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Memo

date: *Mary 23, 2012*

to: *RSC*

from: *D. Beavis*

subject: *Equivalent Dose on the RHIC Berm from an MCI*

The RSC[1] reviewed a new shielding calculation for the STAR shield wall[2] and a preliminary calculation for the RHIC berm for beam losses during a Maximum Credible Incident (MCI). The committee recommended that the new calculations be accepted. The dose calculation for maximum exposure on the RHIC berm during an MCI will be presented in this note.

Beam Upgrades are in progress to increase the proton (and ion) beam intensity and the beam energy. The proton beam losses during an MCI will produce the highest radiation levels on the RHIC berm. The upgraded proton beam intensity will be $5*10^{13}$ protons per ring. The proton energy will be increased from 250 GeV up to a possible upper limit of 300 GeV. An MCI is defined as one half of the beam in a ring hitting a magnet (an MCI at a typical location) at full beam energy**. For a typical location on the RHIC berm the resulting maximum equivalent dose to an individual from an MCI is 130 mrem.** The equivalent dose was calculated using MCNPX[3] with the methods discussed in reference 2. The final results are compared to the RHIC Project analysis. **The RHIC berm is posted as a Controlled Area and no additional access requirements are necessary or recommended.**

Estimate of Equivalent Dose on the RHIC Berm

The Monte Carlo program MCNPX was used to calculation the proton interactions in the RHIC magnets and then transport the produced radiation through the soil. An energy cutoff of 20 MeV was used for the hadrons to reduce the computation time. The magnets were approximated in a fashion similar to that used by the RHIC Project[4].

Radial Material Distribution

Radius (cm)	Material
r<3.8	Vacuum
3.8<r<4.0	Beam pipe (steel with 7.8g/cc)
4.0<r<13.	Cold mass (steel with 7.8 g/cc)
13.<r<39.	Cryostat (steel with 0.15g/cc)
39.<r<250.	vacuum
250.<r<640.	Soil (1.8g/cc)
4.0<r<39.	Drift space (steel with 0.15g/cc)

The distribution of objects in z was copied from the RHIC Project report and is given below. The layout is shown in Figure 1 below. The beginning of the magnet string was started at z=2. meters. The RHIC Project used a thicker beam pipe region but with 1/2 the density of steel. The results should not be sensitive to this change.

Positions of objects in z.

z in meters	Object
z<2.	vacuum
2.<z<3.13	quadrupole
3.13<z<5.25	drift space
5.25<z<14.70	Dipole
14.70<z<16.82	drift space
16.82<z<17.95	quadrupole

A pencil beam of 250 GeV protons were directed to strike sections of the interior of the beam pipe/magnets. The calculations were conducted with the beam starting 1mm into the surface and with an angle of 1 milliradian to the surface. The beam was scrapped on the beam pipe in two locations. The first location was at z=2 meters, which represents the beginning of the first quadrupole. The second simulation had the beam strike at z=7. meters, which is about 1.7 meters into the dipole. The Z distribution of neutron fluence with energy greater than 20 MeV is displayed in Figure 2. The neutron fluence peaks about 3-4 meters downstream of the scrapping location. The height of the peak depends weakly on details of the parameters of the beam direction. The peak value for scrapping in the dipole (green triangles) is $6.4*10^{-8}$n/(cm^2-p). The peak result for striking the quadrupole (red squares) is $5.8*10^{-8}$n/(cm^2-p).

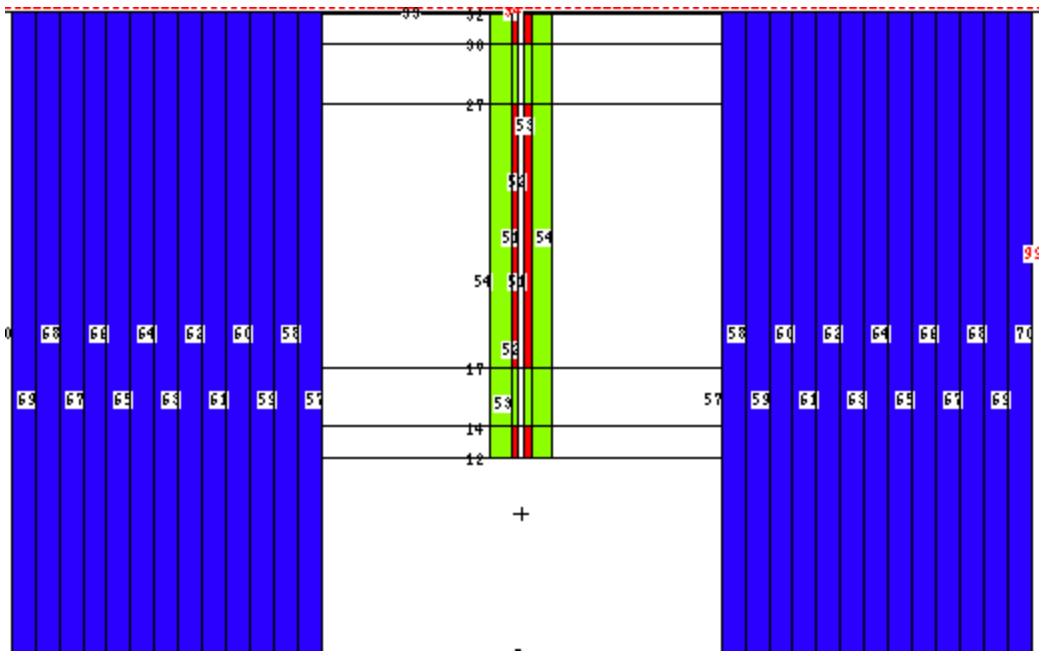

Figure 1: Layout of the RHIC tunnel and the magnet string used in the MCNPX simulation. The first quadrupole is located at z=2 meters. The tunnel radius is 2.5 meters and the soil air boundary is at a radius of 6.4 meters.

The fluence of the high-energy neutrons in the soil as a function of radius is shown in Figure 3. The calculations are well described by an exponential multiplied by $(1/R_t)^2$, where R_t is the transverse distance. The argument of the exponential is d*1.56, where d is the distance in soil in meters. This value is close to the value of d*1.49 reported in reference 4. The coefficient is determined by the soil composition, density and the high-energy cross sections. The coefficients are expected to be in close agreement.

The high-energy neutron fluence outside the soil can be converted into an equivalent dose using a conversion factor. Similar to reference 2, an iron target 3cm in radius and 1 meter long was struck by a 250 GeV proton beam inside a tunnel with radius 1.5 meters and surrounded by 1.5 meters of soil. The neutrons with energy greater than 20 MeV were tallied on the surface along with the total equivalent dose calculated by tracking all particles to low energy. The conversion factor established in this fashion is $7.22*10^{-8}$ rem/(n/cm^2-with e>20 MeV).

The equivalent dose on the berm is a product of the number of 250 GeV protons lost times the neutron fluence with E>20 MeV multiplied by the conversion factor. Beam striking the dipole produces $6.42*10^{-8}$ n/(cm^2-p) with energy greater than 20 MeV. The equivalent dose, H is:

$$H= 6.42*10^{-8(}n/cm^2\text{-}p) * (0.5*5*10^{13}\ p) * 7.22*10^{-8}\ rem/(n/cm^2) = 115\ mrem.$$

This equivalent dose is at the soil surface with a soil thickness of 12.8 feet. Often the equivalent dose is reported 3 feet above the soil surface and with a soil thickness of 13 feet. Adjusting for the increase in energy[5] to 300 GeV, the soil thickness, and the distance above the berm a result[6] of 87 mrem is obtained.

The MCNPX results can be compared to the fault study conducted with 8.62 GeV per nucleon gold beam. The beam-fault study[9] measured 0.36 micro-rads per 10^8 gold ions interacting in a RHIC Magnet. Using the scaling presented in the fault study report we reduce the 87 mrem for a full energy MCI to 0.46 micro-rads. The MCNPX results and the fault study measurements are in good agreement. The result from the RHIC Projects' CASIM calculation was 1.57 micro-rad, which is considerably higher. It is possible to run MCNPX with ions and to use the fault study energy. A more careful comparison may be conducted in the future.

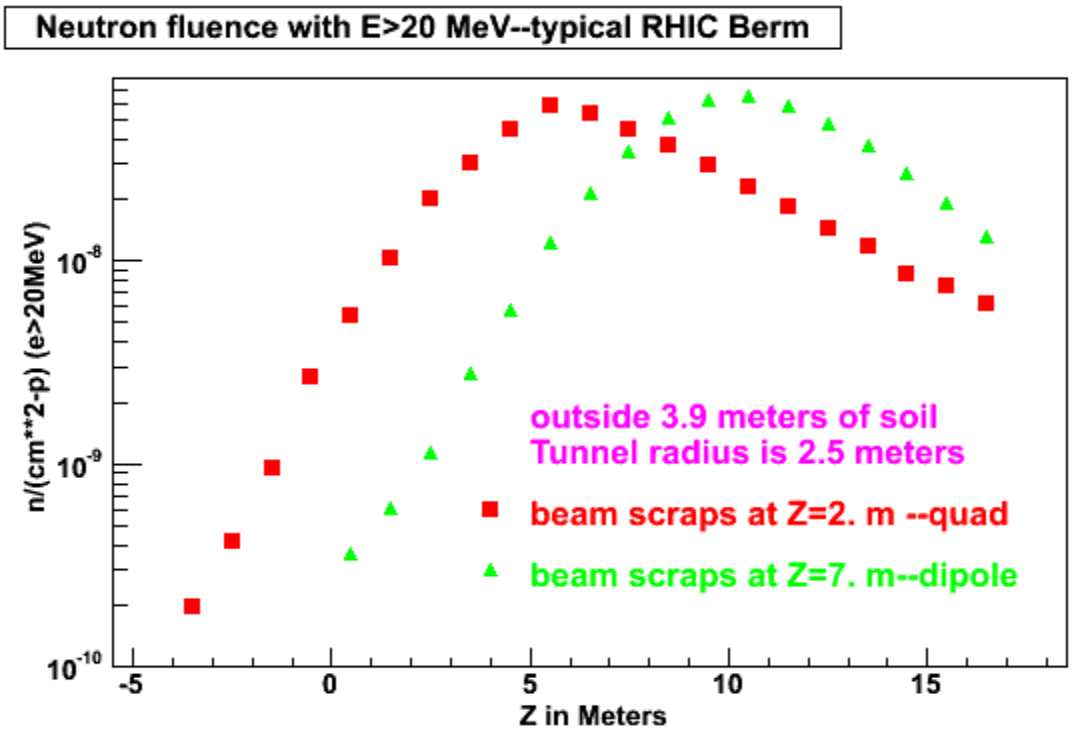

Figure 2: Neutron fluence with energy greater than 20 MeV as a function of z. The red points (sq.) are for the beam hitting the first quadrupole and the green points (tri) are for the beam hitting the dipole.

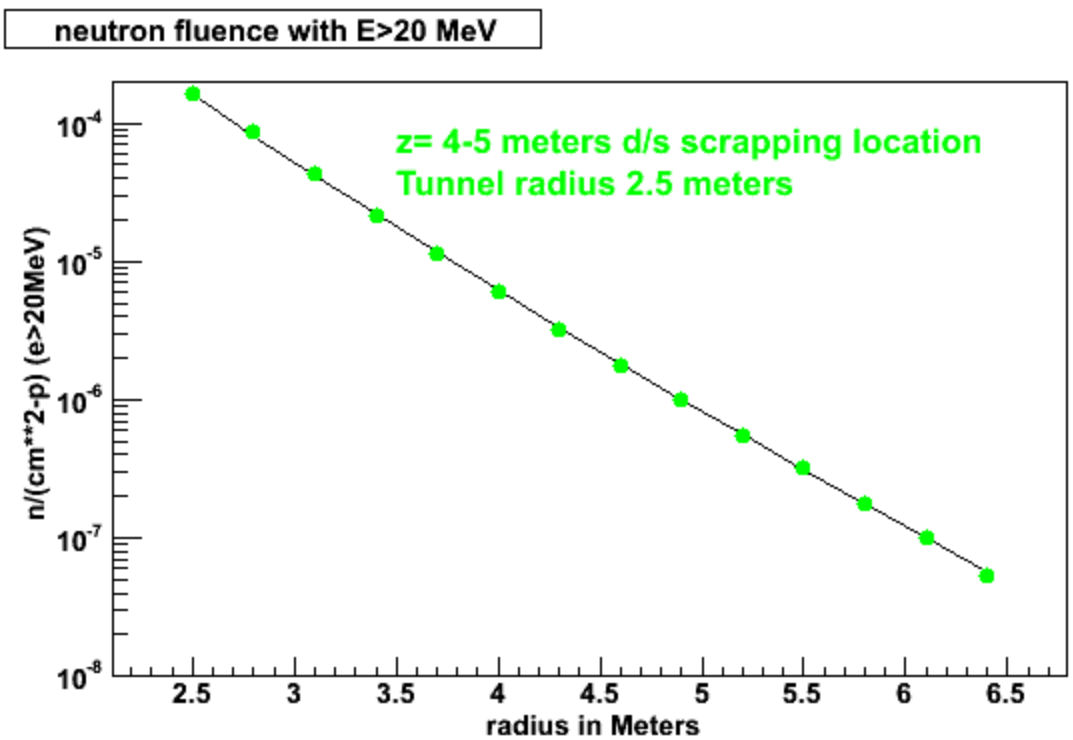

Figure 3: Neutron fluence as a function of depth of soil for neutrons with energy greater than 20 MeV. The air-berm interface occurs at a radius of 6.4 meters. This plot is for the beam hitting the first quadrupole. The line depicts exp(-d*1.56)/(Rt*Rt).

MARS and MCNPX were used to compare[10] the results outside a tunnel when a steel rod was hit. The MARS results were a factor of 1.5 higher that the MCNPX results. This factor was included in the STAR shield wall result to be conservative. Applying this factor would result in a dose of 0.69 micro-rads 10^8 gold ions at 8.62 GeV per nucleon, which is still in good agreement. The factor will be included in the final estimate for the RHIC berm.

Conclusions

The calculations conducted with MCNPX estimate that the maximum equivalent dose to an individual on the RHIC berm during an MCI is 130 mrem. The RHIC berm is posted as a Controlled AREA. There is little likelihood for such an event to occur. No additional access controls are recommended for the berm. It is considered unlikely that an individual would receive more than 100 mrem in a year on the RHIC Berm.

References

1. RSC Minutes of May 9, 2012; http://www.c-ad.bnl.gov/esfd/RSC/Minutes/05_09_12Minutes.pdf
2. D. Beavis memorandum, April 20, 2012; http://www.c-ad.bnl.gov/esfd/RSC/Memos/STAR_wall.pdf
3. MCNPX version 2.7C was used for the calculations in this report. D. B. Pelowitz et al., "MCNPX 2.7.C Extensions", LA-UR-10_00481, March 5, 2010.
4. A.J. Stevens, AD/RHIC/RD-77, Oct. 1994: RHIC SAD Appendix 15; http://www.c-ad.bnl.gov/ESSHQ/SND/RHICSAD/appendices/app15.pdf
5. An energy scaling of $E^{.8}$ is used.
6. This is larger than the preliminary number presented in reference 1. An error in the geometry was corrected and protons hitting the dipole was used instead of hitting the quadrupole.
7. D. Beavis memorandum, June 9, 2010; http://www.c-ad.bnl.gov/esfd/RSC/Memos/STAR_wall_upgrade.pdf
8. A.J. Stevens, AD/RHIC/AD-113, April 1997; RHIC SAD Appendix 25; http://www.c-ad.bnl.gov/ESSHQ/SND/RHICSAD/appendices/app25.pdf
9. A.J. Stevens, "Summary of Fault Studies at RHIC", EPS Tech. Note 156, July 12, 2000; Kin Yip memorandum, May 23, 2012; http://www.c-ad.bnl.gov/esfd/RSC/Memos/kin_MCNPX_5_23_12.pdf