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Memo

date: *August 31, 2010*

to: *RSC*

from: *D. Beavis*

subject: *Skyshine Dose from the RHIC Beam Dumps*

Introduction

The neutrons emerging from the berm over the RHIC beam dumps results in dose to persons on and off the BNL site. This dose which is usually referred to as skyshine was estimated in the RHIC SAD and supporting documents to be less than 1 mrem/yr for the closest location off site. The analysis took into account plans to increase the shielding over the beam dumps to a minimum of 17.5 feet of soil. It also assumed the maximum amount of beam into the dumps that was expected to occur in any single year of operations. This note will re-examine the skyshine from the beam dumps taking into account elevation surveys of the shield thickness, proposed increases in beam intensity and energy, and changes in the operating scenario.

It will be concluded that the future skyshine dose from the RHIC beam dumps will be well below the BNL guidelines for on and off site dose and consistent with the evaluations conducted with the RHIC Project.

Intensity and Energy Upgrades and Annual Beam into the Dumps

Upgrades in beam intensity and energy are under consideration. The beam intensity has been discussed to be a generic factor of two higher than the RHIC Project. The skyshine dose is an issue for yearly exposure limits and not hourly. Therefore, the intensity per fill enters along with the total number of fills that will be put into the beam dumps. An energy increase of 30% is also anticipated and transverse radiation can be scaled from lower energy using that the transverse radiation scales[1] as $E^{0.8}$ The annual dose to a person at the nearest point of the site boundary (east side of William Floyd Parkway) was estimated to be 0.8 mrem in a year by the RHIC Project.

The yearly dose due to skyshine will be examined with updated[2] numbers for the expected yearly operations. A maximum of 500 full energy proton fills per year is expected with a maximum of $5*10^{13}$ protons per ring. The maximum energy of these stores will be 325 GeV. This corresponds to $8.12*10^{18}$ nucleon-GeV/year or a maximum of $1.6*10^{15}$ nucleon-GeV per store. The

maximum Au beam at 130 GeV is $2.8*10^{11}$ ions per ring. The maximum number of gold stores is expected to be 1000. The RHIC Project[3] proposed a very conservative 2345 fills of full energy (100GeV) gold in a year, with $2.28*10^{11}$ Au ions per ring at 100 GeV. For future gold operations the effective beam into the dumps is 31% of what was proposed by the RHIC Project as a maximum. RHIC has never approached this maximum. For future protons the transverse radiation from the beam dumps will be 60% of the gold limit presented by the RHIC Project.

The ten years of operational experience with the RHIC Collider enables one to use less conservative estimates for the maximum amount of beam into the beam dumps. For completeness the skyshine numbers are calculated to check the original analysis. Protons will be used to estimate the skyshine radiation. The final result agrees with the previous analysis. It is recommended that the $1.05*10^{17}$ nucleons at 100 GeV into the beam dumps be used, which is the number used by the RHIC Project.

Method for Estimation of Skyshine Dose

The first step in estimating the skyshine dose is to generate a source term for the radiation. The source term is estimated by propagating 250 GeV protons into a simplified model of the RHIC beam dump and downstream magnets. The created radiation is then transported though the earthen shield till it reaches the surface. Finally, an empirical formula is used to estimate the dose at a distance point due to the neutrons escaping the soil shield. Different methods can be used at each stage of the calculation.

The Monte Carlo code MCNPX[4] version 2.7C is used to estimate the source of radiation and the transport through the shield. The beam dump and shield are approximated with cylindrical symmetry. This approximation allows for substantially decreased computer time and should not limit the reliability of the results for this geometry. Dimensions in the vertical direction are used for the estimate. The Z-axis is chosen along the beam direction with the origin being the front face of the beam dump. The beam dump is composed of Carbon-Carbon (C-C), graphite, and steel. Table I has the dimensions and densities used for the materials in the beam dump.

Table I: RHIC Beam dump model

Material	Density (gm/cc)	Min. radius (cm)	Max. Radius (cm)	Min. Z (cm)	Max. Z (cm)
C-C	1.8	0.	3.	0.	50.8
graphite	1.8	0.	8.9	50.8	315.
iron	7.87	15.24	30.48	0.	50.8
iron	7.87	15.24	30.48	50.8	315.
iron	7.87	0.	30.58	315	515.

MCNPX does not track particles though magnetic fields and does not keep track of the sign of the charged particles. These limitations are not relevant for the calculations conducted in this

note. Secondary particles that leave the dump will then be transported to either the soil shield or interact with the downstream magnets assemblies.

The magnets are approximated similar to that used in reference 5. Table II has a listing of the material distribution used for the magnets.

Table II: RHIC Magnet Model

material	Density (gm/cc)	Min. radius (cm)	Max. radius (cm)	Min. Z (cm)	Max. Z (cm)
vacuum	0.	0.	3.8	615.	3000
Iron mass	7.87	3.8	13.	615.	3000
Iron	0.15	13.	30.48	615.	3000
vacuum	0.	0.	215.	515.	615.

The magnets have been assumed to start one meter downstream of the dump. In reality this distance is slightly longer. The low density iron is an approximation for the material outside the cold mass as discussed by reference 5. The curvature of the tunnel is ignored and magnets string goes to the end of the calculation which in this case was 30 meters.

The earthen shield is treated as a cylindrical shell of soil with an interior radius of 215 cm and an outer radius of 815 cm. The atomic composition used is 8.7% H, 62.3% O, and 29% Si. Trace elements in the soil are not relevant for this analysis. The density is taken as 1.8 gm/cc. It is unclear what density was used in the previous analysis, but densities from 1.6 to 1.9 gm/cc have been used for soil at BNL.

The number of neutrons emerging from the soil with energy greater than 20 MeV is used as input for the empirical shyshine formula. Therefore, the energy cutoffs in MCNPX have been raised to 20 MeV. This increase in the minimum energy of particles saves substantial computer time for the calculation.

The fluence of neutrons with energy greater than 20 MeV has been tabulated by the program for 200 cm bins in Z and for every 30 cm of soil penetration. Figure 1 shows the neutron fluence as a function of radius for a location 300 cm downstream of the beginning of the beam dump.

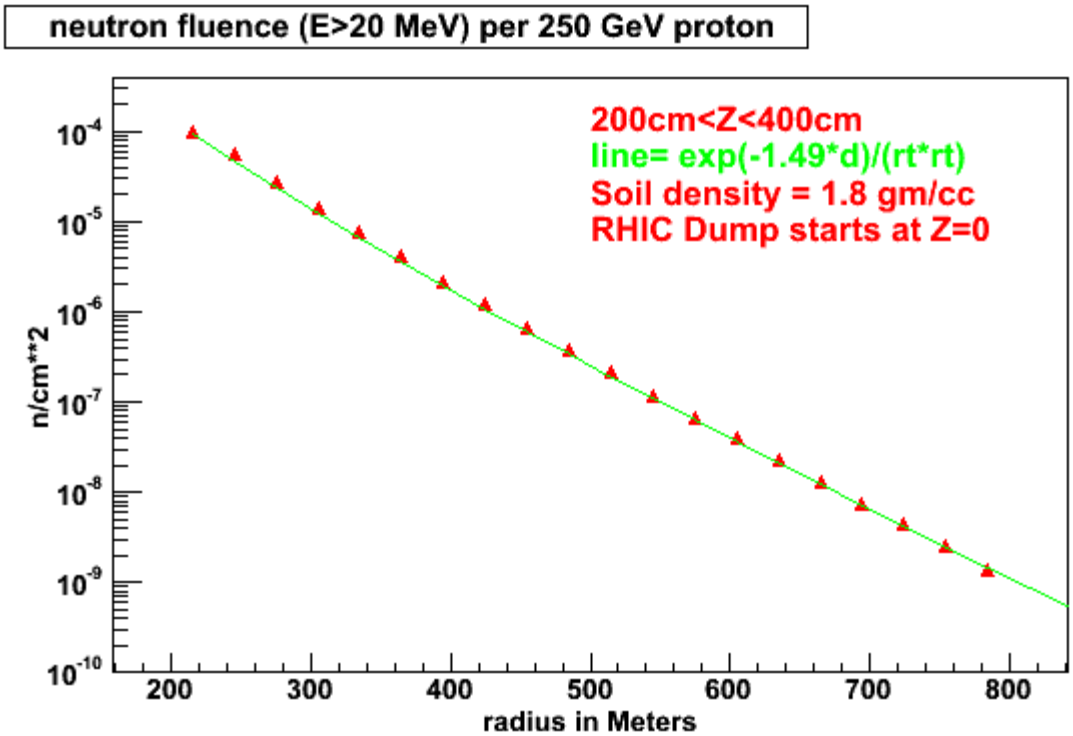

Figure 1: Neutron fluence for 250 GeV protons striking the RHIC beam dump. The approximations are discussed in the text. An exponential curve is shown which can be used to extrapolate to larger shield depths.

The solid curve shown in Figure 1 is an "eyeball" fit to the calculation. The formula can be used to scale the results to thicker soil shields. The attenuation in the soil scales with the density should it be desired to use a different density.

Figure 2 displays the longitudinal dependence of the neutron fluence at different depths of the soil shield. It can be seen that the distribution is rather short in distance. The half width is approximately 6 meters. Only about 11 to 15 meters contribute to the skyshine. The number of high energy neutrons needs to be obtained by integrating the distribution as a function of Z and the transverse dimension X. In evaluating this integration changes in berm elevation need to be considered.

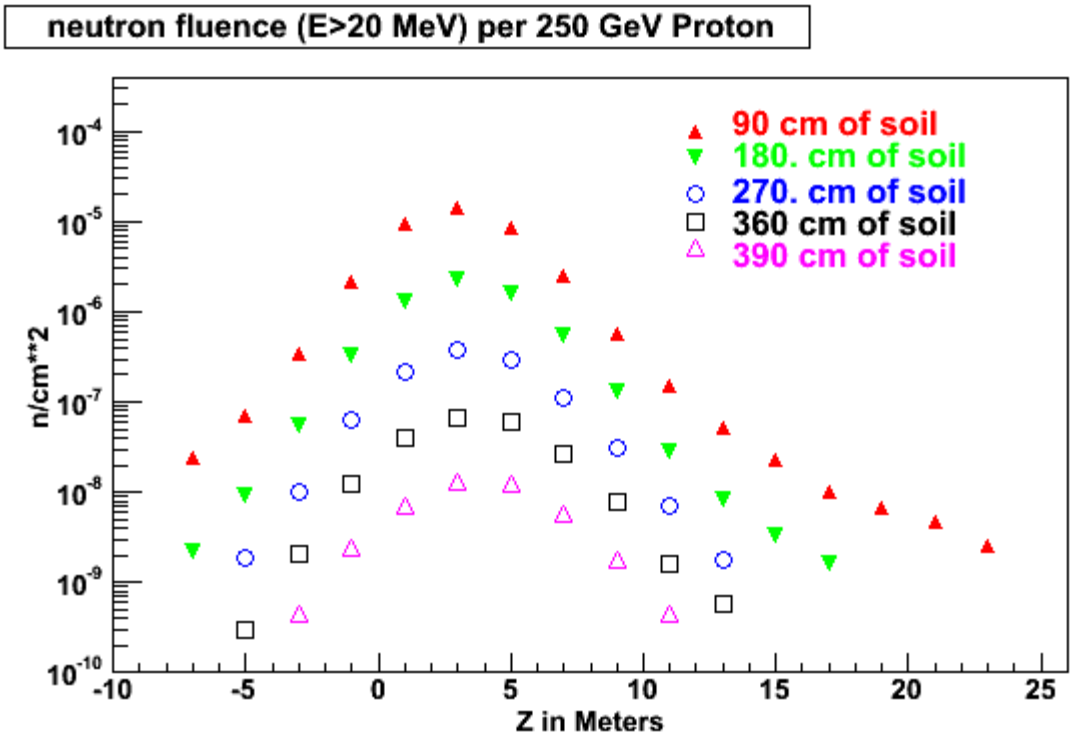

Figure 2: Neutron fluence as a function of longitudinal distance at different depths in the soil shield. The beam dump starts at z=0.

Figure 3 shows the elevation contours for the dump at 10 O'clock (blue beam dump). The dump is under the main plateau of the shield, which has an elevation of 94 feet. The small region with elevation of 95 feet will be ignored in the skyshine calculation. Figure 4 shows a profile of the berm along the beam direction. The entire peak of the radiation pattern is under the 94 foot elevation. The width of the berm is centered over the tunnel. The drop off to the sides can be accounted for in the estimate of the total number of neutrons emerging from the dump. This was done using a spread sheet with the tunnel geometry and the attenuation length of neutrons in the soil. The asymmetry of the shield is taken into account. The effective width of the radiation is 650 cm.

The integration in X and Z provides a total of $1.56*10^{-3}$ neutrons with energy greater than 20 MeV emerging from the berm per 325 GeV proton into the beam dump. A factor of 1.23 was used to scale the 250 GeV result to 325 GeV.

Figure 5 displays the elevation contours over the yellow (9 O'clock) beam dump. The shield is similar but is not as well centered and the start of the beam dump is directly under the 93 foot contour. Figure 6 displays a berm profile along the beam line. The numbers for the blue beam dump have been corrected for the differences to estimate the neutron fluence from the beam emerging from the soil. $2.0*10^{-3}$ neutrons with energy greater than 20 MeV emerge from the berm over the yellow beam dump per 325 GeV proton.

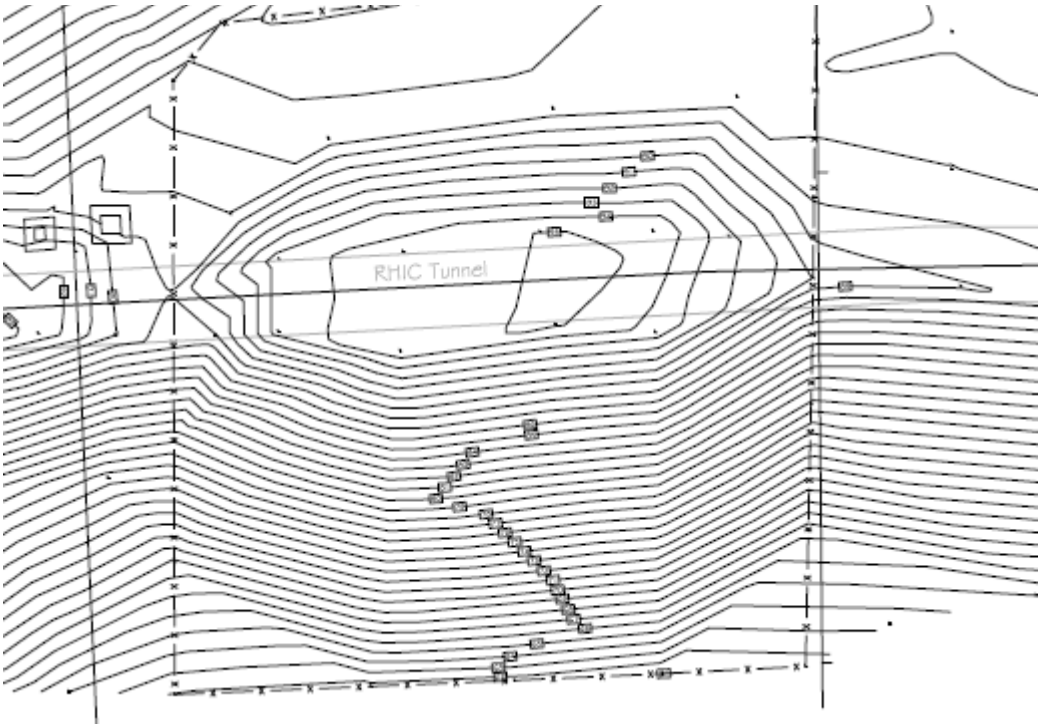

Figure 3: Contours of the soil shield over the 10 O'clock RHIC beam dump. Elevation data was obtained in August 2010. The contour lines at given every 1 foot change in elevation.

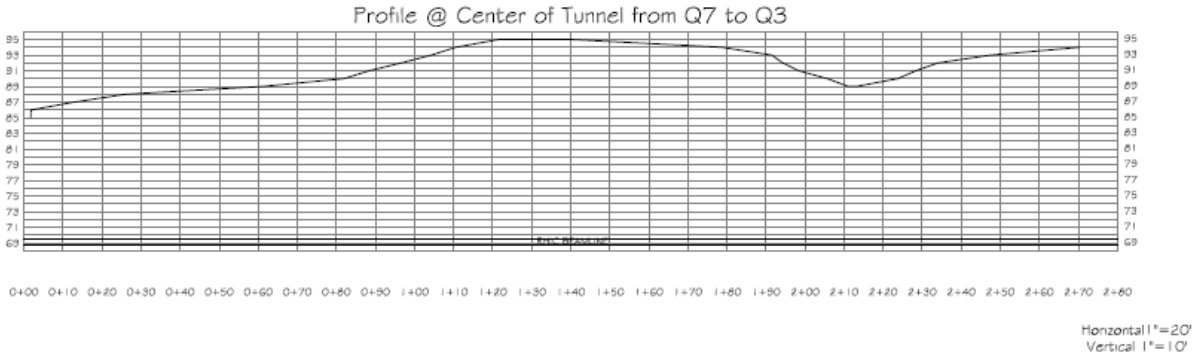

Figure 4: Berm profile for the 10 O'clock (blue) beam dump. The beam dump begins at I+70 in the figure and the peak of radiation is at I+60(number are feet).

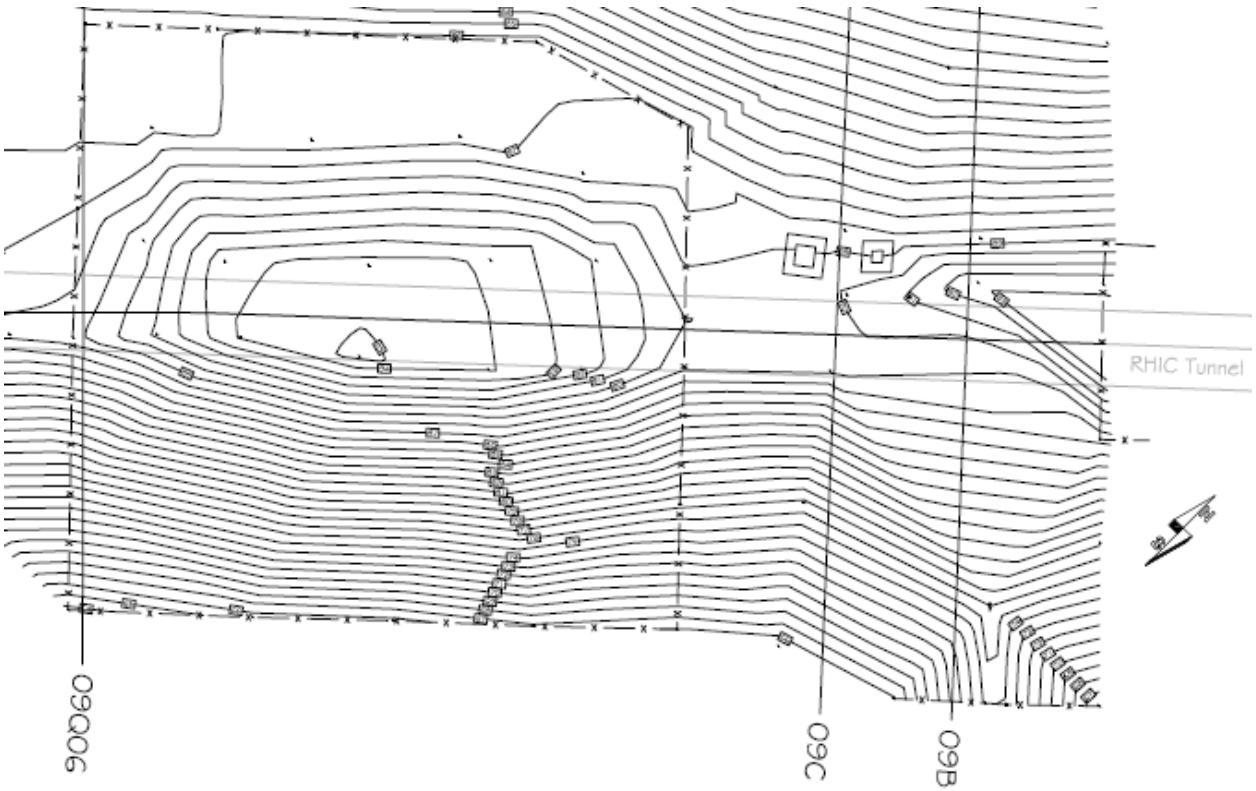

Figure 5: The elevation contours over the 9 O'clock (yellow) beam dump. The yellow dump is under the 93 foot elevation contour.

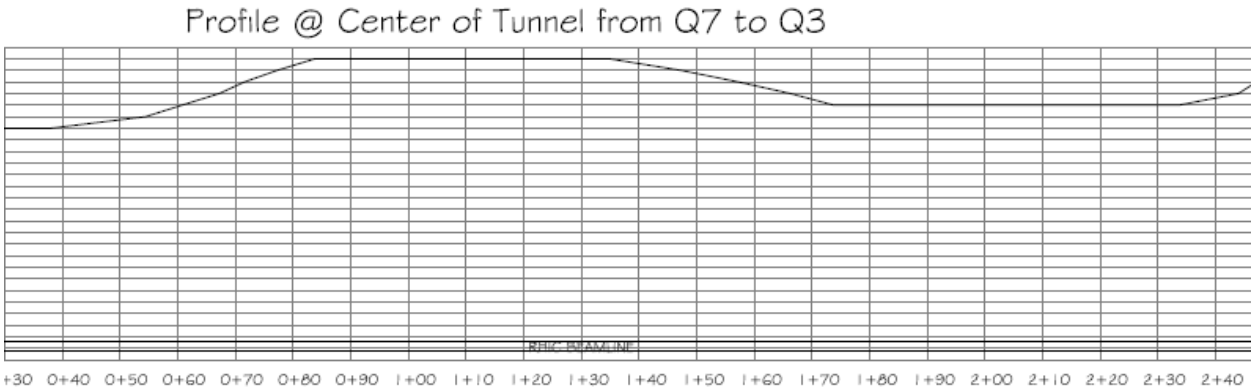

Figure 6: Elevation profile over the Yellow beam dump. The yellow dump is at I+47. The boxes are 1 foot in elevation changes and 10 feet wide. The top of the soil plateau is 94 feet in elevation.

The skyshine dose at a distance R from the RHIC berm is given by the formulation of Distenfeld and Colvett[6] to be:

Dose (in rem) = $8.33*10^{-13} *N_{neu}*(1-e^{-R/47})*e^{-R/600}/R^2$,

where D is the distance in meters and N_{neu} is the number of neutrons with energy greater than 20 MeV emerging from the shield. A factor of two was incorporated into the formula used for RHIC[7] to prepare for the eventual changes to 10CFR835. Distenfeld and Colvett used a flux to dose conversion factor corresponding to 2.5 MeV neutrons as per NCRP Report No. 38, which has a quality factor[8] of 11. The new weighting factor[9] for neutrons at 2.5 MeV is 15. Thus using a factor of two provides a 50% overestimate. The skyshine estimate given below uses the factor of two in the analysis to add some additional conservatism.

Several locations of interest have been tabulated in the table below. The locations at the site boundary are chosen to be the closest for each of the beam dumps. Thus a different location is chosen on the north site boundary for each beam dump although they are not far apart. The closest point on the west site boundary on the east side of the William Floyd Parkway is common to both beam dumps. At this location the two beam dumps would contribute a total of 0.49 mrem in a year. This is well below the total CA-D design goal of less than 5 mrem at the site boundary. Other sources may contribute to the dose at the site boundary.

No occupancy factors have been included in the calculations. Most of the buildings given in Table III are associated with C-AD. Building 938 appears to be the closest building not associated with CA-D. If one included an occupancy factor of 0.25 appropriate for RHIC 24 hours-7 days a week operations and a 40 hour work week the equivalent dose to a full time worker in Bldg. 938 would be 0.02 mrem in a year. The equivalent dose to workers in Bldg 1005S is a factor of 10 smaller.

Table III: Yearly Skyshine Equivalent Dose from RHIC Beam Dumps

location	**10 O'clock (blue) dump**		**9 O'clock (yellow dump**	
	Distance (m)	**mrem/yr**	**Distance (m)**	**mrem/yr**
North site boundary	410	0.13	480	0.11
William Floyd site boundary	380	0.16	290	0.42
W. Floyd common site boundary	380	0.16	320	0.33
Bldg. 1005S	1160	0.005	1130	0.007
Bldg. 930	1280	0.003	1190	0.006
Bldg 938	1520	0.002	1450	0.002
Bldg. 1010B	61	8	61	8
Bldg. 1008	625	0.04	530	0.08

The results presented here can be compared to the value given in the RHIC SAD. The 0.49 mrem can be compared to the number given in the RHIC SAD by adjusting for the total beam into the beam dump. This analysis and the one documented in the RHIC SAD gare in excellent agreement with a yearly dose of 0.8mrem on the east side of William Floyd Parkway.

A measurement over the blue beam dump was conducted in June 2010 while the blue beam was dumped at 5.75 GeV. The dose measured exiting the berm eight feet downstream of the beginning of the beam dump was 0.25 mrem. A neutron fluence to dose conversion factor of calculated by transporting all particles with the standard MCNPX energy cutoffs. The neutron dose was compared to the high energy neutron fluence at a depth of 150 cm of soil. There was no soil at greater distances. A conversion factor of $6.16*10^{-8}$ rem/(n with E>20 MeV) was obtained. The calculation was adjusted for energy and the number of nucleons into the beam dump. The result of the estimate is 0.08 mrem. This is only the dose attributed to neutrons. There is reasonable agreement between the measurement and the calculation.

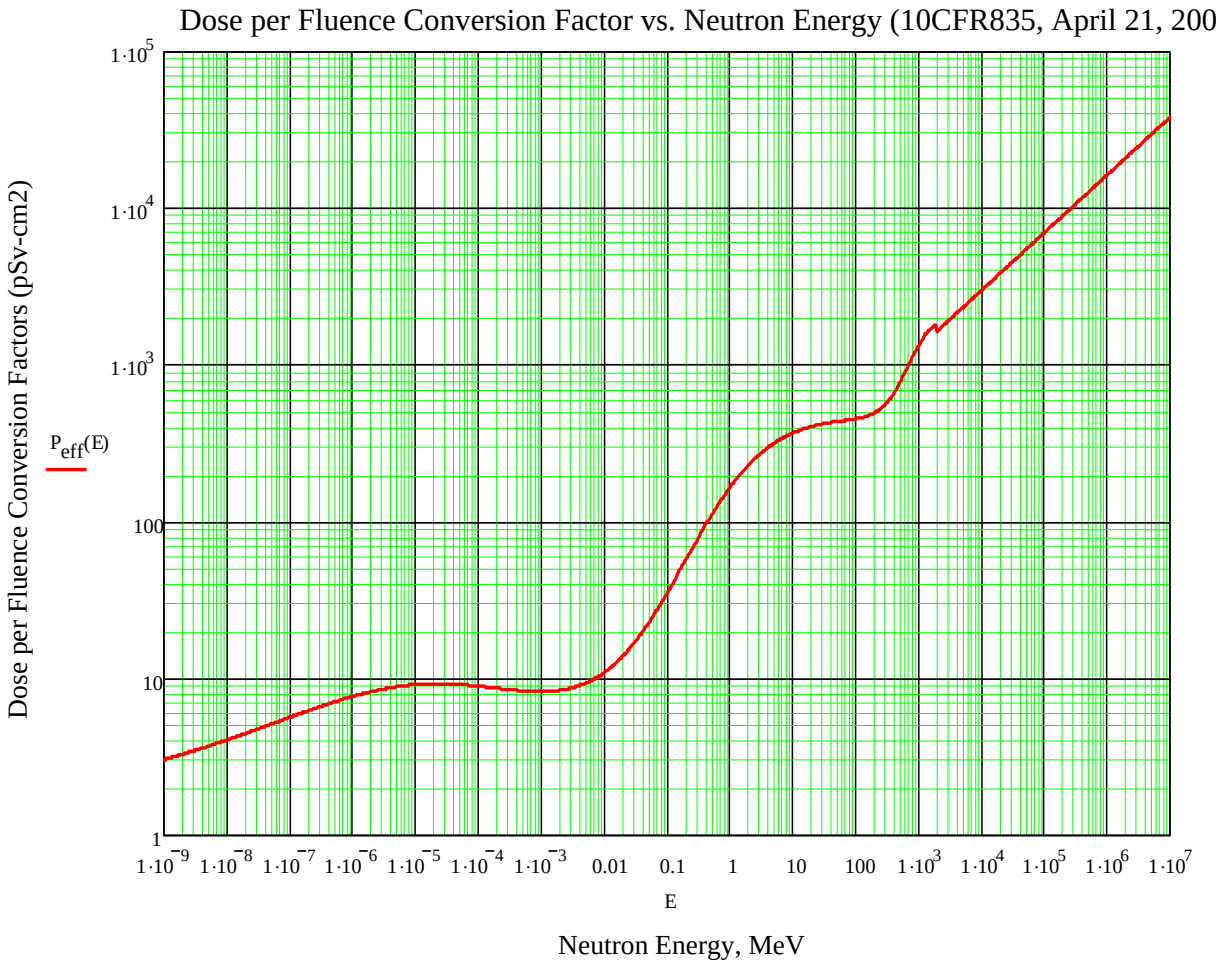

Figure 7: The new fluence to dose conversion factors for neutrons.

The fluence to dose conversion factors as a function of energy used with MCNPX during the later calculations of the RHIC Project were utilized in the calculation above. The new neutron fluence to dose conversion factors[10] were used to examine what effect this would have on the

dose results. It was found that when weighting over the entire neutron energy spectrum that the numbers were within 10%. Thus, a factor of two does not need to be incorporated into dose estimates that were calculated using MCNPX. Most of the early RHIC calculations were conducted with CASIM and not MCNPX.

The beam dump model was modified to include an extra six inches of steel over the beam dump. This analysis was conducted to provide guidance if additional reduction of the off-site dose was desired. The fluence of neutrons with energy greater than 20 MeV was compared at a soil depth of 300 cm. The neutron fluence with additional steel was a factor of 0.41 smaller for the longitudinal region that would contribute to skyshine. This is consistent with shielding attenuations used for steel in simple formulas.

Four monitor TLDs are located in Building 1010. None of the monitor TLDs show any dose due to skyshine neutrons. TLD TK238 is located in the Tech. Lab in a region of the building where it will have less shadowing by local shielding. The sensitivity of these TLDs to neutron dose should be about 5 mrem. The dose at 1010B should be thirty-times higher than the dose at the site boundary as shown in Table III. This provides evidence that the present off-site skyshine dose from the RHIC beam dumps is well below the estimates discussed in this note and well below the CA-D goal of 5 mrem.

There are a number of uncertainties approximations that are present in the evaluation of the skyshine dose. When possible conservative numbers are used to ensure the analysis is an upper limit for the expected dose. A few of these uncertainties are briefly discussed.

The actual soil density at the RHIC ring has not been measured. The analysis has used a value that is considered reasonable. The actual density is most likely within 0.1 g/cc of the 1.8 g/cc used in the analysis. This provides a factor of uncertainty in the range of 0.6 to 1.6.

The appropriate quality factor to apply to the remote dose has been most likely overestimated by a factor of 1.5.

The integrated neutron fluence was increased (rounded up) in the analysis by 20%.

Typically the number of neutrons into the beam dump is not 100% but more like 85%. This provides for a conservative factor of 1.17.

Conclusions and Recommendations

It is concluded that the present analysis is consistent with the analysis conducted for the RHIC Project. The potential dose off-site due to the RHIC beam dumps is small and well below the BNL guidelines. The yearly dose from RHIC operations is 0.5 mrem at the worst location off-site. If the RHIC Project number of nucleons-GeV into the beam dumps is used then the off-site dose is 0.8 mrem in a year. The yearly dose to on-site buildings is very small.

It may be of interest to remove some of the uncertainties in the analysis. In that case the following items are suggested:

1. Place several TLDs to monitor the skyshine dose from the dumps at increasing distance.
2. Measure the actual soil density over the beam dumps or other locations on the RHIC berm.
3. Place monitor TLDs inside the berm fence to measure the yearly dose emerging from the berm over the beam dumps.

References

1. A.H. Sullivan, A Guide to Radiation and radioactivity Levels Near High Energy Particle Accelerators, Nuclear Technology publishing, 1992
2. W. Fischer, private communication August 25, 2010.
3. M. Harrison and A.J. Stevens, "Beam Loss Scenario in RHIC", AD/RHIC/RD-52, January 1993. Also Appendix 8 of the RHIC SAD.
4. D. B. Pelowitz et al., "MCNPX 2.7.C Extensions", LA-UR-10_00481, March 5, 2010.
5. A.J. Stevens, "Radiation from Muons at RHIC", AD/RHIC-46, Feb. 1, 1989. Also in RHIC SAD Appendix 18. See appendix A in the note.
6. Distenfeld and R. Colvett, "Skyshine Considerations for Accelerator Shielding Design", Nucl. Sci. Eng., Vol. 26, pg 117 (1966)
7. A.J. Stevens, "Radiation Considerations Near Collimators", AD/RHIC/RD-113, April 1997. Also appendix 25 of the RHIC SAD. See comment in reference 6 within note.
8. NCRP Report No. 38, Protection Against Neutron Radiation, National Council on radiation Protection and measurements, 1971. See Table 2.
9. R. Karol to D. Beavis private communication. See Figure 7 for the numbers provided.

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