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BERKELEY, CALIFORNIA

SAFETY PROBLEMS ASSOCIATED WITH HIGH-ENERGY MACHINES*

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Complex radiation fields exist around large accelerators, such as the 3-Gev Cosmotron at the Brookhaven National Laboratory and the 6-Gev Bevatron at the University of California Radiation Laboratory. The biologically significant components of these radiation fields are neutrons and gamma rays whose spectra extend over a very wide energy range. Because the neutrons are far more penetrating than the gamma rays, they constitute the principle component of the radiation field that must be measured outside of the accelerator shielding.

PART I. TECHNIQUES USED AT BERKELEY

Neutron Spectrum Outside of a Biological Shield

Because at present, data on the biological danger of neutrons is limited to those of energy less than 10 Mev, it is gratifying to find that the measured average neutron energy in occupied areas is usually considerably less than 10 Mev. Measurements are also made whose energy thresholds are 20 and 50 Mev to make certain that no significant flux of neutrons above these energies is present.

The neutrons produced by high-energy accelerators consist predominantly of evaporation neutrons present in large numbers but with energies of only a few Mev. These neutrons need not be considered in the shielding problem because they are, for practical purposes, eliminated by the first few inches of magnet structure or shielding. In addition to these evaporation neutrons, the accelerators produce high-energy beams of neutrons in stripping, charge-exchange, and knock-on events in the target. These neutrons have energies ranging upwards to the maximum energy of the accelerated particles. After these high-energy primaries have entered the shielding, their neutron spectrum is altered, and there is first an initial build-up and second a coming into equilibrium with low-energy secondary neutrons that arise from evaporation events in the shibiding. After equilibrium is established, i.e., after the peak

*Combining Papers Nos. 352 and 562.

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of the build-up is passed, the neutrons of all energies are attenuated in direct proportion to the attenuation of the primaries, with no further change in the neutron spectrum. This shift of neutron energy toward lower values is so effective that the average energy of those neutrons present in biologically significant numbers outside such a shield may be in the neighborhood of 1 Mev. This energy shift makes it much easier to evaluate the neutron hazard than would be the case with the original high-energy neutrons.

Experimental Measurement of the Average Neutron Energy by the 2-Counter Method

The average energy of neutrons leaking through a biological shield is measured by either of two alternate methods. The first of these methods consists of taking two measurements, one of flux density and the other of energy flux density. Measuring flux density is done by taking a counting rate with a BF_3 counter surrounded by 6.2 cm of paraffin (CH_2), both completely surrounded by a cadmium cover. The response of a BF_3 counter surrounded by this amount of paraffin has been measured and found to be essentially independent of energy over the range extending from a fraction of a Mev to about 20 Mev.[1] If a Hanson-McKibben[2] "long counter" is available, it can also be used to measure this energy-independent flux density if care is taken to correct for the nonisotropic sensitivity of this detector.

An additional measurement is made with a polyethylene-lined proportional counter whose counting rate has been shown to be proportional to the neutron-energy flux density. The validity of this relation between counting rate and energy flux density is based on two assumptions. First, it is assumed that the range as a function of energy E of a proton recoil in this material can be expressed as $R(E) = R_0(E)^{3/2}$. Second, it is assumed that the proton path length in g/cm^2 in the counter gas necessary for detection is negligible compared to $R(E)$. Because these two simplifying assumptions are both good in the range of neutron energies from 0.1 to 20 Mev, true proportionality exists between the counting rate in such a proportional counter and the number of Mev/cm^2 sec available from neutrons in this energy range. The theory of the design and operation of this counter is more fully described in Reference 3. After these two measurements have been made, the average neutron energy is obtained by dividing the energy flux rate by the flux rate.

Experimental Measurement of an Effective Neutron energy by the Single Counter Method

The second of the two methods and frequently a simpler measurement of effective neutron energy requires the use of a BF_3 counter alone surrounded by various thicknesses of paraffin. The BF_3 proportional counter itself is sensitive only to thermal neutrons, and, as paraffin is added around the counter, an increased counting rate is observed until the paraffin becomes thick enough to absorb the thermal neutrons more effectively than it produces them from the incident flux of higher energies. After this thickness is exceeded, the counting rate will decrease as more paraffin is added because of attenuation of the primary neutrons. This build-up and subsequent reduction in counting rate depends upon the average energy of the neutrons as seen in Fig. 1. Data plotted are the counting rates of a single BF_3 counter versus paraffin thickness. The paraffin in each case was covered with Cd and the data have been corrected to simulate an isotropic neutron flux.

Five different neutron sources were used whose energies varied from 25kv to 14 Mev. The counting statistics are more accurate than 1%, but the process of averaging over the 4π solid angle possibly has introduced errors of as much as 10%. The DT neutrons are monoenergetic at 14.1 Mev. The Po-Be neutrons have a calculated and measured average energy of 4.4 Mev. The mock fission neutrons have a calculated average energy of 1.4 Mev. The Po-Li neutrons have a calculated and measured average energy of 400 kev. The Sb-Be neutrons have a calculated and average energy of 25 kev.

If these data are converted to counting efficiency as a function of incident-neutron energy for various paraffin thicknesses, the curves shown in Fig. 2 are obtained. By the use of these relations it is possible to obtain an effective neutron energy even in cases where the neutron flux is far below the presently accepted occupational tolerance level because the sensitivity of a BF_3 counter is high.

Evaluation of the Neutron Hazard

If it is assumed that all of the neutrons present possess the average or effective energy measured by one of the above methods, the neutron radiation hazard may be evaluated from the work of Snyder,[4] which is the basis for the curve shown in Fig. 3. This curve gives the flux of neutrons of various energies needed to produce 100 millirem in 40 hours. As described above the actual neutron spectrum outside an accelerator shielding wall will be similar to that of an evaporation spectrum or a fission spectrum. Because the flux of neutrons producing 100 millirem in 40 hours falls with energy as seen in Fig. 3 from an energy of about 4 kv to about 4 Mev, it is a safe assumption that all of the neutrons have the average energy or effective energy that has been measured by one of the above methods.

20-Mev Threshold Detectors

In order to check the assumption that the major biological exposure outside of an accelerator shield is delivered by neutrons in the energy range up to 20 Mev in which the above two measurements are principally valid, two detectors whose thresholds lie respectively at 20 and 50 Mev are used. The measurements with the 20-Mev threshold are made by detecting the $C^{12}(n, 2n)C^{11}$ reaction in the carbon contained in 1700-g cylinders of plastic scintillator as suggested by the work with liquid scintillators of Roganov et al.[6] These polished cylinders are counted by placing them in contact with a 12.5-cm-diam photomultiplier with an optical bond made by mineral oil. The counting is done inside of a lead enclosure 10 cm thick. The cross section of the carbon reaction is roughly constant at a value of 22 mb from 50 Mev to more than 400 Mev.[6] Fortunately the tolerance flux of neutrons may also be fairly constant in this energy range, making this carbon detector quite meaningful.

It has been found that these large scintillators are especially convenient to use in performing a radiation survey. They are inexpensive to duplicate and may be simultaneously placed at many different locations. After exposure of the scintillators proper interpretation of the counting rate yields data from which isoflux radiation contours of the stray neutron field of a large accelerator may be plotted. An important feature of these detectors is that they are completely immune to pile-up problems caused by high instantaneous counting rates as is often met with in the case of electronic detectors such as ion chambers and proportional counters. A 1700-g piece of plastic scintillator will give 100 disintegrations per minute when the neutron flux over 20 Mev prior to counting has been 1 neutron per cm^2 per sec for a period of about three times the 20.4-min half life of the C^{11} formed. The cosmic-ray and natural-background counting rate is about 1000 counts per minute (cpm). Greater sensitivity can be obtained by a proper selection of the minimum and maximum pulse heights that are counted and by using an anti-coincidence cover of Geiger counters or scintillation counters over the scintillator while it is being counted, to reduce the background radiation.

50-Mev Threshold Detector

The detector with the 50-Mev threshold used for checking the above assumption is a large fission-pulse ion chamber[7] containing effectively 60 grams of Bi^{209} evaporated to a depth of 1 mg per cm^2 onto 42 aluminum plates 30 cm in diameter. The plates are connected by the components of a lumped-constant delay line in such a way that a fission pulse originating between any pair of plates charges the capacity of only one pair of plates at a time, thus allowing 60,000 cm^2 of ion-chamber area to be employed. The practical fission threshold for Bi^{209} is 50 Mev, and the cross-section rises with energy to about 300 Mev and is then fairly constant up as far as it has been measured.[8,9] The bismuth fission chamber is equally sensitive to neutrons and protons above 50 Mev and also to pions, but relatively few of these charged particles are present outside of a thick radiation shield. Thus, this detector is especially useful in measuring the flux of primary neutrons present outside the shielding. This instrument has a sensitivity to 220-Mev neutrons of 60 cpm for the whole chamber when it is immersed in a flux of 60 neutrons per cm^2 per sec.

Lower-Energy Ion Chambers

Considerably smaller fission-pulse ion chambers of conventional design whose plates are coated with Th^{232} or U^{235} are used to take advantage of their energy thresholds of 1.5 Mev and thermal respectively. The U^{235} ion chamber has been found to be especially useful as a monitor of over-all Bevatron operation. It is placed at the center of the main magnet ring where it views the entire machine equally. In this position its measurement of the thermal-neutron flux is to some extent independent of the particular targets or beam-spill characteristics being employed at the time. The U^{235} ion chamber measures the over-all neutron production, which has proved to be well correlated to circulating-beam-current measurements.

Indium-Foil Fast-Neutron Detectors

Another detector[10] which has the same advantages of inexpensive duplication, simultaneity of measurement, and no pile-up problem as the large plastic scintillators is an In foil imbedded in paraffin and surrounded by Cd. This assembly is a cubical box 15 cm on a side made of Cd 0.051 cm thick. Inside the box is a paraffin sphere 15 cm. in diameter made of two hemispheres. Each hemisphere has a recess at the center, 3.0 cm in diameter and 0.3 cm deep in which an In foil is placed. The 0.125-mm-thick foils used weigh about 500 mg each. This detector is sensitive to neutrons from 20 kev upward, with almost uniform efficiency to 20 Mev. The foils are counted in a methane-flow proportional counter, and when activated to saturation in the above assembly, a foil gives about 4 c/m for a fast neutron flux of 1 n/cm^2 sec. The counter has a background counting rate of 10 c/m. A flux as small as 3 n/cm^2 sec has been successfully measured with this detector. The response as a function of energy is similar to that of a BF_3 counter covered by 15 cm of moderating paraffin.

PART II. PROBLEMS AT BROOKHAVEN

Introduction

The Brookhaven Cosmotron is a proton synchrotron that accelerates protons to energies of 3 Gev during 1 sec of a 5-sec cycle. The duration of the radiation pulse may be made to vary from 10 μsec to 100 msec depending upon the particular experimental requirements; the shorter pulses are utilized by the bubble-chamber groups and longer pulses by the counter groups. Beam intensities have approached 10^{11} protons per pulse for internal-beam operation. Discussions of the health physics procedures and instrumentation associated with the Cosmotron and pulsed radiation may be found in several reports.[11, 12, 13]

At present the Cosmotron is shut down for an extended period of time (to January 1959) for major coil modifications, construction of a new and more complete shield, and expansion of the experimental area. When the Cosmotron goes back into operation it is hoped that beam intensities will be increased to approximately 10^{12} protons per pulse because of improved techniques.

External Beams

Despite the increased intensity, however, the new Cosmotron shielding, completely encompassing the machine, will greatly reduce the health physics problems except for experimental runs that utilize beams brought out through ports in the shield. It is expected that the external proton beams will be utilized for approximately 50% of the experimental time.

The Cosmotron was designed to use only one external beam. An ejection magnet brings the beam out of the machine near one of the straight sections with an ejection efficiency of approximately 25 to 30%. The beam follows a northerly course through a port in the shield, across an experimental area, then out of the building and into a large earthen beam catcher 800 feet north of the Cosmotron building. This 40,000-cubic-yard beam catcher is equivalent in thickness to about 15 ft of heavy concrete of 300 lb/ft^3 density, and has reduced the radiation levels beyond it to tolerable values.

The increase in radiation over natural background from the 3-Gev protons striking the beam catcher is insignificant, probably because the secondaries are produced so deep in the catcher that few reach the surface. Little stray radiation results from the passage of the beam through the air. The greatest source of stray radiation is caused by the beam's passing through the port in the shielding and through the various focusing and bending magnets. The addition of a maximum-scattering target (3 inches of Pb) at the focal point in the beam raises the radiation levels by a factor of two or less.

Radiation levels in the external-beam area between the shielding wall and focal points have been measured by use of a small bakelite ionization chamber; dose rates of approximately 1600 rad/hr have been found during external-beam intensities of approximately 1.6×10^{10} protons per pulse.

Personnel are prevented from entering the external-beam area by a fence inside the Cosmotron building and another surrounding the area outside the building, encompassing the entire beam catcher. Also, a television camera has been used so that Cosmotron operators may observe the target area remotely.

Plans are being made for a second external beam to leave the machine in a northwesterly direction. This will enlarge the present external-beam area both inside and outside the building. Targets placed in the external beam may have to be shielded, depending upon location, beam intensity, and operating time.

The external beams may be used either together (each target receiving alternate pulses) or singly. Special regulations are being studied for procedures that will allow personnel to enter that target area in which the beam is not in use.

Experimental Measurements of RBE with a Cloud Chamber

The relative biological effectiveness (RBE) of radiation in areas accessible to personnel at the Cosmotron is estimated to be no greater than 5. In view of some uncertainties involved in this estimate, a safety factor of 2 has been introduced, which increases the operating RBE to 10.

Two experiments have been pursued to find a value of effective RBE. The first uses a diffusion cloud chamber, which is operated in a given region of scattered radiation. Stereoscopic photographs are taken of the tracks, and the length and density of every track is measured with the aid of a projection system. The photographs of the sensitive volume are projected onto a ground-glass screen in a manner that makes possible the measurement of the absolute lengths and dip angles of the tracks. The densities are classified visually, by comparison of the tracks with those made by known particles. The values of linear energy transfer (LET) of these known particles are shown in Fig. 4. Four classes of track density have been chosen, ranging from minimum-ionizing tracks to alpha-particle tracks. These classes are shown in Fig. 5.[14] The length of each track in a specified volume is measured and its density classified. The fraction of the sum of the length of all the tracks in each class can thus be determined. If the average values of LET for each class are used, the fraction of the energy lost in the chamber from each class can be calculated. Then if the energy lost in each class is weighted with the proper RBE for that class, an effective RBE in the particular region studied can be determined.

Experimental Measurements of Effective RBE with a Proportional Counter

The second experiment uses a device that measures the absorbed dose as a function of LET. The device was loaned to Brookhaven National Laboratory by Dr. H. H. Rossi of Columbia University for evaluation of the average RBE for Cosmotron radiation. The instrument is a 4-in. (i.d.) spherical proportional counter constructed of 1/4-in.-thick tissue-equivalent* plastic and (continuously) flushed with tissue-equivalent counting gas

*Tissue equivalent is defined has having approximately the same chemical composition as soft tissue.

at reduced pressure. Preliminary values of average RBE were obtained in the Cosmotron control room and on the balcony in front of the control room. The total dose rates at these locations, as measured with a second tissue-equivalent ionization chamber, were 0.75 and 1.77 mrad/hr, respectively. The stray radiation resulting from an experiment utilizing a gold target in the unshielded west straight section of the Cosmotron was studied. The average circulating-beam intensities were approximately 5×10^9 protons per pulse at 3 Gev. The duration of the radiation pulse was estimated to be from 50 to 70 msec with a repetition rate of 12 pulses per min. The pulse-height distribution from the proportional counter was sorted by use of a 20-channel differential pulse-height analyzer. Runs were made at different bias settings and a total of 120 channels was covered.

By use of the method developed by Dr. Rossi,[15, 16] it was possible to derive a curve showing the distribution of absorbed dose with LET from the pulse-height distribution.[5, 6] This curve, representing the control-room dose, is shown in Fig. 6 along with a curve relating RBE to LET.[14] Also shown is the RBE dose curve, which is the product of the two other curves. By comparing the area under the RBE dose curve with the measured total dose in rads, and making suitable allowance for the dosage below the threshold of the pulse-height analysis, one obtains a value of effective RBE applicable to the radiation in the control room.

Average RBE values of 4 and 3 respectively were obtained in the two locations mentioned above. Because the LET chambers are roughly tissue-equivalent, these values should be applicable to human exposures. They help confirm the belief that the present survey practice is safe. However, additional measurements in numerous locations and for the many different types of Cosmotron experimental programs (which significantly change the LET spectrum of the stray radiation) are necessary before one can obtain a good understanding of the RBE values encountered.

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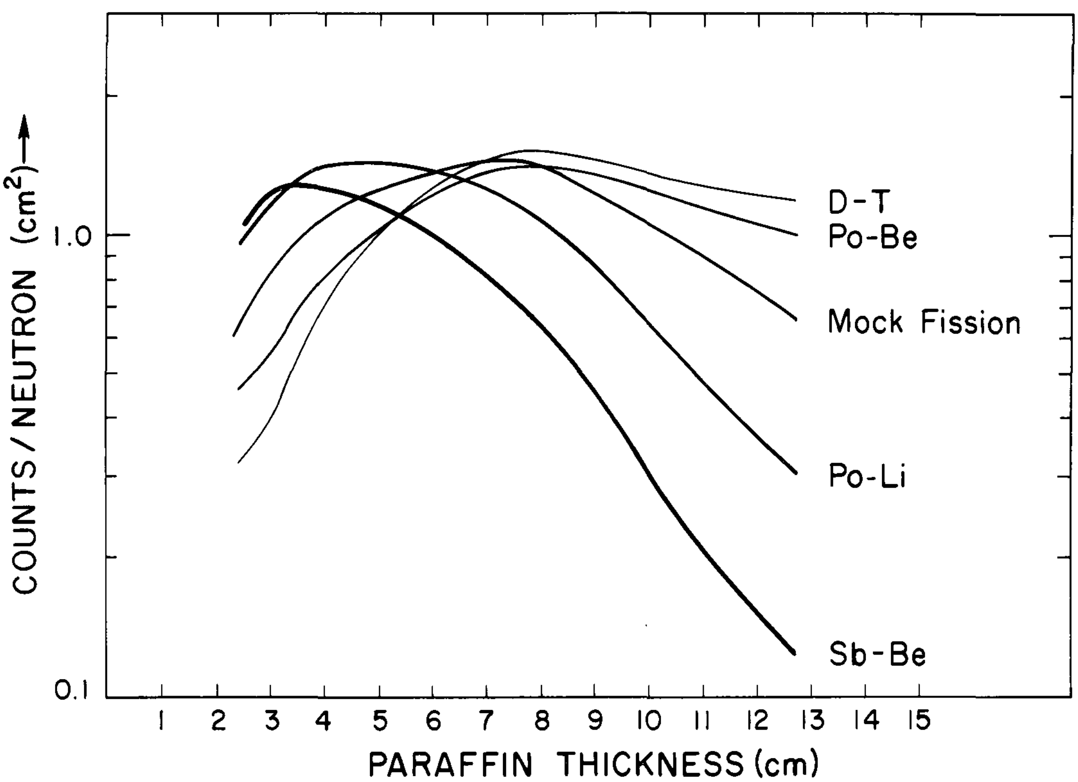

Fig. 1. BF_3 counting rate as a function of paraffin thickness for various neutron sources, corrected to an isotropic flux distribution. The entire assembly was covered by Cd.

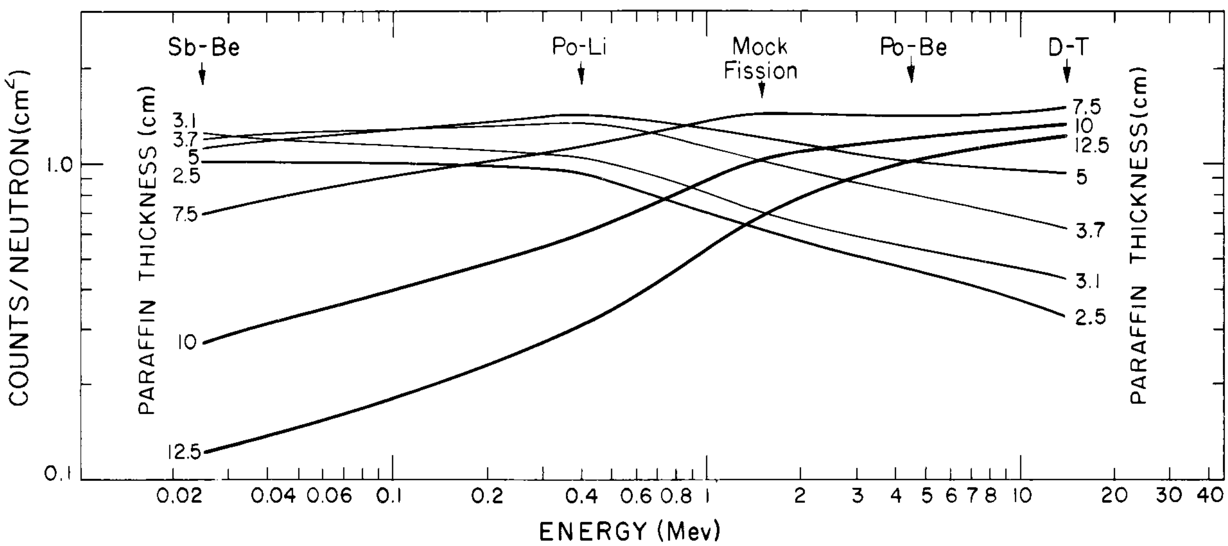

Fig. 2. BF_3 average efficiency as a function of neutron energy for various paraffin thicknesses, corrected to an isotropic flux distribution. The entire assembly was covered by Cd. The averaging over the 4π solid angle has introduced an error of as much as 10%.

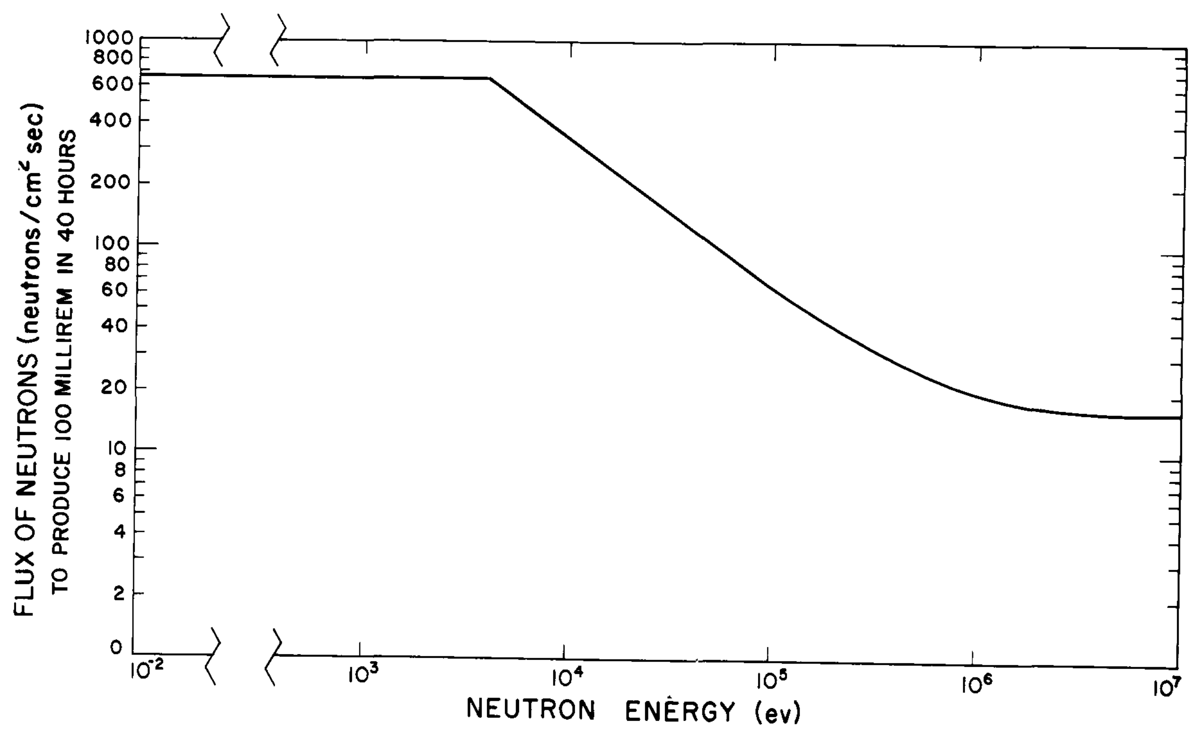

Fig. 3. The flux of neutrons that will produce 100 millirem per 40-hr work week in accordance with the occupational exposure levels adopted in 1957.[14] The data are from NBS Handbook 59[14] and from Snyder.[4] For energies greater than 1 Mev the dose is for the first 4 cm of tissue depth, and for energies less than 1 Mev the dose is the surface or maximum dose.

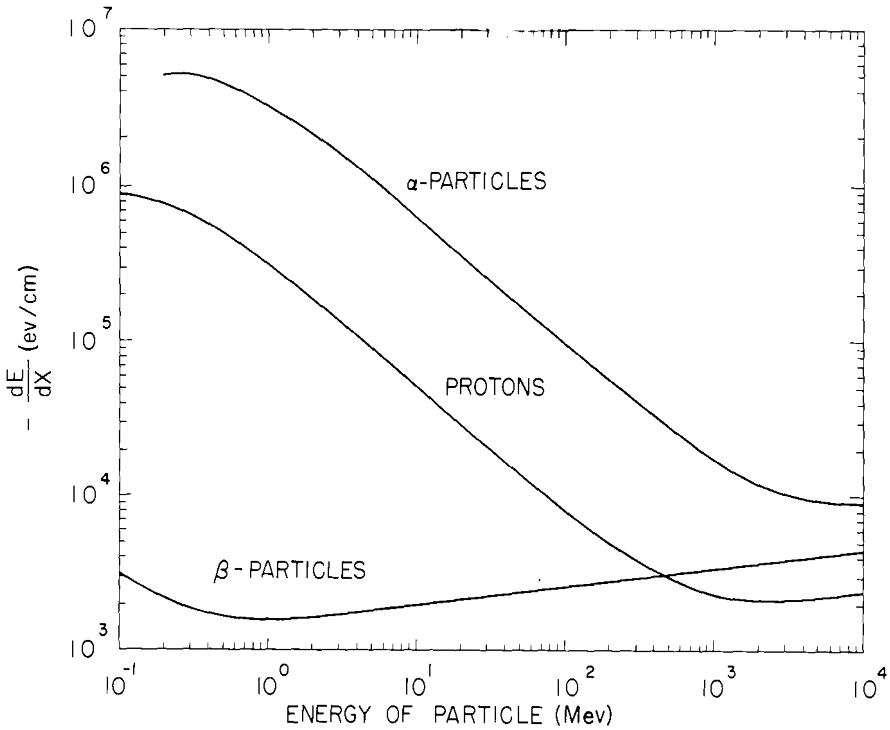

Fig. 4. Linear energy transfer in tissue-equivalent gas as a function of energy (15° C, 760 mm).

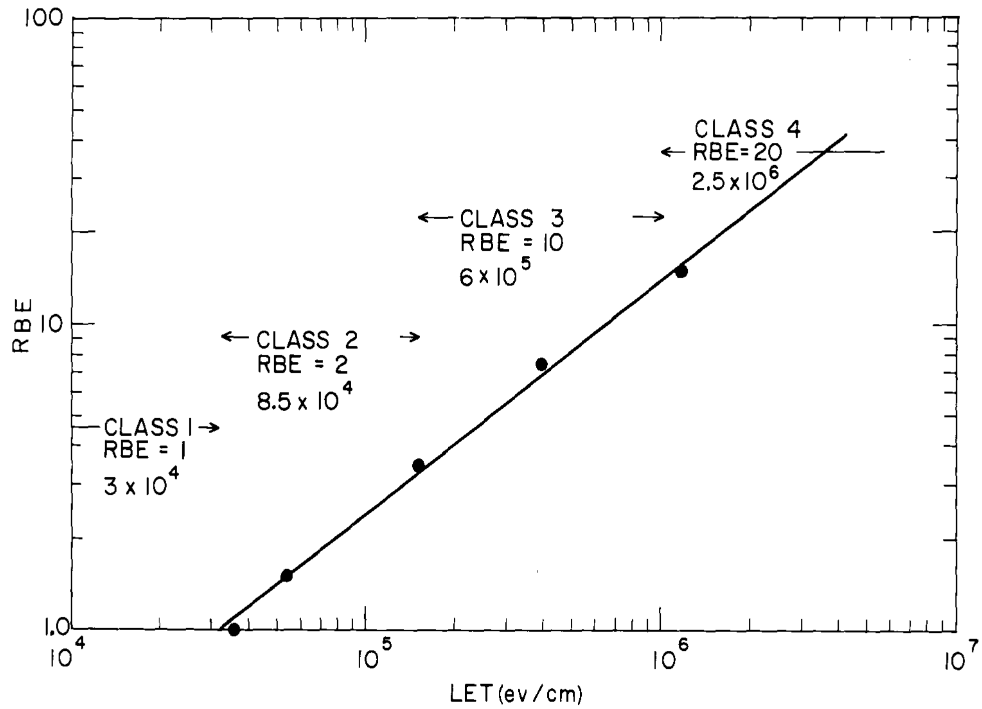

Fig. 5. Relative biological effectiveness (RBE) in air as a function of linear energy transfer (LET). The four classes of track density are shown. Data are from NBS Handbook 59.[14]

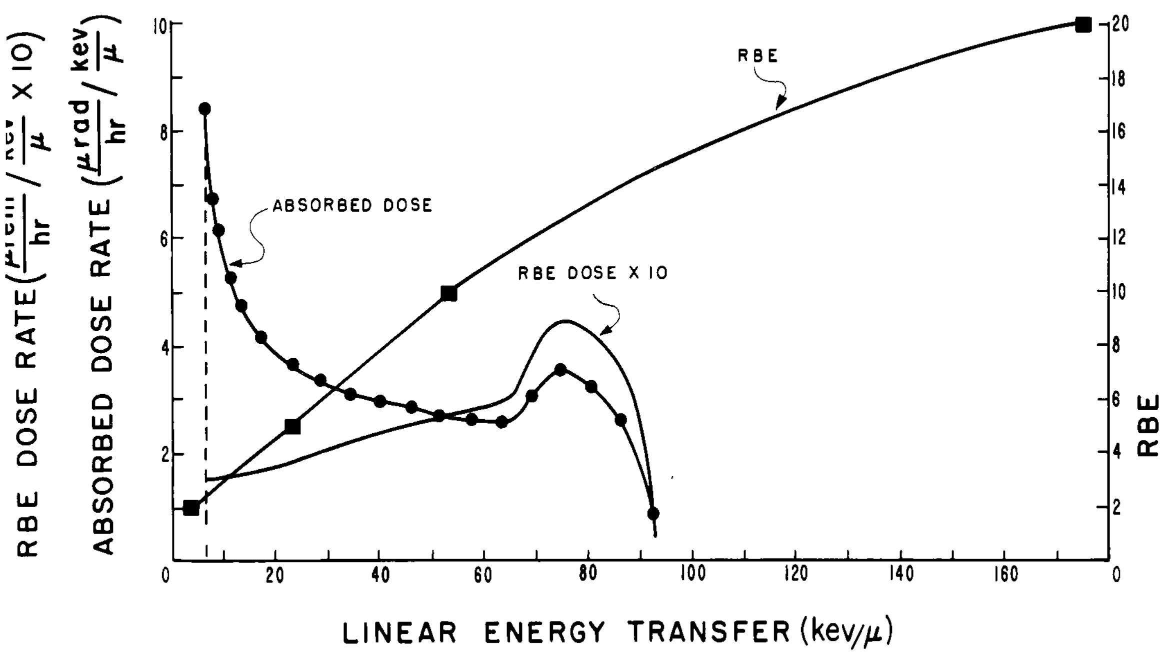

Fig. 6. Absorbed dose and RBE in tissue as a function of linear energy transfer (LET). In addition the RBE dose is shown. Data from NBS Handbook 59, page 48.[14]