Title: A STUDY OF THE STRUCTURAL ACTIVATION CAUSED BY PROTON BEAM LOSS IN THE "ACCELERATOR PRODUCTION OF TRITIUM" LINAC

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A Study of the Structural Activation Caused by Proton Beam Loss in the “Accelerator Production of Tritium” LINAC
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Introduction

The Accelerator Production of Tritium (APT) project at Los Alamos National Laboratory makes use of a high power linear proton accelerator to produce neutrons via spallation reactions in a heavy metal target. The fast spallation neutrons are moderated by a heavy water blanket, and used to produce tritium by means of the reaction: $^3\text{He}(n,p)^7\text{Li}$, APT 1993. Various accelerator designs are currently under consideration. At the time when this study was performed, the project called for a 1 GeV proton linear accelerator with a beam current of 200 mA, i.e., a proton beam power of 200 MW. Given the high power at which the APT accelerator is expected to operate, as well as the heavy maintenance that is likely to be required to keep it operating, it is essential to consider health physics issues at an early stage of the design.

Activation results from beam losses during normal operation (e.g., beam halo), as well as from many anomalous conditions that can arise during accelerator tuning, or from various accident scenarios (e.g. beam steering errors, loss-of-focus). The high-energy protons in the beam will produce neutrons, photons, and a variety of spallation and fission products when they interact with the various components of the accelerator: beam pipes, magnet yokes and coils, cooling fluids, etc. The resulting radioactivity creates large gamma radiation fields in the immediate
vicinity of the accelerator, making access to the accelerator structure difficult at best. In view of the enormous costs and complications associated with remote-handling equipment and operations, it is obviously highly desirable to limit activation to a minimum. High activation levels have other detrimental effects such as large inventories of radiotoxic nuclides, large decay power (gamma heating), as well as radiation damage to components.

Often, too little attention is paid to health physics issues during the design phase of an accelerator. Remedial action taken after the machine is built is often cumbersome and costly. The work presented below is an attempt to take into account some health physics issues at an early stage of the design of the accelerator by developing a methodology to calculate activation levels, dose rates, radionuclide inventories, and air activation. This methodology should prove useful to identify poor designs (from a health physics standpoint), and provide general guidelines for radiation protection and radiation safety planning.

**Computational Methodology and Accelerator Computer Model**

Our main goal was to do an ab initio calculation of induced activity in the APT accelerator, starting with the beam-structure interaction. To be specific, we modeled a pointlike beam loss at a quadrupole magnet. (Measurements at the LAMPF accelerator show that losses are highest at quadrupole magnets because the beam spreads out at those locations and becomes less focused.) The accelerator structure itself was modeled in a rather crude fashion. Several models were produced corresponding to various sections of the accelerator. In each section the proton beam energy was assumed to be constant. Two types of models were developed: one for the Bridge-Coupled Drift Tube Linac (BCDTL) and one for the Coupled Cavity Linac (CCL). In each class,
Figure 1 - The computer model of the 100 MeV BCDTL section of the APT accelerator.

The models differ from each other mainly by the total length of the section; the overall geometry and the materials composition is the same. The BCDTL section accelerates protons from 20 to 100 MeV, operates at 700 MHz, and is comprised of 332 tanks; the CCL portion accelerates protons from 100 to 1000 GeV and is 1032 m long. Magnets were modeled as concentric cylinders (yoke and coil). Materials were homogenized (copper, steel, water) for simplicity. Beam pipes were modeled explicitly, and structural materials - particularly those expected to play a role in neutron moderation - were added where needed (accelerator tunnel and floor, water-cooled bridge-couplers, etc). Figure 1 shows the computer model used for the 100 MeV BCDTL.

These computer models were used with radiation transport and nuclide depletion computer codes to calculate: radiation fields, gamma dose rates, material activation and radionuclide inventories, air activation, and decay power. Interfaces were written to facilitate the transfer of data between codes, as well as to process data (e.g., produce source terms for MCNP) for various codes. A
A simplified diagram showing the interrelations between codes and the flow of data is shown in Fig. 2. The main computer codes are shown in rectangular boxes. They are fairly well-known and will not be described here; the interested reader will find more information in Prael 1989; Briesmeister 1988; Wilson 1993. A modified version of MCNP was used to produce maps of the spatial distribution of gamma dose rates near the accelerator, Waters 1994.

Figure 2 - Computer codes used in the calculation and the flow of data between these codes.
Gamma dose rates are calculated as follows. LAHET is used to calculate the interaction of the high-energy protons with the structural material in the accelerator. Spallation and fission products in each cell of the computer model are saved. Neutrons with energy below 20 MeV are saved and passed on to HMCNP to calculate neutron fluxes in the various cells of the model. These two sets of results are then used by CINDER’90 to calculate radionuclide inventories in each cell, as well as photon source terms and decay power. These photon source terms are then processed and used to define a photon source in MCNP to calculate gamma dose rates. We used the ANSI/ANS-6.1.1 flux-to-dose conversion factors to determine gamma dose rates. Intermediate results obtained during this calculation give access to radionuclide inventories, air activation, and decay power.

Results

Dose rates

Calculations were performed for various sections of the BCDTL and CCL. Results for the low- and high-energy ends of the BCDTL (20 and 100 MeV) and CCL (100 and 1000 MeV) are presented here as they illustrate most of the conclusions reached in our study.

Figure 3 shows the spatial distribution of the gamma dose rate near the 100 MeV section of the CCL 1 hour after the end of the irradiation period. The beam spill corresponds to 1 nA/m of proton current for a total irradiation time of 1 week. Several observations can be made immediately. The dose rate field is quite inhomogeneous: It is obvious that the magnets and cooling manifolds at the end of the accelerator section provide natural shielding against the gamma
radiation field. Clearly, the largest dose rate occurs at the location of the spill. Notice however that the second magnet

![Spatial distribution of the gamma dose for the 100 MeV CCL. Irradiation time is one year; cooling time is one hour. The beam loss is 1 nA.](image)

Figure 3 - Spatial distribution of the gamma dose for the 100 MeV CCL. Irradiation time is one year; cooling time is one hour. The beam loss is 1 nA.

(downstream from the irradiated magnet) shows a fair amount of activity. It is the superposition of these two fairly well localized sources of radioactivity (the two magnets) together with the shielding action of the magnets which produces the dose rate “flare” in the space between the two quadrupoles. Finally, examination of several maps for different irradiation and decay times shows that the spatial location of the “hottest” point (indicated by a cross in Fig.3) outside the magnet radius remains unchanged as the materials “cool down” following the end of irradiation. Fig. 4 shows a comparison of the decay of the peak dose rates plotted as a function of cooling
time for three different irradiation times. Two sets of curves are shown for the 100 Mev and 1 GeV sections of the CCL. The striking feature of this plot is that at 100 MeV, the peak dose rates as a function of time are independent of the irradiation time (1h, 1 wk, 1y), whereas the peak dose rate for the 1 GeV portion of the CCL exhibits a very strong dependence on irradiation time. This seems to indicate that at 100 MeV, there is little build-up of long-lived radionuclides and the dose rate is determined entirely by the nuclides formed during the last few minutes of the irradiation period. The situation is quite different at 1 GeV where longer-lived products are formed in quantities that increase with the irradiation time.

![Graph showing peak dose rate as a function of cooling time for three irradiation times (1 hour, 1 week, 1 year) for 100 MeV and 1 GeV sections of the CCL.](image)

Figure 4 - Peak dose rate as a function of cooling time for three irradiation times. Data is shown for the 100 MeV CCL and the 1 GeV CCL.

**Air activation**

The dominant radionuclides contributing to air activation are \(^{10}\text{C} (T_{1/2}=19.26\text{s}), \(^{11}\text{C} (T_{1/2}=1223\text{s}), \(^{13}\text{N} (T_{1/2}=597.9\text{s}), \(^{15}\text{O} (T_{1/2}=122.2\text{s}), \text{and } \(^{14}\text{Ar} (T_{1/2}=6577\text{s}). \) If we assume that neutron
activation of these products is negligible and that their production rate, \( Y_i \), is constant in time, the asymptotic value of the air activity is given by:

\[
A_\infty = \sum_i (Y_i I)(\lambda_i e)^{-1}
\]

where \( I \) is the proton beam current; \( e \) is the proton charge; and \( \lambda_i \) is the decay constant of the \( i \)-th nuclide. In view of the relatively short half-life of most of the air activation products, this value will be reached a few hours after the beam is turned on. Fig. 5 shows the evolution in time of the air activity for the 100 and 1000 MeV sections of the CCL. The volume of air in the 100 MeV section is 9.5 m\(^3\); it is 13.7 m\(^3\) in the 1 GeV section.

Figure 5 - Air activation for (a) the 100 MeV CCL and (b) the 1 GeV CCL.

Tritium production was also calculated. Because of the relatively long half-life of tritium compared to the time scales involved in accelerator operation, the decay of tritium is negligible and tritium builds up steadily during operation. We calculated tritium production rates of 0.0002 nCi/h/nA and 0.115 nCi/h/nA at the 100 MeV and 1 GeV sections of the accelerator, respectively.
Nuclide production

Most of the activity produced during irradiation is located in the beam pipe where the beam loss occurs. Spallation (as opposed to neutron activation) is the main culprit for the production of radioactive nuclides. A summary of the materials composition used in our calculations is given in Table 1. Figure 6 shows the main contributors to the radionuclide inventory in the 20 MeV and 100 MeV BCDTL and in the 100 MeV and 1 GeV CCL. The active species are different at different energies. At 20 MeV, $^{56}$Co is the main source of radioactivity. At 100 MeV, $^{52}$Mn, $^{54}$Mn, $^{55}$Fe, and $^{51}$Cr are the most active nuclides. At 1 GeV, these nuclides remain important contributors to the total activity, but activity is dominated by $^{62}$Cu and $^{64}$Cu for several hours after irradiation.

<table>
<thead>
<tr>
<th>Location</th>
<th>Material</th>
<th>Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam pipe and valve</td>
<td>SS304</td>
<td>71.92w% Fe, 19.0w% Cr, 9.0w% Ni, 0.08w% C</td>
</tr>
<tr>
<td>Endwall tank manifolds (BCDTL)</td>
<td>SS304 + Water</td>
<td>84.16w% SS304, 15.84v% H$_2$O</td>
</tr>
<tr>
<td>Tank Manifolds (BCDTL)</td>
<td>SS316L + Water</td>
<td>66.34w% Fe, 16.61w% Cr, 11.72w% Ni,</td>
</tr>
<tr>
<td>Beam pipe inside magnets and outer</td>
<td>1005 Steel</td>
<td>2.93w% Mo, 2.07w% O, 0.26w% H, 0.08w% C</td>
</tr>
<tr>
<td>magnet yokes</td>
<td></td>
<td>99.86w% Fe, 0.05w% C, 0.05w% S, 0.04w% P</td>
</tr>
<tr>
<td>Inner magnet yokes</td>
<td>1005 Steel + Void</td>
<td>50v% 1005 Steel, 50v% void</td>
</tr>
<tr>
<td>Magnet conductors</td>
<td>1005 Steel, Copper, Water, Void</td>
<td>26.83v% 1005 Steel, 40.9v% Cu, 2.27v% H$_2$O, 30v% void</td>
</tr>
<tr>
<td>Tank tuning bars and bridge walls</td>
<td>OFE Copper</td>
<td>99.97a% Cu, 0.02a% O, 0.01a% S</td>
</tr>
<tr>
<td>Tank outer walls</td>
<td>OFE Copper + Water</td>
<td>96.38v% OFE Cu, 3.62v% H$_2$O</td>
</tr>
<tr>
<td>Tank beam tube (20 MeV)</td>
<td>OFE Copper + Water</td>
<td>70.95v% OFE Cu, 29.02v% H$_2$O</td>
</tr>
<tr>
<td>Tank coupler manifold (20 MeV)</td>
<td>OFE Copper + Water</td>
<td>91.19v% OFE Cu, 8.81v% H$_2$O</td>
</tr>
<tr>
<td>Tank beam tube (100 MeV)</td>
<td>OFE Copper + Water</td>
<td>92.26v% OFE Cu, 7.74v% H$_2$O</td>
</tr>
<tr>
<td>Tank coupler manifold (100 MeV)</td>
<td>OFE Copper + Water</td>
<td>89.23v% OFE Cu, 10.77v% H$_2$O</td>
</tr>
<tr>
<td>Concrete</td>
<td>Generic concrete</td>
<td>34w% Si, 53w% O, 4w% Ca, 3w% Al, 2w% Fe, 2w% V, 1w% K, 1w% H</td>
</tr>
<tr>
<td>Air</td>
<td>Oxygen, Nitrogen, Argon</td>
<td>23.27w% O, 75.39w% N, 1.34w% Ar</td>
</tr>
</tbody>
</table>

Table 1 - Materials composition used in the computer simulations.

At 1 GeV, the presence of Cu isotopes among the spallation products reflects the fact that a 1 GeV proton is more penetrating, and spallation reactions are no longer largely confined to the stainless steel beam pipe but take place in the copper magnet coils as well.
Figure 6 - Total radionuclide inventory for the 20 MeV and 100 MeV BCDTL and for the 100 MeV and 1 GeV CCL. Irradiation time is 1 year. Beam loss is 1 nA/m.

References

APT $^3$He Target/Blanket Topical Report, LA-12670-MS; 1993.


