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Health and Safety Laboratory

**Stray Radiation Measurements
at Particle Accelerator Sites**

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ABSTRACT

This progress report reviews stray radiation measurements made at representative accelerator sites by members of the Health and Safety Laboratory. Information is presented on radiation levels encountered, personnel monitoring records, economics of radiation protection, and biological effects of ionizing radiation with relation to accelerator operation.

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STRAY RADIATION MEASUREMENTS AT PARTICLE ACCELERATOR SITES

Introduction

The stray radiation field from high energy particle accelerators is comprised of several components, e.g., fast and thermal neutrons, x- and gamma rays, proton recoils, and at sufficiently high energies, heavy particle recoils and mesons.

In order to determine permissible occupancy times for personnel in this radiation field, a measurement is required both of the intensity and the energy of the different components constituting the spectrum. Then, from biological or clinical experience concerning the relative effectiveness of different radiations in producing deleterious effects, the biological hazard may be inferred.

This outlines very briefly the radiation problem with an accelerator in operation.

Also of importance are the radiations encountered when work must be done on the accelerator with the beam off. Induced beta and gamma activities can be of sufficiently high level to require limitations on personnel working time so that serious overexposure is avoided.

This paper is a progress report of a continuing program conducted by the Health and Safety Laboratory. As part of this program, radiation surveys, with particular emphasis on fast neutron measurements, have been conducted at 15 accelerators during the period from January 1953 to August 1954. Discussed in this report are radiation levels encountered, personnel monitoring records, economics of radiation protection, and biological effects of ionizing radiation with relation to accelerator operation.

Types of Particle Accelerators

A particle accelerator is any device which makes use of magnetic and/or electric fields to achieve particles of high energy. For purposes of radiation protection measurements, the most important characteristics of an accelerator are the kinds, intensities, and energies of the particles produced and whether the radiations are produced continuously or intermittently.

The maximum energy of the accelerated particle is not necessarily the maximum energy of the radiations associated with the accelerator. Certain accelerators, which are most appropriately designated as kevatrons, make use of exoergic nuclear reactions in which a charged particle is accelerated only to an energy sufficient to penetrate the coulomb barrier of a target nucleus. Once the accelerated particle is inside the target nucleus, a nucleon can be ejected and will carry away with it, in the form of kinetic energy, the energy which bound it to the nucleus. Thus a kevatron accelerating deuterons to only 500-kev energy produces 14-Mev neutrons when the deuterons bombard a tritium target.

In this section, a brief description of the types of particle accelerators is given.

Fixed Frequency Cyclotron⁽¹⁾

In this device (see Figure 1) a charged positive ion, usually a proton, deuteron, or alpha particle, is accelerated in a magnetic field and receives successive increments of energy as it passes through the instantaneous potential difference of two electrodes called the dees. The basic cyclotron equation is that which governs the motion of any charged particle in a magnetic field:

Figure 1. Massachusetts Institute of Technology conventional cyclotron. The 42-in. diameter pole face of the cyclotron magnet is located over the dee vacuum chamber. The tapered cylinder to the right shields the feed lines from the radiofrequency oscillator. A new target is being inserted in the foreground. (Courtesy of Massachusetts Institute of Technology.)

$$\frac{HZv}{c} = \frac{mv^2}{r}, \quad (1)$$

where

H is the magnetic field strength (oersteds),
 Z is the charge of the particle (esu),
 v is the velocity of the particle (cm/sec),
 c is the velocity of light which converts Z (esu) to Z (emu),
 m is the mass of the particle (g),
 r is the radius of the circular orbit in which the particle moves (cm).

Now the angular velocity, ω , in radians/second is

$$\omega = \frac{v}{r} = \frac{HZ}{mc}, \quad (2)$$

which for a constant magnetic field, charge, and mass is seen to be independent of the velocity and the radius.

If the potential across the dees is adjusted to a frequency, f , equal to $\omega/2\pi$, then each time the particle arrives at the space between the dees it will be in the correct phase to be accelerated by the potential difference across the dee gap.

The kinetic energy, E , in ergs of the emerging particle depends on the velocity achieved on the final half-turn which corresponds to R (cm), the radius of the dee.

Thus, from equation (2), it may be seen that

$$E = \frac{1}{2} m \left(\frac{HZR}{mc} \right)^2 \text{ or } E \text{ (ergs)} = \frac{H^2 Z^2 R^2}{2 mc^2}. \quad (3)$$

Thus, for a fixed field the ultimate energy of the accelerated particle will vary as the square of its charge and inversely as its mass.

It is also feasible to maintain the oscillator frequency for different ions constant and adjust the magnetic field.

One sees from equation (2) that

$$v = 2\pi f R, \text{ or } E = \frac{1}{2} mv^2 = 2\pi^2 f^2 R^2 m. \quad (4)$$

This proportionality between the kinetic energy of the accelerated particle and its mass explains why the energies of alpha particles (${}_2\text{He}^4$), deuterons (${}_1\text{H}^2$), and protons (${}_1\text{H}^1$), are in the ratios of 4:2:1 for any single cyclotron.

The frequencies involved can be obtained by substitution in equation (2) and are of the order of 30 megacycles for protons in a 2×10^4 oersted field and half this for deuterons or alpha particles in a similar field.

Frequency Modulated Cyclotron or Synchrocyclotron^(1,2,3,4). In a fixed frequency cyclotron the resonance condition (equation 2) is upset when the mass, m ,

Figure 2. Columbia University (Nevis Laboratory) synchrocyclotron. The magnet diameter of this synchrocyclotron is 164 in. with the accelerator capable of achieving proton energies up to 385 Mev. Massive shielding is required to attenuate stray radiations to permissible levels. The large overhead crane is used to position shielding components for different experimental arrangements. (Courtesy of Columbia University.)

changes by about 1 percent because of the relativistic increase with velocity. The connection between m , the relativistic mass, and m_0 , the rest mass, is given by

$$m = m_0 \left(1 - \frac{v^2}{c^2}\right)^{-1/2}. \quad (5)$$

This relativistic effect is not the only limitation on the energy attainable by a fixed frequency cyclotron. Due to inhomogeneities in the magnetic field, the beam may be lost unless the field is sloped to restore ions straying from the median plane of the magnet.

In the frequency modulated cyclotron or synchrocyclotron, these limitations are overcome. The frequency of the rf dee voltage is adjusted to decrease as the particle increases in mass so that the voltage drop across the dees occurs at the correct moment for acceleration to take place. The largest conventional cyclotron cannot accelerate protons to more than 15 Mev (30 Mev for deuterons or about 50 Mev for alpha particles) while synchrocyclotrons produce protons with energies of hundreds of Mev -- up to 450 Mev for the largest (e.g., the synchrocyclotrons at the Carnegie Institute of Technology and the University of Chicago). The beam is pulsed, a typical pulse being of the order of 100 μ sec and repeated 100 times per second.

Figure 3. Massachusetts Institute of Technology 12-Mev Vande Graaff accelerator. This accelerator produces high intensity beams of protons or deuterons. The electrons from the ion source impinging at the top of the pressurized steel tank contribute significantly to the stray radiation hazard. (Courtesy of Massachusetts Institute of Technology.)

Electrostatic Generator^(1,5)

In the high energy electrostatic generator or Van de Graaff machine (Figure 3), a moving belt conveys charge to a conducting sphere until the sphere is at equilibrium potential. This state is achieved when the charging current conveyed by the moving belt is balanced by removal of the charge by leakage from the sphere into the surrounding gas dielectric. The tank containing this gas is usually pressurized in modern machines. Another limitation on the attainable potential difference is the insulator breakdown voltage of components of the device including the evacuated tube along which positive ions or electrons can be accelerated.

The highest energy achieved by this device so far is about 10 Mev. Its great advantage is the precision possible in the energy of accelerated particles.

Figure 4 (Above). Sloan-Kettering Institute betatron. Electrons of 25-Mev energy are achieved in this betatron. One important application of this accelerator is its use for therapeutic treatments. Either x-rays or electrons are utilized for attaining desired doses at particular depths in tissues. (Courtesy of Sloan-Kettering Institute.)

Figure 5 (Right). Sloan-Kettering Institute betatron. The Sloan-Kettering Institute betatron schematic of the accelerator shown in Figure 4 exhibits the donut and collimator rings for narrowing beam to desired area. The shielding material is masonite, a composition consisting of elements having a low atomic number to minimize the production of stray x-rays (bremsstrahlung). (Courtesy of Sloan-Kettering Institute.)

Betatron(4, 6)

Electrons in the region of 10 to 300 Mev are produced in a type of accelerator known as the betatron (Figures 4 and 5). This device is essentially a transformer, the secondary winding of which is a stream of electrons moving in a fixed radius of an evacuated chamber called the "donut."

The magnetic field of the betatron, unlike that of the cyclotron, is made variable by the introduction of an alternating current into the coils of a suitably designed magnet. Acceleration of the electrons takes place during only one-quarter of the operating cycle of the magnetic field power which usually has a frequency of 60 cycles per second. At the end of this period ($1/240$ sec), the magnetic field is electrically interrupted and the high energy electrons are either directed at a target for x-ray production or brought out of the donut to be used as a high energy, high intensity beta source.

Because many (γ, n) nuclear thresholds fall below the energies of x-rays produced by a betatron, the fast neutron production of such a device, especially when operated as an x-ray machine, should be considered as part of the stray radiation hazard.

Electron Synchrotron(4, 7)

The electron synchrotron (Figure 6) may be used to achieve electron energies up to 300 Mev and possibly up to 1 Bev. Similar to the betatron in general appearance,

Figure 6. Massachusetts Institute of Technology 300-Mev synchrotron. This accelerator is shown in relation to its associated laboratories. The pulsed nature of this accelerator and the stray radiofrequency associated with its operation make it a difficult device to survey for the neutron components of its stray radiations. (Courtesy of Massachusetts Institute of Technology.)

the synchrotron differs in that it utilizes a radiofrequency accelerating potential in addition to a changing magnetic field to accelerate electrons. In fact, one type of electron synchrotron begins as a betatron, and after the particles have reached 2 Mev in energy (or a velocity of $0.98C$) additional energy is achieved by introducing the radiofrequency.

From the point of view of stray radiation measurements, the synchrotron and betatron present similar problems. An additional complication in the former accelerator is radiofrequency interference of survey instruments.

Proton Synchrotron(3, 4, 8)

The synchrotron principle, involving the use of both varying magnetic and rf fields, is possible for the acceleration of protons as well as electrons (see Figure 7).

Protons are introduced into a vacuum chamber of large diameter after achieving energies of about 5 or 10 Mev from an auxiliary accelerator. A changing high frequency rf field is then used to achieve energies in the Bev region. At the present time, three such accelerators are known to be in operation, two in the USA and one in England:

- 1) Brookhaven National Laboratory -- 3-Bev proton synchrotron often referred to as the Cosmotron, 60-ft diameter orbit.
- 2) University of California, Berkeley -- 6-Bev proton synchrotron known as the Bevatron, 100-ft diameter orbit.
- 3) University of Birmingham, England -- 1.3-Bev proton synchrotron, 30-ft diameter orbit.

The proton synchrotron operational cycle takes 5 or 6 seconds at the end of which time a burst of protons and stray radiations emerges from the accelerator.

The high energies achieved by these accelerators result in many different kinds of particles of unknown spectral distribution. The biological effects of these particles can only be conjectured until this sphere of investigation is more thoroughly explored.

It should be mentioned that work is well under way for the design of a new type of proton synchrotron known as the alternating gradient synchrotron (AGS) which will make use of the recently discovered "strong focusing" principle. It is anticipated that this device, to be constructed at the Brookhaven National Laboratory, will achieve proton energies up to 25 Bev.

Figure 7. Brookhaven National Laboratory proton synchrotron. The Brookhaven proton synchrotron (Cosmotron) is shown schematically. Along with the 6-Bev Berkeley bevatron, this accelerator represents the frontier of accelerator development, although accelerators in the 25-Bev range are well along in the preconstruction design stage.

Drift Tube Linear Accelerator(2, 3, 4)

For the acceleration of heavy positive ions (protons and particles of greater mass), a conceptually simple device is the drift tube accelerator. In this device a positive ion progresses along tubes of increasing lengths in such a way that the particle arrives at the end

of each tube in the correct phase to be accelerated by an impressed rf potential difference existing between two adjoining tubes.

Two such accelerators have been built, one at the University of California (Berkeley) and the other at the University of Minnesota. The California machine has achieved 3-Mev protons while the larger machine at Minnesota has reached 40 Mev and has a design value of 68 Mev.

The advantage of this type of accelerator lies in the very narrow spectral and spatial spread of the emerging ions, which is useful for certain types of nuclear investigations.

Wave Guide Linear Accelerator(2, 3, 4)

Another type of device used for achieving electrons of very high energy is the wave guide linear accelerator. In this device an electron is introduced in correct phase with a high frequency electric field traveling along a wave guide.

An electron will receive a steadily increasing amount of energy until it is finally ejected. The only known limitation on electron energies for this type of accelerator is presumably the practical length of the accelerator. The largest accelerator of this type is at Stanford University and is 220 ft in over-all length. It has achieved energies of 650 Mev, but the design limit of this accelerator is 1 Bev.

Figure 8. Brown University Cockcroft-Walton generator. This accelerator produces deuterons of 500-kev energy, which are used to bombard a tritium target. The resulting interaction is exoergic producing neutrons of 14 Mev. Stray x-ray levels from the back-electron current of the accelerating tube can be significant even without neutron production. (Courtesy of Brown University.)

Kevatron(1, 3)

Devices making use of transformer capacitance arrangements to obtain charged particles of comparatively low energy (in the kev region) are sometimes referred to as kevatrons (Figure 8). The charged particles are then used to bombard a suitable target which interacts exoergically with the bombarding particle.

A very useful type of such device is one in which deuterons of several hundred-kev energy bombard a tritium target and furnish a supply of nearly monoenergetic neutrons of 14-kev energy, free of gamma-ray contamination. Such an accelerator is sometimes referred to as a D-T neutron generator.

The nuclear interaction as explained above is:

A frequently used kevatron circuit is the voltage multiplying device of Cockcroft and Walton. Reference is sometimes made in accelerator circles to a Cockcroft-Walton generator which, as explained above, is a D-T reacting system for the production of neutrons in which the deuterons are furnished sufficient energy to overcome the Coulomb repulsion of the tritium nucleus.

Biological Effect of Accelerator Radiations

An appraisal of the hazards associated with accelerator operation cannot be made without some acquaintance with the extent of clinical experience and experimental information in the field of biological damage, particularly that caused by fast neutrons.

In this summary the authors have made extensive use of the information presented at the Conferences on Radiation Cataracts sponsored by the National Research Council for the Atomic Energy Commission and in particular the excellent paper presented by Ham⁽⁹⁾ at the Fourth Conference, and subsequently published in the American Medical Association Archives of Ophthalmology 50, 618 (1953).

In general, the available evidence may be grouped in the following way:

- a) Cataracts in persons engaged in accelerator work.
- b) Cataracts in persons exposed to irradiation from chain reacting assemblies.
- c) Cataracts in humans as a consequence of irradiation by ionizing radiations other than neutrons.
- d) Occurrence of other biological effects (noncataract) in humans by accelerator radiations.
- e) Cataracts in nonhumans as a consequence of irradiation by fast neutrons and other ionizing radiations.
- f) Effects of radiofrequency oscillations.

Cataracts in Persons Engaged in Accelerator Work

Abelson and Krueger⁽¹⁰⁾ in 1949 reported ten male physicists with some degree of lens opacity presumably incurred while engaged in investigations at cyclotron sites.

Since then Dollfus⁽¹¹⁾ has reported seven cases of cyclotron-induced lens opacities in France, while Krause and Bond⁽¹²⁾ have reported an additional five cases of radiation cataract, three of which are associated with cyclotron operation, one with Van de Graaff machines, and one with "radioactive materials."

The most striking feature of the Abelson and Krueger cases was the uniformly low estimates of their total exposure to neutrons made by the persons concerned.

In a considerable portion of the older published literature, doses are expressed in n-units, a unit no longer used in serious neutron dosimetry. The n-unit is that reading

obtained with a 100-r Victoreen thimble chamber exposed to fast neutrons. A generally accepted conversion is 1 n-unit = 2 or 2.5 rep which, though varying from chamber to chamber, is certainly more precise than the estimates made by the ten physicists.

On a rep basis the neutron estimates ranged from 10 to 300 rep, with a median dose estimate of 125 rep with exposure times varying from 10 to 250 weeks.

Cataracts in Persons Exposed to Irradiation from Chain Reacting Assemblies

Persons in this group may be classified in two categories: those exposed to the radiations from the 1945 nuclear detonations in Japan, and those exposed as a result of critical assembly accidents.

Fillmore⁽¹³⁾ has reviewed detailed physiological studies of 78 persons exposed to radiations from the Hiroshima weapon who subsequently developed lens opacities. He concludes that 50 percent or more of this group received near whole-body doses of radiation and that radiation cataracts were the only late effects in these persons.

Hempelmann et al⁽¹⁴⁾ have reviewed acute exposures experienced by nine scientists at Los Alamos in 1945 and 1946 as a result of exposures to fast chain reacting assemblies. Of these, two died shortly after exposure (9 and 24 days). Of the seven survivors, six showed no lens abnormalities three to four years after exposure. The estimated dose to the eyes of these six persons ranged from 4 to 21 rep.

The most heavily exposed survivor, who received an estimated 45 rep to the eyes, developed a cataract in the left eye three years after exposure and a cataract in the right eye five years after exposure.

Cataracts in Humans as a Consequence of Irradiation by Ionizing Radiation Other than Neutrons

That opacities result from x-ray and radium exposures of the head and eyes in therapy is well known. On the other hand, the prevailing evidence appears to be that relatively massive exposures, considerably in excess of the LD-50 (400 r) and even 600 r of total body x- or gamma radiation, may be below the threshold of the cataractogenic dose.

Merriam⁽¹⁵⁾, for example, reports no cataracts resulting from doses under 1500 r and only one out of 22 eyes showed a cataract after treatment with doses between 1500 and 2000 r of x-rays.

A summary of these findings are exhibited as the first entry in Table 1. Merriam, however, has continued his observations and writes in a private communication (February 1956) "... additional work on a considerably larger series does include some lower doses and there are patients with cataracts at these levels ... they are lower than those as yet reported, and ... there is a considerable difference between single and multiple exposures in the dose necessary to produce a lens opacity."

Hunt⁽¹⁶⁾ asserts that the threshold for cataract production is between 500 and 1000 r for 100- to 200-kvp x-rays. Ham,⁽⁹⁾ taking into account the wide variation in clinical data, cautions that 500 r of x- or gamma radiation should be regarded "as potentially dangerous to the human lens."

Occurrence of Other Biological Effects (Noncataract) in Humans by Accelerator Radiations

Aside from the very serious radiation exposure to scattered electrons from a 1.2-Mev electrostatic generator experienced by six men at the Massachusetts General

Table 1

Radiation	Organism	Threshold dose	Times weekly MPE for humans	Exposures	Number of cases; percent of sample	Time of onset	Remarks	References
Beta	Man	-	-	250 rep (av)	4 eyes (0 %)	Average for entire	-	G.R. Merriam, CRC-2,*
X-Ray	Man	1500-2000 r	5-7 x 10 ³	-	1 eye (4.5 %)	group of 99 eyes	-	Dec. 1950
X-Ray	Man	-	-	6050 r (av)	22 eyes	in 3 years and	-	
Radium	Man	-	-	2950 r (av)	73 eyes	9 months, with an	-	
		-	-	<1000 r	13 eyes (17.8 %)	"inverse ratio be-	-	
		-	-	1000-2000 r	25 eyes (34.2 %)	tween dosage and	-	
X-Ray and Radium	Man	-	-	7590 r (av)	7 eyes (-)	time of onset"	-	
Neutrons	Dog	-	-	60-150 n	0/10 (0 %)	-	-	C. Moses et al, AECU-2527,
		-	-	810-900 n	(60-75 %)	-	-	Mar. 1953
	Rabbit	-	-	52.7-83.7 n	0/16 (0 %)	-	-	
		-	-	(3.1 n fraction)	-	-	-	
		-	-	33-100 n	3	2-5 months	-	
		-	-	(single dose)	-	-	-	
Neutrons, fast	Rabbit	-	-	70 n	-	~2 months	-	T.C. Evans, CRC-2,* Dec. 1950
		-	-	120 n	-	-	-	
		-	-	(40 n fractions)	-	-	-	
X-Ray, 250 kvp		-	-	500 r	0 (0 %)	-	-	
Neutrons, fast	Mice	-	-	60 n	-	-	-	
		-	-	120 n	~100 (100 %)	~3 months	-	
		-	-	(40 n fraction)	-	-	-	
X-Ray, 250 kvp	Mice	15 r	45	15 r	11 (29%)	28 weeks	-	G.C. Upton, K.W. Christenberry,
		-	-	45 r	32 (86 %)	33 + weeks	-	J. Furth, Am. Med. Assoc. Arch.
		-	-	-	-	-	-	Ophthalmol. 49, 164 (1953)
Neutrons, fast	Mice CF #1 (female)	-	-	240-252 rep	16 (100 %)	~3 months	Complete opacities of the lens (Vogel	H.H. Vogel, Jr., CRC-5,
		-	-	182-215 rep	139 (~85 %)	3 months	grade +++) one year after irradiation	Mar. 1954
		-	-	174 rep	21 (~60 %)	4 months	(rbe) for minimum dose to produce	
		-	-	-	-	-	complete opacities ($\gamma/n = \sim 6$)	
Gamma rays (Co ⁶⁰)	Mice CF #1 (female)	-	-	986-1040 r	136 (~15%)	~4 months	-	ANL-5332, pp. 29-31, Oct. 1954
Neutrons, fast (fission)	Rabbit	<2 x 10 ⁹ n/cm ²	~5 x 10 ²	-	-	-	"Comparable effectivity" 5 x 10 ¹⁶ n/cm ²	David G. Cogan, John L. Goff,
		-	-	-	-	-	(14 Mev) 9 x 10 ¹⁰ n/cm ² (fission) 500 r	Elizabeth Graves - AECU-1743,
		-	-	-	-	-	(1.2 Mev gamma)	Jan. 1952
Mixed gamma-neutrons in γ/n dose ratio of approximately 30/1	Rhesus monkey	-	-	26 rep	0 %	-	No opacities	
		6 x 10 ⁶ n/cm ²	1.4	110 rep	(36)	-	30 months after exposure	
		-	-	505 rep	total	-	-	
Gamma Co ⁶⁰		-	-	3000 rep	-	8 months	11-1/2 months after radiation	D.V.L. Brown, CRC-5,
		-	-	2000 rep	-	9 months	-	Mar. 1954
		-	-	1000 rep	-	10-1/4 months	-	
		-	-	500 rep	-	-	-	
Fast neutrons, 14 Mev		-	-	250 rep	-	14-1/2 months	26 months after exposure	D.V.L. Brown, J.E. Pickering,
		-	-	75 r	-	19-22 months	-	CRC-6, Mar. 1955
		-	-	21	-	-	-	
		-	-	850 rep	-	6 months	16-1/2 months after exposure	
		-	-	250 rep	-	12-1/4 months	-	
		-	-	75	-	13-1/2 months	-	
Thermal neutrons		-	-	7500	-	Died in 16 days	19-3/4	
		-	-	2500	-	9 months	-	
		-	-	825	-	14-1/2 months	-	

*Second Conference on Radiation Cataracts.

Hospital⁽¹⁷⁾ in 1945, the available literature is all but nonexistent on noncataract physiological effects experienced by accelerator workers.

Of great interest in this connection is the work of Ingram et al^(18, 19) in connection with the operation of the synchrocyclotron at the University of Rochester. It was reported that very minute exposures to the stray radiations of the accelerator produced an increase in the number of bilobed lymphocytes in the blood of both humans⁽¹⁸⁾ and dogs.⁽¹⁹⁾ The occurrence of these unusual double nuclei was not accompanied by a significant change in the hematological picture usually associated with relatively massive exposure to ionizing radiation.

It is perhaps worthy of mention in this regard that at one large Eastern university which the authors visited they were advised that the technician performing routine hematological tests had a surprisingly good record of determining who was working in the cyclotron area on the basis of subjective appearance of the blood cells. Unfortunately no quantitative data along these lines were available.

Cataracts in Animals as a Consequence of Irradiation by Fast Neutrons and Other Ionizing Radiations

The biological effects of controlled exposures to ionizing radiation are under study at a number of installations. Rats, rabbits, mice, dogs, and, more recently, large simians have been exposed to a great variety of electromagnetic and neutron radiations of different energies (cf. Table 1).

Effects of Radiofrequency Oscillations

On the basis of existing information, it can be said that the case against fast neutrons is well established and fast neutrons should be regarded as the most likely suspect in cataract-producing potential at accelerator sites.

On the other hand, the possibility has not been ruled out, in the opinion of the writers, that the stray rf energy associated with accelerator operation is in itself, or in combination with ionizing radiation, cataractogenic.

Richardson, Duane, and Hines⁽²⁰⁾ have reported experimental production of opacities in the eyes of rabbits by exposure of rabbit eyes to pulsed microwaves of 3-cm wavelength at a 5-cm distance from a generator with a 67-watt average output.

Hines and Randall⁽²¹⁾ furnish lethality data obtained from irradiation with 10- to 12.25-cm microwaves and point out that shielding of the eyes and testes can be effected by covering these structures with close fitting screen wire.

Salisbury, Clark, and Hines⁽²²⁾ speak of 3 watts per cm² as "known to be dangerous," but add that this energy flux rate is not likely to be achieved except in the "immediate vicinity of a powerful transmitter."

Rapid testicular degeneration of rats exposed to 12-cm microwaves is reported by Imig, Thomson, and Hines⁽²³⁾ who caution that "because of the unusual susceptibility of testicular tissue to thermal agents it seems desirable to shield these structures . . . during periods of treatment or exposure."

The relationship between the microwave data and the operation of particle accelerators involving the use of rf fields deserves further exploration.

A summary, by no means complete, of some of the work is exhibited in Table 1. For comparison, the compilation of Merriam's observations is included as the initial entry.

It must be confessed that the animal experimentation to date, though of unquestionable value in the understanding of the mechanism of cataract formation, furnishes little insight into the maximum permissible exposures for humans at high energy accelerator sites. For obvious reasons, most experimental work is confined to relatively

massive short term exposures at high dose rates, whereas accelerator personnel are exposed, in general, to long term exposures at low dose rates.

For persons having responsibilities in evaluating the adequacy of shielding and establishing good radiation control, the guide lines obtained from the animal experiments appear to indicate the need for conservatism and caution pending further work.

Instrumentation

Introduction

In the evaluation of the electromagnetic and neutron dose produced by particle accelerators, a variety of radiation survey instruments have been used by the Health and Safety Laboratory. These are ionization chambers for gamma rays; ionization chambers, proportional counters, and scintillation detectors for neutrons.

Negligible use was made of the valuable photographic film and threshold detection techniques which are not quite so amenable to the 1- to 3-day field surveys during which measurements were made.

Ionization Chambers. By measuring either the rate of change of potential as charge is collected or the potential drop appearing across a known resistor, one can determine the amount of ionization produced by electromagnetic radiation (x- or gamma), beta radiation, or neutrons incident upon the ionization chamber. In a mixed field of gamma rays and neutrons, the resulting ionization current does not differentiate between the agencies producing it.

X- or gamma radiation dose, expressed in roentgens, should properly be measured with an ionization chamber constructed of a material approximating the same effective atomic number as air since the roentgen is defined in terms of the interaction of electromagnetic radiation with air.

One such expression is

$$Z_{\text{eff}} = \left(\frac{\sum a_n Z_n^4}{\sum a_n Z_n} \right)^{1/3},$$

where a = the proportional amount of the n th element, with atomic number Z_n , in the composition.⁽²⁵⁾ Other forms for the estimation of Z_{eff} have been given in the literature.⁽²⁶⁾

On the other hand, this so-called "air-wall" chamber cannot measure the dose due to neutrons in roentgens-equivalent-physical (rep)* since the relation of chamber response to energy absorbed in tissue depends on several variables such as relative cross sections for neutrons, relative stopping power of the chamber material for recoil nuclei, and chamber size.⁽²⁷⁾ In other words, the energy absorption difference between air and tissue for electromagnetic radiation is relatively small, but the difference between air and tissue with respect to neutron interaction is considerable. The tissue dose due to fast neutrons will be generally proportional to the amount of hydrogen present.

For neutron energies lower than 0.5 Mev, the nitrogen content is also important. So, ionization chambers designed for the measurement of radiation doses due to

*The term rep is used throughout the report rather than the preferred rad because most of the references cited refer to the rep. One rep is the quantity of any ionizing radiation which results in energy absorption of 93 ergs/g of tissue. The rad is, simply, that quantity of any ionizing radiation which results in energy absorption of 100 ergs/g of tissue.

neutrons require quantities of hydrogenous and nitrogenous material in the same proportions present in the biological tissue of interest. Such chambers have been built by Failla and Rossi, and will be discussed subsequently.

In order to learn of the component radiations in a mixed field, the surveyor may use two ionization chambers, one whose response is a measure of radiation dose in tissue -- i.e., one made of hydrogenous and nitrogenous material -- and one whose response to neutrons is deficient -- e.g., one made of carbon. Indications of the relative amounts of neutrons and x- or gamma radiation present can also be obtained by changing the gas filling of the same chamber. This, of course, is not as desirable as having the wall material also changed correctly. In practice, one usually estimates the neutron contribution to total dose by means of the more sensitive mechanisms described in the following sections. For example, if a mixed radiation field composed of the maximum permissible gamma-ray level, 300 mrep/week, plus the maximum permissible fast neutron level, 30 mrep/week, were examined, the neutron contribution to the ionization will be only 10 percent of that of the gamma radiation. If one were not aware of the neutron component, it is possible that the stray radiation level would be regarded as only 10 percent more than permissible instead of 100 percent greater.

Proportional Counters. The primary value of the proportional counter lies in the linear relation between the pulse size from the counter and the total ionization produced in the counter by the charged recoil particle initiating the ionization. The sensitivity of the counter to fast neutrons is enhanced considerably by introducing a hydrogenous material into it. Similarly, the use of such materials as boron, which has a high thermal neutron cross section, increases the thermal neutron sensitivity. Since the pulse sizes due to the alpha particles or protons, resulting from neutron interactions, are much larger than those arising from the electrons produced by x- or gamma radiation, one can discriminate against gamma radiation by electronically rejecting the electron pulses.

By the use of an appropriate hydrogenous gas (e.g., methane) and suitable reflectors and absorbers, a counting rate proportional to the tissue dose rate can be achieved for a portion of the neutron energy spectrum. A tissue equivalent proportional counter has been devised by Hurst,⁽²⁸⁾ and a version of this counter is discussed later.

Scintillation Counters.⁽²⁹⁾ If an organic material such as lucite or polyethylene is placed next to a scintillator, the incident neutrons can be measured by observation of the visible light which is produced in the scintillator with a photomultiplier tube. That is, the products of a neutron reaction in the lucite (primarily protons in the case of fast neutrons) will produce visible light if permitted to react with a scintillator. The amount of light, or the number of pulses in a given time is, then, a measure of the incident neutron flux. However, the pulses do not appear to be proportional to the proton recoil energy.⁽³⁰⁾

Threshold Detectors.⁽³¹⁾ A detector which will respond only to neutrons above a certain energy, by any of several mechanisms, is known as a threshold detector. For example, a chamber employing material such as U^{238} or Bi^{209} ^(31, 32, 33) is useful as a detector of neutrons produced by the fission process with energies above 1.1 and 60 Mev, respectively. The S^{32} isotope has value as a threshold detector by virtue of the (n,p) reaction which occurs above neutron energies of about 1 Mev.⁽³⁰⁾

Nuclear Track Film. Nuclear track photographic film can indicate the presence of neutrons by means of the (n,p) reaction occurring in the hydrogenous film. The number of tracks appearing in the developed film will be a measure of the total number of neutrons intercepted by the film. Thus, Kodak NTA film is useful for personnel monitoring purposes for neutrons with energies between about 0.3 and 20 Mev.^(34, 35)

Typical Instruments

During 1953 and 1954, representative survey instruments were used extensively by the Health and Safety Laboratory in connection with stray radiation measurements at accelerator sites. A brief description of each instrument, along with some notes of interest to the surveyor, is given below. A semilog chart indicating the effective range of the various instruments and the most important neutron energies from the viewpoint of the maximum permissible exposure is shown (Figure 9).

Figure 9 (Above). Energy range of neutron instruments.

Figure 10 (Right). Fast neutron dosimeter, AEC Model SPC-6A.

Fast Neutron Dosimeter -- AEC No. SPC-6A, Model E-1. This survey meter (produced by the Radioactive Products, Inc. (see Figure 10)) utilizes a proportional counter, which has been described by G.S. Hurst.⁽²⁸⁾ This argon-methane-filled proportional counter contains two polyethylene radiators and an aluminum absorber arranged so that the counting rate is proportional to a calculated first-collision tissue dose rate, when the counter is irradiated with collimated neutrons with energies of 0.2 to about 10 Mev. Three ratemeter scales permit measurements up to 5, 50, and 500 mrep/hr, respectively. By timing the accumulation of up to 200 counts on an integrating scale, dose rates as low as 0.2 mrep/hr can be measured in about 16 minutes. The adjustment of a gamma radiation discriminator affords a calibration check. With a 25-mg radium source placed 5 cm from the face of the counter, the discriminator should be adjusted until the meter reads 3.5 to 4.5 mrep/hr. The dosimeter is then said to have the correct neutron sensitivity ($0.0145 \text{ cts/n/cm}^2$) and is insensitive to gamma radiation up to 1 r/hr.

Several features have been noticed during the field use of these dosimeters:

- The gamma radiation discriminator setting has changed markedly from day to day on several occasions. It is believed that a discriminator check before each survey is advisable.
- The neutron response appears to be less than the nominal value after the dosimeter has been checked with the 25-mg radium source. This led to the use of correction factors as large as 2. It is conceivable that one dosimeter may appear to be functioning well, in spite of a deficient sensitivity. Thus,

frequent calibration with a standard neutron source is a necessity. Such sources are not always available at the various accelerator sites.

- c) This counter has an approximate 2 to 1 directional response to collimated neutrons. In the measurement of stray radiation, no particular difficulty was experienced because of this characteristic.
- d) The long time (5 minutes) required to obtain a reading in the 5 mrep/hr (ratemeter) scale renders this scale impractical for survey work. Low level measurements were generally made by the rate-of-drift method provided for in this instrument.

Scintillation Counter, Model FN-1, AEC Model SBX-21A. This scintillation counter (the Nucleonic Company of America (see Figure 11)) employs a molded, cylindrical lucite detector containing a dispersion of silver-activated zinc sulfide, and a photomultiplier tube. The survey instrument is a count-rate meter having two scales which can be calibrated with respect to Po-Be fluxes from about 5 n/cm²-sec to about 500 or 600 n/cm²-sec. The detecting phosphor has been described by W. Hornyak,⁽³⁶⁾

and the original survey instrument by J. Handloser and W.A. Higinbotham.⁽³⁷⁾

Originally, it was believed that the protons (which interact with the ZnS-Ag to give light pulses) were produced in the lucite. Subsequent work by G.R. Keepin⁽³⁸⁾ indicates that a significant part of the detector response is attributable to protons from the $S^{32}(n,p)P^{32}$ reaction. In any case, the primary value of this instrument lies in its high sensitivity, quick response and short warm-up time, and its portability, all of which makes this counter valuable as a neutron detector. The sensitivity of the scintillation counter can be increased several factors by using the larger detecting elements and photomultiplier tubes now available.

At about 0.4 Mev the instrument "cuts off," the exact point being determined by the photomultiplier tube gain. This, of course, reduces the validity of a Po-Be neutron calibration in situations involving other neutron energies. Gamma radiation discrimination is effected by means of a 1-megohm potentiometer which permits addition to the 900 regulated volts from the supply. The instrument is generally insensitive to gamma radiation levels up to about

3 r/hr. The sensitivity decreases considerably with decreasing neutron energy from a value of about 1 count per 100 incident 15-Mev neutrons to about 0.02 counts per 100 incident 0.5-Mev neutrons.

Fast Neutron Survey Meter, AEC Model SBX-20A. This scintillation counter (the Lermac Inc., Figure 12) designed by B.W. Thompson⁽³⁹⁾ employs a metal spherical (therefore nondirectional) detector, the inside of which is lined with polyethylene and

Figure 11. Fast neutron scintillation counter, AEC Model SBX-21A.

Figure 12. Fast neutron scintillation counter, AEC Model SBX-20A.

coated with silver-activated zinc sulfide. Protons are produced in the polyethylene during neutron irradiation, and light results as the protons react with the zinc sulfide. The neutron detection mechanism, then, is like the one used in the ZnS-lucite scintillation counter. However, the counter takes advantage of the dependence of sensitivity upon neutron energy by recording the measurement in neutron energy flux density, that is Mev/cm²-sec. Thus, the mean energy of the neutron spectrum must be known in order to learn the neutron flux density (n/cm²-sec). The relation between neutron flux density, ϕ , mean energy, $\bar{E}$, and the counting rate, C , is given by

$$\phi = \frac{C}{(1.0 \times 10^{-27}) N_h A \bar{E}}, \quad (38)$$

where N_h is the number of hydrogen nuclei per cm³. A is the detector area. However, the evaluation of $\bar{E}$ is not easily accomplished, which limits the usefulness of the counter somewhat in stray radiation measurements. As with the ZnS-lucite counter, its primary utility is as a fast neutron detector.

Thompson states that the approximate proportionality between counting rate and energy flux density begins to break down at about 0.5 Mev, depending upon the actual gamma discriminator level.

A suggested procedure for setting the gamma discriminator is to bias out 100 mr/hr of radium gamma, but in this case the instrument may be too gamma sensitive.

Methane-Filled (CH₄) Proportional Counter. This counter can be used in conjunction with a scaling unit.⁽⁴⁰⁾ A methane proportional counter is generally cylindrical in shape and contains gas to a pressure of about 1 atmosphere. A wire electrode

at high potential (approximately 2000 volts) is insulated from the chamber wall, the second electrode. A cathode-follower preamplifier is often used at the counter output and thus permits the use of long cables.

When a methane counter is used in conjunction with a scaler having a variable gain potentiometer, there is an unlimited number of chamber voltage and amplifier gain settings at which neutrons can be detected and measured. In general, it would be desirable to have such a voltage and gain setting that an optimum sensitivity is obtained without having the counting rate influenced by electron pulses due to gamma radiation. Methane counters do not show a significant plateau since the proton recoil energy varies uniformly up to the maximum neutron energy. The sensitivity of a methane counter is generally of the order of 0.04 cts/n/cm^2 , a somewhat higher sensitivity than the tissue equivalent fast neutron dosimeter previously described. However, the counter and scaler arrangement is rather cumbersome.

Boron-Trifluoride-(BF₃)-Filled Proportional Counter (Natural and Enriched in B¹⁰). Because of the relatively high numerical fluxes of thermal neutrons required to produce the maximum permissible dose rate ($2000 \text{ n/cm}^2\text{-sec}$ for .025-ev neutrons compared to about $30 \text{ n/cm}^2\text{-sec}$ for Po-Be neutrons), the thermal neutron hazard is usually unimportant at most accelerator sites compared to the fast. However, BF₃ counters, which are extremely efficient detectors of thermal neutrons, make con-

venient scanning devices in inhomogeneous neutron fields having comparatively low fluxes of thermal neutrons. The BF₃ counter sensitivity drops to a negligible value (1 percent of the maximum) at neutron energies of about 1 electron volt.⁽⁴¹⁾

Recently, a BF₃ counter-scaler arrangement was replaced with a portable BF₃ counter. An SPC-6A fast neutron dosimeter was modified by replacing the Hurst argon-methane-filled proportional counter with a BF₃ counter which permits the measurement of thermal neutron flux densities between 5 and $200 \text{ n}_{\text{th}}/\text{cm}^2\text{-sec}$ (Figure 13). A counter having a fairly uniform response to neutron fluxes from about thermal to 3 Mev has been constructed. The sensitivity of such a counter known as a Hanson-McKibben "long" counter does not vary more than 10 percent in the interval 0.01 to 3 Mev.⁽³⁰⁾ However, the sensitivity is still highly significant down to thermal energies. The thermal contribution can be removed with a suitable cadmium shield.

The Failla-Rossi Tissue Equivalent Chamber. An ionization chamber of this type was obtained from G. Failla and H.H. Rossi in 1953 for use with a vibrating reed electrometer (Figure 14). Tissue equivalent chambers are discussed

Figure 13. An improvised portable BF₃ proportional counter.

Figure 14. A tissue equivalent ionization chamber used with an Applied Physics Corporation vibrating reed electrometer.

in the literature.(27, 42) The conducting tissue equivalent plastic is composed of 9.7 percent hydrogen, 71 percent oxygen, 15.8 percent carbon, and 3.5 percent nitrogen.(27) The gas filling is 64.42 percent CH_4 , 32.38 percent CO_2 , and 3.20 percent N_2 to a total pressure of about 30 cm of mercury. Because of the relatively small dimension of this chamber in terms of the neutron mean free path, its response is due principally to first-collision neutrons. Presumably, the tissue dose indicated by this chamber will be that delivered to a point about 6 mm below the surface of the body (since the chamber wall is $1/4$ in. thick). Of course, the tissue dose in mixed radiation fields will be the total dose contributed by all energies and all types of radiation. Only independent measurements can give the surveyor an idea as to the components of the mixed radiation.

Recently, a portable version of this chamber has been made available by Radiation Industries (SPC-11A).

Charts

The charts below furnish pertinent features of the accelerator sites at which stray radiation surveys have been made by Health and Safety Laboratory groups.

Chart 1 furnishes a code letter for each installation; the name, type, accelerated particle and energy, date of initial operation, spheres of investigation, and the AEC contract number where applicable.

Chart 2 gives the initial cost or estimated replacement cost of the accelerator, an approximate estimate of the annual operating budget, the estimated capital cost of radiation protection, an estimate, where available, of the annual cost for radiation protection, and the number of persons associated with the accelerator operation.

Chart 3 contains information as to the work load of the accelerator, work factors of persons at the site and maximum radiation levels encountered in normal work areas, occasionally occupied (or accessible) inside areas, and unregulated outside areas.

Chart 4 contains cost estimates and descriptive material on the accelerator shielding.

Chart 5 describes regular physiological examinations at the sites.

Chart 6 summarizes the film badge records at sites subscribing to the Brookhaven National Laboratory Off-site Monitoring Service. The film badge packets consist of a conventional beta-gamma sensitive film as well as one with a nuclear track emulsion (NTA) calibrated against a known flux of polonium-beryllium neutrons. The counting of proton recoils in the exposed nuclear emulsion is then a measure of the neutron flux to which a wearer of the film packet has been exposed. This chart furnishes a breakdown of these film badge records in terms of currently accepted maximum permissible weekly doses of gamma radiation and fast neutrons. Under remarks are listed numbers giving a strong indication that at most sites significant personnel exposures are received by a small minority of persons.

Chart 1*						
#	Code letter	Installation	Accelerator	Particle and energy (Mev)	Date of initial operation	General spheres of investigation AEC contract no.
A	CO-CY	Columbia University Pupin Laboratory	Cyclotron	8-10 d	1934	Cross-section measurements resonance levels scattering studies AT(30-1)-Gen-72
B	PR-CY	Princeton University Palmer Laboratory	Cyclotron	18 p	1935 (1951) (rebuilt)	Cross-section measurements scattering studies energy levels nuclear chemistry AT(30-1)-937
C	PI-CY	University of Pittsburgh S.M. Scaife Laboratory	Cyclotron	8.5 p 16 d 32 a	1947	Scattering studies cross-section measurements solid state, nuclear chemistry radiation damage, biological studies AT(30-1)-866 terminated
D	CI-SC	Carnegie Institute of Technology	Synchrocyclotron	440 p	1950	Meson production and scattering mesic atoms radiation damage on crystals nuclear chemistry AT(30-1)-882
E	CO-SC	Columbia University Nevis Laboratory	Synchrocyclotron	385 p	1950	Meson production and scattering ONR
F	MI-CY	Massachusetts Institute of Technology	Cyclotron	15 d 7.5 p 30 a	1940	Physics - energy levels scattering cross section nuclear chemistry Cosmic-ray research Nuclear energy levels AT(30-1)-905
G	MI-SY	"	Synchrotron	340 e		
H	MI-EG	"	Electrostatic generator	12 + ions		
I	MI-VG	"	Van de Graaff	5 + ions		
J	BR-CW	Brown University	Cockcroft-Walton	0.25 d	1954	Nuclear energy levels Cross sections n,p inelastic scattering angular distributions enzyme a AT(30-1)-1082
K	YA-CY	Yale University Sloane Laboratory	Cyclotron	4 d	1939	Biophysics - virus radiation physics - light nuclei energy levels AT(30-1)-568
L	RO-SC	University of Rochester	Synchrocyclotron	250 p	1948	Scattering (n,n), (n,p), (meson-nucleon) AT(30-1)-875
M	BA-CW	Bartol Research Foundation	Cockcroft-Walton	0.10 d	1954	- AT(30-1)-1679
N	BA-VGS	"	Van de Graaff	1.8 p,d	-	-
O	BA-VGS	"	Van de Graaff	5-10 p,d	-	-
*Date of Table, October 1954.						

Chart 2

Cost estimates

Letter	Code designation	Total initial cost or replacement estimate (\$)	Annual operating budget (\$)	Estimated capital cost of radiation protection (\$)	Radiation protection operating costs (\$)	Number of persons
A	CO-CY	75,000 (1934)	250,000	6,000	7,000	26
B	PR-CY	250,000 (180,000 - accelerator alone with basic shield in 1935)	230,000	60,000 (estimate of shield replacement)	No estimate made	52
C	PI-CY	50,000 - 100,000 (1941-1947)	170,000	6,000	No estimate made	85
D	CI-SC	1,500,000 (1948)	500,000	101,153 initial shield 15,000 additional	No estimate made	102
E	CO-SC	2,264,000 accelerator (1950) 750,000 buildings and land	500,000	67,551 initial shield 57,000 additional	5,000/year excluding salaries	60
F	MI-CY	1,000,000 replacement estimate	100,000	50,000	No estimate made	5 (>10% time)
G	MI-SY	1,000,000 replacement estimate	150,000	2,500 initial shield 500 back-stop	No estimate made	40
H	MI-EG	500,000 accelerator	80,000	275,000 initial shield plus building 600 additional	No estimate made	2-10
I	MI-VG	150,000 accelerator	40,000	6,000 initial	No estimate made	6
J	BR-CW	200,000 accelerator, buildings, and grounds	32,000	Nothing	No estimate made	6
K	YA-CY	40,000 - 50,000 accelerator re- placement	51,000	3,500 additional	No estimate made	20
L	RO-SC	1,520,000 cyclotron and equipment ~100,000 buildings	500,000	6,450 initial 17,000 dike, etc.	No estimate made	40

Chart 3								
Radiation level estimates								
Radiation levels; fractions of (fast neutrons) maximum permissible dose rate (40 hr) hourly								
Letter	Code designation	Approximate number of persons	Estimated work load of accelerator (hr/wk)	Estimated work factor of persons (fraction of 40 hr) and persons		Normal work areas	Occasionally occupied or accessible inside areas	Unregulated outside areas
A	CO-CY	26	90-100	>0.2 <0.2	(20) (6)	<0.1	6.0	No measurements made Believed <0.1
B	PR-CY	52	125	>0.2 <0.2	(3) (49)	<0.1	21	No measurements made Believed <0.1
C	PI-CY	85	No estimate made	0.1 - 1.0	(85)	1.3	53	No measurements made
D	CI-SC	102	72	0.2	(102)	4.0	80	4
E	CO-SC	60	75	0.1 - 1.0 <0.1	(45) (15)	15	40	No measurements made
F	MI-CY	5 >10%	No estimate made	>0.2 <0.2	(3) (2)	5.0	2.6	No measurements made
G	MI-SY	40	140-168	>0.2 <0.2	(6) (34)	No measurement made	No measurement made	No measurements made
H	MI-EG	10	No information available	>0.2 <0.2	(2) (8)	2.0	<0.10	No measurements made
I	MI-VG	6	56	>0.2 <0.2	(2) (4)	0	4.0	No measurements made
J	BR-CW	6	56	>0.2	(6)	0.5	10	0.50
K	YA-CY	20	<112	>0.2 <0.2	(3) (17)	2.0	8.0	16.50 along walk
L	RO-SC	40	168	>0.2	(40)	2.0	4.0	10.0 along walk

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Chart 4				
Shielding				
Letter	Code designation	Estimated initial cost of radiation protection (shield) (\$)	Estimated cost of additional protection (\$)	Description of existing shielding
A	CO-CY	6,000	0	3 ft of water in 1/4-in. steel tanks
B	PR-CY	60,000	0	3 ft of iron and limonite concrete
C	PI-CY	6,000	600-800, water windows	4 ft water plus 14 in. brick, 8 ft water, earth roof (26 ft)
D	CI-SC	101,153	15,000	North - 8 ft magnetite concrete East - 8 ft magnetite concrete at beam level, 8 ft lead South - 4 ft magnetite concrete plus earth dike West - 15 ft magnetite concrete loaded with scrap steel
E	CO-SC	67,551	57,000	North - mostly 8 ft iron East - 6 ft concrete plus earth South and west - 6 ft concrete plus iron local shields Roof - 6 ft concrete
F	MI-CY	50,000	0	4 ft concrete, 3 ft on roof, plus 2 ft concrete locally
G	MI-SY	2,500	500	3 ft concrete except in beam - 3 ft lead
H	MI-EG	275,000 including building	600	2 ft concrete walls
I	MI-VG	6,000	0	3 ft concrete
J	BR-CW	0	0	Remote operation - chain link fence (no shielding <u>per se</u>)
K	YA-CY	Part of building	3,500 - 2 additional walls	18 in. brick walls
L	RO-SC	6,450	17,000	Remote operation - local concrete blocks, chain link fence

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Chart 5			
Studies of accelerator workers			
Letter	Code designation	Blood examination	Eye examination
A	CO-CY	Monthly blood counts for 20 persons; quarterly blood counts for 6; annual blood counts for everyone	No
B	PR-CY	Quarterly blood counts	No
C	PI-CY	Quarterly blood counts (weekly blood counts for 6 weeks when exposure exceeds weekly MPE)	Semiannual slit lamp
D	CI-SC	Quarterly for research personnel	Semiannual slit lamp for personnel from research
E	CO-SC	Monthly blood counts	Twice since 1950
F	MI-CY	Blood counts every 4 months for everyone >20 mr/week	Annual slit lamp
G	MI-SY	Blood counts every 4 months for everyone >20 mr/week	Annual slit lamp
H	MI-EG	Blood counts every 4 months for everyone >20 mr/week	Annual slit lamp
I	MI-VG	Blood counts every 4 months for everyone >20 mr/week	Annual slit lamp
J	BR-CW	Periodic blood counts	No
K	YA-CY	Periodic blood counts	No
L	RO-SC	Periodic blood counts	No

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Chart 6																
Site	Accelerator	Accelerated particle and energy (Mev)	Approx. no. of persons employed at site	No. of persons wearing badges	Dates*	Fast neutrons fraction of MPE				Gamma radiation fraction of MPE					Remarks	
						0.5-1.0	1-2	2-3	>3	0.25-0.5	0.5-1.0	1-2	2-3	>3		
Bartol Research Foundation	Van de Graaff	1.8 d	12	12**	8/2/54-	5	1	-	-	5	1	-	-	-	2 persons accounted for all 12 exposures	
	Van de Graaff	5 p	12	12**	1/2/55 b	5	1	-	-	5	1	-	-	-		
	Cockcroft-Walton	0.10 d	2	2		-	-	-	-	-	-	-	-	-		
Brown University	Cockcroft-Walton	0.25 d	6	6	6/15/54- 1/13/55 b	-	-	-	-	-	-	-	-	-	-	
Carnegie Institute of Technology	Synchrocyclotron	440 p	102	51 w	5/1/53- 1/6/55 w	75	3	0	1	253	116	58	19	6	10 persons accounted for 50% of exposures	
Columbia University	Cyclotron	10 d	27	27	11/20/53- 1/6/55 w	9	-	-	-	12	-	1	-	-	14 persons - all exposures	
	Synchrocyclotron	385 p	60		3/2/53- 1/2/55 w	170	49	16	4	48	35	28	9	7	8 persons - 50% of exposures	
Massachusetts Institute of Technology	Cyclotron	15 d	6	6	4/1/53-	1	-	-	-	46	16	-	1	-	2 persons - 83%	
	Synchrotron	340 e	40	11	1/2/55 b	3	-	-	-	13	4	-	-	1	8 persons - 100%	
	Van de Graaff	12 + ions	10	3		1	-	-	-	2	-	-	-	-	2 persons - 100%	
	Van de Graaff	5 + ions	6	3		1	-	-	-	-	-	-	-	-	-	
University of Pittsburgh	Cyclotron	16 d	85	10	7/3/53- 1/6/55 b	8	-	-	1	67	25	17	8	-	6 persons - 73%	
Princeton University	FM Cyclotron	18 p	52	32	3/2/53- 1/2/55 b	8	-	1	-	4	4	-	-	-	14 persons - 100%	
University of Rochester	Synchrocyclotron	250 p	60	60	6/14/54- 1/9/55 b	37	-	1	-	24	6	1	-	-	9 persons - 26%	
Yale University	Cyclotron	4 d	20	11	11/30/53- 1/9/55 b	3	-	-	-	1	1	-	-	-	3 persons - 100%	
*b signifies a bi-weekly period; w signifies a weekly period. **Same persons at both Van de Graaffs.																

Individual Surveys

Stray radiation measurements were made of 15 particle accelerator sites at ten installations in the Eastern United States between January 1953 and August 1954. Some of the accelerators were visited more than once. Results of the individual surveys are given below along with the observations and recommendations which were transmitted to the accelerator operator. In some cases, the specific instrument which yielded a measurement is indicated since measurements made with different instruments do not always agree.

Pupin Physics Laboratory, Columbia

This cyclotron is, nominally, a 10-Mev deuteron accelerator having 36-in. magnet pole pieces and is located in the north side of the Pupin Laboratory basement on the campus. It is shielded by stacks of water cans as shown in the floor plan (Figure 15). Radiation surveys were conducted during two modes of operation. Under the one condition, the 8-Mev deuteron beam was pulsed 4 μ sec out of each 1024 μ sec, the pulses attaining values as high as 700 μ a. The second mode, because of more frequent pulses, produced one-third of the possible average beam current. Results of the first or "low level" survey appear in Table 2; Table 3 shows the "high level" survey findings. Recommendations were based on fast neutron measurements. No quantitative thermal neutron studies were made, though exposed film badges indicated the presence of some thermals by virtue of a high degree of blackening under the cadmium shield in the film badge.

Recommendations: 1) Under the low level operating conditions (Table 2), it was thought that the corridor area in front of the cyclotron vault could be occupied without restriction by informed cyclotron personnel. It was pointed out that because of the lack of positive deterrents, such as interlocking devices, exposure to high radiation levels at the vault entrance was possible. 2) During the so-called high intensity

Figure 15. Plan of the Pupin Physics Laboratory, Columbia University.

Table 2

Radiation levels at Pupin Physics Laboratory, Columbia University (CO-CY),
January 16, 1953. Cyclotron operation: 8-Mev ${}^1\text{H}^2$ on Be to produce
12.4-Mev neutrons (max); cyclotron pulsed 4 μsec of every 1024 μsec
attaining beam currents of about 700 μa (0.4 percent of the time).

Location	Description	Radiation	Fraction MPE*
1	Vault entrance	4.2 mrep/hr 15 mr/hr	11 2.0
2	Vault entrance	1.2 mrep/hr 5 mr/hr	3.0 0.7
6	Water shield void	0.42 mrep/hr	1.1
9	Against shield	Nothing detected	-
10	Against shield	Nothing detected	-
13	Near collimator	0.35 mrep/hr 3 mr/hr	0.9 0.4

operation, it was recommended that no one should pass the fence indicated in the floor plan. Although it was noted that this fence was purely a mechanical device used only at the discretion of the cyclotron operator, it was felt that this rather informal radiation control might be adequate because of the presumably small number of persons directly concerned with cyclotron operation. A review of past film badge records disclosed no sustained significant radiation exposures.

Table 3

Radiation levels at Pupin Physics Laboratory, Columbia University (CO-CY),
January 26, 1953. Cyclotron operation: 1/3 maximum intensity;
12-Mev neutrons by $\text{Be}^9(\text{d},\text{n})\text{B}^{10}$.

Location	Description	Radiation	Fraction MPE
4	Vault entrance	10.7 mrep/hr 160 mr/hr	29 21.3
3	Vault entrance	15.2 mr/hr 250 mr/hr	40.5 33.3
5	Against shield	Nothing detected	-
7	Against shield	Nothing detected	-
8	Against shield	Nothing detected	-
13	Near collimator	21 mrep/hr 150 mr/hr	56 20
14	Behind collimator	Nothing detected	-
15	Outside room 133	Nothing detected	-
11	Fence	Nothing detected	-
16	Control room	Nothing detected	-

Palmer Physical Laboratory, Princeton

The Princeton University frequency modulated (FM) cyclotron is located in a concrete vault in the basement of the physics building on the campus. The magnet has

*Because of the uncertainties in neutron dosimetry, as well as in biological information, an arbitrary factor of two was introduced in calculating the fraction of the MPE in all the summaries.

Table 4

Radiation levels at Palmer Physics Laboratory, Princeton University (PR-CY),
April 7, 1953. Cyclotron operation: 18-Mev $^1\text{H}^1$ on polyethylene to produce
neutrons; beam current = 10^{-8} amp, or about 10 percent of maximum.

Location	Description	Radiation	Fraction MPE
1	Near console stairs	Nothing detected	-
2	3 meters left of collimator	0.80 mrep/hr	2.1
3	1 meter left of collimator	0.80 mrep/hr	2.1
4	Behind scatter chamber	$20 \text{ n}_t/\text{cm}^2\text{-sec}$	1.0
	near entrance (not shown)	No thermals measurable	-
5	Behind end of water shield	Nothing detected	-
6	Escape hatch	$<50 \text{ n}_t/\text{cm}^2\text{-sec}$	-
7	Right of collimator	$540 \text{ n}_t/\text{cm}^2\text{-sec}$	36.0
		$<50 \text{ n}_t/\text{cm}^2\text{-sec}$	-
		4.60 mrep/hr	12.3
8	Work area	$15 \text{ n}_t/\text{cm}^2\text{-sec}$	1.0
		No thermals measurable	-
9	Entrance to No. 8	No thermals measurable	-
10	Balcony over No. 9	$30 \text{ n}_t/\text{cm}^2\text{-sec}$	2.0
		No thermals measurable	-

33-in. diameter pole pieces. This cyclotron is generally operated with a pulsed proton beam with an average beam current between 0.01 and 0.1 μa . Pulses are of a 25- μsec duration and occur about every 500 μsec . During the radiation survey, measurements were made with an 0.01- μa proton beam current and a polyethylene target (Table 4) and a beryllium target (Table 5).

Table 5

Radiation levels at Palmer Physics Laboratory, Princeton University (PR-CY),
April 7, 1953. Cyclotron operation: 18-Mev protons on beryllium to
produce neutrons; beam current = 10^{-8} amp.

Location	Description	Radiation	Fraction MPE
2	3 meters left of collimator	$4000 \text{ n}_t/\text{cm}^2\text{-sec}$	267
11	6 meters left of collimator near console depression	9.2 mrep/hr	24.5

Recommendations: No significant radiation levels were encountered during the use of the polyethylene target except immediately adjacent to the beam collimator. The shielding and radiation practices were quite adequate for the operating and research groups at Princeton. It was noted that the Princeton cyclotron group had availed itself of the Brookhaven National Laboratory off-site fast neutron film badge in March 1953. During cyclotron operation with the thick beryllium target, radiation levels were uniformly high in the experimental area (Locations 2 and 11 in Figure 16). This is an unusual operating procedure conducted outside regular working hours and is scheduled only when neighboring students' areas are not in use.

Figure 16. Plan of the Palmer Physics Laboratory, Princeton University.

S.M. Scaife Cyclotron Laboratory, Pittsburgh

The Pittsburgh cyclotron is a 16-Mev deuteron accelerator which is located partly underground near the University campus in Pittsburgh. The deuteron beam rotates counter-clockwise and then interacts with an appropriate target so oriented that the predominant direction of the radiation is into the side of a hill -- essentially an infinite earth shield. That is, the neutron beam passes from the cyclotron vault through a collimator in an 8-ft-thick water shield into an underground "cave" (cf. floor plan, Figure 17). At the time of the survey, 10-Mev deuterons were permitted to interact with copper to produce 15-Mev neutrons.

Recommendations: First, the adoption of fast neutron personnel monitoring equipment by the Pittsburgh cyclotron group. At the time of the survey, film badges capable of indicating the amounts of beta and gamma radiation dose were in use. Pittsburgh subscribed to the Brookhaven National Laboratory fast neutron film badge service in July 1953.

Secondly, it was recommended that a radiation sign indicating the location of the neutron beam in the "cave" be used. It was pointed out that pencil beams can be peculiarly hazardous because locating them with a survey meter is difficult (Figure 18). Furthermore, it is conceivable that a person wearing a film badge could stand in a narrow beam without exposing his film badge.

It was recommended that any maintenance required inside the pump room not be done during cyclotron operation. If this is not feasible, no person should be permitted to remain in the pump room during cyclotron operation more than 45 minutes in any given week. Since the cyclotron vault door is not interlocked, the installation of an automatic warning device was suggested.

Figure 17. Plan of the Sarah Mellon Scaife Cyclotron Laboratory, Pittsburgh.

Figure 18. An experimental area in the Scaife Laboratory, which is shielded from the cyclotron by a water tank, contains a magnetic analyzer. A "pencil" neutron beam emerges from this magnet to the right.

Table 6

Radiation levels at the Sarah Mellon Scaife Laboratory, University of Pittsburgh (PI-CY),
April 15, 1953. Cyclotron operation: 10-Mev ${}^1\text{H}^2$ on copper to produce
 ~ 15 -Mev neutrons; beam current = 10^{-4} amp.

Location	Description	Radiation	Fraction MPE
1	Contact vault door	40 $\text{n}_f/\text{cm}^2\text{-sec}$ 0.1 mrep/hr	2.7 0.3
2	3 ft from void	150 $\text{n}_f/\text{cm}^2\text{-sec}$ 0.84 mrep/hr	10.0 2.2
3	5 ft from vault door	35 $\text{n}_f/\text{cm}^2\text{-sec}$	2.3
4	Lab doorway	30 $\text{n}_f/\text{cm}^2\text{-sec}$	2.0
5	Head of stairs	0.1 mrep/hr	0.3
6	In beam	70 mrep/hr	187
-	Control room	36 $\text{n}_f/\text{cm}^2\text{-sec}$ 0.1 mrep/hr	2.4 0.3
-	Pump room downstairs	35 mrep/hr	93
-	Paraffin doorway	5.2 mrep/hr	14
-	Paraffin door closed*	Nothing detected	-

*Cyclotron operated with paraffin door closed and pump room generally not occupied.

Table 7

Radiation levels at the Nuclear Research Center, Carnegie Institute of Technology (CI-SC),
April 14, 1953. Cyclotron operation: Beryllium target, meson production;
beam current meter reading = 75-80 μa .

Location	Description	Radiation	Fraction MPE
1	Entrance to excluded area	1550 $\text{n}_f/\text{cm}^2\text{-sec}$ 12 mrep/hr	103 32
2	Shield corner	410 $\text{n}_f/\text{cm}^2\text{-sec}$ 1.95 mrep/hr	27 5.2
3a	Console - front	180 $\text{n}_f/\text{cm}^2\text{-sec}$ 0.98 mrep/hr	12 2.6
3b	Console - behind	86 $\text{n}_f/\text{cm}^2\text{-sec}$ 0.24 mrep/hr	5.7 0.63
4	3 ft from stairs	140 $\text{n}_f/\text{cm}^2\text{-sec}$	9.3
5	Experimental area	70 $\text{n}_f/\text{cm}^2\text{-sec}$ 0.4 mrep/hr	4.7 1.1
6	Vault door	145 $\text{n}_f/\text{cm}^2\text{-sec}$ 0.24 mrep/hr	9.7 0.63
7	10 ft from door	60 $\text{n}_f/\text{cm}^2\text{-sec}$ 0.17 mrep/hr	4.0 0.45
-	Outside double door (Figure 23)	5 mrep/hr	13.3
-	Building (end of proposed fence)	0.9 mrep/hr	2.4
-	Garage (middle door)	0.33 mrep/hr	0.88

Table 8			
Radiation levels at the Nuclear Research Center, Carnegie Institute of Technology (CI-SC), April 16, 1953. Cyclotron operation: No target; beam current meter reading = 75-80 μ a.			
Location	Description	Radiation	Fraction MPE
1	Entrance to excluded area	3 mrep/hr	8.0
8	General work area	~ 10 n _f /cm ² -sec	0.7
9	Beyond end of shield	20 n _f /cm ² -sec	1.3
10	-	75 n _f /cm ² -sec	5.0

Nuclear Research Center, Carnegie Institute of Technology

The 145-in. synchrocyclotron is capable of accelerating protons to energies as high as 440 Mev. It is located in the southeast end of a building in Saxonburg approximately 30 miles from Pittsburgh. Radiation measurements were made during various operating conditions. Tables 7 and 8 give measurements made in 1953 (see floor plan, Figure 19). Tables 9 to 14 are the results of surveys performed in 1954 (see floor plan, Figure 20). It should be noted that this accelerator is one of the largest synchrocyclotrons in terms of the number of persons associated with it, as well as the size of the installation and particle energies possible.

Figure 19. Plan of the Nuclear Research Center synchrocyclotron, Carnegie Institute of Technology, April 1953.

Recommendations (1953): The adoption of the Brookhaven National Laboratory fast neutron personnel monitoring service on a weekly basis was recommended. This service was actually subscribed to in May 1953. It was suggested that the commercial neutron survey meter, used by the Nuclear Research Center, be tested routinely with a known flux of neutrons to verify its calibration. On this early occasion the surveyors found that reliance upon only one neutron detector was likely to give a grossly erroneous estimate of the dose rate. One of the purposes of this survey was to test the efficiency of additional shielding.

As a result of the survey, it was felt that this modified shielding was certainly necessary for safe operation of the accelerator. In fact, it was suggested that personnel occupancy of certain areas be restricted until more shielding was installed.

Finally, it was recommended that, since some of the Carnegie cyclotron workers spend considerably more than 40 hours per week at their duties, the average hourly maximum permissible dose rate should be scaled downward according to the time

Table 9

Radiation levels at the Nuclear Research Center synchrocyclotron,
January 5, 1954 (evening). Operating condition: Meson target (#1);
normal field, counter-clockwise BMLM 185; BMIC: 183.

Location	Instrument*	Neutron flux or dose rate	Fraction MPE
105	ZnS	46 n/cm ² -sec	3.1
106	ZnS	40 n/cm ² -sec	2.7
143	ZnS	40 n/cm ² -sec	2.7
144	ZnS	33 n/cm ² -sec	2.2
145	ZnS	37 n/cm ² -sec	2.5
110	ZnS	58 n/cm ² -sec	3.9
113	ZnS	46 n/cm ² -sec	3.1
112	ZnS	38 n/cm ² -sec	2.5
111	ZnS	33 n/cm ² -sec	2.2
146	ZnS	28 n/cm ² -sec	1.9
115	ZnS	19 n/cm ² -sec	1.3
114	ZnS	28 n/cm ² -sec	1.9
117	ZnS	23 n/cm ² -sec	1.5
116	ZnS	17 n/cm ² -sec	1.1
122	ZnS	44 n/cm ² -sec	2.9
123	ZnS	62 n/cm ² -sec	4.1
126	ZnS	102 n/cm ² -sec	6.8
130	ZnS	49 n/cm ² -sec	3.3
129	ZnS	65 n/cm ² -sec	4.3
128a	ZnS	40 n/cm ² -sec	2.7
128	ZnS	33 n/cm ² -sec	2.2
127	ZnS	35 n/cm ² -sec	2.3
124	ZnS	46 n/cm ² -sec	3.1
120a	ZnS	46 n/cm ² -sec	3.1
120	ZnS	35 n/cm ² -sec	2.3
119	ZnS	23 n/cm ² -sec	1.5
502	ZnS	~10 n/cm ² -sec	0.7
501	ZnS	17 n/cm ² -sec	1.1
503	ZnS	<10 n/cm ² -sec	~0.7
504	ZnS	<10 n/cm ² -sec	~0.7
Corridor (monitor station)	ZnS	<10 n/cm ² -sec	~0.7
Control room (near wall)	ZnS	<10 n/cm ² -sec	~0.7
201	ZnS	~10 n/cm ² -sec	~0.7
218	ZnS	<10 n/cm ² -sec	~0.7
Behind 218 (farthest wall)	ZnS	<10 n/cm ² -sec	~0.7
216	ZnS	<10 n/cm ² -sec	~0.7
Behind 216 (~14 ft)	ZnS	13 n/cm ² -sec	0.9
213	ZnS	<10 n/cm ² -sec	~0.7
Behind 213 (~14 ft)	ZnS	16 n/cm ² -sec	1.1
209	ZnS	19 n/cm ² -sec	1.3
225	ZnS	33 n/cm ² -sec	2.2
Work bench behind magnet oil system	ZnS	13 n/cm ² -sec	0.9
Back doorway	ZnS	16 n/cm ² -sec	1.1
123	CH ₄	38 n/cm ² -sec	2.5
	FND #36	0.75 mrep/hr	2.0
	FND #43	1.12 mrep/hr	3.0
	FND #44	0.97 mrep/hr	3.6

*Instruments used: ZnS-lucite scintillation counter, Raychronix FND #36, #43, #128 and methane counter.

Table 9 (Continued)

Location	Instrument*	Neutron flux or dose rate	Fraction MPE
124	CH ₄	30 n/cm ² -sec	2.0
126	CH ₄	53 n/cm ² -sec	3.5
	ZnS	84 n/cm ² -sec	5.6
130	CH ₄	33 n/cm ² -sec	2.2
120	CH ₄	34 n/cm ² -sec	2.3
146	CH ₄	40 n/cm ² -sec	2.7
113**	CH ₄	37 n/cm ² -sec	2.5
110**	CH ₄	30 n/cm ² -sec	2.0
106**	CH ₄	34 n/cm ² -sec	2.3
	ZnS	42 n/cm ² -sec	2.8
301**	ZnS	84 n/cm ² -sec	5.6
302**	ZnS	172 n/cm ² -sec	11.5
303**	ZnS	120 n/cm ² -sec	8.0
303**	ZnS	124 n/cm ² -sec	8.3
Along fence**	ZnS	11-80 n/cm ² -sec	0.73-5.3
Inside garage**	ZnS	0	-
Inside garage** (west wall)	ZnS	<10 n/cm ² -sec	~0.7
123**	FND #36	0.93 mrep/hr	2.5
	FND #43	1.47 mrep/hr	3.9
	ZnS	61 n/cm ² -sec	4.1
146**	FND #36	0.38 mrep/hr	1.0
	FND #43	0.55 mrep/hr	1.5
	ZnS	33 n/cm ² -sec	2.2
126a**	FND #36	1.18 mrep/hr	3.1
	FND #43	0.89 mrep/hr	2.4
	ZnS	102 n/cm ² -sec	6.8

*Instruments used: ZnS-lucite scintillation counter, Raychronix FND #36, #43, #128 and methane counter.
**Beam current up.

Table 10

Radiation levels at the Nuclear Research Center synchrocyclotron,
January 6, 1954 (evening). Operating condition: No target,
normal beam, BMIC: 48 (100 meg); BMLM: 50.

Location	Instrument	Neutron flux or dose rate	Fraction MPE
111-112	ZnS	~0 n/cm ² -sec	~0.0
115	ZnS	~3 n/cm ² -sec	~0.2
120	ZnS	~7 n/cm ² -sec	~0.5
123	ZnS	35 n/cm ² -sec	2.3
120a	ZnS	19 n/cm ² -sec	1.3
130	ZnS	21 n/cm ² -sec	1.4
101	FND #128	4 mrep/hr	10.7
102	FND #128	6 mrep/hr	16.0
103	FND #128	3 mrep/hr	8.0
104	FND #128	-	-
129	ZnS	33 n/cm ² -sec	2.2
128a	ZnS	21 n/cm ² -sec	1.4
128	ZnS	19 n/cm ² -sec	1.3

Table 10 (Continued)

Location	Instrument	Neutron flux or dose rate	Fraction MPE
127-124 (area)	ZnS	16-21 n/cm ² -sec	1.1-1.4
501	ZnS	<10 n/cm ² -sec	<0.7
201	ZnS	<10 n/cm ² -sec	<0.7
213 (center line)	ZnS	<10 n/cm ² -sec	<0.7
216	ZnS	<10 n/cm ² -sec	<0.7
Bench behind 212	ZnS	16 n/cm ² -sec	1.1
Back door*	ZnS	10-21 cm ² -sec	0.7-1.4
End of cooling tower system	ZnS	21 n/cm ² -sec	1.4
General area	ZnS	10-21 n/cm ² -sec	0.7-1.4
Centrifuge	ZnS	31 n/cm ² -sec	2.1
302-303	ZnS	10-21 n/cm ² -sec	0.7-1.4
Garage	ZnS	not detectable	~0.0
Console	ZnS	<10 n/cm ² -sec	<0.7
Bench behind 212*	ZnS	39 n/cm ² -sec	2.6
	FND #128	0.69 mrep/hr	1.8
Bench in back*	ZnS	39 n/cm ² -sec	2.6
Centrifuge*	ZnS	84 n/cm ² -sec	5.6
213*	ZnS	16 n/cm ² -sec	1.1
220*	ZnS	46 n/cm ² -sec	3.1
202-218*	ZnS	19 n/cm ² -sec	1.3
216*	ZnS	21 n/cm ² -sec	1.4
Control room*	ZnS	~10 n/cm ² -sec	~0.7
Equipment room bay*	ZnS	17 n/cm ² -sec	1.1
123*	ZnS	72 n/cm ² -sec	4.8
120a*	ZnS	43 n/cm ² -sec	2.9
128*	ZnS	47 n/cm ² -sec	3.1

*Beam up: Beam monitor - 48 to 80. Log meter - 50 to 80.

Table 11

Radiation levels at the Nuclear Research Center synchrocyclotron,
January 6, 1954 (morning). Operating condition: Neutron target;
normal field; BMIC: 30 (10 meg); BMLM: 310.

Location	Instrument	Neutron flux or dose rate	Fraction MPE
101-102	FND #36	100 mrep/hr	267
	FND #128	100 mrep/hr	267
	ZnS	-	-
3 feet high 105	ZnS	31 n/cm ² -sec	2.1
106	ZnS	21 n/cm ² -sec	1.4
105a	ZnS	31 n/cm ² -sec	2.1
143 (crack)	ZnS	13 n/cm ² -sec	0.9
144	ZnS	<10 n/cm ² -sec	<0.7
108	ZnS	21 n/cm ² -sec	1.4
145	ZnS	14 n/cm ² -sec	0.9
110	ZnS	12 n/cm ² -sec	0.8
112	ZnS	~10 n/cm ² -sec	~0.7
113	ZnS	~10 n/cm ² -sec	~0.7
114	ZnS	~10 n/cm ² -sec	~0.7
116a	ZnS	~10 n/cm ² -sec	~0.7
115	ZnS	<10 n/cm ² -sec	<0.7

Table 11 (Continued)

Location	Instrument	Neutron flux or dose rate	Fraction MPE
118	ZnS	~ 10 n/cm ² -sec	~ 0.7
120	ZnS	19 n/cm ² -sec	1.3
121	ZnS	21 n/cm ² -sec	1.4
120a	ZnS	42 n/cm ² -sec	2.8
123	ZnS	55 n/cm ² -sec	3.7
122	ZnS	43 n/cm ² -sec	2.9
126	ZnS	80 n/cm ² -sec	5.3
126a	ZnS	97 n/cm ² -sec	6.5
130	ZnS	46 n/cm ² -sec	3.1
129a	ZnS	69 n/cm ² -sec	4.6
129	ZnS	52 n/cm ² -sec	3.5
128a	ZnS	38 n/cm ² -sec	2.5
128	ZnS	31 n/cm ² -sec	2.1
501	ZnS	~ 10 n/cm ² -sec	~ 0.7
502	ZnS	~ 10 n/cm ² -sec	~ 0.7
503	ZnS	< 10 n/cm ² -sec	< 0.7
504	ZnS	< 10 n/cm ² -sec	< 0.7
505 (throughout room)	ZnS	< 10 n/cm ² -sec	< 0.7
Corridor monitor station	ZnS	< 10 n/cm ² -sec	< 0.7
Control room	ZnS	< 10 n/cm ² -sec	< 0.7
Room #128	ZnS	< 10 n/cm ² -sec	< 0.7
201	ZnS	14 n/cm ² -sec	0.9
201a	ZnS	< 10 n/cm ² -sec	< 0.7
216	ZnS	< 10 n/cm ² -sec	< 0.7
14 feet behind 216	ZnS	~ 10 n/cm ² -sec	~ 0.7
213 (mid-pt of wall)	ZnS	~ 10 n/cm ² -sec	~ 0.7
14 feet behind 212	ZnS	17 n/cm ² -sec	1.1
211	ZnS	12 n/cm ² -sec	0.8
3 feet behind 209	ZnS	60 n/cm ² -sec	4.0
205	ZnS	17 n/cm ² -sec	1.1
Equipment room (back door)	ZnS	14 n/cm ² -sec	0.9
Bench near door	ZnS	19 n/cm ² -sec	1.3
End of cooling tower system	ZnS	26 n/cm ² -sec	1.7
Desk near bench	ZnS	21 n/cm ² -sec	1.4
Right of 302 (small door)	ZnS	73 n/cm ² -sec	4.9
303	ZnS	145 n/cm ² -sec	9.7
Along fence	ZnS	19-33 n/cm ² -sec	1.3-2.2
Garage bench	ZnS	Not detectable	~ 0.0
Garage (general)	ZnS	Not detectable	~ 0.0
Repeat with other instruments			
112	CH ₄	16 n/cm ² -sec	1.1
	ZnS	12 n/cm ² -sec	0.8
	FND #36	0.22 mrep/hr	0.6
126a (fire hose)	CH ₄	29 n/cm ² -sec	1.9
	ZnS	88 n/cm ² -sec	5.9
	FND #36	0.85 mrep/hr	2.3
128a	CH ₄	17 n/cm ² -sec	1.1
	ZnS	31 n/cm ² -sec	2.1
	FND #36	0.36 mrep/hr	0.96
Equipment room	CH ₄	~ 10 n/cm ² -sec	~ 0.70
Bench (behind 212)	ZnS	18 n/cm ² -sec	1.2
		21 n/cm ² -sec	1.4
	FND #36	0.22 mrep/hr	
		0.24 mrep/hr	0.6

Table 12

Radiation levels at the Nuclear Research Center synchrocyclotron, January 5, 1953.
 Operating condition: Meson target (π^+); reverse field; BMIC: 65 μ a, (100 meg).
 Raychronix fast neutron dosimeter (#128) used for survey; all measurements
 made approximately 4 ft above floor of Cyclotron Room.

Location	Neutron level mrep/hr	Fraction MPE	Location	Neutron level mrep/hr	Fraction MPE
110	.24	0.64	127	2.85	7.60
112	.59	1.57	128	2.9	7.73
113	.46	1.23	129	5.0	13.33
114	.54	1.44	130	3.0	8.00
115	2.3	6.13	140	18.0	48.00
116	.80	2.13	201	.70	1.87
117	3.0	8.00	202	.12	0.32
118	1.58	4.21	204	.12	0.32
119	.84	2.24	206	.21	0.56
120	3.0	8.00	207	.67	1.79
121	5.0	13.33	501	.73	1.95
122	30.0	80.0	502	.22	0.59
123	20.0	53.33	503	.35	0.93
124	6.0	16.00	504	.17	0.45
125	8.0	21.33	505	.70	1.87
126	15.0	40.00	304	.78	2.08

Table 13

Radiation levels at the Nuclear Research Center synchrocyclotron, January 5, 1954.
 Operating condition: May have been operating with both meson and neutron targets.

Location	Instrument	Neutron flux or dose rate	Fraction MPE
101-103	FND #128	-	-
	FND #43	13.7	36.5
	FND #36	19.2	51.2
	FND #44	18.7	49.9
	FND #139	-	-
	ZnS	1560 n/cm ² -sec	104
103	FND #128	-	-
	FND #36	8.5	22.7
	FND #139	-	-
	FND #44	-	-
	FND #43	4.8	12.8
	ZnS	670 n/cm ² -sec	44.7
103 Repeat	FND #128	-	-
	FND #36	10.7	28.5
	FND #139	-	-
	FND #44	-	-
	FND #43	4.0	10.7
	ZnS	670 n/cm ² -sec	44.7
103 Repeat (1 hr delay)	FND #128	-	-
	FND #36	19.2	51.2
	FND #139	-	-
	FND #44	18.7	49.9
	FND #43	13.7	36.5
	ZnS	1560 n/cm ² -sec	104

Table 13 (Continued)

Location	Instrument	Neutron flux or dose rate	Fraction MPE
106	CH ₄	24 n/cm ² -sec	1.6
(4 ft high)	ZnS	<10 n/cm ² -sec	<0.7
105	CH ₄	37 n/cm ² -sec	2.5
	ZnS	20 n/cm ² -sec	1.3
	FND #36	0.50 mrep/hr	1.9
110	CH ₄	<10 n/cm ² -sec	<0.7
	ZnS	<10 n/cm ² -sec	<0.7
113	CH ₄	~10 n/cm ² -sec	~0.7
115	CH ₄	13 n/cm ² -sec	0.9
	ZnS	<10 n/cm ² -sec	<0.7
123	CH ₄	67 n/cm ² -sec	4.5
	ZnS	37 n/cm ² -sec	2.5
123	FND #128	0.505 mrep/hr	-
	FND #36	0.57 mrep/hr	2.2
301	ZnS	21-33 n/cm ² -sec	1.4-2.2
	FND #36	0.69 mrep/hr	2.6
	FND #128	0.67 mrep/hr	-
302	ZnS	320 n/cm ² -sec	21.3
	FND #36	3 mrep/hr	11.4
		2.35 mrep/hr	8.9
	FND #128	5 mrep/hr	-
Garage	ZnS	Nothing detected	
108	ZnS	<10 n/cm ² -sec	<0.7
112	ZnS	~10 n/cm ² -sec	~0.7
130	ZnS	31 n/cm ² -sec	2.1
129	ZnS	26 n/cm ² -sec	1.7
128	ZnS	19 n/cm ² -sec	1.3
128a	ZnS	19 n/cm ² -sec	1.3

Table 14

Radiation levels at the Nuclear Research Center synchrocyclotron.
One-fifth to one-sixth radiation levels inside vault after shutdown
2:00 a.m. to 9:30 a.m., January 6, 1954.

Location	SIC-17C (Juno)	Fraction MPE	SIC-7C (CP meter)	Fraction MPE
A	41 mr/hr	5.46	42 mr/hr	5.60
B	95 mr/hr	12.6	100 mr/hr	13.4
C	220 mr/hr	29.4	380 mr/hr	50.7
D	170 mr/hr	22.7	200 mr/hr	26.7
E	70 mr/hr	9.35	75 mr/hr	10.0
Center (max)	700 mr/hr	93.5	1100 mr/hr	

N.B. - Highest level in any location was about 1 r/hr.

actually worked in any given week. Because of the uncertainties in the measurement of fast neutron levels, as well as in the knowledge of biological damage due to fast neutrons, it was suggested that the Carnegie group adjust personnel occupancy time so that accumulated doses remain well below the maximum permissible dose.

Figure 20. Plan of the Nuclear Research Center synchrocyclotron, Carnegie Institute of Technology, January 1954.

Recommendations (1954): On the basis of the measurements recorded in Table 14, as well as sustained significant gamma radiation exposures (of the order of two-thirds maximum permissible dose) reported by Brookhaven over a period of several months, it was recommended that operations inside the vault, during the shutdown, be conducted so that personnel exposures are kept well below 75 mr (25 percent of maximum permissible dose) in any given week, since these same persons may also be exposed to unknown quantities of fast neutrons. Furthermore, it was pointed out that the experimental area (100 area) shown in the floor plan, Figure 20, should not be used on a fulltime occupancy basis.

It was suggested that the following criteria be used in the design of new cyclotron shields at sites under contract to NYOO. For regularly occupied areas (Figures 21 and 22), i.e., areas generally occupied 40 hours per week, the shielding should be sufficient to reduce radiation levels to not more than 25 percent of the maximum permissible weekly dose as measured by currently available fast neutron instruments. If this amount of shielding is not consistent with the economics of the site under consideration, the occupancy time should be adjusted to insure that 25 percent of the weekly maximum permissible exposure is not exceeded. Finally it was recommended that the Brookhaven National Laboratory fast neutron film badge service be extended to personnel in the equipment room (200 area). In this same area, the west wall shield should be built up to the ceiling and extended to the centrifuge area (Location 208, Figure 20).

Figure 21 This is the northwest entrance to the Nuclear Research Center's synchrocyclotron vault. The warning light above the entrance is shown, and the local shield blocks near the stairway.

Figure 22 The work area northeast of the Nuclear Research Center's synchrocyclotron is bounded (in the background) by movable local shielding blocks and an electric eye. The surveyor is standing by the control panel.

Figure 23 Outside the Nuclear Research Center's synchrocyclotron building, to the east, is a chain link fence and earth mound which enclose an excluded area. A flashing light above the door indicates "beam on."

Nevis Cyclotron Laboratory, Columbia University

The Nevis accelerator is a 164-in. frequency modulated cyclotron capable of accelerating protons to an energy of 385 Mev. The Nevis cyclotron and its control room are in separate buildings to permit remote operation. The cyclotron area is entered by means of a door located near the roof level at the southeast corner of the cyclotron building. By descending a stairway, one arrives at the main floor of the cyclotron building at the southeast corner of the shield. The experimental area is located in the northern side of the building (Figure 24). Outside the east wall of the cyclotron building is a large earth mound between the cyclotron and control buildings.

Originally, the Nevis cyclotron was shielded by 6 ft of concrete. At the time of the survey, the shield between the machine and the experimental area had been replaced by essentially 8 ft of iron. Some local shielding had been located south of the accelerator inside the vault. This local shielding reduces the neutron intensities caused by the four sets of graphite clippers, which protect the rotating condenser and dee walls from the proton beam. Radiation measurements were made during both

Table 15

Radiation levels at the Nevis Cyclotron Laboratory, Columbia University (CO-SC),
May 18, 1953. Cyclotron operation: π^- production, beryllium target,
ratemeter monitor = 16-20.

Location	Description	Radiation	Fraction MPE
1	Experimental area	55 n_f/cm^2 -sec	3.7
2	Experimental area	75 n_f/cm^2 -sec	5.0
3	Experimental area	150 n_f/cm^2 -sec	10
4	Experimental area	55 n_f/cm^2 -sec	3.7
5	Experimental area	60 n_f/cm^2 -sec	4.0
		1.3 mrep/hr	3.4
6	Experimental area	85 n_f/cm^2 -sec	5.7
		1.3 mrep/hr	3.4
7	Experimental area	40 n_f/cm^2 -sec	2.7
		0.95 mrep/hr	2.5
8	Experimental area	60 n_f/cm^2 -sec	4.0
		0.95 mrep/hr	2.5
9	Experimental area	70 n_f/cm^2 -sec	4.7
10	Experimental area	30 n_f/cm^2 -sec	2.0
		0.87 mrep/hr	2.3
11	Experimental area	40 n_f/cm^2 -sec	2.7
		0.91 mrep/hr	2.4
12	Experimental area	55 n_f/cm^2 -sec	3.7
13	Experimental area	~ 20 n_f/cm^2 -sec	1.3
14	Experimental area	40 n_f/cm^2 -sec	2.7
15	Experimental area	~ 20 n_f/cm^2 -sec	1.3
16	Experimental area	~ 20 n_f/cm^2 -sec	1.3
17	Experimental area	25 n_f/cm^2 -sec	1.7
18	West side cyclotron	180 n_f/cm^2 -sec	12.0
		3.7 mrep/hr	9.6
19	Lavatory	300 n_f/cm^2 -sec	20
		5 mrep/hr	13
	Stairs - first landing	800 n_f/cm^2 -sec	53
		10 mrep/hr	26
	Stairs - top landing	500 n_f/cm^2 -sec	33
		13 mrep/hr	34

Figure 24. Double door is the entrance to the experimental area on north side of the Nevis synchrocyclotron.

Figure 25. A lavatory located in the south portion of the Nevis synchrocyclotron building was subject to significant neutron levels.

Figure 26. The Nevis cyclotron, Columbia University.

Figure 27. The Nevis cyclotron, Columbia University.

Table 16

Radiation levels at the Nevis Cyclotron Laboratory, Columbia University,
May 20, 1953. Cyclotron operation: π^+ production, beryllium target,
ratemeter monitor = 13-16.

Location	Description	Radiation	Fraction MPE
1	Experimental area	145 n_f/cm^2 -sec $\sim 50 n_f/cm^2$ -sec 1.8 mrep/hr	9.7 4.7
2	Experimental area	$\sim 50 n_f/cm^2$ -sec 0.66 mrep/hr	3.3 1.7
3	Experimental area	68 n_f/cm^2 -sec 0.66 mrep/hr	4.5 1.7
4	Experimental area	30 n_f/cm^2 -sec $\sim 100 n_f/cm^2$ -sec 0.52 mrep/hr	2.0 1.3
5	Experimental area	100 n_f/cm^2 -sec 130 n_f/cm^2 -sec 1.0 mrep/hr	6.7 2.6
6	West side area	350 n_f/cm^2 -sec 100 n_f/cm^2 -sec 3.6 mrep/hr	23.3 9.4
7	West side area	260 n_f/cm^2 -sec 6.0 mrep/hr	17.3 15.6
8	West side area	250 n_f/cm^2 -sec	16.7
9	Lavatory	150 n_f/cm^2 -sec 1.75 mrep/hr	16.7 4.6
	Stairs - first landing	380 n_f/cm^2 -sec 3.8 mrep/hr	25.3 9.9
	Stairs - top landing	$\sim 100 n_f/cm^2$ -sec 2.1 mrep/hr	6.7 5.5

negative meson (clockwise beam) and positive meson production (counter-clockwise beam).

Recommendations: Under the conditions of the survey, persons in areas to the north, west, and south of the cyclotron are subject to radiation levels in excess of the maximum permissible. It was suggested that occupancy times be regulated to avoid continuing exposure to high levels of radiation. The use of the Brookhaven National Laboratory film badge was suggested. The presence of narrow radiation beams was noted, and the value of appropriately positioned radiation signs to locate narrow beams was pointed out. It was noted that the south area of the cyclotron building was essentially a passageway, and adequate warning signs were in appropriate places (Figure 25).

If the cyclotron is operated at significantly higher intensities than were encountered at this time, then additional shielding would almost certainly be required or exclusively remote operation would have to be undertaken.

Massachusetts Institute of Technology

Radiation surveys were performed at the following MIT particle accelerators:

- 1) The 42-in. pole piece diameter, fixed frequency cyclotron for accelerating deuterons to 15 Mev (Figure 28).
- 2) The 12-Mev positive ion electrostatic generator (Building 58, Figure 29).
- 3) The 5-Mev positive ion Van de Graaff (Rockefeller Generator).

Table 17

Radiation levels at MIT's 42-in. cyclotron, October 27, 1953. Operating conditions:
15-Mev deuterons on Be target to produce approximately 19-Mev neutrons;
beam current = 60 μ a.

Position	Remarks	Instrument	Average corrected dose or flux rate*	Fraction MPE
1	Recess for vault door at wall	CH ₄	480 n/cm ² -sec	32.0
		ZnS	140 n/cm ² -sec	9.3
		#36	3.6 mrep/hr	9.6
		#123	5.0 mrep/hr	13.3
2	Recess for vault door at wall	CH ₄	110 n/cm ² -sec	7.3
		ZnS	46 n/cm ² -sec	3.1
		#36	2.2 mrep/hr	5.9
		#123	2.7 mrep/hr	7.2
		#130	2.7 mrep/hr	7.2
2a	Same as 2; 3 ft from wall	CH ₄	35 n/cm ² -sec	2.3
		ZnS	21 n/cm ² -sec	1.4
3	Inside scattering chamber	ZnS	165 n/cm ² -sec	11.0
3a	Scattering chamber about 15 in. behind plumbing	CH ₄	90 n/cm ² -sec	6.0
		ZnS	600 n/cm ² -sec	40.0
		#36	8.10 mrep/hr	21.6
3b	Adjacent to plumbing	ZnS	140 n/cm ² -sec	9.3
3c	Aperture to scattering chamber	ZnS	>4000 n/cm ² -sec	>267
		#36	105 mrep/hr	280
		#123	160 mrep/hr	568
		#130	140 mrep/hr	373
4	At console	CH ₄	<2 n/cm ² -sec	<0.1
		ZnS	~0	<0.1
4a	Same as 4 with door to scattering chamber open	CH ₄	5 n/cm ² -sec	0.3
5	Corridor between safe and scattering chamber	ZnS	15 n/cm ² -sec	1.0
6	Between radiochemical bench and cabinet	CH ₄	<2 n/cm ² -sec	<0.1
8	Outside building near tracks	ZnS	46 n/cm ² -sec	3.1
		Juno	20 mr/hr	2.67
9	Outside building as shown	ZnS	21 n/cm ² -sec	1.4
		Juno	12 mr/hr	1.60
*Correction Factors of 1.5 and 2.0 were applied to #36, #123, and #130, respectively.				

Table 18

Radiation levels at MIT's 42-in. cyclotron, October 28, 1953. Operating conditions:
15-Mev deuterons on Mg target; 0.2-0.3 μ a split beam into scattering chamber;
beam current 25 μ a, 21-Mev neutrons.

Position	Remarks	Instrument	Average corrected dose or flux rate	Fraction MPE
1	See Table 17	CH ₄ ZnS	100 n/cm ² -sec 66 n/cm ² -sec	6.7 4.4
1r	3 ft from Position 1, along wall	ZnS	<5 n/cm ² -sec	<0.3
1s	6 ft from Position 1, along wall	ZnS	<5 n/cm ² -sec	<0.3
1t	9 ft from Position 1, along wall	ZnS	7 n/cm ² -sec	0.5
2	See Table 17	ZnS	46 n/cm ² -sec	3.1
4	See Table 17	CH ₄ ZnS	10 n/cm ² -sec 10 n/cm ² -sec	0.7 0.7
5	See Table 17	ZnS	53 n/cm ² -sec	3.5
6	See Table 17	ZnS	15 n/cm ² -sec	1.0
7	Between radiochemical bench and cabinet as shown	ZnS	15 n/cm ² -sec	1.0
10	See Position 7 as shown	ZnS	21 n/cm ² -sec	1.4
11	At entrance to scattering chamber as shown	ZnS	21 n/cm ² -sec	1.4

Table 19

Radiation levels at MIT's 5-Mev positive ion Van de Graaff (Rockefeller Generator),
October 28, 1953. Operating conditions: 2- to 3- μ a proton beam; 1.9-Mev H¹
on Li⁷, 0.2- to 0.3- Mev neutrons.

Position	p energy Mev	n energy Mev	BF ₃ c/m	ZnS n/cm ² -sec	#36	#123	Juno
1. Between tank and stairwell	1.9 2.26 3.07	0.125 0.531 1.38	6 x 10 ³ 4.7 x 10 ⁴ 3.8 x 10 ⁴	~0 ~0 ~0	~0 ~0 ~0	- - -	~0 ~0 ~0
2. Downstairs 3 to 4 ft away from beam	1.9 2.26 3.07	0.125 0.531 1.38	6 x 10 ³ 4.7 x 10 ⁴ 3.8 x 10 ⁴	~0 ~0 ~0	- - -	- - -	- - -
3. Six in. away from beam	1.9 2.26 3.07	0.125 0.531 1.38	6 x 10 ³ 4.7 x 10 ⁴ 3.8 x 10 ⁴	- - ~15	- - -	- 2.5 mrep/hr 3.3 mrep/hr	- - -
4. In beam	1.9 2.26 3.07	0.125 0.531 1.38	6 x 10 ³ 4.7 x 10 ⁴ 3.8 x 10 ⁴	~0 ~36 ~80	- - -	- - 7.3 mrep/hr	- - -

Table 20

Radiation levels at MIT's 12-Mev positive ion accelerator (Building 58),
October 29, 1953. Operating conditions*: 6.5-Mev protons; target
beam current .01 to 0.1 μ a; Al target; approximately 1-Mev neutrons.

Position	Remarks	Instrument	Average corrected dose of flux rate	Fraction MPE
1	South surface of Van de Graaff terminal	Juno ZnS	400 mr/hr ~ 0	53.3 <0.10
2	North surface of Van de Graaff terminal	Juno ZnS	1800 mr/hr 33 n/cm ² -sec	240 2.2
3	West surface of Van de Graaff terminal	Juno ZnS	1000 mr/hr 21 n/cm ² -sec	133 1.4
4	Approximately 15 ft from terminal as shown	Juno ZnS	10 mr/hr ~ 0	1.33 <0.10
5	At water window to 12-Mev lab	CH ₄	<2 n/cm ² -sec	<0.10
Target changed at 1345				
6	At door to 12-Mev lab	CH ₄	<2 n/cm ² -sec	<0.10
7	Neighborhood of beam in 12-Mev lab	ZnS	33 n/cm ² -sec	2.2
*With this type of accelerator, the same nominal operating condition can give entirely different profiles of scattered radiation. This fact was called to our attention by Professor Buechner.				

Table 21

Radiation levels at MIT's 12-Mev positive ion accelerator, October 29, 1953.
Operating conditions: Same as for Table 20 with 6.5-Mev deuterons.

Position	Remarks	Instrument	Average corrected dose or flux rate	Fraction MPE
1	South surface of Van de Graaff	Juno	400 mr/hr	53.3
1a	East surface of Van de Graaff terminal	Juno	350 mr/hr	46.7
2	North surface of Van de Graaff terminal	Juno	2500 mr/hr	333
3	West surface of Van de Graaff terminal	Juno	1400 mr/hr	187
8	Inside door to 12-Mev lab	ZnS	21 n/cm ² -sec	1.4
9	Outside door to 12-Mev lab	ZnS BF ₃	10 n/cm ² -sec 70 n/cm ² -sec	0.7 4.7
10	Inside 12-Mev lab at position shown	ZnS	>4000 n/cm ² -sec	>267
11	At duct opening in shielding of 12-Mev lab	CH ₄ #36 #130 BF ₃	15 n/cm ² -sec 0.32 mrep/hr 0.40 mrep/hr 35 n/cm ² -sec	1.0 0.9 1.1 2.3

Figure 28. The Massachusetts Institute of Technology cyclotron.

Figure 29. The Massachusetts Institute of Technology 12-Mev positive ion accelerator.

A survey of the 340-Mev electron synchrotron was not performed because of the erratic action of the neutron counters. In particular, the methane proportional and zinc-sulfide-lucite scintillation counters gave spurious "neutron" responses. These were attributed to x-ray "pile-up" -- that is, the radiation appeared in sufficiently intense bursts to override the bias setting of the discriminator.

Recommendations: The radiation survey, as well as the Brookhaven National Laboratory film badge records, points to good control of radiation hazards at the MIT particle accelerators. Well illustrated at this institution is the merit of having an independent group responsible for radiological safety.

Nuclear Research Laboratory, Brown University

The Brown University Cockcroft-Walton linear accelerator produces neutrons with energies of about 14 Mev by the $H^3(d,n)He^4$ reaction. The deuterons can be accelerated to energies of 250 kev, although the radiation surveys were conducted during the use of 120-kev and 150- to 160-kev deuterons. It should be noted that the first survey (Table 22) was performed during the first production of neutrons by this accelerator. The Brown accelerator is located in a fenced-in field inside a brick building (Figure 30). The control building is located in one corner of the field, for remote operation of the accelerator.

Recommendations (4/8/54): It was recommended that 1) a beta-gamma survey meter be available for use in the accelerator building during shutdown; 2) the Brookhaven neutron film badge be used for personnel monitoring; 3) the operator be sure that all persons in the area are in the control building prior to start-up.

These recommendations were implemented by June 1954.

Recommendations (6/23/54): It was suggested that 1) a fast neutron survey meter should be available for use at this site; 2) the installation of signs indicating "beam-on" should be considered.

Table 22			
Radiation levels at the Nuclear Research Laboratory, Brown University (BR-CW), April 8, 1954. Cockcroft-Walton operation: 0.120-keV $^1\text{H}^2$ on $^1\text{H}^3$ to produce ~ 14 -MeV neutrons; beam current ~ 1 ma.			
Location	Description	Radiation	Fraction MPE
1	Near #1 outside control building door	$5 \text{ n}_f/\text{cm}^2\text{-sec}$	0.3
-	50 ft west on accelerator building door	$200\text{-}400 \text{ n}_f/\text{cm}^2\text{-sec}$	-
-	East fence near accelerator building	$30 \text{ n}_f/\text{cm}^2\text{-sec}$	2.0
-	Near accelerator column 5 minutes after shutdown	5 mr/hr^*	-
-	10 minutes after shutdown	2 mr/hr^*	-
*Since this date was that of the first neutron production at the Brown accelerator, the radiation near the column was attributed to newly activated and short-lived isotopes.			

Table 23			
Radiation levels at Brown University Nuclear Research Laboratory (BR-CW) June 23, 1954. Cockcroft-Walton operation: 0.15 to 0.16 $^1\text{H}^2$ on $^1\text{H}^3$ to produce ~ 14 -MeV neutrons.			
Location	Description	Radiation	Fraction MPE
1	Control room	$6 \text{ n}_f/\text{cm}^2\text{-sec}$	0.4
2	Along walk	$10 \text{ n}_f/\text{cm}^2\text{-sec}$	0.7
3	Along walk	$20 \text{ n}_f/\text{cm}^2\text{-sec}$	1.3
4	Along walk	$22 \text{ n}_f/\text{cm}^2\text{-sec}$	1.5
5	Opposite door	$33 \text{ n}_f/\text{cm}^2\text{-sec}$ 2 mrep/hr^*	2.2 5.3
6	Northwest corner of building	$130 \text{ n}_f/\text{cm}^2\text{-sec}$	8.7
7	Opposite door	$93 \text{ n}_f/\text{cm}^2\text{-sec}$ 5.3 mrep/hr^*	6.2 14.1
*Tissue equivalent ionization chamber measurements.

Figure 30. The Cockcroft-Walton accelerator building (Brown University) is entered through this excluded area near Position 7.

Figure 31. The Nuclear Research Laboratory, Brown University.

Sloane Physics Laboratory, Yale University

The Yale cyclotron is a 4-Mev deuteron accelerator (28-in. pole piece diameter) located in room 27 of the basement of Sloane Laboratory (cf. floor plan, Figures 32 and 33) on the campus. The control area is nearby in room 26. Directly above the cyclotron are two lecture rooms (51 and 52), one of which was in restricted use during times of cyclotron operation. Details of the surveys are listed in Tables 24 and 25.

Recommendations: Improvements in the Yale cyclotron have resulted in an augmented beam current and, consequently, increased stray radiation levels inside and outside Sloane. 1) It was suggested that radiation levels in a public, uncontrolled area

Figure 32. The first floor of the Sloane Physics Laboratory, Yale University.

Figure 33. The basement of the Sloane Physics Laboratory, Yale University.

Table 24

Radiation levels at Sloane Physics Laboratory, Yale University (YA-CY),
December 2, 1953. Cyclotron operation: 4-Mev ${}^1\text{H}^2$ on lead to produce
 ~ 5.5 -Mev neutrons; split beam into analyzer; beam current = $\sim 5 \mu\text{a}$.

Location	Description	Radiation	Fraction MPE
1	Vault entrance	72 $\text{n}_f/\text{cm}^2\text{-sec}$ 22.5 mrep/hr	4.8 60
2	Vault entrance	1200 $\text{n}_f/\text{cm}^2\text{-sec}$ 105 mrep/hr	80 280
6	Vault entrance center, 6 ft high	100 $\text{n}_f/\text{cm}^2\text{-sec}$ 15 mrep/hr	6.7 40
8	Pump room	22 $\text{n}_f/\text{cm}^2\text{-sec}$	1.5
9	Pump room	250 $\text{n}_f/\text{cm}^2\text{-sec}$ 10.5 mrep/hr	16.7 28
10	Pump room	29 $\text{n}_f/\text{cm}^2\text{-sec}$	1.9
12	Hallway	10 $\text{n}_f/\text{cm}^2\text{-sec}$	0.7
13	Foot of stairway	22 $\text{n}_f/\text{cm}^2\text{-sec}$	1.5
15	Outside walk atop wall	120 $\text{n}_f/\text{cm}^2\text{-sec}$ 19 mrep/hr	8.0 50.7
16	Outside walk atop wall	30 $\text{n}_f/\text{cm}^2\text{-sec}$ 2.8 mrep/hr	2.0 7.5
17	Near console	$<10 \text{ n}_f/\text{cm}^2\text{-sec}$	0.7
18	Doorway, room 51	22 $\text{n}_f/\text{cm}^2\text{-sec}$ 6 mrep/hr	1.5 16.0
19	Southwest corner, room 51	35 $\text{n}_f/\text{cm}^2\text{-sec}$ 5.2 mrep/hr	2.3 13.9
20	Doorway, room 52	10 $\text{n}_f/\text{cm}^2\text{-sec}$ 3.3 mrep/hr	0.7 8.8
22	Library, room 53	Nothing detected	-
23	Room 45	Nothing detected	-
24	Room 51	29 $\text{n}_f/\text{cm}^2\text{-sec}$ 9 mrep/hr	- -
25	Room 52	22 $\text{n}_f/\text{cm}^2\text{-sec}$	-
26	Corridor	10 $\text{n}_f/\text{cm}^2\text{-sec}$	0.7

Table 25

Radiation levels at Sloane Physics Laboratory, Yale University (YA-CY),
December 9, 1953. Cyclotron operation: 4-Mev ${}^1\text{H}^2$ on Be-Cu target
to produce neutrons; beam current = 25 to 30 μa .

Location	Description	Radiation	Fraction MPE
1	Vault entrance	130 $\text{n}_f/\text{cm}^2\text{-sec}$ 7.5 mrep/hr	8.7 20.0
2	Vault entrance	175 $\text{n}_f/\text{cm}^2\text{-sec}$ 56 mrep/hr	11.7 149
3	Right of vault entrance	38 $\text{n}_f/\text{cm}^2\text{-sec}$ 0.8 mrep/hr	2.5 2.1
4	Console	Nothing detected	-
5	Control room doorway	Nothing detected	-
6	Pump room doorway	70 $\text{n}_f/\text{cm}^2\text{-sec}$ 2.4 mrep/hr	4.7 6.4
7	Pump room	22 $\text{n}_f/\text{cm}^2\text{-sec}$ 4.5 mrep/hr	1.5 12.0
8	Behind HV transformer	10 $\text{n}_f/\text{cm}^2\text{-sec}$ 0.33 mrep/hr	0.7 0.9
9	Near HV transformer	76 $\text{n}_f/\text{cm}^2\text{-sec}$ 2.03 mrep/hr	5.1 5.4
10	Pump room, rear	46 $\text{n}_f/\text{cm}^2\text{-sec}$	3.1
11	Door, room 28	170 $\text{n}_f/\text{cm}^2\text{-sec}$ 4.65 mrep/hr	11.3 12.4
12	Blocked-up door, room 27	12 $\text{n}_f/\text{cm}^2\text{-sec}$ 0.46 mrep/hr	0.8 1.2
13	Foot of stairs	14 $\text{n}_f/\text{cm}^2\text{-sec}$	0.9
14	Main door, Sloane Laboratory	Nothing detected	-
15	Outside walk (maximum radiation)	250 $\text{n}_f/\text{cm}^2\text{-sec}$ 13.9 mrep/hr	16.7 37.1
16	Outside walk	330 $\text{n}_f/\text{cm}^2\text{-sec}$ 3.4 mrep/hr	22.0 9.1
18	Doorway, room 51	61 $\text{n}_f/\text{cm}^2\text{-sec}$ 2.1 mrep/hr	4.1 5.6
19	Room 50, rear	165 $\text{n}_f/\text{cm}^2\text{-sec}$ 4.7 mrep/hr	11.0 12.5
Thermal neutron levels for above situation (indium foil activation).			
Location	Thermal level	Fraction MPE	Corresponding fraction fast maximum permissible flux
1	3150	2.1	8.7
Room 51	2500	1.7	11.0
15	1500	1.0	16.7

Figure 34. The entrance to the cyclotron vault of Sloane Physics Laboratory is located at Positions 1 and 2. Water cans to the left shield the control area from scattered radiation.

Figure 35. The concrete blocks (Position 12) in the basement corridor along the wall adjacent to the cyclotron vault provide radiation shielding. (Sloane Physics Laboratory.)

Figure 36. Significant neutron levels (due to scatter through windows) were encountered atop the retaining wall adjacent to this sidewalk on the campus outside Sloane Physics Laboratory.

should not exceed 10 percent of the maximum permissible exposure rate for working areas. The windows between the cyclotron and adjacent Locations 15 and 16 (Figure 33) should, then, be blocked up (Figure 34). 2) Though limited occupancy of lecture rooms 51 and 52 might seem permissible, the surveyors suggested that the use of these rooms be wholly restricted during cyclotron operation. Radiation levels should, in general, be kept as low as practicable, especially with respect to persons not occupationally exposed to radiation. 3) It was suggested that the cyclotron personnel, as well as persons who work more or less frequently in the pump room (Location 29), avail themselves of the Brookhaven fast neutron film badge. This suggestion was actually implemented at the time of the survey.

University of Rochester 130-in. Synchrocyclotron

The Rochester synchrocyclotron is a 250-Mev proton accelerator located adjacent to the main campus of the University. The cyclotron and control areas are in separate buildings for remote operation (cf. plot plan, Figure 37). A large earth dike is located between the cyclotron and control buildings (Figure 38), and local concrete shielding attenuates much of the cyclotron radiation at the source. A 6-ft-high chain link fence encloses the cyclotron areas. At the time of the survey, additional shielding was contemplated to permit higher beam currents which were then impractical because of the

Figure 37. Plot plan of the University of Rochester synchrocyclotron.

Figure 38. The closeup view of the synchrocyclotron building (University of Rochester) shows the excluded area near the west end of the earth dike.

Figure 39. From the north corner of the chain-link fence, one sees the control building (left), the earth dike for radiation shielding, and the synchrocyclotron building (in front of stack).

Figure 40. This public bus stop, near the southwest corner of the chain-link fence (Position 8), was occasionally subject to significant neutron levels during 1954 (RO-SC).

resulting high radiation levels on the campus and interference with nearby radiation experiments.

Surveys were performed during the normal and reverse proton beam modes of operation. In both cases, the beam current was believed to be about $0.2 \mu\text{a}$. Along the north fence, higher radiation levels were found for the normal or clockwise mode (π^+ production) than for the reverse mode (π^- production). Tables 26 and 27 show primarily the fast neutron levels encountered.

Table 26

Radiation levels at the 130-in. synchrocyclotron, University of Rochester (RO-SC),
January 21, 1954. Cyclotron operation: π^- production; beam current = $\sim 2 \mu\text{a}$.

Location	Description	Radiation	Fraction MPE
1	Machine shop southwest corner	80 $\text{n}_f/\text{cm}^2\text{-sec}$ 280 $\text{n}_f/\text{cm}^2\text{-sec}$ 0.61 mrep/hr	5.3 0.2 1.6
2	Machine shop west	10 $\text{n}_f/\text{cm}^2\text{-sec}$ 280 $\text{n}_f/\text{cm}^2\text{-sec}$ 0.40 mrep/hr	0.7 0.2 1.1
3	Machine shop door	$\sim 2 \text{n}_f/\text{cm}^2\text{-sec}$ 75 $\text{n}_f/\text{cm}^2\text{-sec}$ 0.1 mrep/hr	0.1 0.3
4	Control room	Nothing detected	-
5	North gate	Nothing detected	-
6	75 ft west of north corner	52 $\text{n}_f/\text{cm}^2\text{-sec}$	3.5
7	75 ft north of southwest corner	165 $\text{n}_f/\text{cm}^2\text{-sec}$ 3.65 mrep/hr	11.0 9.7
8	Southwest corner	80 $\text{n}_f/\text{cm}^2\text{-sec}$	5.3
-	Bus stop near Location 8	33 $\text{n}_f/\text{cm}^2\text{-sec}$	2.2
9	Old Elmwood Avenue	98 $\text{n}_f/\text{cm}^2\text{-sec}$ 2.1 mrep/hr	6.5 5.6
-	West end of dike	80 $\text{n}_f/\text{cm}^2\text{-sec}$	5.3

Table 27

Radiation levels at the 130-in. synchrocyclotron, University of Rochester,
January 21, 1954. Cyclotron operation: π^+ production;
beam current = $\sim 2 \mu\text{a}$.

Location	Description	Radiation	Fraction MPE
1	Machine shop southwest corner	80 $\text{n}_f/\text{cm}^2\text{-sec}$ 260 $\text{n}_f/\text{cm}^2\text{-sec}$ 0.45 mrep/hr	5.3 0.2 1.2
2	Machine shop west	7 $\text{n}_f/\text{cm}^2\text{-sec}$ 95 $\text{n}_f/\text{cm}^2\text{-sec}$ 0.35 mrep/hr	0.5 0.06 0.93
6	75 ft west of north corner	10 $\text{n}_f/\text{cm}^2\text{-sec}$	0.7
7	75 ft north of southwest corner	61 $\text{n}_f/\text{cm}^2\text{-sec}$	4.1
10	Northwest corner	165 $\text{n}_f/\text{cm}^2\text{-sec}$ 3.4 mrep/hr	11.0 9.1

Recommendations: It was suggested that, in areas having a work factor (fraction of a 40-hr week) of one, the shielding should be sufficient to attenuate radiation levels to not more than 25 percent of the maximum permissible dose rate. This was essentially in agreement with a University of Rochester shielding proposal.

It was suggested that the work factor be adjusted to insure radiation levels at or below 25 percent of the maximum permissible, if the amount of shielding required to fulfill the above criterion is impractical.

Radiation levels in the control building were generally unimportant from a radiation safety viewpoint, except near the south and west windows. It was suggested that these windows be shielded.

The use of the Brookhaven fast neutron film badge for the entire cyclotron staff was urged. Previous to the survey, it was the practice of the Rochester group to wear film badges only when entering the cyclotron area (during shutdown). The value of wearing film badges all the time was emphasized.

Finally, the advisability of keeping radiation to very low levels outside the chain link fence on the campus and along the public sidewalk was pointed out (Figures 39 and 40).

Bartol Research Foundation

Radiation measurements of the Bartol positive ion Van de Graaff generators and the Cockcroft-Walton linear accelerator are summarized. The surveyors assisted the Bartol staff in evaluating the probable efficacy of proposed shielding in the new control room in the Van de Graaff building.

1) Van de Graaff for 1.8-Mev Deuterons. Measurements were made during the production of neutrons by the interaction of the deuteron beam with only the carbon target (approximately 1-Mev neutrons) which was located near the analyzing magnet; this condition will be referred to as "No D, D." Measurements were also made during the simultaneous production of neutrons in the deuterium located in the target room (approximately 3.4-Mev neutrons), as well as the neutrons resulting from the carbon reaction; this is the "D, D" case. The D, D reaction was prevented by placing a quartz block in front of the deuterium target.

Measurements of the attenuation of the "D, D" neutrons in concrete blocks were made in the new control room. The half value layer of the blocks was found to be about 4.3 in. of concrete block for the neutrons detected by the fast neutron dosimeters and about 5.5 in. for the ZnS-lucite-detector-measured neutrons. The discrepancy is probably explained by the fact that the fast neutron dosimeters are substantially more sensitive to neutrons with energies below about 0.4 Mev.

2) Van de Graaff for 5-Mev Protons. During the interaction of 2.1-Mev protons with lithium (0.4-Mev neutrons), fast neutron dosimeter measurements at Position A, with both Van de Graaffs operative, showed no detectable neutron levels.

The tissue equivalent chamber indicated that the neutron exposure rate, in the large Van de Graaff neutron beam about 4 in. from the lithium target, was 13 mrep/hr while the exposure rate, determined with the fast neutron dosimeter, was about 60 mrep/hr. A possible explanation of this difference is that the neutron beam intercepted only a portion of the tissue equivalent chamber while the fast neutron dosimeter was entirely in the beam. At about 3 ft from the target, at Position D near one of the control panels, the neutron exposure rate was found to be 1.56 mrep/hr.

During operation, x-radiation measurements were made in the second floor generating room near the tanks. Levels due to the 5-Mev Van de Graaff tank were negligible up to about 8 ft above floor level. Levels from the small Van de Graaff tank ranged from 40 to 50 mr/hr at waist level to about 1500 mr/hr 8 ft above the floor and

Table 28

Radiation levels near the Bartol Foundation's 1.8-Mev D^2 Van de Graaff, August 25-26, 1954.
1.3-Mev deuterons on deuterium; beam current = 11 μa , or as indicated.

Position	Description	Instrument	Radiation level	Fraction MPE
1	Control room bench (D, D case)	TE FND* #130 ZnS	0.61 mrep/hr Nothing detected Nothing detected	- - -
1	Control room bench (no D, D)	TE	0.46 mrep/hr	-
1	Control room bench (no beam)	TE	Nothing detected	-
2	Control room barrier	ZnS SGM	Nothing detected 0.6-1.2 mr/hr	- -
2	Atop control room barrier	ZnS SGM	~ 10 n/cm ² -sec 1.2 mr/hr	0.5 -
3	Entrance to magnet room	FND #44 FND #130 FND	4.1 mrep/hr 5.1 mrep/hr 60 n/cm ² -sec	10.9 13.5 4.0
4	Near analyzer magnet (about 3 ft from carbon target)	FND #44 FND #130 ZnS** Juno	79 mrep/hr 71 mrep/hr 235 n/cm ² -sec 8 mr/hr	209 189 15.7 -
5	Halfway between deuterium target and outside door	FND #130 ZnS	40 mrep/hr 340 n/cm ² -sec	109 22.7
6	Doorway from target room	FND #44 FND #130 Juno	5.1 mrep/hr 5.5 mrep/hr 4-5 mr/hr	13.5 14.6 -
7	Outside of doorway at Position 6	FND #44 FND #130 ZnS	1.4 mrep/hr 1.5 mrep/hr 20 n/cm ² -sec	3.8 4.0 1.3
7	Same as above (no D, D reaction)	FND #130 ZnS	Nothing detected Occasional count	- -
8	New control room near opening (beam = 20 μa)	FND #44 FND #130 ZnS	5.2 mrep/hr 5.7 mrep/hr 185 n/cm ² -sec	14.0 15.1 12.3
8	New control room, 8-in. concrete block (beam = 20 μa)	FND #44 FND #130 ZnS	1.42 mrep/hr 1.50 mrep/hr 65 n/cm ² -sec	3.8 4.0 4.3
8	New control room, 16-in. concrete block (beam = 20 μa)	FND #44 FND #130 ZnS	0.48 mrep/hr 0.53 mrep/hr 29 n/cm ² -sec	1.3 1.4 1.9
9	New control room 4 ft behind opening (beam = 20 μa)	ZnS	140 n/cm ² -sec	9.3

*FND - Fast neutron dosimeter, SPC-6A.

**ZnS - Response decreased noticeably as magnet was approached.

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Figure 41. The Bartol Research Foundation Van de Graaff accelerators.

at contact with the tank. At the entrance to the room, levels had decreased to about 1 mr/hr. Moving the aluminum shield on the SIC-17C over the chamber window had no perceptible effect on the x-radiation measurements, which indicates that the radiation had the energy to be expected from back electron current bremsstrahlung of up to 5 Mev.

3) Cockcroft-Walton Accelerator, 90-Kev Deuterons. At the time of the survey, the accelerating potential was 90 kv, and the beam current about 15 μ a. Neutrons with energies up to about 14 Mev were obtained from the ${}^1_1\text{H}^3(\text{d},\text{n}){}^4_2\text{He}$ reaction. A neutron flux density measurement made 75 cm from the tritium-zirconium target suggested a neutron yield of about 3×10^6 n/sec.

In the control room, fast neutron levels were somewhat less than 0.1 mrep/hr. X-radiation near the ion source, upstairs, with beam off produced exposure rates of about 30 mr/hr at a distance of 1 ft.

Recommendations: The following general recommendations were made.

- 1) That when the new control room in the Van de Graaff building is in operation, concrete blocks (3 deep) be stacked over the opening leading to the small Van de Graaff vault (Position 8). This thickness (approximately 22 in.) should reduce fast neutron levels to a value well below the MPE.

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Table 29

Radiation levels near The Bartol Foundation's large Van de Graaff.
2.1-Mev protons on lithium.

Position	Description	Instrument	Radiation level	Fraction MPE
A	New control room (opening to accelerator)	FND #130	Nothing detected	-
B	In neutron beam 4 in. from target	FND #130 TE*	61 mrep/hr 13 mrep/hr	163 -
C	Off beam center 4 in. from target and 4 in. from center line	FND #130	6.8 mrep/hr	18.1
D	Off beam center 3 ft from target	FND #130	1.56 mrep/hr	4.2
E	On table near entrance to 1.8-Mev Van de Graaff	TE	0.28 mrep/hr	-

*Beam intercepted only a small part of the tissue equivalent ionization chamber.

Table 30

X-radiation levels near tops of Van de Graaff tanks (second floor) during simultaneous operation.

Position description	Radiation level
Entrance to second floor room	~1 mr/hr
Waist level - 3 ft from small tank	40-50 mr/hr
8 ft up, at contact	1000-1500 mr/hr
Contact, large tank, waist level	~1 mr/hr

Table 31

Radiation measurements near Bartol Institute's Cockcroft-Walton accelerator.
90-kev deuterons on tritium; beam current = ~15 μ a.

Position	Description	Instrument	Radiation level	Fraction MPE
1	75 cm from tritium-zirconium target	FND #44	0.80 mrep/hr	2.13
		FND #130	0.93 mrep/hr	2.48
		ZnS	43 n/cm ² -sec	2.15
		TE	0.69 mrep/hr	-
2	145 cm from target	TE	0.15 mrep/hr	-
3	Control area 2 ft behind blocks	FND #130	<0.1 mrep/hr	-
		TE	0.08 mrep/hr	-
4	Near ion source 1 ft away	Juno	30 mr/hr	4.0

- 2) In the future, the thermal neutron flux density measurement in the new control room may be indicated.
- 3) It was suggested that visible warning signals should be located at both entrances to the accelerator rooms to indicate when the machines are in operation. These warning devices should be interlocked with the accelerating voltage circuits of each Van de Graaff.
- 4) The voltage should be turned down when the deuterium target area is entered in order to place the quartz block in position near the target, or, alternatively, provision should be made to move the quartz block into and out of position, remotely, from the new control room.
- 5) The upstairs Van de Graaff tank room appears to present no special problem in radiation safety. A sign indicating that high x-ray levels do exist near the small tank can be posted outside the tank (generator) room door.
- 6) Under the conditions of the survey of the Cockcroft-Walton accelerators (90-kev deuterons and a 15- μ a beam), any place beyond a distance of about 4 ft from the tritium target is below the permissible neutron level.
- 7) In the upstairs room of the Cockcroft-Walton building, radiation levels are of little importance. However, the electrocution hazard from the unshielded high voltage points in this room appears to be a real one.
- 8) The installation of a warning sign (e.g., a blinking red light), outside the entrance to the Cockcroft-Walton building, indicating the "radiation beam on or off," was recommended.

Conclusions and Recommendations

The investigations reported here have led the writers to the following conclusions:

(a) We are not inclined to the opinion that sizable groups of accelerator personnel are being exposed to radiation intensities which will result in long term deleterious effects. This belief is tempered, however, by the large gaps remaining in practical dosimetry and the utter insufficiency of information on the biological effects of heavy charged particles in the range exceeding 14 Mev.

b) Accelerators are now being designed which will produce charged particles (and stray radiations) up to 25 Bev. Proton synchrotrons in the 1- to 6-Bev region are already in operation. Synchrocyclotrons have been operating since 1949 which produce protons and stray neutrons in the range of 200 to 500 Mev. In this connection it is most important to observe that almost all the biological information to date on fast neutron irradiation of biological material has been with neutrons of 14 Mev and less.

The extrapolation of permissible levels from these data to energies more than one hundred and even one thousand times greater is, in our judgement, inadmissible.

One may argue on the basis of linear energy transfer considerations that particles resulting from very high energy machines are less deleterious in biological effect than lower energy particles of higher specific ionization. However, this is a conjecture which should be established empirically.

It is recommended that an intensive program of animal experimentation be undertaken in the neutron energy region from 14 Mev to 6 Bev with currently available accelerators to delimit as expeditiously as possible areas of potential hazard.

c) There is a tendency at many accelerators for the total site personnel exposure to be accumulated by a very few individuals. Project directors should be made cognizant of this tendency so that it may be guarded against by appropriate rotation of personnel in those accelerator operations associated with significant radiation exposure.

d) The possible effect of microwave production by radiofrequency sources at high energy particle accelerators appears to require more attention than it has received.

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