Shielding and Activation Study for Proton Medical Accelerators

H. B. Knowles*, J. L. Orthel, and B. W. Hill
G. H. Gillespie, Associates, Inc.**, P. O. Box 2961, Del Mar, CA 92014

Abstract

A preliminary study has reviewed much of the pertinent data on the required radiation shielding and radioactivation processes associated with the operation of a 70-250 MeV proton accelerator to be used for cancer therapy. As a result, a "tool kit" has been prepared for designing appropriate shielding and evaluating radiation hazards from activation around such accelerators. It includes general principles, a simple desktop computer program for preliminary facility design and the use of the LCS Monte Carlo program. The anticipated integration of the ORIHET program with LCS will provide detailed activation information.

I. INTRODUCTION

One new accelerator for proton radiation therapy is already operational at the Loma Linda University Medical Center, and two more are in the late planning stage. These are expected to have similar proton beams: average currents up to 20 nA and energies from 70 to 250 MeV. The LLUMC facility can be used as a paradigm for studying radiation protection, even though other facilities may include different types of accelerators and facility designs.

The technical concerns include: a) Projected changes in limits on radiation exposure for both occupational personnel and the general public, together with the possible impact of proposed new *quality factors* for neutrons. b) Identification of source terms for fast neutrons (and gamma rays) with respect to location, intensity, directionality, and energy spectrum. Accelerator physics input and experience are needed. c) Verification of the attenuation properties of shielding materials for the radiation of concern, principally neutrons, by experimental and theoretical methods. d.) Determination of the reduction of dose equivalent by ducts and mazes needed in a radiation therapy facility. e) Evaluation of the radioactivation hazard, especially that which occurs in the treatment rooms and can affect clinical personnel.

II. RADIATION EXPOSURE

The existing annual limits on *dose equivalent* in California (this study was commissioned for a California site) are:

5.0 rem (50 mSv) for occupational radiation workers
0.5 rem (5 mSv) for the general public

The limit for the general public will soon be reduced to 0.1 rem, without changing the radiation worker limit. However, it is believed that the latter will also soon be reduced to 2 rem, under the urging of the ICRP and NCRP. The ICRP has also issued a recommendation for a change (generally, an increase) in the neutron *quality factor*[1]. Because so many conversion data were available using only the present values, these have been retained in this study, but an estimate of the effect of instituting the new values has been made.

*H. B. Knowles, Physics Consulting, consultant to G. H. Gillespie, Associates, Inc.

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III. NEUTRON SOURCES

The highest energy protons will cause the greatest hazard. Two recent experimental studies near 250 MeV have been used to test computer simulations. Siebers' work was done at 230 MeV and measured both energy deposition (*absorbed dose*) and quality factor, by simultaneously performing microdosimetry[2]. Meier obtained the raw neutron spectrum from targets struck by both 113 MeV and 256 MeV protons[3,4]. These data were compared to predictions made by LCS[5]. A best fit was found (for all data) by using the combination of cascade mechanism, multistage preequilibrium model and nuclear evaporation called "LAHETpqr2". This appears to predict neutron fluxes accurately (within a factor of two) and may provide still better values of dose equivalent, when used together with fluence-to-dose-equivalent tables of Belogorlov[6]. Pearlstein has devised an analytic expression for the quantity $d^2\sigma/dEd\Omega$ that can be used to estimate a neutron yield and spectrum in an arbitrary direction[7]. The spectra so obtained are "harder" than those from a thick target, and thus lead to overestimating shielding requirements.

IV. ATTENUATION IN SHIELDING

Siebers' experiment included neutron attenuation in concrete, and used the LCS code (with the prq2 switch) to calculate attenuation, so that it could be compared to measured values. A "zero-depth source term", called $H_O R^2$, can also be calculated and compared to experiment by the equation:

$$HR^2 = H_o R^2 \exp -(\frac{s}{\lambda}) \quad (1)$$

in which λ is the attenuation length in the shield material (here, concrete), s, the thickness of the shield, H or H_O the dose equivalent per stopping proton and R the distance from the neutron source to the observation. We have redone the calculations of Siebers, and find no results that differ significantly from his. These are presented in Table 1, where they are compared to Siebers' experimental values in comparable directions. The attenuation of dose equivalent, H, is emphasized because this is the single parameter of concern.

Both the zero depth source term and the attenuation length increase with angle to the beam, θ. The calculations slightly overestimate both parameters and therefore give conservative values. We have also compared the Siebers values (at the $\theta = 0°$ and $90°$ directions) to those calculated from the work of Braid, *et al.*[8]. They are in good agreement in the "forward" direction, but, in the "lateral" direction, both the zero-depth source term and the attenuation length are significantly larger than the calculated values obtained by both Siebers and ourselves. The comparison of λ requires that the distance be given in areal density (kg/m^2) because of the unusually low density of the concrete used in the Siebers experiment (1.88 g/cm^3). The calculated dose-equivalent attenuation lengths in Table 1, which we recommend, are in very reasonable agreement with the well-established neutron attenuation lengths in concrete[9]. It is well established that other shielding materials (earth, iron, high-density concrete) can replace concrete if substituted on the basis of areal density, except that a sufficient thickness of hydrogenous

Table 1. Zero-Depth Source Intensities and Attenuation Lengths from Siebers 230 MeV Data

Experimental			LCS Calculated		
θ	H_oR^2 (Sv-m^2)	λ_{eff} (kg/m^2)	θ	H_oR^2 (Sv-m^2)	λ_{eff} (kg/m^2)
0°	$(8.6 \pm 0.8)\times10^{-15}$	910 ± 30	0-10°	$(6.6 \pm 0.4) \times 10^{-15}$	991 ± 28
22°	$(4.6 \pm 0.5)\times10^{-15}$	876 ± 34	10-30°	$(5.0 \pm 0.2) \times 10^{-15}$	1040 ± 21
45°	$(2.1 \pm 0.2)\times10^{-15}$	746 ± 24	40-50°	$(2.3 \pm 0.1) \times 10^{-15}$	894 ± 21
90°	$(6.9 \pm 0.8)\times10^{-16}$	519 ± 21	85-95°	$(1.0 \pm 0.2) \times 10^{-15}$	534 ±26

material must be on the personnel side of the shield.

V. ATTENUATION IN MAZES AND DUCTS

While plug doors are commonly used in physics-oriented accelerator facilities, they are undesirable in a therapy facility because of possible adverse reactions of patients. It is also noted that the treatment room at the end of a maze (which must be large enough to pass a hospital gurney) is a copious source of radiation: the patient is in reality a beam dump and other losses occur in the beam transport system. Numerous investigations of radiation transport through mazes have done using various Monte Carlo codes. Experiments have also been performed, often using simple fission neutron sources [10,11,12,13]. This is a fairly satisfactory substitute for the neutron fluxes induced by a high-energy proton beam, because most of the dose equivalent transmitted through maze is carried by low-energy neutrons. Thermal neutrons are generated by collisions with the walls and tend to build up as the maze is traversed. All investigators found this effect. In addition, Vogt examined the effect of varying the water content of the concrete walls, and found it to be significant[11].

We explored dose-equivalent attenuation in a three-legged maze (Fig. 1.) using LCS. The neutron "source", a beam stop intercepting 250 MeV protons, was centered on the

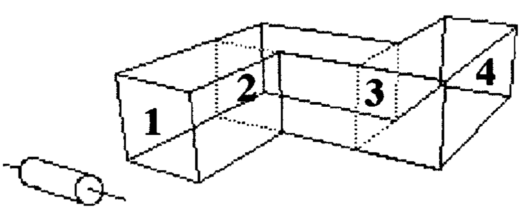

Fig. 1. Maze problem geometry. Protons impinge on a cylindrical target in the foreground, producing radiation. The dose equivalent is tabulated for each of the four windows.

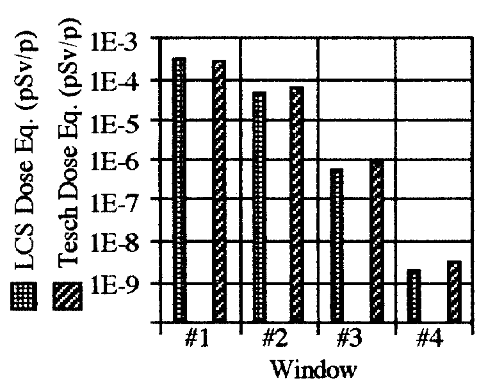

Fig. 2. Predictions for neutron dose equivalent in sample maze problem.

first leg, and also offset from the centerline. At each of four successive Windows, the neutron fluence per stopped proton and the dose equivalent per proton was determined. The analytic expressions for attenuation developed by Tesch were also used[13]. These are as follows: in the first, centered leg, the attenuation is simply given by an inverse-square dependence along the maze centerline, with a factor of 2 for dose equivalent buildup in the walls:

$$H(r_1) = \frac{2H_oR^2}{r_1^2} \tag{2}$$

while in the second leg, there is an attenuation factor which must be used to multiply the dose equivalent value obtained from Eq. (2) at the end of the first leg. If r_2 is the centerline distance along the second leg, this attenuation factor is $f(r_2)$:

$$f(r_2) = \frac{\exp-(r_2/0.45) + B\exp-(r_2/2.35)}{1+B} \tag{3}$$

where the quantity B is related to the cross-sectional area of the maze A by

$$B = 0.022A^{1.3} \tag{4}$$

Subsequent legs are measured in distances r_3, r_4, etc., along the maze centerline and the attenuation has the same form as given in Eq. (3) for the second leg. Tesch also determined, empirically, that the second-leg attenuation must be multiplied by a factor of two for a high-energy (accelerator beam stop) source. These recipes were compared to the LCS calculations for the maze geometry of Fig. 1, and the comparisions appear in Fig. 2. There is agreement within a factor of 2. The more realistic case of the off-centerline source was also examined and will be discussed below.

Ducts, defined here as shield penetrations with an average diameter of 30 cm or less, are needed for power, cooling, and other utilities. The principal vector of dose equivalent is, again, low-energy neutrons, and their transport behavior in ducts has been understood for at least 40 years by the nuclear power industry[14].

VI. ACTIVATION

Radionuclides are principally produced by high energy protons and by low-energy neutrons, especially those that thermalize and capture. The model of the cascade-evaporation process in LAHET predicts some residual radionuclides, although its accuracy has been questioned. A plot of the radionuclide distribution produced per proton by 230 MeV protons on concrete appears in Fig. 3. An improved prediction would result when LCS is linked with ORIHET[15]. The equivalent CINDER90 code has already been integrated with LCS but has not been released.

There is special concern about the clinical personnel who must tend the patients after treatment. Typically, a brief 1-2 min. irradiation is followed by a 15-20 min. interpatient time. It can be shown that the clinical staff are likely to receive more dose equivalent from radionuclides with half lives of the order of the interpatient time than from shorter- or longer-lived activities, provided that the latter have not been allowed to build up over a long time. Components with such long decay times would of course be routinely replaced, but nature has been unkind in the matter of radionuclides created in the body itself: there is a high production of the radionuclide

^{11}C, which decays by positron emission with a 20.4 minute half-life.

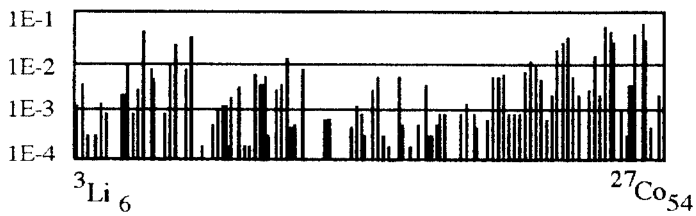

Fig. 3. Number of isotopes produced in concrete per incident proton (vertical axis) versus isotope, from the LAHET code. The incident proton energy is 230 MeV, and all cascade particles down to 20 MeV contribute to production.

Sullivan[16] observes that the statistical distribution of half-lives from proton bombardment of iron or copper varies as 1/(half-life). An average of the number and energies of the gamma-rays produced is then used to estimate the effects. When the total dose equivalent to clinical personnel during one interpatient period was determined, assuming an iron or copper component of the beam "nozzle" and a loss of 10 nA of protons in 20g/cm^2 of material, it was found that, at a distance of 1 meter, the dose equivalent would be 0.57 mrem. A more detailed, conventional calculation for equivalent loss in aluminum gave a result of about one-quarter of this value of dose equivalent, supporting the well-known fact that aluminum is a better material than iron or copper in terms of activation.

VII. THE PTFshield PROGRAM

PTFshield is a simple program that operates on a desktop computer. It is intended for first-order scoping of shielding and maze design, to be supplemented if necessary by LCS computations. It includes: 1) the Pearlstein model for neutron source terms as functions of beam energy and angle, or, the thick-target Meier data (interpolated or scaled); 2) the empirical attenuations found by Braid, *et al,*; 3) the neutron-fluence-to-dose tables of Belogorlov, *et al*; 4) the Tesch maze attenuation relations, Eqs. (2) and (3), are used to estimate both centered and non-centered sources.

VIII. SUMMARY AND CONCLUSIONS

Much that is published about shielding and activation in the energy domain below 250 MeV is self-consistent, and a great deal of this information can be represented by a limited number of analytic expressions, or at least, simple calculations. However, the LCS code system is a very powerful and reliable computational tool for more detailed exploration of the problems associated with shielding of such an accelerator. When ORIHET (or CINDER) are included, the expanded code system will also determine activation from high energy particles.

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