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Title:

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Author(s):

S. K. Lee, C. A. Beard, W. B. Wilson, L. L. Daemen,
D. J. Liska, L. S. Waters, M. L. Adams

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Structural Activation Calculations Due to Proton Beam Loss in the APT Accelerator Design

S.K. Lee, C.A. Beard, W.B. Wilson, L.L. Daemen, D.J. Liska and L.S. Waters

*Los Alamos National Laboratory
Los Alamos, New Mexico 87545*

M.L. Adams

Texas A&M University

Abstract. For the new, high-power accelerators currently being designed, the amount of activation of the accelerator structure has become an important issue. To quantify this activation, a methodology was utilized that coupled transport and depletion codes to obtain dose rate estimates at several locations near the accelerator. This research focused on the 20 and 100 MeV sections of the Bridge-Coupled Drift Tube Linear Accelerator. The peak dose rate was found to be approximately 6 mR/hr in the 100 MeV section near the quadrupoles at a 25-cm radius for an assumed beam loss of 1 nA/m. It was determined that the activation was dominated by the proton interactions and subsequent spallation product generation, as opposed to the presence of the generated neutrons. The worst contributors were the spallation products created by proton bombardment of iron, and the worst component was the beam pipe, which consists mostly of iron. No definitive conclusions about the feasibility of hands-on maintenance can be determined, as the design is still not finalized.

INTRODUCTION

In recent years, a significant interest has developed in the design and use of high-power linear accelerators (LINACs). Several different efforts have been initiated that would require the use of such power, including the Accelerator Production of Tritium (APT) project [1], the Accelerator Transmutation of Waste (ATW) program[2,3], and the Accelerator Based Conversion of plutonium (ABC) program[4], among others. Each of these projects requires the generation of an intense neutron source to drive the system, which translates into a need for a high-energy (800-1600 MeV), high-current (100-250 mA) accelerator operating with a high availability (>90%).

All of the accelerators for these programs are still in the design phase. The APT design, however, is the most complete to date. High-power accelerators make activation of the accelerator structure and its surrounding containment a serious concern. This activation is a direct result of beam loss occurring during normal operation: lost incident particles interact with the structure, producing a variety of radioactive species. These radioactive species could potentially create large dose rates in the immediate area. Accelerator operators would like to avoid this scenario, as it could preclude hands-on maintenance of the structure. The ability to perform hands-on maintenance is highly desirable, as it avoids the additional expense and complication of developing and utilizing remote maintenance technology. For currently operating accelerators, operators rely on manual measurements for information regarding the safety of the surrounding environment. But since these new high-power accelerators are still in the design stage, manual measurements cannot be made.

The activation, therefore, has not yet been quantified for accelerators of this high power. It should, however, be an important consideration before a design is finalized and constructed. Having the ability to predict the activation would save a significant amount of time and money. Knowing the level of activation associated with a certain amount of beam loss occurring during steady-state operation will allow for possible design changes or additional safeguards to enable hands-on maintenance of the machine. The general methodology used in determining the activation could also be used to test design variations in future revisions.

Since the activation cannot be directly measured, computational methods must be used. Methods are now available to perform these calculations and obtain reasonable results. The computational method used in this work couples transport and depletion codes to obtain estimates of dose rates near the accelerator.

This research focused on the Bridge Coupled Drift Tube LINAC (BCDTL) section of the APT accelerator design. As the APT design represents the most complete linear high-power accelerator design in the world at current standing, it was chosen as the baseline model for research described here. This design has the added advantage of being applicable to the several other accelerator projects in progress. The BCDTL accelerates charged particles from 20 to 100 MeV and is comprised of several sections. For this effort, two sections were modeled, one each at the beginning and end of the BCDTL.

Hence, the purpose of this work was to develop a model to predict the structural activation of the BCDTL portion of a high-power linear accelerator, and to use this model to estimate dose rates resulting from the activation. The activation was calculated for several operational histories. Three irradiation periods were considered, for one hour, one week, and one year. For each irradiation period, results were obtained for four separate decay times: ten seconds, one hour, one week and one year.

CALCULATIONAL METHODOLOGY

In order to determine the structural activation due to proton beam loss, a calculational method incorporating several codes was utilized. The structural activation was quantified in terms of dose rates. Figure 1 outlines the general procedure followed for this research.

Fig. 1. Flowchart for calculational methodology.

This methodology makes use of the LAHET Code System (LCS)[5] developed at Los Alamos National Laboratory. The main code in the LCS, LAHET[5], was used to transport the incident high-energy protons, compute the resulting nuclear interactions, and transport particles emitted with energies greater than 20 MeV. Though the theoretical basis for the code relies on particles of energy of at least 50 MeV, for the activation problem, the code will be used for particles in the range of 20 to 100 MeV. LAHET, therefore, was benchmarked in that energy range to determine its useful ranges and limitations. In the benchmarking, the code must accurately predict three quantities: the magnitude of the neutron yield generated through proton interactions, the angular and energy distributions of the resultant neutrons, and the residual nuclei produced by the proton interactions (spallation products). In each case, the calculated results were compared with experimental results found in literature, and one of two materials was used, copper or iron, as they make up the majority of the accelerator structure.

For protons incident on copper, the difference between the calculated and experimental yields did not exceed 30% in the proton energy range of 5–25 MeV, and the yields predicted by LAHET for 5–25 MeV protons on copper can be assumed to be within this margin. For protons incident on iron, the yields determined by LAHET are at worst accurate within a factor of three in the proton energy range of around 6 MeV. For most of the range (12–25 MeV), however, the calculated yields appear to be accurate within 50%. The next quantities studied were the energy and angular distributions of the neutrons produced by the activation of the accelerator components. LAHET accurately predicts the energy distribution of the resultant neutrons. The differences are larger at energies below about 8 MeV, but still within a factor of three. This overprediction at lower energies will lead to a conservative estimate: the lower energy neutrons cause greater amounts of activation. For the angular distribution, the LAHET results are more forward-peaked than are the experimental results. Hence, any axial spatial dependence observed in the results must be treated with caution. Finally, several spallation product reactions were studied, and LAHET predicted the spallation product yield fairly accurately. As expected, the results can be considered accurate for proton energies above 50 MeV. At less than 50 MeV, all of the yields can be considered accurate to within a factor of four.

In the LAHET calculations, generated neutrons of energies below 20 MeV were written to a source file. This file then served as the source for subsequent transport of the neutrons using HMCNP[5] (a version of the Monte Carlo transport code, MCNP[6]), which then determined the neutron flux in the accelerator structure.

In addition to the neutron flux, it is also important to know the quantities of spallation products generated and nuclides destroyed, as all three are key inputs used in the later depletion calculations. To obtain these results, HTAPE [5] (another code in the LCS) was utilized. HTAPE is designed to edit the history file created by LAHET. The history file is a record of the outcome of every event. It includes such information as the type of event, the location of the event, the energy of the incident particle, and a description of any particles introduced into the system. There are different edits available in HTAPE, including quantities of residual nuclides and gas produced.

Once the total spallation product yield and neutron flux distribution were known, CINDER'90[7] was used to determine gamma production rates in the structures of interest. CINDER'90 is a code designed to determine radionuclide inventories and their subsequent decay. Once CINDER'90 had determined gamma production rates, the resulting gammas were transported using MCNP, which determined the desired dose rates.

MODEL DEVELOPMENT

In order to be able to determine the structural activation associated with accelerator beam loss, a baseline accelerator design had to be chosen to create a new computer model. The APT design was selected, and this research was focused on the BCDTL section of the accelerator. This section operates at twice the original frequency (700 MHz) and current (200 mA) and is comprised of 61 separate tanks. As previously stated, in the BCDTL the beam particles are accelerated from 20 to 100 MeV over a length of almost 94 m. This section is an innovative design that was incorporated to accommodate high frequency by using a bridge coupler. Figure 2 provides a more detailed view of the BCDTL components and layout.

Fig. 2. BCDTL schematic diagram for 100 MeV section.

Using the detailed engineering drawings of the accelerator design from the APT project, simplified three-dimensional computer models were created. The 20 and 100 MeV sections were modeled to provide meaningful bounds for the activation levels in this portion of the accelerator. It was neither practical nor beneficial to completely model the structure to the level of detail contained in the engineering drawings. Instead, the modeling effort focused on the most important accelerator components. For each energy (20 and 100 MeV), the model included the quadrupoles, a tank assembly on either side for symmetry, and the entire associated bridge coupler, including the water channels used for its cooling. The 20 MeV section, however, has multiple bridges, so its model also contained a portion of the two additional bridges, located symmetrically about the quadrupoles. All known components containing water or other neutron-moderating materials were included in order to properly model increased activity due to neutron capture. Minor components, such as individual bolts, were omitted as was any support structure located too far away to be of interest. It was also not practical to include surrounding structures, such as possible coolant pipes in the accelerator tunnel, as their location in completely undetermined. Figures 3 and 4 show a side view of the 20 and 100 MeV section computer models, respectively.

One challenge in this effort was modeling the steady-state beam loss. During the CCL effort [1], experiments performed at Los Alamos Meson Physics Facility (LAMPF) showed that the quadrupole was the most significant place for activation [1]. Figure 5 shows the results of the measurements for the 200 MeV portion of the CCL, which was the lowest energy portion of the accelerator that was measured. The LAMPF design does

Fig. 3. Side view of 20 MeV BCDTL section computer model.

Fig. 4. Side view of 100 MeV BCDTL section computer model.

not incorporate a BCDTL, so measurements of this structure were not possible. However, since the quadrupole design for the BCDTL is similar to that in the LAMPI CCL, the activation behavior should also be similar. Furthermore, the shape of the beam dictates that beam loss is most likely to occur in the quadrupole because there the beam spreads out and becomes less focused. Based on these considerations, the beam loss was assumed to occur at the beginning of a quadrupole pair. In actuality, beam loss will occur all along the accelerator line. Assuming that the entire beam loss in the modeled sections occurs at a single point maximizes the peak dose produced and therefore yields a conservative result.

Fig. 6. Point detector locations for dose rate calculations

RESULTS

It is of interest to know the peak dose rate in each section of the accelerator, both the numerical value and its location. Calculations show that the 100 MeV results are higher than those for the 20 MeV section. It is therefore expected that the peak dose rate for the BCDTL section will be found in the 100 MeV results. Furthermore, the results show that the maximum dose occurs after the longest irradiation time (one year) and the shortest decay time (ten seconds) of the several times considered for this study. Figure 7 shows the axial distribution of this peak photon dose rate at each of the two radial locations. For this specific scenario, the peak photon dose rate occurs at the central detector at the 25-cm radius and its numerical value is approximately 6 mR/hr. The dose rate is approximately an order of magnitude smaller at the same axial location for the 100-cm radius.

Fig. 7. Axial photon dose rate distribution for 100 MeV BCDTL section at two radial locations (one year irradiation and ten seconds decay).

The dose rate as a function of time is also of interest, because an initially high dose rate might not be so troublesome if it decays away fairly quickly, avoiding the need for remote maintenance. Figure 8 shows a comparison of the decay rates for each energy (20 and 100 MeV) at the 25-cm radial location. For simplicity's sake, only one irradiation time was used, arbitrarily chosen as one year. Since dose (based on energy deposition) can be proportional to decay power (energy emitted), the extensive results produced by the CINDER'90 calculations can be analyzed to attempt to determine the dominant dose producing nuclide(s). CINDER'90 generates several tables that rank the isotopes according to the parameter of interest, one of which is decay power. Table 1 shows the decay power of these isotopes for the 100 MeV section after one year of irradiation for each of the four decay times.

Fig. 8. Peak photon dose rate at 25 cm as a function of decay time.

Table 1. Decay Power of Ten Worst Isotopes at Each Decay Time at 100 MeV.

Ten Seconds		One Hour		One Week		One Year	
Isotope	Decay Power (W)	Isotope	Decay Power (W)	Isotope	Decay Power (W)	Isotope	Decay Power (W)
Mn-52	1.4827e-5	Mn-52	1.4753e-5	Mn-52	6.2362e-6	Mn-54	2.0332e-6
Cu-62	1.1073e-5	Cu-61	7.7466e-6	Co-56	4.6230e-6	Co-56	1.8515e-7
Cu-61	9.4884e-6	Co-56	4.9209e-6	Mn-54	4.5022e-6	Co-60	8.1163e-8
Fe-53	5.6173e-6	Mn-54	4.5723e-6	V-48	9.5504e-7	Zn-65	2.2547e-8
Co-56	4.9227e-6	Cu-64	1.4946e-6	Co-58	4.2843e-7	Fe-55	1.6838e-8
Mn-54	4.5727e-6	V-48	1.2888e-6	Cr-51	1.1928e-7	Co-58	1.2947e-8
Cu-64	1.5878e-6	Mn-56	1.1291e-6	Co-60	9.2324e-8	Co-57	1.1832e-8
Cu-60	1.5851e-6	Co-55	6.7109e-7	Zn-65	6.2376e-8	Sc-46	1.6815e-9
Mn-56	1.4762e-6	Cu-62	6.5834e-7	Sc-46	3.2479e-8	V-49	1.3269e-9
V-48	1.2911e-6	Co-58	4.5843e-7	Co-57	2.9487e-8	Ni-63	1.3219e-10

For this case, Mn-52 is the dominant isotope for up to a week of decay. With a half-life of 5.591 days [10], there will be a negligible amount after only about two weeks. Cu-61 also makes a significant contribution in the early decay times, but with a half-life of only 3.35 hours [10], it does not remain for long. After longer periods of decay, on the order of one year, Mn-54 becomes the dominant isotope, with a half-life of 312.2 days [10]. Co-56 also makes a contribution, but its half-life is only 77.3 days [10]. For the 20 MeV case, Co-56 is the dominant isotope throughout the decay period.

With the exception of Cu-61 and Cu-64, these isotopes are all spallation products created by proton bombardment of the iron present in the accelerator structure. The Cu-61 isotope is also a spallation product, created by proton bombardment of copper, whereas the Cu-64 isotope could either be a spallation product of Cu-65 or created by neutron capture in Cu-63. These results, therefore, provide indication that the activation of the structure is mainly the result of the proton loss and the subsequent creation of spallation products, as opposed to the presence of the generated neutrons.

Finally, in addition to the dominant isotopes, it is important to identify the specific accelerator components that contribute significantly to the activation. The worst-case scenario, after one year of irradiation and ten seconds of decay for each section, was studied further. For the central detector at the 25-cm radius of the 100 MeV section, MCNP output showed that the beam pipes in the quadrupole section were the worst of the components, contributing almost 99% of the total dose rate (5.7 mR/hr out of 5.76 mR/hr total). The remaining components' contributions were all at least two orders of magnitude lower.

The worst-case scenario for the 20 MeV section was also analyzed. Again, the worst component was the beam pipes in the quadrupole region. At this energy the beam pipes completely dominate the total dose rate, and the remaining components all have dose rates several orders of magnitude smaller.

CONCLUSIONS

The peak dose rate of 6 mR/hr occurs at the detector closest to the quadrupoles at a radius of 25 cm, also the closest to the location of the modeled beam loss. The component determined to have the highest amount of activation, the beam pipe in the quadrupole section, was also the closest component to the beam loss. The location of the beam loss plays a major role in the distribution of the dose. Hence, the results obtained here cannot be considered definitive. These results, however, are useful in that most of the beam loss is expected to occur in the quadrupoles, due to the shape of the beam at that point. Also, because the major contributor is the beam pipe, which is present throughout the modeled portion of the accelerator, the dose characteristics should be similar regardless of the beam loss location.

Another important conclusion drawn from these results is that the activation in this energy range is dominated by the proton interactions and the subsequent spallation product generation, particularly from spallation of iron. Iron is the main element in the composition of the beam pipe, which has been shown to be the most activated component in the accelerator structure.

When using these results, caution must be taken to consider their degree of accuracy. Most of the spallation products that were found to dominate the activation were analyzed in the benchmarking effort. It was determined that LAHET accurately predicts the presence of the spallation products to within a factor of four. This can then be assumed to be true for the overall dose rates.

Therefore, multiplying the obtained result by a factor of four yields a peak photon dose rate of approximately 24 mR/hr. As the APT design has not been finalized yet, however, the amount of maintenance required is still unknown. Therefore, no definitive conclusions can be drawn about the feasibility of performing hands-on maintenance for this particular design. This dose rate does appear reasonable, however, when compared

with the LAMPF measurements shown in Figure 5, which exhibit peaks as high as 100 mR/hr.

There are several additional areas in the field of accelerator activation that need to be studied before a complete characterization is achieved. Several design variation studies would be of interest. These and other comparisons (such as the use of different materials) can all be easily performed with this methodology. A similar study of the higher energy portion of the APT design (100-1000 MeV) is currently underway and should be completed soon.

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