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PORTABLE MIXED RADIATION DOSE EQUIVALENT METER

Alan V. Kuehner, John D. Chester and John W. Baum

October 26, 1972

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HEALTH PHYSICS AND SAFETY DIVISION
Informal Report

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N O T I C E

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PORTABLE MIXED RADIATION DOSE EQUIVALENT METER*

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REVISED ABSTRACT

A portable instrument has been developed which measures both absorbed dose and total dose equivalent rates over 6 orders of magnitude. It is based on a 20 cm diameter modified Rossi-type tissue equivalent linear energy transfer (L) spectrometer. The detector is sealed for up to six months with gas purity maintained by means of a desiccant. Detector microphonics are avoided by using a Benjamin-type electrode structure. Dose equivalent values are obtained by means of a simple electrometer plus biased amplifier system. This system uses the detector as an ion chamber with gas gain, and at the same time as a proportional counter. The total current from the detector is proportional to absorbed dose. Two biased amplifiers give additional gain to pulses from particles with L's greater than 3.5 keV/ μ . These weighted pulses, when added to the current measurement, yield an output proportional to dose equivalent. An internal alpha source permits several calibration checks to be made without external sources or equipment. When tested with monoenergetic neutrons and neutrons plus gammas, the instrument's errors have been less than $\pm 12\%$.

A recent application of the instrument has been to measure the natural background radiation profile at elevations up to 60,000 feet. For this measurement it was adapted for automatic data recording using two voltage to frequency converters and a register which prints the integral doses every 2 minutes. In this form it is capable of monitoring dose rates over 3 decades without range switching.

* Research carried out at Brookhaven National Laboratory under contract with the U. S. Atomic Energy Commission.

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DETECTOR DESIGN

A portable instrument has been developed which can measure total absorbed dose and dose equivalent in mixed radiation fields. The detector is based on a Rossi-type tissue equivalent (TE) linear energy transfer (L) spectrometer [1] modified to make it more suitable for use in a portable survey meter. Fig. 1 illustrates the principal features of the original and modified detectors. Each consists of a 0.6 cm thick spherical shell 20 cm in diameter, made of Shonka-type A-150 [2] conducting plastic. Both are filled with a mixture of CH_4 (66%), N_2 (3%), and CO_2 (31%) at a pressure of 10 Torr. The detectors then simulate a tissue sphere approximately 3 μ in diameter. The spheres are maintained at a high negative potential in order to produce proportional gas gain at the center collecting electrode. The original Rossi design achieves uniform field strength and therefore gas gain along the center wire by means of a helical field shaping electrode. This electrode is a very soft spring and may readily be displaced by vibration or mechanical shock, producing output pulses resembling particle events or shorts resulting in current surges sufficient to damage the input stage of the electronics.

The present design (after Benjamin) [3] obtains the desired uniformity of gas gain by means of field shaping electrodes at the ends of the central collecting wire. These electrodes depress the gas gain near the ends of the wire where it would otherwise be quite high. By proper choice of the diameters of the collecting electrode, field shaping electrode and the opening in the sphere in relation to the sphere diameter, it is possible to obtain nearly uniform gas gain for charged particles traversing all parts of the detector.

To minimize leakage currents between the high voltage and the collecting electrode, guard rings have been added to the original Benjamin design. This permits the measurement of currents smaller than 10^{-13} amps, corresponding to dose rates less than 10 $\mu\text{rad/hr}$. Since, unlike most proportional counters, the total detector current as well as the pulse information is used to determine the instrument output, stray currents to the collecting electrode could seriously degrade performance.

Previous work [4] has shown that the TE plastic from which the sphere is made contains a large amount of water which may be released over periods of several years. Principally because of this water vapor it has been impossible to maintain gas purity for extended operation with the detector sealed. Since the detector is operated at low pressure, very little water vapor contaminating the counting gas will seriously reduce the system gain. A side chamber containing anhydrous P_2O_5 desiccant has been added which absorbs much of the water vapor and allows sealed operation. Initially, because of outgassing of vapors other than water and selective absorption of the fill gas by the counter walls, refill is required at about one week intervals. However, by maintaining the detector at its operating pressure with desiccant attached it is slowly conditioned, requiring gas refills at progressively longer intervals. The spheres now in use have been conditioned for about three years and will maintain acceptable gas purity for up to six months. The precaution has been taken of using double "O" ring seals at all joints to limit diffusion through the seals as a source of contamination.

The detector also incorporates a collimated alpha source which is used for calibration checks. A shutter controls the entrance of alphas to the detector, producing a highly reproducible count rate making it possible to completely evaluate the instrument operation without the use of external radiation sources.

DETECTOR THEORY

The detector produces a pulse of electrons proportional to the L of a charged particle passing through the gas and to the length of its track within the gas volume. Since particles may traverse any cord of the sphere, from a diameter to grazing the gas volume, mono- L particles produce a variety of pulse sizes. If the source of these particles is on the inside surface of the sphere, a rectangular spectrum (number of events vs. event size) is produced. This spectrum is a sensitive test of uniformity of gas gain throughout the sphere, and was used initially to verify proper operation of the modified Benjamin electrode structure.

If the source of mono- L particles is at a large distance from the detector (more than 4 detector diameters), the pulse spectrum approximates a triangle. The approximation is less than perfect due to a number of causes including poor detector resolution, particle tracks which stop or start within the gas, and tracks which bend within or reenter the counting gas.

The spectrum obtained from a radiation field may be considered to be composed of a summation of these approximately triangular spectra, each produced by a particular L component of the radiation. This composite spectrum of events could range from minimum ionizing of $> 0.2 \text{ keV}/\mu$ to $500 - 1,000 \text{ keV}/\mu$ for heavy ions near the ends of their tracks. An example of the event size spectrum obtained using a $PuBe$ neutron source and normalized to a 1μ sphere is shown in Fig. 2. The sharp decrease in counts at about 100 keV deposited and again at about 500 keV indicates the maximum event size of recoil protons and heavy ions produced by neutrons colliding with elements in the TE wall of the counter. This spectrum also illustrates that an instrument based on this detector must be able to contend with a wide dynamic range in both pulse size and rate.

The usual procedure for obtaining a measurement of dose equivalent from this type of detector has included the collection of a spectra on a multichannel analyzer, reduction of this data to a spectrum of absorbed dose as a function of L by the use of a laborious hand process [5,6] or a computer program [7,8], multiplying the dose for each L increment by the appropriate quality factor (Q), and summing these products to obtain the dose equivalent. This complicated procedure has limited the usefulness of this detector for applied measurements.

A gain function developed by Baum [9] gives a means of directly obtaining the dose equivalent by means of an amplifier system which gives varying gain to each pulse as a function of its size. Fig. 3 shows this curve as a function of pulse size as well as the Q curve as a function of L. A portion of all triangular spectral components is given a gain of 1. This results in proper output for spectra with no components due to particles with L's greater than 3.5 keV/ μ . For events which deposit 3.5 to 175 keV in a 1 μ sphere, the gain curve lies above the Q curve. This is to compensate for the low gain given to the small pulses of each spectral component. Above 175 keV deposited the Q and gain curves again coincide. Since Q is no longer increasing with L, the compensation given to the intermediate size pulses correctly adjusts the total output for the high L spectral components.

Several techniques have been considered as a means of obtaining this required response curve [10] and one of them, the biased amplifier system, has been developed and used in the several survey and digital recording instruments described here.

CIRCUITS

The instruments all use the same basic circuits for extracting dose and dose equivalent information with minor modifications in range, time constants and switching, and with additional digitizing and printing circuitry added to some. Complete circuit diagrams and calibration procedures will be included in a Brookhaven National Laboratory Health Physics and Safety internal report. Fig. 4 is a diagram illustrating principal components in the survey type instrument. The high voltage supply is an efficient oscillator type adjustable from 1,000 to 1,300 volts and normally operated at 1200V. This high voltage supply must be very stable, since a 1% increase in its output will be reflected as a 30% increase in instrument output due to higher gas gain.

Ionization produced in the detector is collected on the center wire producing a current pulse. This pulse has two effects. First, the charge sensitive preamplifier produces a voltage pulse with a 10 μ sec time constant which has a height proportional to the original event size. This pulse is used by the two biased amplifiers. The second effect is a current to the electrometer. This produces a positive output proportional to the input current and therefore to the absorbed dose. The electrometer's time constant is about 3 seconds.

A simple electrometer circuit is used consisting of one metal oxide field effect transistor (MOSFET) and one PNP transistor. Gain is controlled by means of a high impedance ($10^6 \Omega$ to $10^{10} \Omega$) feed-back resistor. The electrometer input resistor has no effect on gain, but is used to

provide decoupling of the electrometer from the preamplifier. The input resistor in conjunction with the preamp input capacitor also provides some filtering of high voltage input spikes, minimizing this as a source of damage to the MOSFET in the electrometer.

The voltage pulse from the preamplifier is used by the two biased amplifiers. The gains of these two amplifiers are set so that pulses smaller than the desired bias levels will not pass the diode pumps at their outputs. The capacitors forming the first part of these diode pumps are selected to control the net current out for pulses greater than the bias. The summing amplifier produces a voltage proportional to the total current from the pumps and with a time constant of 3 seconds. This output plus the electrometer output is summed and displayed as dose equivalent rate.

The first biased amplifier operates on all pulses greater than its bias level of 13.35 keV (deposited in the 3μ sphere) and gives that portion of the pulse which is greater than the bias an effective gain of 5.6 relative to the electrometer. The second biased amplifier operates on all pulses greater than its bias level of 93 keV and gives that portion above its bias a gain of 18.5 relative to the electrometer. Since most spectra have many more events in the small pulse region, the first biased amplifier must handle many more pulses than the second, and therefore requires a pole zero correction network to properly shape the pulses to minimize pulse pile-up problems.

An electrometer gives uniform gain to all pulses from the detector. An ideal biased amplifier gives zero gain to all pulses smaller than its bias level, small effective gain to pulses just exceeding its bias, and progressively higher effective gains to larger pulses. This results from the fact that incoming pulses are reduced in size by an amount equal to the value of the bias. Fig. 5 shows a plot of the sum of the effective gains of the electrometer and two ideal biased amplifiers superimposed on the desired gain function. The pulse height scale is in keV deposited in a 1μ detector. The differences are small and improve somewhat for the actual biased amplifiers. Since biasing is obtained by means of the relatively "soft" cutoff of the diode pumps, pulses slightly smaller than the bias will pass at much reduced levels. This is reflected in the rounding of the curve labeled "Real Biased Amplifier" in Fig. 5. The break in the electrometer and first biased amplifier curve at about 100 keV is due to saturation of the first biased amplifier. This saturation causes the effective gain of the sum of the three amplifiers to follow the desired curve more closely for the very high L components of the spectra. Computer simulations of an ideal instrument show that the largest error is about 12% for mono-L radiation of 10 keV/ μ . However, since all real radiation fields produce particles with a variety of L's in the detector, systematic errors should be less than this amount.

Since within the instrument there are voltages proportional to both absorbed dose and to dose equivalent, it is possible to electronically take their ratio and have a direct indication of Q. Such an instrument was built and tested but has not yet been used in applied measurements.

CALIBRATIONS AND TESTS

Tests have been made with mixtures of neutrons and gamma rays and with monoenergetic neutron sources. Fig. 6 shows the result of one such test using a variety of monoenergetic neutron sources. The neutron source used to determine the point at 80 keV was later found to be significantly contaminated with gamma rays, and due to the variable nature of this contamination exact correction for it was not possible. Neutron energies from 80 keV to 1.6 MeV were obtained using protons on a tritium target. The energy is selected by control of incident proton energy and the position of the detector with respect to the proton beam and target. The 4.5 MeV point was determined as a weighted average of the neutrons from a PuBe source. The 14 MeV point was obtained using deuterons on tritium. In all cases a tissue equivalent ion chamber was also exposed and the instruments indicated absorbed dose was consistently within $\pm 5\%$ of the ion chamber's output. Measured values of Q were compared to the values given in ICRU Report 20 for the quality factor at the point of maximum dose equivalent in a 30 cm thick tissue equivalent phantom. Comparison was also made with values given in NCRP Report 38 for Q at 1 cm depth in a 30 cm cylindrical phantom. From 80 keV to 14 MeV the maximum difference of the indicated value of Q from either of these sets of data was -12% at .6 MeV.

Tests with gammas only or with mixtures of PuBe neutrons with gammas give absorbed dose and dose equivalent values within a few percent of the calculated values.

Since these instruments may be used in a variety of environments, temperature compensation has been built into them. The principal variation in gain was caused by the temperature sensitivity of the high voltage supply which resulted in an output temperature coefficient of about $-1.4\%/^{\circ}\text{C}$. Compensation, consisting of a single thermistor, resulted in a reduction of this value to less than $\pm .1\%/^{\circ}\text{C}$.

Switches in each instrument permit the output of the electrometer and the two biased amplifiers to be displayed independently. These switches plus the internal alpha source provide several checks on instrument operation. Without external sources electrometer errors may be corrected and errors in the gain of either biased amplifier or the bias level of the second biased amplifier may be detected. These measurements also provide a measure of the presence of contaminants in the detector fill gas. Since these contaminants alter the shape of the detector's output pulse, the gain given by the preamplifier is reduced but the electrometer's gain is unaffected. Therefore a change in the output of the biased amplifiers with respect to the electrometer may indicate contamination of the counting gas and that the detector should be refilled.

APPLICATIONS

This instrument has been used to monitor absorbed dose and dose equivalent rates at the Brookhaven National Laboratory Medical Research Reactor (MRR). Table I compares these results in terms of Q with values obtained using several other techniques. The column labeled "L Spectrometer" was obtained using a Rossi-type spectrometer with gas flow and a tissue equivalent ion chamber [11]. The Bonner sphere and Harwell counter data were

also combined with the ion chamber to obtain their indicated value of Q. The film badge data is based on the gamma and neutron doses registered on a BNL film badge.

The first three locations showed significant changes in Q as a function of relatively minor changes in position. This was easy to map using the biased amplifier system, but somewhat more difficult using the two detectors the other systems require.

Another application of this instrument has been the measurement of natural radiation at elevations of 10 to 60 thousand feet and geomagnetic latitudes ranging from 36° to 70° north as part of a study to determine population exposure due to present commercial and future supersonic transport (SST) passenger flights. Instruments and tissue equivalent ion chambers previously used could not properly weight high L charged particles. Since a significant fraction of the dose can be due to these particles, an underestimate of the dose is expected. Since the present system responds properly to these particles as well as neutrons and gamma rays, it provides a better measure of the total dose equivalent.

For this study four instruments were prepared with voltage to frequency converters, digital integration and printout for both absorbed dose and dose equivalent. These modified instruments were able to automatically record integrated doses at rates from 10 $\mu\text{rem/hr}$ to 10 mrem/hr . Completely automatic operation was essential since these instruments were to be carried on a variety of aircraft in locations generally inaccessible during flight. Since no power could be drawn from the aircraft, the instruments were designed to operate on internal batteries for at least eight hours at maximum dose rate. Normal battery life is at least twice as long at low dose rates. Some of the results of the aircraft study are shown in Fig. 7. Dose equivalent rates encountered ranged from 25 to 700 $\mu\text{rem/hr}$, with Q's of from 1 to 2.2. The error bars shown represent ± 1 standard deviation and are based on the counting statistics of the ideal instrument. Agreement with several studies [12,13,14] was found to be quite good after corrections for variations in solar activity were made. A complete analysis of these reports is included in the Final Report of the Federal Aviation Administration Advisory Panel on Radiobiological Aspects of the SST [15], and in "Direct Measurement of Dose Equivalent in Aircraft" [16].

The output from a typical flight is shown in Fig. 8. The values plotted are absorbed dose rate and dose equivalent rate averaged over two minute intervals. Since the dose rates were quite low, total averaging periods of 30 to 80 minutes were required to reduce statistical variation to acceptable levels. The spikes in the curves at low dose rates are principally due to alpha contamination inherent in the tissue equivalent plastic. This conclusion is based on analysis of the event size spectrum of these pulses and on long-term counting of detector materials in a low background alpha counter. The additional variation at high dose rates is due to poor counting statistics on high L events.

COUNTING STATISTICS

Since the relatively rare high L pulses have a much larger effect on the indicated dose equivalent than on the absorbed dose, statistical

variation in the dose equivalent rate is greater than that in the absorbed dose rate. Fig. 9 shows the expected statistical variation of the absorbed dose and dose equivalent channels as a function of Q. Computer evaluation of several hundred real and simulated spectra showed that those with the same Q had similar statistical variation independent of detailed spectral structure.

Evaluation was made on the basis of a simulated multichannel analyzer. After generating an event spectrum in the computer, the counting statistics in each channel were evaluated. The total count and its standard deviation were then weighted proportional to the effect of the biased amplifier system on pulses of equivalent size. All channels were summed to obtain the indicated dose equivalent and its standard deviation. A similar procedure without weighting gives the indicated absorbed dose and its standard deviation. From these values the value of Q and its standard deviation were calculated. These results were then all normalized to a fixed dose equivalent rate, integration time and detector size. The number of channels used for each analysis was taken to be the smallest number consistent with the condition that doubling the number of channels changed the result by less than .5%. After evaluation of many spectra the results were plotted. One initially surprising result was that Q can be measured with higher precision than either absorbed dose or dose equivalent at large values of Q. This is due to the non-independent nature of the measurements of absorbed dose and dose equivalent. This shows one unique advantage of using a single detector to obtain both.

The data in this figure have been normalized to a 20 cm diameter detector, 2 minute integration times, and a dose equivalent rate of 1 mrem/hr. The experimental points were determined directly from the output of one of the integrating instruments. The normalization is readily changed to other conditions using the following equation:

$$\frac{\text{Fractional Deviation}_1}{\text{Fractional Deviation}_2} = \sqrt{\frac{\text{Time}_2}{\text{Time}_1}} \times \sqrt{\frac{\text{Dose Rate}_2}{\text{Dose Rate}_1}} \times \frac{\text{Detector Diameter}_2}{\text{Detector Diameter}_1}$$

Statistical variation is the principal limit on operation at low dose rates. Pulse pile-up becomes a problem at dose rates above 10 rem/hr with this large detector. Higher dose rates can be monitored if a small detector is used. A 10 cm diameter detector on one of the survey instruments extends the upper dose rate limit to 40 rem/hr.

SUMMARY AND CONCLUSIONS

An instrument has been designed, built, tested, and is in use which is able to measure absorbed dose, dose equivalent and quality factor for mixed radiation fields. Dose assessment is derived from the output of a tissue equivalent linear energy transfer spectrometer by means of an electrometer and biased amplifier system. The measurement is based on the event size spectrum of particles measured in a 20 cm diameter detector filled with gas at low pressure to simulate a 3 μ sphere. Among the applications of this instrument have been measurements of absorbed dose and dose equivalent at locations around the BNL site, including an instrument intercomparison at the BNL MRR. The instrument has also been used to

measure the dose to aircraft passengers and crew due to solar and galactic sources. These measurements were taken at altitudes and geomagnetic latitudes covering the range of most present commercial and proposed SST flights.

TABLE I
Q VALUES AROUND THE BNL MEDICAL RESEARCH REACTOR

<u>Biased Amp System</u>	<u>L Spec- trometer + Ion Chamber</u>	<u>Bonner Sphere + Ion Chamber</u>	<u>Harwell Counter + Ion Chamber</u>	<u>BNL Film Badge</u>	<u>Location</u>
5.6	5.8	9.5	7.7	2.1	Flaw in East Door
2.0	1.9	2.1	2.0	1.5	East Wall
2.5	2.7	2.8	2.8	1.1	West Door
1.4	1.7	1.6	1.4	1.1	West Wall
1.2	1.4	1.5	1.3	1.0	S.W. Wall

FIGURE CAPTIONS

- Fig. 1 Detector Designs
 A) Original design showing helical field shaping
 electrode, after Rossi, et al. [1].
 B) Present design showing new field shaping electrodes
 and guard rings, after Benjamin, et al. [3].
- Fig. 2 Event size spectrum obtained using a PuBe neutron source.
 Normalization is to energy deposited (keV) in a 1 μ sphere.
- Fig. 3 Quality factor as a function of linear energy transfer and
 gain as a function of pulse size.
- Fig. 4 Circuit used in the survey instruments.
- Fig. 5 Gain of the biased amplifier system as a function of the
 energy deposited (keV) in a 1 μ sphere.
- Fig. 6 Quality factor measured by one of the survey instruments
 as a function of neutron energy compared to ICRU and NCRP
 recommended values.
- Fig. 7 Dose equivalent rate as a function of elevation and geo-
 magnetic latitude.
- Fig. 8 Output of one of the automatic digital recording instruments
 showing statistical fluctuations and variation in dose rate
 with changes in elevation.
- Fig. 9 Expected statistical variation in absorbed dose, dose
 equivalent and quality factor for 2 minute integration of
 1 mrem/hr radiation fields using a 20 cm diameter detector.

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LET SPECTROMETER
PROPORTIONAL COUNTER DESIGN

A. WITH HELIX (after ROSSI et al)

B. WITH FIELD SHAPING ELECTRODES (after BENJAMIN et al)

Fig. 1

Detector Designs

- A) Original design showing helical field shaping electrode, after Rossi, et al. [1]
- B) Present design showing new field shaping electrodes and guard rings, after Benjamin, et al. [3].

Fig. 2

Event size spectrum obtained using a PuBe neutron source. Normalization is to energy deposited (keV) in a 1μ sphere.

Fig. 3

Quality factor as a function of linear energy transfer and gain as a function of pulse size.

Fig. 4
Circuit used in the survey instruments.

Fig. 5

Gain of the biased amplifier system as a function of the energy deposited (keV) in a 1μ sphere.

Fig. 6
Quality factor measured by one of the survey
instruments as a function of neutron energy

Fig. 6

Quality factor measured by one of the survey instruments as a function of neutron energy compared to ICRU and NCRP recommended values.

Fig. 7
Dose equivalent rate as a function of
elevation and geomagnetic latitude.

Fig. 8

Output of one of the automatic digital recording instruments showing statistical fluctuations and variation in dose rate with changes in elevation.

Fig. 9

Expected statistical variation in absorbed dose, dose equivalent and quality factor for 2 minute integration of 1 mrem/hr radiation fields using a 20 cm diameter detector.