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Memo

date: *Friday, September 14, 2001 (Amended Tuesday, October 30, 2001)*

to: *RSC Files*

from: *E. T. Lessard*

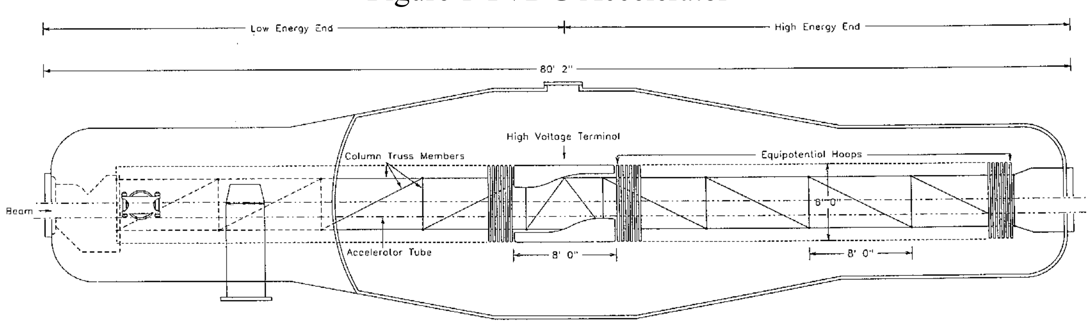
subject: *Estimates of Contamination from Deuteron Beam in the TVDG*

This memorandum documents contamination in the TVDG insulating gas that results after producing a deuteron beam. Based on the following analysis and for 8 weeks of deuteron operations, less than 200 dpm per 100 cm^2 of P-32 contamination will remain on the walls of the TVDG acceleration tank. This estimate assumes contamination adheres to the tank walls and does not remain with the insulating gas as the gas moves back into storage cylinders. Most likely, the contamination will remain dispersed in the gas. According to the BNL Radiological Control Manual, the designation “Contamination Area” applies if the removable surface contamination is greater than 1,000 dpm per 100 cm^2.

An acceleration tank encloses the insulating gas and the particle-beam line at the TVDG. The tank is shown in Figure 1 and it encloses a vacuum pipe, a charge-exchange region in the center of the tank and a high-energy terminal. Deuteron beam loss at the charge-exchange region and at the high-energy terminal creates neutrons, neutrons that in turn activate the insulating gas.

The calculation for contamination also shows the dose equivalent rate from neutrons outside the tank to be less than a few mrem per hour. This dose rate corresponds to normal beam losses associated with the average hourly deuteron beam.

Figure 1 TVDG Accelerator



General Physical Data:

Total Weight:	375,000 lb
Volume:	11,250 ft^3
Nominal Pressure:	12 atm

Calculations

Table 1 lists the binding energies for nuclides of interest in deuteron-nucleus reactions that produce neutrons in the TVDG beam-line. The potential target materials that may be struck by the deuteron beam include materials made of carbon, stainless steel, copper or tantalum.

Table 1 Binding Energy of Nuclides of Interest[1]

Nuclide	Binding Energy, MeV
H-2	2.224573
C-12	92.161753
N-13	94.105267
Fe-54	471.758653
Co-55	476.822923
Fe-56	492.253892
Co-57	498.281524
Co-59	517.308113
Ni-60	526.841574
Cu-63	551.361251
Zn-64	559.093585
Cu-65	569.209453
Zn-66	578.133004
Ta-181	1452.238715
W-182	1459.332840

Using the binding energies for nuclides before and after collisions with deuterons, the Q-values for reactions with target atoms were determined. The Q-value is the difference in rest mass of the system of particles before and after the deuteron-nucleus reaction. Positive Q-value reflects a decrease in rest mass and an increase in kinetic and radiant energy after the reaction. Q-value plus kinetic energy of the deuteron, either 6 or 12 MeV depending on location in the Tandem tank, is listed given in Table 2 for the predominant reactions that produce neutrons.

Three products of deuteron-nucleus reactions in Table 2 are radioactive: 18-hour Co-55, 271-day Co-57 and 10-minute N-13. The Co radionuclides tend to be entrained in the surface of the stainless steel beam pipe and would not spall into the surrounding insulating gas. Production of N-13 from nuclear reactions in the charge-stripping foil would be minimal due to the thinness of the foil. In addition, the stripping foil is in its own vacuum and the N-13 will be unable to mix with the insulating gas in the TVDG tank.

[1] http://www2.bnl.gov/CoN/

Table 2 Significant Neutron Producing Reactions in the TVDG Beam Line

Deuteron Reaction	Q-Value Plus 6 MeV at Charge Exchange Region of TVDG, MeV	Q-Value Plus 12 MeV at High Voltage Region of TVDG, MeV
H-2 + C-12 → N-13 + n + Q	5.72	11.7
H-2 + Fe-54 → Co-55 + n + Q	8.84	14.8
H-2 + Fe-56 → Co-57 + n + Q	9.80	15.8
H-2 + Co-59 → Ni-60 + n + Q	13.31	19.3
H-2 + Cu-63 → Zn-64 + n + Q	11.5	17.5
H-2 + Cu-65 → Zn-66 + n + Q	12.7	18.7
H-2 + Ta-181 → W-182 + n + Q	10.9	16.9

Neutron energies will be near the Q-value plus kinetic energy of the deuteron as listed in Table 2 due to conservation of momentum. The neutron fluence will be forward peaked. Neutron yield ratios are about 10 to 1 at 0^{o} versus 90^{o}.[2] This forward peaking of neutron fluence was taken into account for the estimate of neutron dose rate outside the tank.

The gas composition is roughly SF_6 50%, N_2 35%, CO_2 10%, O_2 5% by volume. This is a very rough estimate because there has not been a recent analysis, but it is good enough for this purpose. The operating pressure is about 12 atmospheres. The ideal gas approximation was used to estimate the atom densities listed in Table 3.

Table 3 Atom Density of TVDG Insulating Gas

Insulating Gas Target Atom	Atom Density, atoms cm^{-3}
Carbon	3.2E19
Fluorine	9.6E20
Nitrogen	2.3E20
Oxygen	9.7E19
Sulfur	1.6E20

The sulfur cross-sections for neutron reactions are shown in Figure 2. Similar graphs are available for nitrogen, oxygen, fluorine and carbon via Reference 3. The volume macroscopic cross-sections listed in Table 4 for the range of energies shown in Table 2 were calculated based on atom densities listed in Table 3. Total-absorption, n,p and n,t cross-sections were determined in order to calculate the production rates of 14-day P-32, 5730-year C-14 and 12.3-year tritium. A mean cord-length of 1200 cm was used as the thickness of insulating target gas. This assumption results in an overestimate of the thickness of gas seen by the neutrons in all directions and thus overestimates the potential contamination produced.

[2] Table F.4 in NCRP Report 51, Radiation Protection Guidelines for 0.1-100 MeV Particle Accelerator Facilities, National Council on Radiation Protection and Measurements, 7910 Woodmont Avenue, Washington, D.C., 20014.

[3] http://hpngp01.kaeri.re.kr/CoN/endfplot.shtml

Figure 2 Total, Elastic, Inelastic and n,p Cross Sections for Neutrons on Sulfur

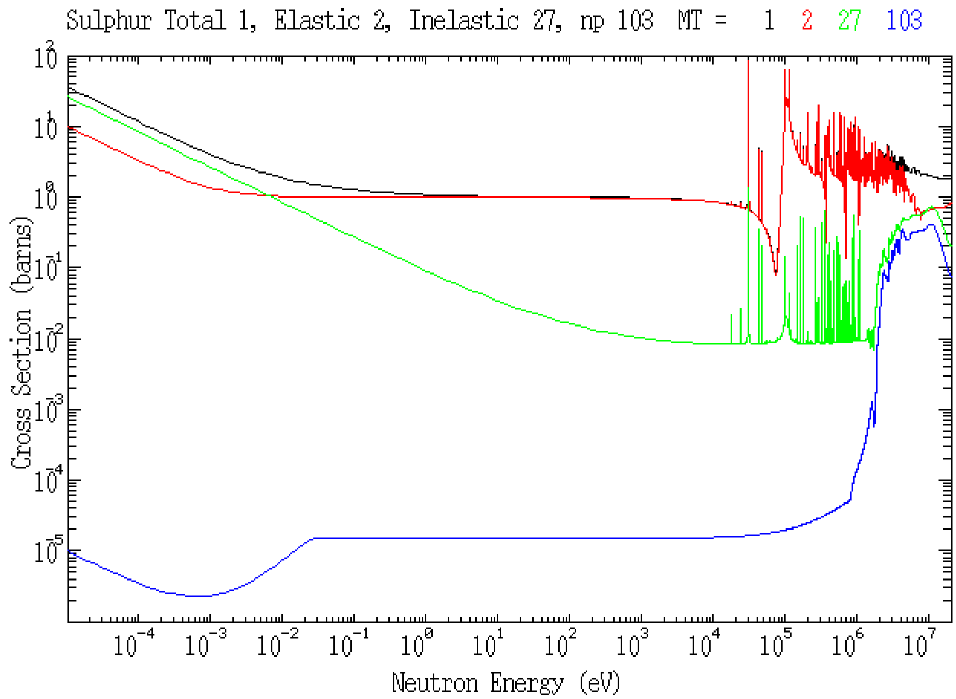


Table 4 Volume Macroscopic Cross-Sections

Target Atom	Reaction	Cross-Section, cm^{-1}
Sulfur	Total Absorption	1.0E-4
Fluorine	Total Absorption	1.9E-4
Carbon	Total Absorption	9.7E-6
Oxygen	Total Absorption	4.8E-5
Nitrogen	Total Absorption	1.1E-4
Sulfur	n,p to produce P-32	6.3E-5
Nitrogen	n,p to produce C-14	9.0E-6
Nitrogen	n,t to produce tritium	6.8E-6

The total absorption cross-section is 4.6E-4 cm^{-1}. The fraction of neutrons absorbed in a 1200-cm thick layer of insulating gas is:

$$1 - e^{-(4.6E-4cm^{-1})(1200cm)} = 0.43$$

The fraction of absorbed neutrons that result in P-32 is 0.14 (6.3E-5 cm^{-1}/4.6E-4 cm^{-1}). The fraction of absorbed neutrons that result in C-14 is 0.020 (9.0E-6 cm^{-1}/4.6E-4 cm^{-1}). The fraction of absorbed neutrons that result in tritium is 0.015 (6.8E-6 cm^{-1}/4.6E-4 cm^{-1}).

Thieberger has provided an estimate of dose-equivalent rate at 1-meter from a stopped deuteron beam for different energy deuterons. Measurements were made with a 28 MeV deuteron beam and the results were extrapolated to 12 MeV deuterons.[4] The target was copper and the extrapolation is tabulated in Table 5. The neutron-fluence rate per unit current that corresponds to the dose-equivalent rate per unit current is listed. The neutron-fluence rate was based on conversion parameters listed in Table B.3 of NCRP Report 51.[5] In addition, total neutron yield per unit current or per deuteron-nucleus interaction are listed in Table 5 and given in units of n s^{-1} μa^{-1} and n d^{-1}. The total neutron yield extrapolations listed in Table 5, which are based on Thieberger's measurements, compare favorably with measurements of total neutron yield per unit deuteron current given in Figure F.2 of NCRP 51.

Table 5 Dose Equivalent Rate, Fluence Rate and Total Neutron Yield from Copper per Micro-amp of Deuteron Current and Total Neutron Yield per Deuteron-Nucleus Interaction

Deuteron Energy, MeV	Dose Equivalent Rate at 1 m from Cu Target, mrem h^{-1} μa^{-1}	Neutron Fluence Rate at 1 m, n cm^{-2} s^{-1} μa^{-1}	Total Neutron Yield, n s^{-1} μa^{-1}	Total Neutron Yield per Deuteron, n d^{-1}
6	40	270	1.1E7	1.8E-6
12	1000	6800	2.9E8	4.7E-5

In order to estimate the contamination buildup from the total neutron yield in Table 5, the target atoms for deuteron losses are assumed to be predominantly copper or iron. A loss of 20% of the deuteron beam is assumed to occur at the charge-exchange region of the tank and a loss of 2% of the beam is assumed at the high-energy region of the tank.[6] A. Stevens estimates a total of 6.96E17 deuterons during an 8-week period are required to meet the physics and beam tuning needs for RHIC studies.[7] Assuming a 22% loss in the acceleration tank, then a total of 8.5E17 deuterons are accelerated. Based on the total neutron yields in Table 5, 3.4E11 neutrons are created at the charge-exchange region and 8.0E11 neutrons at the high-energy terminal of the tank. Assuming the loss of deuterons is uniform over the 8-week period, and the neutrons are all roughly the same energy from either loss location in the acceleration tank, see Table 1, an average neutron production rate of 1.6E6 n s^{-1} is estimated in the tank.

The fraction absorbed, the fraction resulting in P-32 and the average neutron production rate combine to yield the P-32 atom production rate as follows:

$$\left(1.6E6ns^{-1}\right)\left(0.43\right)\left(0.14\right) = 9.6E4s^{-1}$$

The P-32 activity after 8-weeks of uniform buildup and decay is:

$$\left(9.6E4s^{-1}\right)\left(1 - e^{-\left(0.0495d^{-1}\right)\left(56d\right)}\right)\left(\frac{1\mu Ci}{3.7E4s^{-1}}\right) = 2.4\mu Ci$$

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[4] Peter Thieberger, private communication. Estimates based on Ohnesorge's "universal curve."
[5] NCRP Report 51, Radiation Protection Guidelines for 0.1-100 MeV Particle Accelerator Facilities, National Council on Radiation Protection and Measurements, 7910 Woodmont Avenue, Washington, D.C., 20014.
[6] P. Thieberger, private communication. Losses are based on experience at the TVDG.
[7] "TTB Operating Scenario for Deuterons Delivered to RHIC," A. Stevens, Appendix 1 of the TTB USI, October 2001.

In a similar way, 6.9E-6 μCi of C-14 and 2.4E-3 μCi of tritium are estimated. The tank has a surface area of about 3E6 cm^2. If the radioactivity from P-32, C-14 and tritium remain on the walls of the tank, then less than 200 dpm per 100 cm^2 would result. However, the insulating gas is removed from the tank before entry and little contamination is expected to remain if the contamination stays suspended in the gas.

Experience shows that 300 ft^3 of gas (3%) must be replaced annually. Thus, a NESHAPS evaluation was done for an annual release listed in Table 6 and was included as Appendix 7 of the TTB USI.

Table 6 Estimate of Annual Airborne Activity

Nuclide	Activity Released in One Year, μCi
H-3	0.00007
C-14	0.0000002
P-32	0.07

Because the neutrons are forward peaked in a ratio of 10 to 1 relative to lateral, an estimate of dose rate outside and directly downstream of the high-energy end of the tank can be made. Assuming: 1) the 4π neutron-yield listed in Table 5 is spread over 1/10th the surface of a sphere, 2) the average neutron production rate is 1.6E6 n s^{-1}, 3) the neutrons are not absorbed in the tank and 4) the accessible surface is 8 feet from the high-energy loss point, yields about 70 n cm^{-2} s^{-1}. This corresponds to 10 mrem h^{-1} based on the fluence rate to dose equivalent rate conversion factor in Table B.3 of NCRP Report 51 for neutrons with energy between 10 and 20 MeV. If the neutron energy spectrum shifts to thermal energies due to scattering in the insulating gas and the tank wall, then this would lead to about 40 times less dose rate. Thus, the dose rate outside the tank wall is likely to fall between 0.3 and 10 mrem/h. It is noted that access to this region of the Tandem Van de Graaff is restricted during operations with deuterons.

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