RESIDUAL RADIATION LEVELS IN THE ORNL Mc^2 CYCLOTRON

C.B. Fulmer, K.S. Toth and J.B. Ball
Oak Ridge National Laboratory(*)
(Presented by A. Zucker)

An essential part of the ORNL study of an isochronous cyclotron designed to accelerate 100 μA of protons to an energy of 810 MeV is a realistic appraisal of residual radiation levels that will result from operation of the machine. This study includes calculations made at Oak Ridge, the results of which are compared with experimental activation data obtained from colleagues at other laboratories. The richest source of experimental data has been the CERN Synchro-Cyclotron. This paper summarizes some of the results of the residual-radiation study for the Mc^2 Cyclotron.

A general formula was derived for calculating the γ ray dose rates outside slabs of materials irradiated with fast particles. It is assumed that a collimated beam of particles impinges normal to the slab. The incident beam intensity I_0 is attenuated in the material by the macroscopic geometry cross-section Σ_t. Thus, at a depth x in the slab,

$$I(x) = I_0 \exp(-\Sigma_t x).$$

The production rate of spallation product j at position x is

$$R_j(x) = I(x)\Sigma_j,$$

where Σ_j is the macroscopic cross-section for the reaction.
After a bombardment time t_b and a cooling time t_c, the concentration of product j, as a function of x, is

$$N_j(x) = \frac{1}{\lambda_j}\left\{R_j(x) \quad [1 - \exp(-\lambda_j t_b)] \quad \exp(-\lambda_j t_c)\right\},$$

where λ_j is the radioactive decay constant for product j. The activity A_j of j, as a function of x, is

$$A_j(x) = N_j(x)\lambda_j .$$

At a point P, a distance d outside the slab, the flux $\Phi_j(x)$ of photons resulting from $A_j(x)$ is

$$\Phi_j(x) = \left[A_j(x) \exp(-\mu_j x)\right] / 4\pi (x + d)^2 ,$$

(*) Operated for the USAEC by Union Carbide Corporation.

where μ_j is the absorption coefficient for the radiation. The radiation dose rate $D_j(x)$ due to $A_j(x)$ is[1]

$$D_j(x) = \text{const}\ \Phi_j(x)E_j\ ,$$

where E_j is the energy of the photons. The total dose rate at the point P due to all activity from product j distributed along the incident beam path is obtained by integration :

$$D_j = \text{const}\ I_0\ \Sigma_j\ E_j(1 - e^{-\lambda_j t_b})\ e^{-\lambda_j t_c} \int_0^{x_{max}} \frac{e^{-(\Sigma_t + \mu_j)\,x}}{(x + d)^2}\, dx,$$

where x_{max} is the smaller quantity of the slab thickness and the range of the incident protons in the slab material. In actual calculations, the integration does not need to extend to the range of several hundred MeV protons because of the exponential attenuation of the γ radiation in the material. The analytical evaluation of the integral yields a slowly converging infinite series, therefore numerical integration is used to evaluate D_j. For the total dose rate at the given point P the D_j's for all the spallation products must be evaluated. Since the amount of computation is enormous, the calculation was programmed for the IBM-7090 computer.

Cross-sections for the production of radioactive products in the material were taken from published studies of spallation reactions induced by protons of this energy range. The IBM-7090 computation determines the dose rate, for specific bombardment and cooling times, at the slab surface, at 10 cm, and at 1 m. Buildup of intensity due to the production of secondary fast particles is not included in the computer calculation. An allowance for this must be made in the case of oblique incidence of the primary beam.

Barbier[2] placed samples of various materials inside the CERN Synchro-Cyclotron for a period of three months. He then removed the samples and measured decay curves for the γ radiation emitted. As a test, a calculation was made for a 3-month bombardment by a 1 μA, 600 MeV proton beam on 1 mm thick C, Al, Fe, and Cu samples. For comparison the experimental and calculated decay curves, shown in Fig. 1, were normalized where the aluminium curves flattened out (this is where Na^{22} is the dominant activity in aluminium). It should be pointed out that the experimental data

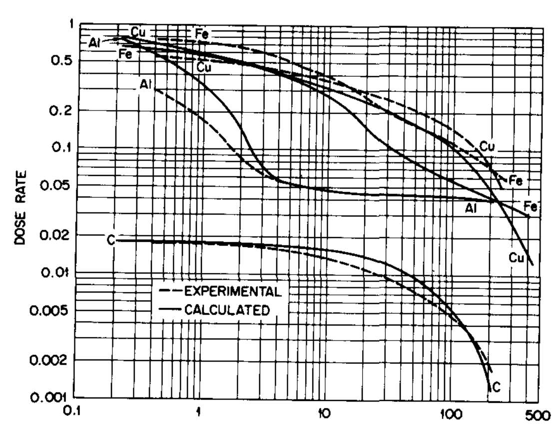

Fig. 1 Calculated and experimental residual radiation decay curves for carbon, aluminium, iron and copper activated by proton-induced spallation reactions.

Table I. Ratio of Calculated to Experimental Dose Rates

	Days of Cooling				
	0.4	2.1	21	100	210
Carbon	1.03	1.03	1.27	1.06	0.67
Aluminum	1.93	1.57	normalized	normalized	normalized
Iron	0.83	0.74	0.58	0.49	0.61
Copper	1.29	1.02	0.82	0.74	0.69

are in counts/(cm sec) while the calculated curves are in units of radiation dose rate. Since dose rates are dependent on gamma energy the normalization factor for a particular material is not a priori the correct normalization factor for other materials, nor for a large range of cooling times. Table I lists the ratio, calculated dose rate/experimental dose rate, at several decay times. The ratios are in most cases unity, within a factor of two. It is believed, therefore, that the calculation can be used to determine residual dose rates to within a factor of two.

Barbier[2] also placed a variety of samples outside the Synchro-Cyclotron in the path of the fast neutron beam emitted from internal meson targets. A comparison of the decay curves obtained from these activated samples with those determined from proton-irradiated materials showed that the shapes of the two sets of curves are similar. This supports the assumption that fast neutrons and protons induce essentially the same spallation reactions.

The experimental data obtained by Barbier do not include information needed for absolute normalizations for either proton- or neutron-induced activities. A comparison of the activities obtained inside and outside the cyclotron showed, however, that the spallation cross-sections for fast neutrons and for protons are of about the same magnitude. All of the samples inside were exposed to the same flux; also, all of the samples outside had the same exposure. The observed activity ratios of inside-exposed samples to outside-exposed samples were the same, within a factor of two, after 100 days of cooling time.

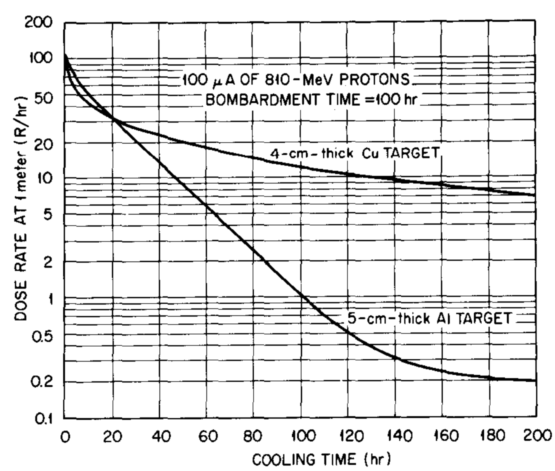

Fig. 2 Calculated residual radiation dose rates at one meter from copper and aluminium targets after 100 hr bombardment with 100 μA of 810 MeV protons.

Dose rates were calculated for a 100 μA beam of 810 MeV protons striking 4 cm thick copper and 5 cm thick aluminum targets for a period of 100 hours. The residual radiation dose rates at a distance of 1 m from the targets were plotted as a function of cooling time (Fig. 2). The high radiation levels indicate the necessity for either nandling these targets remotely or shielding them.

The calculations discussed above are for the special case of a collimated beam of particles impinging normal to the surface of a block of material. The calculations can be used, however, to estimate the residual radiation levels from distributed fluxes of particles and for oblique angles of incidence on the stopping material. The residual radiation level between the pole faces of the Mc^2 Cyclotron was estimated as follows.

If the beam is of high quality, such as the electron model (Analogue II) indicates, the principal source of activation will be from beam lost during extraction. For a 100 μA beam and 90% extraction efficiency about 10 μA would be slowed and scattered by the extraction system. The magnetic field will cause the charged particles to move to smaller radii and they will impinge on the pole faces at oblique angles. Barbier[2)] has obtained data which shows that the specific activation decreases with depth x in the pole face approximately as exp (-0.5x), where x is in cm.

Computer runs were made in which the incident beam was attenuated according to the factor -0.5/cm instead of by the geometric macroscopic cross-section. This calculation predicts the residual radiation level where all activity is concentrated in a small area. The computed value was increased by a factor of 4 for fast-particle build-up in the stopping material and by a factor of 10 to account for the oblique angle of incidence. It was also assumed that the activity is uniformly distributed over the pole-face area. The ratio of the gamma flux due to the distributed activity in the pole gap to the gamma flux at a given distance from all of the activity concentrated in a small area was determined. This ratio multiplied by the dose rate obtained from the computer run gives the dose rate due to the distributed activity.

This method of estimating the residual radiation level was applied to the CERN data. A 1 μA beam of primary protons was assumed. The curve in Fig. 3 is the computed residual radiation level after 1000 hr of cyclotron operation; the experimental points shown were measured by Barbier[2)] 15 days after a cyclotron shutdown. They were obtained at over 30 widely distributed locations throughout the cyclotron. For the detector used 10^6 counts/sec for 0.5 MeV gammas corresponds to about 1 R/hr. In an actual case the activity is not uniformly distributed on the pole faces; thus, the distribution of the experimental points is not surprising.

The agreement of experimental and calculated radiation levels for the CERN machine suggests that estimates based on the same assumptions are valid for the Mc^2 Cyclotron. The estimated ranges thus obtained are shown in Fig. 4. The upper curves are for pole faces of iron and copper (sector coils). The lower curves show the residual radiation levels if the pole faces are covered with 4 cm of carbon. The results indicate that residual radiation levels can be reduced by more than an order of magnitude by covering the pole faces with a few cm of carbon.

The curves shown in Fig. 4 do not include activation due to evaporation neutrons. For the pole faces in the Mc^2 Cyclotron the evaporation neutrons are estimated to contribute ~ 50 mR/hr to the radiation levels encountered between 1 and 10 days after machine shutdown.

The radiation levels in the cyclotron vault result from several contributions. The activity produced on the pole faces will be shielded by the cyclotron itself; the radiation levels outside the cyclotron due to this activity should not exceed a few percent of the radiation level in the cyclotron gap. There will be local hot spots wherever any beam is stopped in the external beam optics system. For example, if 1 μA of 810 MeV protons impinge on a thick slab of iron until saturation, the radiation level one meter away (with no shielding) one hour after shutdown will be between 1 and 2 R/hr. Thus, the external beam optics system must be designed to avoid stopping appreciable quantities of the beam in unshielded locations.

One local area of above average radiation level in the cyclotron vault will be the region of the cyclotron vacuum tank that is irradiated by the forwardly peaked spallation neutrons produced in the beam extraction apparatus. If 10 μA of protons impinge on the extraction apparatus and produce an average of one fast neutron per proton, a 20 cm x 50 cm area of the vacuum tank in the forward direction will be bombarded with ~ 10^{12} fast neutrons/sec. The residual radiation level one meter away, due to the induced activity in the vacuum tank wall, is estimated to be ~ 100 mR/hr one hour after machine shutdown.

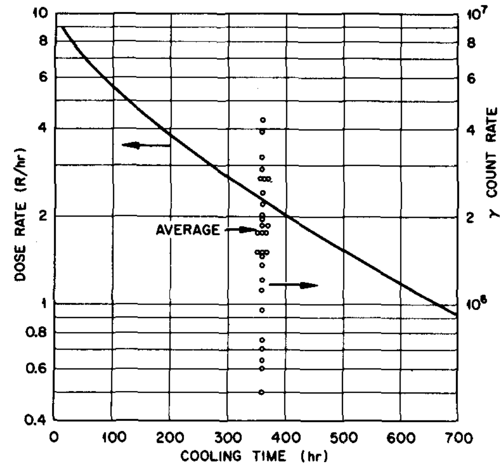

Fig. 3 Residual radiation levels in CERN Synchro-Cyclotron gap. Solid curve is calculated. The experimental points were measured 15 days after cyclotron shutdown. For the detector used, 10^6 counts/sec of 0.5 MeV gammas corresponds to ~ 1 R/hr.

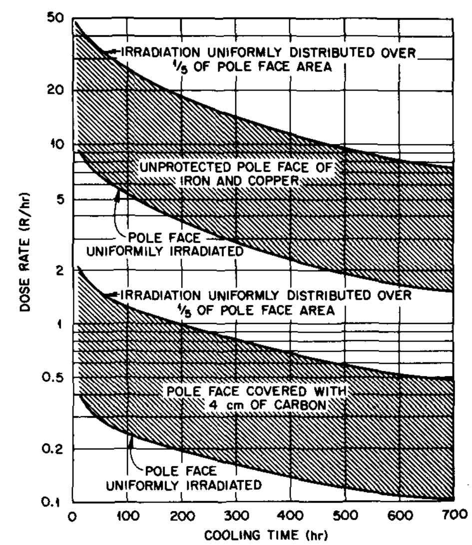

Fig. 4 Calculated residual radiation levels in the Mc² Cyclotron after 1000 hr operation with 10 μA of protons being scattered into the pole faces by the beam extraction apparatus.

Activation of the atmosphere in the cyclotron vault and beam rooms will result from both spallation reactions and thermal neutron capture. Investigations indicated that for all operations (except any that might discharge activity into the atmosphere) one air change per hour in the shielded area will maintain activity concentrations below the maximum concentrations permissible for 40 hr/week whole-body exposure.

References

1. S. Glasstone, Principles of Nuclear Reactor Engineering, D. Van Nostrand, pp. 542-545 (1955).

2. Two of us, CBF and KST, were visitors at CERN Feb. 18-March 1, 1963. During this visit we were generously given access to extensive unpublished data obtained by M. Barbier and co-workers at CERN. Barbier has kindly permitted us to use this data in our work.