RESIDUAL RADIATION STUDIES

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Summary

Studies of residual radiation levels to be encountered in high beam intensity accelerators are reported. Calculated residual radiation decay curves are compared with experimental data. Previously reported work with 600-MeV protons is extended to a wider range of bombardment times. The experimental and calculated decay curves for C, Al, Fe, and Cu are compared by normalizing the intensities of the ^{22}Na activity in the aluminum. The experimental and calculated decay curves agree within a factor of 2 or 3 over a range of cooling times for bombardment times that range from 3 hrs to 2 years. Data obtained from one group of samples exposed to 19 - 26 GeV protons for 5 months are also compared with the calculated decay curves.

Introduction

Accelerator technology is sufficiently developed that serious consideration is being given to construction of machines capable of producing 0.5 to 1 GeV proton beams with intensities ranging from hundreds of micro-amperes to tens of milliamperes. An essential part of the planning of an accelerator of such high intensity is a quantative estimate of the residual radiation levels that will result from operation of the machine. Adequate shielding and remote handling facilities must be provided for safe operation and maintenance of the accelerator and associated experimental facilities.

Estimates of residual radiation levels for a particular accelerator will be based on detailed calculations for that installation. The work reported in this paper is an attempt to determine the reliability of such calculations. Our approach to the problem is to compare calculated decay curves with experimental data for a wide range of bombardment time. The calculations were done at ORNL and the experimental data were obtained at CERN. In an earlier report[1] calculated decay curves were compared with experimental data obtained from 3-hr and 3-mo bombardments. In the work reported here the calculations are compared with data obtained over a wider range of bombardment time.

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The method of calculation[2] takes into account each of the spallation products (those with half lives less than 10-min are neglected) and sums the contributions to obtain the gross residual radiation level as a function of bombardment time and cooling time. Both gamma flux and radiation dose rate were calculated. If cross section data were available for all spallation products formed by the interaction of high energy particles with the structural materials in an accelerator installation the residual radiation levels could be computed for any assumed bombardment. Since such data are not available for all materials, we have made calculations for a few materials which are extensively used in accelerator construction, and for which spallation cross section data[3-7] are available over the range of 0.5 - 1 GeV.

The experimental data were obtained from samples of materials exposed to either the direct or the scattered beam of 600-MeV protons in the CERN Synchrocyclotron. The residual radiation measurements were made by counting the emitted gammas with a 3 x 3 in. NaI(Tl) scintillation counter. Integral counting rates were measured as a function of cooling time.

Exact agreement between calculated and experimental results is not expected. The total detection efficiency of NaI(Tl) crystals varies with gamma energy[8]; it decreases by a factor of ~ 2 between 0.1 and 2 MeV. Gamma dose rates are approximately linearly dependent (in the calculations a linear dependence was assumed) over the range of gamma energies involved. For the calculations of gamma flux there is no energy dependence.

Calculations and Data at 600 MeV

Experimental and calculated residual radiation decay curves for a 3-hr bombardment with 600-MeV protons can be compared in Figure 1. The experimental data were obtained from thin samples exposed to a proton flux of $\sim 10^9$ p/cm^2 - sec. An averaged counting efficiency, based on previous measurements, was used to convert the experimental counting rates to dose rates. Good agreement is obtained for C and Al. For Fe and Cu the general shapes of the calculated and experimental decay curves agree and the magnitudes agree within a factor of two or three. The discrepancies are not surprising when the experimental errors in a bombardment of short duration by a beam of low intensity are considered.

The calculated dose rate and the experimental counting rates obtained for a 3-mo exposure to scattered 600-MeV protons can be compared in Fig. 2. The two sets of curves are normalized at the flat part of the Al decay curve where $^{22}Na(T_{1/2} = 2.58y)$ is the dominant activity. The calculated and experimental decay curves agree within a factor of ~ 2 throughout the range of the data. Figures 1 and 2 were presented in an earlier report[1] but are included here for comparison with data from a larger range of exposures.

The calculated and experimental decay curves for a 96-hr 600-MeV proton bombardment are shown in Fig. 3. Again, the curves are normalized for the ^{22}Na activity in Al. The ordinate scale is in gamma flux for the calculated curves and in counting rate of the detector for the experimental curves. Except for the portions of the curves for Cu for cooling time <100 hrs the experimental and calculated curves agree within a factor of ~ 2 throughout the range of cooling time.

Also, thin samples were exposed inside the CERN Synchrocyclotron for a period of two years and the gross activity decay curves measured. The measurements cover the range of cooling time from 660 to 7600 hours. The experimental and calculated decay curves are shown in Fig. 4. The ordinate scales are the same as in Fig. 3 and the sets of curves are normalized on the same basis. The experimental and calculated decay curves agree within a factor of <2 throughout the range of the experimental data.

Residual Radiation Dose Rates

Figures 1 to 4 permit comparison of experimental and calculated gross activity decay curves for a wide range of bombardment times. Although the beam intensity for the experimental data was not measured, except for the low intensity 3-hr bombardment (Fig. 1), the agreement obtained for the 96-hr, 3-mo, and 2-yr irradiations demonstrates that the spallation cross section data used in the calculation are reasonably accurate and complete, and that calculations can be used with confidence to predict residual radiation levels in accelerator installations.

The experimental data obtained at the CERN Synchrocyclotron include a number of samples that are not shown in Fig. 1-4. For most of these the available spallation cross section data are not as complete as for C, Al, Fe, and Cu. The agreement between calculated and experimental results in the above figures suggests that calculated dose rate curves for Al might be used to determine dose rate scales for the larger number of curves included in the experimental data.

The experimental gross activity decay curves for several samples that were bombarded for 96 hrs with a 600-MeV proton beam are shown in Fig. 5. The ordinate scales were determined from calculations for Al; the scale is the dose rate at 1 meter for a collimated beam of 1 μA. It is also the dose rate outside a large slab uniformly irradiated with a flux of 10^8 particles/cm^2-sec. The calculation is for a collimated beam. The conversion of the results of the calculation for distributed fluxes is discussed in Ref. 1.

The experimental gross activity decay curves obtained for the 2-yr bombardment are shown in Fig. 6. The ordinate scale was determined by the calculation for Al. We believe that these curves are reliable to within a factor of ~ 3, which is probably as accurate as the intensities of bombarding particles can be predicted.

The ordinate scales in Fig. 5 and 6 are for targets of specific thicknesses, as indicated. Residual radiation levels are obviously dependent on target thickness. In Fig. 7 calculated residual radiation decay curves are shown for Al samples of various thicknesses for bombardment times of 96 hrs and of 2 years. These curves can be used with those in Fig. 5 and 6 to extrapolate residual radiation dose rates for targets of specific thicknesses.

Accelerator designers and operators are interested not only in the decay of residual radiation but also the radiation level at some specific time after machine shutdown. In Fig. 8 are shown calculated residual radiation dose rates as functions of bombardment time. The curves shown are for 20 cm thick samples bombarded with 600-MeV protons. There are two curves for each sample. The upper one is for 1 day of cooling time and the lower is for 1 month.

High Energy Data and Calculations

While most of our experimental data were obtained with 600-MeV protons, one group of thin samples was exposed at the CERN Proton Synchrotron. They were placed 3.5 meters from a target and 10° from the forward beam direction. The samples were exposed to 19-26 GeV protons and fast neutrons. After 5 months they were removed and the residual radiation decay curves were measured.

Spallation cross section data for 28-GeV protons on C, Al, and Cu were tabulated from published measurements[5,9] and used to calculate residual radiation decay curves for a 5-mo exposure. The calculated and experimental decay curves are shown in Fig. 9. The ordinates for the experimental curves are counting rates and for the calculated curves they are gamma flux. The curves were normalized for the ^{22}Na activity in Al. Except for the short-life activity in Al the agreement is reasonably good. The data suggest that the ^{24}Na cross section for 19-26 GeV protons on Al is somewhat larger than the value used in the calculations. The agreement obtained between the calculated and experimental decay curves is encouraging but additional work is needed before conclusions about residual radiation calculations for this high energy region will be as valid as for the 600-MeV energy.

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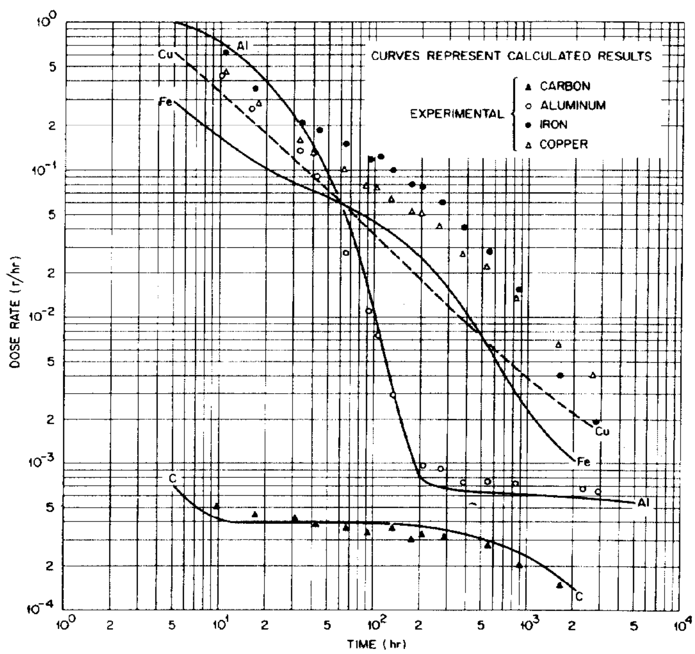

Fig. 1—Calculated and experimental residual radiation decay curves for thin samples irradiated for 3 hrs with 600-MeV protons.

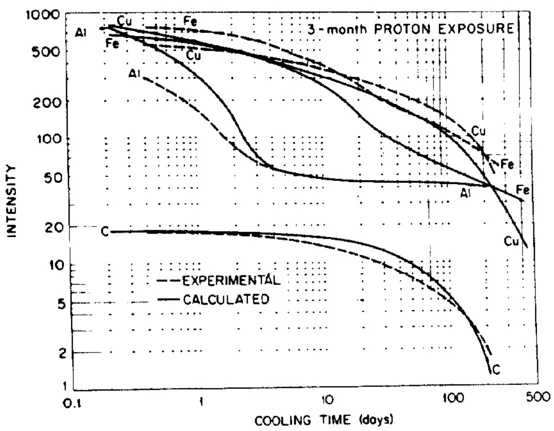

Fig. 2—Calculated and experimental residual radiation decay curves for samples irradiated with 600-MeV protons for 3 months. The calculated curves are dose rates and the experimental curves are counting rates of the detector per gram of sample material. The experimental and calculated curves are normalized for the flat part of the Al curve.

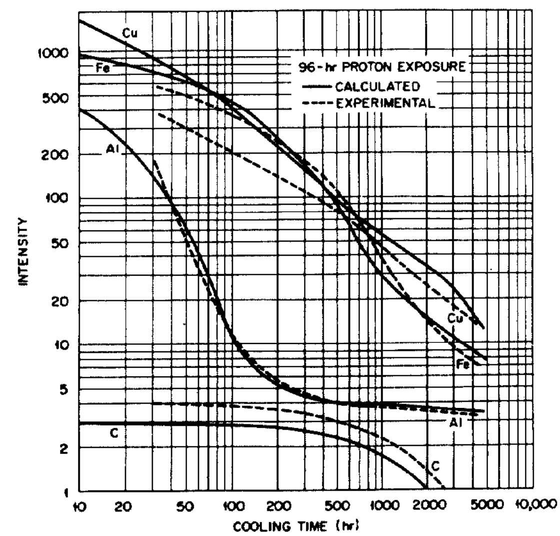

Fig. 3—Calculated and experimental residual radiation decay curves for samples irradiated with 600-MeV protons for 96 hours. The calculated curves are gamma fluxes 1 meter from the sample and the experimental curves are counting rates of the detector per gram of sample material. The experimental and calculated curves are normalized for the flat part of the Al curve.

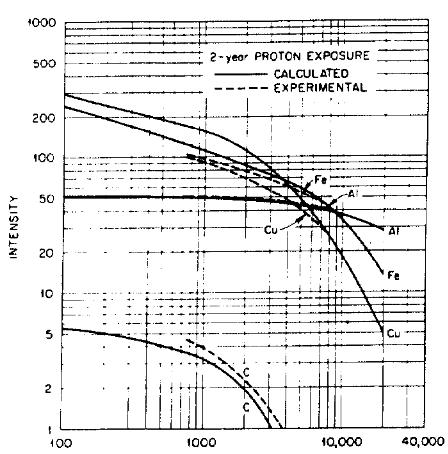

Fig. 4—Calculated and experimental residual radiation decay curves for samples irradiated with 600-MeV protons for 2 years. (Details as per Fig. 3.)

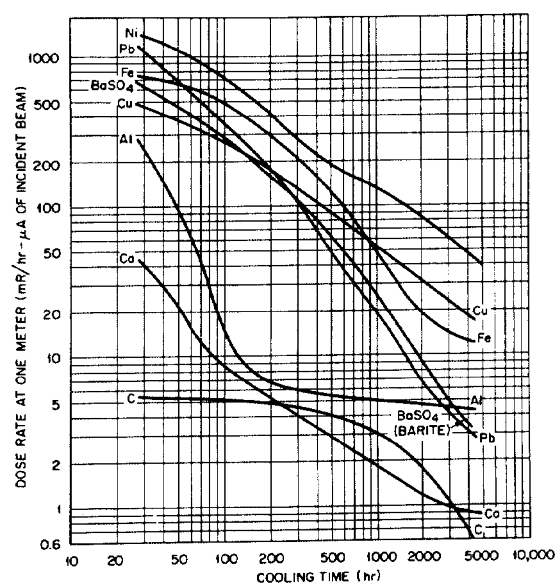

Fig. 5—Residual radiation levels for 1-cm thick samples irradiated for 96 hours with 600-MeV protons. The ordinate scale is also applicable for dose rates outside large 1-cm thick slabs irradiated with a uniform flux of 10^8 protons/cm^2-sec for 96 hours.

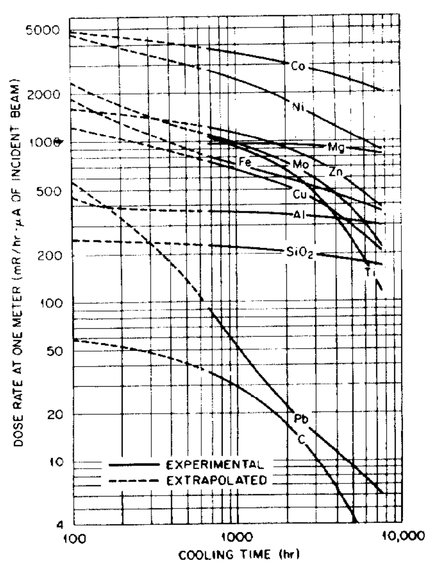

Fig. 6—Residual radiation levels for 20-cm thick samples irradiated for 2 years with 600-MeV protons. The ordinate scale is also applicable for dose rates outside large 20-cm thick slabs irradiated with a uniform flux of 10^8 protons/cm^2-sec for 2 years.

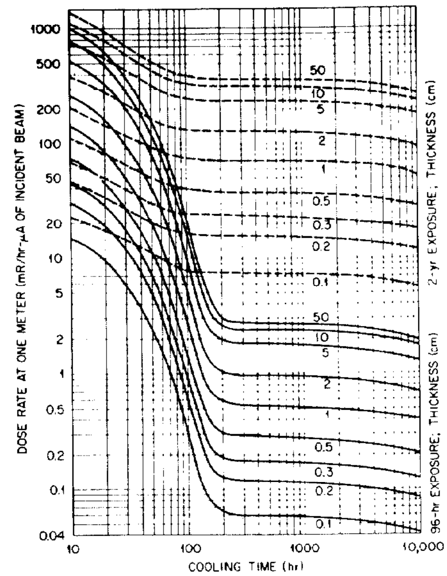

Fig. 7—Dose rate vs cooling time for aluminum samples of various thicknesses irradiated with 600-MeV protons for periods of 96 hours and 2 years.

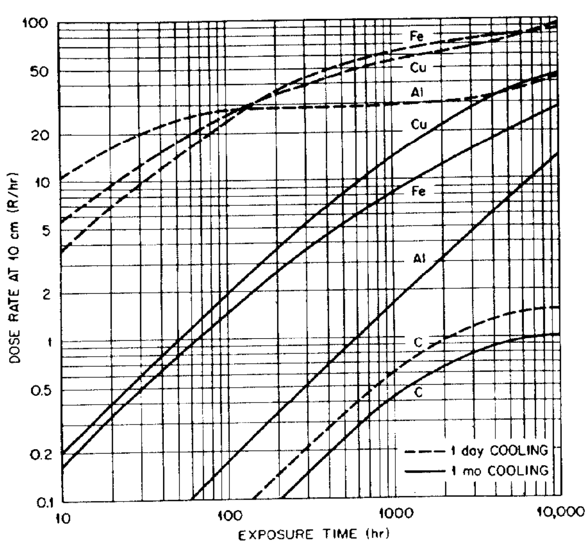

Fig. 8—Residual radiation levels for 20-cm thick targets irradiated with 1-μA beams of 600-MeV protons.

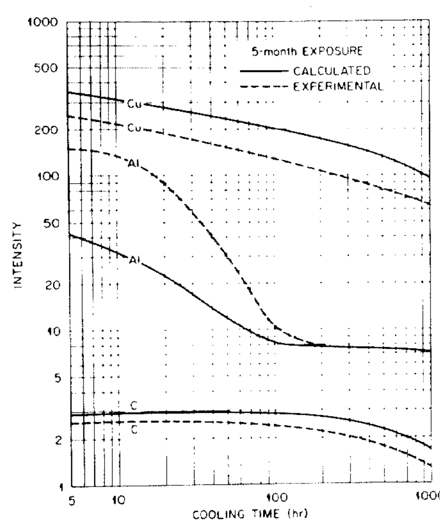

Fig. 9—Calculated and experimental residual radiation decay curves for samples exposed in the CERN proton Synchrotron for 5 months. (Details as per Fig. 3 and 4.)