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Memo

date: *June 25, 2012*

to: *RSC*

from: *D. Beavis*

subject: *Maximum Equivalent Dose near RHIC B-2 and B-1 Vents during an MCI*

The potential equivalent dose outside several shields has been calculated in previous notes[1,2] using MCNPX[3]. The results have been lower than the estimates conducted by the RHIC Project using the obsolete program CASIM[4]. A fraction of the difference between the original estimates and the new estimates is a result of the guidance the RHIC Project used for planning for an increase in the neutron quality factor. The neutron quality factor has been officially increased and is smaller than used by the RHIC Project. Additional differences are the associated with model differences. CASIM is not available to explicitly compare with MCNPX but it is assumed that MCNPX provides an accurate result.

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**.** The B-2 vents are the worst case condition examined in the RHIC documents[5]. The ventilation shafts have covers/caps. The RHIC Project assumed that the closest a vent cover could be to the berm was 3 feet. **The maximum equivalent dose estimated one meter above the berm on the vent cover is estimated to be 1030 mrem in this report. The maximum equivalent dose one foot to the side of a B-2 vent is 300 mrem.** The dose decreases quickly with distance from the vent shaft. This result is in good agreement with the B-2 result presented[6] in Appendix 16 of the RHIC SAD when scaled for intensity and energy (1270 mrem). It would be expected[7] that the other vents will be in close agreement with the scaled RHIC Project documentation.

The vents are located around the RHIC berm which is posted as a Controlled Area during beam operations. A portion of the vents are inside secured areas and are not a concern during operations. The berm is presently a Controlled Area. Access changes near the vents will need to be considered and possibly implemented before increasing the beam intensity. The probability to receive exposure near a vent is considered small.

Estimate of Equivalent Dose at a B-2 Vent

The Monte Carlo program MCNPX[3] was used to calculation the proton interactions in the RHIC magnets and then transport the produced radiation through the soil and the void of the vent. All particles were transported to low energy to estimate the equivalent dose emerging from the ventilation shaft. Several runs were conducted with photons and the photon contribution to equivalent dose was determined to be 10%. Photons were eliminated from some of the calculations to reduce computation time and a factor of 1.1 was used to account for their contribution. The calculations were performed with 250 GeV protons and then scaled to 300 GeV with $E^{.8}$ energy scaling of transverse radiation.

The RHIC magnets and tunnel geometry were approximated in a fashion similar to that used by the RHIC Project. A dipole was assumed to be adjacent to the vent. The material assigned to the dipole is tabulated in Table I below. The proton beam transport was initiated in the beam pipe at a point 1 mm into the pipe, with an outward angle of 1 milli-radian, and no divergence. A view of a B-2 vent is shown in Fig. 1.

Table I: Radial Material Distribution of Dipole

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)

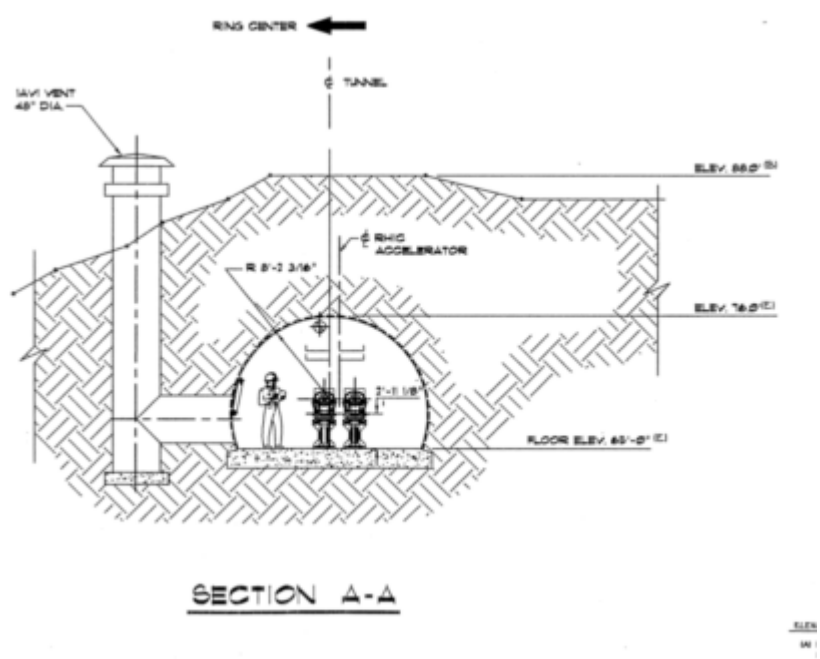

Figure I. B-2 vent 1AV1.

The geometry was approximated into MCNPX. Fig. II shows a view of the material used in MCNPX. The final results were calculated with the two magnets. The effect or a second magnet away from the vent was less than 1%. **The beam always struck the magnet on the vent side, which produces more radiation into the ventilation shaft.** The geometry is divided into sections to avoid transport in areas that should not contribute substantially to the dose through the vent. The soil density is 1.8 g/cc. The tunnel floor was approximated as soil rather than light concrete. Surfaces inside the vertical shaft were used to record the dose along the vertical shaft using MCNPX F2 flux tallies modified with a dose function. The dose was also recorded on surfaces 50, 100, and 150 cm ground level with a surface area equal to the shaft area. The equivalent dose was also recorded on the sides of the vent at distances of 0 cm, 15 cm, 30 cm, and 60 cm.

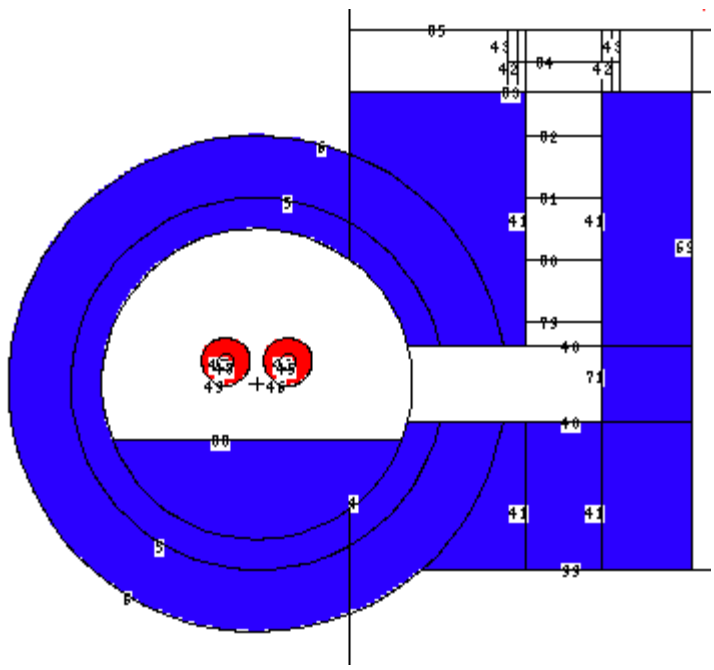

Figure 2: MCNPX geometry for a B-2 ventilation shaft.

The equivalent dose along the vertical shaft axis is given in Table II for an MCI with the proton beam transport initiated 100 cm upstream of the ventilation shaft axis. The attenuation along the shaft agrees well with the labyrinth formula[8] used by the RHIC Project. A.J. Stevens[6] used the labyrinth formula to extend the estimate from the ground surface to the minimum height where a vent cover would exist, 3 feet above the soil. Surface 85 is 100cm above the soil surface. The (1270) at surface 85 is the scaled result given by A.J. Stevens. Typically the soil surface is sloped near the vents and is higher on the side closest to the ring, as demonstrated in Fig. I.

Table II: Equivalent Dose at Surfaces Perpendicular to Vertical Shaft Axis for B-2 Shafts.

Surface	Distance from Horz. Shaft (cm)	Equivalent Dose (mrem)	Ratio to surface 80 (labyrinth formula)
80	140	29,100	1.0
81	240	12,500	.428 (.399)

82	340	5,700	.196 (.187)
83 (berm surface)	410	3,030	.104 (.117)
84	460	1,880	.065 (.085)
85 (100 cm above berm)	510	1,370 (1270)	.047 (061)

Surfaces were used around the shaft to determine the equivalent dose with distance from the side of the ventilation shaft. Surface 41 is the shaft radius of 61cm, surface 42 has a radius of 76 cm, and surface 43 has a radius of 91 cm. The vertical portions of these cylindrical surfaces were divided into 0-50 cm above ground, 50 to 100 cm above ground, and 100-150 cm above ground. The equivalent doses for the surfaces are given in Table III.

Table III: Equivalent Dose at Surfaces near a B-2 vent for an MCI

Surface	Dose (0-50cm) mrem	Dose (50-100 cm) mrem	Dose (100-150cm) mrem
41 (shaft radius)	2,100	1,480	660
42 (15 cm larger then shaft)	520	780	430
43 (30 cm larger than shaft)	320	400	260
8 (60 cm larger than shaft)	130	200	130

The initial starting position of the proton beam was incremented along the tunnel axis to test the sensitivity to the scrapping position. A location 1 meter upstream of the vent axis was found to be near the maximum and used for the final estimations. Table IV has the relative strength as a function of z, distance along the beam direction from the horizontal vent axis. Lower statistics were used and the ratio was determined in the lower portion of the vertical shaft at surfaces 79 and 80.

Table IV: Relative Source Strength.

Z Location (cm)	Surface 79	Surface 80
-300	0.39	0.43
-200	0.66	0.72
-100	1	1
0	0.84	0.87
+100	0.33	0.35

MCNPX has an option to use point detectors to evaluate dose. Point detectors were placed on the axis of the vertical shaft and results compared for several examples. The vertical height of 470 cm is where the vent exits the soil, which corresponds to surface 83 in Table II. The results are shown in Table V with the neutron doses scaled to an energy of 300 GeV and multiplied by 1.1 to account for photon contributions. There is a systematic difference of about 10% between the results in Table II and using the point detectors. The point detectors are on the shaft axis

where the values in Table II are averages over the shaft diameter. In addition, the point detector cannot take the angle into account. It is therefore expected that the point detectors will be higher than using the F2 surface-averaged flux.

Table V: Dose Estimate using Point Detectors

Y in cm	B-2 vent (mrem)	B-2 vent opposite magnet (mrem)	B-1 vent (mrem)
200	33,500	11,930	22,200
300	13,500	4,980	8,650
400	6,280	2,320	3,890
470	3,380	1,220	1,987
520	2160	790	1,280
570	1570	560	930

The dose estimates using the F2 flux calculations are expected to be more accurate. However, the point detectors obtain a result in about $1/10^{th}$ the computation time for the simulated geometry. Based on these results a B-1 vent should have 60% of the equivalent dose than a B-2 vent 3 feet above the berm (570 cm). This agrees well with the value 57% that the RHIC Project had for the ratio of B-1 to B-2 vents. At three feet above the berm the area directly over the shaft (vent cover) is less than 1 rem in an MCI for a B1 vent. The maximum equivalent dose 1 foot to the side of a B-1 shaft is 240 mrem.

A simulation was performed with the beam scrapping the magnet on the opposite side of the ring as a vent. In the simulation the proton beam transport was started 100cm upstream of a B-2 vent shaft and the side of the magnet facing the vent was hit. The equivalent dose was reduced by a factor of three due to the shielding provided by the adjacent magnet which is between the targeted magnet and the vent.

The B-2 and B-1 vents have a small re-entrant cavity at the bottom of the vertical shaft as shown in Figure 1. The question was posed by R. Karol as to how much we might benefit from taking this into account in the Monte Carlo program. The MCNPX model was modified to simulate the re-entrant cavity in the calculation. The result was a net reduction of 25% for the dose exiting the vent. The model of the B-2 vent with re-entrant cavity is shown if Fig. III. A similar reduction should be expected for the B-1 vents. Not all types of ventilation shafts at RHIC have re-entrant cavities. **The calculations in the tables above should be multiplied by 0.75 to arrive at a more realistic dose estimate.**

The labyrinth formula can be used to provide an overestimate of the dose at elevations higher than the 100 cm used earlier. The overestimation was demonstrated in Table II above and also noted in the RHIC Project documentation for extending from the ground level to three feet. At 2 meters above the berm the equivalent dose directly over the shaft is 565 mrem for a B-2 vent. The elevation of the vent covers may approach or exceed two meters above the berm for some locations.

The maximum equivalent dose out B-2 and B-1 vents during an MCI are given in Table VI. The point detector numbers have been used to scale[9] the F2-flux numbers for the B-2 vents to arrive at the numbers for B-1 vents. If necessary the B-1 shaft can be more carefully simulated. In Table VI there is only one case that exceeds 1 rem . There are two cases where the equivalent dose is between 500 and 1000 mrem, which are marked in yellow. All equivalent doses at one foot to the sides of the vents are below 500 mrem and are marked in green.

Table VI: Maximum Equivalent Dose at B-2 and B-1 vents

location	Maximum equivalent Dose (mrem)
B-2 Vent 1 meter above shaft	1030
B-2 vent 2 meters above shaft	570
B-2 vent 1 foot to side at 50-100cm elevation	300
B-1 vent 1 meter above shaft	610
B1-vent 2 meters above shaft	320
B1-vent 1 foot to side at 50-100 cm elevation	180

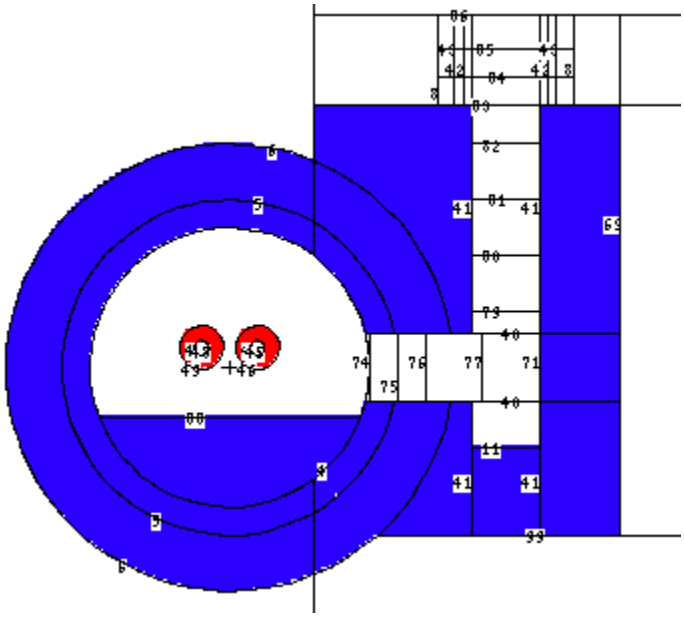

Figure III: B-2 vent with the re-entrant cavity at the bottom of the vertical Shaft.

There are some potential uncertainties in the calculations. It was noted in reference 1 and 2 that for deep shield calculations MARS estimated[10] the dose to be 50% higher than MCNPX. The source of this difference was not determined. To be conservative for the berm and shield walls this factor was incorporated without knowing which result was more accurate. This factor has not been applied to the numbers given in this report but should be considered in evaluating the risk of dose near a vent. An MCI for most of the ring is assumed to be 50% of the beam in a ring. Larger percentages may be possible but were not considered credible, except for specific locations.

The likelihood of an MCI to occur is expected to be small. If the insertion regions, dumps, and collimators are excluded then there is no known incident where a beam loss approaching the scale size assumed for an MCI has occurred. A combination of beam loss monitors and magnet quench detectors reduce the likelihood of large beam losses at arbitrary locations around the RHIC ring. These none credited controls provide defense-in-depth to prevent large beam losses and protect the superconducting magnets. There is less than a 5% chance[11] that should an MCI occur that it will be within 1.5 meters of a vent opening.

Conclusions

The risk of a person receiving any exposure above 200 mrem near a vent is small. A simple estimate is presented to demonstrate how infrequent this possible exposure could occur. Assuming one MCI event occurs in the arcs (non-insertion regions) once every five years is a reasonable assumption and consistent with present operating experience. There is about a 5% probability the MCI occurs within 2 meters of a vent. There is much less than a 1% chance that a person will be standing within two feet of a vent during an MCI. It is concluded that a person may receive an exposure above 200 mrem during an MCI once every 10,000 years. We expect that this is conservative. The maximum dose on top of the typical berm area is 130 mrem for an MCI. This probably represents the greater potential risk for exposure over 100 mrem. The frequency could be reduced if work was not allowed near vents during beam operations or controlled via work permits. This could also be used to decrease the risk for exposure on the berm in general.

The exposure area is very limited for the ventilation shafts and the potential frequency of occurrences is quite small. However, unexpected exposures are taken seriously and the approach to a solution will most likely include considering perception by DOE and the general public beyond meeting exposure requirements risk evaluation. Based on the C-AD SAD[12] the risk for this hazard would be classified **extremely low risk**.

References

1. Note on STAR Shield Wall see ; http://www.c-ad.bnl.gov/esfd/RSC/Memos/STAR_wall.pdf
2. Note on RHIC berm see ; http://www.c-ad.bnl.gov/esfd/RSC/Memos/RHIC_berm_052312.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. For CASIM reference see A Van Ginneken and M. Awschalom, "High Energy Particle Interactions in Large Targets", FNAL, 1975.
5. Appendix 16 of the RHIC SAD; http://www.c-ad.bnl.gov/ESSHQ/SND/RHICSAD/appendices/app16.pdf
6. See A.J Stevens memorandum of August 28, 1998 in RHIC SAD Appendix 16.
7. This comment is based on the demonstrated accuracy of the universal attenuation curves for labyrinths which were used by the RHIC Project. Once the correct neutron quality

factor and source term are determined then one should expect the results to scale to other labyrinths. If the angle from the source to the labyrinth to the duct is substantially different then it should be checked.

8. K. Goebel, G.R. Stevenson, J.T. Routti, and H.G. Vogt, "Evaluating Dose Rates Due to Neutron Leakage Through Access Tunnels of the SPS", CERN LABII-RA/Note/75-10 (1975).
9. This provides a conservative estimate for the side fo the B-1 vent since the area of the hole to the area of the circle around the vent is smaller than the B-2 vent.
10. Kin Yip Memorandum of May 23, 2012; http://www.c-ad.bnl.gov/esfd/RSC/Memos/kin_MCNPX_5_23_12.pdf
11. This is a crude estimate based on Table IV, the number of vents, and the circumference of the ring.
12. http://www.c-ad.bnl.gov/ESSHQ/SND/2011%20SAD%20and%20ASEs/C-AD%20SAD%20Final%208-5-11.pdf