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ABSTRACT

In order to insure suitable accuracy in health physics measurements of very-high-energy radiation, it is first necessary to lay a proper foundation of knowledge and understanding of the radiation field. This should be done by choosing detectors and analyzing systems that are selective in their response to the radiation of interest and with satisfactory sensitivity. In complex radiation fields, such as those produced by particle accelerators, it is necessary to use several detectors, each with its own range of response and sensitivity. For example, to evaluate the radiation field produced by a proton accelerator of more than 500 MeV energy the neutron energy spectrum must be measured with a series of different detectors whose energy threshold and response as a function of energy are well known.

Statistical accuracy in these measurements is based on reducing background in the detection system and controlling its fluctuations. In addition, sensitivity should be such that count rates and signal-to-noise ratios are large. This usually means a large volume or mass of detector.

Experimental accuracy is based on knowing the response of the detector as a function of energy, both as regards selectivity and sensitivity. Experimental parameters and operating conditions of the accelerator should be varied, to check for reasonable variations in detector response. Proper monitors should be used so that data taken at different times can be normalized. Results from different detectors should be compared for consistency and compliance with physical principles.

After the radiation field is described in physical terms, i.e., energy spectrum and intensity of each of the components, one can then proceed with some confidence to the use of detectors whose response is ambiguous (rad or rem meters), but which may be of practical use. Shielding for personnel and equipment can be accurately specified, and one can predict the effect of changes in operating conditions of the accelerator.

This analytic approach to very-high-energy radiation monitoring requires time and effort, but these are repaid by the accuracy, flexibility, and understanding achieved.

I. INTRODUCTION

One of the most interesting problems in the field of accelerator radiation monitoring is that of balancing cost and effort against quality of information obtained. Given extremely generous limits on cost and effort, in theory one can measure all necessary data on the radiation field. Or, if expense is no object, one can shield an accelerator until the dose due to radiation penetrating the shield is arbitrarily small. Of course, in actual practice neither of these choices is usually available. Instead, those responsible for health protection and radiation monitoring of very-high-energy sources must strike a balance between these opposing factors of cost on one hand and accurate data of good quality on the other.

Before going on to discuss methods of achieving accuracy and good quality measurements, I would like to define what I mean by the term "accurate data of good quality." Obviously it does not refer solely to statistical accuracy, although that is certainly an important part. Rather, "accurate data of good quality" should first provide an understanding of the quantity measured in reproducible physical terms, and second, provide enough information so that changes in the radiation field can be controlled and predicted. This definition then requires that measurements of high-energy accelerator radiation be made with instruments and detectors whose response is well understood and whose sensitivity is such that statistical errors are small. In other words, accuracy of measurement combines both statistical and experimental accuracy to the highest degree consistent with the effort and expense considered reasonable for the particular circumstance.

II. ACHIEVING STATISTICAL ACCURACY

This is perhaps the best understood and most easily accomplished aspect of overall accuracy, --which is not to say that it is always achieved. In fact, unless great care is taken in the planning and execution of radiation measurements some of the inherent accuracy provided by great detector sensitivity will be lost. Examples of the statistical accuracy possible with some representative neutron detectors in use at Lawrence Radiation Laboratory are given in Table I.

To achieve these statistical accuracies, considerable attention has been given to reducing background in the detectors themselves and in the counting systems used with them. We have built a special low-background room for use with carbon scintillators and aluminum threshold detectors.[1] The walls, floor, and roof of the room are 4 to 5 feet thick

1. Harold R. Wollenberg and Alan R. Smith, A Concrete Low-Background Counting Enclosure, Health Phys. 12, 53-60 (1966).

Table I. Accuracy of representative neutron detectors.

Detector	Background	Response to unit flux within the indicated energy	Statistical accuracy commonly achieved (%)	Remarks	Refs.
Moderated BF_3 counter	2 to 3 counts/min	400 cpm 0.02 to 20 MeV	±3	Cylindrical Cd-covered moderator 6 cm thick	2
Bismuth fission ion chamber	< 1 count/hr	1.05 cpm at zero bias, 50-MeV threshold	±5	≈60 g bismuth effective in producing fission fragments	3
$C^{12}(n, 2n)C^{11}$ in plastic	133 counts/min	88 cpm[a] at 85% efficiency 20-MeV threshold	±1 to 3	5-in. right cylindrical scintillator counted on 5-in. phototube	4
$Al^{27}(n, \alpha)Na^{24}$	68 counts/min	65 cpm at 14 MeV,[a] 6-MeV threshold	±1 to 3	8×4-in. NaI crystal, 1.2 to 2.9 MeV, 8×1-in. Al disk	5
Hg (n, spall.)Tb^{149}	<6 counts/hr	2.8×10^{-2} cpm[a] 500 MeV threshold	±3 to 10	480 g Hg in irradiated sample	6
Emulsion for neutron spectroscopy	<1 track per field	10^7 n/cm^2 from 2 to 20 MeV produces convenient track density	±20	600-μ emulsion, pellicle requires special developing techniques	7
Moderated In foil	8 counts/min	10 cpm/gm[a] 0.02 to 14 MeV	±3	15-cm right cylindrical moderator, Cd-covered, 0.5-g foil counted on proportional counter	8
Moderated Au foil	8 counts/min	3 cpm/gm[a] 0.02 to 14 MeV	±3	15-cm right cylindrical moderator, Cd-covered, 0.5-g foil counted on proportional counter	
Moderated Co disk	8 counts/min	1.8 cpm = 1×10^7 n/cm^2 0.02 to 14 MeV	±1 to 3	55-g disk counted on 4×2-in. NaI crystal, 15-cm right cylindrical	9
Polyethylene-lined proportional counter	<1 count/min	1 c = 15 MeV/cm^2 at zero bias 0.050 to 20 MeV		Lining 1/8 in. thick	2

a. At saturation and t_0.

2. B. J. Moyer, Survey Methods for Fast and High-Energy Neutrons, Nucleonics 10[5], 14-19 (1952).

3. W. N. Hess, H. W. Patterson, and R. Wallace, Delay-Line Chamber Has Large Area, Low Capacitance, Nucleonics 15[3], 74-79 (1957).

4. Joseph B. McCaslin, A High-Energy Neutron Dosimeter, Health Phys. 2, 399-407 (1960).

5. Alan R. Smith, Threshold Detector Applications to Neutron Spectroscopy at the Berkeley Accelerators, in Proceedings of the First Symposium on Accelerator Radiation Dosimetry and Experience, Brookhaven National Laboratory, November 3-5, 1965.

6. Joseph B. McCaslin and Lloyd D. Stephens, High-Sensitivity Neutron and Proton Flux Detector with a Practical Threshold Near 600 MeV, Using Hg (spallation) ^{149}Tb, Health Phys. (to be published).

7. Hiraoki Akagi and Richard Lehman, Neutron Dosimetry in and Around Human Phantoms by the Use of Nuclear Track Emulsion, Health Phys. 9, 207-220 (1963); Ronald P. Omberg and H. Wade Patterson, Application of the Stars Produced in a Nuclear Emulsion to the Determination of a High Neutron Energy Spectrum, Lawrence Radiation Laboratory Report UCRL-17063, Feb. 1967.

8. Lloyd D. Stephens and Alan R. Smith, Fast Neutron Surveys Using Indium-Foil Activation, Lawrence Radiation Laboratory Report UCRL-8418, Aug. 1958.

9. Alan R. Smith, A Cobalt Neutron-Flux Integrator, Health Phys. 7 40-47 (1961).

and are made of concrete containing a serpentine aggregate and a specially selected low-activity cement. This wall thickness effectively isolates the interior of the room from natural radioactivity in the vicinity, and is also an effective shield against the soft component and neutrons in cosmic radiation. Supplementary shields of low-activity lead bricks are used inside the room. These closely surround the phototubes and NaI crystals used as detectors in the C and Al counting systems. The observed background in the NaI crystal is due primarily to cosmic radiation, and secondarily to radioactivity in the crystal, its housing, and its phototube. The approximate percent contribution to the background from each of these sources is given in Table II. A typical variation in the NaI(Tl) crystal (8 in. diam $\times$ 4 in. thick) background given in Table I is ± 1 count/min over a period of 6 months; a similar percentage fluctuation also exists in the C system. The variation is due mainly to changes in the penetrating cosmic radiation, and possibly in the beam levels of our accelerators. The penetrating cosmic radiation can be monitored with the NaI crystal by observing muon events that produce pulses much larger than any arising from γ-ray

Table II. Percent contribution to background in the energy interval 1.2 to 2.9 MeV in the NaI gamma spectrometry system at LRL-Berkeley.

Source	Contribution (%)
Cosmic rays	80-90
Fixed natural activities	10-20
Radon and thoron in air, accelerator radiation	not observable

activities under investigation. Both these muon events and sample activities can be observed and recorded simultaneously, on a noninterfering basis. We have recently established the existence of a linear relationship between this muon intensity and the background count rate in our crystal; we find that muon events can be used to generate a correction factor which eliminates all statistically significant variation from the background response. Air is supplied to the cave by a blower through an absolute filter, and we do not observe any fluctuation in the background due to radon and thoron. This is probably because the supplementary Pb shields are 2 to 4 in. thick and fit closely around the crystals, to exclude as much ambient air as possible.

In summary, statistical accuracy of ± 5% can usually be achieved in practice, and with some additional effort, ± 1%. It is usually worthwhile to make the effort, since good solid "statistics" lend credibility to the measurements, make it easier to discover small experimental errors, and allow the health physicist to concentrate on the interpretation of data and the planning of further measurements.

III. ACHIEVING EXPERIMENTAL ACCURACY

Before the statistical accuracy inherent in a detection system can be realized, there are some important requisites which must be met. For our purposes in accelerator monitoring, one of the most important of these is knowing the response of the detector as a function of energy, to the different components which may be present in the radiation field. Because neutrons are almost always the radiation which contributes most to personnel exposure and thus need to be measured most accurately, detectors should be chosen which have a minimum response to other radiation. Examples of such detectors are given in Table I. Others which make use of (n, γ), (n, p), and (n, α) reactions are also useful in this regard, such as ^{32}S(n, p)^{32}P.[10]

In our experience at Lawrence Radiation Laboratory with particle accelerators of various energies, only γ rays and perhaps μ mesons ever interfere with neutron measurements. Protons, electrons, and other particles are never troublesome, but frequently the effects of gamma or

10. K. B. Shaw, The Measurement of Accelerator-Produced Neutron Flux Using the ^{32}S(n, p)^{32}P Reaction, Rutherford High Energy Laboratory Report NIRL/R/31, 1963.

muon radiation in some of our detectors needs to be understood or eliminated. In this connection, an oscilloscope is necessary to inspect pulse shape and time distributions when testing for gamma effects in electronic counters for neutron detection. Also, with any sort of detector it is often instructive to compare results with some other detector whose response or method of operation is different. For example, the neutron spectrum inferred by use of threshold detectors can and should be compared with the neutron spectrum derived from emulsion data. Such a comparison is shown in Fig. 1. If agreement is found, it is encouraging, but when different detectors purportedly measuring the same quantity disagree this certainly must be understood.

During actual measurements at an accelerator it is advisable to arrange to have the operating parameters varied both in energy and in intensity, if this is at all possible. Careful work, under these circumstances, with a group of different detectors will test for reasonable changes in the response of each of the detectors. When the source is pulsed, as is common at accelerators, the use of an oscilloscope will help avoid unsuspected losses in electronic counters due to failure to resolve closely spaced pulses. This problem of "pile-up" is one of the reasons why a comparison should be made between a detector subject to such loss and one which is not, such as an activation foil.

It is particularly important to have available and to make use of standard sources for calibration of detectors. At our Laboratory we regularly use the isotopic neutron sources listed in Table III. The last source listed in the table has been calibrated twice by the U. S. National Bureau of Standards and twice by the manufacturer with no departure from the uncertainty listed. It serves as our "most accurate" standard.

Table III. Average energy and neutron emission for some LRL standard neutron sources.

Neutron source	$\bar{E}_N$(MeV)	Q (10^6n/sec)	Error (%)	Determined by
SbBe	0.025	2.5^a	± 4	LRL
$Pu^{238}Li$	0.305	2.58	± 2	NBS
$Pu^{238}F$	0.695	4.05	± 5	Manufacturer
$Pu^{238}B$	2.36	7.28	± 2.3	NBS
$Pu^{239}Be$	3.85	6.71	± 5	Manufacturer
$Pu^{238}Be$	4.40	0.0269	± 7	Manufacturer
$Pu^{238}Be$	4.40	86.0	± 2.3	NBS
$Pu^{239}Be$	4.19	1.56	± 3	NBS

a. per curie of Sb.

We also, regularly but infrequently, use 14-MeV neutrons from the d, T reaction and higher-energy neutrons from deuterons stripped in Be to measure reaction cross sections and detector response functions.

Because the measurement of high-energy radiation sources always extends over some period of time (years in some cases), it is also necessary to use some accurate and stable monitor or set of monitors. A set is better than a single monitor so that different operating parameters can be held constant or their variance made known. At most accelerators the operating parameters of the machine are adequately monitored and all that is necessary is to be sure that these pertinent data are recorded. The recording should include at least integrated and average beam current, pulse rate and length, target material, and beam on target. In addition, one or more moderated BF_3 counters or other low-energy neutron detectors will provide necessary supplementary data and should be used. Low-energy neutron monitors are recommended, since they are sensitive to the total number of neutrons of all energies that are produced. A single low-energy neutron monitor is better than none, but is not able to provide all the desirable spatial information; therefore multiple monitors are recommended.

I hope I have succeeded in giving the impression that experimental accuracy is achieved only by making a conscious and continued effort. It is not something that comes about with only one measurement of high-energy radiation or even one series of measurements. Accuracy--and confidence in measurement--comes from being able to describe the whole radiation field in physical terms, from being able to understand relationships among components of the radiation field, from collecting an extensive body of self-consistent data, and from careful and methodical attention to every detail of each measurement. Our experience at LRL shows that if this care is taken, experimental accuracy approaching the statistical accuracy of the measurement is possible. However, it will usually turn out that experimental accuracy is limited by the accuracy of calibration with isotopic neutron sources or with beams of higher-energy neutrons (± 3 to 10%). When a not-well-known response function or cross section limits the accuracy (± 10 to 30%), this error can sometimes be reduced or constrained by comparing results from two or more detectors. With threshold detectors this technique is used to estimate neutron spectra near our accelerators. We use a reasonable response function for each of several detectors and, with an assumed neutron spectrum, calculate count rates for each detector. These calculated count rates are then compared with those obtained experimentally. If the spectrum is known, knowledge of the response function can be gained, and if the response functions are known, a good estimate of the spectrum can be made. [5] Figure 1 shows some typical spectra estimated in this way, along with the results from two emulsion techniques. When results obtained by such different techniques agree this well, we believe that errors in calibration and detector response should not be summed linearly, but should be combined so that the uncertainty varies only within a limit set by the worst-known detector.

IV. ACCURACY IN DOSE ESTIMATION

After a period of time during which we have made a series of radiation field in physical terms, we then can make good theoretical estimates of the dose. We make a dose estimate by first using the relationships between flux and dose given in Table IV to get the dose due to neutrons in the entire neutron spectrum.[11] We add to this the dose the contribution from γ rays and other ionizing radiation which we measure with ion chambers. We find that the dose per neutron in the spectra given in Fig. 1 and for other typical accelerator spectra varies between the rather narrow limits of 3.5 and 7×10^{-8} rem/neutron.

Table IV. Analytic expressions for dose equivalent vs neutron energy.

Energy range (MeV)	n $cm^{-2} sec^{-1}$ equivalent to 1 millirem hr^{-1}
$<10^{-2}$	232
10^{-2}-10^{0}	$7.48/E^{2/3}$
10^{0}-10^{1}	7.20
$>10^{1}$	$12.8/E^{1/4}$

I have referred to the rem unit, and its derivation from the rad by use of QF (quality factor), as a theoretical dose because of the uncertainty of the true biological effects of high-energy radiation. This uncertainty, we believe, is one of the most important reasons for making an analytic study of the radiation field. For if the radiation field is not analyzed and understood in physical terms, how can one know which QF to use? Or, if only a "rem meter" is used, and if in the future the definition of the rem changes, how can old exposures be compared with new? Another worthy argument for an accurate, analytic series of measurements is the situation that arises when a measurement with a rad-meter or rem-meter indicates that the radiation level should be reduced. Analytic measurements will help decide how the reduction shall be done, but measurements in "rads" or "rems" alone give no such information.

V. CONCLUSION

I have argued that accuracy in very-high-energy radiation monitoring can be achieved only through an analytic study of the radiation field; that careful planning and attention to experimental detail are mandatory; and that the limiting factors in accuracy are uncertainty in detector response function and biological effect. Now, I would like to propose some steps to improve agreement between different laboratories on the meaning and accuracy of very-high-energy radiation monitoring.

11. Ralph H. Thomas, The Radiation Field Observed Around High-Energy Nuclear Accelerators, in Proceedings of XI International Congress of Radiology, Rome, September 22-28, 1965.

I suggest that this be begun by interlaboratory exchange of detectors which have been exposed to known fluxes of neutrons. Initially the work should be concerned with the intercomparison of calibration sources, because neutrons in this energy range always contribute a major fraction of the total exposure even for high-energy accelerators that are well shielded. For this a moderated cobalt disk is ideal. It is adequately sensitive, and the half-life of Co^{60} is so long that exposure and decay time need not be known to great accuracy. Also, the same exposed disk can be counted by many laboratories. We at LRL-Berkeley are prepared to send a Co disk and moderator to any laboratory for exposure to their standard neutron sources. We are also prepared to send to any laboratory a Co disk which has been preexposed to any of our sources listed in Table III. This exchange of irradiated disks should confirm the equality of all of our standard sources. If large differences appear we should study and understand them.

We are also prepared to send an emulsion to any of you who request it. The emulsion should first be exposed to about 5×10^7 n/cm^2 and then returned to us for development and scanning. After these are completed we will return the raw data (proton-recoil energy distribution) and the inferred neutron spectrum. Emulsion data should provide a good comparison on neutron spectra of either isotopic standard sources or accelerator spectra. If duplicate disks or emulsions are desirable they can be provided.

If this program is popular and successful, we plan to go on to the intercomparison of detectors exposed to higher-energy neutrons. For this purpose, a useful detector would be the production and observation of bismuth fission-fragment tracks in plastic or mica. We are now learning to use this technique, and expect that it will be ready for application in the near future.

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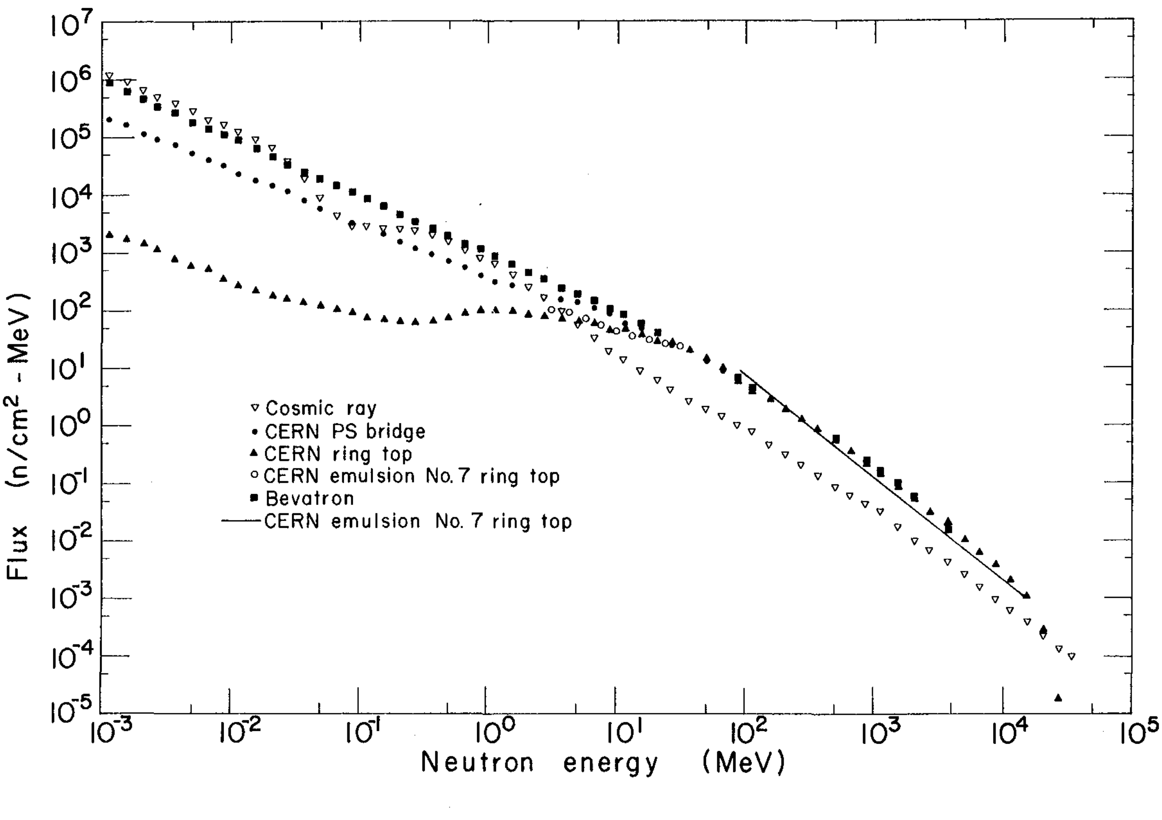

Flux (n/cm^2 - MeV)
Neutron energy (MeV)
Cosmic ray
CERN PS bridge
CERN ring top
CERN emulsion No. 7 ring top
Bevatron
CERN emulsion No. 7 ring top
XBL675-3144

Fig. 1