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PRACTICAL NEUTRON DOSIMETRY AT HIGH ENERGIES

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ABSTRACT

Dosimetry at high energy particle accelerators is discussed with emphasis on physical measurements which define the radiation environment and provide an immutable basis for the derivation of any quantities subsequently required for risk evaluation. Results of inter-laboratory dosimetric comparisons are reviewed and it is concluded that a well-supported systematic program is needed which would make possible detailed evaluations and intercomparisons of instruments and techniques in well characterized high energy radiation fields. High-energy dosimetry is so coupled with radiation transport that it is clear their study should proceed concurrently.

1. INTRODUCTION

This paper discusses practical dosimetry at high energies and is quite general in nature. It assumes that the reader is unfamiliar with accelerator Health Physics, but rather than demonstrate many of its assertions by detailed discussion refers the reader to the original literature. The arguments presented draw mainly from the authors' experience with dosimetry at high energy proton accelerators but we believe that they demonstrate general principles. The experience summarized here has been gleaned over many years and by many people. It has been reported widely in the literature [USAEC 57, BON 62, USAEC 65, USAEC 67, USAEC 69, CERN 71, THO 76]. To review it here would be both repetitive and confusing. The interested reader is referred to the original papers cited.

The general thrust of the arguments presented here is that the most practical systems of dosimetry at high energies require physical measurements that define the radiation environment. The parameters that define the biological detriment to humans exposed at low doses and dose rates are still uncertain. With St. Paul we can agree that "we see through a glass darkly" [PAU 54]. We may therefore expect the determination of the risk resulting from radiation exposure to be refined as our knowledge increases. Precise determination of the physical parameters of the radiation field, however, provides an immutable basis for the derivation of any physical quantities subsequently required for a risk determination.

Any scientific discussion should begin with a definition of terms. In order to clarify the discussion that follows later in the paper, we will define what is meant by the words "Practical," "Dosimetry" and "High-Energies," which appear in the title, before proceeding further.

<u>Practical</u> - The Oxford English Dictionary defines this as: "of, pertaining or relating to practice; consisting or exhibited in practice or action"

and notes - "often applied to that department of a subject, art, or science which relates to practice as distinguished from theory" [OXF 71].

This definition is most helpful - we will discuss what is actually done, rather than what is theoretically desirable, giving the practitioner the benefit or the doubt in assuming that what is done is done because it is the best possible. It should be noted that there is no mention of the word routine in this definition. In this paper systems of dosimetry will be discussed that are feasible - but not necessarily routine. As we shall see, high energies present some of the most severe and sophisticated practical problems to the dosimetrist. It should not therefore be surprising that many different experimental

techniques are in current use - the practical development of technique has not yet reached a stage of uniformity. One way in determining what is, in fact, practical is to evaluate what techniques are in use at high-energy laboratories. Freytag and Nachtigall [FRE 70] surveyed 23 accelerator laboratories, in 1969, asking what experimental techniques were used to determine dose equivalent rate. At these centers only one had an LET spectrometer in common use and three others in occasional use. All the laboratories, on the other hand, used particle spectrometer measurements in their routine operations. This finding is still true today, as we shall see in Section 6 of this paper, which evaluates dosimetry intercomparisons.

Dosimetry - Is understood to mean the process of interpretation of physical measurements of parameters of a radiation field in terms of quantities of interest to a health physicist for the purpose of radiation protection.

High Energy - The term "high energy" is one that has taken changing meanings as the particle energies commonly available in the laboratory have changed. In the early 1950's high energy was often taken to mean above 3 MeV (By virtue of the definition of the unit of exposure, the Roentgen). Any choice is necessarily arbitrary. In a recent report the ICRU defined high energy as greater than 100 MeV [ICRU 78b]. In this paper, therefore, we will discuss the techniques of dosimetry in the environment of particle accelerators that accelerate particles to energies greater than 100 MeV, or of the cosmic radiation (which is produced by primary particles with kinetic energies greater than 100 MeV).

High-energy dosimetry may, in principle, involve measurements in situations where a wide variety of particles distributed over a wide energy range are present. Such situations, however, are rare in Health Physics.

We may define three conditions in which dosimetry is needed:

(1) Beam Dosimetry - measurement in essentially pure, often monoenergic, non-divergent beams. Such measurements may be made with great accuracy. Typical examples would be: physics experiments (e.g., determination of absolute cross sections); beam dose rate determinations for radiotherapy. [NEL 76, THO 80].

(2) Out-of-Beam Dosimetry - measurements close to beams, targets, magnets etc., to determine the parameters of the scattered radiation. Such measurements are very difficult to interpret. Typical examples would be:

radiation damage studies to accelerator components; determination of absorbed dose to healthy tissues surrounding irradiated tumors and accident dosimetry. [SMI 80].

(3) Health Physics Dosimetry - usually at low average dose rates, although instantaneous dose rates may be high.

This paper deals only with the last topic. However, techniques of beam dosimetry are very important and often form the basis for health physics dosimetry. The interested reader is referred to the literature [LAU 69, RAJ 69, THO 80].

High-energy particles interact with matter to produce copious lower energy particles, in processes called cascades. In practical dosimetry the electromagnetic and hadronic cascades are of greatest practical importance and have been extensively discussed in the literature [ICRU 78b].

The health physicist will most likely be required to make measurements in situations where these cascades are well-developed. Under such conditions the uncharged particles (photons, neutrons) often dominate and practical high-energy dosimetry resolves itself into measurements of two components, albeit distributed over a wide energy range. Particle energies may extend up to the primary particle energy and down to (in the case of neutrons) thermal energies under these conditions. Typically, a large fraction of the absorbed dose is deposited by low-energy particles and thus there are important similarities between "high" and "low-energy" dosimetry [PAT 73]. Low energy particles are produced, however, and therefore they appear to be transported by high energy particles. The dose distribution characteristics in high-energy radiation fields are therefore different from the more familiar low-energy situations [SHA 69].

Having made this point it is clear that care must be taken in applying low-energy techniques to high-radiation fields. The presence of high-energy particles may, in some instances, perturb the readings of low energy detectors.* Many of the current uncertainties in high-energy dosimetry arise from inadequate information on the response of detectors to secondary radiations.

*Footnote: (A specific example would be where elastic scattering of neutrons above 1.02 MeV confuse the signals produced by the inelastic $(n + He^3) \rightarrow (p + T + 0.764\ MeV)$ reaction in a He^3 spectrometer system.)

2. HISTORICAL BACKGROUND

The first serious high-energy radiation studies around particle accelerators reported in the literature began to appear in the middle and late fifties. Naturally enough they originated in those laboratories with significant radiation problems. Those laboratories that built their early synchrocyclotrons underground were not particularly active in these studies because they had few problems. [They might, however, be compared with the ostrich who avoids perceived difficulties by making their perception impossible.]

Many of the early qualitative and quantitative data originate from the early proton synchrotons operated at Brookhaven National Laboratory (the Cosmotron) and the Radiation Laboratory of the University of California* (the Bevatron).

Experience at the 184-inch synchrocyclotron at Berkeley and the early proton synchrotrons - the Cosmotron and Bevatron - rapidly established the qualitative nature of their radiation environments outside thick shielding [SMI 58, SMI 62, PAT 65]. A general rule emerged, showing that neutrons between 0.1 and 10 MeV contributed more than 50% to the dose-equivalent contribution of the radiation field; γ-rays and low-energy neutrons contributed about 10-20%, and the balance was made up by neutrons greater than 10 MeV in energy. These early studies have been reported by Lindenbaum [LIN 57], Moyer [MOY 57] and Patterson [PAT 57], and summarized by Patterson and Thomas [PAT 73].

In order to understand the dosimetric problem in a qualitative manner, Moyer and his colleagues leaned heavily on analogy to cosmic radiation. They argued that the radiation environment outside high-energy accelerator shields, *must in some respects*, be similar to that which exists at the base of the earth's atmosphere, - for example, the neutron spectrum produced by the interaction of galactic protons with the Earth's atmosphere [HES 59]. Patterson et al used the analogy to suggest that *neutrons* between 0.1 and 20 MeV would dominate the contribution to neutron dose equivalent around high energy accelerators [PAT 59]. This suggestion led to the strategy, subsequently found to be largely sound, of concentrating on neutron measurements in that energy range. Moyer in fact as early as 1954 identified the experimental techniques that would be of value in high energy dosimetry at accelerators:

"(1) for the determination of the flux density and spectrum of unidirectional fast neutrons: proportional counters, scintillation counters, photographic emulsions;

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(2) for the determination of thermal neutron flux densities, regardless of direction: counting techniques based on neutron capture in boron, activation foils;
(3) for the approximately absolute determination of energy flux density delivered by fast neutrons, independent of energy spectrum or angular direction: polyethylene-lined proportional counter;
(4) for the contribution to energy absorption in tissue due to neutrons, where the effects due to γ-rays are known and may be corrected for: cavity chambers or tissue-equivalent chambers." [MOY 54]

One of the authors writing in 1972 commented on this list by saying:

> "Such a list, if written today, would look much the same. Sullivan [SUL 69], in reviewing dosimetric techniques used at particle accelerators up to 1969, showed that, although there has been a steady improvement over the past 18 years in the techniques listed by Moyer, few basically new ideas have arisen. Perhaps the two most important new techniques absent from Moyer's list and mentioned by Sullivan were the use of ionization chambers to estimate the quality factors for mixed radiation fields and the development of activation detectors capable of yielding neutron spectra adequate for health physics purposes." [THO 72]

By 1972 the course for the future development for techniques of high-energy dosimetry seemed clear. Speaking of the period 1965-1971, one of the authors wrote:

> "Actually, however, the last six years have resulted in solid, if not spectacular, achievement in neutron dosimetry with threshold detectors at accelerators. Given this depth of understanding of radiation environments, the response of any detector(s) used to monitor accelerator radiation may be correctly interpreted. Several authors have examined the errors involved in using a routine monitoring system based on a small number of activation detectors [GIL 68, SHA 69, RIN 68].
>
> For example, a moderated BF_3 counter, suitably calibrated, will almost always estimate dose-equivalent to about a factor of 2, in a wide range of accelerator spectra. If an additional measurement using the $^{12}C(n, 2n)^{11}C$ reaction is made, the accuracy can be improved to much better than 50% (usually 20% or better). Furthermore, since the measurements and their evaluation take quite a short time (typically one hour or less), threshold detectors may be used as the basis of a very practical routine monitoring system." [THO 72]

At that time work proceeded in the following areas:

(1) clarification of the definition of the concept of dose equivalent [PAT 71, RIN 71, RIN 72].
(2) development of new activation detector techniques [ROU 69];
(3) incorporation of Bonner-spheres and activation detectors;
(4) improvement of neutron spectrum unfolding routines;
(5) improvement in the interpretation of neutron spectra in terms of dose equivalent.

3. DOSIMETRY

3.1 Introduction

At high energy facilities dosimetric measurements are needed for five distinct reasons:

(a) routine radiation surveys for radiation protection purposes, at dose equivalent rates in the range 1-10 mSv s^{-1};
(b) interpretation of personal dosimeters;
(c) environmental monitoring;
(d) accident dosimetry;
(e) beam intensity measurements
(f) radiation measurements in regions of high radiation intensity, to enable an understanding of the radiation environment so that improvements may be made, e.g., by the addition of shielding.

High energy facilities are primarily research instruments and their radiation environments are initially unknown. Some fundamental understanding of these radiation phenomena must be obtained and radiation detectors initially designed for nuclear physics research were often the natural choice for these measurements. This coupled with the strong background in physics at accelerator laboratories has led to an approach to dosimetry somewhat different than is usual in other branches of health physics

There are indeed strong arguments for laying a firm physical foundation to dosimetry even in health physics where the accuracy required is not great. We shall attempt to show in this paper that even for the limited purposes of health physics a physical specification of the radiation environment presents the most practical basis for dosimetry.

3.2 Dose Limits

One of the goals of the health physicist must be to set standards of protection at which exposure to ionizing radiations will produce either no deleterious effects, or at least, effects which are "acceptable" both to society in general and to the exposed individual in particular.

Since the biological effect on humans irradiated at low doses and dose rates (a few rads per year) are not yet fully understood the basis for our current radiation protection standards cannot be entirely scientific.

Administrative considerations, as well as extrapolations from data obtained at high doses and dose rates, and for species other than Man, are necessary in setting limits.

The development of the concepts used in radiation protection are widely published in the scientific literature, and in particular in the reports of the NCRP, ICRP & ICRU to which the reader is referred [NCRP 71b, ICRP 63, ICRU 71a, 71b, 73, 76, 80, TAY 79]. This history will not be extensively discussed here. Suffice to say that the last decade has seen considerable flux in the concepts used in radiation protection. The logical progression from dose equivalent through the MADE to the dose equivalent indices is of great importance in high energy dosimetry (as was the general acceptance of fluence to dose equivalent conversion as an acceptable dosimetric technique) [ICRP 70, ICRP 73]. Following the lead of the British Committee on Radiation Units and Measurements the ICRU finally agreed that the dose equivalent has physical dimensions in its Report 19 [BOA 72, ICRU 71a].

The most recent authoritative statement of concepts to be used in radiation protection is contained in ICRP Report 26 [ICRP 77]. This report, which is the culmination of many years of critical evaluation and discussion, makes two very important recommendations by defining the effective dose equivalent as the quantity of interest in health physics and relating it directly to the risk of deleterious effects.

It will be remembered that dose equivalent, H, is defined by:

$$H = \int_0^{Lmax} Q(L)\ D(L)\ dL \qquad (1)$$

where L is the collision stopping power of the charged particle and referred to as the linear energy transfer, LET.

Q(L) is the quality factor of the particle at LET,L.
D(L) is the absorbed dose deposited by charges particles with LET between L and L + dL.

The effective dose equivalent, $\mathcal{H}$, is defined by:

$$\mathcal{H} = \sum_i w_i H_i \qquad (2)$$

where H_i is the dose equivalent in tissue i, w_i is the relative sensitivity of tissue, and there are i tissues.

By definition: $$\sum_i w_i = 1 \qquad (3)$$

The risk R, of some detriment arising from this exposure, is then given by:

$$R = r\mathcal{H} = r\sum_i w_i H_i = r\sum w_i \int_0^{L_{max}} Q(L)D(L)dL \qquad (4)$$

where r = risk of detriment per unit dose equivalent.*

At the present time ICRP has identified seven tissue categories (i = 7), defined their relative radiosensitivities and given the value of $r = 10^{-2}\ Sv^{-1}$ [ICRP 77].

Equation (4) might suggest that the most practical way of evaluating effective dose equivalent would be to measure the LET distribution directly. There are both theoretical and practical objections to such a strategy.

We have already seen (Section 1) that LET - spectrometers are not widely used at high energy laboratories for radiation protection dosimetry. This relative unpopularity is explained by a variety of factors - (a) large volume of chamber needed for adequate sensitivity precludes depth-dose studies (b) likelihood of encountering saturation problems in intense pulsed radiation fields typical of accelerator operation (c) mechanical sensitivity (d) environmental sensitivity, e.g., humidity, temperature. Of even greater significance however is the theoretical concern that there may be some fundamental changes in the basis for radiation protection dosimetry, which we will mention in the next section.

3.3 Dose Equivalent Instruments versus Physical Measurements

Over the past 15 years there has been a continuing debate between those dosimetrists who wish to limit their measurements to what is required solely for health physics survey purposes and those who wish to utilize their data for additional purposes.

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* It should be noted that the absorbed dose D(L) is an average dose for the entire volume of the tissue of interest.

There can be no argument that instruments that roughly indicate dose equivalent rate are of great value but their use is limited to radiation surveys - and even here they may show deficiencies. It is well known that many neutron "rem-meters" over respond to intermediate energy neutrons [LAR 70, NAC 72]. The size of the Brookhaven National Laboratory universal dose equivalent instrument [KUE 72, 73a, 73b], which is of suitable sensitivity for radiation protection measurements, makes it practical only for surveys in free air in which the radiation field is fairly uniform over distances of ~20 cm. Measurements with this instrument must therefore be preceeded by measurements establishing field uniformity. Measurements with the Brookhaven instrument alone give no information on the attenuation characteristics of the radiation field.

Tesch [TES 70] has described two counters which may be used for neutron dosimetry in the energy region 10 - 100 MeV. The first instrument consists of a liquid scintillator with the pulse height selected to give the required dose equivalent responses function. Pulses originating from particles other than neutrons are suppressed by pulse shape discrimination. The second counter is a simple extension of the multisphere method [BRA 60]. In his paper Tesch discusses the limited need for accuracy in radiation protection:

> "it is, however, questionable whether there is any point in aiming at a sensitivity curve with deviations considerably smaller than 50% since the concept of a quality factor is only a very rough approximation."

This comment reveals the limited design constraints placed upon "rem-meters" when these instruments are to be used solely for radiation surveys.

If, however, measurements are to be applied to the variety of tasks listed in the introduction to this section, physical measurements of the radiation field are to be preferred. This coupled with the possibility that there will be continuing refinement in dosimetric concepts and quantities makes a convincing argument for physical measurements. The case is supported by current practice since particle fluence measurements are almost universally made at high energy laboratories.

One of the basic assumptions of radiation protection which may be challenged is the Q-L relationship which is now about twenty years old [ICRP 63]. Mole has questioned whether we may still continue to use a single quality factor in radiation protection for a given LET, regardless of the tissues being irradiated and the particular biological end-point of concern [MOL 79]. Rossi has gone so far as to propose a substantial increase in the quality factor for fission neutrons [ROS 77, ROS 78] and further to suggest that linear energy transfer might better be replaced by another quantity (Lineal energy) to describe radiation quality [DEN 78]. Bond [BON 78a, 78b], on

the other hand, disagrees with some of Rossi's proposals. This debate is extremely lively and one which will have a significant influence on the quantities used in radiation protection in the future.

4. AVAILABLE TECHNIQUES OF DOSIMETRY

Neutron dosimetry is better understood in the region below 20 MeV than at higher energies. This is largely due to continuing extensive and detailed study of both detectors and neutron sources in well controlled or at least well understood environments. As a result, detector response functions were adequately characterized and inter-laboratory consensus established for a variety of instruments. Detector calibrations have been performed with monoenergetic neutrons from continuous and pulsed sources. (α,n) and spontaneous fission sources have also been extensively used and information concerning their energy spectra continues to be upgraded [ING 80].

Zielczynski has briefly discussed the uncertainties in mixed radiation dosimetry [ZIE 70]. He cites two major difficulties:

(1) Determination of response functions of radiation detectors,
(2) Interpretation of measurements, and determination of accuracy.

At higher energies (energies >20 MeV), calibration and test facilities available to health physicists are not usually well characterized with respect to the spectral composition of the individual components of the radiation field. Often the temporal distribution is complex with periods of high peak intensity superimposed on an otherwise uniform beam spill. Complexity of instruments, techniques, data reduction and analysis has also increased to the extent that the "best" methods of neutron dose evaluation and energy spectra determination are not generally thought to be compatable with frequent, routine or spur of the moment evaluations with which the operational accelerator health physicist must contend.

As a result, radiation measurements near high energy particle accelerators tend to proceed along two fronts. Dosimetrists continue their quest for techniques which permit direct accurate measurements to be made of the entire radiation field. We have witnessed the development of several noteworthy systems such as the LET spectrometer of Rossi [ROS 55], the modified LET spectrometer of Kuehner et al [KUE 72,73], the differential recombination chambers of Zielczynski [ZIE 62,64] and Sullivan [SUL 63], and lately the scintillation method of Pszona [PSZ 71].

Extensive low resolution physical measurements of neutron spectra have been made for personnel protection purposes [SMI 65, ROU 69, THO 79], to study accelerator shielding and the

cosmic ray neutron spectrum. Many laboratories use some variation of these techniques usually in more limited fashion to supplement measurements made by other means.

All techniques which encompass the multi-decade energy span found at high-energy particle accelerators share some of the following disadvantages:

(1) count rate dependence in intense fields
(2) interference by associated components of the field
(3) uncertainties introduced with spectrum unfolding
(4) complexity of the technique (setup, calibration, stability)
(5) time required to make a measurement and evaluate the data
(6) lack of complete documentation or characterization of one or more components of the measurement set.

On the second front, many if not most, operational accelerator health physicists recognize the manpower and time committment required for proper use of the techniques described. As a consequence they often elect a more realistic approach to certain routine survey tasks by using a smaller number of better understood detectors and perhaps some conservative assumptions which may be based on more extensive prior measurements. In general, for this type of effort, an evaluation is made of dose equivalent below 20 MeV, and either a single measurement made to account for the component at higher energies or, for fields in which the spectrum is known, a correction factor, usually of the order of 2-3, is applied to the dose equivalent determination at lower energies.

The distinction between energy regions is often made at 20 MeV because that is near the upper limit of useful response for portable moderated thermal-neutron detectors, and because 20 MeV is the threshold for the $^{12}C(n,2n)^{11}C$ reaction. This reaction provides a sensitive convenient means of measuring high-energy neutron fluence [McC 60]. One must, however, be aware of the possibility of competing reactions: $^{12}C(p,pn)^{11}C$, $^{12}C(\gamma,n)^{11}C$ and reactions with other high energy particles.

Table 4.1 shows the fraction of neutron dose equivalent due to neutrons of energy less than 20 MeV for several different high-energy accelerator radiation areas. The BF_3 gas proportional counter is often used because it can be made in a wide range of sizes and sensitivities, has excellent photon discrimination, and normally has a long and stable life. LiI scintillators are also successfully used with moderators (as are ^3He detectors) but one should be aware of possible effects of the accelerator's stray magnetic field on photomultipliers.

An alternative technique to the use of Andersson-Braun and Leake detectors for the region below 20 MeV is afforded by the combined use of a moderated BF_3 neutron flux detector and the Moyer polyethylene-lined argon-CO_2 gas proportional (PE) counter.

Table 4.1

FRACTION OF DOSE EQUIVALENT DUE TO NEUTRONS BELOW 20 MeV

Accelerator	Energy (Gev)	Beam Particle	% of Neutron dose equivalent less than 20 MeV	Reference
Nimrod	7	p^+	85	Perry et al [PER 66]
CERN	24	p^+	22	Gilbert et al [GIL 68]
CERN PS Bridge	24	p^+	32	"
Bevatron Lateral shield	6.2	p^+	48	"
Bevatron above septum	6.2	p^+	35	McCaslin et al [McC 77]
SLAC ESA	19.5	e^-	32	"

The PE detector has a response which is proportional to energy fluence so that the PE/BF_3 ratio gives the average neutron energy, $\bar{E}_n$. The flux to dose conversion factor for $\bar{E}_n$ can then be applied to the flux density measurement to estimate the dose equivalent. How well this technique approximates the true dose equivalent will depend on the spectral distribution of neutrons. For example, the data of Ing et al [ING 80] gives the average neutron energy, $\bar{E}_n$ = 0.5 MeV, for a ^{238}Pu-Li source and an average dose equivalent of 1.82 x 10^{-8} rem cm^2/n. The PE/BF_3 counter technique would overestimate the dose equivalent by a factor of 1.4 by declaring the average dose equivalent (corresponding to $\bar{E}_n$ = 0.5 MeV) to be 2.57 x 10^{-8} rem cm^2/n.

Care must always be exercised when using the PE counter, especially at electron accelerators to assure that photon pile-up is not interfering with the measurement.

Tesch [TES 70] has described methods of dose equivalent evaluation to be used with Andersson-Braun [AND 63a, 63b] or Leake [LEA 67, 68] type neutron dose meters which extend the measurement range to 100 MeV, beyond which, Tesch points out, neutrons usually don't contribute significantly to the total

dose equivalent because of their reduced numbers. The detector he describes is a 4.7 cm diameter by 4.7 cm Ne-213 organic scintillator with pulse shape discrimination circuitry to discriminate against photons. With selection of threshold at 8.5 MeV, the instrument response is proportional to dose equivalent over the energy range of interest with variations of about ±15%. Because the threshold is set higher than usual for this type of detector, the photon response is not as severe a problem as it might be for a system designed for lower energy neutrons.

For those situations where photon pile-up is a problem Tesch describes the use of an 18-inch polyethylene moderator fitted to a Leake instrument which had been modified to use a ^{3}He proportional counter for increased sensitivity and photon rejection. The sum combination of a Leake dose meter response multiplied by 1.3 and the 18-inch detector response is reported to be proportional to neutron dose equivalent within ±50% over the energy range from 10^{-4} MeV to 100 MeV.

Table 4.2 summarizes methods which may be used for approximate radiation surveys, while Table 4.3 summarizes various major techniques which utilize "rem-meters" or "dose-equivalent" instruments for direct dose equivalent assessment.

5.1 NEUTRON SPECTROMETRY

There are many examples in high-energy dosimetry where a knowledge of neutron spectra has been crucial to the understanding of observations - particularly at particle accelerators.

Thus, for example, in 1960 Baarli and his colleagues noted that neutrons with energy above 20 MeV contributed a much larger fraction of dose equivalent outside earth shielding than had been observed outside concrete shielding at the CERN 28 GeV proton synchrotron (CPS) [BAA 64,65]. It was possible to demonstrate by a determination of the neutron spectrum that this effect was due to the increased effectiveness of wet earth in removing intermediate energy neutrons [GIL 68].

A second example is the establishment of the presence of a significant high-energy neutron component to the radiation field outside the shielding of the Stanford 20 Gev Linac [McC 77]. This observation had been predicted by De Staebler [DES 65], but there had been some controversy as to its magnitude prior to these measurements. Table 4.1 shows that the contribution of dose equivalent from neutrons above 20 MeV is very similar for both proton and electron accelerators - precisely as suggested by De Staebler.

There seems to be a great deal of support in the literature for the determination of neutron spectra whenever possible. However, few high-energy health physics groups attempt to determine spectra. This is probably because spectrum determination is seen to be difficult and time-consuming. This need not necessarily be the case.

Table 4.2

APPROXIMATION METHODS FOR RAPID SURVEY EVALUATION

Technique	Description	References
1. Moderated thermal neutron detector only. Reading multiplied by a factor of 2-3	May be similar to a) Andersson-Braun rem counter which uses a BF_3 gas proportional counter and layered boron-loaded plastic moderator to shape response to fit ICRP DE curve, b) Leake-type ^3He detector with spherical moderator c) Other moderated detectors which respond to flux density (the appropriate spectral flux to dose factor must be applied) d) Suitably moderated indium, gold foils.	AND 63 LEA 68 STE 58
2. Moderated thermal neutron detectors as shown above plus a high energy detector such as $^{12}C(\gamma,11C)$	The dose equivalent estimated from each of the detectors is additive. Correction factors may be applied if prior spectral knowledge warrants doing so. Andersson-Braun or Leake rem meter in conjunction with 18-inch spherical moderator.	McC 60 GIL 68 TES 70
3. Method 2 above with the addition of air and TE ionization chambers	The addition of the ion chambers allows the DE contribution from gamma and charged particles to be included in the total DE determination. Dividing the total DE by the DE as determined from the TE ion chamber yields an "effective" QF which may lend confidence to the validity of the measurement. (This is the Cerberus technique of Hofert, when a moderated BF_3 rem ion chamber is used).	HOF 72
4. TE ion chamber. Reading multiplied by a factor of 5 to 10	This technique allows quick estimation of the upper limit of DE in unknown fields when a conservative value of QF is used.	COW 53
5. Scintillation Method	A TE ion chamber is used in conjunction with an organic scintillator (response is dependent on LET) to estimate total DE in high energy accelerator radiation fields.	PSZ 71 PSZ 77

Table 4.3

MAJOR TECHNIQUES FOR DIRECT DOSE EQUIVALENT ASSESSMENT OF ACCELERATOR-PRODUCED NEUTRONS

Technique	Description	Principle Use	References
1. Paired ion chambers	One chamber is tissue equivalent; the other is made with non-hydrogenous walls and gas of low atomic number.	Indicates maximum DE (±15%) for neutrons ≤10 MeV.	GOO 68
2. Moderated LiI, ^3He, BF_3 detectors	Moderator tailored to give response similar to DE response (E_n) curves.	< 20 MeV	
3. Recombination-type TE ion chambers	Characteristics of columnar recombination are used to determine the LET of charged particles. QF is inferred from the chambers under conditions wherein the ion collection efficiency of one detector is strongly dependent on LET while the other detector's response is largely independent on LET.	Used in high energy mixed radiation fields.	ZIE 62 SUL 63 SUL 64 ZIE 64
4. LET spectrometer	Spherical TE ion chamber at a pressure equivalent to one micron chamber diameter. Response proportional to product of LET and track length. Data computer-processed to yield differential LET spectrum. The total dose equivalent is obtained by folding the associated QF over the entire LET spectrum to get the DE spectrum and then summing over the DE spectrum.	High energy mixed radiation fields.	ROS 55
5. BNL DE meter	Modification of Rossi LET spectrometer (more rugged, improved ion chamber field shape and leakage, and reduced need for frequent gas re-filling). Two signals are extracted; one is proportional to dose rate independent of LET; the other is processed by non-linear amplifiers to produce an amplitude dependence which varies as does QF with LET.	High energy mixed radiation fields.	BAU 69 KUH 73
6. Scintillatin	TE ion chamber, with organic scintillator which has a response dependent on LET	High energy mixed radiation fields.	PSZ 71 PSZ 77
7. Moderated BF_3+NE 213 proton recoil detector	DE determined by sum of 2 instrument readings: (1) Andersson-Braun or Leake rem meters, and (2) NE-213 organic scintillator biased at 8.5 MeV.		TES 70

We have seen that the MADE may be often determined to within a factor of two by measurement with a moderated thermal neutron detector, (Section 4). It is not immediately certain that a great improvement in accuracy is obtained, in proportion to the additional complexity involved, when more detectors are used. This is usually because the new data are not often effectively used. Table 5.1 summarizes the major systems that have been used to determine neutron spectra around high-energy accelerators.

5.2 Examples of Neutron Spectra

It is perhaps unfortunate, particularly in view of their value, that the attempts to measure neutron spectra for health physics purposes at high-energy accelerators has almost entirely been limited to work at the Lawrence Berkeley Laboratory and the Rutherford Laboratory. Neither of these laboratories any longer have accelerators operating in the forefront of high-energy physics and one purpose of this paper is to make a plea for the continuation of this work in other institutions.

The spectra measured at high-energy accelerators and in the upper atmosphere have been described in the literature [GIL 68, THO 73, McC 77, HEW 76, HEW 78, STE 78, STE 78, HEW 80]. They have led to important increases in our understanding of high-energy phenomena. However, these spectra are now rather outdated and there still remains the need to follow up these early investigations by undertaking a systematic study of the influence of several physical parameters on neutron spectra.

Of some recent interest is the investigation of the uncertainties in neutron spectra unfolded from Bonner sphere data [STE 78]. The understanding of these uncertainties can lead to important improvements in our experimental techniques.

5.3 The Interpretation of Neutron Spectrum Measurements

Assuming that neutron spectra of sufficient accuracy may be obtained there are still some difficulties of interpretation. The additional complexities of the angular distribution of the neutron field set an ultimate limit to the accuracy in effective dose equivalent that may be obtained, unless extremely elaborate measures are taken.

It should be recognized that operational health physicists will, in most cases, make measurements in free air. Measurements in phantoms are inconvenient and, in the vast majority of health physics measurements, not practical. The size of the instruments described are usually so large that the measurements must be made in free air.

In our opinion it should be the function of the two international commissions (ICRP and ICRU) to provide means of translating the measurements actually made to the quantities needed in radiation protection.

Table 5.1

Major Techniques for Neutron Spectroscopy

Technique	Description	Principle Use	References
1. Threshold detectors	Active (e.g., Bi fission counter) and passive (e.g., $^{12}C(n,2n)^{11}C$) detectors may be used separately or combined along with an appropriate spectrum unfolding code. Low resolution technique but can be reliable for accelerator produced neutron spectra which is devoid of sharp structure. Activation detectors have the advantage of immunity to counting losses at high fluence rates.	High energy mixed radiation fields.	SMI 65 THO 79 ROU 69
2. Nuclear emulsion	1) Proton recoil spectrum measurements can give +/-20% accuracy for 2-20 MeV neutrons for fluence of 10^7 in 600μ emulsion. 2) Star prong production, 20-300 MeV. Both techniques yield reliable results; both are relatively insensitive, tedious, and time consuming, using techniques and equipment no longer in readiness at many laboratories.	High energy mixed radiation fields.	LEH 64 AKA 63 REM 65 PAT 69
3. Spark chamber	Large array approximately 1m x 1m with alternating converters and spark counters, has anticoincidence shield for external charged particles. Track length and angle are measured and input to unfolding code. Useful range: 30 MeV at 15% efficiency to 300 MeV at 0.5% efficiency.	High energy mixed radiation fields.	RIN 69 RIN 74 MAM 74 LIM 73
4. Multisphere	Hydrogenous spheres up to 18 inches diameter house thermal neutron detectors. Possibility of photon pulse pile-up during high instantaneous fluence rates when Li I is used. This problem is lessened with ^3He detectors. Activation and track detectors may also be used. Response is from thermal to 50 MeV or higher. Response functions depend largely on calculation.	High energy mixed radiation fields.	NAC 72
5. Proton-recoil telescope	Requires point source, lacks sensitivity required for personnel monitoring, high resolution method. Invaluable for research efforts.		MAD 73

Particle fluence measurements are almost universally made around particle accelerators. The conversion of these measurements to MADE has caused some difficulties: Thus, Shaw et al [SHA 69] showed that errors of up to a factor of two are possible.

It is clear that only a rough estimate of dose equivalent may be made at high energies unless the energy spectrum, angular distribution and spatial and temporal variations of the radiation field are known. In most cases these parameters will not be well measured and our knowledge of H is therefore correspondingly uncertain.

6. DOSIMETRY INTERCOMPARISONS

6.1 Introduction

While not difficult to understand, it is an unfortunate fact that no high-energy physics laboratory has been able to devote resources to the establishment of a permanent facility dedicated entirely to the study of high-energy radiation protection. The reason is not hard to understand. Radiation protection problems are usually acute in nature: they are usually rapidly solved by empirical methods. Once solved they are no longer of particular concern. In an atmosphere of budgetary constraints high-energy accelerators which are no longer "at the frontier" of science are taken out of service. (Examples of high-energy accelerators which have been de-commissioned during the past decade include the "Mark III," "Nina," the "Cosmotron," "Nimrod" and the "ZGS.") This is unfortunate because such accelerators could be applied to the study of a host of problems in applied science and technology. Not the least of these would be the study of high-energy radiation and radiological physics.

No University department of physics, nuclear engineering or radiology has found accelerator radiation problems sufficiently intellectually challenging (or economically rewarding) to establish a permanent group investigating such phenomena.

There can be no doubt that beam dosimetry has benefited greatly from intercomparisons. (For example the international neutron beam dosimetry intercomparison sponsored by the ICRU [ICRU 78a]). Similarly accident and personal dosimetry in reactor radiation environments have benefited from the series of measurements made at the Health Physics Research Reactor of the Oak Ridge National Laboratory [AUX 65, POS 74, DIC 77].

One of the few accelerator facilities that has devoted a considerable effort to dosimetry studies is the Radiological Research Accelerator Facility (RRAF) stituated at Brookhaven National Laboratory and operated by the Radiological Research Laboratory at Columbia University [RAR 79]. A variety of charged particle beams (protons, deuterons, ^{3}He ions) in the energy

range 1.7 to 5.4 MeV and neutrons up to 15 MeV are available. The dosimetry efforts of the facility have been devoted to primary beams. However, an example of the extremely important role that a dedicated facility can play is given in ICRU Report 27 [ICRU 78a]. That report describes the International Neutron Dosimetry Intercomparisons that were carried out at RRAF for fission neutrons (^{252}Cf spectrum) and neutrons of 0.67, 2.1, 5.5, and 15.1 MeV. A similar facility offering high-energy beams and facilities for both in-beam and scattered radiation dosimetry is urgently needed.

6.2 CERN - Lawrence Berkeley Laboratory - Rutherford Laboratory: 1966

During an extensive shielding experiment carried out at the CERN 28 GeV proton synchrotron by groups from CERN, the Lawrence Berkeley Laboratory and the Rutherford Laboratory some dose intercomparisons were made [GIL 68].

Measurements of neutron flux density using paraffin-wax moderated indium and gold activation detectors [STE 58] and plastic scintillator were compared. Measurements were made in several locations above the earth shielding. The first fact of interest found as a result of these comparisons was that the standard ^{239}PuBe source calibrations of CERN and LBL differed by 15% although the absolute emission rate of both had been calibrated to an accuracy of ±3%. Both these calibrations were traceable to the U.S. National Bureau of Standards (LRL) and the Radiochemical Center, Amersham (CERN). This discrepancy to the knowledge of the authors has never been resolved. It does however, point out that nothing should be taken for granted in planning dose intercomparisons.

When the uncertainty in the absolute source intensity is removed the flux density measurements agree to within about 5%. Table 6.1 shows the values obtained at one location above a concrete shield.

Table 6.1
Comparison of Flux Measurements Above Concrete Shielding - CERN PS

	DETECTOR	
GROUP	MODERATED FOIL ($n\ cm^{-2}s^{-1}$)	C^{11} PRODUCTION ($n\ cm^{-2}s^{-1}$)
CERN	235	124
LBL	246	132

Having established that the flux density measurements were in good agreement the groups went on to compare the dose equivalents estimated in radiation surveys.

A location above a concrete shield at the CPS was chosen where the dose equivalent due to photons and charged particles was less than 10% of the total dose equivalent. Both groups used moderated foils or BF_3 counters and plastic scintillators.

In addition the CERN group used a boron-lined ionization chamber while the LBL group used aluminum activation detectors and a bismuth fission counter. Table 6.2 compares the estimated neutron dose equivalent rate in selected energy intervals.

Gilbert et al [GIL 68] analyzed the differences between these two measurements in some detail. It will be recalled that the basic measurements of neutron flux density by both groups had been shown to be in good agreement. However, the LBL estimate of neutron dose equivalent rate is ~35% greater than that due to the CERN Group. The CERN estimate of 33 millirem hr^{-1} was obtained with a moderated BF_3 counter which has some response to neutrons up to 20 MeV. This value of 33 mRem hr^{-1} should therefore be compared to the LBL value of 22 mRem hr^{-1}.

At neutron energies below 20 MeV therefore the CERN value is higher than the LBL value by a factor of 1.5. At energies above 20 MeV the CERN value is lower than the LBL value by a factor of three.

Table 6.2
Comparison of Estimated Dose Equivalent Rates
CERN and LBL

NEUTRON ENERGY INTERVAL	DOSE EQUIVALENT RATE (mRem/h)	
	CERN	LBL
< 1 eV	< 1	-
10^{-6} MeV $\leq$ E $\leq$ 10^{-1} MeV	-	1
10^{-1} MeV < E $\leq$ 15 MeV	33	19
15 MeV < E $\leq$ 20 MeV	-	2
E > 20 MeV	12	37
Total	45	59

The authors conclude "...and so physical measurement is ruled out as an explanation for the difference in dose equivalent estimation... The remaining difference, which is by far the most important, is clearly related to a difference of interpretation of the neutron dose equivalent associated with neutrons that are above 20 MeV in energy... Thus, we conclude that the differences in dose equivalent estimation are largely due to administrative decisions, and are not related to any disagreement between physical measurements techniques employed by the two groups."

6.3 Brookhaven National Laboratory - Lawrence Berkeley Laboratory Stanford Linear Accelerator Intercomparison: 1975

In 1975 two dose intercomparisons were made by teams from the Brookhaven National Laboratory (BNL), Lawrence Berkeley Laboratory (LBL), and the Stanford Linear Accelerator Center (SLAC) [McC 77].

Measurements were made in radiation fields outside shielded areas of the Bevatron of the University of California (a 6 GeV weak-focussing proton synchrotron) and the 20 GeV electron linear accelerator of Stanford University. In the areas selected dose rates differed by more than an order of magnitude, being higher at the Bevatron. Beam duty factors differed, being 0.1 at the Bevatron and 3×10^{-4} at SLAC. Measurements of neutron flux density were made with a moderated BF_3 counter, bismuth fission chamber and several activation detectors (see Section 4). The absorbed dose rate due to photons and charged particles was measured with ionization chambers. Neutron dose equivalent was measured using an Andersson-Braun "Rem-meter" and the BNL Universal dose equivalent instrument was used to determine the dose equivalent rate and average quality factor of the radiation field.

The results of these intercomparisons are disturbing.

Table 6.3 summarizes the data obtained at Stanford. The total dose equivalent rates determined by the three groups are in good agreement. But more detailed inspection shows this to be probably fortuitous. The dose equivalent rates due to the separate neutron and photon components differ by a factor of about 1.5 (the BNL Universal instrument does not, of course, give the dose equivalent rates due to the separate components). It was suggested by McCaslin et al that the measured value of the photon dose equivalent rate by the LBL group might be high due to the sensitivity of their chamber to fast neutrons. The SLAC group estimate of neutron DE rate is probably high since it was determined by an Andersson-Braun Counter. However, by folding the neutron spectrum with the energy-response of the instrument a reading of only 0.2 mRem h^{-1} would be expected. That is to be compared with the observed value of 0.7 mRem h^{-1}. Comparison of the quality factors determined also reveals internal inconsistency. The high value of neutron quality factor determined by the SLAC group points to an overestimate of neutron dose equivalent.

Table 6.3
Comparison of Dose Measurements Made
at the Stanford 20 Gev Electron Linac

Group	Total Dose Equivalent Rate (mRem h^{-1})	Neutron Dose Equivalent Rate (mRem h^{-1})	Photon Dose Equivalent Rate (mRem h^{-1})	Neutron Quality Factor	Total Quality Factor
BNL	1.2				2.5
LBL	1.0	0.49	0.51	4.8	1.6
SLAC	1.0	0.70	0.31	11.0	2.7

The results obtained around the Bevatron are, at first sight, even more disquieting (see Table 6.4). Here the DE rates determined by the three groups differ by more than a factor of 2. One can be reasonably confident that it is unlikely that the LBL group could be in serious error in making measurements in an environment so familiar to them. It is from this vantage point that these data will be analyzed.

The values given for the total quality factor are in fair agreement - an agreement which is probably fortuitous. The photon dose equivalent rate measurements agree. The Andersson-Braun Counter used by SLAC would underestimate the neutron dose equivalent around LBL because of its diminishing response at high-energies. From the neutron spectrum determined by the LBL group it was estimated that the Andersson-Braun reading should be increased by a factor of 2.7. If this correction is made the LBL and SLAC estimates of neutron dose equivalent rates are in agreement. Counting loss difficulties due to the radio-frequency structures superimposed on the Bevatron beam pulses may account for some of the problem.

6.4 CERN - Brookhaven National Laboratory - Badan Jadrowych Institute: 1975

Höfert [HÖF 75a] has described a comparison of dose equivalent measurements made at several locations around accelerators at CERN.

Measurements were made with instruments of the CERN Health Physics Group, the Universal Dose Equivalent Instrument of the Brookhaven National Laboratory [KUE 73a, KUE 73b] and a commercially available recombination chamber [MET 73] developed by Zielezynski [ZIE 62,64] of the Institut Badan Jadrowych.

Table 6.4
Comparison of Dose Measurements
Made at the Bevatron

Group	Total Dose Equivalent Rate (mRem h^{-1})	Neutron Dose Equivalent Rate (mRem h^{-1})	Photon Dose Equivalent Rate (mRem h^{-1})	Neutron Quality Factor	Total Quality Factor
BNL	30				4.2
LBL	51	48	3.0	5.9	4.6
SLAC	21	18	2.8	11.0	4.7

The dosimetry systems, which were used in several different radiation environments that are described in Table 6.5 fall into three broad categories with either muons, intermediate and fast neutrons or high-energy hadrons dominating or contributing a large fraction of the dose equivalent. Measurements are summarized in Table 6.5.

Höfert gives a detailed analysis of the measurements and the interested reader should refer to the original paper.

Overall the agreement between the three systems is fair. When neutrons play an important role, the CERN system seems to consistently give a value of H higher than either the recombination chamber or the Universal Dose Equivalent Instrument. This is perhaps to be expected in view of the fact that the intermediate-energy and fast neutron components of dose equivalent are determined by a Rem-Ion chamber and ^{11}C threshold detectors which are used with a conservative fluence to dose equivalent conversion factor [HOF 75b]. As is to be expected, agreement is much better when the radiation field is dominated by radiation of low LET (Section A, Table 6.5). Overall agreement to within about ±25% in both Quality Factor and Dose Equivalent Rate is seen. Höfert does point out that calibration plays an important part in the assessment of accuracy: for example, the Recombination Chamber readings of Dose Equivalent Rate differ by a factor of about 1.22 depending whether a broad parallel beam geometry or an equilibrium condition calibration factor is used.

6.5 Ames Collaborative Study of Cosmic Ray Neutrons: 1975-1979

During the period 1975-1979 a study of the intensity and spectrum of neutrons produced by the interaction of galactic cosmic radiation with the earth's atmosphere was undertaken at

Table 6.5
CERN 1975 INTERCOMPARISON DATA

Description of Radiation Field	CERN		Badan Jadrowych Institute Recombination Chamber		BNL Universal Dose Equivalent Instrument	
	$\dot{H}$ (uGyh^{-1})	Q	$\dot{H}$ (uGyh^{-1})	Q	$\dot{H}$ (uGyh^{-1})	Q
A. Muons very important						
(a) Experimental Area	16.5	1.7	17.3	2.1	16.8	1.7
(b) End Stop	29.9	1.5	27.0	1.5	31.0	1.4
B. Intermediate and Fast Neutrons Dominate						
(a) Opening to Labyrinth	228	3.4	178	3.4	153	2.2
(b) Normal to Shielding (Fast Neutrons Dominate)	317	6.1	268	7.5	242	4.2
(c) Linac Area (Fast Neutrons Very Important)	452	8.6	406	9.7	349	7.6
C. High Energy Neutrons Dominate or Very Important						
(a) Lateral Shielding	380	4.0	367	5.6	470	4.5
(b) Lateral Shielding	175	4.6	152	5.1	222	4.6

the Ames Research Center, NASA. This series of measurements which has been described in several publications in the literature [HEW 76, HEW 78, STE 78, HEW 80], involved the participation of groups from the Ames Research Center of the National Aeronautics and Space Administration, Brookhaven National Laboratory, The Lawrence Berkeley Laboratory, and the Lawrence Livermore National Laboratories of the University of California, and the State University of California at San Jose.

The measurements, made in the "accelerator like" radiation environment at altitudes of up to 12.5 km enabled some comparisons to be made of dose measurements by the participating groups.

The conclusions from this study show that the application of a variety of techniques including activation detectors, the BNL universal dose equivalent instrument, ionization chambers, moderated BF_3 counters, and Bonner spheres gave internally consistent data of "fair" accuracy and agreement in terms of "dose equivalent" to better than a factor of two.

6.6 Serpukhov - CERN 1978

Antipov et al have reported measurements made in three locations around the 70 GeV proton synchrotron of the Institute of High-Energy Physics in Serpukhov [ANT 78]. This is perhaps the most detailed and thorough dosimetry intercomparison carried out at a high-energy facility.

The instruments used by the Serpukhov group included a Rossi-type LET-Spectrometer [ROS 55], a recombination chamber referred to as (SUKHONA-2), and determinations of the neutron dose equivalent were made from measurements with moderated thermal neutron detectors and of the production of ^{11}C [BOR 74]. Measurements were simultaneously made by the CERN group and are summarized in Table 6.6 which gives six separate estimates of dose equivalent at each of three locations. The first three estimates labelled KM-1 (SNMO-5), KM-1 (SNMO-3) and KM-2 (SNM-3) may be considered as similar estimates using slightly different moderater size for the estimate of intermediate and fast neutrons, and variations in analysis.

7. SUMMARY AND CONCLUSIONS

This review of practical dosimetry around high-energy installations leaves the authors with a certain sense of disappointment and frustration.

The basic strategy for developing a successful system of dosimetry had been identified by the mid-fifties and a great deal of success in its implementation achieved in the decade that followed. By 1965 the basic experimental techniques still in use today had been developed. Some reasonable successes in elucidating neutron spectra found in working environments had

Table 5.5

SUMMARY OF DOSE MEASUREMENTS AT SERPUKHOV

Location	Methods	H 10^{-6}rem	D 10^{-6}rad	Q
Above accelerator roof concrete shielding. Hadrons E<20 MeV dominate Dose Equivalent	KM-1 (SNMO-5)	33.6 ± 2.0	10.5 ± 0.7	3.2 ± 0.6
	KM-1 (SNMO-3)	29.5 ± 1.8	10.0 ± 0.7	3.0 ± 0.3
	KM-2 (SNM-3)	24.0 ± 2.0	7.0 ± 0.4	3.4 ± 0.4
	Cerberus	26.9 ± 1.6	6.4 ± 0.3	4.2 ± 0.3
	Sukhona-2	28.6 ± 3.0	6.8 ± 0.3	4.2 ± 0.4
	LET spectrometer	19.6 ± 2.0	7.0 ± 0.4	2.8 ± 0.3
Beside lateral shielding of accelerator. Neutrons E<20 MeV dominate dose equivalent.	KM-1 (SNMO-5)	38.7 ± 3.1	9.9 ± 0.7	3.9 ± 0.3
	KM-1 (SNM-3)	21.1 ± 1.2	7.6 ± 0.6	2.8 ± 0.3
	KM-2 (SNM-3)	19.1 ± 1.4	5.4 ± 0.3	3.5 ± 0.4
	Cerberus	29.3 ± 1.5	4.8 ± 0.3	6.1 ± 0.5
	Sukhona-2	18.0 ± 2.3	5.0 ± 0.3	3.6 ± 0.4
	LET spectrometer	10.8 ± 1.1	5.4 ± 0.3	2.0 ± 0.2
Beside lateral shielding near beam channel. Muons dominate dose equivalent.	KM-1 (Rh^{103})	6.7 ± 0.6	5.9 ± 0.5	1.1 ± 0.2
	KM-2 (x2) (Rh^{103})	6.6 ± 0.9	5.4 ± 0.3	1.2 ± 0.2
	Cerberus	5.30± 0.33	5.2 ± 0.3	1.02± 0.10
	Sukhona-2		6.3 ± 0.3	
	LET spectrometer	6.5 ± 0.6	5.4 ± 0.3	1.2 ± 0.1

Despite the general good agreement differences of ~50% may be seen in determinations of H by different techniques.

been obtained by 1968. Maximum dose equivalent estimates could be made to within a factor of two, or better, and the way seemed clear for improvements in detail which would lead to accuracies of ~±30%. As we have seen from the discussion of intercomparison studies this promise has not been fulfilled.

The basic reason for this lack of progress has been the lack of any systematic program to develop the needed and well understood refinements in technique that are necessary. It is unfortunate that no university department, national laboratory, or even international laboratory has found the problems of accelerator dosimetry of sufficient intellectual challenge to mount the sustained program of research and development needed.

With the present resources available progress could most easily be made by collaborative efforts. Even the large accelerator laboratories have rarely devoted sufficient resources to adequately address the problem. Significantly enough, most of our successful solutions to the problems of high-energy dosimetry have resulted from joint efforts.

We suspect that it is only when the applications of high-energy dosimetry are coupled with their theoretical study at a single laboratory endowed with adequate resources that sustained and significant progress will be made. The basis for such a program might contain the following elements:

(i) the establishment of dedicated high-energy facilities that can provide a variety of radiation environments for dosimetric studies (electron and proton accelerators are needed: primary and secondary beams must be available over a wide range of energies);

(ii) organization of a series of dose measurement intercomparisons at these dedicated facilities. Groups from all laboratories interested in high-energy dosimetry should be invited to participate. The studies should begin in simple environments (e.g., monoenergic, non-divergent beams) and work towards comparison in occupational environments;

(iii) compile a library of neutron spectrum unfolding routines and undertake a systematic study of their performance. Identify the optimum use of each routine, evaluate errors in spectrum determination from available dosimetry systems [ROU 80];

(iv) compile a library of neutron spectra found under operational conditions. Study these spectra in a systematic way as a function of important parameters, e.g., shielding material, target, primary particle energy.

The problems of high-energy dosimetry are so coupled with the problems of radiation transport that it is clear their study should proceed concurrently. It is certainly true that there is a host of practical needs for such studies--nuclear power reactor shielding; radiation exposures at SST altitudes; medical accelerator radiation protection; absorbed dose distribution in patients undergoing radiotherapy, to mention only a few. It would seem to us self-evident that these could all be covered under the umbrella of fundamental radiation dosimetry and transport investigations. If field measurements using different techniques are even to be successfully intercompared, or the effective dose equivalent determined from physical measurements of radiation environments, radiation transport calculations are vital.

We believe that such a combination of practical and theoretical fields of endeavor could present an intellectual challenge worthy of acceptance by a university department and a challenge which we hope will soon be accepted.

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