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Calculation of the Radioactivity Produced in the Cooling Loops of the CDF SVX II Detector

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Introduction

The SVX II detector, a major component in the upgrade of the CDF Detector for Run II, is located very near to the beam interaction point and will be subjected to high fluences of hadrons and leptons from the proton-antiproton collisions that will take place at the vertex. The SVX II detector is being constructed in 5 layers with each layer equipped with cooling loops. A water-ethylene glycol mixture will be circulated through these cooling loops in order to remove heat from the detector. In response to a request by CDF, a calculation of the concentrations of radioactivity that will be produced in this cooling medium has been performed and is described in this note.

Description of the Calculation

The following equation describes the buildup of specific activity, a_i, of a particular radionuclide, i, as a function of irradiation time, t_{irrad} (sec), in a mixture of chemical elements;

$$a_i(t_{irrad}) = \sum_j n_j \sigma_{ji} \phi \left[1 - \exp(-\lambda_i t_{irrad})\right] \qquad (\text{Bq cm}^{-3}). \qquad (1)$$

In this equation, it is assumed that the mixture is exposed to a uniform flux density of particles of a particular type or energy, ϕ (cm^{-2}s^{-1}), that is constant over time. Also, n_j is the number density (cm^{-3}) of atoms of element j in the mixture and σ_{ji} is the cross section (cm^2) producing radionuclide i from the interactions of particles of a particular type or energy with element j. λ_i is the decay constant (s^{-1}, inverse meanlife) of radionuclide i. After the irradiation has ceased, if the radioactivity is allowed to decay for a time period t_{decay} , the specific activity present will be a function of the decay time, t_{decay}, as follows:

$$a_i(t_{decay}) = a_i(t_{irrad}) \exp(-\lambda_i t_{decay}) \qquad (\text{Bq cm}^{-3}). \qquad (2)$$

To express these concentrations in the more conventional units of pCi cm^{-3}, one should multiply the results of either Eqs (1) or (2) by a factor of 27.02. K. Schuh[1] has provided the following information about the cooling system. Its total volume will be between 135 gallons (5.11 x 10^5 cm^3) and 150 gallons (5.68 x 10^5 cm^3). For conservatism, the smaller value was used for the total system volume in these calculations. The mixture is taken to be 28 % ethylene glycol by volume. Since the density of water is 1 g cm^{-3}, the density of ethylene glycol is 1.1088 g cm^{-3}, and the chemical formula of ethylene glycol is $C_2H_6O_2$, one determines the number densities of the three constituent elements of the mixture given in Table 1.

Table 1 Atomic number densities of elements found in the coolant mixture

Element	n_j (atoms cm^{-3})
H	7.16×10^{22}
C	1.87×10^{22}
O	2.65×10^{22}

The cooling loops in each layer have very small volumes with the vast majority of the total volume of the system constituting a reservoir external to the radiation field. These, volumes are provided in Table 2.

Table 2 Volumes of coolant loops in the various layers of the SVX II detector

Layer Number	Volume (cm^{-3})
0	1.2
1	2.1
2	3.3
3	4.2
4	7.8

The CDF Collaboration has extensively studied the levels of radiation expected to be delivered to the 5 layers of the SVX II due to important concerns related to radiation damage. In the Technical Design Report for SVX II[2], the values of the fluence delivered to each layer as a function of time, normalized that equivalent to 500 MeV protons has been calculated with the results given in Figure 1.

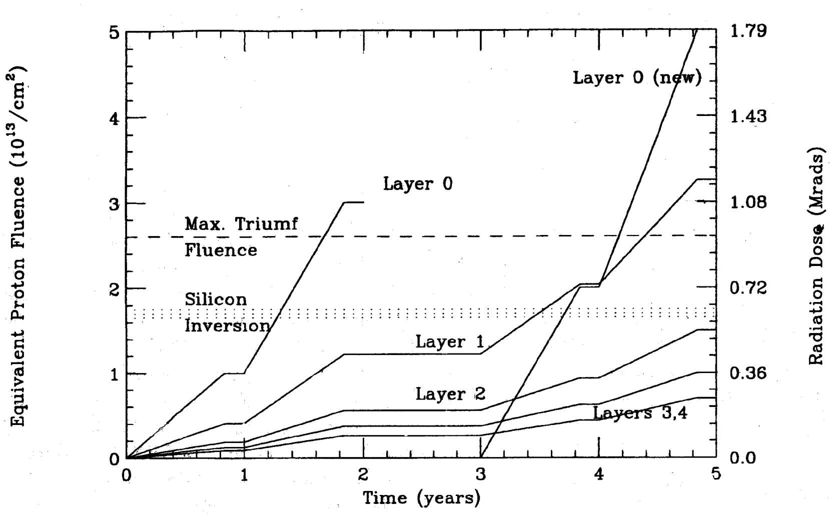

Figure 1 Plot of equivalent fluence of 500 MeV protons delivered to layers 0-4 of SVX II during Tevatron Run II. These correspond to integrated luminosities of 1 fb^{-1}, 2 fb^{-1}, 0 fb^{-1}, 2 fb^{-1}, 3 fb^{-1} for years of operation 1, 2, 3, 4, and 5 respectively. This figure was adapted from Reference 2. The planned replacement of layer 0 after the 2nd year of operation has been ignored in the present calculation.

These values of time-integrated fluence were, then, converted to flux densities, ϕ, to be used in Eqs. (1) and (2) by simply assuming the former to be delivered uniformly during each successive planned operational period of slightly less than one year.

The values of σ_{ji}, were obtained from the standard reference by Barbier[3] except those related to the production of ^{3}H which was taken from the results of Konobeyev and Korovin[4]. For the elements found in the coolant mixture, only 5 radionuclides having lifetimes of significance are produced. Table 3 gives the cross sections used in the calculation.

Table 3 Production cross sections relevant to the present calculation

Radionuclides, *i*	**Decay Constants, λ_i (s^{-1})**	**Cross Section, σ_{ji} (mb) *j* = Carbon**	**Cross Section, σ_{ji} (mb) *j* = Oxygen**
^{3}H[a]	1.78×10^{-9}	20	25
^{7}Be	1.51×10^{-7}	10	8
^{11}C	5.69×10^{-4}	25	10
^{13}N	1.16×10^{-3}	cannot produce	5
^{15}O	5.67×10^{-3}	cannot produce	35

[a] In principal, ^{3}H could be produced from hydrogen by means of two sequential thermal neutron capture reactions, $^{1}H(n,\gamma)^{2}H$ followed by $^{2}H(n,\gamma)^{3}H$. However this is unimportant due to the fact that the cross sections for both thermal capture reactions involved are fractions of a millibarn. Also, the flux density of thermal neutrons within the SVX II should be quite small due to the lack of thermalizing (hydrogenous) material present.

It is straightforward to proceed with the calculation according to Eqs. (1) and (2) along with the various other parameters provided in the above discussion. The specific activities were calculated in each of the 5 layers. Then, the total activities in each layer were calculated by multiplying by the layer volumes. These were summed to get the total activities. Dividing by the total system volume assuming uniforming mixing, one gets the specific activity in the coolant. For convenience, Microsoft Excel™ was used to perform these calculations.

Results

The operational scenario depicted in Figure 1 was followed. After each operational period, the concentrations were allowed to decay according to the "down time" between runs indicated in Figure 1. These calculations were then added to the radioactivity produced during the subsequent operational period, simultaneously taking further decay into account. Table 4 gives the calculated of concentrations in the coolant both immediately following the end of the designated period of operations and just prior to the resumption of operations for the subsequent cycle. It was assumed that no water would be exchanged, with resulting further dilution, in the replacement of the Layer 0 components planned after the second year of running. After "reasonable" decay periods, as anticipated, the only radionuclides still present will be ^{3}H and ^{7}Be. The concentrations are quite small compared with regulatory standards that are also provided in this table[5]. Thus, it is highly likely that the only radiological concerns pertinent to waste disposal would relate to the ethylene glycol. The ethylene glycol solution will, however, be subject to disposal as an Illinois Special Waste. At the time of disposal, a sample should be drawn and analyzed for verification.

Table 4 Specific activities of various Radionuclides in SVX II coolant after the completion of various years of operation under Run II conditions (pCi cm^{-3}). Calculated concentrations are provided for both immediately following cessation of operations and after the specified period of shutdown. Regulatory standards for drinking water are given for comparison.

	^{3}H	**^{7}Be**	**^{11}C**	**^{13}N**	**^{15}O**
End of Year 1 Run	4.75×10^{-3}	4.07×10^{-2}	7.64×10^{-2}	1.38×10^{-2}	9.66×10^{-2}
0.2 Yr Later	4.70×10^{-3}	1.57×10^{-2}	0	0	0
End of Year 2 Run	1.40×10^{-2}	8.17×10^{-2}	0.153	2.76×10^{-2}	0.193
1.2 Yr Later	1.31×10^{-2}	2.69×10^{-4}	0	0	0
End of Year 4 Run	2.20×10^{-2}	8.14×10^{-2}	0.153	2.76×10^{-2}	0.193
0.2 Yr Later	2.18×10^{-2}	3.14×10^{-2}	0	0	0
End of Year 5 Run	3.51×10^{-2}	0.123	0.229	4.14×10^{-2}	0.290
0.2 Yr Later	3.47×10^{-2}	4.73×10^{-2}	0	0	0
Regulatory Standard	20	40	400	NA (gaseous)	NA (gaseous)

Acknowledgements

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References:

1. K. Schuh, private communication, March 2000.

2. CDF II Technical Design Report, Fermilab-Pub-96/390-E, November 1996.

3. M. Barbier, *Induced Radioactivity*, (North-Holland Publishing Company, Amsterdam and London, Wiley Interscience Division, John Wiley and Sons, Inc, New York, 1969).

4. A. Yu. Konobeyev and Yu. A. Korovin, "Tritium Production in Materials from C to Bi Irradiated with Nucleons of Intermediate and High Energies", Nucl. Instr. and Meth. in Phys. Res. B82 (1993) 103-115.

5. The value for ^{3}H is from Code of Federal Regulations, Title 40, Part 141.16, "National primary drinking water standard for beta- and gamma- emitting radionuclides", 1976 while the values for ^{7}Be and ^{11}C are taken from U. S. Department of Energy Order 5400.5, "Radiation Protection of the Public and the Environment" (1990).