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PHYSICAL DOSIMETRY IN TYPICAL BIOLOGICAL EXPERIMENTS WITH FAST NEUTRONS FROM A CYCLOTRON SOURCE

C. W. Sheppard and E. B. Darden

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C. W. Sheppard and E. B. Darden

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PHYSICAL DOSIMETRY IN TYPICAL BIOLOGICAL EXPERIMENTS WITH FAST NEUTRONS FROM A CYCLOTRON SOURCE

C. W. Sheppard E. B. Darden

During the past year, a large amount of biological material has been exposed in a fast-neutron facility which receives radiation from the 86-in. cyclotron. The physical methods which were used for semi-quantitative dosimetry were somewhat inelegant, but for use as a preliminary study of neutron effects in biological systems hitherto subjected to limited exploration, or to none at all, they have been sufficiently satisfactory for present purposes. Among the results of the experiments were data of great value in the conduction of recent difficult and expensive field experiments which are described elsewhere.[1] Furthermore, these cyclotron experiments should, in general, be representative of the situation in many earlier neutron investigations by others, so our findings will be of great interest to all who are concerned with the biological effects of fast neutrons. The results also clearly indicate the direction, from the physical point of view, in which at least a portion of future biological research with neutrons must proceed.

ORNL 86-in. CYCLOTRON FACILITY

The cyclotron has been described elsewhere.[2] Figure 1 is a picture of the machine, and the overall installation is shown in Fig. 2. The Biology facility consists of a small closed lead box with inside dimensions of approximately 3 by 3 by 8 in. and a wall thickness of 2 in. and is located on the outside of the dee chamber[3] (Fig. 3, lead box A). Neutrons produced by the *p-n* reaction on beryllium that was bonded to a water-cooled aluminum target traverse the target, the target supports, the walls of the dee chamber, and the walls of the lead box before they strike the biological specimens placed in the box. The radius vector from the target to the box makes an angle of approximately 30 deg with the axis of the 22-Mev proton beam striking the target. The uncertainty in the amount of degradation produced by the intervening material and the unknown amount of scatter of neutrons from the large mass of material surrounding it both contribute to a large uncertainty in the neutron energy, which remains to be satisfactorily explored by physical methods. The fact that the facility is close to a target of large dimensions makes the directional distribution additionally uncertain, and thus energy measurements by convenient and familiar standard procedures are seriously limited in precision. It is eminently reasonable, however, that the energy spectrum of Gugelot[4] fairly well represents the distribution of the neutron energies emitted by a thin target bombarded with 16-Mev protons and observed in the forward direction. In order to get a first approximation to the energy distribution (Fig. 4), we have made a correction for the different bombarding energies and emergent angle in our experiments plus the effect of target thickness and degradation.

The 2-in. lead wall is more than sufficient to reduce the effect of the gamma radiation in the beam by a factor of 2. In general, a thicker wall will probably not reduce the radiation much further, since gamma rays will be increasingly produced by inelastic collisions of the neutrons with the lead. More lead will also further degrade the neutrons because considerable energy is lost in these collisions. Although further studies should be conducted, the evidence is fairly clear that the gamma-ray contamination is not serious under the present conditions.

The absence of very much hydrogen or other material with a low atomic number helps to minimize the slow-neutron component in the empty box. The fact that biological material affects the neutrons is an experimental complication which is inherent and must be accepted. An appreciable, but still unknown, component of the energy spectrum is in the range between a few volts and 10 kilovolts. This range of neutron energies is, at present, the one most intractable to quantitative physical or biological experimentation when collimation of the neutrons is impossible, as it is here.

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(1) C. W. Sheppard and E. B. Darden, *Radiation Measurement Problems in Recent Field Experiments* (to be published).

(2) R. S. Livingston, "The Oak Ridge 86-Inch Cyclotron," *Nature* 170, 221-3 (1952).

(3) The larger facility, B, at the left in Fig. 3 was used briefly by the Experimental Pathology Group, but was later replaced by a similar lead box with 1-in.-thick walls.

(4) P. C. Gugelot, "Neutron Spectra from Nuclear Reactions Induced by 16-Mev Protons," *Phys Rev* 81, 51-60 (1951).

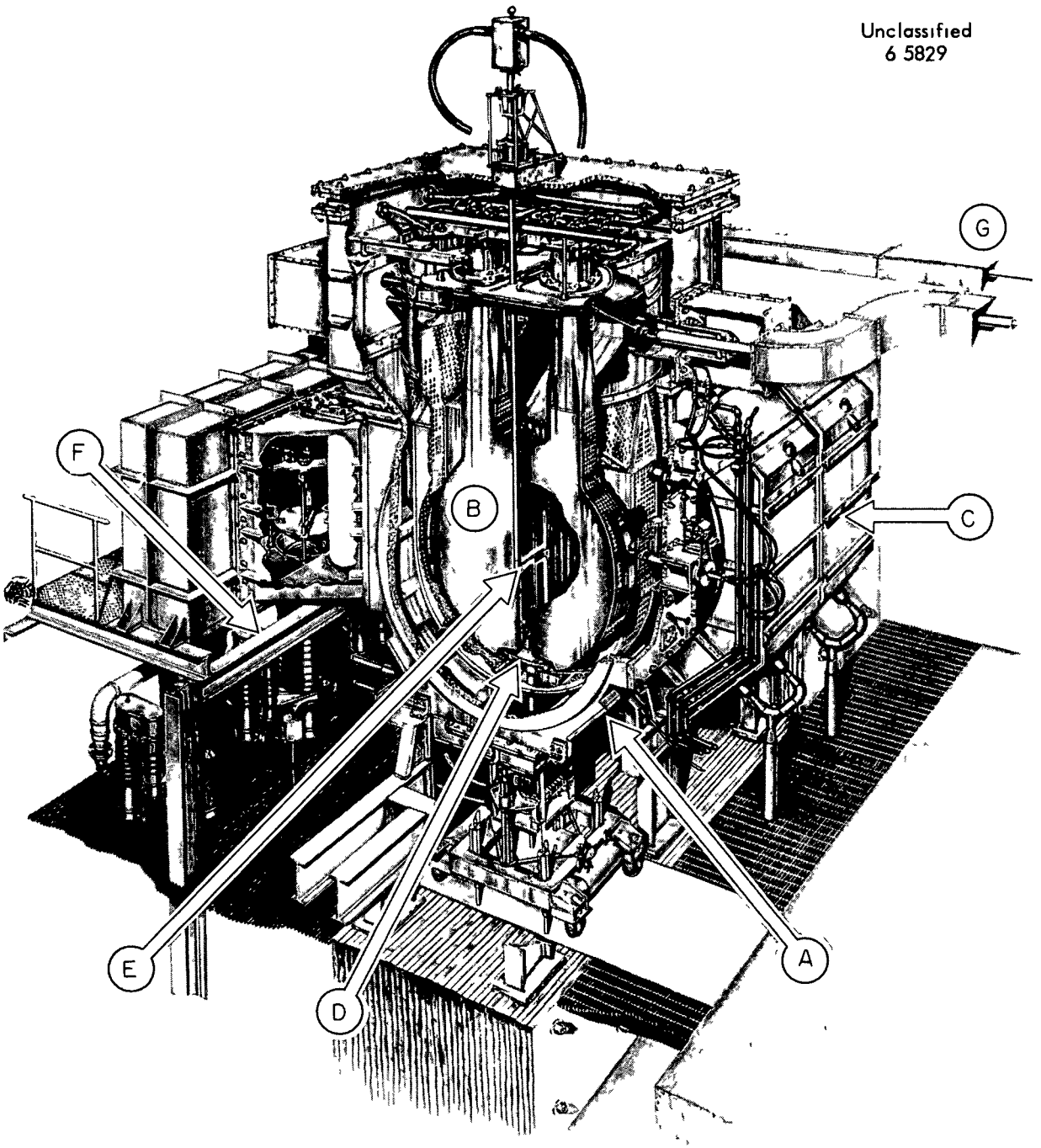

Fig. 1. ORNL 86-in. Cyclotron. A is the location of the small neutron-exposure facility. For the large facility, see Fig. 3. Ions are produced by the ion source E and are accelerated between the dees B by use of a radiofrequency current delivered through the transmission lines G. The magnetic field produced by coils C causes the ion to spiral outward and to strike the target D. The vacuum is maintained by the pumping system F. The forepumps are not shown.

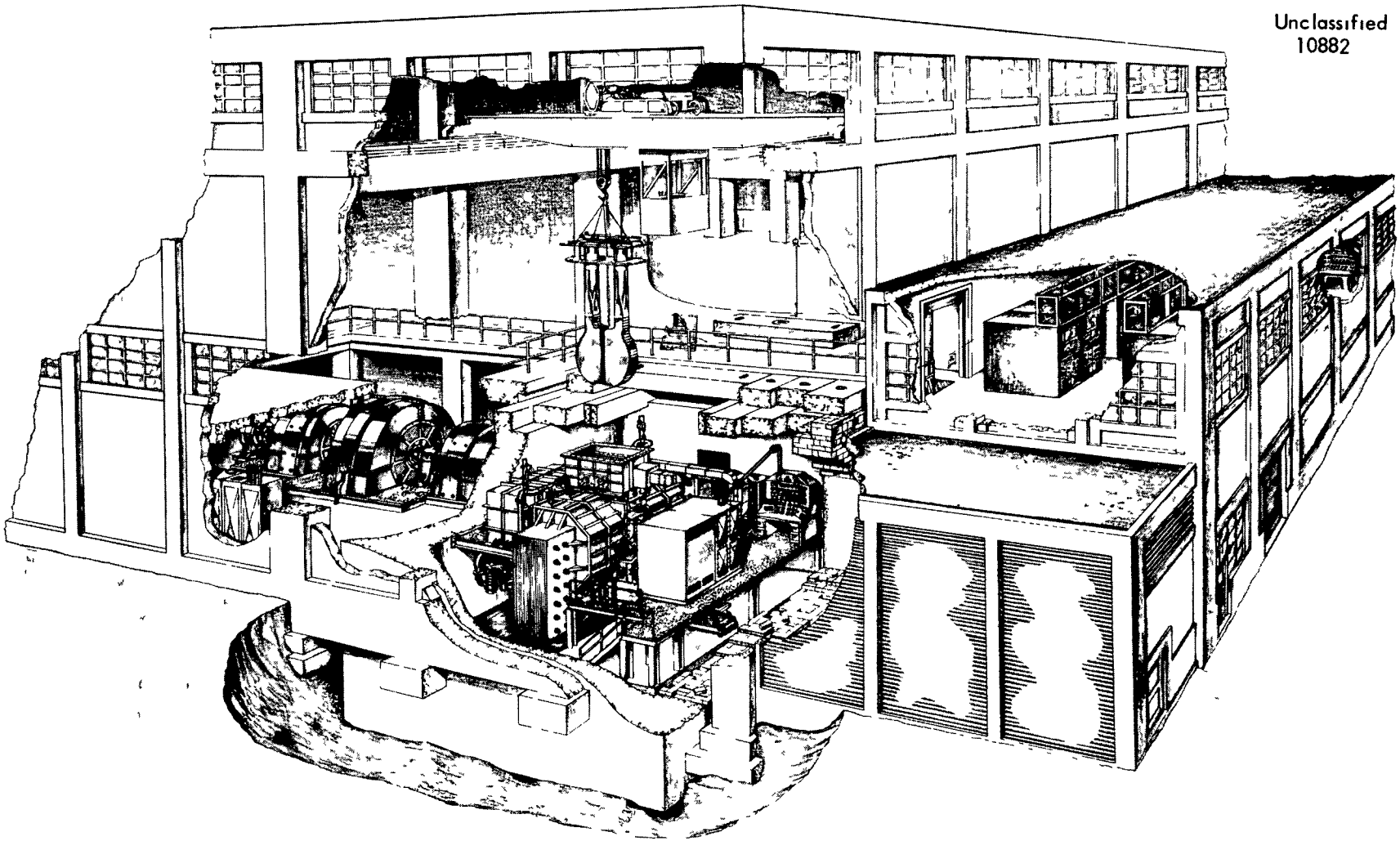

Fig. 2. Over-all Cyclotron Installation. Note the thick concrete shield surrounding the unit. The large motor generator at the left supplies current for the magnetic coils. The dees are in the process of being removed and hang suspended over the unit. The high-voltage power for the oscillator is supplied by the box-like structures in the upper right foreground, and the control desk is situated at the extreme right rear.

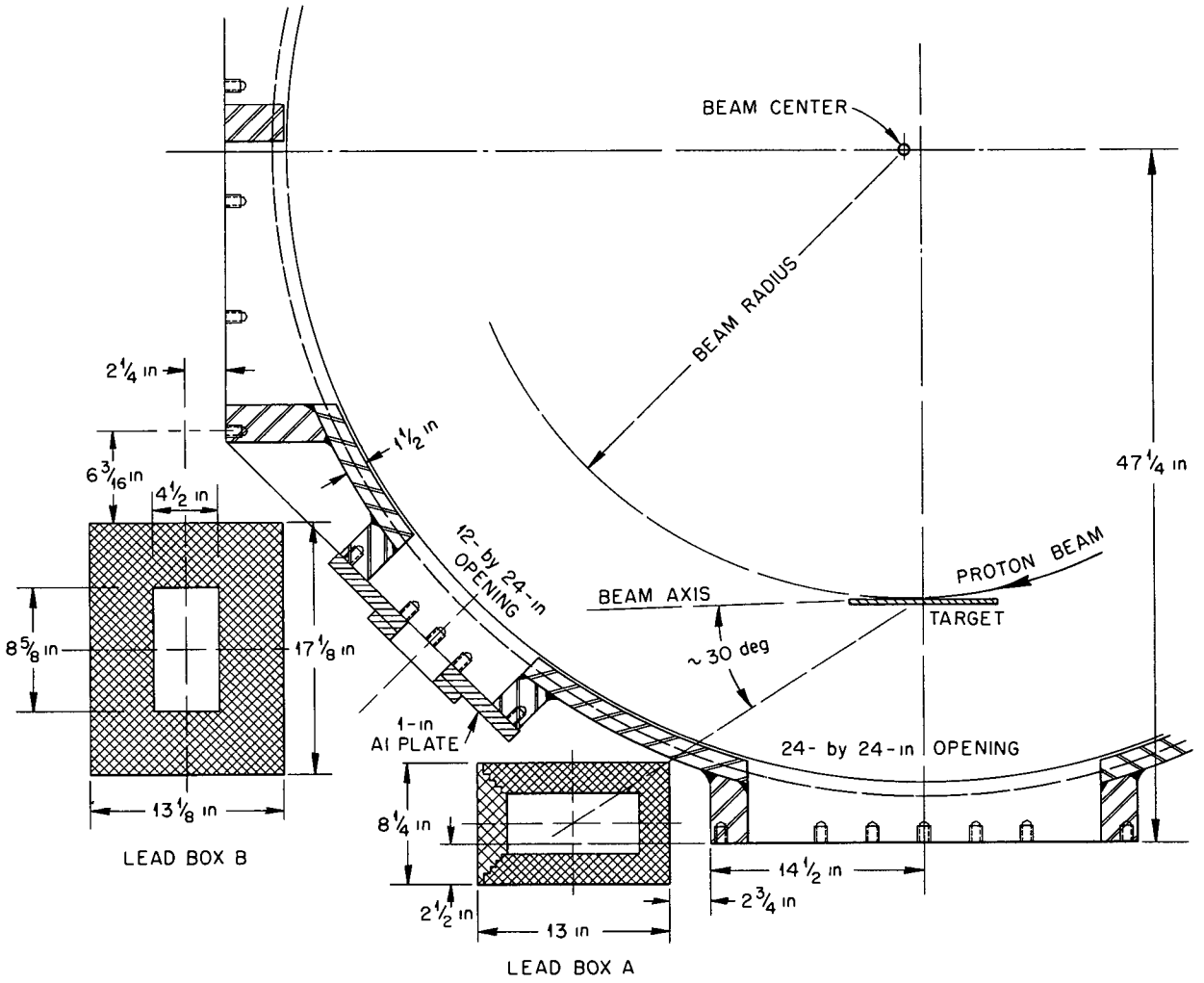

Fig. 3. Location of the Exposure Facilities A and B. The box B has recently been replaced by a box of roughly equivalent outer dimensions but with a 1-in. lead wall. Both facilities lie in the axial plane of the steel chamber containing the dees. The chamber wall is as shown, but only the important components are indicated.

FAST NEUTRON DOSIMETRY

The neutron was discovered only a little over 20 years ago, therefore it is not surprising that methods of fast-neutron dosimetry are under less satisfactory control than those for other types of radiation. Although not the only ones, the biggest problems are

1. the measurement of fast-neutron exposures in the presence of gamma rays,
2. the characterization of the neutron-energy spectrum,
3. the determination of the depth dose in terms of surface dose and the determination of the effect of backscattered neutrons at the surface in exposures of large animals,
4. the relation of neutron dose in a given object to neutron flux.

A few selected literature references on the subject are refs. 5, 6, 7, and 8. At present, the best method for neutron dosimetry seems to be the

(5) L. D. Marinelli, "Practical Aspects of Radioactivity Measurements, Calibration," *Nucleonics* 8, No. 6, S 20-32 (1951).

(6) L. H. Gray, "The Ionization Method of Measuring Neutron Energy," *Proc. Cambridge Phil. Soc.* 40, 72-102 (1944).

(7) J. G. Beckerley, *Neutron Physics*, AECD-2664 (Oct. 16, 1951).

(8) P. H. Abelson, ed., *Proceedings of the Conference on Radiation Cataracts and Neutron Effects*, NP-1826 (Feb. 17, 1950).

one based on the Bragg-Gray principle.[9,10] This method, however, has the outstanding weakness that gamma radiation must be kept to a minimum, since the gamma-ray dose is not distinguishable from the neutron dose. The principle is at its best when ion chambers with hydrogenous walls are used, and this led Aebersold and Lawrence[11] to develop the "Berkeley system" of dosimetry which we have used in the present study. The method involves the use of the standard Victoreen x-ray dosimeter. The number of scale divisions of deflection produced by the neutrons on the roentgen scale of the instrument (using a 100-r Victoreen dosimeter) is called the "dose" in *n* units. Calibration is achieved by applying the multiplication factor 2.5 to the scale reading to convert *n* to rep. For a 25-r instrument, the upper case *N* was often used, although it is not entirely clear that this was essential. We will use the lower case *n* for all cases. The advantage of the Berkeley method is that it can be used in a confined space with a strongly polydirectional neutron flux. The strong magnetic field of the cyclotron does not seem to interfere.[12] The method can be used to measure integrated fluxes between 10 and 250 rep and, under favorable conditions, probably up to 600 rep, but with less reliability. The maximum dose rate that can be properly determined is probably 1000 rep/min, which is the range of biologically interesting neutron exposures. The method has been used in this laboratory from time to time in the past[13] but without any critical evaluation. One of the principal criticisms is the high uncertainty in the conversion factor from *n* to rep, which could be as low as 2.0 or as high as 3.0 for an individual chamber. Nevertheless, either fortuitously or otherwise, if the factor 2.5 is used to convert the earlier neutron work in this laboratory to rep, the result is not seriously in disagreement with later investigations.

The gamma-ray contamination at neutron energies which are not too high can be estimated by exposing an ion chamber that has walls composed of a material of high atomic number. We have made a bismuth chamber that is similar to a beryllium chamber that was recently described[14] for use in a slow-neutron field. Bismuth is quite insensitive to slow neutron activation, and the bismuth nuclei are so heavy that even the head-on collision of fast neutrons below 5 Mev cannot eject recoils of sufficient energy to produce ions The precise calibration of such a chamber in roentgens is difficult, since the energy of the gamma rays is not well known. However, a sufficiently accurate calibration should be obtainable by exposing the chamber to a known dose of Co^{60} gamma rays of roughly 1.2-Mev energy and by assuming the response to be proportional to the sum of the cross

(9) L. H. Gray and J. Read, "Measurement of Neutron Dose in Biological Experiments," *Nature* 144, 439-40 (1939).

(10) H. H. Rossi and G. Failla, "Neutrons Dosimetry," in *Medical Physics*, vol. II, p. 603-7, ed. by O. Glasser, The Yearbook Publishers, Chicago, 1950.

(11) P. C. Aebersold and J. H. Lawrence, "The Physiological Effects of Neutron Rays," *Ann Rev. Physiol* IV, 25-48 (1942).

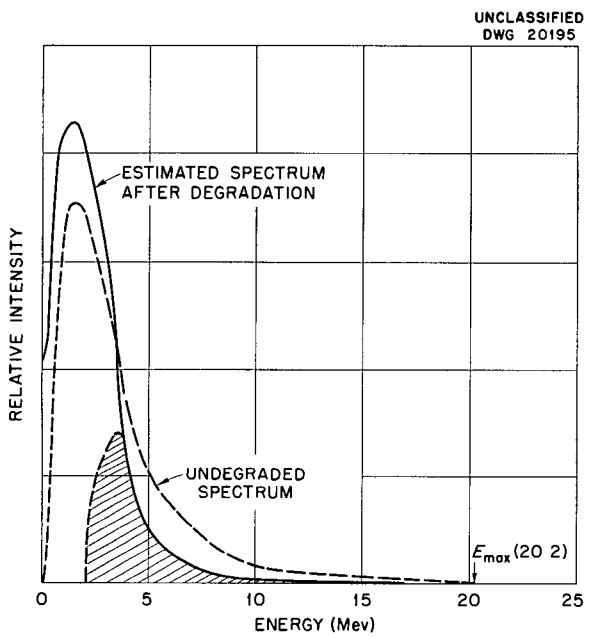

Fig. 4. Spectrum of Neutrons in the Biological Facility. The dashed curve is the best estimate of our spectrum after correcting the data of Gugelot for the different bombarding energy, the 30-deg angle of observation, and the effect of the thick target in our cyclotron. The solid line represents the spectrum after correcting for the approximate effect of degradation by the metallic structures. The shaded area under the curve represents the approximate fraction of the neutrons which activate a sulfur threshold detector.

(12) P. C. Aebersold and G. A. Anslow, "Fast Neutron Energy Absorption in Gases, Walls, and Tissue," *Phys Rev* 69, 1-21 (1946).

(13) N. H. Giles, Jr. and A. D. Conger, "Chromosomal Interchanges Induced in *Tradescantia* Microspores by Fast Neutrons from Uranium Fission," *J Cellular Comp Physiol* 35, suppl. 1, 83-8 (1950).

(14) E. B. Darden, Jr., C. W. Sheppard, and L. C. Emerson, "A Condenser Type Ion Chamber for the Measurement of Gamma-Radiation in the Presence of Thermal Neutrons," *Rev. Sci. Instr.* 23, 568-9 (1952).

sections that result from Compton absorption and from the production of photoelectrons and pairs. A rough estimate of the conversion of the reading thus obtained to that for the unknown radiation can be made by use of an effective energy in the region of 2.5 to 3.0 Mev, where the absorption of gamma rays passes through a minimum, and by multiplying by the ratio of the gamma-ray cross sections for this energy as compared with 1.2 Mev. Not only will selective filtration favor these energies, but the attenuation is not very sensitive to gamma-ray energy in this region. Rough studies indicate that the wall of the chamber is thick enough to ensure at least approximate equilibrium. Since the gamma-ray contamination is not large and since many of the neutron biological effects per rep are much larger than the gamma-ray effects, the uncertainty is probably not particularly serious. The biggest uncertainty will be in the determination of the neutron dose from determinations of total dose.

PHYSICAL TESTS IN THE NEUTRON FACILITY AND METHODS FOR CONTROLLING BIOLOGICAL EXPOSURES

In all biological studies, the relative exposures were determined by means of a fast-neutron counter placed outside the cyclotron shield. It was possible to achieve reasonably low counting rates only because of the large attenuation by the shield. The counter was calibrated before each run with the Victoreen dosimeter. Two different Victoreen dosimeters were used at different times, one was a standard red Bakelite 25-r dosimeter (25-r-4) and the other (100-r-7) was a special chamber developed by Raper at ORNL several years previously. The special dosimeter was the same as a 100-r Victoreen unit, but the thimble was replaced with a black thimble made of a conducting plastic that consisted of a mixture of graphite and Lucite.

The conversion factor, that is, the ratio of the dose in rep to the reading in *n* units, for the red chamber was determined on October 9, 1952, at which time H. Rossi visited the Laboratory and assisted in comparing the readings obtained with those of a tissue-equivalent ion chamber which he provided.[10] For the 25-r-4 dosimeter, the factor was found to be 1 unit on the 25-r scale equals 2.5 rep. The fact that this value is practically identical with the values used by Aebersold and Anslow is probably fortuitous, since the factor is somewhat variable from chamber to chamber among different Victoreen dosimeters.

The conversion factor for Victoreen 25-r-4 was also tested against a chamber geometrically similar to the bismuth chamber but that has polyethylene walls and is filled with ethylene gas. The walls are coated with a thin transparent layer of Aquadag. The basis of this type of chamber is discussed by Dainty.[15] Further comparison was made with a chamber that was produced in our own shop and that follows the Rossi-Failla design. Table 1 shows the results of these tests. We believe that the fluctuations in the readings of our Rossi-Failla chamber were related in some way to the instability in its gas pressure. The third value of 2.64 for the calibration factor was obtained by making the calibration within an hour of filling.

The ratio of the reading of the red to the black chamber for equal exposure to neutrons was determined on October 13, 1952. The mean of ten separate determinations of the ratio was 0.66, the ratios varying between 0.65 and 0.70. From this, the conversion factor for the 100-r-7 is computed to be 1.64. The appreciable difference in response between the two chambers for equivalent exposure to neutrons is obviously attributable to the different composition of the two thimbles, since the relative x-ray responses are extremely close. Lucite contains more hydrogen per cubic centimeter of wall material than Bakelite and should produce more ionization, however, the precise estimation of the relative sensitivities of the chambers is not possible because of the lack of knowledge of the exact composition of the walls of the two chambers and of the graphite coating on the inner surface of the 25-r-4

(15) J. Dainty, *Report on Fast Neutron Dosimetry*, CRM-482 (1950).

TABLE 1. DETERMINATIONS OF CALIBRATION FACTOR FOR CHAMBER 25-r-4

DATE	METHOD	VALUE
10/9/52	Original Rossi-Failla chamber	2.47
2/5/53	Ethylene-polyethylene chamber	2.63
2/9/53	Ethylene-polyethylene chamber	2.37
2/16/53	ORNL Rossi-Failla chamber (first filling)	3.04
2/20/53	ORNL Rossi-Failla chamber (second filling)	1.95
2/23/53	ORNL Rossi-Failla chamber (third filling)	2.64
	Mean	2.51

From the biological effect of the radiation, we have some independent evidence concerning the reliability of our calibration. Recently, Kirby-Smith, in two independent experiments five months apart, compared the chromosomal aberrations produced in *Tradescantia* microspores by neutrons with the results obtained earlier by Giles and Conger[13] by a fission spectrum of neutrons. In both experiments, his mean aberration frequency fell within 10% of theirs. Although the aberration frequency for this particular material is known to be quite reproducible, further information concerning the effects of neutrons of different energies and a better understanding of the energy distributions of the neutrons in the two experiments would be required before this agreement could be shown to be other than accidental.

The maximum neutron intensity which can be achieved with the cyclotron depends on the condition of the target. Unless the best construction technique is used, considerable loss of beryllium may occur after extensive use, therefore it is generally wise for the investigator to inspect the target from time to time. Experiments with a bare aluminum target indicated that considerable loss of beryllium must occur before the effect of the neutrons from aluminum bombardment become serious. Optimum yield from beryllium at present is about 200 rep/min or, roughly, 1.5×10^9 neutrons/cm^2·sec. In specific cases where targets are less than perfect, target life may be materially reduced under these conditions. At average intensities of one-fourth this rate, our targets seemed to last for many weeks of intermittent exposure. The minimum exposure which can be made reliably at present seems to be about 5 rep. It usually takes about 20 to 30 sec to obtain stable operation of the cyclotron, which limits the shortness of the exposure. Lower intensities could probably be achieved with further investigation.

One complicating factor in these experiments is the variation of neutron intensity in different parts of the facility. In the following description, the portion of the facility closest to the target will be considered as the "rear." The variations in readings taken with the black chamber at different points in the facility on October 14, 1952 are shown in Fig. 5. The approximately twofold difference in the dose in the rear as compared with that in the front compartment is consistent with the idea that most of the neutrons come fairly directly from the target, at least in the region of the facility. The figures on which Russell's mouse exposures were based are taken at the extreme rear-center of the facility, that is, about halfway between the floor and the ceiling of the lead box. In a typical experiment, mice exposed at the extreme rear will get about this average dose, but the upper portion of the animal will get about 10% more and the lower portion 10% less. When four mice are exposed, the two in the more forward portion of the facility will be further away from the cyclotron target and will also be shielded slightly by the other two mice. The dose at the level of the testes was determined relative to that in the

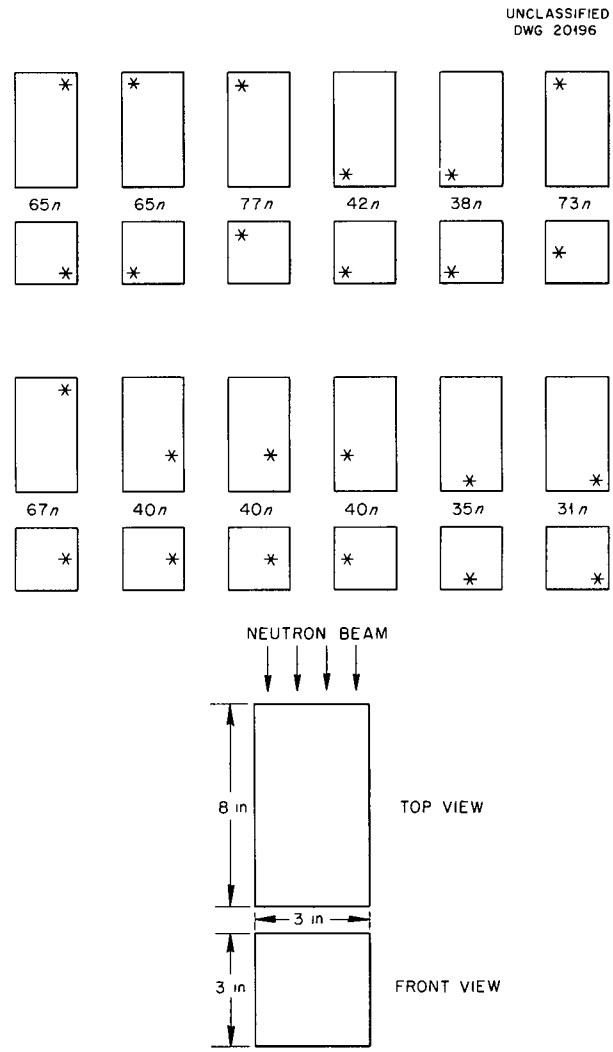

Fig. 5. Variation in Victoreen Dosimeter Readings (*n* units) at Different Locations in the Small Facility. At the left are two views of the facility, the front view is as seen by an observer looking through the box toward the target. The same orientations also apply to the locations signified by asterisks in the group of sketches on the right, the accompanying number is the reading at the given location.

rear center of the empty box. The mean of four readings each is shown in Fig. 6, together with the corresponding location. The values are for animals placed head upwards with their axes vertical.

The fluctuations in the ratio of Victoreen dosimeter readings to neutron counts will give some idea of the fair, but certainly not perfect, reliability of the neutron counter in measuring individual neutron exposures. Table 2 shows a typical set of runs made on October 13, 1952. Fluctuations of as much as 20% from the mean can occur at times, therefore it is advisable, wherever possible, to use some type of separate integrating dosimeter, such as a sulfur threshold detector, which can be placed with the irradiated material during each exposure. Often, however, a skilled operator can obtain very reproducible repeat runs when the cyclotron is operating well. When the ratio of Victoreen-to-counter readings on different days is determined, the fluctuations are also considerable (Table 3).

In addition to the neutron counter, there are independent data from which the relative neutron output can be roughly estimated. Total integrated energy dissipated on the target can be determined from calibrated records of the differential in water temperature between inflow to and outflow from the target. This was closely proportional to total neutron counts. At low beam currents, the integrated current generally was much less reliable.

The success of the bismuth ion-chamber estimation of gamma-ray contamination depends upon the effect being small when compared with the dose from the neutrons. The energies of the gamma rays not being known makes the bismuth reading somewhat unreliable, but it should certainly be within a factor of 2 of the true roentgen readings. The bismuth chamber measured consistently about 12% of the reading of Victoreen 100-r-7. Correcting the reading for the wavelength effect gives 17 rep/100 divisions on the Victoreen. Thus, for every 100 scale divisions on the dosimeter, there would be about 148 rep of neutrons and 17 rep of gamma rays, or 10.3% of the dose. If even a 100% error in the bismuth estimate is assumed, the worst conceivable situation would be 131 rep of neutrons and 34 rep, or 21%, of gamma rays. If lead shielding were not used, the gamma-ray effect would be

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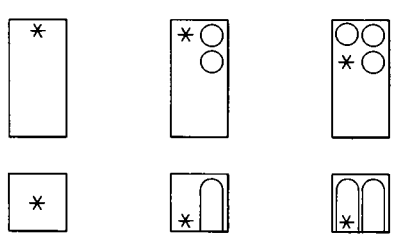

MEAN OF FOUR DETERMINATIONS (n per 1600 counts) 66 0 56 6 46 8

Fig. 6. Readings of the Dosimeter (see Fig. 5) in the Presence of Plastic Tubes Containing Mice (Shown Schematically). The observed ratios of the readings were b/a = 0.86, c/a = 0.71, c/b = 0.83.

TABLE 2. REPEAT DETERMINATIONS OF THE RATIO OF THE READINGS OF VICTOREEN DOSIMETER 100-r-7 TO THOSE OF THE NEUTRON COUNTER TAKEN ON OCTOBER 13, 1952*

READING		RATIO (n per 1600 counts)
Counter	Victoreen Dosimeter (units on 100-r scale)	
30 × 16	18	60
40 × 16	20	50
48 × 16	28	58
48 × 16	32	67
49 × 16	24	49
48 × 16	26	54
100 × 16	56	56
		Mean 56.3

*Measurements were made at the extreme rear center on the floor of the facility.

TABLE 3. RATIO OF READINGS OF THE VICTOREEN DOSIMETER TO THOSE OF THE COUNTER ON DIFFERENT DAYS*

RATIO OF VICTOREEN TO COUNTER (n per 1600 counts)	DATE
50	8/28/52
51	8/29/52
59	9/30/52
69	12/18/52
58	1/15/53
Mean 57.4	

*Measurements were made at the extreme rear center on the floor of the facility.

twice as great and would be quite objectionable. As is often the case, the biological effects will have relative biological efficiencies (RBE) considerably greater than 1, thus the neutron effects will predominate. However, in establishing dose-effect relationships, the reading for the gamma-ray component will have to be subtracted, and if this is a large fraction and not well known, the neutron dosage will be correspondingly uncertain. The presence of unknown gamma rays will, of course, produce an underestimation of the RBE. The decrease in gamma-ray intensity at points located toward the front of the facility is not so great as the decrease in the neutrons. The ratio of about 3 5 for the gamma rays as compared with 1 2 for the neutrons is probably due to some of the gamma rays originating nearby, probably in the lead walls of the facility.

The amount and nature of the slow-neutron contamination in the facility was determined by gold activation. In one experiment, there were about ten fast neutrons for every slow neutron in the energy range of the gold-capture process. This includes resonance, as well as thermal neutrons, because little difference is to be expected in the smallness of their contribution to the biological effect. Since the effect is small, it can be assessed sufficiently well by considering only one representative biological effect. From Conger's observations on *Tradescantia*, 5×10^9 thermal neutrons/cm^2 is equivalent to about 1 r of x rays.[16] This flux of fast neutrons (1 Mev) will produce an energy absorption of about 10 rep. The exposure to a 10% flux of slow neutrons, which are 10% effective at most, gives a 1% net effect, therefore the slow-neutron contamination need not be seriously considered for inclusion in the overall biological effects.

Repeated comparisons of the activation of sulfur and phosphorus threshold detectors by the neutrons with the flux expected from the Victoreen readings indicate that only about 10% of the neutrons have energies greater than about 3 Mev. Our information concerning the spectrum is discussed in the Appendix. From the statistical theory of nuclear reactions,[17] the neutron energy distribution should be closely similar in form to the Maxwell-Boltzmann distribution of energies of gas molecules at constant temperature. The neutron energies could thus be predicted if the temperature were known. Actually, for light elements, the theoretical prediction of temperature cannot be satisfactorily made. We have used the experimental results of Gugelot[4] that were obtained at 16-Mev bombardment energy on a thin target observed in the forward direction. Correction is made for the higher energy in our experiments by assuming the temperature to be proportional to the square root of the proton energy, and correction is also made for our emergent angle of 30 degrees. A rough correction is included for the infinitely thick target and for the degradation of the neutrons in the walls of the facility and cyclotron chamber. The result in Fig. 4 represents the best estimate at the present time. Rough determinations of total neutrons above the sulfur threshold shown as the shaded portion under the solid curve indicate that there is a sulfur flux of about 20%, which differs from the measured value by a factor of 2. A better characterization awaits the calibration of fission counters and the development of other physical instruments not presently available.

CONCLUSION

The experiments described can in no way be considered to represent precise quantitative radiobiology. In all cases, the results are internally consistent and have at least the surface appearance of reliability. Nevertheless, when the physical methods which are available for neutron study and the rigorous interchecks which are possible when experiments are done under proper physical conditions are considered, the situation is not particularly gratifying. For all experiments such as those on killing bacteria which require doses of 20,000 rep or more, the cyclotron continues to be the best fast-neutron source, and cyclotron experiments have proved to be highly useful for preliminary screening tests. Nevertheless, the results obtained emphasize that the majority of further efforts must be devoted to the more precisely measurable biological effects which occur at lower neutron intensities. Monoenergetic neutron sources should be used. The neutrons should be produced under good geometrical conditions, and care must be taken to control scattered radiation and to prevent the production of unwanted gamma rays and slow or epithermal neutrons. Neutron fluxes should be quantitated under precisely measurable conditions by using techniques now well established for this purpose.[18] By using the Bragg-Gray principle, these fluxes should be correlated with

(16) A. D. Conger and N. H. Giles, "The Cytogenetic Effect of Slow Neutrons," *Genetics* 35, 397-419 (1950).

(17) J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics*, Wiley, New York, 1952.

(18) H. H. Barschall, L. Rosen, R. F. Taschek, and J. H. Williams, "Measurement of Fast Neutron Flux," *Revs Mod Phys* 24, 1-14 (1952).

precisely determined neutron dose in various tissue-equivalent phantoms. Intercalibration must be made with various types of neutron dosimeters and methods of flux measurements, and phantom dose relations must be related to dose delivered to critical loci in biological materials. These considerations have led us to plan a facility that is currently being installed in the Biology Division for improved neutron studies.[19]

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[19] Y-12 Engineering Division, *Fast Neutron Facility for the Biology Division of ORNL*, AEC Preliminary Proposal No. 114 (1953).

APPENDIX

ESTIMATION OF THE NEUTRON SPECTRUM

The distribution in energy of the emitted neutrons from the $Be^9(p,n)\ B^9$ reaction will be affected by several factors, namely, the angle of observation (30 deg in the present experiments), the relation between the energy and depth of penetration in the thick target at the moment of formation of the compound nucleus, the cross section at that energy, the distribution of nuclear energy levels, which affects the spectrum of the emitted neutrons when observed from a system in which the center of mass of the proton and target nucleus are at rest, and the energy of the incident protons (22 Mev). Unfortunately, not all these quantities are accurately known, and one at least – namely, the cross section for the formation of the compound nucleus – is based on the admittedly crude estimates by Blatt and Weisskopf.[17] The neutron spectrum in the center of mass system is given by Gugelot for 16-Mev protons.[4] We assume that the nuclear temperatures are proportional to the square root of the bombarding energy, and thus that they express the relation for other bombarding energies. The variation in proton energy along the tract is estimated from the range-energy relation of Aron, Hoffman, and Williams.[20] Conversion from center-of-mass coordinates to laboratory variables is made by elementary mechanical considerations using nonrelativistic expressions and conservation of energy and momentum.

By taking the above considerations into account, the rate of emission of neutrons in the energy range between E_2 and $E_2 + dE_2$ per square centimeter of target material is

$$n(E_2)\, dE_2 = F \left[\int_0^{22} N(E_1)\, P(E_2,E_1)\, \sigma(E_1)\, dE_1 \right] dE_2 ,$$

where $N(E_1)\, dE_1$ is the number of target nuclei per square centimeter at the point in the path of the incident proton where its energy is E_1, F is the number of incident protons per square centimeter per second, $P(E_2,E_1)$ is the fraction of emitted neutrons at that point whose energy lies in the given interval, and $\sigma(E_1)$ is the cross section for the reaction for incident protons of energy E_1 (taken as the cross section for formation of the compound nucleus only). The result of graphically integrating the expression is given in Fig. 4 (dashed line). The degradation of the radiation by the intervening layers of iron and lead is equally difficult to describe precisely. We assume that above 3 Mev[21] the cross section for inelastic scattering by lead is roughly constant and equal to 3.3 barns.[22] For 2 in. of lead and 1½ in. of iron equivalent to about 1½ in. of lead, the net effect is that of about 9 cm of lead. Under these conditions, roughly 0.9 of the neutrons above 3 Mev will disappear from the high-energy group and appear as a quasi-Maxwellian energy distribution in a range below 4 Mev. The admittedly crude estimate of the effect is indicated by the difference between the dashed and the solid lines in the figure. The solid line represents our best guess of the degraded spectrum. Since there will be some thermal neutrons present, the curve is shown as intersecting the ordinate axis at some finite, but arbitrarily chosen and somewhat uncertain, value.

[20] W. E. Siri, *Isotopic Tracers and Nuclear Radiations*, p. 99, McGraw-Hill, New York, 1949.

[21] B. J. Feld, "On the Inelastic Scattering of Fast Neutrons," *Phys Rev* 75, 1115-23 (1949).

[22] E. R. Graves and L. Rosen, "Distribution in Energy of the Neutrons from the Interaction of 14-Mev Neutrons with Some Elements," *Phys. Rev.* 89, 343-8 (1953).