radiographer to be outside the area the entire time the source is exposed. Therefore, assuming the radiographer was at the boundary for every shot, his estimated annual dose would be 0.89 mrem/hr X 144 minutes per shift / 60 minutes per hour X 406.25 shifts per year which equals 868 mrem/year.

Nothing prevented other workers from working next to the boundary so they would also receive this dose. However, it was also reported that radiographers would sometimes leave the area unattended and the other workers would walk through the area rather than around it.

From section 4.2 it is assumed that the typical radiography schedule resulted in 8 short examinations and 2 longer examinations per shift. These examinations totaled 144 minutes per shift. The short

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examinations were reported to take one to two minutes while the longer ones could be as much as 90 minutes. It is unreasonable to assume the radiographer left the area during a one or two minute examination. He has to be there in time to retract the source to obtain the appropriate film exposure. Therefore, eight minutes of the 144 minutes per shift are assumed to be used during short examinations and no one walked through the area. For the remaining 136 minutes, it is unrealistic to assume someone paced back and forth within the area the entire time. The purpose was likely to take a short cut, not to receive radiation exposure. Given these conditions, a reasonably bounding value of 10% is used to account for the amount of the available time a person actually walked through the area. That equates to 13.6 minutes per shift.

A person working at floor level not associated with the radiography operation is then assumed to be exposed while walking through the area for 13.6 minutes per shift. That person is further assumed to be exposed at the boundary of the area for the remaining 130.4 minutes per shift.

Using the technique described in Attachment C, the average dose rate while walking through the area is estimated to be 6.10 mrem/hr. At 13.6 minutes per shift and 406.25 shifts per year, this results in an annual dose of 562 mrem from walking through the area. Additionally, he is assumed to be at the boundary the remaining 130.4 minutes per shift. At 0.89 mrem/hr for 406.25 shifts per year, this results in an additional dose of 786 mrem per year or a total annual dose of 1348 mrem.

When the sources were used outside of the radiography room, it was possible for an area to be set up on the same side of the building as the crane pulpit. As previously noted, the crane was constantly in use so it would not remain over the sources for the duration of every examination. Therefore, again using the equation in section 6.1 and assuming a 25 foot height above the floor, and a maximum distance of 305 feet down the building, the average dose rate in the pulpit would be 0.16 mrem/hr. That dose-rate for 144 minutes per shift and 406.25 shifts per year results in an annual dose of 159 mrem.

As previously described, an estimate of the dose for an individual on the roof can be based on the equation in section 6.1. The height above the floor is assumed to be 38 feet, which is the lowest portion of the roof according to figure 2. Again, the maximum distance from the source is assumed to be 305 feet, which would occur when the source area is setup in the middle of the building (lengthwise). This produces an average dose rate of 0.145 mrem/hr, which results in an annual dose of 142 mrem.

6.3 St. Louis Testing Sources

St. Louis Testing sources were reported used outdoors on large Westinghouse castings. The castings were placed on a rail car and moved to the end of a railroad spur presumably to allow a large unpopulated area to be roped off without interfering with plant operations. A former St. Louis Testing employee reported that an area was roped off that would limit the dose rate to 2 mrem/hr. The examinations on these castings lasted 180 hours. Also, 10 examinations were done over a six month period.

At the reported rate of the examinations, they were occurred for a total of 1800 hours in a six month period or 3600 hours per year. An individual at the boundary full time would potentially receive a dose of 7200 mrem per year. One individual, however, cannot stay at the boundary for 180 straight hours. Radiographers at GSI reported an average workweek of 65 hours or 3250 hours per year. Dividing that by 8750 hours in a year means the radiographers were at work 37.1% of the time. The 7200 mrem of dose at the boundary 100% of the time can be multiplied by the 37.1% reported work schedule to obtain a maximum annual dose of 2671 mrem in a year.

This value assumes a radiographer is located at the boundary every time an examination is conducted while they are at work. While it is possible GSI radiographers helped St. Louis Testing personnel during the examinations, it is much less likely other GSI employees spent so much time working outdoors near the railroad spur. An assumption can be made that no more than half of their time was spent next to the boundary. Therefore, for GSI employees other than radiographers, an estimated annual dose of 1336 mrem can be calculated.

6.4 Portable X-ray units

From the transcript in section 4.4 it appears that, if the portable x-ray unit was used routinely, it was in the shooting area of the old betatron building after 1964. At this point, Landauer was supplying film badges for radiographers at GSI. While it has been reported that they did not wear their film badges outside the betatron buildings, it was also reported that they **always** wore them inside the betatron buildings (Transcript, July 7, 2006; pg. 49; Transcript, August 11, 2006; pg. 34; Transcript, August 22, 2006; pg. 23, 45). Therefore, it appears doses from the portable x-ray units would have been recorded on the available film badge records.

If this unit was used outside of the betatron building, the dose could be bounded by considering that the film used with the unit would be similar to that used with the isotopic sources. This implies that the film would need to be exposed to a similar dose to produce a usable image. Regardless of the dose rate delivered by the unit, the dose on the film side of the metal would be similar to that delivered by the isotopic sources. Since the metal would be some of the thinnest examined at GSI, the dose on the unit side of the metal would be lower than many of the examinations performed with the isotopic sources. Also, while the isotopic sources emit radiation isotropically, the x-ray unit emits radiation directionally towards the object being examined.

With a low frequency of use, shorter examinations (due to thinner metal) and directional radiation, the radiographer dose from the portable x-ray units should be considerably less than that from isotopic sources. Therefore, a bounding estimate would be based on isotopic sources rather than the portable x-ray unit.

6.5 Summary

From the doses calculated above, the highest dose applicable for a category of workers for a given time period were chosen. Two categories of workers were chosen: radiographers, and all other workers. The radiographer category includes radiographer helpers and anyone else that would be associated with the radiography work near the sources. Working on unrelated projects near the area is covered in the other category. A summary of the resulting dose estimates are shown in Table 3.

The dose estimate for those associated with radiography is 3573 mrem/yr from 1953 to 1962 and 2671 mrem/yr from 1962 to 1966. For all other employees, the dose estimate is 1353 mrem/yr from 1953 to 1962 and 1348 mrem/yr from 1962 to 1966.

The dose from the portable x-ray units was not estimated. The discussion in section 6.4 provides the rationale for assuming other sources of radiation dose would bound those from using the x-ray units.

The appropriate time frame for St. Louis Testing's involvement at the site is not known. All indications are that radiography at GSI was performed by only a few radiographers prior to 1962. In 1962, the work ramped up quickly and this is likely the time frame that St. Louis Testing was called on to help accomplish some of the work. The dose estimate for use of the Ra-226 sources, however, exceeds the estimate for the St. Louis Testing sources. Therefore, it is not necessary to determine if St. Louis Testing started prior to 1962.

Table 3 – Summary of Dose Estimates (mrem)

Source	Applicable years	Radiographer	Others at floor level	Crane operator	Roof	Max Other non-radiographer
Ra-226	1953-1962	3573	1353	177	158	1353
GSI Co-60 (outside radiography room)	1962-1966	868	1348	159	142	1348
GSI Co-60 (radiography room)	1962-1966	1170	1170	39	38	1170
St. Louis Testing sources		2671	1336	n/a	n/a	1336
X-ray unit						
Maximum	1953-1962	3573	1353	177	158	1353
Maximum	1962-1966	2671	1348	177	158	1348

7.0 Dosimetry Data

A check on the estimated doses can be accomplished using personal dosimeter data from GSI radiographers. Several issues have been reported that would prevent a direct comparison but a qualitative comparison is still possible.

First, it appears GSI used pocket dosimeters. Pocket dosimeters are often used by radiographers and other nuclear workers entering elevated radiation fields. They are referred to by various names, pocket dosimeters, pencil dosimeters, Self-Reading-Pocket Dosimeters (SRPDs) or just dosimeters. Workers at GSI indicated:

- They would use them if they were assisting an isotope operator (Transcript, July 7, 2006; pg. 54);
- Isotope operators always wore their film badges and dosimeters (Transcript, July 7, 2006; pg. 110); and,
- Wore dosimeters along with film badges (Transcript, August 22, 2006; pg. 23)

The primary benefit to a pocket dosimeter over other types (e.g., film badges) is that the wearer can read his own accumulated dose at anytime. The disadvantages include the fact that the reading is less reliable and the dosimeter can be more easily affected by environmental and physical stresses. For example, pocket dosimeters are known to sometimes go off scale after a mechanical shock and high humidity can cause the reading to "drift" high.

Figure 4 shows a typical pocket dosimeter. This one is a Civil Defense model but others were produced by various companies in various colors sizes and scales.

Figure 4 – Typical Self Reading Pocket Dosimeter

Figure 5 shows a drawing of a typical pocket dosimeter. The principle of the dosimeter is basically that of an electroscope. A charge is put on the fibers where one fixed and one movable fiber repel each other. As ionizing radiation ionizes the air in the chamber, the charge is collected on the fibers and they repel each other a little less. As the charge is lessened, the movable fiber casts a shadow across a scale showing a higher dose.

Figure 5 – Interior of a Typical Self Reading Pocket Dosimeter

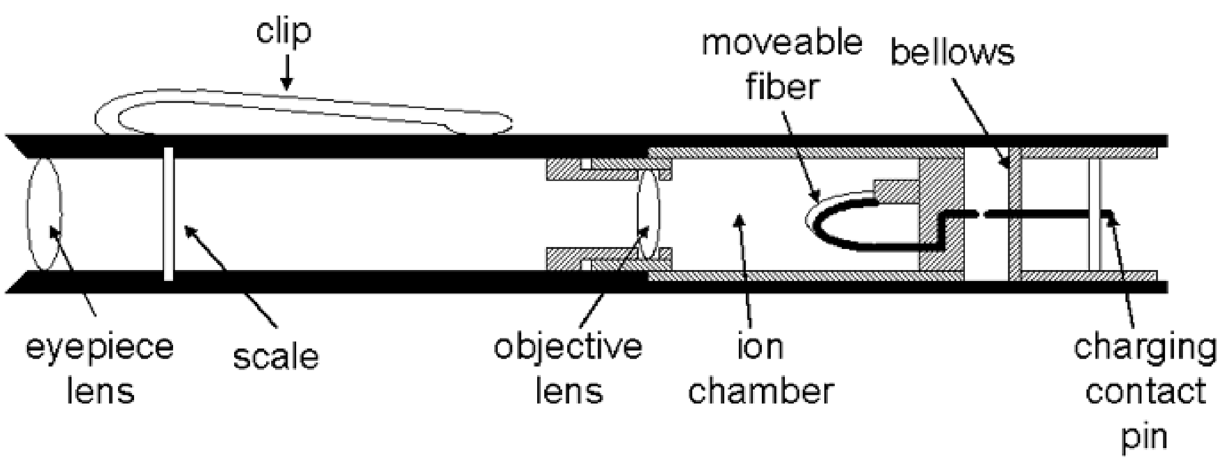

Figure 6 shows the scale of a typical 0-200 mR pocket dosimeter. This is what the wearer of the dosimeter would see when he read it. A line from top to bottom would appear to indicate the accumulated dose since the last time the dosimeter was zeroed.

Figure 6 –Self Reading Pocket Dosimeter Scale

To use a pocket dosimeter, someone typically "zeros" the dosimeter using a charger before it is issued. The initial reading (ideally zero) is recorded and, at the end of the day, the dosimeter is read for the final reading. It can also be read at anytime during the day by the wearer. At the end of the day, the beginning reading (if not zero) is subtracted from the final reading to determine the dose received that day.

When pocket dosimeters are used, the only record would be a log of the daily entries. Using such a log, daily readings can be summed to determine weekly, monthly or even annual doses. It is not known what GSI did with any logs that were kept, but indications are that they did keep a log and tracked doses to some extent. The best evidence that the doses were reviewed is the account by a former worker of the events surrounding his pocket dosimeter, which indicated a high reading. He indicated that he zeroed the dosimeter at the start of his shift and at the end of the shift recorded a high reading in the dosimeter log book. The next day the supervisor dismissed it as improper zeroing of the dosimeter (Transcript, July 7, 2006; pg. 51)

It is likely these logs were used by GSI as the basis for the statement in their initial AEC license application that the average dose was less than 25% of the AEC dose limits.

From 1964 to 1973, Landauer supplied GSI with film badges. The badges were only supplied to those in the non-destructive assay group. Former workers have reported that the film badges were not worn outside the betatron buildings. It was further stated that this was company policy because hot sparks in the other areas of the plant could burn holes in the film (Transcript, December 16, 2009; pg. 247; Transcript, May 12, 2010; pg. 255). Others claim that film badges or pocket dosimeters were always worn when working with isotopic sources:

- "If … our duties took us to those buildings, we wore badges". (Transcript, July 7, 2006; pg. 43)
- They would use them (pocket dosimeters) if they were assisting an isotope operator (Transcript, July 7, 2006; pg. 54)
- Isotope operators always wore their film badges and dosimeters (Transcript, July 7, 2006; pg. 110)
- Wore dosimeters along with film badges (Transcript, August 22, 2006; pg. 23)

No statements could be found where any former worker directly claimed film badges were not worn by radiographers when working with isotopic sources outside the betatron building.

By taking these statements all together, it is difficult to reconcile them in any other way than to conclude that:

- Film badges were not worn outside the betatron building in areas where hot sparks could burn the film.
- Radiography would not likely occur in an area where hot sparks would burn through the x-ray film.

This implies film badges were worn when working with the isotopic sources outside the betatron building as confirmed by the statements of several workers. The statements that the film badges were not worn outside the betatron building appears to be a general statement that has a single exception of working with the isotopic sources.

When the film badges were processed, any readings of 10 mrem or more were recorded. An analysis of the film badge results from GSI indicates that more than 99% of the readings were below 10 mrem. It also indicates the badges were exchanged weekly. This implies an annual dose of 500 mrem should routinely result in some weekly readings greater than 10 mrem. The lowest annual dose estimate for radiographers was 868 mrem for x-ray examinations taken outside the radiography room in #6 building.

The highest annual dose for radiographers is that received by helping St. Louis Testing. This dose, 2671 mrem would easily be detected on the film badges. This indicates the dose estimates are bounding.

Prior to film badges, it is likely pocket dosimeters were used to track a radiographer's exposure. The dose estimate for this time frame is 3273 mrem per year. This equates to a weekly dose of 71.5 mrem which is approximately 24% of the weekly dose limit of 300 mrem. This estimate correlates well with the statement by GSI in its initial AEC license application that the average exposure was less than 25% of the AEC limit.

8.0 References

AEC 1963, *Energy Dependence Determinations in the 60-180 KeV Range with an X-ray Machine of Varying Output*, U.S. Atomic Energy Commission, A. Shambon, A. Zila, R. Sanna, HASL-133, February 1963.

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ML093451452 pp. 11-16, *Survey of the Radiographic Exposure Facility at General Steel Industries*, January 19, 1963

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OCAS 2007, *Site Profiles for Atomic Weapons Employers that Worked with Uranium and Thorium Metal - Appendix BB: General Steel Industries*, Battelle-TBD-6000, Appendix BB, Rev. 0, June 25, 2007.

NCRP 1954, National Council on Radiation Protection and Measurements, *Permissible dose from External Radiation Sources of Ionizing Radiation*, Report 17 (NBS Handbook 59), National Bureau of Standards, U.S. Department of Commerce, September 24, 1954.

Transcript, July 7, 2006, *GSI Affidavit Testimony, transcript; July* 7, 2006; SRDB Ref ID: 47972

Transcript, August 11, 2006, *GSI Affidavit Testimony*, transcript; August 11, 2006; SRDB Ref ID: 47973

Transcript, August 22, 2006, *General Steel Industries Worker Outreach Meeting*, transcript; August 22, 2006; SRDB Ref ID: 47971

Transcript, October 14, 2009, *Advisory Board on Radiation and Worker Health, TBD-6000/6001 Work Group*, October 14, 2009

Transcript, December 16, 2009, *Advisory Board on Radiation and Worker Health, TBD-6000/6001, Appendix BB Work Group*, October 14, 2009

Transcript, May 12, 2010, *Advisory Board on Radiation and Worker Health, Work Group on TBD-6000*, May 12, 2010

References listed with a code starting with "ML" are Nuclear Regulatory Commission accession numbers from a freedom of information act required (PA-2010-0012). References can be obtained at this internet address:
http://adamswebsearch2.nrc.gov/idmws/ViewDocByAccession.asp?AccessionNumber=ML093510887

ATTACHMENT A – ACTION NOTICE OF X-RAY UNITS

3rd DAY . . . THURS., NOV. 13 (Cont.)

DARKROOM AND CAMERA EQUIPMENT
PAKO Model 13 PHOTO PRINT DRYER, S/N 65578
ALOYT ROTARY PRINT DRYER
OSCAR FISHER FILM PLATE DRYER, 4 x 5, S/N 14417
ANDREX X-RAY UNIT, Model A1652, S/N 34248, 250 KV 8 MA Directional Unit W/Hydraulic Lift Cat. @ A2501, S/N 34248, Portable
~~GE X-RAY, Model QX-250 Industrial Size...~~
2 OMEGA, Model D, 4 x 5 ENLARGERS
2 BURKE 8 x 10 Model 2B CONTACT PRINTER
2 BRUMBERGER 5 x 7 CONTACT PRINTER
ARKAY LOAD MASTER PRINT WASHER, Model 1620A
OSCAR FISHER WATER TEMP. CONTROLLER, #14530 W/Stain-

DISPENSARY

WESTINGHOUSE X-RAY, 200 MA Autoflex, Post Style 31M980978, S/N M305282 Table Style 982419-A, S/N 48-11-104, Synamax Tube, Model HD 25, S/N K66185, Carr S/S Developing Sink W/Water Mixing Unit, Max. Size 14" x 17"
E & S Resuscitor, Triple Portable Model
CASTLE STERILIZER, Model 669, S/N Z8740
TURBO WATER BATH, w/111e Electric Turbine Model HM-255
BURDICK SHORT WAVE DIATHERMY, MF/490, S/N 9297, New 1967
ELECTRIC EYE CHART
X-RAY VIEWERS
Cabinets
Sink
Refrigerator

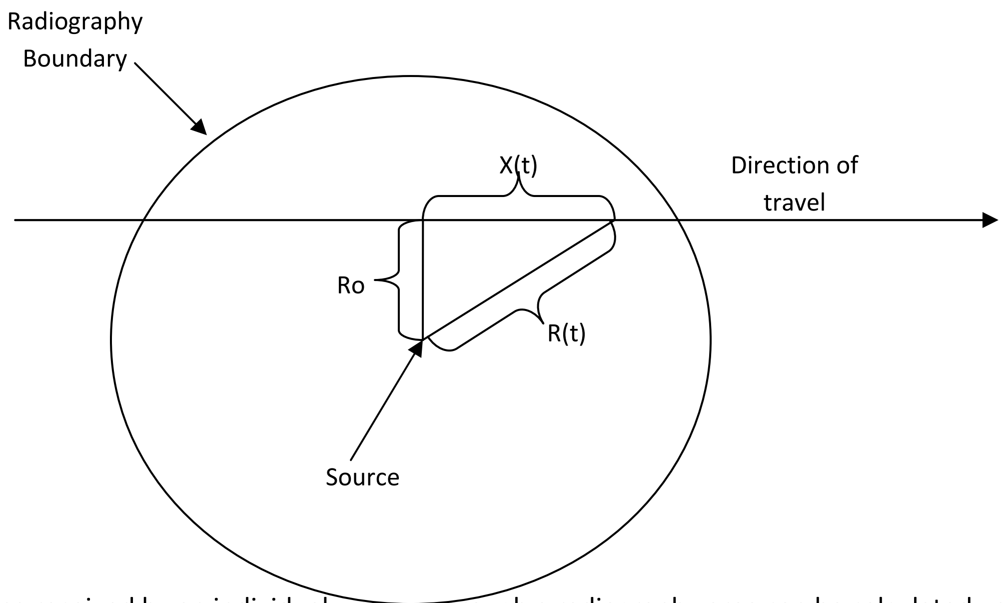
ATTACHMENT B – Worker Interview on Fishing Pole Technique

From: Anigstein, Robert (CDC/NIOSH/OD) (CTR)
Sent: Sunday, October 10, 2010 3:56 PM
To: Ziemer, Paul (CDC/NIOSH/OD); Beach, Melsa J. (CDC/NIOSH/OD);
Munn, Wanda I. (CDC/NIOSH/OD)
Cc: Katz, Ted (CDC/NIOSH/OD); Mauro, John (CDC/NIOSH/OD) (CTR);
Allen, David (CDC/NIOSH/OD); Neton, Jim (CDC/NIOSH/OD); Hinnefeld,
Stuart L. (CDC/NIOSH/OD)
Subject:Worker Interview

On [REDACTED], 2010, at approximately 12:30 PM EDT, I called [REDACTED], a former GSI worker, to obtain information about fishpole radiography using radium sources. [REDACTED]was employed at GSI and performed radiography using the radium sources, starting in 1956.
According to [REDACTED], the source was kept in a lead shield with a small opening on top. There was a lead lid to cover the shield, but over 90% of the time, the shield was left open on top. A string, 4 to 6 ft long, was tied to the source capsule--the string was permanently left on the capsule. The other end of the string was attached to the end of a pole that was 4 to 6 ft long. [It is not clear to me if the pole was permanently attached to the string or if the string was attached to the pole when the source was to be deployed.] To perform a radiographic exposure, the casting was set up with the film cassettes in place. The radiographer lifted the source out of the lead shield, holding the end of the pole. [REDACTED] estimates that the exposed source was 4 to 6 ft from his body. He then walked over to the casting, put the source in place, and walked away, leaving the pole at the edge of the casting. He estimates the elapsed time from the removal of the source from the shield to its placement next to the casting to be no more than 12 to 15 sec. At the end of the exposure, the procedure was reversed and the source replaced in the shield.

[REDACTED]asked to see my report of the telephone call, so that he could make any necessary corrections. Since he does not have e-mail access, this will have to be done by regular mail, so I anticipate a period of a week or more before I get a response. Due to the proximity of the work group meeting, I am sending this preliminary, unverified report of the conversation for the information of the work group.

ATTACHMENT C – 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:

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

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:

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

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:

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

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

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:

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

It is unlikely that an individual walked through the area for the sole purpose of receiving radiation exposure. It is more likely the person simply took a shorter path rather than going around the marked off area. Therefore, the individual could have walked through at any distance from the source. The dose was calculated for an Ro value equal to one foot from the source as well as every distance (in one foot increments) from there to the boundary of the delineated area. Each of these values was divided by the time it would take to walk through the area at that Ro to obtain a dose rate. The individual dose rates were then averaged to determine the overall dose rate.

The 1 foot dose rate values from table 1 were utilized, along with an assumed walking velocity of 3 ft/sec. This is approximately 2 miles per hour and presents fairly slow pace. The dose rate for the Ra-226 source was calculated to be 6.16 mR/hr and the dose rate for the Co-60 source was calculated to be 6.1 mR/hr.