General Steel Industries Layout man Beta Skin Dose

Response Paper

National Institute for Occupational Safety and Health

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BACKGROUND SUMMARY

The Advisory Board Work Group (WG) on TBD 6000 reviewed many potential exposure scenarios for the General Steel Industries' (GSI) Appendix and the Special Exposure Cohort Petition (SEC) petition. These discussions resulted in an agreed-upon method for most exposure scenarios and assumptions to be used in a revised *GSI Appendix BB*. These included: (1) The technique to determine beta dose calculations for Betatron Operator and (2) a Layout man exposure scenario for the photon dose calculations from working on freshly x-rayed castings. NIOSH used the agree-upon-methodology to calculate the beta dose for the Layout man. The beta dose for the betatron operator was also calculated in the revision, which is a separate issue in the Appendix revision. During the revision, NIOSH found the already agreed-upon parameters and exposure scenario resulted in a beta skin dose overestimate for the Layout man.

In a 2014 review of *Appendix BB (SCA 2014)*, Sanford Cohen & Associates (SC&A) concluded their calculated beta dose to the Layout man larger than the *Appendix BB* revision. Following the review, NIOSH and SC&A exchanged e-mails and files to understand SC&A's revised position on the agreed-upon parameter and exposure scenarios for beta dose calculations to the Layout man. NIOSH recognized the need to discuss beta dose potential, as well as, an exposure scenario from working on freshly x-rayed castings. SC&A appears to have modified the agreed-upon approach for beta-dose calculations, which caused a dose over-estimate.

This is a response paper to SC&A's proposed change to the agreed-upon scenario for dose recalculation for the Layout man. We have outlined below the agree-upon approach, examined SC&A recent proposal, and have recommended a revised approach to estimate the beta-skin dose to the whole body and the extremities (e.g., hands and forearms) in our response.

AGREED-UPON SCENARIO

The scenario for the Layout man's photon dose who worked outside of the betatron building on a single large casting during most of a shift assumed:

1. Casting was repeatedly x-rayed using a short shot routine (i.e., 3-minute shots with 12 minutes between). That meant 532[1] short-shots were performed before the Layout man received the casting.
2. It took 15 minutes (after the last shot) before the Layout man began casting work.
3. The Layout man worked on this single large casting for a full shift. (The only exception is being interrupted by other castings discussed.) The work was interrupted to mark-up a freshly x-rayed casting near completion, according to a [redacted for privacy] statement.

[1] The number of short shots is based on page 7 of the January 12, 2014 SC&A memo (SCA 2014) dealing with calculating gamma dose to the layout man. The steel was assumed to have 30 hours of prior betatron exposure according to the December 5, 2013 SC&A memo dealing with calculating beta dose to the betatron operator (SCA 2013).

4. The castings that would interrupt the Layout man's work were assumed to: (1) have been exposed to long shots of 60 minutes; and (2) x-rayed 400 times just before the Layout man's casting work started (SCA 2014 p. 7).
5. The Layout man's exposure duration ranged from 15 minutes up to 8 hours and 15 minutes following the single large casting x-ray. The exposure, after interruption of castings, ranged from 15 to 90 minutes (75 minutes of exposure). New freshly-x-rayed interrupting casting was assumed to take place after the 75 minutes of exposure.
6. Work on the interrupting casting was assumed to take 10% of the shift, based on a statement of the [redacted for privacy] . [redacted for privacy] said that the Layout man would typically spend a full 8-hour shift marking-up a large casting. He added the Layout man could sometimes be interrupted to mark-up a casting that had just been radiographed and close to shipment (SCA 2014 page 7). The scenario assumed the remaining single large-casting work was 90% of the work for each shift.
7. The full-shift dose from the interrupting casting was calculated by multiplying the dose per casting by 6.4, which is the average number of castings that could be processed through this scenario in an 8-hour shift.
8. The initial dose rate from the castings was calculated by first using MCNP to determine the production rate of each isotope. This production rate, combined with the decay constant for each isotope, was used to determine the buildup of each isotope. The build-up time for the short-shot scenario was 26.6 hours (532 shots of 3 minutes each). This was 26.6 constant hours of exposure to the x-ray beam without the 12 minutes per shot of additional decay time. Similarly, the long-shot scenario used 400 hours of continues x-ray-beam exposure.
9. The dose for each scenario was calculated for contact, 1 foot and 1 meter distances from the casting. The beta dose to the hands and forearms was calculated by applying the contact dose for 90% of the time and the 1 meter dose for the remaining 10% of the time. The dose to the rest of the skin of the body was calculated by applying the 1-foot dose for 90% of the time and the 1-meter dose for 10% of the time.

NEW SC&A SCENARIO

In December 2014, memorandum, SC&A revised its position that the beta-dose calculations used will vary significantly from a gamma-dose approach (SCA 2014a). The distinct difference in the calculation is that no single large-casting approach exists. The SC&A model uses only interrupting casting scenarios, even though a GSI [redacted for privacy] this activity "might sometimes" happen. In addition, the interrupting casting scenario was changed from being created by 100% long shots to being created by 64% short shots and 36% long shots. Lastly, SC&A used a 30 hour continuous x-ray of the castings prior to the Layout man receiving the casting. This is different than the Layout man exposure scenario used for the gamma dose calculation, which was based on 400 hours for long shots (used for the interrupting casting) or 1596 minutes for short shots (used in the single large casting calculation).

NIOSH RESPONSE

NIOSH reevaluated the applicability of the gamma dose scenario to the estimation of beta dose. As a result, propose a change to the values and techniques employed in the estimation of beta dose to the skin because:

1. The physical impossibility of the betatron irradiation scenarios that were used in both the originally agreed-upon model and the scenario used in SC&A's recent review paper; and
2. The excessively long irradiation times used to bound photon dose were considered acceptable because the photon dose from the irradiated steel was a small (~0.2%) component of the overall photon dose. Thus, bounding calculation use in this case was considered acceptable. This is not necessarily true for the beta exposure scenario.

Please note that Table 6 of *Appendix BB Rev.1* for the estimated photon dose to the Layout man from the irradiated steel at 20.8 mrem/year (out of the total 9000 mrem/year total photon dose.)

Casting Interruption Occurrences

We propose using the already-agreed-upon value of 10% of the work shift for casting that interrupts the work.

NIOSH is not aware of any basis to remove a single large-casting scenario from the calculation. The [redacted for privacy] indicated that a casting "might sometimes" interrupt the work; however, the Layout man would normally work on a single casting the full 8- hour shift. This assumes that 10% of the time each shift represents an interrupting casting appears to be favorable.

Fraction of Short/Long Shot

NIOSH proposes using this ratio in the calculations for *both* the single large casting and the interrupting casting

In the original SC&A report (SCA 2008), referenced and quoted in its January 12, 2014, memo (SCA 2014), the scenario used was that of a single large-casting created 100% short shots and the interrupting casting created by 100% long shots. Then, in its latest calculations, SC&A provided a *mixture* of short and long shots for the interrupting casting *and* eliminated the single large casting scenario. The ratio of short and long castings in the latest memo was taken from betatron operator calculations (64% short / 36% long). However, that ratio was the amount of time each type of casting was worked within the betatron building.

The ratio was based on the number of shots being 10% long shots and 90% short shots and applying the length of time each type of shot took. The Layout man would be marking the locations for a shot or for a defect found in a shot. The time necessary to do this work would be unaffected by how long the x-ray exposure occurred for that shot. That means it would take just as long to mark a location for a short shot as it would to mark a location for a long shot. The appropriate ratio should be 10% long shots and 90% short shots.

Isotope Production Rate

NIOSH proposes adjusting the production rate to properly account for the chosen scenarios.
The production rate of isotopes in steel was calculated using MCNP.

That production rate assumes the betatron beam is exposing the steel for the entire shot scenario (i.e., during the actual irradiation and in between shots) and the created isotopes are always decaying. In reality, the isotopes are only created when the betatron beam is on and the beam is not always on. The short shot scenario assumes a 3-minute shot followed by 12 minutes of time between shots. The long shot scenario assumes a 60 minute shot followed by 15 minutes between shots. There is therefore a considerable amount of time that the production of an isotope stops while the decay of that isotope continues resulting in a lower concentration of the isotope. To correct for the effect of this non-continuous exposure, an effective production rate must be determined using the technique discussed in Appendix A of this response paper.

Impossible Scenario

In the scenarios for both the short and long shots, the assumption has been that the casting was x-rayed continuously for many hours prior to the Layout man receiving the casting. The SC&A calculation in the December 2014 memo used 30 hours of prior exposure for both the long and short shots. Every 75 minutes, a new freshly exposed casting is moved to the Layout man. For the short shots, the x-ray exposure to the casting occurs for 3 minutes out of every 15 minutes it is being examined in the betatron building. For the long shots, it is 60 minutes out of every 75 minutes. With these parameters, it would take 150 hours to achieve 30 hours of x-rays to the casting using the short shot scenario while the long shot scenario would take 37.5 hours to complete. *Clearly it is not physically possible for a casting to be examined in the betatron room for 37.5 hours and provided to the Layout man every 75 minutes.* Such a scenario that would result in the highest yet physically possible dose is one in which 2 castings are alternated repeatedly.

For the long-shot scenario, the interrupting casting scenario would start with casting A being x-rayed for 60 minutes followed by a 15 minute break for the casting to be moved out of the betatron building so the Layout man can begin working on it. During the 15 minutes, casting B is moved into the betatron building. For the next 60 minutes, casting B is x-rayed while the Layout man works on casting A. Once this x-ray is completed, the next 15 minutes is used to switch the castings back and the process repeats. For short shots, the exact same scenario would apply except the shot time is 3 minutes and the time between shots is 12 minutes so the process would repeat every 15 minutes instead of 75 minutes.

For the single large casting on which the Layout man works most of the shift, there is still an issue of being physically impossible. For gamma exposure to the Layout man, the short shot scenario uses 532 shots of 3 minutes each. Including the 12 minutes between shots, requires about 5.5 days to complete this number of shots. But, it's assumed the Layout man would be exposed to a freshly-exposed casting for every shift worked. Even if he worked only one shift per day, the scenario requires a casting to be x-rayed for 5.5 days every 24 hours. A similar situation can be seen for the long shot scenario of 400 prior shots as well as the scenario of 30 continuous hours of x-rays.

Again, a scenario that yields the highest dose, while still being physically possible, is one in which two castings are alternated. The first is x-rayed for 24 hours just before the Layout man begins working on the casting. It is important to note that this 24 hour period is not one continuous x-ray but rather an x-ray routine matching the short or long shot scenarios. At the end of the 24 hour period, the casting is moved to the Layout man and a second casting is placed in the betatron building for a 24 hours period of x-rays. After another 24 hours, the castings switch places and this process continues.

It is important to note that the effective production rate calculated in an appendix to this paper is correct for a consistent routine of intermittent production. In the case of the single large casting, there are two different intermittent production periods. The first being the x-ray and film change routine and the second being the 24-hour period that this routine is performed followed by the 24 hours outside the betatron building for which no x-ray exposures occurs. The appendix begins on page 9 of this document and discusses this calculation.

Prior Casting Irradiation Time

The amount of time the castings are irradiated prior to the Layout man receiving them is inconsistent with that used for the gamma exposure calculation. For the gamma dose, this source of exposure was small compared to other sources. Therefore it is only necessary to have a bounding scenario for the gamma dose and it is not necessary for it to be consistent with the beta dose.

We can resolve the issue for beta dose in a favorable manner is to assume the physically-possible scenarios continue indefinitely until the isotopes reach an equilibrium value. This equilibrium value is below the value that would be achieved from continuous x-ray exposure. For many of the isotopes, assuming this equilibrium value will have little affect because their relatively short half-life will produce an equilibrium value with any reasonable estimate of prior exposure time. The concentration of longer lived isotopes would be overestimated to some extent but the dose from those isotopes is only a portion of the overall dose so overestimating that portion does not produce a large overestimate of the Layout man's dose.

RESULTS OF THE PROPOSED APPROACH

Using the effective production rate approach proposed in our response paper, the doses to the Layout man for various exposure scenarios are calculated in Table 1 to provide values for the beta dose rates in mrad per 8-hour shift. These values are not prorated to any scenario; rather they represent the dose rate if the depicted scenario were undertaken for the entire shift. For the single large casting scenario, the Layout man exposure occurs 15 minutes to 8 hours and 15 minutes following irradiation of the casting. For the interrupting casting scenario, the Layout man exposure starts 15 minutes after the casting irradiation and ends 15 minutes or 75 minutes after that for the short and long shot scenarios respectively. Table 2 combines the values in Table 1 using parameters discussed in this white paper. Assuming an average of 406.25 shifts per year, the annual beta dose to the Layout man would be 264 mrad to the hands and forearms and 147 to the rest of the skin. The short and long shot values in the table are based on 10% of the time being 1 meter away and 90% of the time being close (contact for hands and forearms, 1 foot for other skin). The composite value is based on 90% of the dose coming from castings irradiated from the short shot routine and the remaining 10% from the long shot routine. The combined values are calculated by assuming the single large casting dose accounts for 90% of the Layout man's time with the interrupting casting representing the remaining 10% of the time.

Table 1 – Layout man Beta Dose per 8 hour Shift (unadjusted)

	Single Casting		**Interrupting Castings**	
	mrad/ shift	mrad/ casting	casting/ shift	mrad/shift
Short shot contact	0.305	0.055	32	1.751
Short shot 1 ft.	0.161	0.033	32	1.063
Short shot 1 m	0.052	0.012	32	0.387
Long shot contact	2.610	1.055	6.4	6.753
Long shot 1 ft.	1.366	0.621	6.4	3.974
Long shot 1 m	0.436	0.221	6.4	1.416

Table 2 – Layout man Beta Dose per 8 hour Shift (combined scenarios)

	Short (mrad/shift)	**Long (mrad/shift)**	**Composite (mrad/shift)**
H&F single casting	0.279	2.392	0.491
H&F interrupting casting	1.614	6.219	2.075
Combined H&F			0.649
skin single casting	0.150	1.273	0.262
skin interrupting casting	0.995	3.719	1.267
Combined skin			0.363

REFERENCES

SCA 2008, S. Cohen & Associates, *Review of "Site Profiles for Atomic Weapons Employers that Worked Uranium and thorium Metals – Appendix BB: General Steel Industries," Battelle-TBD-6000, Appendix BB, Rev 0.*, SCA-TR-TASK1-0024, April 21, 2008.

SCA 2013, Memo from Robert Anigstein and John Mauro, SC&A, *Review of Skin Doses at GSI*, December 5, 2013

SCA 2014, Memo from Robert Anigstein and John Mauro, SC&A, *Update of Doses from External Exposure at General Steel Industries*, January 12, 2014

SCA 2014a, Memo from Robert Anigstein and John Mauro, SC&A, *Review of "Site Profiles for Atomic Weapons Employers that Worked Uranium Metals Appendix BB – General Steel Industries," Revision 1*, December 10, 2014

APPENDIX

Calculation of Buildup from Intermittent Production

CONTINUOUS BUILDUP

The buildup of radionuclides created in steel during the x-ray by a betatron can be described mathematically by the following equations:

Equation 1

$$\frac{dC}{dt} = P - \lambda C$$

C = the number of atoms of a particular nuclide
P = the production rate of that nuclide (atoms per sec)
λ = the decay constant for that nuclide (sec^{-1})

Solving for C produces *Equation 2*

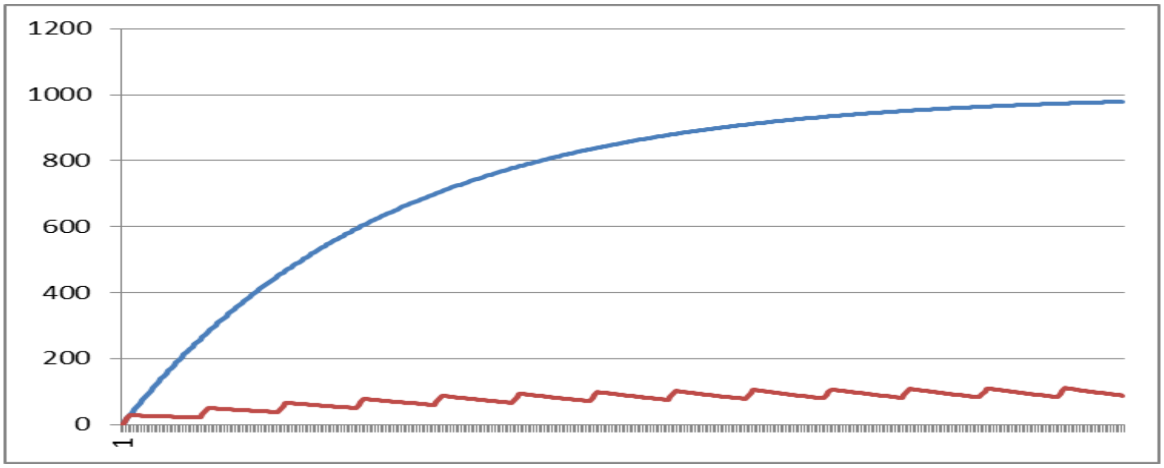
$$C = \frac{P}{\lambda}\left(1 - e^{-\lambda t}\right)$$

Equation 2 produces a smooth buildup curve approaching an equilibrium value where the production rate equals the decay rate. By inserting infinity for time, it can be seen that the equilibrium value would be P/ λ. This smooth buildup curve is shown as the upper curve in figure A1. The equation assumes the nuclides are continuously created at the same time that they are continuously decaying.

However, in the case of GSI, a casting is x-rayed for a period of time and then the betatron is turned off while that film is collected. A new film is put in place and the betatron head is repositioned. This intermittent production combined with a continuous decay leads to a saw-toothed pattern shown as the lower curve in figure A1 on the next page.

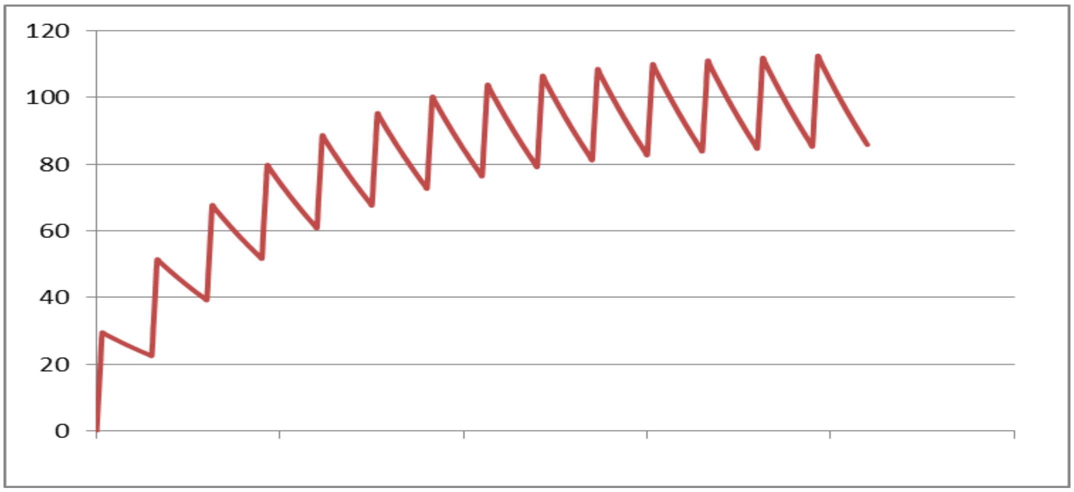
(continued)

Figure A1 – Continuous and Intermittent Buildup Curves



It can be seen more clearly in Figure 2 that this saw-toothed pattern will also build up to an equilibrium value but that value will be lower than the continuous production curve.

Figure A2 – Intermittent Buildup Curve



INTERMITTENT EXPOSURE

For our purposes, it is necessary to find the value of the peaks of the saw tooth curve. That would represent the activity in the casting immediately after the x-ray exposure. In order to find the value of the peaks, it is first noted that the peaks follow a similar continuous buildup pattern, the shape of which is dictated by the decay constant. Therefore, an equation for a continuous buildup curve that matches the peak values can be constructed if a new equilibrium value is determined that adjusts for the intermittent production rate.

In order to find this new equilibrium value, it is first noted that the concentration at the first peak (C_1) is equal to equation 2 if the time is set equal to the length of time of the x-ray exposure (3 minutes for the short shot scenario). The full cycle time from the end of one x-ray to the end of the next x-ray is 15 minutes for the short shot scenario. Therefore, the continuous buildup equation depicting the peaks of the saw toothed pattern would have to start 15 minutes prior to the end of the first shot.

Equation 3

$$C_1 = \frac{P}{\lambda} * \left(1 - e^{-\lambda t1}\right) = \frac{P_{eff}}{\lambda} * \left(1 - e^{-\lambda tc1}\right)$$

P_{eff} = the effective production rate
t1 = the shot time (amount of time the actual x-ray beam is turned on)
tc1 = cycle time (amount of time from the end of one x-ray to the end of the next x-ray)

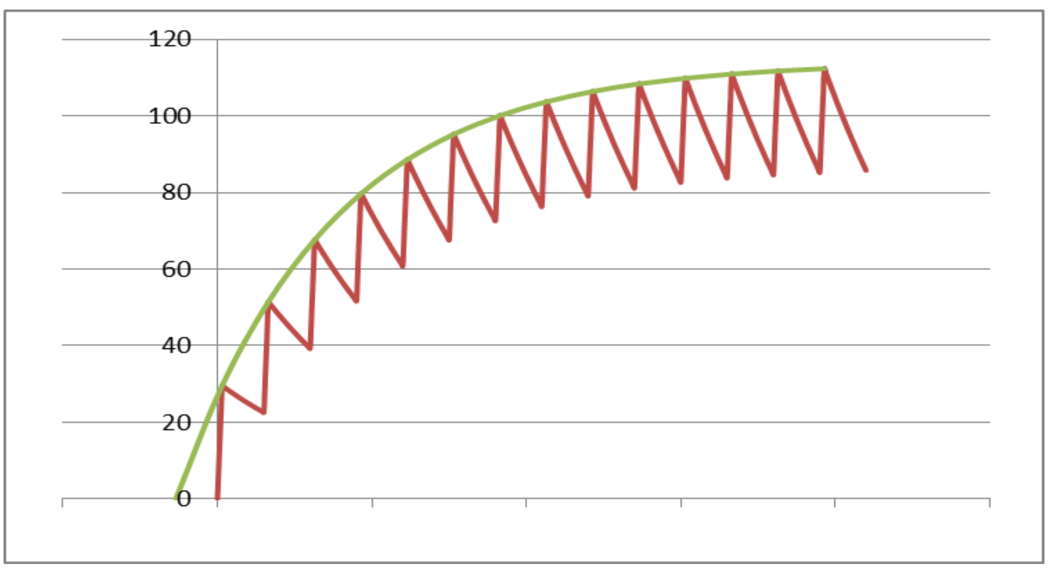
Rearranging the equation to solve for Peff/λ provides the next equation.

Equation 4

$$\frac{P_{eff}}{\lambda} = \frac{P}{\lambda} * (1 - e^{-\lambda t1})/(1 - e^{-\lambda tc1})$$

By replacing P/λ in equation 2 with P_{eff}/λ above and assuming time equals zero 15 minutes prior to the end of the first shot, a new continuous buildup curve can be produced as shown in figure A3.

Figure A3 – Intermittent Buildup Curve and Effective Continuous Curve



This new curve eventually reaches an equilibrium value of P_{eff}/λ. The effect of this adjusted production rate will depend on the half-life of the particular isotope. Table A1 below shows the adjustment for both the short and long shot scenarios for the longest and shortest lived isotopes used in the GSI beta dose calculation. The adjustment in the table is the adjustment to the equilibrium value.

Table A1 – Parameters for Effective Production Rate

	Short Shots	**Long Shots**
Shot time (minutes)	3	60
Cycle time (minutes)	15	75
Adjustment for Fe53 (8.51 minute half-life)	.307	.995
Adjustment for Mo99 (65.94 hr. half-life)	.200	.801

It can be seen that in the case of Fe-53, the long shot adjustment is small (nearly 1). This is due to the fact that the 60 minute x-ray is long enough to nearly reach and the equilibrium value (approximately 7 half-lives). Since it nearly reaches equilibrium during a single shot, the intermittent production has little effect on the maximum value. For a longer lived isotope, the adjusted equilibrium is nearly proportional to the fraction of the cycle time that the isotope is actually being produced (60 min/75 min or 3 min/15 min).

SECOND INTERMITTENT EXPOSURE

The Layout man beta dose scenario for GSI utilizes two types of castings. One casting on which the Layout man works for the entire shift (single large casting) and the other is a freshly exposed casting that interrupts this work periodically (interrupting casting). Both types of castings are exposed many times prior to the Layout man working on them.

For the interrupting casting, the maximum starting dose rate would be associated with the equilibrium value for each isotope. That equilibrium would have to be adjusted based on the shot time and cycle time as described above.

For the continuous casting, the same adjustment is necessary however since the Layout man is working on this casting the entire shift, an additional adjustment is necessary. The proposed scenario in the body of this white paper is for two castings to be worked in an alternating fashion. The scenario calls for one casting to be x-rayed during a 24 hours period while another casting is being worked on by the Layout man. The castings and switched every 24 hours. While the casting is in the betatron building, the x-ray exposure is not continuous but intermittent according to the short or long shot routine. The equation for the intermittent exposure described above can be used to determine the appropriate equilibrium value for this period. However, it would not accurately represent the equilibrium value of the casting without accounting for the second 24 hour period when the casting is outside the betatron building. A new equilibrium activity must be calculated in this case that not only reduces the production rate for the intermittent exposure between shots but also for the intermittent exposure periods in and out of the betatron building.

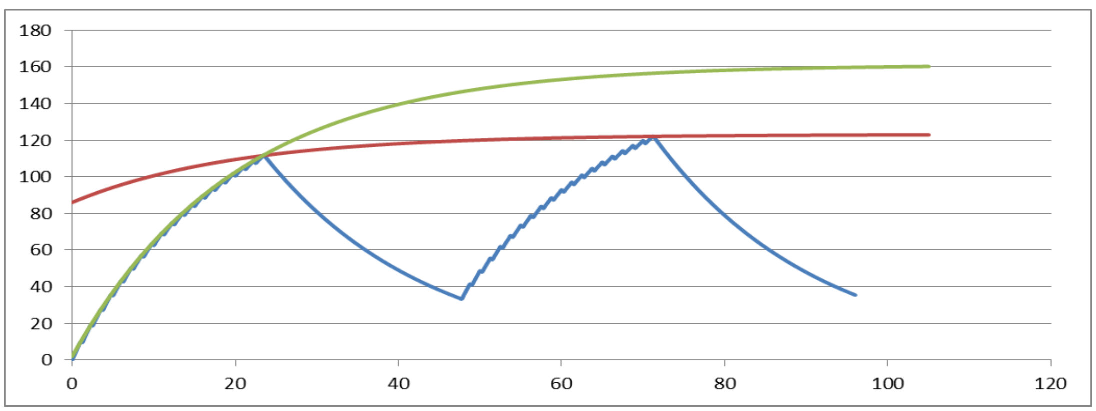
In order to find this value, the same technique described above will work. However, that technique relies on a single consistent cycle time. In this case, we would have one cycle consisting of the shot time and time between shots and a second cycle consisting of 1 day in the betatron building and one day outside of the building. The new adjusted production rate (P_{eff2}/λ) can be found the same way as the first adjusted production rate by simply substituting the first effective production rate (P_{eff}/λ) for P/λ in equation 4. The new shot time and cycle time must also be substituted for t1 and tc1. This results in the following equation:

Equation 5

$$\frac{P_{eff2}}{\lambda} = \frac{P_{eff}}{\lambda} * \frac{1 - e^{-\lambda t2}}{1 - e^{-\lambda tc2}} = \frac{P}{\lambda} * \frac{1 - e^{-\lambda t1}}{1 - e^{-\lambda tc1}} * \frac{1 - e^{-\lambda t2}}{1 - e^{-\lambda tc2}}$$

Where t2 and tc2 represent the production time (24 hours) and the total cycle time (48 hours) for the larger intermittent exposure period. Figure A4 depicts a continuous buildup function using these equilibrium values.

Figure A4 – Intermittent Buildup Curves and Two Effective Continuous Curve



In Figure A4, you can see the saw toothed curve actually includes another saw toothed curve on the buildup side of the curve. Another curve follows the first buildup side but continues to increase above the second peak of the saw toothed curve. This is the continuous curve using P_{eff}/λ and is identical to figure A3 with the scales changed. An additional line shows a continuous curve that matches each peak of the larger saw toothed curve. That is the continuous buildup function using P_{eff2}/λ as the equilibrium value.

Table A1 is reproduced as Table A2, with the second cycle parameters included and the adjustment values recalculated.

Table A2 – Parameters for Effective Production Rate (Two Different Intermittent Periods)

	Short Shots	**Long Shots**
Shot time (minutes)	3	60
Cycle time (minutes)	15	75
Production time (hours)	24	24
2nd cycle time (hours)	48	48
Adjustment for Fe53 (8.51 minute half-life)	.307	.995
Adjustment for Mo99 (65.94 hr. half-life)	.113	.451

Comparing these values to the values in table A1, it can be seen that this additional decay period has no effect on the equilibrium value for the short lived isotope. The isotope essentially decays away during the 24 hour decay period and starts from zero each time. For the long lived isotope, a noticeable effect can be seen.