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Author
Patterson, H. Wade.

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H. Wade Patterson

November 17, 1965

Berkeley, California

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SUMMARY

Since the late 1940's the Health Physics Department has been responsible for accelerator radiation monitoring and shielding at the Lawrence Radiation Laboratory in Berkeley. During this time we have made radiation measurements and shielding studies on the 60-inch cyclotron, the 184-inch cyclotron, the electron synchrotron, the electron linear accelerator, the Bevatron, the heavy-ion linear accelerator, the proton linear accelerator, and the 88-inch cyclotron. Our measurements have mostly been made with the purpose of identifying the various components of the radiation field and determining their energy distribution. A general rule that has emerged from our studies is that fast neutrons (0.1 to 10 MeV) dominate the biological hazard of the radiation field existing near a well-shielded particle accelerator by contributing more than half the total rem dose. Gamma rays and low-energy neutrons contribute 10 to 20%, and high-energy neutrons make up the balance. We have therefore emphasized the development and use of neutron detectors that allow us to estimate the neutron spectrum. (Measurements of accelerator radiation in rad or rem units are not generally made, since they give no information that can be used to recommend protective shielding.)

Neutron detectors that we have found most effective are moderated slow-neutron detectors, threshold reaction detectors, emulsion, and the polyethylene-lined proportional counter. The accelerator neutron spectrum that we infer from the response of these detectors is nearly the same as the measured cosmic-ray neutron spectrum. Furthermore, the shape of the measured spectrum is consistent with that calculated by several independent groups and individuals.

We have also used our detectors to successfully predict the effect of shielding with a wide variety of materials to both protect personnel and reduce radiation background around bubble chambers, NaI crystals, and plastic scintillators.

Techniques of measurement, application of specific detectors to certain problems, and practical illustrative examples of monitoring problems and their solutions are given in some detail.

ACCELERATOR RADIATION MONITORING AND SHIELDING AT THE LAWRENCE RADIATION LABORATORY, BERKELEY

I. INTRODUCTION

Since the late 1940's the Health Physics Department has been responsible for accelerator radiation monitoring and shielding at the Lawrence Radiation Laboratory in Berkeley. During this time we have made radiation survey measurements and shielding studies of the radiation fields produced by the following accelerators.

1. <u>60-Inch cyclotron</u>

Particles accelerated	protons	deuterons	alphas
Maximum energy (MeV)	12	24	48
Average beam current (μA)	70	80	50

2. <u>184-Inch synchrocyclotron</u> (modified in 1957)

Particles accelerated	protons	deuterons	alphas
Maximum energy (MeV)	730	460	910
Average beam current (μA)	0.75	0.75	0.25
Maximum energy before modification (MeV)	350	190	380

3. <u>Synchrotron</u> (electron synchrotron)

Particles accelerated	electrons
Maximum energy (MeV)	340
Maximum intensity	2×10^9 electrons/pulse

4. <u>Electron linear accelerator</u>

Particles accelerated	electrons
Maximum energy (MeV)	7.5
Average beam current (μA)	200

5. <u>Bevatron</u> (proton synchrotron)

Particles accelerated	protons
Maximum energy (MeV)	6200

Maximum intensity	5×10^{12} protons/pulse, internal 2×10^{12} protons/pulse, external

6. Heavy-ion linear accelerator

Particles accelerated	deuterons, C^{12}, N^{14}, O^{16}, Ne^{20}, A^{40}, and others
Maximum energy (MeV)	10/nucleon
Average beam current (μA)	0.01 - 4.0

7. Proton linear accelerator

Particles accelerated	protons
Maximum energy (MeV)	32
Average beam current (μA)	0.1

8. 88-Inch cyclotron

Particles accelerated	protons	deuterons	alphas
Maximum energy (MeV)	60	60	130
Average beam current (μA)	30	40	20

(presently limited by deflector cooling).

In addition to these differences in energy and type of particle accelerated, it is also pertinent to recognize that we have experienced great variations in the kind and amount of shielding at the accelerators. The 60-inch cyclotron had water tank shielding. The 184-inch synchrocyclotron and the Bevatron have operated with partial shielding of both ordinary and heavy concrete and of iron. The Hilac is a strong x ray source along the accelerating portion of the machine and a strong neutron source in the target areas. Here also a combination of iron and concrete shielding is used. Changes in the experimental program also require changes both in shielding and in operating conditions, and therefore we have to recognize and solve a very wide variety of health physics problems. For example, besides evaluating accelerator radiation fields for health protection, we may be asked to recommend shielding for a bubble chamber or an array of large scintillators, or to predict the change in the quality of a radiation field when some characteristic of a distant accelerator is changed.

As a result both of our responsibilities and of our experience we have concluded that an adequate understanding of accelerator radiation fields requires a variety of detectors and instruments. It is not, in most cases, sufficient to make a measurement with a single instrument which reads in units proportional to the assumed degree of hazard. It is not enough to say only "The radiation level here is too high"; rather, this statement should be followed with an accurate description of the radiation field and a recommendation for protective measures. In accord with theory, we have found that neutrons dominate the biological hazard and, consequently, the thickness of shielding required around particle accelerators; as a result, we have put considerable emphasis on the development and use of instruments for determination of neutron flux and energy.

II. DETECTORS AND INSTRUMENTS

Neutron detectors that we have found most effective and widely useful are moderated slow-neutron detectors, threshold reaction detectors, emulsion, and the polethylene-lined proportional counter. Each detector, however, is, under certain conditions, subject to severe restrictions on it validity, and careful attention must be given to energy response, directionality, pulse pile-up, and unwanted background. No single detector can give good information under all conditions of use, and whenever possible a number of different detectors and methods of data analysis are used to check and compare the results obtained from each.

To supplement our own evaluation of accelerator radiation fields we have from time to time encouraged other health physicists, from outside our own Laboratory, to come and make measurements with detectors, using techniques in which they are expert. G. Failla, and Failla and H. Rossi, on two visits, used tissue-equivalent ionization chambers. Rossi and L. Phillips later made several determinations of the LET spectrum. L. Solon, P. Klevin, J. McLaughlin, K. O'Brien, and R. Sanna of HASL have also used tissue-equivalent chambers and most recently nuclear emulsion. We find these independent measurements valuable as a check on our own measurements and as a way of comparing the usefulness of different techniques. For example, we have found that in our accelerator radiation fields the response of a simple, air-filled plastic-walled ion chamber is nearly the same as a tissue-equivalent chamber.

Slow-Neutron Detectors

Slow and thermal neutrons do not, in our experience, contribute much to the total dose received outside the usual accelerator shield. However, we occasionally need to measure slow-neutron flux, for the purpose of estimating the activation by capture of accelerator structures, and the β- and γ-ray levels thus induced. For these measurements, we typically use foils of In and Au, with and without Cd covers, and also BF_3-filled proportional counters. We calibrate these detectors by immersing them in a large tank of water, in which a fast-neutron source is fixed at a known distance. We also use a hollow, thick-walled concrete cube for slow-neutron calibration. When a fast-neutron source is suspended in the center of a cavity in concrete, a known slow-neutron flux is produced in the cavity by diffusion and back-scattering. This calibration flux depends only on the emission of the source and the interior surface area of the cavity.

Fast-Neutron Detectors

We use these same slow-neutron detectors covered with paraffin or polyethylene, to measure fast neutrons. When slow neutrons are excluded from the assembly by an outer layer of Cd, usually 0.020 in. thick, the response of the detector to the neutrons slowed down by paraffin or polyethylene may be plotted against moderator thickness to produce a so-called buildup curve. The shape of this curve and the location of the peak, if any, give information about the energy distribution of the fast neutrons. When a moderator 6 cm thick is used, the response of the detector is almost independent of neutron energy over the interval 0.03 to about 20 MeV, and is in units of neutrons/cm^2 per count. We find that the moderated-foil detectors of In, Au, or Co are particularly useful for making a large number of simultaneous measurements. The activity induced in the foils is measured with Geiger counters, proportional counters, and NaI crystals. The range of sensitivity of these detection systems is such that we can adequately measure both environmental background levels and any level of neutron flux produced by an accelerator.

At the Bevatron, where the acceleration time is about 2 seconds and the pulse rate is 10 to 11 per minute, we find a moderated Geiger tube covered with Ag foil to be very useful. A scaler that counts Geiger tube pulses is gated off during the time the Bevatron is accelerating beam, but the Ag foil is capturing neutrons that have been slowed down in the moderator. At the end of the acceleration and targeting cycle, the Geiger tube scaler is gated on, and now counts the activity induced in the Ag. By adjusting the amount of Ag and the duration of the "on" gate, we can make the number of counts equal to the time-average neutron flux. This instrument is used as an area monitor or for radiation surveys, and in controlling access to certain areas, or automatically stopping Bevatron operation if radiation exceeds a predetermined value.

Energy Flux Detector

Another type of fast-neutron detector that we find very useful is the polyethylene-lined proportional counter. This counter is filled with an A-CO$_2$ mixture and lined with up to 1/8 in. of polyethylene; it is calibrated by extrapolating to zero the bias curve produced by recoil protons under conditions of constant gain and high voltage. The zero-bias intercept is found, both by calculation and by experiment, to be 15 MeV/cm^2 per count over the range of neutron energy 0.1 to 20 MeV. If simultaneous measurements are made with a flux detector, then MeV/cm^2 ÷ neutrons/cm^2 immediately gives an average neutron energy. This can be compared with data from other detection systems, and in our experience we find good agreement. The sensitivity of this detector is adequate for most practical applications around our accelerators.

For flux and energy calibration of all our fast neutron detectors, we use neutrons from a variety of isotopic fast-neutron sources as well as from (d, d) and (d, T) reactions. The isotopic sources are carefully compared and calibrated by us, by the manufacturer, and in certain cases by NBS, using the Mn bath technique and moderated BF_3 counters. The accelerator neutron sources are calibrated by associated particle counting, with moderated BF_3 counters, and with threshold detectors.

Threshold Detectors and Nuclear Emulsion

We also use threshold detectors for measuring neutron spectra. We have developed a method, useful in the neutron energy interval 2 to 30 MeV which depends on the activation of Ni, Co, Fe, Mg, Al, and I by (n, p), (n, α), and (n, 2n) reactions. Knowledge of the cross sections for these reactions is crucial; although most have been measured, the rest must be estimated as closely as possible. After exposure of a series of different elements, the activity induced is first identified with a NaI crystal and multichannel analyzer, and then reduced by computation to absolute disintegration rates. These disintegration rates are in turn compared with those that should be produced by an assumed neutron spectrum; the comparison is repeated with slight changes in the assumed neutron spectrum until it produces activities matching those actually observed. We use this technique to measure neutron spectra produced at an accelerator target and to evaluate shielding, and are now trying to extend its usefulness to higher neutron energies and smaller integrated fluxes.

Another basic way of measuring a neutron energy spectrum is to measure the track-length distribution of proton recoils in a nuclear emulsion. We use Ilford L.4 600-μ emulsions. Our scanning microscope has been adapted to function with a card punch, so that the x, y, and z coordinates for the end points of each track can be stored on demand. When the end points for 1000 or more tracks have been stored, a computer generates a proton recoil spectrum, taking into account emulsion shrinkage and the decreasing probability with increasing track length that a track will start and stop in the emulsion. A smooth curve is drawn by hand through the individual points in the proton recoil spectrum and this curve is then differentiated to produce a neutron spectrum. An integrated exposure between 5×10^6 and 10^8 n/cm^2 is ideal for usual spectra from isotopic sources and accelerators. The useful neutron energy interval is from 1 or 2 to about 20 MeV. Below this energy the recoil tracks are too short to measure accurately, and background due to α tracks and protons from $N^{14}(n, p)C^{14}$ in the emulsion is troublesome. Above this energy the number of tracks is too small for meaningful statistics, and background due to cosmic ray neutrons may need to be allowed for.

For higher-energy neutrons, which are present in small numbers outside well-shielded accelerators and may be present in large numbers in beams and where the shielding is thin, we use two additional threshold reactions applied in special ways. These are the (n, 2n) reaction in C^{12} and the bismuth fission reaction. We expose large cylinders (about 1.7 kg) of plastic scintillator and then use a photomultiplier to count the C^{11} produced in it. (If high-energy protons are present in the radiation field, they compete with the neutrons in producing C^{11} and must be allowed for.) The cross section for this reaction is known well enough for health physics purposes from its threshold at 20 MeV to about 30 GeV. The bismuth fission process is detected in an ion chamber with bismuth-coated parallel plates. Operation of the chamber in the pulse mode discriminates strongly against γ rays and all low-energy reactions, since the ratio of fission pulse height to pulse height of other particles is in the order of their energy ratio. Protons can also initiate fission in bismuth, but an anticoincidence blanket allows us to subtract their effect, which in most practical cases is very small. The bismuth fission cross section is also known well enough for our purposes from its 50-MeV threshold to about 30 GeV. Both these detectors, C and Bi, have been carefully calibrated in known fluxes of high-energy neutrons, and C has also been calibrated with protons.

Ion Chambers

We often use plastic-wall ion chambers in accelerator radiation surveys and apply an estimated quality factor to the results. As the output current from these is small we use them with vacuum tube electrometers, the Lindemann electrometer, and the vibrating-reed electrometer, and recently with an insulated-gate field-effect transistor. This transistor is operated in the enhancement mode and its high-input impedance is made possible by the insulation of a thin SiO_2 layer between the input and other elements of the device. With respect to input capacity, transconductance, stability, temperature sensitivity, leakage current, and supply current required, it compares very favorably with vacuum tube and vibrating-reed electrometers. It is extremely well suited for use in a portable instrument.

III. REGULAR SURVEY TECHNIQUES

Most accelerators operate as pulsed sources of radiation, and for this reason the pulse-resolution ability of detectors and their electronics may be a problem. We check this by observing pulse rates with an oscilloscope and by varying whatever machine parameter controls the radiation intensity. The presence of unwanted background--for example, gamma radiation in neutron counters--must be tested for and eliminated by the use of shielding or by changing the gain or discrimination level of the detection system. We also find it mandatory to record data during a survey from some monitor detector. This may be a detector that we have installed for this purpose or it may be some other device used by the accelerator crew to monitor machine operation. We find that an accurate and reliable monitor provides the only means by which data taken at different times can be truly compared. Finally, we must also be sure that magnetic and radio-frequency fields are shielded from or do not affect our instruments, so that we can rely on the measurements.

A complete radiation survey at each accelerator at least once a year is necessary. This is made under maximum ouput conditions and in many locations. Particular attention is given to known weak spots in the shield, such as door edges, thin roofs, and holes, but it is essential that enough separate points be measured to provide an approximate three-dimensional view of the radiation field. Such a survey reveals any unsuspected deficiencies in the shield and shows how these may be corrected.

x and Gamma Radiation

When we know that the radiation field is entirely electromagnetic (i.e., no particulate radiation) we use ionization chambers and film. The ion chambers may be either rate-reading or integrating. We can measure attenuation coefficients by adding incremental layers of shielding to either type of detector.

Radiation Fields Involving Neutrons

In mixed radiation fields, we require that an understanding of the relative neutron and γ-ray doses be obtained, and that some information on the neutron spectrum be acquired. Typically, an initial survey is made with four instruments which give approximate answers as to
(a) total ionization, with a plastic-walled ionization chamber;
(b) slow-neutron flux density, with a bare BF_3 counter or foils;
(c) energy flux delivered by fast neutrons, with a polyethylene-lined proportional counter;
(d) fast-neutron flux, with a moderated BF_3 counter.

If we decide that the total radiation field approaches or exceeds tolerable levels, or if we know that high-energy neutrons are present, then further surveys are made. These measurements are more analytic in character than those of the initial survey. We take paraffin buildup curves for a BF_3 counter and an ion chamber, activate C and Al threshold detectors, make measurements with a Bi fission chamber, and expose nuclear emulsion. When we wish to make simultaneous measurements at many different points, we use--in addition to the C, Al, and emulsion--moderated foils of In, Au, or Co.

Area Monitoring

At representative locations near each accelerator and at four stations near the boundary of the Laboratory, we record both the rate of exposure and the integrated amount. For this we use chart recording ionization chambers, count-recording Geiger-tube detectors, β-γ film, nuclear emulsion, moderated Co foils, and moderated BF_3 counters. We have developed a very successful telemetry system, which transmits pulses over telephone wire, to bring back to our building count-rate data from the BF_3 counters. The system is cheap and extremely reliable, and gives us a continuous review of the operation of each accelerator. Operational changes at accelerators that cause unduly high radiation levels can be dealt with at once.

Personnel Monitoring

Almost every employee of the Laboratory is issued a β-γ film badge; in addition, about 900 employees have Eastman Type A neutron films. The films are developed and interpreted monthly. The β-γ films are calibrated with Ra, while the neutron films are calibrated with fast neutrons of various energies. Each person's neutron exposure is recorded in terms of proton recoil tracks per microscope field of view, and this is translated into neutrons/cm^2 and rem, based on knowledge of the neutron spectrum. Whenever a personnel film indicates an exposure above 400 mrem in any one month an investigation is made, the exposure is re-evaluated if necessary, and the results are given to the individual and his supervisor and also recorded. Pocket ionization chambers are worn by some individuals, and by everyone in certain areas. At present, no Laboratory employee has exceeded the maximum permissible exposure given by the (age-18) 5-rem formula.

IV. GENERAL RESULTS

Our array of detectors, systems, and techniques has been used over the years to take data at all the accelerators listed above. Proper interpretation of these data leads to a series of conclusions as follows:

Intensity vs Distance

At distances less than about 250 feet, the radiation field intensity depends very strongly on shielding configuration and target location. At greater distances, the accelerator may usually be considered as a point source and we see that the radiation field decreases as $1/r^2$ or somewhat faster out to a few thousand feet, the present limit of our measurements.

Differential Neutron Spectrum

The neutron spectrum outside well-shielded proton and other heavy-particle accelerators closely resembles the cosmic-ray neutron spectrum observed in the atmosphere. The accelerator neutron spectrum decreases with energy, approximately as 1/E, from thermal energies to 1 to 10 MeV. (This observation is supported by a consideration of neutron scattering in non-absorbing media.) At 1 to 10 MeV there may or may not be a flattening of the spectrum due to the production and scattering of evaporation neutrons. At higher energies, the neutron spectrum also falls off as 1/E in the forward direction from targets and where the shielding is thin; but in most areas around our accelerators we see a decrease that is somewhat steeper. At energies approaching the primary particle energy the spectrum becomes very steep. These observations agree with cosmic-ray data and nucleon-cascade calculations made at our Laboratory and elsewhere.

Neutron Dose

When the neutron spectrum has been measured, the dose delivered by it can be calculated by reference to NBS Handbook 63 and ICRP recommendations. The dose per neutron having energy greater than 10 MeV is somewhat uncertain, but independent calculations give results in good agreement and we choose to use the expression, $30.2/E^{1/4}$, for the flux of neutrons, unaccompanied by secondaries, that will deliver 100 mrem per 40 hours. Near thin shields, we find that the dose per neutron is about 4.5×10^{-8} rem; in normally occupied nearby areas, and at considerable distances, the dose drops to about 3×10^{-8} rem/neutron. In the thin-shield case, up to 50% of the neutron dose comes from neutrons above 20 MeV, while in most situations less than 20% of the neutron dose comes from these high-energy neutrons. Slow neutrons contribute at most a few percent, and the γ-ray portion is about the same.

In summary, neutrons dominate the radiation field; of these, neutrons of energy 0.020 to 20 MeV contribute most of the dose. Less than 10% of the total dose comes from γ rays and other ionizing radiation. The mean biologically effective neutron energy is always between 0.5 and 10 MeV, and in most practical cases is between 1 and 2 MeV.

Activation

We have measured induced activity in accelerator structures with ion chambers and Geiger-tube detectors, at times after shutdown from minutes to about 30 days. We find that the controlling half-life increases with time, and observe a mixture of radioisotopes by γ-ray spectrometry that explains this. Prominent isotopes which we see at the Bevatron and 184-inch synchrocyclotron are Al^{28}, Mg^{27}, Na^{24}, and Na^{22} in Al; Mn^{56}, Mn^{54}, Mn^{52} and V^{48} in Fe; Cu^{64}, Co^{58}, Mn^{52}, Zn^{65}, and V^{48} in Cu. Ultimately Co^{60} remains in Cu, Mn^{54} in Fe, Na^{22} in Al, and Be^{7} in C.

N^{13}, O^{15}, and A^{41} can be seen in the air inside shields, but these and the activities induced in dust and dirt produce only a small fraction of the total exposure received by workers during repair and maintenance. However, all induced activity should be controlled to prevent the spread of contamination.

V. APPLICATION TO SPECIAL PROBLEMS

On frequent occasions in accelerator Health Physics it is necessary to solve a problem in radiation protection. We have had some success in this regard having to do with shielding.

Wood Shielding

At one time, the Bevatron was being operated with only side shielding and some rather thin concrete over the straight sections. The magnet quadrants had no top shielding, except for the 2 ft of Fe in the magnets themselves. Under these conditions, the number of accelerated protons was increased to a degree that made the radiation field in nearby areas greater than that permitted for long-term exposures. After an analytical study of this radiation field, we were able to show that (surprisingly) there was a very large component in the neutron spectrum near 0.1 MeV. This made it possible to temporarily install inexpensive wood shielding, which brought a factor of about 10 in protection, instead of using expensive concrete shielding or limiting Bevatron operation. The effect that we predicted for the wood was confirmed by another series of measurements after it was installed. Since then we have found situations at other accelerators in which wood shields are also worthwhile, both for personnel and for equipment shielding.

Bevatron Roof Shield

Later the Laboratory was authorized by the AEC to modify the Bevatron and to increase the beam intensity by about a factor of 50. We were asked to recommend the proper roof-shield thickness and to include another factor of 2 for the removal of the temporary wood shield. We again studied the radiation field with our array of instruments and made calculations using our own data and other information. After the roof and certain other shielding were installed, we repeated the study and found that the overall effect of the recommended shield was to reduce the total intensity by a factor of 90 to 100, the exact value depending on the particular detector and its location. Since the half-thickness for attenuation of neutrons of Bevatron energies is about 18 in., we are well pleased with the results from our detectors and the capability that they give us to predict the effect of shielding on accelerator radiation.

We have had similar problems at other accelerators and have solved them successfully, but we could not have done so by making measurements with only one detector or with detectors which respond only in units of rads or rem. These do not give the information necessary to answer the questions we are asked.

VI. PLEA FOR SOME UNIFORM TECHNIQUES

Without undue exaggeration the present situation in accelerator health physics can be described as follows. There are no standard detectors or methods of measurement. Instruments are used that purport to measure flux, rads, rem, QF, LET, roentgens, energy flux, and energy spectrum; results are reported in all these units. Consequently, an accurate physical description of the radiation field outside an accelerator shield cannot be exchanged between laboratories, and this in turn leads to confusion and disagreement.

There has recently been appointed by the Division of Operational Safety, AEC Headquarters, an Advisory Panel on Accelerator Safety. I suggest that this group consider our problem and then recommend some standard detectors and uniform techniques. In my own opinion the detectors and techniques should at least meet the following criteria.

1. They should be well understood in principle.
2. They should be selective as to both energy and type of radiation.
3. The response should be in physical units.
4. They should be capable of interlaboratory calibration.
5. The meaning of the results should not depend on a future committee decision.

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The work reported here is largely the work of the members of the Health Physics Department at the Lawrence Radiation Laboratory, Berkeley, working under the direction of B. J. Moyer, Administrative Head. The bibliography that follows reflects these multiple contributions, but certain individuals have made outstanding contributions in quality, quantity, and duration, and deserve special mention. They are Henry Dakin, Richard Lehman, Joseph McCaslin, Alvin Miller, Michael Pick, Alan Smith, Lloyd Stephens, William Wadman, and Roger Wallace.

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