AN IONIZATION CHAMBER FOR THE DIRECT MEASUREMENT OF DOSE EQUIVALENT

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1. INTRODUCTION

In order to estimate the hazard from ionizing radiation in an environment containing an unknown radiation mixture, it is necessary either to analyse the radiation field in detail and determine the contribution to the radiation hazard from the individual components or to measure the radiation field with an instrument that has a response to radiation near to that of the accepted biological response.

The accepted quantity for radiation protection purposes that determines the biological hazard potential of radiation is the dose equivalent. This is defined as the product of absorbed dose and a factor, the quality factor (QF), depending on the linear energy transfer (LET) at which the energy is absorbed in tissue1). Hence an instrument is required that measures absorbed dose with an efficiency that varies with LET in the same manner as does the QF.

The initial recombination of ionization in a gas depends on the density of ionization along the tracks of particles causing the ionization and it has been shown, both experimentally2) and theoretically3) that if the ionization current is measured at two selected polarizing voltages then the difference current can be made to depend on LET in a manner such that it will be reasonably proportional to dose equivalent4). This difference current obtained with two different recombination conditions can be measured with the same chamber by changing the polarization potential, requiring that the radiation field is constant in time, or with a double chamber, arranged such that the net output is the difference in current from the two chambers. Operation in this manner requires both that the radiation field is uniform over the two chambers and that the volumes of the chambers are identical. These limitations may be quite severe as the difference current for gamma rays is only of the order of 3% of the current from either chamber.

The device described in this paper is an attempt to overcome these difficulties by using a double chamber where the polarizing voltage is made to alternate between the two values required to give the correct response. The output current is then the mean of the difference current from both chambers and is independent of uniformity of radiation field and whether or not the two halves of the chamber have identical volumes.

2. THE IONIZATION CHAMBER

No attempt was made to design and construct a chamber specially for these studies. Two existing parallel-plate tissue-equivalent chambers[3)] were modified such that they had a common collector and were mounted in a common pressure casing. The chambers are made up of a series of 15 cm diameter polarizing electrodes and collector electrodes of 12.5 cm diameter surrounded by a guard ring. The plates are all of 5 mm thick tissue-equivalent plastic. Each chamber has two collector electrodes and three polarizing electrodes mounted with a 4 mm gap between them. The effective volume of each chamber was 168 ccs. The electrical capacity of the chambers was:

- polarizing electrodes - collector	160 pfs
- polarizing electrodes - ground	230 pfs .

Separate high voltage connections were made to the two chambers. The collectors were connected together internally. The guard rings of both chambers were isolated from ground and brought to a common connection through the pressure casing. The chamber was filled with tissue-equivalent gas (64.4% CH_4; 32.5% CO_2; 3.1% N_2 by partial pressure).

The DC amplifier used was a Victoreen vibrating reed amplifier (type 475 B). This was selected on the grounds of availability and was not modified in any way.

3. THE HIGH VOLTAGE SWITCH

3.1 Requirements

The requirement is to step the polarization voltage between two values, with as large a voltage step as possible. The step has to be in exactly opposite phase on the two halves of the chamber such that the net induced voltage on the collector due to the change over is zero (or as small as possible). The size of the step has also to be identical on the two chambers.

Several methods of switching and balancing the voltage step were tried. Electronic switching using two high voltage transistors as an unsaturated bistable pair driven from an external pulse generator could be made to work. However, the circuit required continuous balancing due to the presence of thermally produced currents and a considerably more sophisticated circuit would be necessary to obtain the required degree of stability. Any circuit using a double switch will have synchronization problems. To overcome this a simple circuit employing a single switch was developed.

3.2 The switching circuit

The layout of the circuit is shown in Fig. 1 and the function of the components given in Table 1.

Table 1

Components of switching circuit

R_1,R_1'	1 MΩ matched, limits current from HT supply, R_1 controls rise time of pulse at A, R_1' controls fall time at B.
R_2,R_2'	100 kΩ limits current surge through relay contacts when closing. $R_2 + R_2'$ control fall time at A and rise time at B.
R_3,R_3'	10 MΩ matched, step voltage pulse differentiated through these resistors with T.C. = $R_3C_1 = R_3'C_1' = 7.5$ sec. Value must be $\gg R_1,R_1'$ so that current taken does not cause large voltage drop at C and D.
R_4	Ten-turn 100 kΩ potentiometer. Fine control on step height.
R_5	25 kΩ variable, used to simulate impedence of HV supply and so maintain symmetry. Acts as a coarse balance control.
C_1C_1'	0.75 μf DC isolating condensers. Must have high value compared to chamber capacity. Matched to better than 10%.
C_2C_2'	Parasite balancing condensers.

The switching is made with a single contact reed relay (Fabrimex type MR021) driven with an external pulse generator. The maximum voltage step that can be obtained is limited to about 400 V on account of the maximum rating of 1000 V across the open reed contacts. The calculated HT voltage of 970 V is required to obtain a 400 V step. With contacts open V_C = 970 V, V_D = 0. With contacts closed, V_C = 570 V, V_D = 400 V. These voltage steps appear at A and B as the voltage across the condensers C and C' is negligible. The pulse is differentiated through R_3 and R_3' with a long time constant determined by C_1R_3 and $C_1'R_3'$ ($\sim$ 7 sec). If the centre of R_4 is grounded the voltage swing at A and B reaches a final state of ± 200 V relative to ground. The centre of R_4 is biased to about - 170 V (a value selected when the chamber is calibrated) when the voltage step will be between + 30 and - 370 V.

The high voltage unit needs to supply a 500 μA pulse and should be stabilized such that the current can be established in a short time compared to the rise time of the voltage at A. Five different makes of high voltage units were tried, the most suitable was found to be a valve operated unit (IDL type 532 A). The bias applied to the centre of R_4 was obtained from a 5 MΩ potentiometer chain connected to the high voltage supply.

3.3 The step pulse shape

The rise and fall times of the voltage pulse must be less than about 0.1% of the period of the pulse. This requirement comes about as the time that the polarizing electrodes are positive or negative will not be the same due to the finite rise and fall time of the step pulse and hence a difference current will result due to this effect. The pulse rise and fall should also be fast so that the voltage passes through the regions of volume recombination as quickly as possible.

The effective capacity on which the voltage pulse is produced, is about 200 pfs. The pulse rise time at A and fall time at B is determined by this capacity and R_1 and R_1' which gives a time constant of 200 μsec. The fall of the pulse at A (and rise at B) is much faster as the chamber capacity is shorted by the relay closing and is determined by the chamber capacity and the 200 kΩ in series with the relay. This gives a time constant of about 40 μsec.

These rise and fall times of the step voltage pulse limit the frequency at which the chamber can be operated with the circuit values shown to below about 10 cycles/sec.

3.4 Circuit performance

The switching contacts have a variable open and closed time and the output voltage pulse has ragged edges when the contacts close due to 'bouncing'. However, as these variations are faithfully transmitted in reverse phase to A and B, they do not impair the performance of the circuit.

The voltage seen at the collector of the chamber with an oscilloscope using a $10^7\ \Omega$ probe can be balanced to zero with R_4 during the pulse. During the switch over a 10 kilocycle ringing is observed, presumably due to parasitic inductance in the loop A B D C, which sets the limit on the performance of the circuit.

As the circuit is symmetric, a good temperature stability is expected.

4. OPTIMIZATION OF CHAMBER PARAMETERS

4.1 DC optimization

Curves of collected ionization current were made with DC voltages in a gas pressure ranging from 2.5 to 7 kg/cm^2 using gamma rays from ^{137}Cs and PuBe ns. From these curves a gas pressure and polarizing voltage could be selected where the fraction of ions recombining was approximately in the ratio of 7.5 to 1 for neutrons and gamma rays. This condition occurred with $p = 5.0$ kg/cm^2 and $V = 30$ V. To obtain 30 V as the lower voltage in the 400 V step the centre of R_4 needs to be biased to - 170 V when the two voltages in the step will be + 30 and - 370 V. The measured DC difference currents at these two voltages were:

$$\gamma_{\text{rays}} = 2.5 \cdot 10^{-15}\ \text{A/mrad/h}$$

$$\text{neutrons} = 1.9 \cdot 10^{-14}\ \text{A/mrad/h} .$$

The ratio of these currents = 7.6, which is sufficiently nearly the QF of PuBe ns. The differential sensitivity of the chamber is therefore $2.5 \cdot 10^{-15}$ A/mrem/h for both neutrons and gamma rays.

4.2 An estimation of the LET dependence of the chamber

Some idea of the sensitivity of the chamber to radiations of other LET's can be estimated. The collected ionization current under conditions of initial recombination has been shown to depend on voltage, pressure and local ionization density along the track of the particle (ℓ) by[3]:

$$i = \frac{i_o}{1 + \ell p F(\frac{V}{p})}$$

where i_o is the available current.

Using this expression and assigning values of $\ell = 3.5$ keV/μ and 35 keV/μ to gamma rays and neutrons, $F(\frac{V}{p})$ can be determined experimentally for the values of V/p used to make the DC polarization curves. Having established a mean value of $F(\frac{V}{p})$ at V/p = 6 and 74 (the values applicable to the two voltages of the step), the difference current from the chamber as a function of ℓ is then given by:

$$\Delta i = i_o \left[\frac{1}{1+1.1 \cdot 10^{-3} \ell} - \frac{1}{1+8.0 \cdot 10^{-3} \ell} \right] .$$

This expression normalized to unity at $\ell = 3.5$ keV/μ is plotted in Fig. 2, where it is shown that the expected response has a remarkable similarity to the dependence on ℓ required for the chamber sensitivity to conform to the recommended QF-LET relation.

5. OPERATION OF THE CHAMBER WITH THE STEPPED VOLTAGES

5.1 Electrical performance

The alternating voltage on the collector plates did not appear to seriously disturb the performance of the amplifier provided the step was correctly balanced. The influence of the AC component was first checked with the chamber and a current calibrator connected in parallel to the input of the amplifier. The amplifier reading was the same independent of whether or not the alternating voltage was applied; the effect being seen as a ripple on the DC output from the amplifier and flicker on the meter needle. This ripple was measured with an AC millivolt-meter connected to the output of the amplifier, which is taken to read RMS Volts at all frequencies used.

With the chamber alone connected to the amplifier this ripple was measured as a function of frequency on the 1 V range of the amplifier where the DC sensitivity is full scale 10^{-12}A. This is shown in Fig. 3. As the output of the amplifier is 30 V full scale on all ranges the measured ripple has been divided by 30 to give 'RMS ripple referred to the input'. The rapid increase in amplitude of the ripple at very low frequencies is due to a resonance with the output circuit of the amplifier.

The effect of the alternating component on the performance of the amplifier was studied by deliberately unbalancing the step voltage until the amplifier showed an adverse effect. With the chamber operating between the voltage values selected, a gamma source was brought up to give about half-scale reading on the 1 V range. The ripple was then increased by turning the 10-turn balancing helipot R_4. The ripple (again RMS referred to input) and the mean current reading were observed as a function of the setting of R_4. This is shown in Fig. 4. When properly balanced the noise drops to about 13 mV, i.e. less than 2% of full-scale reading. The amplifier appears to be able to stand a considerably out of balance condition before its DC amplification properties suffer. However, the flicker on the meter needle increases in proportion to the measured ripple. These measurements indicate that the amplifier will work on a range 10 times more sensitive than the one used here.

5.2 Performance when measuring radiation

Straight forward operation of the chamber with the alternating voltages gives a net output difference current larger than that expected from recombination effects alone. This current is found to be frequency dependent. The effect is caused by the difference in equilibrium ion densities in the gas at the two different electric field strengths. This difference current is given by:

$$\Delta i = \frac{2fd^2p}{u} \left(\frac{i_+}{V_+} - \frac{i_-}{V_-}\right)$$

where i_+ and i_- are the currents collected from either half of the chamber with V_+ and V_- applied; f is the repetition frequency, d the plate spacing, p the gas pressure and u the negative ion mobility (when V_- greater than V_+). The effect can be used to estimate the negative ion mobility. Measurements with gamma rays give a value of 1.57 $cm^2\ sec^{-1}\ V^{-1}$ for the mobility in tissue-equivalent gas at a pressure of 1 kg/cm^2.

To overcome the effect of this frequency dependent current, the guard ring around the chamber collectors was isolated from ground and connected to a positive voltage. The field from the guard then assists ion collection in the half of the chamber that is at positive polarizing voltage and works against the field of the half of the chamber at negative voltage. By adjusting guard voltage V and frequency, the effect of the guard can be made to balance the unwanted current. The effect is illustrated in Fig. 5, where the net current per mrem/h for gamma rays and neutrons is plotted against frequency. With the guard grounded the sensitivities for neutrons and gammas are the same (and equal to the DC sensitivity) only at zero frequency. With 40 V on the guard the neutron and gamma sensitivities are equal at a frequency of 5.8 cycles/sec. The sensitivity with the guard at 40 V and 5.8 cycles/sec is $3.15 \cdot 10^{-15}$ A/mrem/h which is higher than the DC value.

The electric field from the guard has evidently modified the ion collection field around the edges of the collector electrodes and changed slightly the recombination conditions.

5.3 Effect of dose rate

Some dose-rate dependence can be expected as the collection field passes through zero twice during each voltage cycle. To test this the sensitivity was measured in dose rates up to 10 rem/h of gamma rays. The results are summarized below.

Table 2

Dose-rate dependence of sensitivity

Dose rate mrad/h	Sensitivity A/mrem/h	Relative Sensitivity
20	$3.15 \cdot 10^{-15}$	1.0
100	$3.15 \cdot 10^{-15}$	1.0
1000	$3.35 \cdot 10^{-15}$	1.06
10,000	$3.95 \cdot 10^{-15}$	1.24

As can be seen high dose rates increase the sensitivity and this increase is not excessive up to dose rates of 10 rad/h.

CONCLUSIONS

The results reported here show that it is possible to operate an ionization chamber with a pulsed polarizing voltage supply. DC currents of the order of $3 \cdot 10^{-14}$ A were measurable when a 400 V step was applied to the polarizing electrodes with a frequency of about 6 per second. By alternating the polarizing voltage on a double ionization chamber, the output current is the mean difference current from both parts of the chamber. This difference current can be made proportional to dose equivalent by suitable selection of gas pressure, polarizing voltages, voltage step repetition rate and potential applied to the guard electrode. With the chamber described, dose rates down to 10 mrem/h could be measured. However, the sensitivity can be considerably improved and an instrument based on these principles, with adequate sensitivity for health physics measurements, seems feasible.

Acknowledgements

I would like to thank Mr. B. Moy for his assistance with this project.

REFERENCES

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2) M. Zielczynski, Neutron Dosimetry II, 397, Int. Atomic Energy Agency, Vienna (1965).

3) A.H. Sullivan, CERN 1-69 (1969).

4) A.H. Sullivan, Proc.Conf. Radiation Protection in Accelerator Environments, Rutherford High Energy Lab.,60 (1969).

FIGURE CAPTIONS

Fig. 1 The switching circuit for obtaining stepped voltages on the polarizing electrodes of the double ionization chambers.

Fig. 2 The expected response of the chamber as a function of LET compared to the response required to conform to the ICRP recommendations.

Fig. 3 The ripple at the output of the electrometer as a function of frequency.

Fig. 4 The AC and DC output of the amplifier as a function of balance of voltage step.

Fig. 5 Frequency dependence of the sensitivity of the chamber for guard voltages of 0 and +40 V.

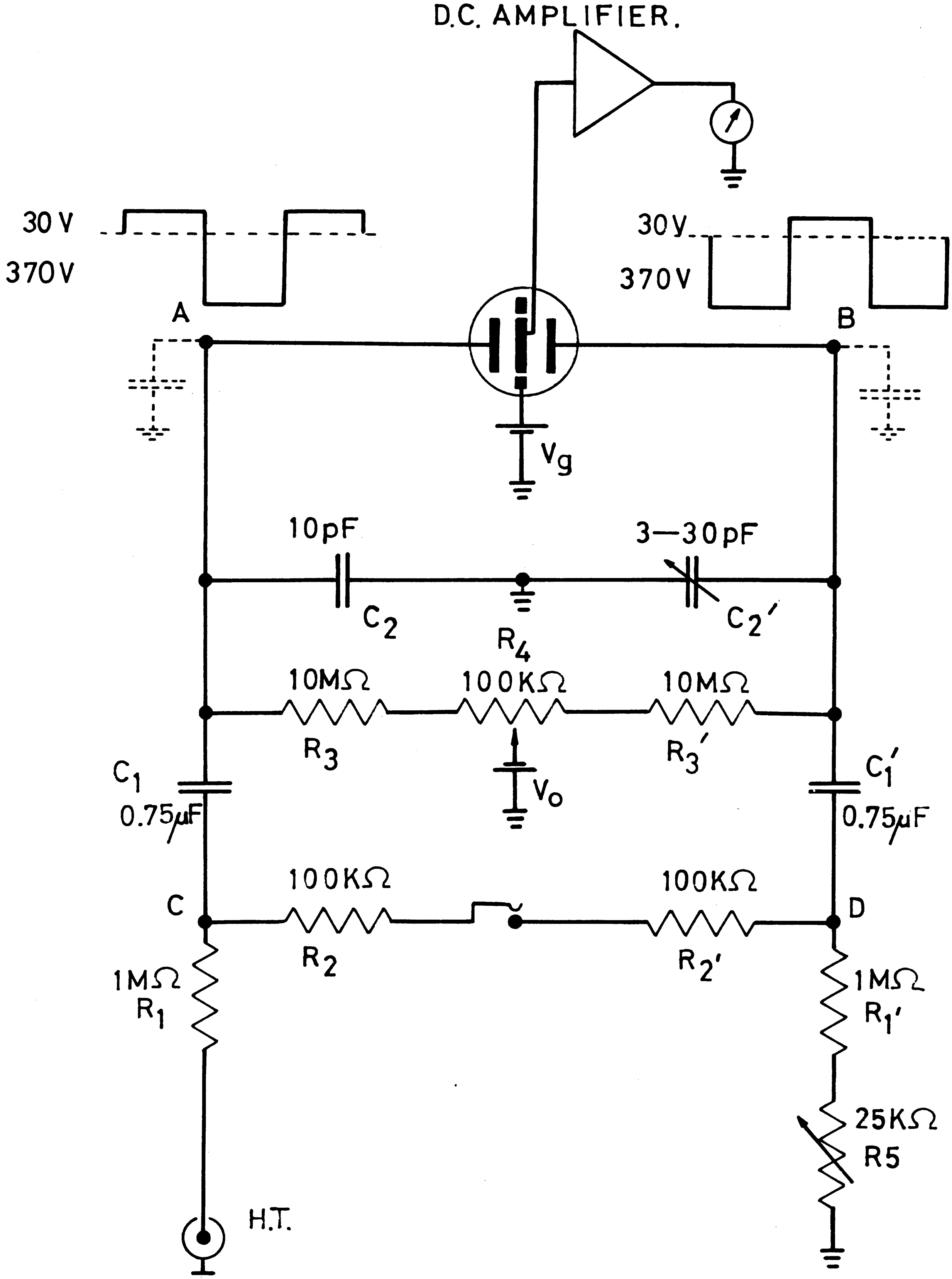
D.C. AMPLIFIER.
30 V
370V
30V
370V
A
B
V_g
10pF
3—30pF
C_2
C_2'
R_4
10MΩ
100KΩ
10MΩ
R_3
R_3'
C_1
0.75μF
V_o
C_1'
0.75μF
C
100KΩ
100KΩ
D
R_2
R_2'
1MΩ
R_1
1MΩ
R_1'
25KΩ
R5
H.T.

Fig. 1

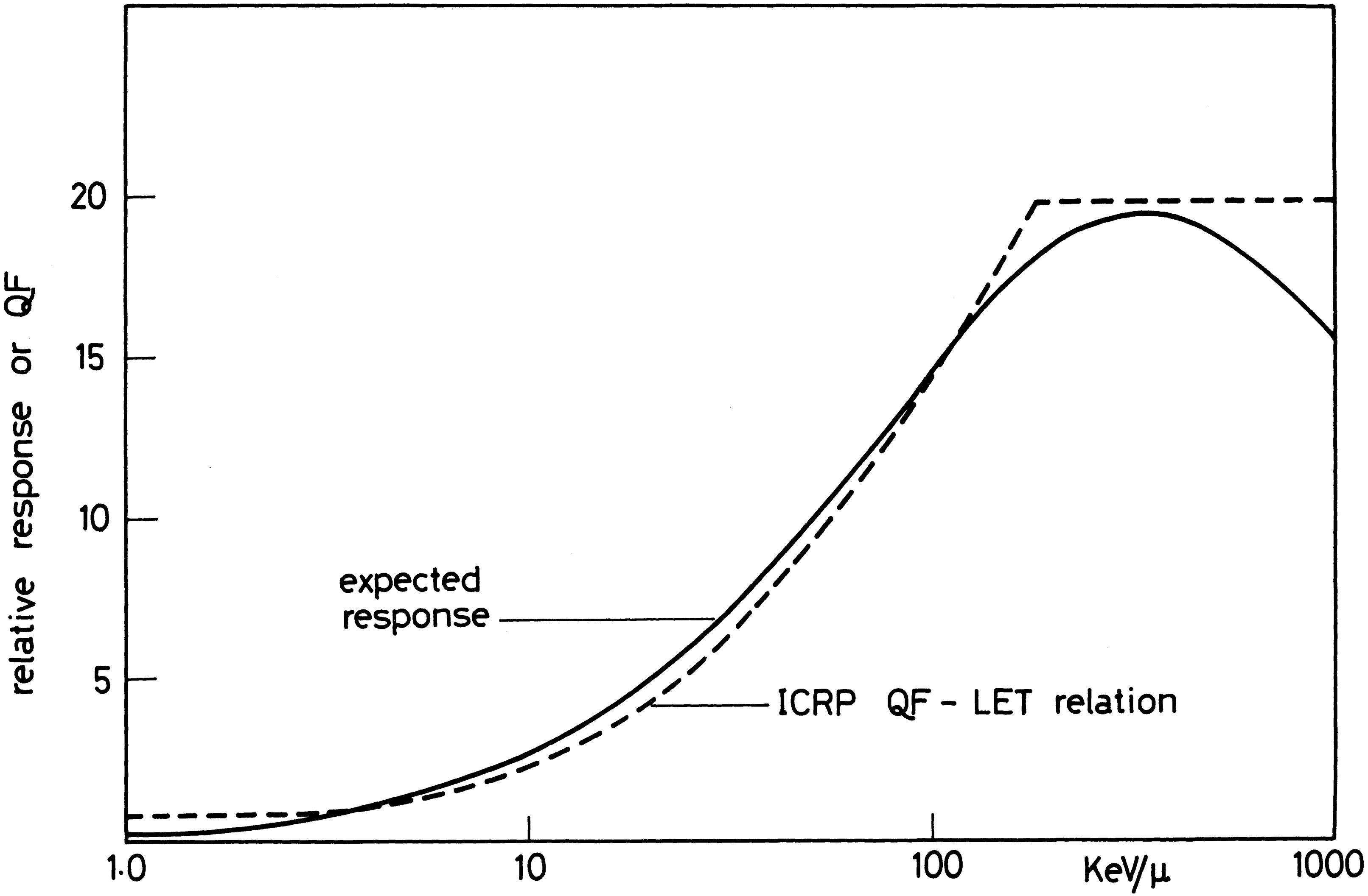
relative response or QF
20
15
10
5
expected response
ICRP QF - LET relation
1.0
10
100
KeV/μ
1000

Fig. 2

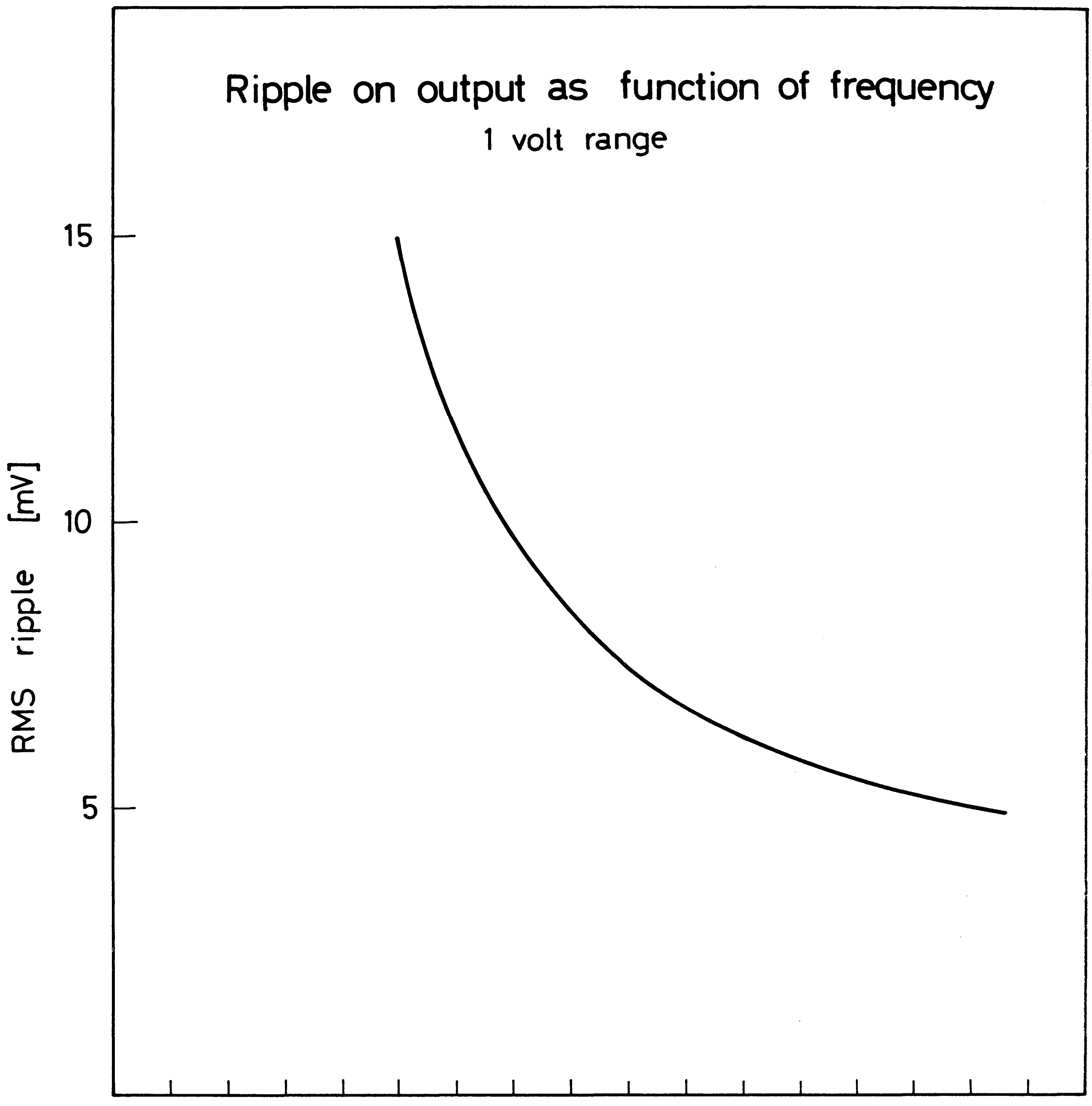
Ripple on output as function of frequency
1 volt range
RMS ripple [mV]
15
10
5
0
5
10
15
frequency [c/sec]

Fig. 3

Amplifier output as a function of balance
of voltage step
1 volt range 5·8 cycles/sec

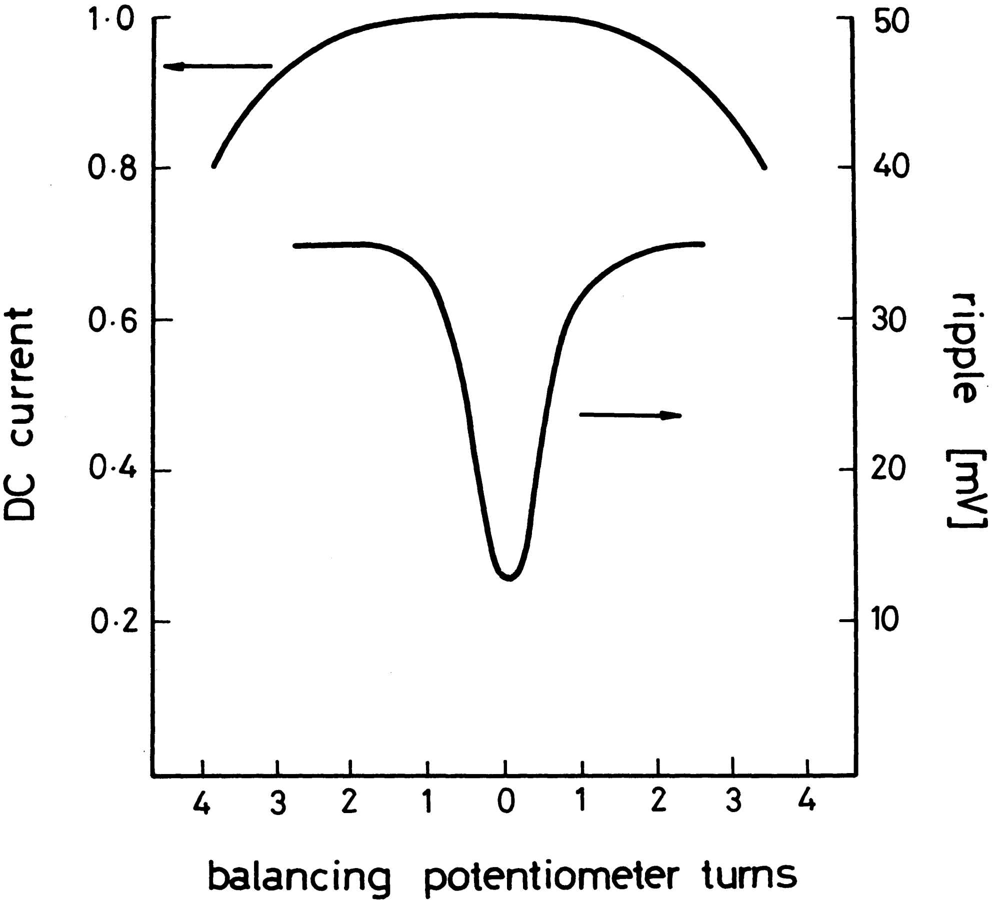

Fig. 4

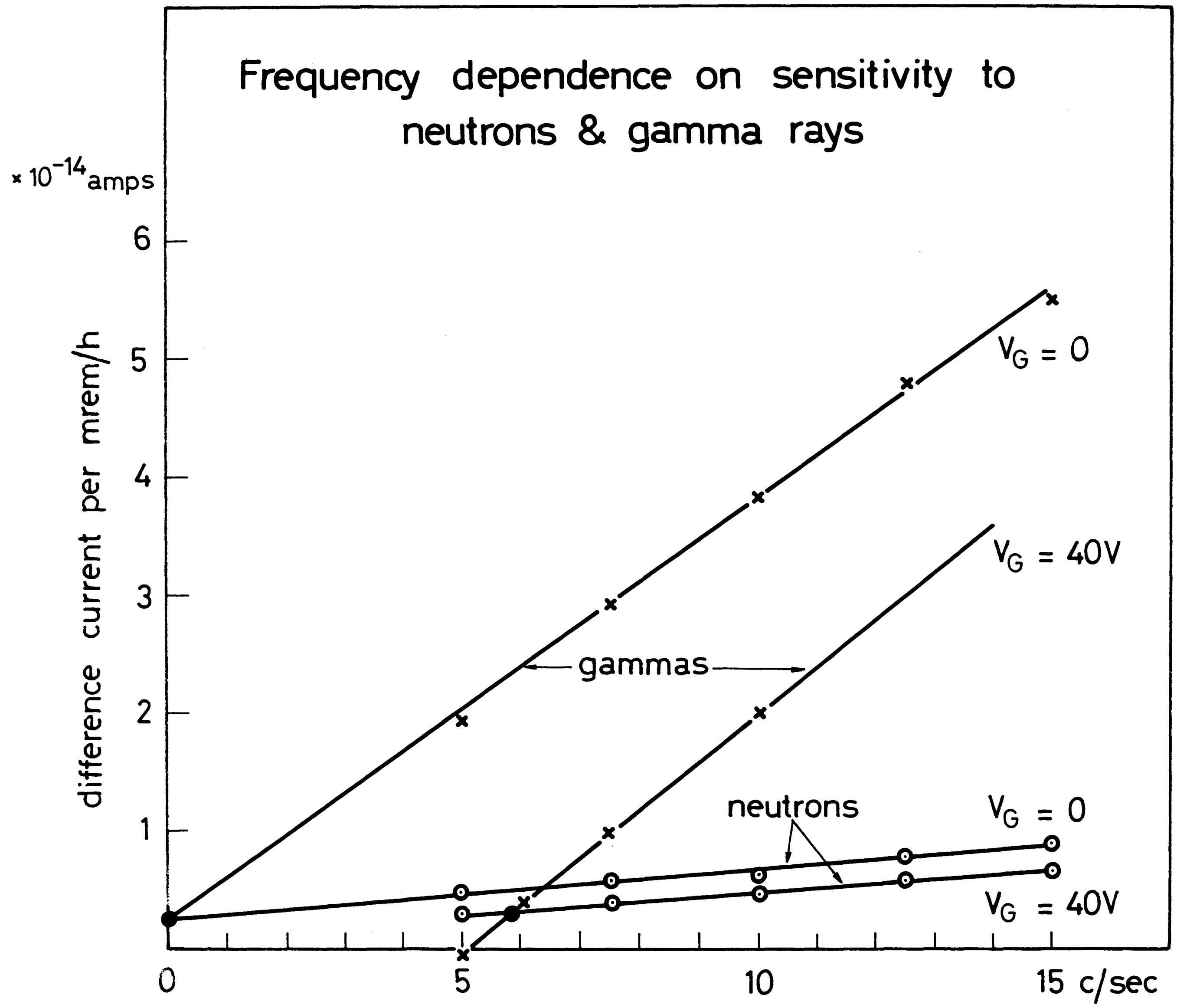
Frequency dependence on sensitivity to neutrons & gamma rays
$\times 10^{-14}$ amps
difference current per mrem/h
6
5
4
3
2
1
0
5
10
15 c/sec
$V_G = 0$
$V_G = 40V$
gammas
neutrons
$V_G = 0$
$V_G = 40V$

Fig. 5

Paper : An ionization chamber for the direct measurement of dose-equivalent

SRDOC: You have shown the response curve of your instrument and marked it "expected response". Have you performed an actual calibration measurement?

SULLIVAN: Only with gamma-rays and Pu-Be neutrons. High LET calibrations with alpha particles are to be made. I showed the expected response only to demonstrate that the response of the chamber can be readily controlled.

STEVENSON: Have you tried your device out in a pulsed radiation field?

SULLIVAN: No measurements have so far been made, but no difficulty is expected, provided there is no synchronization between the radiation pulse and the alternate polarized voltages.

MOOS:

i) What is the rise-time of the pulses?

ii) What is the duration of the ringing you mentioned in your system?

SULLIVAN:

i) The rise-time at A is controlled by R_1 and the chamber capacity, and gives about 200 μsec. The fall-time depends on R_2 and R_2^1 and is about 40 μsec. The rise- and fall-times at B are the reverse of those of A.

ii) The original pulse persists for about 500 μsec.