National and International Standardization of Radiation Dosimetry

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NATIONAL AND INTERNATIONAL STANDARDIZATION
OF RADIATION DOSIMETRY

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FOREWORD

Public concern about all aspects of radiation safety has generated a strong demand for reliable measurement of ionizing radiation, a demand that applies not only to the protection of man and his environment but also to those activities in which radiation work plays an essential role — in medicine, nuclear power, industrial radiation processing and scientific research. All these require regulation of some kind, and in many countries new or revised rules have been issued concerning the use of ionizing radiations, leading to a requirement for standardization in dosimetry on both the national and international levels.

The introduction of the international system of units (SI) in the field of radiation measurement has engendered a critical appraisal of the concepts and quantities as well as of the units. This has coincided with a period in which a transition in outlook is apparent — there being a movement away from the quantity exposure towards the quantity absorbed dose (or air-kerma) for appropriate radiation qualities. Thus it seemed timely to reconsider and discuss the realization of the primary radiation units and their dissemination through the entire calibration chain to provide practical units for accurate measurements in the field.

It had also become clear that, in order to widen the availability — both geographically and numerically — of calibrated radiation measuring apparatus, the efforts of the national primary standards laboratories would have to be supplemented. In some of the larger industrialized countries, enlarged schemes for providing calibration services have had to be set up, with the national standards laboratory as the primary reference centre. For many countries now entering the field of nuclear energy, or using radiation in medicine and industry, the setting up of Secondary Standard Dosimetry Laboratories (SSDLs) appeared to provide the most suitable and economic solution to the problem of disseminating radiation units. The SSDL's role is to calibrate tertiary and field dose meters and to serve as the necessary link between the primary standards laboratories and the radiation user. The world-wide spread of such SSDLs — within the frame of the IAEA/WHO Network of SSDLs — gives rise to a need for them to collaborate with each other and with primary standards laboratories to ensure that standards are truly uniform.

When preparing the Symposium on the National and International Standardization of Radiation Dosimetry, it therefore seemed appropriate to discuss, in addition to primary standards and the work of primary standards laboratories, the specific tasks of SSDLs, the presentation of results and uncertainties throughout the calibration chain, as well as the organization and
results of dose intercomparisons such as those initiated by international, regional and national laboratories. In this context a discussion on national and international standards for the performance of dose meters, and the procedures for verification and type testing also seemed to be very relevant.

It is imperative that work on the basic physics phenomena related to dosimetry be continued and discussed at international meetings. Basic data, characterizing the interaction processes between radiation and matter, enter into the calibration chain; this requires international standardization of the numerical values. Here again it becomes evident that the task of the standardizing laboratories cannot be confined to calibrations of secondary or tertiary standard dose meters against primary or secondary standards, respectively; it must include a follow-up of the entire chain of dissemination of the radiation unit, providing the ultimate user with a clear instruction on how to determine the absorbed dose at a specified point from the reading of the instrument.

In the field of medicine, codes of practice for radiation therapy dosimetry with photon and electron radiation have been issued by a number of national and international committees. Some of these recommendations are at present under review or are the subject of revision. New formalisms have been suggested which might replace the widely used exposure calibration factor and the dose conversion factors. This new approach seems not only to be more consistent and accurate, it leads also to a unified procedure for photon and electron radiation.

Progress in standardization of radiation dosimetry is closely related to the activities of the International Commission on Radiation Units and Measurements (ICRU). Involved in this subject ever since 1925, the ICRU has had more impact on standardization in radiation measurement than any other organization. At present, one of the activities of ICRU is to provide information on the various factors needed for calculating the basic physical properties of absolute radiation standards.

Of the ten sessions of the Symposium, two were devoted to calibration work at the national standardizing laboratories, two to work at SSDLs and related international activities, two to standardization and calibration in radiation protection, one to standardization and calibration of radioactive sources, one to basic physical aspects, and two to absorbed dose determinations. A total of 65 papers were presented, nine of which were given by invited speakers. The 137 participants represented 26 countries and eight international organizations. The Proceedings, published in two volumes, include the papers and the subsequent discussions.

For the convenience of the reader and to improve the volumes as a reference source, the order of the papers does not follow the order of the Symposium programme, and participants are advised to consult the Author or Preprint-Symbol Indexes in Vol.II to determine the exact location of a paper of interest.
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BASIC PHYSICAL ASPECTS
SOME THEORETICAL ASPECTS OF ELECTRON AND PHOTON DOSIMETRY*

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Abstract

SOME THEORETICAL ASPECTS OF ELECTRON AND PHOTON DOSIMETRY.

The dosimetry standardization programme at the National Bureau of Standards (NBS) has a number of theoretical components. These include the compilation of standard cross-section data sets, the theoretical analysis of detector response to various radiations, the spectral and directional characterization of radiation sources, and the determination of absorbed-dose distributions in irradiated media. This paper describes recent results, with emphasis on photon and electron dosimetry. A discussion is given of some recent developments pertaining to photon attenuation coefficients and electron stopping powers. Response functions are presented for intrinsic germanium detectors (used to measure the output of diagnostic X-ray machines) and for sodium iodide detectors (used to measure the spectral characteristics of one of the NBS 60Co irradiation facilities). As examples of source characterization, calculations are described pertaining to the passage of high-energy electron beams through foils. Consideration is given to thin foils used to spread the electron beam, and to thick foils used as bremsstrahlung converters. The results include the energy spectra and angular distributions of the transmitted electrons and emergent bremsstrahlung photons. An example of the calculation of absorbed-dose distributions is given for irradiation of a carbon phantom by a 60Co gamma-ray beam.

INTRODUCTION

The standardization of radiation dosimetry is not entirely an experimental endeavor but must also rest on a sound theoretical basis. At the National Bureau of Standards there is a long-standing collaboration between experimenters and theorists in the area of dosimetry. The theoretical work generally falls into the following categories: (1) the critical evaluation and compilation of electron and photon cross sections needed in radiological physics; (2) the theory of radiation detectors;

* This work was supported in part by the Division of Biomedical and Environmental Research of the United States Department of Energy, the Office of Naval Research, and the NBS Office of Standard Reference Data.
(3) the characterization of standard radiation sources and fields; and (4) the prediction of absorbed-dose distributions. The purpose of this talk is to describe some recent work on these topics.

PHOTON ATTENUATION AND ENERGY-ABSORPTION COEFFICIENTS

At the National Bureau of Standards there has for many years been a continuing program of evaluating and compiling photon cross sections [1-7]. These compilations are updated from time to time to take into account the accumulation of new experimental data as well as improvements of theory. In the first few figures we show how the experimental input data, and the compiled values, change in the course of time. These changes are illustrated for the case of carbon which is one of the most frequently used materials in radiation detectors. Figure 1a shows experimental values of the total attenuation coefficient for carbon at 8.04 keV (Cu K$_\alpha$ x-rays) measured during the period 1909 to 1977. Although the reported error limits tend to shrink for the more recent measurements, the convergence of the measured values is not all that might be desired. In fact, the most recent measurements appear to define a downward trend.

Figure 1b shows the carbon total attenuation coefficient at 10 keV as given in various compilations over the last 40 years. In this case, the compiled values show a better convergence in time, with agreement among the recent compilations to within 1-2%.

Neither theory nor experiment is fully adequate as the basis for systematic tabulation of accurate photon cross sections. The NBS compilation efforts depend on an intricate mixture of both. There has been, however, a gradual transition toward the use of more theoretical data. Even in those areas where theory is not fully adequate, it serves as a basis for interpolating among the often scanty experimental data. The mixture of theory and measurement in the most recent compilation can again be illustrated for carbon. Figure 2 shows the total attenuation coefficient from 100 eV to 20 MeV. Below 1 keV (see Fig. 2a), the extensive photoeffect calculations of Veigele et al. [22] (done in a non-relativistic, dipole approximation) are not sufficiently accurate. In this region the adopted values are based on measured data with the theoretical results aiding in the interpolation to unmeasured elements. Between 1 keV and 5-10 keV, the relativistic photoeffect calculations of Scofield [23], using Hartree-Slater wave functions, provide an adequate

* The figures will be found before the references on pages 20–39.

1 It should be noted that carbon is a particularly bad case, with a 6% discrepancy between the adopted value and the latest measurement.
basis for tabulation. These calculations can be further improved by a simply applied correction based on wave functions from more accurate Hartree-Fock potentials [23,24]. These corrected results tend to fall within the ~5%-spread of the measured data. From 10 keV to a few MeV (see Fig. 2b), the sum of the Scofield photoeffect cross section and recent theoretical scattering cross sections [25] gives the total attenuation coefficient with an estimated uncertainty of about 2%. In fact, in this energy region, recent compilations rely on theoretical results almost exclusively, with little or no experimental adjustment.

In the energy region above 1.022 MeV, the most important new theoretical input pertains to the pair-production cross section. To obtain the presently adopted curve in Fig. 2b, the low-energy theories of Øverbø [26] and of Tseng and Pratt [27] and the high-energy Davies-Bethe-Maximon [28] theory corrected for screening effects were used. The predictions of these theories were corrected by an empirically-modified, energy-dependent Coulomb correction factor [7]. The estimation of this correction factor is made difficult by the presence in measured data of the photonuclear giant dipole resonance feature [29-31], which contributes up to 5-10% to the total cross section. This feature occurs at energies from ~20-25 MeV for low-Z elements, down to ~12-14 MeV for high-Z elements. More recently, an analysis by Gimm and Hubbell [32], based on a more exact theory [33] with relativistic screening, new theoretical results for the Coulomb correction [34], and extensive 10-150 MeV total attenuation coefficient measurements [35], suggest that pair-production cross sections above 10 MeV for all Z's may be predicted theoretically to an accuracy of 1% or better, without empirical adjustments. These new theoretical results differ from previously compiled pair-production cross sections (e.g., reference [6]) by less than 1% for Z ≤ 29, but by as much as 4% for Z = 82 at 10 MeV.

The uncertainty in the mass energy-absorption coefficient is expected to be larger than that of the total attenuation coefficient. For the interpretation of air ionization chamber measurements, one is often interested in the ratio of mass energy-absorption coefficients — e.g., for air to that for the carbon wall material [36]. In this case, much of the uncertainty tends to cancel. For photon energies from about 0.5 to 1.5 MeV (including 137Cs (0.66 MeV) and 60Co (1.25 MeV) gamma rays), both μ/ρ and μ_{en}/ρ can be very nearly represented in terms of the free-electron Compton-scattering process alone (i.e., binding effects and coherent scattering are small). In this energy region, the (μ_{en}/ρ)_{air}/(μ_{en}/ρ)_{carbon} ratio is estimated to be accurate to ±1%, perhaps as accurate as ±0.3%.
However, at lower energies the uncertainties increase, and may amount to several percent. Ratios derived from various compilations are given in Fig. 3 for 10 and 30 keV. The 6% decrease in this ratio between the 1969 and 1977 NBS values at 30 keV is traceable primarily to a 10% increase in the carbon photoeffect cross section at this energy.

ELECTRON STOPPING POWER AND RANGE

Over the years, a number of tabulations [38-40] of electron mean energy loss and range have appeared. Such mean values are not sufficient for the accurate description of electron penetration in matter because of the effects of energy-loss straggling, pathlength straggling, and of detours due to multiple elastic-scattering. Stopping-power and range data are important however because they are essential input data for detailed transport calculations and for the interpretation of experimental dosimetry data.

The experimental determination of electron stopping power and range is made difficult by the complicated relationship of these quantities to the observed transport phenomena. However, they can readily be obtained theoretically, except at low energies.

Mean Collision Energy Loss

Above a few keV, the mean collision loss can be obtained from the Bethe stopping-power formula [41,42]. This formula depends on the properties of the medium through three parameters: the ratio of atomic number to atomic weight, Z/A; the mean excitation energy I; and the density effect correction δ. The density effect correction, as formulated by Sternheimer and Peierls [43], depends only on the density, Z/A and I. Thus, the problem of calculating the mean collision energy loss reduces to the problem of obtaining values for the material constant I.

Information on I-values comes from two main sources: (1) from the analysis of measured proton stopping-power and range data, and (2) from oscillator-strength distributions. Proton data are used for various reasons. They are much more plentiful than electron data, they can be interpreted without the need for elaborate multiple-scattering corrections, energy-loss straggling is less important, and bremsstrahlung effects are absent. On the other hand, the analysis of proton data is complicated by the presence of strong atomic binding effects (inner-shell corrections).
The uncertainties of the I-values can be as great as 10 percent. However, because I enters into the stopping power logarithmically, the resulting uncertainties of the mean collision energy loss are much smaller. The variation of the mean collision energy loss with I is shown in Fig. 4 for water, carbon and air. Four different sets of I-values were considered in this comparison. One is a set recommended in 1963 by a committee of the National Academy of Sciences-National Research Council [44]. The second set was recommended by Dalton and Turner [45,46] in the late 1960's. The third set was given recently by Andersen and Ziegler [47] who re-analyzed all of the available proton data, and who explicitly took into account the fact that -- due to atomic shell effects -- the mean excitation energy is an irregular function of the atomic number. Finally, the fourth set considered was derived by Zeiss et al [48] from measured oscillator-strength distributions for gases. For example, we see from Fig. 4 that a 10% change in I, from 65.1 eV to 71.6 eV, for water results in changes of the mean collision energy loss of 1.9% at 10 keV, 1.3% at 100 keV, and 0.6% at 1 MeV. Note that for condensed media, the dependence on I of the mean collision energy loss dissappears at high energies due to the fact that the asymptotic value of the density effect correction contains a log I term which cancels that in the Bethe formula.

Electron stopping-power and range tabulations based on use of the Bethe theory have usually been extended only down to an energy of 10 keV because the theory is considered to be increasingly unreliable below that energy. For a few materials, attempts have been made to derive stopping-power values down to energies of a few eV. From the analysis of low-energy electron range data in air and collodion [50], a committee of the ICRU [51] has deduced stopping powers for water. Low-energy stopping-power values can also be obtained through the combination of cross sections for ionization and excitation by electron impact. The adequacy of the atomic and molecular cross sections available for this purpose is gradually improving. Stopping-power values for various gasses have been derived in this manner by Green and collaborators [52].

In the course of low-energy transport calculations we have made a tentative analysis of the cross section data for water vapor. Our results are consistent, above 10 keV, with a mean excitation energy of 71.7 eV, close to the values recommended by Dalton and Turner and by Zeiss et al. In Fig. 5, a plot is given of the ratio of this stopping power to the result of the Bethe formula (evaluated with I = 71.7 eV). The differences amount to ~10% at 1 keV and ~15% at 200 eV.
It is also of interest to see how the ratio of stopping powers is affected by the choice of I-values. For example, chamber-wall-to-air ratios are needed in the cavity-ionization theory of Harder [53,54] for electron beams. As shown in Table I, the carbon/air stopping-power ratios based on I-values derived from three sources ([44], [45,46], and [47]) differ by less than 1% for electron energies above 10 keV.

### Mean Radiative Energy Loss

The mean energy loss per unit pathlength due to the emission of bremsstrahlung is obtained from knowledge of the differential bremsstrahlung cross section. Information on this cross section is still incomplete. Experimental information is scanty, and for systematic tabulations of the mean radiative energy loss, recourse must be had to theory. There is a large body of analytical bremsstrahlung theory, available in various approximations (with and without the Born approximation, high-energy approximation, screening corrections). The available theoretical expressions have been reviewed by Koch and Motz [55], who recommend the use of certain combinations of cross sections in different energy regions and the use of empirical correction factors. The cross section set recommended by them has been used in earlier energy-loss tabulations [39,40]. Using more recent experimental data and theoretical developments, we have adopted a somewhat different combination of cross section formulas [56] for use in electron-photon transport calculations with the computer code ETRAN/DATAPAC [57].
A significant advance in the state of the art has taken place in recent years through the work of Pratt, Tseng, and colleagues [58-61] who avoided various approximations inherent in the older theories and relied heavily on numerical evaluation of matrix elements. These calculations require a large amount of computer time, and it is impossible for the time being to compute the bremsstrahlung cross section routinely for all conditions of interest. However, enough computations have been carried out to obtain a data base suitable for interpolation, and bremsstrahlung cross sections (including the mean radiative energy loss) are available for targets with atomic numbers from 2 to 92 and for electron energies from 1 keV to 2 MeV [62]. The basic calculations are probably accurate to better than ~3%, and the interpolated body of results is stated to be accurate to 10% or better.

The mean radiative energy loss in carbon and gold is shown in Fig. 6. Three curves are given: one from our 1964 tabulations [39]; the second from the ETRAN/DATAPAC data set [57], and the third derived from the Pratt-Tseng calculations [62]. It can be seen that the 1964 results\(^2\) are too high by as much as 20-30% in certain energy regions, whereas the ETRAN/DATAPAC values used since 1968 agree with the Pratt-Tseng results within the 10%-limits of uncertainty above 100 keV in gold and above 10 keV in carbon. Below 100 keV in high-Z materials the ETRAN/DATAPAC values are too high due to an underestimate of screening effects. However, because at these energies less than ~3% of the total energy loss is due to bremsstrahlung, this discrepancy should have caused no serious problem in most applications.

For the results of Fig. 6, the \(Z^2\) coefficient of the nuclear bremsstrahlung cross section was replaced by \(Z(Z+1)\) in order to approximately account for the bremsstrahlung produced by interactions of the incident electron with the atomic electrons. Because of the absence of either a complete theory of electron-electron bremsstrahlung or definitive low-Z experiments, there is little guide for treatment more accurate than using \(Z(Z+\eta)\) with \(\eta \approx 1\) (see, e.g., reference [55]). The uncertainty associated with this correction becomes more serious for low-Z elements. However, even in carbon a change of \(\eta\) from 1.0 to 1.5 would increase the mean radiative energy loss by only 7%, which is still of the order of the uncertainty in the present information on the basic nuclear bremsstrahlung energy loss.

\(^2\) In the tabulation by Pages et al. [40], the data set recommended by Koch and Motz is used, and their mean radiative energy loss appears to fluctuate about the values from Ref. [39].
Range

The mean range \( r_0(T_0) \), also called the c.s.d.a. range because it is derived in the continuous-slowing-down approximation, is defined as the integral of the reciprocal of the total stopping power over the energy range from the initial energy \( T_0 \) down to some very low cut-off value. The c.s.d.a. range is a strictly theoretical quantity and not an observable one. It is, however, easily evaluated without recourse to complex transport calculations and serves as a useful characteristic length describing electron penetration.

Using only mean range and stopping-power information one can obtain an estimate of the depth dose in the continuous-slowing-down, straight-ahead approximation. More realistic results are obtained by including multiple elastic scattering, energy-loss straggling, and the transport and deposition of both bremsstrahlung photon and knock-on electron energy. The effects of various approximations are illustrated in Fig. 7 for a 30-MeV, broad parallel beam perpendicularly incident on a semi-infinite water phantom. The curve labeled "STRAGGLING" is the most accurate result obtained by us. In Fig. 8, a set of calculated depth-dose curves is given for electron beams with energies between 1 and 60 MeV. These results were calculated using our most accurate model. In Figs. 7 and 8, the depth dose \( D(z) \) is shown multiplied by \( r_0/T_0 \) forming a dimensionless quantity and plotted versus \( z/r_0 \), where \( z \) is the depth. This scaling greatly reduces the dependence of the results on the electron energy \( T_0 \) and facilitates interpolation.

The intersection of the straight-line extrapolation of the linear portion of the depth-dose curve with the axis (or background level) defines the extrapolated or practical range \( r_p \) (see Fig. 7). Values of \( r_p \) in water have been determined from the results in Fig. 8 and are shown in Fig. 9a in terms of the ratio \( r_p/r_0 \). Below 10 MeV, multiple-elastic-scattering detours cause \( r_p \) to be smaller than \( r_0 \); above 10 MeV, collision and radiative energy-loss straggling dominates, resulting in \( r_p \) being larger than \( r_0 \). Information on the c.s.d.a. range \( r_0 \) for water is given in Fig. 9b. Our values of the practical range were fitted, for 1 MeV \( \leq T_0 \leq 60 \) MeV, to an accuracy of 1% by the formula

\[
\frac{r_p}{T_0} = 0.499 \frac{T_0}{r_0} - 0.111
\]

where \( r_p \) is in g/cm² and \( T_0 \) in MeV.
The precise interpretation of dosimetry measurements requires knowledge of the spectral and angular distributions of the radiation incident on the detector. For this reason the spectroscopy of standard radiation sources and fields is a proper concern in radiation dosimetry. Spectral information can be obtained from radiation transport calculations which include the details of the source and measurement geometry. If the spectral information is obtained experimentally, one needs to know the response of the spectrometer to the incident radiation, and transport calculations can here again provide valuable information. We now discuss (a) calculations of response functions for photon detectors used in spectral measurements of gamma-ray and x-ray sources, and (b) calculations of the energy and angular distributions of electrons and bremsstrahlung photons emerging from foils bombarded by electron beams.

### NaI Response Functions

The spectrum of a collimated $^{60}$Co gamma-ray beam used in the instrument calibration program at the National Bureau of Standards was measured using a 12.7 cm diameter, 10.2 cm thick (5 in x 4 in) NaI detector collimated to admit a beam 3.8 cm in diameter [63]. The unfolding of the measured pulse-height distributions was accomplished by means of a numerical least-square matrix inversion technique [64] using response functions for monoenergetic photons. The limited number of suitable monoenergetic gamma-ray sources and the complex structure of the response function itself make it extremely difficult to develop -- solely on an experimental basis -- a body of data with detail sufficient for the accurate interpolation necessary in the unfolding procedure. Instead, the detector response was determined from Monte Carlo calculations of the spectrum of energy deposited by the gamma ray in the detector, convoluted with the measured Gaussian resolution function. This work is an extension of previous calculations for 7.62 cm x 7.62 cm (3 in x 3 in) NaI detectors [65].

The photofraction, the number of total-energy-absorption events per detected photon, is given in Fig. 10 for the 12.7 cm x 10.2 cm detector. The dashed curve was obtained by neglecting the escape of unscattered iodine x-rays produced in photoelectric absorption events, so that the difference between the curves represents the fluorescence x-ray escape probability. Complete response functions, including the Compton continuum, are given in Fig. 11, corresponding to a resolution of 11% for the $^{137}$Cs (0.661 MeV) line.
A typical spectrum of scattered radiation is shown in Fig. 12. This spectrum is for the case of a 25 cm x 25 cm field at a source-to-detector distance of 1 meter. The contribution from photons scattered to energies between 0.1 and 1.0 MeV is 19% of the incident photons. The spectrum above 1 MeV could not be reliably deduced from the unfolded data; instead, the area under the curve in this region (~5%) was determined, and the spectrum was represented by flat distributions for each of the 1.17 and 1.33-MeV lines.

Ge Response Functions

The response of high-purity (intrinsic) Ge detectors has been calculated for very narrow beams of photons with energies from ~10 to 200 keV. This geometry corresponds to the pinhole collimation used by Fewell and coworkers [66,67] of the Bureau of Radiological Health in their measurements of spectra produced by diagnostic x-ray generators. The measurements were undertaken to obtain data necessary for the accurate assessment of radiation protection requirements, patient dosimetry, and imaging system characteristics. Collimation to narrow beams in these measurements has two advantages: it reduces the incident radiation intensity to levels of manageable counting rates, and for a given detector size it maximizes the photofraction.

Calculated photofractions are shown in Fig. 13 for a number of commercially available detector sizes. Below 60 keV, these detectors are effectively infinite slabs, and the photofraction is independent of detector size and simply the complement of the fluorescence x-ray escape fraction. At higher energies, the escape of Compton-scattered photons significantly reduces the photofraction. The fluorescence x-ray escape fraction calculated for the 4 mm x 6.2 mm diameter Ge detector is given in Fig. 14. The points (and solid curve drawn through them) are from the Monte Carlo calculations. The dashed line is from an analytical formula which takes into account backscattering but not forward and side escape [68].

The conversion of a pulse-height distribution to a photon spectrum is illustrated in Fig. 15, based on the use of the response functions calculated for the 4 mm x 6.2 mm diameter Ge detector. The points are the pulse height distribution measured by Fewell [69] for a tungsten-target x-ray generator operated at 149 kVp with 8 mm Al filtration. A line-subtraction

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3 A multiplicative factor of $\frac{1}{4}$ has been left out of the formula given in reference [68]. The numerical results given there, however, appear to include this factor.
TABLE II. DISCRETE-LINE COMPONENTS OF AN X-RAY BEAM

<table>
<thead>
<tr>
<th>Line Designation</th>
<th>Energy (keV)</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>W Kα₁</td>
<td>59.318</td>
<td>6.40 x 10⁴</td>
</tr>
<tr>
<td>W Kα₂</td>
<td>57.982</td>
<td>3.61 x 10⁴</td>
</tr>
<tr>
<td>W Kβ₁</td>
<td>67.244</td>
<td>1.72 x 10⁴</td>
</tr>
<tr>
<td>W Kβ₂</td>
<td>69.066</td>
<td>6.53 x 10³</td>
</tr>
<tr>
<td>W Kβ₃</td>
<td>66.951</td>
<td>8.89 x 10³</td>
</tr>
<tr>
<td>W Kβ₄</td>
<td>69.294</td>
<td>9.77 x 10¹</td>
</tr>
<tr>
<td>W Kβ₅</td>
<td>67.684</td>
<td>4.02 x 10²</td>
</tr>
<tr>
<td>Re Kα₁</td>
<td>61.140</td>
<td>6.44 x 10³</td>
</tr>
<tr>
<td>Re Kα₂</td>
<td>59.718</td>
<td>3.66 x 10³</td>
</tr>
<tr>
<td>Re Kβ₁</td>
<td>69.310</td>
<td>1.53 x 10³</td>
</tr>
<tr>
<td>Re Kβ₃</td>
<td>68.994</td>
<td>7.92 x 10²</td>
</tr>
</tbody>
</table>

aFrom a tungsten-target (containing also rhenium) x-ray generator operated at 149 kVp with 8 mm Al filtration.

and backward-stripping unfolding method yields the continuous portion of the photon spectrum, shown as the dashed curve. The derived intensities of the characteristic K x-ray lines from the target are given in Table II.

As a check on the validity of the unfolding procedure, the continuous photon spectrum plus the discrete-line contribution was convoluted with the response functions. The resulting "theoretical" pulse-height distribution (solid curve in Fig. 15) is in good agreement with the experimental pulse-height distribution.

Electron Beam Spectra

With low-energy electron accelerators, the vacuum window can have a significant effect on the energy and angular distributions of the transmitted electron beam even in the absence of any additional material used to spread the beam. When the foil is sufficiently thin compared to the electron range, the energy
degradation and angular dispersion of the transmitted beam are small and can be evaluated accurately from well-established analytical theories which treat separately the energy loss [70] or the angular deflection [71,72]. For thicker foils, a more elaborate treatment is required. One approach is to combine the thin-foil theories by a Monte Carlo method [73].

Figure 16 shows energy spectra of transmitted electrons as obtained by applying such a Monte Carlo approach for electrons with energies between 100 and 400 keV and for foils of beryllium, aluminum, and titanium. The spectral information can be summarized in terms of the most probable energy $E_p$ and the full-width at half-maximum $W$. As shown in Fig. 17, for titanium foils, these two quantities fall along universal curves when expressed as fractions of the incident energy $E_0$ and plotted against the foil thickness expressed as a fraction of the mean range $r_o$.

With high-energy accelerators used in electron-beam radiotherapy, beam-spreading foils (often high-Z materials) are introduced to cause some angular divergence in the beam and thereby produce a more uniform, large radiation field at the target position (say, ~1 meter from the foil). Figure 18 shows calculated energy spectra of electrons transmitted through such a scattering foil, and the emergent bremsstrahlung, for the case of a 30-MeV electron beam incident perpendicularly on a 0.4-mm Pb foil. Spectra are shown for transmission through a bare foil and for transmission through the foil plus 1 meter of air between the foil and the target position. Figure 18a shows the energy spectra of transmitted electrons that emerge with directions in a 20-degree cone around the direction of incidence. The most probable energy of the transmitted electrons is quite close to that predicted by Landau's [70] energy-loss straggling theory. The full-width at half-maximum is approximately twice as large as that given by Landau's theory, due to the additional straggling caused by bremsstrahlung production. Figure 18b shows the bremsstrahlung intensity distribution, i.e. the energy-weighted photon spectrum, again for a 20-degree cone of emergence. Whereas the shape of the electron spectrum is significantly changed by the further passage of the beam through 1 meter of air, the shape of the bremsstrahlung intensity distribution remains practically unchanged. The dashed line in Fig. 18b is the spectrum predicted by the classical Kramers [74] expression.

Figure 19 shows calculated angular distributions of transmitted electrons and emergent bremsstrahlung photons for the case of a 10-MeV beam incident perpendicularly on a 0.1-mm Pb foil. The angular distribution of the electrons, plotted semi-logarithmically vs. the square of the deflection angle, is a
straight line for deflection angles up to 20°. This indicates that the angular distribution is Gaussian. In fact, the width of this Gaussian is numerically quite close to that given by analytical small-angle-approximation multiple-scattering theories, as evaluated, for example, by Brahme [75].

The amount of energy transmitted into the angular interval from 0° to θc is shown in Fig. 20a separately for the electron and bremsstrahlung components of the degraded 10 MeV beam. Note that the addition of 1 meter of air decreases the electron energy transmission but slightly increases the emergent bremsstrahlung. This is demonstrated also in Fig. 20b which gives the photon/electron ratio of energy transmitted for the 30 MeV beam.

**Thick Target Bremsstrahlung**

Another source-characterization problem involves the conversion of electron-beam energy into bremsstrahlung through the use of thick foils. In addition to the energy and angular distribution of the bremsstrahlung, the bremsstrahlung yield is of interest, i.e. the fraction of the incident electron energy that is converted into photon energy. Extending earlier calculations of thick target bremsstrahlung [56], we have accumulated new data on the yield as function of target material and thickness.

Let \( Y(\theta_c) \) be the fraction of incident energy emerging in the form of bremsstrahlung photons in the angular interval 0° to \( \theta_c \). The total forward yield \( Y(90°) \) is given in Fig. 21 for carbon, aluminum, copper, and tungsten targets with thicknesses up to twice the electron range and for electron energies from 1 to 60 MeV. The yield increases with radiator thickness until the broad-beam attenuation of the photons outweighs the increase in production. It can also be seen that the total forward yield increases with the radiator atomic number \( Z \).

If, however, we consider the yield in a small forward cone which more closely corresponds to actual irradiation geometries, the use of a high-Z radiator material may not be advantageous. This is shown in Fig. 22 where \( Y(\theta_c) \) is given for aluminum and lead radiators with a thickness approximately equal to one c.s.d.a. range bombarded by 25-MeV electrons. It can be seen that although the yield for the total forward hemisphere is twice as large for lead as for aluminum, for cone angles \( \leq 10° \) there is little difference. This is due to the fact that in high-Z materials there is stronger angular diffusion of the electrons so that a smaller fraction of the bremsstrahlung photons are emitted within a small-angle cone. This effect is
demonstrated also in Fig. 23 which gives the yield at 30 MeV for various cone angles, as a function of atomic number Z. We see that for angles \( \leq 10^\circ \), any choice of radiator material will give comparable bremsstrahlung yields. Similar findings have been made experimentally [76,77].

For thick aluminum and lead radiators (thickness \( \approx 1 \text{ r}_{\alpha} \)) bombarded by 25 MeV electrons, the spectrum of photons transmitted in the angular interval 0° to 3° is given in Fig. 24. As found also experimentally [76], the aluminum spectrum is somewhat harder than that from lead.

**ABSORBED DOSE FROM A \( ^{60}\text{Co} \) GAMMA-RAY SOURCE**

We have calculated the absorbed dose in a cylindrical carbon phantom irradiated by gamma rays from a collimated \( ^{60}\text{Co} \) point source. Special attention has been paid to the transition region at shallow depths where energy transport by secondary electrons strongly affects the absorbed-dose distribution.

The assumed geometry, which closely resembles that of the arrangement used for the \( ^{60}\text{Co} \) absorbed-dose measurements at the BIPM [78], is shown in Fig. 25. The \( ^{60}\text{Co} \) source is located at a distance \( t \) from the surface of the phantom and is collimated so that the radiation is confined to a cone of half-angle \( \theta_2 \), which gives rise to a circular field with radius \( R \) at the phantom surface. Within the phantom we consider a cylindrical detector region with a radius \( r \) and thickness \( \Delta z \), located at depth \( z \). We have considered only the 1.33 and 1.17-MeV \( ^{60}\text{Co} \) lines incident on the phantom and have neglected any scattered components from the source.

If electron motion is to be taken into account, the most straightforward approach would be a complete photon-electron transport calculation that provides the secondary electron flux as a function of energy and position. The depth dose could then be obtained by multiplying this flux by the electron stopping power and integrating over all spectral energies. Such an electron flux calculation was done, including all Compton and photoelectrons set in motion by 10,000 photons incident on the phantom. The resulting depth-dose distribution exhibited considerable statistical fluctuations (5-10%). We therefore adopted a computationally more effective alternative approach in which the initial part of the calculation involved only the photon flux distribution and energy-absorption coefficients, and in which the transport of energy by secondary electrons was treated in a separate Monte Carlo calculation.
Dose from Unscattered Photons

If the motion of secondary electrons is disregarded, it can be shown that the absorbed dose in the detector region due to unscattered photons is

\[ U(z) = \frac{k_0}{\pi r^2} \mu_{en}(k_0) \frac{\mu_{en}(k_0)}{\rho} \left[ E_1(\mu_0 z) - E_1(\alpha \mu_0 z) \right] \]

where \( k_0 \) is the incident photon energy (1.33 or 1.17 MeV), \( \mu_{en}/\rho \) is the mass energy-absorption coefficient, \( E_1 \) is the exponential integral, \( \mu_0 \) is the total attenuation coefficient for \( k_0 \), \( \tan \theta_2 = R/t \), and

\[ \alpha = \left[ 1 + \frac{r^2}{(z+t)^2} \right]^{1/2} \]

The factor \( 1 - \cos \theta_2 \) is introduced to normalize the dose to one photon incident on the phantom.

The energy-absorption coefficient \( \mu_{en} \) takes into account energy transfer to electrons but discounts energy subsequently emitted by the electrons as bremsstrahlung, which is assumed to escape. If \( \mu_{en} \) were replaced by \( \mu_{tr} \) which does not discount the bremsstrahlung energy [7], then \( U(z) \) would be the kerma.

Dose from Scattered Photons

Using Monte Carlo calculations in which 50,000 histories were sampled for each of the two \(^{60}\text{Co} \) photon energies, the differential pathlength distribution \( y(k,z) \) of photons, integrated over the detector region, was evaluated as a function of depth \( z \). The quantity \( y(k,z)dk \) is the pathlength through the disk-shaped detector region defined above of photons with energies between \( k \) and \( k + dk \). We can then obtain the average photon flux spectrum \( F(k,z) \) in the detector region as the quantity \( y(k,z)/\Delta z \). A typical photon flux spectrum is shown in Fig. 26. Also given is the corresponding secondary electron flux spectrum. These spectra, normalized to one incident photon, are for a depth of 2 cm in the phantom, but except in a small region near the phantom surface their shapes are only slightly depth-dependent. In the photon spectrum of Fig. 26 the unscattered components are represented by vertical arrows at the two \(^{60}\text{Co} \) source energies. Also there are marked discontinuities at 0.214 and 0.210 MeV, which are the lowest energies that can be reached in a single Compton scattering.
The dose contribution from scattered photons can be expressed in terms of a dose build-up factor $B(z)$ defined as

$$B(z) = 1 + \int_0^k k F_s(k,z) \frac{\mu_{en}(k)}{\rho} dk + \int_0^k k F_u(k_o, z) \frac{\mu_{en}(k_o)}{\rho}$$

where $F_u$ and $F_s$ are the unscattered and scattered components of the photon flux obtained from the Monte Carlo calculations.

The results for $B(z)$, smoothed as a function of $z$ by a least-squares procedure, are given in Fig. 27. It can be seen that the curves bend somewhat with depth. The departure of these curves from linearity\(^4\) is due to the fact that both the incident photon field and the detector region have a finite extent.

Transport of Energy by Electrons

The transport of energy by secondary electrons can be described in terms of a spreading function $\Phi(z-z')$. The quantity $\Phi(z-z')dz$ is the fraction of energy given to electrons at depth $z'$ that is deposited at depths between $z$ and $z + dz$. The spreading function has been evaluated in a separate Monte Carlo calculation, assuming a 1.25 MeV Compton source that releases electrons with energies and angles predicted by the Klein-Nishina cross section. In this calculation, the primary gamma-ray is assumed to be traveling in the positive $z$ direction. The source function thus defined is not completely appropriate for application to large depths in the phantom where there is an appreciable flux of scattered photons with a broad energy and angular distribution. However, the spreading function has its most noticeable effect at shallow depths, in the transition region, and at these depths the photon flux is dominated by the forward-moving unscattered photons. Therefore, for depths $\lesssim 2 \text{ g/cm}^2$ where the dose from scattered photons is $\lesssim 10\%$ (see Fig. 27), the use of the assumed source function seems fully justified.

The spreading function is given in Fig. 28. Because the escape of bremsstrahlung energy has already been included by

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\(^4\) In contrast, build-up factors for broad beams are nearly linear over similar depths (see, for example, Spencer and Lamkin [79]).
the use of $\mu_{en}$ in the evaluations of $U(z)$ and $B(z)$, the normalization is such that

$$\int_{-\infty}^{\infty} \Phi(z-z')dz = 1$$

**Depth Dose and Transition Curve**

The final expression for the absorbed dose $D(z)$, averaged over the detector region, is given by

$$D(z) = \int_{0}^{z_{PH}} U(z') B(z') \Phi(z-z')dz'$$

The dose was evaluated for both of the $^{60}$Co source energies and the average is given in Fig. 29. The transition region, in which the effect of secondary electron motion is important, extends to a depth of ~ 0.5 g/cm$^2$. Beyond this depth, electron quasi-equilibrium has been established. If there is air between the source and phantom, rather than a vacuum as assumed in this calculation, then the transition to equilibrium will have already taken place, to some extent, before the gamma-rays reach the phantom.

*The references commence on page 40, following the figures.*
FIG. 1. Photon mass attenuation coefficients $\mu/\rho$ for carbon, given relative to the value from the most recent NBS tabulation [7].

1a. Measured values for 8.04 keV (Cu $K_\alpha$ x-rays). References are given in [8], except for 74MI [9], 75CA [10], and 77LA [11].

1b. Compiled values for 10 keV, from the tabulations of Allen [12], Victoreen [13, 14], NBS [2, 3, 4, 6, 7], Davisson [15, 16], Heinrich [17], LASL [18, 19], LLL-NBS [20], ICRU [21], and Kaman [22].
FIG. 2. Comparison of total photon cross sections measured in carbon, with values adopted in recent NBS evaluation [7].

2a. Energy range 0.1 to 30 keV. Cross sections are scaled by multiplication of the factor $E^{2.6}$ to reduce the dependence of the results on the photon energy $E$.

2b. Energy range 0.1 to 20 MeV. Cross sections are multiplied by $\sqrt{E}$.
FIG. 3. Air/carbon mass energy-absorption coefficient ratios at 10 keV and 30 keV. Ratios obtained from values given in the tabulations of NBS [5–7], ICRU [21, 37], and LASL [18, 19].

FIG. 4. Dependence of the relative stopping power on the assumed value of the mean excitation energy $I$. The symbols $\bigcirc, \triangle, \square, \triangledown$ indicate $I$-values from [44], [45, 46], [47], and [48, 49], respectively.
FIG. 5. Ratio of estimated low-energy stopping power for water vapor to the prediction of the Bethe formula (with $I = 71.7 \text{ eV}$).

FIG. 6. Mean radiation loss for electrons in carbon and gold. Results of the exact calculations of Pratt, Tseng et al. [62] for energies up to 2 MeV (solid curves) are compared with values from [56, 57] (chain-dotted curves) and from [39] (broken curves).
FIG. 7. Effect of various approximations on the calculation of electron depth-dose distribution. Results pertain to a broad beam of 30 MeV electrons perpendicularly incident on a semi-infinite water medium, and are given in terms of scaled, dimensionless quantities. The depth-dose $D$ is multiplied by the ratio of the mean range $r_0$ to the electron energy $T_0$, and the depth $z$ is expressed as fractions of $r_0$. The most accurate results, the solid curve marked STRAGGLING, includes the effects of energy-loss straggling, multiple-scattering angular deflections, and the production and transport of both bremsstrahlung photons and knock-on electrons. The practical range is determined by the straight-line extrapolation of the linear portion of the depth-dose curve.

FIG. 8. Depth dose in water for broad beams of electrons with energies from 1 to 60 MeV.
FIG. 9. Electron range.
9a. Ratio of the practical range $r_p$ to the c.s.d.a. range $r_0$ for electrons in water, as a function of electron energy $T_0$. The results are derived from calculated depth-dose curves for broad beams.
9b. Mean (c.s.d.a.) range of electrons in water. Results given as the ratio of the mean range $r_0$ to the initial electron energy $T_0$. 
FIG. 10. Calculated photofractions for a 12.7 cm dia. × 10.2 cm (5 in dia. × 4 in) NaI detector. Results are for a 3.8 cm diameter beam of photons with energy $E_0$. Broken line curve was obtained by disregarding escape of iodine fluorescence x-rays.

FIG. 11. Calculated response functions for a 12.7 cm dia. × 10.2 cm (5 in dia. × 4 in) NaI detector, for a beam diameter of 3.8 cm and photon energies from 0.1 to 1.5 MeV. The resolution is 11% for the 0.661 MeV $^{137}$Cs line, and the channel width is 7.1 keV. The area under each curve is equal to 7.1 times the detection efficiency.
FIG. 12. Spectrum of scattered photons from one of the NBS collimated $^{60}$Co instrument-calibration sources. Results pertain to a 25 cm $\times$ 25 cm field at a source-to-detector distance of 1 meter. Results indicate that 76% of the photons reaching the detector are unscattered, 19% are scattered to energies between 0.1 and 1 MeV, and 5% are scattered to energies above 1 MeV.

FIG. 13. Calculated photofraction $P_0$ for cylindrical Ge detectors. Results are for a very narrow beam of photons incident along the detector axis.
FIG. 14. X-ray escape fraction $P_{K_e}$ for a cylindrical Ge detector, as a function of photon energy $E_0$. Points, and the solid curves drawn through them, are from Monte Carlo calculations for very narrow photon beams. The broken curve is from a simple, approximate formula [68]. Results are given for both the $K_{\alpha} (9.875 \text{ keV})$ and $K_{\beta} (10.986 \text{ keV})$ fluorescence x-rays of germanium. Note that the $P_{K_{\beta}}$-values have been multiplied by 10.

FIG. 15. Spectrometry of a $149 \text{ kV}(\text{pk})$ x-ray beam. Points are the pulse-height distribution measured by Fewell [69] with a $4 \text{ mm} \times 30 \text{ mm}^2$ intrinsic Ge detector. Broken curve is the unfolded continuous component of the x-ray spectrum. Solid curve was obtained by convoluting the unfolded spectrum (continuous plus discreet-line components) with the calculated response functions, and represents the theoretical pulse-height distribution.
FIG. 16. Calculated energy spectra of electrons transmitted through foils. The curves, normalized to unit area, pertain to electrons transmitted with energy $E$, regardless of angle.

(a) Dependence on foil thickness $z$; for titanium foils and incident electron energy $E_0 = 200$ keV. (b) Dependence on incident energy $E_0$; titanium foil thickness $z = 1$ mil (11.43 mg/cm$^2$).

(c) Dependence on foil material; $E_0 = 200$ keV, $z = 2$ mils. (1 mil = 0.001 in = 25.4 µm.)
FIG. 17. Most probable energy $E_p$ and the full-width at half-maximum $W$ of the spectra of electrons transmitted through titanium foils. The curves are composites drawn through the Monte Carlo results (shown as points) for source energies $E_0$ between 100 and 400 keV.
FIG. 18. Calculated energy spectra of radiation transmitted through a beam-spreading foil, in the angular interval $0^\circ$ to $20^\circ$. The curves, normalized to unit area, pertain to electrons incident with energy $T_0 = 30$ MeV, and are given for two cases: a 0.4 mm Pb foil, and a 0.4 mm Pb foil followed by 1 meter of air.

18a. Transmitted electrons. Number spectra of electrons transmitted with energy $T$.

18b. Transmitted bremsstrahlung. Intensity distribution (energy-weighted spectrum) of photons transmitted with energy $k$. The presence of air does not significantly affect the spectral shape. The broken line is the Kramers [74] spectrum.
FIG. 19. Calculated angular distributions (number per steradian) of radiation transmitted through a beam-spreading foil. The curves, arbitrarily normalized, pertain to 10 MeV incident electrons and correspond to a 0.1 mm Pb foil (broken curves) and a 0.1 mm Pb foil followed by 1 meter of air (solid curves).

19a. Transmitted electrons. Monte Carlo results (shown as points) and straight lines fitted to them are for electrons transmitted with energies greater than 0.35 MeV.

19b. Transmitted bremsstrahlung. Angular distribution of the number of photons transmitted with energies greater than 10 keV.
FIG. 20.  Relative contributions of electron and bremsstrahlung energy to the radiation transmitted by beam-spreading foils. Results pertain to the fraction of energy transmitted into the cone of half-angle $\theta_c$.

20a. Incident electron energy $T_0 = 10$ MeV; 0.1 mm Pb foil.

20b. Incident electron energy $T_0 = 30$ MeV; 0.4 mm Pb foil.
FIG. 21. Total forward thick-target bremsstrahlung yield $Y(90^\circ)$ as a function of radiator foil thickness $z$. Results are given for incident electron energies $T_o$ from 1 to 60 MeV. Quantity given is the fraction of incident energy transmitted in the form of bremsstrahlung photons in the angular interval $0^\circ$ to $90^\circ$. 
FIG. 22. Cumulative thick-target bremsstrahlung yield $Y(\theta_c)$ as a function of forward cone half-angle $\theta_c$. Quantity given is the fraction of incident energy $T_0 = 25$ MeV transmitted in the form of bremsstrahlung photons in the angular interval $0^\circ$ to $\theta_c$. Results were calculated for aluminum and lead targets with thicknesses approximately equal to the electron mean range.

$T_0 = 25$ MeV

Pb : $z = 0.9$ cm = 10.2 g/cm$^2$ = 0.956 $r_0$
Al : $z = 5.2$ cm = 14.0 g/cm$^2$ = 1.107 $r_0$

FIG. 23. Cumulative thick-target bremsstrahlung yield $Y(\theta_c)$ as a function of target atomic number $Z$. Points, and curves drawn through them, represent Monte Carlo results for $T_0 = 30$ MeV and target thickness $z = r_0$. 

$T_0 = 30$ MeV

$Z = r_0$
FIG. 24. Intensity (energy-weighted spectrum) of transmitted bremsstrahlung radiated in the angular interval 0° to 3°. Results pertain to 30 MeV incident electrons and targets with thickness \( z \approx r_0 \), and are normalized to 100 incident electrons.

FIG. 25. Configuration of \(^{60}\)Co source, carbon phantom, and detector region assumed in calculation of absorbed dose. The detector region is a disk with radius \( r = 2.25 \) cm, and thickness \( \Delta z = 0.2 \) cm.
FIG. 26. Flux spectra of photons and electrons established in the carbon phantom due to $^{60}\text{Co}$ irradiation. Results are for the depth interval 2.0 to 2.2 cm and are averaged over the detector region. Unscattered incident photons (1.33 and 1.17 MeV) are indicated by the vertical arrows.

FIG. 27. Dose build-up factor as a function of depth in the carbon phantom. This quantity was calculated neglecting electron motion and represents the ratio of the total absorbed dose to that from unscattered photons. Results are given separately for the 1.33 and 1.17 MeV $^{60}\text{Co}$ gamma rays, and are averaged over the detector region.
FIG. 28. Transport of energy by Compton electrons. The quantity $\Phi(z - z') dz$ is the fraction of the energy given in Compton interactions to electrons at depth $z'$ that is deposited at depths between $z$ and $z + dz$. Results were calculated taking into account the spectrum and angular distribution of Compton electrons set in motion by 1.25 MeV gamma rays traveling in the positive $z$ direction.

FIG. 29. Absorbed dose as a function of the depth $z$ in the carbon phantom due to $^{60}$Co irradiation. Results are averaged over the detector region. Curves D include the effect of electron motion; curve K does not.
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DISCUSSION

A. JANSSENS: Could you give us a survey of the possible errors in the tabulated energy absorption coefficients?

S.M. SELTZER: My colleague will answer that question.

J.H. HUBBELL: A survey of possible errors in the energy absorption coefficients for the low-Z materials discussed in this paper is given in the paper we cite as Ref. [7]. That is, for the total attenuation coefficient $\mu/\rho$ in the range 0.1 to 0.5 keV the error is $\pm 10\%$ to $\pm 20\%$; for 0.5 to 5.0 keV it is $\pm 5\%$; and...
for 5 keV to 10 MeV it is ± 2%, except for an asymmetric uncertainty for hydrogen of ± 50% to 10% due to molecular effects. The possible errors in the derived $\mu_{\text{en}}/\rho$ energy absorption coefficients would be somewhat in excess of these uncertainties.

A. JANSSENS: I have found in my experiments that the ratio of energy absorption coefficients air to gold at 170 keV (this is above the K-edge in gold) could be overestimated by about 25%. Do you think such a discrepancy is possible?

J.H. HUBBELL: Just above the K-edge of gold (80.7 keV), where it is not obvious how to treat the fluorescence and bremsstrahlung cascade (a mixture of very soft and harder X-rays), a 25% discrepancy between a given measurement and tabulated values such as those given in Ref. [18] is possible. For a photon energy as high as 170 keV, an error of 25% in the $\mu_{\text{en}}/\rho$ air/gold ratio seems less likely. However, as indicated in Tables 1 to 7 of Ref. [6], for lead, differences between $\mu_{\alpha}/\rho$ and $\mu_{\text{en}}/\rho$ of the order of 25% are seen in this energy region.
PRACTICAL, ACCURATE METHODS FOR MEASURING THE m-VALUES OF IONIZING GASES

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Abstract

For accurate measurements of processing-level dose rates with ionization chambers, it is essential to estimate the ion collection factor accurately. This is considerably affected by volume ion recombination in the ionizing gases. If the well-known formulae of Boag are considered, the m-value (\(= \sqrt{a/ek_k}\)) of the gases and the theoretical equivalent gap length between the chamber electrodes have to be estimated accurately. However, with the commonly used ionizing gases, with the exception of air, or with the usual shapes of practical chamber electrodes, it is difficult to obtain accurate values for m and the gap length. The reason for the difficulties are reviewed briefly from theoretical and experimental viewpoints. The principles of new, practical and reliable methods of obtaining the two kinds of quantity are then presented. Insofar as Boag’s theory is valid, the methods presented are expected to be useful for obtaining the m-values of any kind of gas under any conditions of interest, as well as the equivalent gap length for ionization chambers with any shape of electrodes, however complex. Using several kinds of ionization chamber, both of common and special design, the m-value of atmospheric air was determined to be quite stable over a range of ionization rates from about \(10^{-2}\) to about \(10^{3}\) esu/cm\(^3\)-s (3.3 pC/cm\(^3\)-s to 0.33 \(\mu\)C/cm\(^3\)-s). The m-values of some ionizing gases, namely He, Ne, Ar, Kr, Xe, CO\(_2\) and C\(_2\)H\(_4\), are also reported. Using the normalized saturation curve of air, a practical and reliable method of obtaining the equivalent gap length was established. From the above results, it seems to be possible to measure higher dose rates, up to \(10^5\) Gy/h in air (\(\sim 10^7\) R/h), even under poor saturation conditions, with an error of less than a few per cent.

1. INTRODUCTION

The main problem in the so-called processing-level radiation dosimetry lies in the development of measuring methods suitable for high ionization rates. For accurate measurements of such high dose rates with ionization chambers, it is
vital to estimate accurately the rate of ion recombination losses which occur in the ionizing gases. The well-known theoretical formula by Boag [1] is used to determine the ion collection factor, $f$, under high ionization rates and under nearly saturated conditions, where this factor is larger than about 0.7. In the application of the above formula, however, it is necessary to obtain accurate data on the m-value of the ionizing gas and the equivalent gap length between the chamber electrodes.

As far as atmospheric air is concerned, the m-value has been examined repeatedly by many scientists, and it is known to be nearly constant at a value of $36.7 \pm 2.2$ under near saturation conditions [2–4]. For the other gases, such as CO$_2$ or C$_2$H$_4$ currently used for neutron dose measurements, and argon or some other rare gases used for special experiments, however, the values have not been accurately determined so far.

As will be mentioned later, it is very hard to determine the useful m-values from theoretical calculations. It is also quite troublesome and ambiguous to determine the value by the usual experimental methods. Further, it is difficult to obtain useful data concerning the equivalent gap length of the chamber in practical cases, since the electrodes are not usually of a simple shape.

1.1. Difficulty in determining the m-value by theoretical methods

The m-value is defined as:

$$m = \sqrt{\frac{\alpha}{e k_+ k_-}}$$

where $\alpha$ is the ion recombination coefficient, $k_+$ and $k_-$ are the mobilities of positive and negative ions in the gas of interest, respectively, and $e$ is the electronic charge. Therefore, before obtaining a numerically correct m-value by calculation, one obviously has to know the values of the physical quantities under the conditions of interest. Generally, the mobilities of positive ions in pure gases have been studied under low-pressure conditions (of the order of 1 torr). Such values are tabulated [5, 6]. Although only a few results for negative ions are available in the tables, it is considered that the mobilities of negative ions, except for those of some special ions such as the H$^-$ ion in H$_2$ gas, are nearly equal to the values for the positive ions. Besides, when the electrons are included among the negative carriers, the rate of movement of electrons in the negative carriers is affected by quite small amounts (ppm order) of impurity gas molecules in the gas of interest. However, the radiation measurements are usually performed at higher pressures than are those of the mobility measurements. Under such high-pressure conditions (about 760 torr), the mobilities are quite difficult to determine. This is because many different species of ion appear in the ionizing gas [7] and, depending upon the gas conditions, the effective mean value of their mobilities changes quite easily.
FIG. 1. The usual method of estimating the m-value of air from experimentally determined gradient of a line representing an $f$ versus an $f/4T^2$ plot.

Turning to the problem of the ion recombination coefficient, there are many kinds of recombination process; these processes may be classified into the two kinds of recombination, ion-ion recombination and electron-ion recombination. The ion-ion recombination includes four kinds of process, mutual neutralization, dissociative mutual neutralization, radiative recombination, and three-body recombination. The electron-ion recombination also includes four kinds of process, di-electronic recombination, dissociative recombination, radiative recombination, and three-body recombination. The share taken by each process depends upon the gas pressure and is usually affected by small amounts of impurity molecules. At the present stage, determination of the correct ion recombination coefficients still requires theoretical and experimental investigation.

It is, therefore, clear that calculation is not possible with existing data and, hence, the m-value must be determined by some other method if possible. It must be remembered that the m-value of any ionizing gas is usually not constant;
FIG. 2. Typical saturation curves of ionizing gases which have the m-values of unity and 36.7.

\[ f = \frac{1}{1 + \frac{1}{6} \xi^2} \]

\[ \Gamma = \frac{V}{a^2 \sqrt{q_0}} \left( \frac{m}{\xi} \right) \]

FIG. 3. Cross-sectional view of an ionization chamber having a complex electrode shape comprising a hemisphere and a restricted cylinder.
it is, indeed, quite variable, depending upon gas conditions, such as species, impurity ratio, pressure, ion density, etc. Fortunately, the m-value of atmospheric air, even though it includes certain unknown impurities, was found to be nearly constant for a wide range of values of the ion collection factor.

Experimental determinations of the m-value have usually been performed using methods based upon measurements of the saturation characteristics of the gas of interest [8, 9]. In such a case, the m-value is obtained from the gradient of a special curve which expresses the relation between the ion collection factor, f, and the experimental value of \( f/d_{q_0}/4V^2 \) (see Fig.1). However, this method seems somewhat complicated and, furthermore, it might introduce ambiguity in obtaining the m-value. Therefore, it is concluded that this method is not convenient in most practical cases.

1.2. Difficulty in determining the equivalent gap length

As seen in Boag's theory, for idealized spherical or infinite cylindrical chamber electrodes, the special correction factors expressed by the symbols of \( K_{\text{sph}} \) and \( K_{\text{cyl}} \) can be used to correct the chamber gaps into the idealized parallel-plate separations. However, except for a well designed parallel-plate chamber having a wide guard plate, the chambers in practical use do not have electrodes of simple shape. Their shapes may be treated as a complex combination of parallel plate, sphere or cylinder, etc., and hence the shape correction factor, \( K \), will be expressed as a combination of various factors, such as \( K_{\text{sph}} \) and \( K_{\text{cyl}} \); it is usually quite difficult to obtain a correct value of \( K \).

2. NEW METHODS OF OBTAINING THE m-VALUES OF IONIZING GASES AND THE EFFECTIVE GAP LENGTHS FOR COMMONLY USED CHAMBERS

2.1. m-value

First, it is assumed that the saturation curve of the chamber filled with air is correctly expressed by Boag's theoretical formula:

\[
f = \frac{1}{(1 + \frac{1}{\xi^2})}
\]

where \( \xi = md^2 \sqrt{q_0/V} \), \( d(\text{cm}) \) is the theoretical chamber plate separation (referred to as gap length), \( q_0 \) (esu/cm\(^3\)-s) is the saturated ionization rate\(^1\), \( V \) (volt) is the

\(^1\) To simplify comparisons with existing data, this work is reported in CGS electrostatic units of charge (esu). To convert to SI units: 3.00 esu of charge = 1 nC (1 esu of charge = 3.33564 \times 10^{-10} \text{ C}).
applied voltage across the gap of $d$, and $m = \sqrt{\alpha/ek_e}$ (Eq.(1)). If the $m$-value is unity, the saturation curve is readily drawn as the curve A in Fig.2, which shows the relation between the ion collection factor, $f$, and the specific normalized variable, $\Gamma$, where:

$$\Gamma = \frac{V}{d^2\sqrt{q_0}} = \frac{m}{\xi}$$  \hspace{1cm} (3)

Since the variable $\xi$ is equal to $m/\Gamma$, and $f$ is only a function of $\xi$, the value of $f$ determined by $1/\Gamma$ is identical to that determined by $m/m\Gamma$. It then follows that if the curve B (broken line in Fig.2) is obtained in the same way as curve A, using the experimental data with the gas of interest, the separation between the curve B and the curve A at any $f$-value gives the required $m$-value of the ionizing gas used in the measurement. In this case, the distance of curve B from curve A is defined as the ratio of the $\Gamma$-value on curve B to that on curve A for a given $f$-value. In the application of this method, the value of $q_0$ may be obtained by Greeping's method [2], and the value of $d$ must be accurately known. If a chamber with non-parallel-plate electrodes is used, the correction factor, $K$, for obtaining the equivalent gap length must be correctly determined by the method presented in § 2.2. As an example, a point A on the solid curve in Fig.2 is taken at $f = 0.86$ and $\Gamma = 1$. In this example, the $m$-value of the gas of interest is found to be 36.7 at $f = 0.86$.

2.2. Equivalent gap length

According to Boag's theory, if the $m$-value is fixed at a constant value for the ionizing gas of interest, the ion collection factor, $f$, depends only on the specific variable, $\Gamma$. In this case the gap length is considered for the theoretically equivalent parallel-plate shape, which can be obtained by using Boag's correction for a true sphere or an infinitely long cylinder. In practice, commonly used chambers are not of parallel-plate shape. Therefore, it is quite difficult to find the pertinent correction factor, $K$. For the present example, a practical chamber is assumed to have electrodes composed of two parts, a combination of portions of a hemisphere and of a finite cylinder (Fig.3). Then the desired correction factor, $K$, is obtained as follows:

$$d_{\text{meas}} = a_{\text{meas}} - b_{\text{meas}}$$  \hspace{1cm} (4)

$$d_t = p_1K_{\text{sph}}kd_{\text{meas}} + p_2K_{\text{cyl}}kd_{\text{meas}} = Kd_{\text{meas}}$$  \hspace{1cm} (5)

$$K = k(p_1K_{\text{sph}} + p_2K_{\text{cyl}})$$  \hspace{1cm} (6)
where \( a_{\text{meas}} \) and \( b_{\text{meas}} \) are the measured inner radius of the outer electrode and the radius of inner electrode, respectively. In the present case, \( a_{\text{meas}} \) and \( b_{\text{meas}} \) are either directly measured or calculated (from an accurate diagram). The constants \( p_1 \) and \( p_2 \) account for the different electrode shapes, and \( k \) is the preliminary correction factor for the error in direct measurement or calculation of \( d \). It should be noted that merely knowing \( k \) is not sufficient to obtain the desired equivalent gap length. To avoid confusion in this treatment, the theoretically correct value of \( d \) is symbolized as \( d_t \) instead of \( d \).

It is practically impossible to find the “correct” values of \( p_1 \), \( p_2 \) and \( k \). If one uses an incorrect value of \( d \) in plotting the saturation curve, the resulting curve will be shifted from the correct one in the direction of the abscissa, just as in the case shown in Fig.2 for the \( m \)-value; hence, the estimated \( \Gamma \) value would be \( K^2 \) times larger than the correct one. As shown in Fig.4, the shift distance is defined as \( S = \Gamma_{\text{meas}}/\Gamma_t \), where the incorrectly estimated \( \Gamma \)-value and the correct \( \Gamma \)-value are symbolized as \( \Gamma_{\text{meas}} \) and \( \Gamma_t \), respectively, for clarity. If the theoretically-correct saturation curve is known for a standard gas which has a constant \( m \)-value, it follows from the definition of \( \Gamma \) that:

\[
SV = \frac{d_t^2}{d_{\text{meas}}^2} = \frac{V}{\sqrt{q_0}} = \gamma = \Gamma_{\text{meas}}
\]

Therefore:

\[
d_t/d_{\text{meas}} = \sqrt{S} = K
\]

Equation (8) shows that the observed shift distance is equal to the square of \( K \).

3. EXPERIMENTAL RESULTS

3.1. \( m \)-value of atmospheric air

One of the authors has already shown in an earlier paper\(^2\) that Boag’s theory is useful for a range of ionization rates from about 0.01 to 25 \( \text{esu/cm}^3\cdot\text{s} \), and that the \( m \)-value remains constant at a value of \( 36.7^{+0.8}_{-0.5} \) as long as \( f \) is greater than about 0.6. However, these facts have not been confirmed for a range of ionization rates extending much above \( 30 \text{esu/cm}^3\cdot\text{s} \). In the present experiments, the constant \( m \)-value of atmospheric air has been confirmed at higher ionization rates, up to 967 \( \text{esu/cm}^3\cdot\text{s} \). The experimental conditions under which the data have been obtained over a range of ionization rates from about 0.01 to 1000 \( \text{esu/cm}^3\cdot\text{s} \) are briefly described below.

\(^2\) In the report of Ref. [10] the \( m \)-value is defined as \( m = \sqrt{(20/3)ek_k} \); hence the values referred to in it are \( \sqrt{2/3} \) times the values described in the present paper.
For ionization rates less than about 30 esu/cm\(^3\)-s, a special parallel-plate, free-air chamber shown in Fig. 5 was used. The collecting electrode of this chamber is of the disk type. The disk has a diameter of 20 mm, and the wall material can be any one of the following: graphite, aluminium, copper or Perspex. The gap length is continuously variable from nearly 0 to about 40 mm, and it can be measured easily by a remote control system with a reproducibility of ±0.002 mm. Since the gap length has to be set correctly, it was calibrated carefully before making experiments using a calibrated block gauge of 20.00 mm. The ionization rate in the chamber was varied by changing the distance from the \(^{60}\)Co gamma-ray source of about 126 TBq (3400 Ci), and the ionization currents were measured with a calibrated vibrating reed electrometer using a calibrated air condenser.

For measurements over the range of ionization rates from about 6 to \(10^3\) esu/cm\(^3\)-s, another parallel-plate free-air chamber shown in Fig. 6 was used. This chamber has a wall made of aluminium and a fixed gap length of 1.0 mm. The ionization rate was varied by changing the distance from the \(~1.85\) PBq (50 kCi) \(^{60}\)Co gamma-ray source.
Experimental results show that Boag's theory is valid over a range of ionization rates from about $10^{-2}$ to $10^3$ esu/cm$^3$·s, and over a range of ion collection factors from about 0.6 to a value nearly in the saturated region. Over the ranges mentioned above, the m-value was constant, having a value of $36.7 \pm$ a few per cent, as shown by Greening's careful inspection [2]. Also, it was found that the m-value of the air does not depend on the wall material or on physical parameters such as air temperature ($17-27^\circ$C), air pressure (752-768 torr), air relative humidity (55%-85%), and ionization rate ($10^{-2}-10^3$ esu/cm$^3$·s). The saturation characteristics of the air are shown in Fig.7. As was pointed out by Boag in his paper, when $f$ is less than about 0.6, the saturation curve seems to approach a value given by his previous formula:

$$f = \frac{1}{(1 + \sqrt{(1 + \frac{3}{4} f^2)})}$$  \hspace{1cm} (9)
and this is recognized in Fig. 8. In this region, the curve seems to be fitted by an m-value of 47.8, according to the above formula. It is interesting that these normalized saturation curves under different conditions still coincide with each other even at such low values of $f$ as about 0.2, where the effective applied voltage $V$ may be much affected by the space charge in the ionizing volume.

3.2. m-values of ionizing gases other than air

For measurements of the m-values of ionizing gases other than atmospheric air, the ionization chamber shown in Fig. 9 was used. The chamber gap length is fixed at 9.0 mm and the filling gas in the small ionizing volume was kept at a constant pressure by keeping pressure equilibrium throughout the system. The gas pressures were measured and monitored by a pressure gauge with an uncertainty of a few torr at about atmospheric pressure (~ 760 torr). The small amounts (ppm order) of several kinds of impurity gases contained in the ionizing gases used in those experiments are detailed in Ref. [10]. The apparent m-values of these gases at an $f$-value of 0.86 were obtained using a method to be described later. These m-values of the different gases are taken at $f = 0.86$ to provide a common data point, necessary because of the difficulty of obtaining true
saturation conditions. The following characteristics of the saturation curves were obtained by measuring the ionization current due to either positive or negative ions.

3.2.1. Helium

Both ions in helium gas were found to be quite unstable. The m-value of the negative ions was found to be about 11.2, on average. In the case of the positive ion current measurements, the system was more unstable and delicate at ionization rates below about $10^2 \text{ esu/cm}^3\cdot\text{s}$.

3.2.2. Neon

Positive and negative ions of neon are unstable at lower ionization rates (less than several esu/cm$^3\cdot\text{s}$). As the ionization rate rises to values greater than several
FIG. 8. Comparison between the experimental and theoretically calculated saturation curves for air.

\[ f = \frac{2}{1 + \sqrt{1 + \frac{3}{\lambda} \xi}} \quad m=36.7 \]

\[ f = \frac{1}{1 + \frac{1}{6} \xi} \quad m=47.8 \]

\[ \xi \approx 0.022 \rightarrow 1.2 \]

\[ \Gamma = \frac{V}{d^2 \sqrt{a_0}} \]

FIG. 9. Parallel-plate, disk-type of chamber with a gas inlet (dimensions in millimetres).
esu/cm\(^3\)-s, both the positive and negative ion currents become sufficiently stable to provide an m-value. The observed m-values are 17.7.

3.2.3. Argon

The positive ion current is stable at any ionization rate. The negative ion current is unstable at the lower ionization rates (less than several esu/cm\(^3\)-s), but becomes stable at ionization rates above about 10 esu/cm\(^3\)-s. The m-value for argon is found to be 22.4.

3.2.4. Krypton and xenon

Krypton and xenon are quite stable, both for the positive and the negative ions. The m-values of krypton and xenon are found to be 29.6 and 38.0, respectively.

3.2.5. CO\(_2\) and C\(_2\)H\(_4\)

The chamber shown in Fig. 10 was used for measurements with CO\(_2\) and C\(_2\)H\(_4\). The two kinds of gas were tested separately. Before filling the chamber, the air was exhausted to about 10\(^{-4}\) torr and the chamber was flushed three times with the gas to be used. The pressure was kept constant and measured as for the previously mentioned chamber (shown in Fig. 9). The m-values of CO\(_2\) and C\(_2\)H\(_4\)
FIG. 11. Experimentally determined stable saturation curves for various ionizing gases. The $m$-values at $f = 0.86$ are tabulated.

FIG. 12. Cylindrical free-air cavity chamber (dimensions in millimetres).
were found to be 60.3 and 45.8, respectively. It appears to be difficult to obtain a saturated ionization current with ethylene gas.

3.2.6. Results

The experimental results on the saturation characteristics of the several ionizing gases are shown, with their m-values at $f = 0.86$ indicated, in Fig.11.

The saturation patterns of commonly used gases become stable under conditions of high ionization rate. The m-values under unstable conditions are generally much larger than those under stable conditions. This might be due to the fact that the impurity molecules which affect the stability of the saturation pattern of the gas disappear under such conditions. Detailed discussion of this matter has been undertaken in an earlier publication [10].

3.3. Equivalent gap lengths of several commonly used chambers

To confirm the proposed theory for obtaining the equivalent gap length, six chambers, having different electrode shapes, were used, filled with atmospheric
FIG. 14. Specific saturation curve for air. Can be used to obtain the ion collection factor, \( f \), by making use of the observed ionization rate \( q_{\text{meas}} \) in atmospheric air. \( V \): applied voltage; \( d \): equivalent gap length.

Air. Their electrode shapes are as shown in Figs 5, 6, 9, 10 and 12 (two chambers of different sizes). As mentioned in the previous section, if the collection factor is greater than about 0.2, the saturation curves with air in the chamber shown in Fig. 5 are quite stable and do not depend upon the experimental conditions such as ionization rate, gap length, wall material, applied voltage, and air constituents. Even under high ionization rate conditions, up to about 1000 esu/cm\(^3\)-s, the same curve was obtained with the chamber shown in Fig. 6 (which has an accurately determined gap length) as with the chamber shown in Fig. 5. This curve is shown as the curve D in Fig. 13. Therefore, the curve may be taken as a universal standard saturation curve for air, and this is shown extended to lower \( f \)-values as the curve S in Fig. 13.

The curves with the other chambers have been found to be shifted along the abscissa, as expected from the present theory. In Fig. 13 the curves obtained with the chambers shown in Figs 9, 10 and 12 are designated by E, A and C, respectively; the curve B is obtained with a small chamber similar to the one shown in Fig. 12. Experiments were performed at ionization rates of 0.94, 6.23, 10.5, 23.3, 57.6, 174, 264, 497, 608 and 967 esu/cm\(^3\)-s. In Fig. 13, the experimental results with the chambers of the curves A and C at ionization rates below 1 esu/cm\(^3\)-s are
also included. It must again be emphasized that the saturation pattern does not depend upon the ionization rate. Therefore using Eq. (8), the theoretical correction factor, \( K \), for the equivalent gap length is found to be \( \sqrt{1.23} \), \( \sqrt{2.0} \), \( \sqrt{2.25} \), \( \sqrt{1.0} \), and \( \sqrt{0.9} \) for the chambers A, B, C, D and E, respectively.

4. DISCUSSIONS AND CONCLUDING REMARKS

In the present work, the saturation characteristics of ionizing gas obtained experimentally are described by the relation between the ion collection factor, \( f \), and a normalized variable, \( \Gamma \), which is a function of \( q_0 \), the ionization rate under saturation conditions. To determine \( q_0 \), it is necessary to obtain the value of \( f \). When one applies this relation to the determination of the value of \( f \), it is necessary to know the value of \( q_0 \). This is a non-determinable system. Fortunately, however, this difficulty can be overcome in the following way. As long as a stable saturation characteristic of an ionizing gas can be assured, a specific saturation curve can be drawn in a normalized form in terms of \( \Gamma_{\text{exp}} \), the experimentally obtained \( \Gamma \)-value, which is a function of the observed ionization rate \( q_{\text{meas}} \), though not of \( q_0 (= q_{\text{meas}}/f) \). The variable \( \Gamma_{\text{exp}} \) can be expressed as follows:

\[
\Gamma_{\text{exp}} = \frac{V}{d^2 \sqrt{q_{\text{meas}}}} = \frac{V}{d^2 \sqrt{q_0/f}} = \frac{\Gamma}{\sqrt{f}}
\]  

(10)

where \( V \) is the applied voltage and \( d \) is the equivalent gap length multiplied by the correction factor, \( K \). In Fig. 14, the proposed method is illustrated for the case of the air. This method can also be used for other ionizing gases, if the stable saturation curve is assured under the conditions of interest. When applying the above method practically, it is sufficient to determine the equivalent gap length under the low ionization rate conditions instead of under the high ionization rate conditions for which one desires the data. When determining the applied voltage \( V \), the contact potential between the electrodes should be carefully taken into account.

Another important result obtained in the present work is that the \( m \)-value of commonly used gases have been shown, in general, to change according to the gas conditions, the amount of impurities, the ionization rates, and the ion collection factor, \( f \). This result explains the fact that the normalized saturation curve for a gas varies with the experimental conditions, especially at low ionization rates. Generally it seems that the saturation curves do not follow the prediction in Boag's theory, according to which the \( m \)-values are assumed to be constant. On the other hand, the \( m \)-value of air does not depend on the ion collection factor, \( f \), beyond a value of about 0.6, nor on the ionization rates; its saturation curve is quite stable, though the reason for this is not as yet understood theoretically. At high ionization rates, other gases, including Ne, Ar, Kr and Xe, etc., have \( m \)-values which are not
constant, but they only depend upon the ion collection factor, $f$, and therefore
stable saturation patterns are obtained.

The above results suggest that the ion recombination processes might be much
more involved than previously expected, and hence the $m$-values can easily change
with the gas conditions. Further investigations into these problems are required
for development of processing-level radiation dosimetry based on ionization
measurements. If the highest degree of accuracy is needed in ionization measure­
ments with air, its impurity components should be carefully examined, and should
be specified with the results of future measurements.

ACKNOWLEDGEMENTS

The authors would like to express their thanks to Messrs. I. Yamachi and
J. Nawoi of the Electrotechnical Laboratory for their work on the experiments
at the Takasaki Radiation Chemistry Research Establishment. The authors are
especially indebted for much kind advice to Dr. M. Yamashita of the Electro­
technical Laboratory, and to Prof. Y. Nishiwaki of the Atomic Energy Research
Institute, Kinki University.

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[1] BOAG, J.W., "Ionization Chambers", Radiation Dosimetry (ATTIX, F.H., ROESCH, W.C.,
178.
[9] RITZ, V.H., ATTIX, F.H., An ionization chamber for kilocurie source calibration,
[10] MORIUCHI, Y., Estimation of General Ion Recombination Loss in High Intensity Radiation
Dosimetry, Researches of the Electrotechnical Laboratory, Report No. 736 (1973).

DISCUSSION

L.H. LANZL: In the case of ionization chambers using electron collection
(or partial electron collection), would Boag's theory be adequate? Boag's theory
makes reference to a single term for negative ion mobility; and for air, since it contains oxygen, only the heavy negative ion mobility is required. In some chamber geometries with filling gases such as argon, does one get both heavy negative ion collection and electron collection?

Y. MORIUCHI: Every ion recombination theory (including those of Boag and Mie) assumes idealized particles which have identified constant mobilities as a mean value, irrespective of whether they are electrons or heavy ions.
DEPENDENCE OF THE $\bar{W}$-VALUE ON THE ATOMIC NUMBER OF HEAVY IONS

M.N. VARMA, J.W. BAUM
Brookhaven National Laboratory,
Associated Universities, Inc.,
Upton, New York,
United States of America

Abstract

DEPENDENCE OF THE $\bar{W}$-VALUE ON THE ATOMIC NUMBER OF HEAVY IONS.

$\bar{W}$-values (the average energy required to form an ion pair) were determined for $^{35}\text{Cl}$ ions in nitrogen and tissue-equivalent gas. These values were compared with previously reported $\bar{W}$-values for oxygen ions and alpha particles in the same media. This comparison was made at two specific values of energy per atomic mass unit (u) of the incident ions. At an energy of 2.57 MeV/u, the comparison shows that $\bar{W}$ is 12% and 10% higher for oxygen ions in tissue-equivalent and nitrogen gas, respectively, relative to the alpha particle $\bar{W}$. At an energy of 0.77 MeV/u, a similar comparison shows that $\bar{W}$ is 20% higher for $^{35}\text{Cl}$ ions and 10% higher for $^{16}\text{O}$ ions in tissue-equivalent gas; and 12% and 10% higher, respectively, in nitrogen gas, relative to the alpha particle $\bar{W}$. These results indicate that $\bar{W}$-values depend not only on the energy per atomic mass unit of heavy ions but also on their charge.

1. INTRODUCTION

In radiation dosimetry (utilizing gas-filled ionization chambers) one quantity of fundamental importance is the average energy required to form an ion pair ($\bar{W}$). The literature contains many papers on measurements of $\bar{W}$ for alpha particles in various gases and a few for other heavy ions in a limited number of gases. It was expected that $\bar{W}$ would increase with decreasing velocity of the ion and this has been experimentally confirmed by many authors [1—4]. However, it was found that $\bar{W}$ was nearly constant as a function of energy for alpha particles in argon, although below about 500 keV some decrease in $\bar{W}$ was observed by Chemtob et al. [5]. A review article by Myers [6] provides a summary of available $\bar{W}$-values for heavy ions.

* Work performed at Brookhaven National Laboratory under contract with the United States Department of Energy.
heavy ions. Measurement results of $\bar{W}$ for oxygen ions of a few MeV/u energy\(^1\) were reported by Varma et al. [7, 8]. A preliminary measurement of $\bar{W}$ for chlorine ions of 27 MeV energy in Rossi tissue-equivalent (TE) gas was also made by Varma et al. The present paper briefly describes the experimental method used for measurement of $\bar{W}$ for alpha particles and heavy ions. Comparisons of $\bar{W}$-values obtained for alpha particles, oxygen ions and chlorine ions in nitrogen and TE gas are made.

2. EXPERIMENTAL METHOD

Details of experimental methods and procedures employed in $\bar{W}$ determination for alpha particles and for other heavy ions were reported in Refs [3] and [7], respectively. The cylindrical ionization chamber used in these measurements was 30 cm in diameter and 1 m long. The incident ions were made to stop completely in the chamber by raising the filling gas pressure. The ionization current produced by these ions was measured using a vibrating reed electrometer. The energy spectrum of alpha particles and oxygen ions was measured using a heavy-ion solid-state detector. The energy of the $^{35}$Cl ions was determined from magnetic deflection of the beam, the field strength being measured by nuclear magnetic resonance. Research-grade nitrogen and tissue-equivalent gas (64.4% methane, 32.2% carbon dioxide and 3.4% nitrogen) were used in these measurements.

3. DATA REDUCTION

3.1. $\bar{W}$ for alpha particles

The ratio of ionization current in argon gas (the reference gas) to that in the experimental gas was measured. This ratio was then multiplied by the previously determined $\bar{W}$ for the reference gas to yield the applicable $\bar{W}$ for the experimental gas. Thus:

$$\bar{W} = \frac{I_A}{I_E} \bar{W}_A$$ (1)

where $I_A$ and $I_E$ are the extrapolated saturation ionization currents in the reference and experimental gases, respectively, and $\bar{W}_A$ is $\bar{W}$ for the reference gas.

---

\(^1\) In the SI system of units, atomic mass unit is now abbreviated as u.
### TABLE I. $\bar{W}$ FOR ALPHA PARTICLES AT VARIOUS ENERGIES

(a) In nitrogen

<table>
<thead>
<tr>
<th>Weighted mean energy, $\bar{W}$ (MeV)</th>
<th>Experimental $\bar{W}$ (eV per ion pair)</th>
<th>$33.53 + 5.87E^{-\frac{1}{2}}$ (eV per ion pair)</th>
<th>$35.64 + 3.34E^{-1}$ (eV per ion pair)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.37</td>
<td>36.4 ± 0.07</td>
<td>36.1</td>
<td>36.3</td>
</tr>
<tr>
<td>3.12</td>
<td>36.5 ± 0.07</td>
<td>36.9</td>
<td>36.7</td>
</tr>
<tr>
<td>1.09</td>
<td>38.8 ± 0.08</td>
<td>39.2</td>
<td>38.7</td>
</tr>
<tr>
<td>0.48</td>
<td>42.3 ± 0.08</td>
<td>42.0</td>
<td>-</td>
</tr>
<tr>
<td>0.50</td>
<td></td>
<td>-</td>
<td>42.3</td>
</tr>
</tbody>
</table>

(b) In tissue-equivalent gas

<table>
<thead>
<tr>
<th>Weighted mean energy, $\bar{W}$ (MeV)</th>
<th>Experimental $\bar{W}$ (eV per ion pair)</th>
<th>$27.96 + 5.71E^{-\frac{1}{2}}$ (eV per ion pair)</th>
<th>$29.99 + 3.37E^{-1}$ (eV per ion pair)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.37</td>
<td>30.72 ± 0.06</td>
<td>30.4</td>
<td>30.6</td>
</tr>
<tr>
<td>3.12</td>
<td>31.08 ± 0.06</td>
<td>31.2</td>
<td>31.1</td>
</tr>
<tr>
<td>1.09</td>
<td>33.58 ± 0.07</td>
<td>33.4</td>
<td>33.1</td>
</tr>
<tr>
<td>0.49</td>
<td>36.88 ± 0.07</td>
<td>36.2</td>
<td>-</td>
</tr>
<tr>
<td>0.56</td>
<td></td>
<td>-</td>
<td>36.6</td>
</tr>
</tbody>
</table>

The alpha-particle energy at which the determined $\bar{W}$ was applicable was determined by weighting the energy spectrum with respect to the variation in $\bar{W}$ with energy. For this purpose the variation in $\bar{W}$ with energy was assumed to follow empirical relations:

$$\bar{W} = a + \frac{b}{E^2}$$  \hspace{1cm} (2)

(as suggested by Cranshaw et al. [9]) and:

$$\bar{W} = a_1 + \frac{b_1}{E}$$  \hspace{1cm} (3)
TABLE II. $\bar{W}$-VALUES FOR OXYGEN AND CHLORINE IONS IN NITROGEN AND TISSUE-EQUIVALENT GAS

<table>
<thead>
<tr>
<th>Mean energy (MeV)</th>
<th>Ion</th>
<th>Experimental $\bar{W}$ (eV per ion pair)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>in nitrogen</td>
</tr>
<tr>
<td>34.5</td>
<td>oxygen-16</td>
<td>38.6 ± 0.54</td>
</tr>
<tr>
<td>41.1</td>
<td>oxygen-16</td>
<td>38.9 ± 0.54</td>
</tr>
<tr>
<td>27.0</td>
<td>chlorine-35</td>
<td>41.1 ± 1.08</td>
</tr>
</tbody>
</table>

Due to the small width at half maximum of the alpha energy spectrum, the $\bar{W}$ weighted mean energies obtained from relations (2) and (3) were approximately the same.

3.2. $\bar{W}$ for other heavy ions

In contrast to alpha $\bar{W}$ determination, in which ratios were used, the absolute $\bar{W}$ was determined for other heavy ions. In this case the saturation ionization current per incident ion was measured. From this measurement, the number of ion pairs formed per incident ion was determined. The mean energy per incident ion was determined by weighting the measured energy spectrum with respect to the number of particles at different energies. $\bar{W}$ was determined from the average energy per incident ion divided by the average number of ion pairs formed per incident ion.

4. RESULTS FOR $\bar{W}$

4.1. Alpha particles

The $\bar{W}$-value for alpha particles was determined at $\bar{W}$ weighted mean energies of 0.49, 1.09, 3.12 and 5.37 MeV. Results for nitrogen and tissue-equivalent gas are given in Table I. Results of a generalized least-squares fit to functions (2) and (3) for nitrogen and TE gas are also provided. It is of interest to note that both the empirical relations provide a good fit to the data in the energy range studied.
TABLE III. EXTRAPOLATED \( \bar{W} \) FOR ALPHA PARTICLES, OXYGEN AND CHLORINE IONS IN NITROGEN AND TISSUE-EQUIVALENT GAS AT 2.57 AND 0.77 MeV/u

<table>
<thead>
<tr>
<th>Energy (MeV/u)</th>
<th>Ion</th>
<th>W (eV per ion pair)</th>
<th>in nitrogen</th>
<th>in TE gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.57</td>
<td>alpha</td>
<td>35.4 ± 0.07</td>
<td>29.8</td>
<td></td>
</tr>
<tr>
<td>2.57</td>
<td>oxygen-16</td>
<td>38.9 ± 0.54</td>
<td>33.4 ± 0.47</td>
<td></td>
</tr>
<tr>
<td>0.77</td>
<td>alpha</td>
<td>36.5 ± 0.07</td>
<td>31.08 ± 0.08</td>
<td></td>
</tr>
<tr>
<td>0.77</td>
<td>oxygen-16</td>
<td>40.1 ± 0.6</td>
<td>34.80 ± 0.5</td>
<td></td>
</tr>
<tr>
<td>0.77</td>
<td>chlorine-35</td>
<td>41.1 ± 1.8</td>
<td>37.60 ± 1.6</td>
<td></td>
</tr>
</tbody>
</table>

FIG.1. Variation of \( \bar{W} \) in nitrogen and in tissue-equivalent gas for heavy ions as a function of the atomic number of the incident ions. (Where no error bars are indicated, the errors are smaller than the points.)
4.2. Other heavy ions

The $\bar{W}$-value for 34.5 MeV oxygen ions [7] in nitrogen gas was found to be $38.6 \pm 0.54$ eV per ion pair. The $\bar{W}$ for 41.1 MeV oxygen ions [8] in tissue-equivalent gas was found to be $33.4 \pm 0.47$ eV per ion pair. For 27 MeV chlorine ions, preliminary $\bar{W}$-values of $37.6 \pm 1.6$ eV per ion pair in tissue-equivalent gas and $41.1 \pm 1.6$ eV per ion pair in nitrogen gas were determined. The values are preliminary, owing to relatively large statistical fluctuations and steady drifts with time of the beam intensity calibration. Table II summarizes these $\bar{W}$-values. The applicable $\bar{W}$-values for alpha particles, oxygen and chlorine ions at two specific energies (2.57 and 0.77 MeV/u) are given in Table III.

5. CHARGE DEPENDENCE OF $\bar{W}$

For oxygen and chlorine ions, the energy dependence of $\bar{W}$ was assumed to follow a relation similar to that obtained for alpha particles. Thus, the $\bar{W}$-values for heavy ions and alpha particles were estimated at two specific velocities (MeV/u) using Eq. (2). This provides for convenient comparison of values as a function of the atomic number of the incident ions. These data are shown in Table III and are also plotted in Fig. 1.

It can be seen from Fig. 1 and Table III that $\bar{W}$ for oxygen ions was about 12% higher than $\bar{W}$ for alphas in tissue-equivalent gas at about 2.57 MeV/u and about 10% higher at 0.77 MeV/u. Similarly, $\bar{W}$ for oxygen ions was about 10% higher than $\bar{W}$ for alphas in nitrogen at both 0.77 MeV/u energy and at 2.57 MeV/u.

Thus these results indicate a systematic increase in $\bar{W}$ for heavy ions as a function of atomic number for a given initial velocity (MeV/u). It is of interest to note that measurements of $\bar{W}$ for heavy ions like recoil ThC', fission fragments, and 7Li reported in Myers' article [6] do not show a systematic change in $\bar{W}$ with either atomic number or velocity of the incident ions. However, Myers points out that $\bar{W}$-values for these ions are less reliable than those for alpha particles or protons.

ACKNOWLEDGEMENT

The authors wish to thank C.B. Meinhold for continued encouragement and helpful discussions on this work.

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IAEA-SM-222/02


DISCUSSION

H.O. WYCKOFF: What was the charge state of the ions used?
M.N. VARMA: The initial charge entering the chamber was 6+ for oxygen ions and 3+ for chlorine ion measurements.

J.C. McDONALD: Do you plan to measure $\bar{W}$ for the propane-based tissue-equivalent gas, which would be of interest for microdosimetric measurements?
M.N. VARMA: Both Rossi-types of tissue-equivalent gases (methane-based and propane-based) are used in microdosimetry. We have no plans to use propane-based tissue-equivalent gas at present, but if more people are interested, we can perform such measurements.

J.C. McDONALD: Could you measure $\bar{W}$ for high-energy protons, say in the range 150–200 MeV, which are of interest for radiation therapy?
M.N. VARMA: No. The experimental apparatus described is not capable of measuring $\bar{W}$ for high-energy protons because of their long range.
Abstract

HIGH-ENERGY RADIATION DOSIMETRY: $C_\lambda$, $C_E$ AND SOLID-CAVITY THEORY.

In high-energy photon and electron beam dosimetry, the factors $C_\lambda$ and $C_E$ are used. The concept is useful. However, the derivation of the $C_\lambda$ and $C_E$ entail approximations which may have led to inconsistent results in the past. Fregene has argued against this approach and suggested the application of solid-cavity theory in the estimation of $C_\lambda$ and $C_E$. In this paper, this has been attempted and the pattern of variation of $C_\lambda$ and $C_E$ factors for a typical chamber is compared with ICRU data at similar radiation energy. The solid-cavity theory takes account of the wall of a thimble chamber of different material to the medium in relating dose in gas to dose in phantom. It was found that equivalent $C_\lambda$ and $C_E$ data for high-energy photons and electrons based on this approach gave values over a wide energy range that did not vary by as large a percentage as did those of ICRU.

To obtain a meaningful absorbed-dose estimation by means of a cavity of material different from the medium, an appropriate cavity-correction expression has to be applied. In the absence of such an expression in ionometric dosimetry, $C_\lambda$ and $C_E$-values [1–3] based on the assumption that a thimble chamber in a water phantom is a Bragg-Gray cavity would inevitably lead to inaccuracies in absorbed-dose estimation. The magnitude of errors introduced into dosimetry by this approximation over a wide range of radiation energy may not be as small as presumed by Greene and Massey in 1968 [4–6]; this approach has been criticized by Franz [7], Nahum and Greening [8], apparently for photons only, and Fregene [9] for photon and electron beams.

There have been indications for over a decade from careful ferrous sulphate work that values of $C_\lambda$ and $C_E$ recommended by ICRU may be in error. Fregene [10], in measurements of $G$(Fe$^{3+}$) values over a wide range of radiation energies by ionometric and microcalorimetric methods (not based on $C_\lambda$ and $C_E$), obtained a plot of $G$(Fe$^{3+}$) against LET that predicted no difference between $G$(Fe$^{3+}$) values of photons and electrons of similar LET. Law and Naylor [11],
using $C_\lambda$ and $C_E$ data, found statistically significant differences for photons and electrons at high energies. Nahum and Greening [8] also reported some discrepancies in the ICRU $C_\lambda$ data.

In this report a semi-empirical solid-cavity expression based on the secondary electron spectrum phenomenon and linear radiation energy deposition over small thicknesses has been applied in the estimation of $C_\lambda$ and $C_E$-values, a departure from past methods.

Taking the ICRU equation for the conversion factor [12, 13], assuming a Bragg-Gray cavity:

$$C_\lambda \text{ or } C_E = A \cdot s_{m,g} \cdot p_{m,g} \cdot \frac{W}{e}$$

where $A$ is a correction for attenuation in the chamber wall during exposure calibration, $s_{m,g}$ is the mass stopping power ratio for the medium (water) to the gas (air), $p_{m,g}$ is a perturbation factor for the beam, and $W/e$ is the energy expended in air per ion pair formed. From Ref. [13], $A = 0.985$, $(W/e) = 0.869$, $p_{m,g} = 1.00$.

From my semi-empirical solid-cavity expression [9], one obtains:

$$C_\lambda \text{ or } C_E = A \cdot \left[ \frac{1}{s_{g,m}} + \left( 1 - \frac{1}{s_{g,m}} \right) \frac{x^*}{r_{eq}} \right] s_{w,g} \cdot p_{m,g} \cdot \frac{W}{e}$$

where one is now considering the mass stopping power ratio for the wall material to the gas, $s_{w,g}$, and the wall thickness, $x^*$, is less than or equal to the mean equilibrium depth of secondary electrons set in motion within the chamber wall, $r_{eq}$.

Data obtained from these are compared with ICRU data [12, 13] and those of Nahum and Greening [8] in Tables I and II. It is worth noting that, in the solid-cavity approach, account is taken of the solid wall of material, different from the medium, in the ionization dosimetry of high-energy photons and electrons. Some of the attractions of this approach are given below:

(a) A common expression has been applied in the derivation of $C_\lambda$ and $C_E$, as would be the case when dealing with an ideal Bragg-Gray cavity in a medium.

(b) The thimble chamber, for which the wall is also considered, is not assumed equivalent to a Bragg-Gray cavity in water (medium), which it is not. This assumption is a feature of other methods.

(c) The mass energy absorption term which appears in a non-symmetric fashion in the ICRU $C_\lambda$-value is eliminated.

Table I shows $C_\lambda$-values calculated from the solid-cavity expression, compared with both ICRU and Nahum and Greening's data. For $C_E$, experimental data
TABLE I. VALUES OF $C_\lambda$

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{60}$Co 1.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.95</td>
<td>0.95</td>
<td>0.950</td>
</tr>
<tr>
<td>4</td>
<td>0.94</td>
<td>0.94</td>
<td>0.958 (4.5 MV, linac)</td>
</tr>
<tr>
<td>5</td>
<td>0.959</td>
<td>0.94</td>
<td>0.956</td>
</tr>
<tr>
<td>6</td>
<td>0.94</td>
<td>0.93</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>0.954</td>
<td>0.92</td>
<td>0.942 (13 MV, betatron)</td>
</tr>
<tr>
<td>12</td>
<td>0.948</td>
<td>0.91</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>0.942</td>
<td>0.90</td>
<td>0.937 (19 MV, betatron)</td>
</tr>
<tr>
<td>18</td>
<td>0.934</td>
<td>0.90</td>
<td>0.937 (27 MV, linac)</td>
</tr>
<tr>
<td>20</td>
<td>0.928</td>
<td>0.89</td>
<td>0.930 (27 MV, betatron)</td>
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<tr>
<td>25</td>
<td>0.922</td>
<td>0.88</td>
<td>0.922 (31 MV, betatron)</td>
</tr>
<tr>
<td>30</td>
<td>0.919</td>
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</tr>
</tbody>
</table>

Based on FeSO$_4$ dose meter measurements of Almond [2] and ICRU data are similarly compared with the solid-cavity expression data in Table II.

In general, the agreement between $C_\lambda$ and $C_E$ data obtained from the solid-cavity expression and from ICRU [12, 13] is within 1% at the lower energies, namely up to 10 MeV for electrons and 4 MeV for photons. The differences increase with energy both for $C_\lambda$ and $C_E$, reaching 5% and 6% for photons and electrons, respectively, at 40 MeV.

It is worth noting from Table I that Nahum and Greening’s $C_\lambda$-values agree very well with data obtained from the solid-cavity expression. Their $C_E$-values, however, are said to agree with ICRU’s, which is hardly surprising, since both sets of data were obtained on the assumption that the thimble chamber in water is a Bragg-Gray cavity.
TABLE II. VALUES OF $C_E$

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>1 $^{60}$Co</td>
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<td>0.922</td>
</tr>
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<td>0.927</td>
<td>0.922</td>
</tr>
<tr>
<td>6</td>
<td>0.903</td>
<td>0.893</td>
</tr>
<tr>
<td>9</td>
<td>0.885</td>
<td>0.858</td>
</tr>
<tr>
<td>10</td>
<td>0.875</td>
<td>0.848</td>
</tr>
<tr>
<td>12</td>
<td>0.866</td>
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<tr>
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<tr>
<td>40</td>
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</table>

TABLE III. INCONSISTENCY IN ICRU $C_\lambda$ AND $C_E$ DATA

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
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<tbody>
<tr>
<td>6 MeV photons</td>
<td>0.94</td>
<td>0.958</td>
</tr>
<tr>
<td>6 MeV electrons</td>
<td>0.93</td>
<td>0.925</td>
</tr>
<tr>
<td>10 MeV photons</td>
<td>0.93</td>
<td>0.954</td>
</tr>
<tr>
<td>10 MeV electrons</td>
<td>0.893</td>
<td>0.903</td>
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</tbody>
</table>
TABLE IV. TESTING THE VALIDITY OF THE SMALL-CAVITY APPROXIMATION FOR $C_\lambda$

<table>
<thead>
<tr>
<th>Spectrum, $E_{\text{max}}$ (MeV)</th>
<th>$C_\lambda$ (Fregene) [9]</th>
<th>$C_\lambda$ (ICRU) [12]</th>
<th>$C_\lambda$ (ICRU, corrected)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$C_\lambda$ (Bragg-Gray)</td>
<td>$C_\lambda$ (Bragg-Gray)</td>
<td>$C_\lambda$ (Bragg-Gray)</td>
</tr>
<tr>
<td>2</td>
<td>0.978</td>
<td>0.960</td>
<td>1.008</td>
</tr>
<tr>
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<td>0.990</td>
<td>0.964</td>
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<td>0.992</td>
<td>0.952</td>
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</table>

The solid-cavity data for $C_E$ differ from the ICRU data in the same direction as do the $C_\lambda$ data, i.e. they are higher than ICRU's. The solid-cavity approach is different in that a primary electron beam traversing the walls of a chamber is regarded as generating secondary electrons characteristic of the wall material [9, 10]. This phenomenon is taken into account in the solid-cavity approach by the weighted term in expression (2).

In short, the "walled" thimble chamber in a water phantom is not treated as a Bragg-Gray cavity. Because of this omission in the other two treatments, their $C_E$ data are probably in error. It is worth noting that the $C_E$ data obtained from the solid-cavity expression and those given by Almond [2], resulting from experimental work based on FeSO$_4$ dose meter measurements, agree very well over the energy range 6 to 18 MeV.

Table III reveals some inconsistencies among the ICRU $C_\lambda$ and $C_E$ data, while the solid-cavity expression data appear more self-consistent. For example, at 6 MeV photon and electron energies, although the mean secondary electron energies differ by a factor of 2 at the respective ICRU depths, ICRU data for $C_\lambda$ and $C_E$ (0.94 and 0.93) are virtually identical. The solid-cavity approach gives a difference of 3.5%, with the lower energy photon beam value being higher — as it should be. A similar comparison at 10 MeV reveals that the ICRU data difference is now 4.1%, while the solid-cavity expression data give a difference of 5.1%. This shows up one lack of self-consistency in the ICRU data, while Nahum and Greening [8] discuss others.
In Tables IV and V, the values of $C_\lambda$ and $C_E$ at different energies for both ICRU data and solid-cavity expression data are divided by $C_\lambda$-values obtained assuming an ideal Bragg-Gray cavity. Since the ICRU data were obtained by assuming a Bragg-Gray cavity, the quotient of the ICRU data should be unity if no other errors are present, while the solid-cavity expression quotient should tend to unity with increasing energy. This is because, if the solid cavity expression is truly representative of the thimble-chamber situation, it should tend to the Bragg-Gray value with increasing energy. This expectation is satisfied, as can be seen in Tables IV and V. The ICRU data from references [12] and [13] do not appear satisfactory.

If, however, the ICRU data are corrected as suggested in 1977 by Hott and Kessaris and by Williams, the result shown in column 4 of Table IV is obtained. The results are better, but still not completely satisfactory. If the correction is applied to Table I, for example, there will be no agreement at low energies. The ICRU $C_E$-values also appear to incorporate some errors.

CONCLUSION

A new approach has been applied in the derivation of $C_\lambda$ and $C_E$-values, namely the use of a semi-empirical solid-cavity expression which treats photons and electrons by a single expression and eliminates the assumptions and approximations inherent in previous methods.
In conclusion, I would wish to state the following:

1. Present-day dosimetry of high-energy photons and electrons is wanting;
2. $C_x$ and $C_e$ data recommended by ICRU and applied over the last decade were based on an inadequate concept: they contain appreciable discrepancies and are, therefore, misleading;
3. A solid-cavity expression that takes into account differences between the medium and the wall in thimble-chamber dosimetry is necessary for reliable absorbed-dose estimations.

REFERENCES


DISCUSSION

P.R. ALMOND: I am not sure why you call your approach “solid-cavity theory” when in fact you have an air cavity in a solid medium; surely this is a gas cavity.

A.O. FREGENE: The expression used in connection with the solid-cavity $C_x$ and $C_e$ data is derived from the solid-cavity principles deduced by myself for a two (solid) compartment system consisting of a medium and a solid-cavity detector. Hence the title.

P.R. ALMOND: If you have a gas cavity in a solid medium, even without a wall you will have a boundary effect; you can use the wall of an ionization chamber to suppress this wall effect. Marsh has shown for electron beam dosimetry that a thin wall of air-equivalent material will suppress the boundary effect, and for electrons at least you do not want a water-equivalent walled chamber.
A.O. FREGENE: Boundary effects are a feature of any two media in contact; the effect is further modified to an unknown extent, but not eliminated, by the introduction of a third medium — a wall of different material. The Bragg-Gray relations, as used in cavity theory, apply to a two-media situation (medium and gas cavity). Hence when we have a three-media situation, an appropriate cavity expression must be applied; it does not matter what you call the theory.

A. JANSSENS: How were you able to eliminate the ratio of energy absorption coefficients from your expression for $C_\lambda$?

A.O. FREGENE: In an ideal cavity — a point cavity — the $C_\lambda$ expression would have no $\mu_{en}/\rho$ term, which is an approximation in the case of thimble chambers. Similarly, the solid-cavity approach, which is an extension of the Bragg-Gray situation, does not feature the $\mu_{en}/\rho$ term.

A. JANSSENS: The definition of $C_\lambda$ implies the use of a chamber calibrated for exposure, which is proportional to the absorbed dose in air, apart from the $(W/e)$ value and minor corrections; therefore the ratio of energy absorption coefficients air to water would appear to be an essential parameter.

A.O. FREGENE: Please refer to what I have just said. My theoretical approach is an extension of small-cavity requirements to the chamber, and as I have already said the small-cavity situation does not entail the $\mu_{en}/\rho$ term.

J.C. McDONALD: Do you think that some of these problems could be eliminated by the use of a chamber and phantom that are homogeneous and either water or tissue-equivalent?

A.O. FREGENE: That would be ideal, and would satisfy Bragg-Gray requirements; the three-media (medium, wall, cavity) situation does not satisfy Bragg-Gray relations and requires an appropriate cavity theory. At present this is not generally appreciated.

B.R. THOMADSEN: At the University of Wisconsin we have constructed ionization chambers with walls made of the water-equivalent material suggested by Dr. David White. We have just begun to collect data, and so far have no results to report. However, we hope that eliminating the difference between the medium and wall material will reduce the problem to one which can be solved explicitly.

A.O. FREGENE: This approach was advocated by me last year (see Ref. [9] of the paper). It certainly does reduce the problem to that of a Bragg-Gray cavity and, as you say, it is then a problem that can be explicitly solved.

*Editorial Note:* The main results presented in this paper have been obtained from the semi-empirical Eq. (2), given on page 74. Unfortunately, the author's paper, quoted as Ref. [9], is not available. It seems difficult, therefore, to determine the range of validity of the equation.
CALIBRATION OF DOSE METERS IN TERMS OF ABSORBED DOSE IN WATER FOR $^{60}$Co $\gamma$-RADIATION

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Abstract

A new arrangement for calibrating therapy-level dose meters in terms of absorbed dose in water for $^{60}$Co $\gamma$-radiation by means of a graphite calorimeter has been constructed. A discarded medical $^{60}$Co source with an activity of about 37 TBq in a "home-made" housing served as irradiation facility. The timing error of the shutter is less than 75 ms. The dose rate at a distance of one metre from the source within a water phantom at a depth of 5 cm is about 0.1 Gy/min. As a first step, the absorbed dose rates for given beam geometries in a graphite phantom were determined by means of the quasi-adiabatic calorimeter developed at the Physikalisch-Technische Bundesanstalt (PTB). The unit of absorbed dose rate in graphite is realized with an uncertainty of less than 0.5% (confidence level, 90%), this figure resulting from adding in quadrature the component uncertainties. Commercial ionization chambers of different shapes can be inserted into the phantom and be calibrated in terms of absorbed dose in graphite. Three different methods have been worked out or are in preparation for converting the calibration factors referred to graphite into factors referred to water. The first method consists of determining corresponding points in graphite and water for equal absorption of the primary beam. The absorbed dose due to primary and scattered radiation can then be converted from a value in graphite to that in water. The second method applies the principle of transfer systems as described in ICRU Report 14: a transfer ionization chamber is used in both phantoms, once under equilibrium conditions and once under Bragg-Gray conditions, thereby allowing the determination of correction factors. The third method is the direct application of the calorimetric principle to a water phantom, making use of the change in conductivity of an aqueous salt solution with temperature. The latter method is only briefly discussed.

1. INTRODUCTION

It is recommended in ICRU Report 14 [1] that water be used as the standard material for measuring the absorbed dose of high-energy photon radiation. Among the reasons for this are: (i) that its radiation interaction properties are similar to those of most biological tissues; (ii) that its composition is constant and it is universally available; and (iii) that water is the medium for which most information
on radiation field and dose distributions is available [2, 3]. At least until 1977, no standards laboratory had tried to determine the absorbed dose directly in water. As a consequence of the principle of disseminating only the units of those quantities which are measured by the primary standards, it was left to the customer to derive the absorbed dose in water from other quantities, in this case from exposure free in air [4, 5]. This method is unsatisfactory because it entails relatively great measuring uncertainties and the risk of mistakes. To our knowledge, at present only the National Bureau of Standards (USA) offers to calibrate dose meters in terms of absorbed dose in water for $^{60}\text{Co} \gamma$-radiation.

Based on the experience of calorimetric absorbed-dose measurements gained at the Physikalisch-Technische Bundesanstalt (PTB) over a period of several years, a programme for determining absorbed dose in water was started. Since it is difficult to make direct measurements of absorbed dose in water, it was decided to determine first the absorbed dose in a reference material, the properties of which are better suited for calorimetry. Graphite is one such material.

The next step consisted of finding ways of converting the measured value of absorbed dose in graphite into that of absorbed dose in water. The aim was to use different and independent methods in order to achieve a lower uncertainty for the result. The following methods were studied:
(a) Calculation of absorbed dose in water from that in graphite for points in the phantom that are equivalent as to irradiation conditions, using data giving the ratios of the mean energy absorption coefficients of graphite and water;
(b) Use of ionization chambers which are calibrated within the graphite phantom and transferred to a water phantom; the calibration factor for absorbed dose in water is determined by changing the thickness and composition of the chamber wall;
(c) Use of chemical dose meters as transfer instruments in a fashion similar to the method of using the transfer ionization chambers;
(d) Construction of a water calorimeter for direct determination of absorbed dose in water.

The first three of these methods are practically ready for use at PTB. The fourth method will need further investigation, its drawbacks being a low sensitivity and the need for corrections for the presence of foreign material in the absorber wall. After a short description of the experimental arrangement, only methods (a) and (b) are described in some detail. Method (d) is discussed briefly.

2. EXPERIMENTAL ARRANGEMENT

2.1. Irradiation facility

A medical type of $^{60}\text{Co} \gamma$-ray source with an activity of about 37 TBq (1000 Ci) that was to be discarded by a hospital was installed in a PTB-made
housing. It was intended to achieve similar conditions with respect to scattered radiation as are met with in radiotherapy, but some features of the facility had also to meet the requirements for a radiation source in a primary standards laboratory. The fast shutter forming part of the irradiation facility guarantees a timing error of less than 75 ms. The time from first "appearance" of radiation to full radiation is about 200 ms.

Graphite cavity ionization chambers serving as primary standards of exposure with $^{60}$Co $\gamma$-radiation [6] were used to attribute exposure rates to the beam for several geometrical conditions.

Absorbed doses in a graphite phantom under corresponding conditions were measured using a quasi-adiabatic calorimeter that represents the national primary standard for the unit of absorbed dose in graphite [7].

2.2. The calorimeter for determining the absorbed dose, $D_g$, in graphite

Several types of calorimeter for the determination of absorbed dose in graphite are described in detail in the literature (see, for example, Refs [8—10]). Construction, operational mode and some characteristics of the PTB-absorbed dose calorimeter can be briefly summarized as follows.

Highly purified graphite as absorbing material is used for completely converting the radiation energy imparted to the graphite into heat; the amount of radiation energy not converted into heat can be neglected. The radiation energy imparted is determined by comparing it with the precisely measurable amount of electrical energy that produces the same rise in temperature. Thermistors in a Wheatstone bridge are used as temperature sensors. An absorbed dose in graphite of 1 Gy raises the temperature by $1.6 \times 10^{-3}$ K. The calorimeter arrangement consists of three parts, the absorber (25 mm dia., 2 mm thick), a jacket and a mantle, one inside the other, separated by evacuated spaces. A particular effort is made to keep all parts of the calorimeter at the same temperature. Due to the low absorption of radiation an almost homogeneous heating up during irradiation is guaranteed. For the electrical calibration, however, a separate, controlled heating of absorber, jacket and mantle is necessary to obtain an equal temperature rise in all parts. The small difference remaining can be taken into account by observing the temperature/time curve of the absorber. The calorimeter can thus be regarded as quasi-adiabatic. With the calorimeter, absorbed doses above 0.5 Gy can be measured with an uncertainty of less than 0.5% provided that the measurement time does not exceed about 10 min. Temperature drift rates as low as $10^{-6}$ K/min can be reached.

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1 This figure results from adding in quadrature the component uncertainties and corresponds to a confidence level of better than 90%.
TABLE I. CALCULATIONAL DATA

Ratio of mass attenuation coefficients (column 2) of water, w, and graphite, g, and the ratio of mass energy absorption coefficients of water and graphite (column 3) as function of energy (column 1). In column 4 the ratio of the fluences of scattered photons within an energy interval of 0.1 MeV to the fluences of the primary photons is given.

<table>
<thead>
<tr>
<th>Photon energy (MeV)</th>
<th>( (\mu/\rho)_w )</th>
<th>( (\mu/\rho)_g )</th>
<th>( (\mu_{en}/\rho)_w )</th>
<th>( (\mu_{en}/\rho)_g )</th>
<th>S/F</th>
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<td></td>
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<tr>
<td>0.1</td>
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<td></td>
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<td>1.108</td>
<td></td>
<td></td>
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<tr>
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<td></td>
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<tr>
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<td>1.109</td>
<td>1.104</td>
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</table>

3. PERFORMANCE OF THE METHODS

3.1. Calibration of dose meters in terms of absorbed dose, \( D_g \), in graphite

Most types of commercially available ionization chambers can be fitted, without leaving air gaps, into the graphite phantom and they can be calibrated in terms of absorbed dose in graphite with an overall uncertainty of less than 1.5%.

3.2. Determination of absorbed dose in water, \( D_w \), by calculation from the radiation field

A way of deriving the absorbed dose at a point in a water phantom from the measured value of absorbed dose at a corresponding point in a graphite
phantom, both irradiated with the same $^{60}$Co beam, has been given by
Loevinger [11]. Corresponding points are defined by their having the same
distance from the source, the same depth in the phantom in terms of number
of atomic electrons per unit area and by being irradiated with a beam, the
diameter of which is adapted to the atomic electron densities. The surface is
assumed to be flat and perpendicular to the beam axis. The attenuations of the
primary beam are in this case equal in both media because, for photon energies
from about 0.1 MeV to 1.5 MeV, the ratio of the attenuation coefficient of
graphite to that of water is nearly independent of energy and equal to the ratio
of atomic electron densities (Table I, column 2). The primary photon flux
densities are thus the same at corresponding positions in both phantoms. For
graphite at a depth of 5 g/cm$^2$ and a field size of 100 cm$^2$, Monte Carlo
calculations show that about 50% of the photon flux density consists of
scattered photons [12] (Table I, column 4). But taking into account the energy
absorption coefficients, it can be shown that 80% of the absorbed dose at this
depth is due to the primary beam. This 80% of the absorbed dose in graphite
has to be scaled up to allow for the higher mass energy absorption coefficient
of water as compared with that of graphite at 1.25 MeV. The same has to be
done for the 20% contribution of the scattered radiation. The ratio of energy
absorption coefficients $\mu_{en}/\rho$ does not vary markedly with energy (Table I,
column 3) and is nearly the same as that for the primary photons. Therefore
the relation:

$$D_w = \left(\frac{\mu_{en}/\rho}{\mu_{en}/\rho}\right)_w D_g \approx 1.105 D_g \quad (1)$$

is valid to a good approximation. A more detailed evaluation would have to
consider the somewhat different geometry for the origin of the scattered radiation
and would have to use improved Monte Carlo calculations that take into account
the actual primary spectrum. At the present time, calibrations according to
this method can be carried out, but since the evaluation of the uncertainty is
difficult due to the reasons mentioned above, the relatively high uncertainty
of ± 3% is quoted as a conservative estimate.

3.3. Ionization chambers as transfer instruments

The principle of using transfer systems is discussed in ICRU Report 14 [1].
It involves applying the Bragg-Gray principle with thin-walled chambers and the
conditions of charged-particle equilibrium (CPE) with chambers having thick
air-equivalent walls. Such considerations lead to the following equation for a
thin-walled ionization chamber:

\[ D_w = D_g \cdot \frac{J_w}{J_g} \cdot \frac{s_{w,a}}{s_{g,a}} \cdot \frac{P_w}{P_g} \]  \hspace{1cm} (2)

and are described in Ref. [1]. The symbols represent:

- \( J_w \): Ion dose (charge divided by mass) in the ionization chamber positioned in the water phantom;
- \( J_g \): Ion dose (charge divided by mass) in the ionization chamber positioned in the graphite phantom;
- \( s_{w,a} \): Ratio of mean mass stopping power of water to that of air;
- \( s_{g,a} \): Ratio of mean mass stopping power of graphite to that of air;
- \( P_w \): Perturbation correction for the displacement of water by the chamber;
- \( P_g \): Perturbation correction for the displacement of graphite by the chamber.

On the other hand, if the chamber wall is thick enough to establish charged-particle equilibrium, the following equation holds:

\[ D_w = D_g \cdot \frac{J'_w}{J'_g} \cdot \frac{u_{w,a}}{u_{g,a}} \cdot \frac{P'_w}{P'_g} \]  \hspace{1cm} (3)

where

\[ u_{w,a} = \frac{(\mu_{en}/\rho)_w}{(\mu_{en}/\rho)_a} \]

and

\[ u_{g,a} = \frac{(\mu_{en}/\rho)_g}{(\mu_{en}/\rho)_a} \]

A thin-walled graphite ionization chamber of wall thickness 0.5 mm and volume 0.6 cm\(^3\) was built. The chamber resembles the thimble type of ionization chambers which serve as primary standards of exposure for \( \gamma \)-radiation [6]. The chamber fits closely into the graphite phantom at the point where the absorbed dose, \( D_g \), is measured by calorimetric means. In the water phantom, the chamber can be used with caps of different wall thickness, enabling the realization of both modes of transfer.

Dividing Eq.(2) by Eq.(3), and tentatively assuming that the factors \( P_w/P_g \) and \( P'_w/P'_g \) are equal to unity, one would expect:

\[ \frac{J_w}{J'_w} = \frac{s_{w,a}/s_{g,a}}{u_{w,a}/u_{g,a}} \]  \hspace{1cm} (4)
where \( J_w \) and \( J'_w \) are essentially the readings of the ionization chamber in water with and without the graphite cap. Experimental results show that Eq.(4) is valid.

3.4. Direct determination of absorbed dose in water by calorimetry

Some preliminary experiments to determine the absorbed dose in water directly by calorimetry have been carried out. The temperature dependence of the electrical conductivity of an aqueous salt solution of low concentration serves as temperature sensor [13]. The conductivity is determined using an a.c. Wheatstone bridge with a lock-in amplifier at a chosen frequency. Volume heating for the electrical calibration is carried out by a current of a different frequency that does not interfere with the temperature measurements (Fig. 1). The sensitivity of this calorimeter is less than that of the graphite calorimeter using thermistors as temperature sensors by a factor of 20. Several technological problems have still to be solved to satisfy the requirements of an absorbed dose primary standard.
REFERENCES


DISCUSSION

M. OBERHOFER: It may be of interest in this context that Dr. Pychlau of the Physikalisch-Technische Werkstätten Dr. Pychlau KG (PTW), Freiburg, Federal Republic of Germany, has been performing similar measurements. Instead of using a graphite phantom he uses a water phantom. Absorbed dose is measured by a Fricke system. The ionization chambers are thus calibrated in terms of absorbed dose for different low-energy photons. The ionization chamber with the least energy dependence over the whole energy range is then used for absorbed dose assessment. Such a chamber can be purchase from PTW.

H. REICH: It was Pychlau’s aim to demonstrate that chambers developed to have a low energy dependence of response when calibrated in terms of exposure show a strong energy dependence at energies below 100 keV when calibrated in terms of absorbed dose in water, and vice versa. This underlines the necessity of setting up primary standards for the units of absorbed dose, although Pychlau does not make that point explicitly.
S.C. ELLIS: You briefly described a project to operate an absorbed-dose calorimeter with an aqueous salt solution as the calorimetric medium. Will it be necessary to apply a correction for any thermal defect arising from radiation-induced chemical change in the solution?

H. REICH: Thermal defects due to chemical reactions are to be expected and will have to be corrected for. So far it is not clear whether the uncertainty of this correction represents a serious handicap for the method.

R. LOEVINGER: Your important studies are some of the most valuable contributions now being made to the establishment of reliable absorbed-dose calibrations traceable directly to calorimeters. Such calibrations traceable to a graphite calorimeter were first offered by the National Research Council of Canada; although the National Bureau of Standards (USA) does offer such a service also, it is still provisional, because of some uncertainty in just the problem that you are investigating, namely the conversion of absorbed dose to carbon into absorbed dose to water. The method of making that conversion attributed to me (your Ref.[11]) is not the method currently favoured at NBS.

Electrical conductivity is not the only temperature-dependent property of water that can be used for absorbed-dose determination. The temperature-dependence of the refractive index of water has been used at NBS to measure the ionizing radiation energy deposition in water. This is done by counting interference fringes of holograms formed by successive helium-neon laser light exposures made immediately before and after a short irradiation of a water volume by a high-intensity electron beam.²

WALL EFFECTS IN GAMMA-RAY DOSIMETRY

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Abstract

WALL EFFECTS IN GAMMA-RAY DOSIMETRY.

When a chemical dose meter such as the Fricke dose meter is used as a secondary dosimetry standard, the effect of the irradiation vessel's wall on the dose meter readings is often disregarded. This paper shows that this effect can be significant and depends upon the wall material, the dosimetry solution, the size of the irradiation vessel and the spectra of the gamma rays. Measured values for the Fricke dose meter are compared with theoretical values based upon a modified cavity theory. Differences are accounted for by the differences in build-up factors between the wall material and the dose meter material as a function of the dose meter distance from the cobalt-60 source in water.

1. INTRODUCTION

When calibrating a radiation source it is desirable to make an accurate determination of the energy absorbed in the irradiation configuration. This is usually accomplished by distributing dosimeters throughout the product and using the change in a physical property of the dosimeters as being proportional to the absorbed dose in the product. Experimenters usually are aware of the necessity for correcting the measured dose for the difference in the stopping power of the dosimeter material and the product. They however often neglect to correct for the effect caused by the discontinuity in the dosimeters between the vessel wall and the dosimeter material.

This problem of discontinuity between materials with different atomic numbers (Z) has been of concern to the radiologist since the late 1930's when Gray [1] described the effect of secondary electrons knocked out of the wall of ion chambers on the dose recorded by the ion chambers.

Spiers [2] developed a theoretical treatment to account for the effect of the secondary electrons in the transition zone between bone and soft tissues. Since this classical paper a number of additional theoretical studies [3,4,5,6,7,8] have been conducted to improve upon the method and to evaluate the effect in geometries more complex than the original slab geometry. Experimental studies have been conducted by a number of researchers [9,10,11,12] in an effort to evaluate this effect.
Dutreix and fellow workers have published a number of papers [13,14,15,16] where they have experimentally measured the absorbed dose profiles at and near boundaries between a number of common materials exposed to a cobalt-60 source. These experimenters used a very flat ionization chamber constructed of carbon to measure the absorbed dose.

2. INTERFACE EFFECTS

2.1 Radiation Effect

Figure 1 represents a typical curve of the dose profile at the interfaces between two materials of different Z values. It should be noticed that there are differences in the shape of the curve depending on the Z of the material that the radiation first penetrates.

This variation has been accounted for by Dutreix and Bernard [16] by the fact that in an equilibrium condition the absorbed dose is a composite of the electrons moving in the forward direction and electrons back-scattered in the opposite direction. When the interface between the high Z and low Z materials is approached the back-scattered electrons are lost into the low Z material because it is less efficient in back-scattering these low energy electrons. These secondary electrons from the high Z material (high Z back-scatters electrons) are attenuated and absorbed in the low Z materials. The depression in the absorbed dose observed in the low Z material is due to the lack of the low energy photons close to the boundary. The spectrum of low energy photons build up to a new equilibrium spectrum in the low Z material.
The observed increase in the absorbed dose in the low Z material at the interface between the low Z and high Z can be accounted for by the absorption of the back-scattered electrons produced in the high Z materials.

2.2 Chemical Effect

In addition to the overall enhancement or reduction in the absorbed dose in the dosimeters at its interface depending upon the direction of the incident photon beam, the absorbed dose can also be modified by chemical effects of the vessel wall, the dosimeter material, and photons produced in transparent vessels. Paterson [10] and Morkovin and Feldman [11] observed radiation kill of microorganisms to a larger extent than would be expected when the walls of the irradiation vessel are very close to the same Z as the biological material. Their conclusion was that the wall produced chemicals that killed the organisms. It can be expected that if quartz vessels are used to contain the dosimeter material and the dosimeter material itself is not transparent to photons produced in the wall of the vessel they could also appreciably change the absorbed dose near the wall by photo chemical reactions. In ampules or vessels of polyethylene and polypropylene, hydrogen atoms released in the wall may diffuse into the solution and cause chemical reactions in the solution.

2.3 Effect on Measurement Using Dosimeter Solution in Ampules

These are but a few of the phenomena that could cause an effect at the surface interface and result in the dosimeter giving readings not representative of the absorbed dose in the product.

When preparing dosimetry standards it is imperative to take into account the correction for the wall effect. We usually measure the G-value of the Fricke dosimeter using large irradiation vessels where the wall effect is minimum, but on the other hand we usually use small vessels like 5-ml ampules to calibrate a dose and the G-value measured using the large vessels. We must take into consideration therefore that the dose measured by these dosimeters must be modified by an amount to correct for these effects. The surface phenomena can be considered to disturb the dose only close to the wall of the vessel. The integrated perturbation in absorbed energy is then proportional to the surface area A. Without the surface effect the absorbed energy integrated over the volume V is proportional to the volume. The correction is therefore proportional to A/V.

The results presented in this paper confirm the occurrence of such a wall effect and indicate that for Fricke dosimeters irradiated in pyrex vessels a correction should be applied. Because all calibrations conducted at Natick have been made using a standard 5-ml ampule as the dosimeter vessel, we have minimized the effect by standardizing the geometry.

3. MATERIALS AND METHODS

A series of irradiation vessels were constructed of pyrex glass such that the ratio of their surface area A to volume V varied from 2.6 to 15.4 cm−1. The inside diameter of these vessels varied from 2.6 mm to 16 mm. In order to minimize the dose nonuniformity, they were constructed such that their overall lengths were all approximately 15 cm.
FIG. 2. Effect of irradiation vessel diameter on the average absorbed dose expressed as the absorbed dose ratio between the measured value and the value for the largest diameter vessel. The points represent the measured values of this study and the line represents values taken from Burlin's theoretical study using a modified cavity theory [6].

TABLE 1

<table>
<thead>
<tr>
<th>Height (cm)</th>
<th>Diameter (cm)</th>
<th>Volume (cm³)</th>
<th>Ratio A/V*</th>
<th>% Increase In Ferric Ion</th>
</tr>
</thead>
<tbody>
<tr>
<td>58.8</td>
<td>0.026</td>
<td>3.12</td>
<td>15.42</td>
<td>1.066</td>
</tr>
<tr>
<td>14.3</td>
<td>0.038</td>
<td>1.91</td>
<td>10.67</td>
<td>1.044</td>
</tr>
<tr>
<td>15.2</td>
<td>0.058</td>
<td>4.13</td>
<td>7.08</td>
<td>1.033</td>
</tr>
<tr>
<td>15.2</td>
<td>0.080</td>
<td>7.39</td>
<td>5.13</td>
<td>1.018</td>
</tr>
<tr>
<td>14.7</td>
<td>0.170</td>
<td>32.65</td>
<td>2.49</td>
<td>0</td>
</tr>
</tbody>
</table>

* A/V = \( \frac{2\pi r^2 + 2\pi rh}{\pi r^2 h} = \frac{2}{h} + \frac{2}{r} = \frac{2}{h} + \frac{4}{D} \)

For the smallest diameter tube, because its length was approximately 59 cm, it was necessary to form it into a loop whose outside diameter was kept less than 16 mm. All other vessels were straight tubes with 12/24 glass joints at one end.

The cobalt-60 irradiator used for this study is a shaped cylinder source contained in a lead filled stainless steel shield. The dose along the central axis of this irradiator is uniform to ± 3% over a vertical distance of 15.3 cm.
To minimize the radial dose distribution, all vessels were irradiated on the axis of a water-filled metal container, 10.8 cm in diameter by 17.8 cm high (a No. 3 cylinder). All irradiations were for 20 minutes.

Prior to use the irradiation vessels were rinsed with singly distilled water and baked at 540°C for 4 hours. The vessels were then rinsed a minimum of three times with the Fricke dosimetry solution before the final filling. The change in the ferric ion concentration after irradiation was measured at 305 nanometers and 25°C using a Cary 118 spectrophotometer.

4. RESULTS

4.1 Effect of Irradiation Vessels Diameter

Figure 2 shows the percent increase in the measured ferric ion concentration as a function of the irradiation vessel’s internal diameter. The points represent the measured values as shown in Table I, and the line represents the predicted increase based upon the results of Burlin [6] using a modified cavity theory. It is observed that the cavity theory values and our measured results are in reasonable agreement.

Dutreix and Bernard [16] measured the effect and range of the effect of cobalt-60 gamma rays passing through a glass-water interface. They observed that there is a direction dependence on the observed effect, but that the range of the effect in water is constant at about 2 mm. His results show that, when the gamma rays pass through the glass before entering the water, there is a depression in the absorbed dose at the interface of 2%. If the rays pass first through the water before entering the glass, there is a buildup in the absorbed dose to a maximum at the interface of 8%. Assuming that for most production irradiations the gamma ray will pass through the dosimeter from all directions and not just from one side, the predicted effect to the dosimeter as a result of the glass-water interface can be assumed to be the average of the two effects observed by Dutreix. By numerical integration it was determined that the surface effect for irradiation from two sides could be approximated by a slab 0.3 mm in thickness with an average effect 5% higher than the dose received beyond the range of the secondary electrons.

4.2 Effect of Irradiation Vessels Surface Area on the Absorbed Dose

Assuming the range of the secondary electrons, originating at the interface of the glass irradiation vessel and the water equivalent dosimeter material, is between 0.3 and 2 mm in the dosimeter material, as determined by Dutreix [16]; the observed dose received by the dosimeter is equal to the dose resulting from the secondary electrons at the interface and the dose received beyond the range of the secondary electrons. Because of the limited range of the secondary electrons, the perturbation in absorbed radiation contributing to the total dose is proportional to the surface area of the irradiation vessel. The absorbed radiation energy integrated over the volume is on the other hand proportional to the volume. It therefore can be assumed that the increase in absorbed dose reported by many researchers [19,20,21,22] where the diameter of the irradiation vessel is relatively large compared to the average range of the secondary electrons, greater than 2 mm in diameter, can be approximated by the surface area (A) to volume (V) ratio of the irradiation vessel.
FIG. 3. The percent change in average absorbed dose as a function of the area to volume ratio of the irradiation vessel. The cavity values are taken from Ref. [6] for spheres with diameter of 4 to 40 mm. The ferrous-cupric and ceric values are from Ref. [22] and the ferrous values are from this study.

Mathematically this effect can be expressed as

$$\Delta D = K \frac{A}{V} \cdot D$$  \hspace{1cm} (1)

where $\Delta D$ is the increase in absorbed dose ($D$), $K$ is an experimentally determined constant with the dimension of a centimeter, $A$ is the surface area of the dosimetry vessel in square centimeters, and $V$ is its volume in cubic centimeters.

Sehested, Brynjolfsson, and Holm [21] experimentally determined the $K$ value for the Fricke dosimeter in glass and in polyethylene vessels to be 0.0178 and 0.0124, respectively. For the ferrous-cupric dosimeter and ceric dosimeters in glass vessels, the $K$ values were determined to be 0.018 and 0.0125, respectively, by Jarrett and Halliday [22]. Using the calculated values of Burlin [6] for the Fricke dosimeter in silica vessels, a $K$ value of 0.0016 is obtained for spheres with diameter between 4 and 40 mm.

Using the irradiation conditions described in this paper we determined $K$ to equal 0.0043 for the Fricke dosimeter in pyrex vessels.

Figure 3 is a plot of the percent change in the average absorbed dose expressed as the absorbed dose ratio between the measured value and the value for the largest diameter vessel. The slope of these curves is proportional to the $K$ values as obtained from Burlin's
TABLE II

CO–60 GAMMA–RAY BUILDUP FACTORS IN SiO₂
DIVIDED BY BUILDUP FACTORS IN DIFFERENT DOSIMETERS
AS A FUNCTION OF DISTANCE IN WATER FROM A COBALT–60 SOURCE

<table>
<thead>
<tr>
<th>Dosimeters</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>glass</td>
<td>1</td>
<td>1.15</td>
<td>1.26</td>
<td>1.33</td>
</tr>
<tr>
<td>water</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>glass</td>
<td>1</td>
<td>1.14</td>
<td>1.25</td>
<td>1.32</td>
</tr>
<tr>
<td>Fricke</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>glass</td>
<td>1</td>
<td>1.15</td>
<td>1.26</td>
<td>1.33</td>
</tr>
<tr>
<td>Fe(0.001)Cu</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>glass</td>
<td>1</td>
<td>1.13</td>
<td>1.23</td>
<td>1.29</td>
</tr>
<tr>
<td>Fe(0.006)Cu</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>glass</td>
<td>1</td>
<td>1.11</td>
<td>1.22</td>
<td>1.26</td>
</tr>
<tr>
<td>Ce(0.032)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>glass</td>
<td>1</td>
<td>1.09</td>
<td>1.10</td>
<td>1.12</td>
</tr>
<tr>
<td>Ce(0.10)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$\mu_t = \text{total absorption coefficient}$

$r = \text{distance in cm}$

Theoretical studies [6] and the measured values of Jarrett and Halliday [22] and of this study.

The K value of 0.0124 for the Fricke dosimeter in polyethylene is considerably higher than would be expected for a water equivalent dosimeter irradiated in a vessel whose atomic number is very close to that of water. Dutreix [16] using an ion chamber determined a depression at the interface of 5% when the gamma rays go from the water into the polyethylene wall and an increase of 2.5% when the ray penetrates the wall first. This means the sum effect at the surface should be a depression of approximately 2.5%. Because Sehested et al. observed a K value of 0.0124, it is assumed that the dosimeter is affected by some effect in addition to the secondary electrons; probably a chemical effect.

5. DISCUSSION

There is thus an obvious discrepancy between the theoretical calculations of Burlin and the experimental results. Brynjolfsson [23] and Brynjolfsson et al. [24] have shown that the ratio of dose in the glass versus the dose in the dosimeter material varies significantly with the distance from a cobalt-60 source in water. This ratio is shown in Table II.
FIG. 4. The dose correction factor $K$ as a function of dosimeter material and distance from a cobalt-60 source in cm of $H_2O$. The upper curve is for the Fricke and ferrous-cupric dosimeter in glass, and the lower curve is for 0.032M ceric sulfate dosimeter in glass.

$\times$ = the study $+$ = Ref. [21] $\square$ = Ref. [22].

The primary interaction of gamma rays with matter is localized on individual atoms. The boundary between two materials with respect to gamma ray absorption varies sharply. The secondary, tertiary, etc. electrons produced in these reactions can diffuse into the dosimeter material a distance in the order of a few millimeters. Different atomic species produced by the reactions can likewise diffuse considerable distances. These electrons and atomic species can carry absorbed energy across boundaries and perturb the dose at the interface.

Let us postulate that:

Postulate 1. If the primary energy absorbed per electron in two materials is the same, then the energy diffusion across the boundary between the two materials cancels.

Postulate 2. If the primary energy absorbed per electron in the two materials is $Q_1$ and $Q_2$, then the energy diffusion per cm$^2$ across the boundary is proportional to the difference $Q_2 - Q_1$. 
We will define the diffusion range, \( d \), as the average diffusion range of the species carrying the energy across the boundaries. Therefore, we have for the dosimetry vessel:

\[
\frac{\Delta D}{D_1} = \frac{A}{V} \left( \frac{(d \cdot \rho) (Q_2 - Q_1)}{Q_1} \right)
\]  

(2)

where \( \Delta D \) is the average dose perturbation in the dosimeter, \( D_1 \) is the dose in the dosimeter without the perturbation or wall effect. \( A \) is the surface area in \( \text{cm}^2 \) of the dosimeter vessel in contact with the dosimeter material of volume \( V \) in \( \text{cm}^3 \). \( Q_1 \) is the average energy absorbed per electron without the perturbation or wall effect, and \( Q_2 \) is the energy absorbed per electron in the wall material. \( \rho \) is the ratio between the electron density of the wall material and the solution, and it is approximately proportional to the ratio of the mass densities.

For Co-60 gamma rays the values of \( Q_2 \) and \( Q_1 \) will be proportional to the buildup factors \( B_2 \) and \( B_1 \). From Eq. (1) and Eq. (2) we obtain:

\[
K = \frac{(\rho \cdot d) (B_2 - B_1)}{B_1}
\]  

(3)

Table II shows that for \( \mu_{TF} = 1 \), that is for \( r = 15.8 \text{ cm} \) of water for Co-60, the value of \( B_2/B_1 \) for glass/Fricke is 1.14. The value of \( (B_2 - B_1)/B_1 \) in Eq (3) is then 0.14.

If we set the average diffusion distance, \( (\rho \cdot d) \) for the secondary electrons equal to about 0.1 (the actual value will vary with the photon spectrum) we get when we substitute into Eq (3) for the Fricke dosimeter at 15.8 cm that:

\[
K = 0.1 \cdot 0.14 = 0.0014
\]

in reasonable agreement with the experimentally determined values by [21] and [22]. The ratio \( (B_2 - B_1)/B_1 \) for 5 cm distance in water is about \( 1/3 \cdot 0.13 = 0.043 \). If we insert this value into Eq (3) for the Fricke dosimeter at 5 cm we get:

\[
K = 0.1 \cdot 0.043 = 0.0043
\]

in agreement with the experimental value of 0.0043. The value, \( (B_2 - B_1)/B_1 \) for 15.8 cm water and for glass versus 0.032 M ceric (from Table II) is equal to 0.11. When we insert that value into Eq (3) for the 0.32 M ceric sulfate dosimeter we get:

\[
K = 0.1 \cdot 0.11 = 0.011
\]

which is also in reasonable agreement with the experimental value of 0.0124 of Jarrett and Halliday [22].
6. CONCLUSIONS

Allowance must be made for the difference in Z of the dosimeter wall and the dosimeter material, chemical effects of the vessel wall on the dosimeter material, energy degradation of the primary gamma spectra as well as the area to volume ratio of the vessel. For the surface effect to be less than one percent in the Fricke dosimeter, the glass dosimeter vessel internal diameter must be greater than 10 mm.

The observed increase in the dosimeter response can be represented by the A/V ratio of the dosimeter vessel for vessels whose diameter is greater than the average range of the secondary electrons as shown in Figure 4.

It is essential when establishing dosimetry standards to account for the effect of the dose at the transition zone. This effect can best be estimated by using the ratio of the A/V of the dosimeter and the experimentally determined K value.

REFERENCES


10. Feng, P., Measurement of dose distribution produced by high energy electrons which can be applied to the dose distribution characteristics of the accelerator under a wide variety of conditions, Armour Research Foundation, QMF&CI Rpt 5–598 4 (1960).


DISCUSSION

W.L. McLAUGHLIN: Can your correction factors for glass-wall effects, as applied to the ferrous sulphate dose meter, possibly account for apparent discrepancies between generally reported ferric ion yield values (i.e. 
\[ G(\text{Fe}^{3+}) = 15.6 \text{ ions per 100 eV; } 9.74 \times 10^{17} \text{ J}^{-1} \]) for gamma rays emitted by a cobalt-60 source, as determined usually with solutions held in 2 to 5 cm\(^3\) glass ampoules, and the yield values reported by Allen for 1 or 2 MeV electrons (i.e. 
\[ G(\text{Fe}^{3+}) = 15.4 \text{ ions per 100 eV; } 9.62 \times 10^{17} \text{ J}^{-1} \]), for which he used essentially "wall-less" dose-meter solutions — that is, solutions in fairly large open Petri dishes irradiated from the top by the electron beam?

R.D. JARRETT: Yes, we believe the lower G-value of 15.4 measured by Allen can be accounted for by the fact that he used an essentially "wall-less" configuration.

W.K. SINCLAIR: I am very pleased to see this kind of correction investigated systematically, as its possible influence on G-values is obvious. I wonder if you have made any calculations or measurements at lower energies of X-rays, at 200 kV(pk) and below, where the effects may also be appreciable. The difference between the walls and the dose meter will be more critical, but the range of the secondary electrons will be much smaller, and thus the net effect may be larger or smaller than for \(^{60}\)Co.

R.D. JARRETT: No, we have not.

C.A. JANSSENS: I refer to your comparison of the increase in the Fricke dose with increasing surface-to-volume ratio with the Burlin theory. The general cavity theory which we proposed a few years ago predicts a slope of the decrease in the wall contribution with cavity dimension that is smaller by a factor of about 0.4 than the decrease according to the Burlin theory. I therefore expect good agreement between our theory and your experiment.

A.O. FREGENE: In investigations of boundary effects, the physical situation presented by, say, the Cu/Zn boundary is quite often further complicated by introducing a detector made of a third material. This reminds one of Heisenberg’s uncertainty principle — we are disturbing the situation we want to measure. In ferrous sulphate measurements it is better to have a wall of a material such as Perspex or Melinex, which is more like the dose-meter solution, than to introduce problems by using Pyrex walls. However, for intercomparison purposes only, Pyrex is perfectly acceptable.

R.D. JARRETT: I agree that the wall of the dose-meter should be of a material with an atomic number close to that of the dose-meter solution. However, many users of dose meters for one reason or another select glass vessels to hold their dose-meter solutions. The purpose of this paper is to make them aware of the effect that the surface of the dose-meter wall has on the response of the dose meter.
CORRECTION FACTORS IN GAMMA-RAY DOSIMETRY

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Abstract

CORRECTION FACTORS IN GAMMA-RAY DOSIMETRY.

The effect of build-up factors on the measurements of dose have been investigated theoretically and experimentally. The K-fluorescent radiation emission is calculated for cerium and the lighter elements (Cu, Fe and S) to obtain the mass energy transfer coefficients for these elements, and hence the build-up factors of several dose meters — with fluorescent radiation assumed to be (1) all escaping from, and (2) all absorbed in the dose-meter volume. The fractions of the fluorescent radiation that would be absorbed in these dose meters are also estimated. In order to compare the theoretical prediction with experiment, theoretical expressions for the absorbed dose rate and the build-up factors due to an extended source are next derived, which, when expressed in terms of a form factor for the source, retain all the expressions for a point source. Experiments were performed at the Radiation Laboratory of the US Army Natick Research and Development Command in which four chemical dose meters were used: the ferrous-cupric, and the ceric-cerous systems at three different concentrations. The experiments were carried out with a 60Co cylindrical γ-ray source in air and at 64 cm distance from a large 60Co source in a water pool. The build-up factors for these two sources correspond to μγ = 0.2 and 4.25, respectively. It is found experimentally that, for μγ = 4.25, the absorbed dose for a ceric-cerous system with 0.1M ceric-cerous concentration is higher than that with 0.01M ceric-cerous concentration by a factor of 1.25. The theoretical prediction for this factor is 1.21. For four different dose meters, the G-values as determined by these experiments are: 2.33 for 0.01M Ce4+ + 0.01M Ce3+, 2.33 for 0.016M Ce4+ + 0.009M Ce3+; 1.95 for 0.01M Ce4+ + 0.09M Ce3+, all in 0.4M H2SO4; and 0.560 for 0.006M FeSO4 + 0.060M CuSO4 in 0.005M H2SO4.

1. INTRODUCTION

Absorbed Dose Rate and Buildup Factor

We start with the fundamental equation for the gamma-ray energy absorbed per second in an infinitesimal volume dx dy dz at a point P(x,y,z). This equation defines the dose rate in Gy·s⁻¹ (10⁶ erg·g⁻¹·s⁻¹).

\[
d = 1.60 \times 10^{-10} \int_0^E \max E \cdot \frac{d\phi(E)}{dE} \cdot \frac{\mu_{tr}(E)}{\rho} \cdot dE
\]  
(1)

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where $E = $ photon energy in MeV

$$\phi(E) = \text{photon flux density in number of photons per } \text{cm}^2 \text{ per second},$$

i.e., the number of photons with energy less than $E$ which enter a sphere of unit cross sectional area per second at point $P$

$$\frac{\mu_{tr}(E)}{\rho} = \text{mass energy transfer coefficient of the material at } P \text{ for photons of energies lying in the interval between } E \text{ and } E + dE, \rho \text{ is the density of the material in } g \cdot cm^{-3}.$$  

One notes that

$$E \frac{d\phi(E)}{dE} \cdot dE = dl(E)$$

is the photon energy flux density i.e., the intensity, in the energy interval $(E, E + dE)$ in MeV-$cm^{-2} \cdot s^{-1}$. Eq. (1) follows from the basic equation for the absorption of the primary photon flux by $dm = d(\rho x) g \cdot cm^{-2}$ of material,

$$d(dl) = (dl) \cdot \frac{\mu}{\rho} \cdot d(\rho x)$$

(2)

when a mass energy transfer coefficient

$$\frac{\mu_{tr}(E)}{\rho}$$

is used in Eq. (2) instead of the mass total absorption coefficient $(\mu/\rho)$ for the primary photons.

For a Co–60 point source, the energy spectrum at a distance $r$ from the source will consist of two $\delta$ functions (the two primary spectral lines) at 1.17 MeV and 1.33 MeV and a continuum background of lower energy photons. The two photons $E_1 = 1.17$ MeV and $E_2 = 1.33$ MeV emitted from the source may be approximated, at a distance $r$, by two photons of $E_0 = 1.25$ MeV each. If the strength of the source is $C$ bequerel, and the attenuation coefficient, or the “total absorption coefficient” of the medium is $\mu(E_0)$ for photons of energy $E_0$ (= 1.25 MeV in the present case), then

$$\frac{dl(E)}{dE} = C \cdot \frac{\exp(-\mu r)}{4\pi r^2} \left[ E_1 \delta(E_1) + E_2 \delta(E_2) \right] + \text{continuum}$$

$$\triangle C \cdot \frac{\exp(-\mu r)}{4\pi r^2} \cdot (E_1 + E_2) \cdot \delta\left(\frac{E_1 + E_2}{2}\right) + \text{continuum}$$

The degraded (continuum) part of the spectrum will be denoted by $dl(E,r)/dE$, and Eq. (1), after integrating out the $\delta$ function, becomes

$$d = 1.60 \cdot 10^{-10} \cdot C \cdot$$

$$\left[ \frac{2.5 \exp(-\mu r)}{4\pi r^2} \cdot \frac{\mu_{tr}(E_0)}{\rho} + \int_{E_0}^{E_0} \frac{dl(E,r)}{dE} \cdot \frac{\mu_{tr}(E)}{\rho} \cdot dE \right]$$
or \[ d = 1.60 \cdot 10^{-10} \cdot C \cdot I_0 \frac{\exp(-\mu r)}{4\pi^2} \cdot \frac{\mu_{tr}(E_0)}{\rho} \]

\[
\left[ 1 + \frac{\int_{E_0} \exp(\mu r) \cdot 4\pi^2 \frac{dl(E,r)}{dE} \cdot \frac{\mu_{tr}(E)}{\rho} dE}{I_0 \frac{\mu_{tr}(E_0)}{\rho}} \right]
\]

(3)

where \( I_0 = 2 \cdot 1.25 \text{ MeV} \)

\( E_0 = 1.25 \text{ MeV} \)

Had there been no degradation of the spectrum, we would have \( dl(E,r)/dE = 0 \) and Eq. (3) would become

\[ d = 1.60 \cdot 10^{-10} \cdot C \cdot I_0 \frac{\exp(-\mu r)}{4\pi^2} \cdot \frac{\mu_{tr}(E_0)}{\rho} \]

(4)

i.e., the expression in the bracket of Eq. (3)

\[ \exp(\mu r) \cdot 4\pi^2 \cdot \frac{dl(E,r)}{dE} \cdot \frac{\mu_{tr}(E)}{\rho} \]

becomes unity.

The primary line spectrum is always degraded into a line spectrum (of smaller intensity) given by the factor \( (I_0 \exp(-\mu r)/4\pi^2) \) and a continuum part due to interactions, the integral term inside the brackets of Eq. (3), which thus accounts for a genuine gamma-ray buildup in the medium as the primary photons propagate through it.

\( B(r) \) of Eq. (5) is called, therefore, the buildup factor for the absorbed dose rate or the absorbed dose at point \( P(x,y,z) \).

Eq. (3) may then be written as

\[ d = 1.60 \cdot 10^{-10} C \cdot I_0 \frac{\exp(-\mu r)}{4\pi^2} \cdot \frac{\mu_{tr}(E_0)}{\rho} \cdot B(r) \]

(6)

If at point \( P \), we place a dosimeter, the rate of the dose absorbed by it will be given by Eq. (6). The buildup factor \( B \) is given by Eq. (5). From these equations it is seen that, in order to arrive at an accurate value of the absorbed dose rate, it is important that we know accurately the spectral distribution \( dl(E,r)/dE \) of the degraded gamma rays at \( P(x,y,z) \), and the mass energy transfer coefficient \( \mu_{tr}(E)/\rho \) of the materials which make up the dosimeter, for the entire energy range covered.
2. ENERGY TRANSFER COEFFICIENT WITH FLUORESCENT RADIATION CORRECTION I

The mass energy transfer coefficient is the sum of the three absorption coefficients derived from the interaction cross-sections for photoelectric absorption, Compton scattering and pair production, and corrected for the energy non-absorptive parts of the three interactions:

\[
\mu_{tE}(E) = \frac{\tau}{\rho} \left(1 - \frac{\delta}{\hbar \nu}\right) + \frac{\sigma_a}{\rho} + \frac{\kappa}{\rho} \left(1 - \frac{2mc^2}{\hbar \nu}\right)
\]

(7)

where \(\frac{\tau}{\rho} = \) photoelectric mass absorption coefficient

\(\frac{\sigma_a}{\rho} = \) the energy absorption component of the Compton process

\(\frac{\kappa}{\rho} = \) mass absorption coefficient due to pair production

\(1 - \frac{\delta}{(h \nu)} = \) correction that accounts for the fraction of energy escaping as fluorescent radiation per photoelectric interaction at energy \(E = h \nu\)

\(1 - \frac{2mc^2}{(h \nu)} = \) rest mass correction factor for the pair production to account for the escaping annihilation photons.

The mass energy transfer coefficient of Eq. (7) is to be distinguished from the so-called “mass absorption coefficient”

\[
\mu_a = \frac{\tau}{\rho} + \frac{\sigma_a}{\rho} + \frac{\kappa}{\rho}
\]

(8)

The cross sections for the three fundamental processes are well known so that accurate values of \(\mu_{tE}/\rho\) can be obtained when correction for fluorescent radiation \(1 - \delta/h \nu\) is known. For a Co-60 source, the correction for the pair production term, \(1 - 2mc^2/(h \nu)\), can be neglected.

In Reference [1], it was assumed that the fluorescent radiation emitted is absorbed again by the dosimeter, i.e. \(\delta=0\).

In most dosimeters applied to measure dose in biological systems this is a good assumption. But if the dosimeter contains high atomic number elements such as Ce, a significant amount of the fluorescent radiation may often escape.

We have extended, therefore, the calculations in Reference [1] by: (I) assuming that the fluorescent radiation entirely escapes from the dosimeter, (II) estimating the part of the fluorescent radiation that would be absorbed again by the dosimeter.

For correction I, we calculate, for each energy, the first term of Eq. (7), the photoelectric absorption corrected for fluorescent radiation emission, according to the following equation
 where \( \omega_k \) is the fluorescent yield,

\[
\omega_k = \frac{\text{number of K-shell X-rays}}{\text{number of K-shell X-rays} + \text{number of Auger electron events}}
\]

and

\[
E_k = \text{K-shell energy}
\]

In Eq. (9), we consider only the fluorescent radiation from the K-shell, since fluorescent radiation from the L and higher shells, being very much softer, will be practically all absorbed in the volume under consideration.

The fluorescent emission does not change the photoelectric cross section, hence it does not change the photoelectric mass absorption coefficient \( \tau/\rho \), but it does make the energy transfer \( E \) that is locally absorbed smaller by a factor of \( (1 - \delta/E) \). Inspection of Eqs. (1) and (2) shows that it is convenient to incorporate this factor with the absorption coefficient \( \mu_\text{p}/\rho \), and re-define this new coefficient as the mass energy transfer coefficient.

The same remark holds for the correction factors for the other two terms in Eq. (7) for Compton scattering and pair production.

Table I gives for cerium, the values of \( \tau/\rho \) and \( \mu_\text{tr}/\rho \) thus calculated, and \( (\mu_\text{tr}/\rho)_{FA} \), the mass energy transfer coefficient with fluorescent radiation assumed to be all absorbed (FA) again in the volume under consideration. It will be noted that the values of \( (\mu_\text{tr}/\rho)_{FA} \) are just that of \( \mu_\text{p}/\rho \). The values of \( \tau/\rho \) and \( (\mu_\text{tr}/\rho)_{FA} \) are from the compilation by Storm, Gilbert and Israel [2], with interpolation and extrapolation for the values at those energies not given by these authors.

The values of these three coefficients, \( \tau/\rho \), \( \mu_\text{tr}/\rho \) and \( (\mu_\text{tr}/\rho)_{FA} \), for Cu, Fe and S are similarly computed and are given in Tables II, III, and IV.

In Figures 1 and 2, we show \( \tau/\rho \) and \( \mu_\text{tr}/\rho \) for Ce, Fe and S.

In calculating the correction for fluorescent emission, Eq. (9), the fluorescent yield \( \omega_k \) for the K-shell is computed from the following equation given by Hagedoorn and Wapstra [3].

\[
\frac{\omega_k}{1 - \omega_k} = (-6.4 \cdot 10^{-2} + 3.4 \cdot 10^{-2} Z - 1.03 \cdot 10^{-6} Z^3)^4
\]

where \( Z \) = atomic number. For Ce, Cu, Fe, and S, it is equal to 0.89, 0.39, 0.29, and 0.049, respectively.

**3. CALCULATIONS OF THE BUILDUP FACTORS WITH FLUORESCENT RADIATION CORRECTION**

To calculate the absorbed dose rate \( d \) and the buildup factor \( B \) in Eqs. (5) and (6), we need the values of the spectral distribution \( dI(E,P)/dE \) at point \( P \). We use, as
<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>( \tau/\rho ) (cm(^{-1}))</th>
<th>( \mu_{\text{tr}}/\rho ) (cm(^{-1}))</th>
<th>( (\mu_{\text{tr}}/\rho)_{FA} ) (cm(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
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<td>188.0</td>
<td>188.0</td>
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<tr>
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<td>58.5</td>
<td>58.6</td>
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<td>25.9</td>
<td>25.9</td>
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<tr>
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<td>7.92</td>
<td>7.92</td>
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<td>3.45</td>
<td>3.45</td>
<td>3.45</td>
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<tr>
<td>0.040449</td>
<td>3.22</td>
<td>3.20</td>
<td>3.22</td>
</tr>
<tr>
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<td>14.20</td>
<td>3.977</td>
<td>14.20</td>
</tr>
<tr>
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<td>8.85</td>
<td>3.56</td>
<td>8.87</td>
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<td>2.26</td>
<td>4.11</td>
</tr>
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<td>0.10</td>
<td>2.20</td>
<td>1.42</td>
<td>2.21</td>
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<td>0.306</td>
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<td>0.103</td>
<td>0.115</td>
<td>0.127</td>
</tr>
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<td>0.40</td>
<td>0.0456</td>
<td>0.0659</td>
<td>0.070</td>
</tr>
<tr>
<td>0.50</td>
<td>0.0250</td>
<td>0.0476</td>
<td>0.0494</td>
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<tr>
<td>0.60</td>
<td>0.0160</td>
<td>0.0397</td>
<td>0.0406</td>
</tr>
<tr>
<td>0.80</td>
<td>0.0084</td>
<td>0.0319</td>
<td>0.0323</td>
</tr>
<tr>
<td>1.00</td>
<td>0.0055</td>
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<td>0.0287</td>
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<td>1.50</td>
<td>0.0027</td>
<td>0.0247</td>
<td>0.0247</td>
</tr>
</tbody>
</table>

*\( \tau/\rho \) = mass photoelectric absorption coefficient

\( \mu_{\text{tr}}/\rho \) = mass energy transfer coefficient with fluorescent radiation assumed to be all escaping from the volume under consideration

\( (\mu_{\text{tr}}/\rho)_{FA} \) = mass energy transfer coefficient with fluorescent radiation assumed to be all absorbed again in the volume under consideration

In reference [1], the values of \( \exp (\mu r) \cdot 4\pi r^2 \cdot \text{d}l(E_r)/(\text{d}E) \) given by Goldstein and Wilkins [4] for a point isotropic Co-60 source immersed in water, at distances of \( \mu r = 1, 2, \) and 4.

Table V gives the buildup factors \( B_{FE} \) and \( B_{FA} \) so calculated. \( B_{FE} \) denotes the case when the fluorescent radiation is assumed to escape entirely from the volume under consideration and \( B_{FA} \) the case when all the fluorescent radiation is absorbed.
TABLE II*

\( \tau/\rho, \mu_{tr}/\rho \) AND \((\mu_{tr}/\rho)_{FA}\) FOR COPPER

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>( \tau/\rho ) (cm(^2) g(^{-1}))</th>
<th>( \mu_{tr}/\rho ) (cm(^2) g(^{-1}))</th>
<th>((\mu_{tr}/\rho)_{FA}) (cm(^2) g(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>224.0</td>
<td>145.6</td>
<td>224.0</td>
</tr>
<tr>
<td>0.015</td>
<td>75.8</td>
<td>58.1</td>
<td>75.8</td>
</tr>
<tr>
<td>0.02</td>
<td>33.9</td>
<td>27.97</td>
<td>33.9</td>
</tr>
<tr>
<td>0.03</td>
<td>10.6</td>
<td>9.36</td>
<td>10.6</td>
</tr>
<tr>
<td>0.04</td>
<td>4.49</td>
<td>4.11</td>
<td>4.50</td>
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<td>0.05</td>
<td>2.29</td>
<td>2.15</td>
<td>2.31</td>
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<td>1.35</td>
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<tr>
<td>0.08</td>
<td>0.570</td>
<td>0.562</td>
<td>0.587</td>
</tr>
<tr>
<td>0.10</td>
<td>0.291</td>
<td>0.300</td>
<td>0.310</td>
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<td>0.15</td>
<td>0.084</td>
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<td>0.010</td>
<td>0.0366</td>
<td>0.0367</td>
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<td>0.0045</td>
<td>0.0315</td>
<td>0.0315</td>
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<td>0.0025</td>
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<td>0.0296</td>
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<tr>
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<td>0.0016</td>
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<td>0.0286</td>
</tr>
<tr>
<td>0.80</td>
<td>0.0008</td>
<td>0.0271</td>
<td>0.0271</td>
</tr>
<tr>
<td>1.00</td>
<td>0.0005</td>
<td>0.0260</td>
<td>0.0260</td>
</tr>
<tr>
<td>1.25</td>
<td>0.0003</td>
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<tr>
<td>1.50</td>
<td>0.0002</td>
<td>0.0240</td>
<td>0.0240</td>
</tr>
</tbody>
</table>

*See footnote of Table I for the meaning of the three coefficients.

The values of \( B_{FA} \) given in Table V differ somewhat from those given in Table II of the previous calculations [1]; e.g. for Ce, it is 236 instead of 241. This is because different widths \( \Delta E \) were used in the numerical integration of the integral in Eq. (5), and the interpolated and extrapolated values of \( \mu_{tr}/\rho \) and \( \exp(\mu r) \cdot 4\pi r^2 \cdot dI(E,r)/dr \) were read from the graphs in both cases. It should be emphasized, however, that we are here calculating the corrections. A difference of a few percent in the corrections will not affect the results and the conclusions in any way.

4. FLUORESCENT RADIATION CORRECTION II

In the above calculations, we assume that the fluorescent radiation emitted from the dosimeter materials either all escapes from the dosimeter, giving thus the buildup factor \( B_{FE} \), or is entirely absorbed by the dosimeter, giving thus the buildup factor \( B_{FA} \). The actual situation, of course, will lie between these two extreme cases, i.e., the fluorescent...
TABLE III*

$\tau/\rho$, $\mu_{tr}/\rho$ AND $(\mu_{tr}/\rho)_{FA}$ FOR IRON

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>$\tau/\rho$ (cm$^2$.g$^{-1}$)</th>
<th>$\mu_{tr}/\rho$ (cm$^2$.g$^{-1}$)</th>
<th>$(\mu_{tr}/\rho)_{FA}$ (cm$^2$.g$^{-1}$)</th>
</tr>
</thead>
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<tr>
<td>0.01</td>
<td>178.0</td>
<td>141.3</td>
<td>178.0</td>
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<td>0.015</td>
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<td>50.03</td>
<td>58.0</td>
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<tr>
<td>0.02</td>
<td>25.7</td>
<td>23.05</td>
<td>25.7</td>
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<tr>
<td>0.03</td>
<td>7.88</td>
<td>7.35</td>
<td>7.89</td>
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<tr>
<td>0.04</td>
<td>3.32</td>
<td>3.16</td>
<td>3.33</td>
</tr>
<tr>
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<td>1.67</td>
<td>1.61</td>
<td>1.68</td>
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<td>0.410</td>
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<td>0.427</td>
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<td>0.225</td>
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<td>0.0809</td>
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<td>0.0340</td>
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<td>0.0306</td>
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<td>0.0293</td>
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<tr>
<td>0.60</td>
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<td>0.0005</td>
<td>0.0274</td>
<td>0.0274</td>
</tr>
<tr>
<td>1.00</td>
<td>0.0003</td>
<td>0.0264</td>
<td>0.0264</td>
</tr>
<tr>
<td>1.25</td>
<td>0.0002</td>
<td>0.0252</td>
<td>0.0252</td>
</tr>
<tr>
<td>1.50</td>
<td>0.0002</td>
<td>0.0243</td>
<td>0.0243</td>
</tr>
</tbody>
</table>

*See footnote of Table I for the meaning of the three coefficients.

Radiation emitted is only partially absorbed by the dosimeter, the unabsorbed part will escape from the dosimeter to the surrounding medium.

The portion of the fluorescent radiation absorbed by the dosimeter could be estimated as follows.

If the photon flux density is $d\phi(E)$, then the induced fluorescent photon flux is $\omega_k \cdot d\phi(E) \cdot \tau_{h\nu}/\rho$ per g·cm$^{-2}$ thickness of the fluorescent radiation-producing material where $h\nu=E$ is the energy of the primary photons. If $E_k$ is the photon energy in the fluorescent radiation, and $\mu_{tr}(E_k)/\rho$ the mass energy transfer coefficient of the material...
### TABLE IV*

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>$\tau/\rho$ (cm²·g⁻¹)</th>
<th>$\mu_{tr}/\rho$ (cm²·g⁻¹)</th>
<th>$(\mu_{tr}/\rho)_{FA}$ (cm²·g⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>50.5</td>
<td>49.9</td>
<td>50.5</td>
</tr>
<tr>
<td>0.015</td>
<td>15.5</td>
<td>15.4</td>
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<td>5.5</td>
</tr>
<tr>
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<td>1.88</td>
<td>1.88</td>
<td>1.89</td>
</tr>
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<td>0.744</td>
<td>0.753</td>
<td>0.755</td>
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<td>0.367</td>
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<td>0.0348</td>
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<td>0.0002</td>
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<td>0.0298</td>
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<td>0.0001</td>
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<td>0.0289</td>
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</tr>
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<td>0.00000</td>
<td>0.0257</td>
<td>0.0257</td>
</tr>
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</table>

*See footnote of Table I for the meaning of the three coefficients.

### TABLE V

<table>
<thead>
<tr>
<th>Element</th>
<th>Z</th>
<th>Distance $\mu r = 1$</th>
<th>Distance $\mu r = 2$</th>
<th>Distance $\mu r = 4$</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>$B_{FE}$ $B_{FA}$</td>
<td>$B_{FE}$ $B_{FA}$</td>
<td>$B_{FE}$ $B_{FA}$</td>
</tr>
<tr>
<td>S</td>
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<td>6.86 6.87</td>
<td>13.9 13.9</td>
</tr>
<tr>
<td>Fe</td>
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<td>8.60 9.00</td>
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<td>43.6 45.7</td>
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<td>29</td>
<td>10.9 11.8</td>
<td>26.1 28.3</td>
<td>56.7 61.5</td>
</tr>
<tr>
<td>Ce</td>
<td>58</td>
<td>19.0 38.4</td>
<td>47.1 102.0</td>
<td>106.7 236.1</td>
</tr>
</tbody>
</table>

*Subscript FE denotes that all of the fluorescent radiation escapes and FA denotes that all of the fluorescent radiation is absorbed.
FIG. 1. Mass energy transfer coefficient and photoelectric mass absorption coefficient for cerium.

FIG. 2. Mass energy transfer coefficient and photoelectric mass absorption coefficient for iron and sulphur.
at energy $E_k$, then the fluorescent energy absorbed by an effective thickness $\Delta m = \Delta(\rho l)$ of the material is equal to

\[
(\text{Fluorescent energy flux density}) \cdot \frac{\mu_{\text{tr}}(E_k)}{\rho} \cdot \Delta m
\]

\[
= \left( \omega_k \cdot d\phi(E) \cdot E_k \cdot \frac{\tau_{\text{tr}}}{\rho} \right) \cdot \frac{\mu_{\text{tr}}(E_k)}{\rho} \cdot \Delta(\rho l)
\]  

(11)

for small values of $\left( \frac{\mu_{\text{tr}}(E_k)}{\rho} \right) \cdot \Delta(\rho l)$.

For a ceric dosimeter of 0.1M Ce(SO$_4$)$_2$ and 0.4M H$_2$SO$_4$, the effective $\left[ \frac{\mu_{\text{tr}}(E_k)}{\rho} \right] \cdot \Delta(\rho l)$ for $l = 1$ cm, is

\[
\left[ \frac{\mu_{\text{tr}}(E_k)}{\rho} \right] \cdot \Delta(\rho l)
\]

effective

\[
= \left[ \frac{\mu_{\text{tr}}}{\rho} \cdot 0.994 + \frac{\mu_{\text{tr}}}{\rho} \cdot \frac{0.1 \text{ ACe}}{1000} \right] +
\]

\[
\left[ \frac{\mu_{\text{tr}}}{\rho} \cdot \frac{32}{96} + \frac{\mu_{\text{tr}}}{\rho} \cdot \frac{64}{96} \right] \cdot \frac{0.6 \text{ ASO}_4}{1000} +
\]

\[
\frac{\mu_{\text{tr}}}{\rho} \cdot \frac{0.8 \cdot \text{ AHe}}{1000} \cdot 1.066
\]

\[
= 0.131 \text{ (for } l = 1 \text{ cm)}
\]

or

\[
= 0.123 \text{ (for } \Delta(\rho l) = 1 \text{ g cm}^{-2})
\]  

(12)

(13)

Thus for such a ceric dosimeter, per centimetre dimension, about 13% of the K-fluorescent energy from ceric atoms will be re-absorbed by the dosimeter.

From Berger's calculation [5], we see that if the dosimeter was water-equivalent, approximately 7.7% of the fluorescent radiation would be absorbed per cm of the dosimeter. The ceric dosimeter solution of 0.1M has $\mu_{\text{tr}}/\rho = 0.123$ versus $\mu_{\text{tr}}/\rho = 0.062$ for water, we therefore multiply 7.7% by 0.123/0.062 = 15%, in good agreement with our estimation, Eq. (12), given above for the percentage of absorption of the fluorescent radiation per cm in such a ceric dosimeter.

For a ceric dosimeter of 0.01M Ce(SO$_4$)$_2$ and 0.4M H$_2$SO$_4$, the corresponding percentage of absorption of the K-fluorescent radiation by the dosimeter is about 7% per cm dimension of the dosimeter.

5. BUILDUP FACTOR FOR A COMPOSITE MATERIAL

We now calculate the buildup factors for ceric dosimeters of two different ceric concentrations, for three different distances from the point isotropic Co–60 source immersed in water, since such calculations with fluorescent radiation assumed to be totally absorbed show strong ceric concentration dependence [1].
### TABLE VI

**BUILDUP FACTORS B(r)_{FE} AND B(r)_{FA} FOR TWO CERIC DOSIMETERS AT DIFFERENT DISTANCES FROM A POINT ISOTROPIC CO-60 SOURCE IMMERSED IN WATER**

<table>
<thead>
<tr>
<th>Dosimeter</th>
<th>Distance</th>
<th>μr = 1</th>
<th>μr = 2</th>
<th>μr = 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dosimeter (1)</td>
<td>B_{FE}</td>
<td>B_{FA}</td>
<td>B_{FE}</td>
<td>B_{FA}</td>
</tr>
<tr>
<td>0.01M Ce(SO₄)₂</td>
<td>2.071</td>
<td>2.095</td>
<td>3.407</td>
<td>3.475</td>
</tr>
<tr>
<td>0.4M H₂SO₄</td>
<td>3.891</td>
<td>4.546</td>
<td>7.420</td>
<td>8.975</td>
</tr>
<tr>
<td>H₂O</td>
<td>1.090</td>
<td>1.189</td>
<td>1.142</td>
<td>1.308</td>
</tr>
<tr>
<td>Ratio (2)/(1)</td>
<td>1.090</td>
<td>1.189</td>
<td>1.142</td>
<td>1.308</td>
</tr>
</tbody>
</table>

### TABLE VII

**ABSORBED DOSES RELATIVE TO WATER, d_{S}/d_{W}, OF THE TWO CERIC DOSIMETERS AT DIFFERENT DISTANCES FROM A POINT ISOTROPIC CO-60 SOURCE IMMERSED IN WATER**

<table>
<thead>
<tr>
<th>Dosimeter</th>
<th>Distance</th>
<th>μr = 1</th>
<th>μr = 2</th>
<th>μr = 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dosimeter (1)</td>
<td>(d_{S}/d_{W})_{FE}</td>
<td>(d_{S}/d_{W})_{FA}</td>
<td>(d_{S}/d_{W})_{FE}</td>
<td>(d_{S}/d_{W})_{FA}</td>
</tr>
<tr>
<td>0.01M Ce(SO₄)₂</td>
<td>1.015</td>
<td>1.027</td>
<td>1.025</td>
<td>1.046</td>
</tr>
<tr>
<td>0.4M H₂SO₄</td>
<td>1.103</td>
<td>1.217</td>
<td>1.167</td>
<td>1.364</td>
</tr>
<tr>
<td>H₂O</td>
<td>1.103</td>
<td>1.217</td>
<td>1.167</td>
<td>1.364</td>
</tr>
</tbody>
</table>
From Eq. (5) for the buildup factor, it follows that the buildup factor for a composite material made up of elements \(X_1, X_2, X_3, \ldots\) with the buildup factors \(B_1, B_2, B_3, \ldots\) and mass energy transfer coefficients \(\mu_1/\rho_1, \mu_2/\rho_2, \mu_3/\rho_3, \ldots\) at 1.25 MeV photon energy, and weight fractions \(A_1, A_2, A_3, \ldots\), is given by Eq. (12) of [1],

\[
B(r) = \frac{B_1(r) \cdot \frac{\mu_1}{\rho_1} \cdot A_1 + B_2(r) \cdot \frac{\mu_2}{\rho_2} \cdot A_2 + \ldots}{\frac{\mu_1}{\rho_1} \cdot A_1 + \frac{\mu_2}{\rho_2} \cdot A_2 + \ldots}
\]

(14)

since the mean mass energy transfer coefficient of the composite material is

\[
\left(\frac{\mu}{\rho}\right) = \frac{\mu_1}{\rho_1} \cdot A_1 + \frac{\mu_2}{\rho_2} \cdot A_2 + \ldots
\]

(15)

The buildup factors \(B_{FE}\) and \(B_{FA}\) for the two ceric dosimeters thus calculated are given in Table VI, where we also show the ratios of the corresponding buildup factors for the two dosimeters.

In Table VII we give the ratio of the absorbed dose rates \(d_s\) in these two dosimeters relative to the absorbed dose rate \(d_w\) in water,

\[
\frac{d_s}{d_w} = \frac{\left(\frac{\mu_{tr}}{\rho}\right)_s \cdot B_s(r)}{\left(\frac{\mu_{tr}}{\rho}\right)_w \cdot B_w(r)}
\]

(16)

using the value of \(\left(\frac{\mu_{tr}}{\rho}\right)_w \cdot B_w(r)\) previously calculated for water.

6. COMPARISONS OF THEORY WITH EXPERIMENT

A series of experiments was performed from February to July 1976 in order to demonstrate the rather large differences in the dose absorbed by dosimeters of different materials, and which have been irradiated with the same source for the same duration. We report here the results obtained with a Fe—Cu dosimeter and three ceric dosimeters of different ceric-cerous concentrations.

6.1 Dosimeters Used

The Fe—Cu dosimeter solution has the following composition — 0.006M FeSO\(_4\), 0.060M CuSO\(_4\) and 0.005M H\(_2\)SO\(_4\), and that of the three ceric dosimeters: 0.01M Ce\(^{4+}\) and 0.01M Ce\(^{3+}\), 0.016M Ce\(^{4+}\) and 0.009M Ce\(^{3+}\), and 0.01M Ce\(^{4+}\) and 0.09M Ce\(^{3+}\), all in 0.4M H\(_2\)SO\(_4\).

The ampules used were 3.7 x 1.63 cm diameter.

These four dosimeters will be referred to as FeCu (6/60), Ce (10/10), Ce (16/9) and Ce (10/90). Their buildup factors \(B(r)\) are calculated as before for the two cases, a) all fluorescent radiation escapes (FE) and, b) all fluorescent radiation is absorbed (FA). The values are tabulated in Table VIII along with their density \(\rho\) and their \(\mu_{tr}(E_0)/\rho\).
### TABLE VIII

**BUILDUP FACTORS OF THE FOUR DOSIMETERS USED**

<table>
<thead>
<tr>
<th>Dosimeter</th>
<th>$\rho$</th>
<th>$\frac{\mu_{tr}(E_o)}{\rho}$</th>
<th>$\mu_r = 1$</th>
<th>$\mu_r = 2$</th>
<th>$\mu_r = 4$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$B(r)_{FE}$</td>
<td>$B(r)_{FA}$</td>
<td>$B(r)_{FE}$</td>
</tr>
<tr>
<td>Ce(10/10)</td>
<td>1.0489</td>
<td>0.02964</td>
<td>2.092</td>
<td>2.139</td>
<td>3.462</td>
</tr>
<tr>
<td>Ce(16/9)</td>
<td>1.0517</td>
<td>0.02965</td>
<td>2.101</td>
<td>2.159</td>
<td>3.485</td>
</tr>
<tr>
<td>Ce(10/90)</td>
<td>1.0936</td>
<td>0.02958</td>
<td>2.252</td>
<td>2.477</td>
<td>3.874</td>
</tr>
<tr>
<td>FeCu(6/60)</td>
<td>1.011</td>
<td>0.02971</td>
<td>(2.061)</td>
<td>2.061</td>
<td>(3.391)</td>
</tr>
</tbody>
</table>
6.2 Gamma-Ray Sources Used

Two gamma-ray sources were used: a) the NUMEC-source which contains $6 \cdot 10^{14}$ Bq and consists of about 25 cm long Co–60 strips arranged in a cylindrical configuration of 7.6 cm radius, and, b) the main Co–60 source which contains $8.1 \cdot 10^{16}$ Bq and consists of two parallel plaques of Co–60 strips. The two plaques are 146 cm x 180.3 cm in area and 53.3 cm apart. The dosimeters were placed on a perpendicular to the center of the plaques and 64 cm away from the nearest plaque.

In the NUMEC, the value of $\mu r$ is equivalent to about 3 cm of water, or $\mu r = 0.2$, which accounts for the effect of the source thickness and the ampule size. The main source was under water and in the dosimeter position the effective value of $\mu r = 4.25$.

6.3 Spectrophotometer Used

A Cary 15 spectrophotometer was used for measurement of the optical density changes of the dosimeter solutions in the usual way for determining the changes in the ceric concentrations.

6.4 Generalized Expression of the Absorbed Dose Rate Due to an Extended Source

It can be shown that for an actual extended source, the absorbed dose rate at point $P(x,y,z)$ is still given by a generalized equation of the form of Eq. (6):

$$d = 1.60 \times 10^{-10} \cdot l(r) \cdot \frac{\mu r(E_0)}{\rho} \cdot B(r)$$  \hspace{1cm} (17)

where

$$l(r) = \sum l_i(r_i) = \sum C_i \cdot l_o \cdot \frac{\exp(-\mu r_i)}{4\pi r_i^2}$$  \hspace{1cm} (18)

$$B(r) = \frac{\sum l_i(r_i) \cdot B(r_i)}{\sum l_i(r_i)}$$  \hspace{1cm} (19)

$r_i$ = distance between source element $i$ and point $P(x,y,z) = P(r)$. For a continuous distribution, $\Sigma_i$ is to be replaced by integrals.

$B(r)$ in Eq. (19) for an extended source may be approximated by the buildup factor for a point source at some arbitrarily chosen point $r_o$ and multiplied by a "form factor" $F(r,r_o)$ of the extended source such that:

$$B(r)_{\text{extended source}} = B(r) = B(r_o)_{\text{point source}} \cdot F(r,r_o)$$  \hspace{1cm} (10a)

We note that the form factor $F(r,r_o)$ for a finite source will approach unity at great distances from the source

$$F(r,r_o) \to 1, \quad \text{for } r, r_o \to \infty$$  \hspace{1cm} (19b)
<table>
<thead>
<tr>
<th>Irradiator and Medium</th>
<th>Dosemeter</th>
<th>( \Delta \text{OD} ) (Ce(10/10))</th>
<th>( \Delta \text{OD} ) (FeCu(6/60))</th>
<th>( \Delta \text{OD} ) (Ce(10/10))</th>
<th>( \Delta \text{OD} ) (FeCu(6/60))</th>
<th>( \Delta \text{OD} ) (Ce(10/10))</th>
<th>( \Delta \text{OD} ) (FeCu(6/60))</th>
</tr>
</thead>
<tbody>
<tr>
<td>NUMEC (Air)</td>
<td>Ce(10/10)</td>
<td>52.30</td>
<td>10.95</td>
<td>10.95</td>
<td>10.95</td>
<td>10.95</td>
<td>10.95</td>
</tr>
<tr>
<td></td>
<td>Ce(16/9)</td>
<td>52.47</td>
<td>2.33</td>
<td>2.33</td>
<td>2.33</td>
<td>2.33</td>
<td>2.33</td>
</tr>
<tr>
<td></td>
<td>Ce(10/80)</td>
<td>45.53</td>
<td>1.95</td>
<td>1.95</td>
<td>1.95</td>
<td>1.95</td>
<td>1.95</td>
</tr>
<tr>
<td></td>
<td>FeCu(6/60)</td>
<td>4.775</td>
<td>0.560</td>
<td>0.560</td>
<td>0.560</td>
<td>0.560</td>
<td>0.560</td>
</tr>
<tr>
<td>MAIN UNDERWATER</td>
<td>Ce(10/10)</td>
<td>34.18</td>
<td>(2.33)</td>
<td>(2.33)</td>
<td>(2.33)</td>
<td>(2.33)</td>
<td>(2.33)</td>
</tr>
<tr>
<td></td>
<td>Ce(16/9)</td>
<td>3.018</td>
<td>(0.560)</td>
<td>(0.560)</td>
<td>(0.560)</td>
<td>(0.560)</td>
<td>(0.560)</td>
</tr>
<tr>
<td></td>
<td>Ce(10/80)</td>
<td>56.18</td>
<td>(2.33)</td>
<td>(2.33)</td>
<td>(2.33)</td>
<td>(2.33)</td>
<td>(2.33)</td>
</tr>
<tr>
<td></td>
<td>FeCu(6/60)</td>
<td>4.848</td>
<td>(0.560)</td>
<td>(0.560)</td>
<td>(0.560)</td>
<td>(0.560)</td>
<td>(0.560)</td>
</tr>
<tr>
<td></td>
<td>Ce(10/80)</td>
<td>36.90</td>
<td>(1.95)</td>
<td>(1.95)</td>
<td>(1.95)</td>
<td>(1.95)</td>
<td>(1.95)</td>
</tr>
<tr>
<td></td>
<td>FeCu(6/60)</td>
<td>3.018</td>
<td>(0.560)</td>
<td>(0.560)</td>
<td>(0.560)</td>
<td>(0.560)</td>
<td>(0.560)</td>
</tr>
<tr>
<td></td>
<td>Ce(10/80)</td>
<td>36.95</td>
<td>(1.95)</td>
<td>(1.95)</td>
<td>(1.95)</td>
<td>(1.95)</td>
<td>(1.95)</td>
</tr>
<tr>
<td></td>
<td>FeCu(6/60)</td>
<td>33.48</td>
<td>(2.33)</td>
<td>(2.33)</td>
<td>(2.33)</td>
<td>(2.33)</td>
<td>(2.33)</td>
</tr>
</tbody>
</table>

*Based on molar extinction coefficient of Ce\(^{3+}\) at 320 nm = 5580 M\(^{-1}\) cm\(^{-1}\) and of Fe\(^{3+}\) at 305 nm = 2200 M\(^{-1}\) cm\(^{-1}\).
6.5 Method of Analysis

The absorbed dose \( D \) measured by a chemical dosimeter is proportional to the change of optical density \( \Delta OD \)

\[
D = K' \frac{\Delta OD}{\epsilon \cdot G(X) \cdot \rho \cdot \bar{l}}
\]

(20)

where \( K' = 0.9647 \times 10^7 \) when \( D \) is in grays, and other symbols have their usual meanings, \( \epsilon \) the molar extinction coefficient, \( G(X) \) the molecular changes per 100 eV, \( \rho \) the density, and \( \bar{l} \) the dimension of the photometric cell.

Thus, with the same exposure, two dosimeters will have the ratio of their \( \Delta OD \)'s as follows:

\[
\frac{(\Delta OD)_1}{(\Delta OD)_2} = \frac{\epsilon_1 \cdot G(X_1) \cdot \rho_1}{\epsilon_2 \cdot G(X_2) \cdot \rho_2} \cdot \frac{D_1}{D_2}
\]

(21)

and \( D_1 \) and \( D_2 \) are given by Eq. (17) and the irradiation time \( t \)

\[
D_1 = d_1 \cdot t
\]

\[
D_2 = d_2 \cdot t
\]

so that

\[
\frac{(\Delta OD)_1}{(\Delta OD)_2} = \frac{\epsilon_1 \cdot G(X_1) \cdot \rho_1}{\epsilon_2 \cdot G(X_2) \cdot \rho_2} \cdot \frac{(\mu_{11}/\rho)_1}{(\mu_{11}/\rho)_2} \cdot \frac{B_1(r)}{B_2(r)}
\]

(23)

6.6 Experimental Results

Table IX summarizes the results obtained. The mean observed \( \Delta OD \)'s listed in the Table were each obtained from a number of experiments. They are corrected for decay and normalized to the same irradiation time. The error in each experimental determination is estimated to be about 2%. For the experiments in the NUMEC irradiator, accurate doses of the experiments were available from separate determinations using Fe—Cu dosimeters which had been calibrated against the Fricke dosimeter. From the observed \( \Delta OD \) and for a given dose, \( G(X) \) values of the four dosimeters were calculated using Eq. (20) for \( \epsilon_{Fe} = 2200 \) and \( \epsilon_{Ce} = 5580 \). The values are listed in the Table IX.

From the observed \( \Delta OD \), we obtained the experimental values of the ratios of \( \Delta OD \),

\[
\frac{\Delta OD \ (Ce)}{\Delta OD \ (FeCu \ (6/60))} \quad \text{and} \quad \frac{\Delta OD \ (Ce)}{\Delta OD \ (Ce(10/10))}
\]

which are shown in Table IX along with the theoretical predictions from Eq. (23) with the \( B(r) \) values calculated for the case of partial escape of the fluorescent radiation and listed in Table VIII as \( B(r)_{Fe,\text{partial}} \) for \( \mu r = 4 \) for the UNDERWATER experiments.
In Figure 3, we show the ratio \( \frac{d_s}{d_w} \) of the absorbed dose rate (\( d_s \)) of dosimeter Ce(10/90), Ce(10/10), FeCu(6/60) and the Fricke, to that of water (\( d_w \)), as a function of distance \( \mu r \). For Ce(10/90) and Ce(10/10), the partial re-absorption of the K-fluorescent radiation in the dosimeter ampule that is 3.7 cm high and 1.63 cm in diameter, gives the curves in the two shaded bands.

It is estimated that for the dimension of the dosimeters used, the percentage of absorption of the fluorescent radiation is about 18% for Ce(10/10) and Ce(16/9), and about 27% for Ce(10/90).

In the NUMEC irradiator the \( \Delta \text{OD} \) values obtained are used to calculate the G-values. But the exact check on the theory can first be made when we compare these values with the determination of \( \Delta \text{OD} \) for dosimeters at some distance under water from the source. It is seen from Table IX that the agreement between theory and experiment is satisfactory.
But the effects of the buildup factors going into the absorbed dose formula for a dosimeter can be seen in an even more striking way when we form the "water" to "air" ratio of the optical density changes ΔOD, i.e.:

\[
\frac{\Delta OD(\text{Ce}(10/90))}{\Delta OD(\text{Ce}(10/10))}
\]

In this "water" to "air" ratio, all factors of Eq. (23) cancel out except the four B(r)'s for water and air.

\[
\begin{align*}
\frac{\Delta OD(\text{Ce}(10/90))}{\Delta OD(\text{Ce}(10/10))} &= \frac{1.08 + 1.10}{0.87} = 1.25 \text{ (Experimental)} \\
\end{align*}
\]

with an uncertainty in the numerator and in the denominator of about 2%, or in the overall "water" to "air" ratio of about 4%.

The theoretical value of the ratio of Eq. (24)

\[
\frac{\Delta OD(\text{Ce}(10/90))}{\Delta OD(\text{Ce}(10/10))} = 1.044 \times (\text{correction factor for extended source})
\]

\[
= 1.21 \text{ (Theoretical)}
\]

where the correction factor for the source (a plane source versus point source) is about 1.01. Had we used Berger's value [5] for the absorption of soft gamma rays comparable to the fluorescent radiation rather than our rough estimate in Eq. (12), we would have obtained a value of 1.24 to be compared with the experimental value of 1.25.

The agreement between the theoretical and experimental values of this "water" to "air" ratio, i.e., the ratio on the L.H.S. of Eq. (24), is satisfactory.

7. CONCLUSION

From the analysis given in Section 6, we see that the various theoretical predictions are borne out by the experiments.

Indeed, apart from the theory, our experimental result of Eq. (24) means that at \( \mu r = 4.25 \) in water the absorbed dose of a Ce(10/90) dosimeter is about 1.25 times that of a Ce(10/10) dosimeter, that is:

\[
\begin{align*}
\frac{D(\text{Ce}(10/90))}{D(\text{Ce}(10/10))} &= 1.25 \\
\end{align*}
\]

as can be seen by repeated substitutions of Eqs. (20) and (21) for two chemical dosimeters into Eq. (24).
REFERENCES


DISCUSSION

H.H. EISENLOHR (Scientific Secretary): Did you take the real spectrum of the $^{60}$Co source into consideration in your numerical calculations?

C.P. WANG: Yes, we did. Indeed, we considered the whole spectrum, line and continuum, in our numerical calculations of the build-up factors.

L. FITOUSSI: Your expression for the absorbed dose rate in Eq.(6), generalized by Eq.(17), is applicable not only under the conditions you set forth, but necessarily also under conditions of secondary charged particle equilibrium (the electrons in this case).

C.P. WANG: You are referring to photon-electron equilibrium. That is exactly what is assumed in our basic Eq.(1), from which Eq.(6) and Eq.(17), the latter generalized for an extended source, follow. Thank you for referring to this point.
CALCULATION OF THE FLUENCE OF SECONDARY PHOTONS, COMPTON AND FLUORESCENCE, GENERATED BY ATTENUATION IN THIN WALLS*

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Abstract

CALCULATION OF THE FLUENCE OF SECONDARY PHOTONS, COMPTON AND FLUORESCENCE, GENERATED BY ATTENUATION IN THIN WALLS.

The problem of determining the effective attenuation of X and γ-rays, considering Compton scatter and the absorption of fluorescence photons, can in principle be solved if the walls are sufficiently thin to allow one to neglect multiple interactions. The integrals occurring in the basic equations have been partly calculated analytically, in the specific case of a cylindrical wall, in order to facilitate the numerical computations. A multiplication factor has been defined, as the ratio of the dose delivered by secondary photons to the dose delivered by primary photons, normalized to the product of the scatter or fluorescence cross-section and the wall thickness.

The calculations show that this multiplication factor can be much larger than unity; it is, therefore, clear that serious errors could occur if this effect is ignored. A survey is given of the behaviour of the multiplication factor as a function of the wall diameter, the distance from the measuring point, the energy and other parameters. This method of computation has been used to evaluate the contribution of scattered photons to the ionization in the carbon $^{60}$Co γ-ray reference chamber of the BIPM, Sèvres. This contribution has previously been estimated by extrapolating experimental data on dose enhancement by additional walls. Our calculations show that this extrapolation method is invalid and might cause an error of about 1%. The significance of the present calculations to the making of absolute ionization measurements using cavity chambers is discussed.

* This work was partially supported by the Interuniversity Institute of Nuclear Sciences.
1. INTRODUCTION

This paper deals with the calculation of the fluence of secondary photons generated by attenuation in thin walls, such that multiple interactions can be disregarded. The method of computation is an extension of the methods used in Ref. [1] for fluorescence photons and in Ref. [2] for Compton-scattered photons. Computation of the energy deposited by secondary photons in thin walls is required when a measured absorbed dose or ionization is to be converted into the fluence of primary photons of known energy or energy distribution, or to the exposure, free in air, for a narrow beam at the point of interest or of reference. For instance, calibration of a dose meter with a free-air chamber or with a transfer chamber, depends upon the following equations:

\[ D_m = \psi (\mu_{en}/\rho)_m Q \]  
\[ R = \frac{\psi (\mu_{en}/\rho)_{air}}{W} \]  

where \( D_m \) is the absorbed dose in the dose meter of material \( m \), \( R \) is the exposure at a reference point in the absence of the dose meter and the surrounding body, \( \psi \) is the energy fluence of the primary photons at the same point, \( (\mu_{en}/\rho)_{air} \) and \( (\mu_{en}/\rho)_m \) are the mass energy absorption coefficients, and \( W \) is the average energy absorbed per ion-pair. If the creation of secondary photons can be disregarded, the factor \( Q \) reduces to the ratio of the average fluence of primary photons within the dose meter volume to the fluence at the point of reference, and equals, for a plane-parallel beam, the average narrow-beam attenuation of the photons:

\[ Q_{att} = \frac{1}{V} \int_V dV \exp\{-\frac{\mu}{\rho} t(\vec{r})\} \]  

\( t(\vec{r}) \) being the distance traversed by the photons within the medium before reaching a point within the volume \( V \) of density \( \rho \) and mass attenuation coefficient \( \mu/\rho \).

The secondary photons generated by such attenuation will traverse the dose meter with a probability close to unity when the solid angle subtended by the dose meter at the point of creation of the secondaries is large. This is also true for a nearly forward emission of secondaries, such as for Compton scatter at high energies. The effective attenuation coefficient in Eq. (3) then approaches the energy absorption coefficient (see, for instance, Ref. [3]).
When the irradiated body surrounding the dose meter is large in the direction perpendicular to the radiation field (broad-beam case), and when the secondary photons are emitted in all directions, the number of secondaries traversing the dose meter can be much larger than the number of primaries removed from the beam in the narrow-beam attenuation correction. The effective correction factor, Q, thus becomes greater than unity, and may be significant even if the narrow beam attenuation is negligible.

2. GENERAL FORMULATION

The number of secondary photons created in a volume element $dV_B$ around a point with co-ordinate $\mathbf{r}_B$, and traversing without further interactions a volume element $dV$ with co-ordinate $\mathbf{r}$, equals:

$$dV_B S(\omega) d\Omega \exp \{-\mu'(|\mathbf{r}_B - \mathbf{r}|)\}$$

(4)

The source strength $S(\omega) d\Omega$ is the number of secondary photons emitted per unit path length and per unit fluence of the primary photons, in the interval of solid angle $d\Omega$ around the direction $\omega$. This interval is related to the volume element $dV$, which has a cross-sectional area $dA$ and an average chord length $dl$ in the direction $\omega$, by the equation:

$$d\Omega = \frac{dA}{(\mathbf{r}_B - \mathbf{r})^2}$$

(5)

The source strength is a constant for the photoeffect, and equals the Klein-Nishina differential cross-section for the Compton scattering:

$$S(\omega) \propto \left(1 + z^2 + \frac{\alpha^2 (1 - z)^2}{(1 + \alpha(1 - z))^2} \right) (1 + \alpha(1 - z))^{-2}$$

(6)

with $\alpha = h\nu/m_0 c^2$, $z = \cos \theta$, and where $\theta$ is the scattering angle.

The secondary photons are attenuated over a distance $|\mathbf{r}_B - \mathbf{r}|$ with an attenuation coefficient $\mu'$, taken at the particular energy of the fluorescence photons, or at the energy of scattered photons corresponding to their direction:

$$h\nu' = \frac{h\nu}{(1 + \alpha(1 - z))}$$

(7)

If multiple interactions are disregarded, the narrow beam attenuation coefficient can be used for $\mu'$, although the energy absorption coefficient is, in general, a better approximation.
The energy transferred to secondary electrons in the volume element $dV$ equals:

$$dV_B \ S(\omega) \left( \exp\{ -\mu'(\vec{r}_B - \vec{r})\} \right) \frac{dA}{(\vec{r}_B - \vec{r})^2} \ \rho \ dl \ \hbar' (\mu'_{en}/\rho)$$  \hspace{1cm} (8)

where $(\mu'_{en}/\rho)$ is the energy absorption coefficient of the secondary photons. Under conditions of secondary electron equilibrium, the total dose deposited by the secondary photons equals:

$$D_s = \frac{1}{V} \int_V dV \int_{V_B} dV_B \left( \exp\{ -\mu(\vec{r}_B)\} \right) S(\omega) \left( \exp\{ -\mu'(\vec{r}_B - \vec{r})\} \right)$$

$$\times \frac{1}{(\vec{r}_B - \vec{r})^2} \ \hbar' (\mu'_{en}/\rho)$$  \hspace{1cm} (9)

t($\vec{r}_B$) being the distance traversed by the photons before reaching a point within the volume $V_B$, which is the sum of the dose meter volume and that of the surrounding medium.

Calculation of this expression is difficult, except in some cases with high symmetry, such as for a cylindrical wall with a small dose meter on the central axis. The following paragraphs deal with this particular case.

3. CYLINDRICAL WALL

The ratio of the dose deposited by secondary photons, $D_s$, to the dose deposited by the primary photons, $D_p$, at the same point of measurement, can be scaled to the integrated source function $\bar{S}$:

$$\bar{S} = 2\pi \int_0^\pi \sin \theta \ \ d\theta \ S(\theta) \ (\hbar'/\hbar)$$  \hspace{1cm} (10)

which equals:

$$\bar{S} = \tau_{K,L} \ \omega_{K,L} \ \frac{\hbar \nu_{K,L}}{\hbar \nu}$$  \hspace{1cm} (11)
for the K, L . . . fluorescence photons, and:

$$\mathcal{S} = \sigma_s$$  \hfill (12)

for the Compton effect (symbols as used in Ref. [4]). It can also be scaled to the thickness, \( t \), of the wall. This scaling yields a “multiplication factor” \( p \), defined by:

$$p = \frac{D_s}{D_p} \cdot \frac{1}{St}$$  \hfill (13)

For a cylindrical wall of radius \( b \), the multiplication factor is given by the expression:

$$p = \frac{1}{St} \left( \exp\{\epsilon(\mu_1 t + \mu_2 v)\} \right) \int_0^t \int_0^b dx \int_0^{2\pi} dy \left( \frac{1}{r^2} \left( \frac{\mu'_{en}}{\mu_{en}} \right) \right) \left( \exp\{-\epsilon \mu'_1 \frac{t-x}{\cos \theta} \} \right) \left( \exp\{-\epsilon \mu'_{2 \nu} \frac{v}{\cos \theta} \} \right)$$  \hfill (14)

In this expression, the measuring point can be in front of (\( \epsilon = -1 \)) or beyond (\( \epsilon = +1 \)) the wall (in the direction of the beam), at a distance \( v \) from the surface; \( \mu \) and \( \mu' \) are the attenuation coefficients of primary and secondary photons in the media of the wall (index 1) and in the space between the wall and dose meter (index 2). For points inside a body, the forward and backward contributions for \( v = 0 \) are to be summed.

This expression can be computed numerically, but has been partly worked out analytically to facilitate the computations. The variable \( y \) is replaced by a variable \( z \) which equals \( \cos \theta \), or:

$$z = (t - x + s)/r$$  \hfill (15)

$$r = \sqrt{y^2 + (t - x + s)^2}$$  \hfill (16)

After changing the order of integration of the variables \( x \) and \( z \), and computing the integral in \( x \), the following expression is obtained:

$$p = \frac{1}{St} \int_0^{\epsilon} dz S(z) \left( \frac{\mu'_{en}}{\mu_{en}} \right) \left( \exp\{\epsilon(\mu_2 - [\mu'_{2 \nu}/z]) v \} \right) \left( \frac{1}{([\mu'_{1 \nu}/z] - \mu_1)} \right) \left( \frac{ev}{\sqrt{b^2 + v^2}} \right) \left( 1 - \exp\{\epsilon(t - t_0) (\mu_1 - [\mu'_{1 \nu}/z]) \} \right) \left( 1 - z^2 \right)^{-\frac{1}{2}}$$  \hfill (17)

with \( t_0 = t \) or \( (v - b|z|) (1 - z^2)^{-\frac{1}{2}} \), whichever is smaller.
This integral can easily be computed by means of a numerical (Simpson or Newton-Coates) integration programme. It is advantageous to split up the integration at the value:

\[ z = e(t + v) \left( (t + v)^2 + b^2 \right)^{-\frac{1}{2}} \]  

(18)

at which

\[ t = (v - b|z|) \left( 1 - z^2 \right)^{-\frac{1}{2}} \]  

(19)

4. FLUORESCENCE PHOTONS

Further analytical calculation is in general not possible. An expression for the dose contribution of the fluorescence photons in the central plane of a semi-infinite wall (b = \( \infty \)), has been proposed in Ref. [1].

The expression for the escape probability \( g \), which is related to the multiplication factor \( p \) by:

\[ (1 - g) = p \tau_a t \]  

(20)

is:

\[
g = 1 - \frac{\tau^{(K)} - \tau^{(K)}_t}{2\tau} \left[ \ln \left| \frac{\tau + \tau^{(K)}}{\tau - \tau^{(K)}} \right| + E_i(\tau t - \tau^{(K)} t) - E_i(-\tau t + \tau^{(K)} t) \right.
\]

\[ - (e^{\tau t} - e^{-\tau t}) E_i(-\tau^{(K)} t) \]  

(21)

where \( E_i \) is the notation for the exponential integral [5]. This expression has been extended to points at any depth \( t' \) in a plate of thickness \( t' + t'' \), and corrected for the difference between the total attenuation and energy absorption coefficients, and the photo-attenuation coefficient of the fluorescence photons (\( \tau^{(K)} \) in Ref. [1]).

The general expression of the multiplication factor \( p \) is thus:

\[
p = \frac{1}{2\mu t} \left[ \ln \left| \frac{\mu + \mu^{(K)}}{\mu - \mu^{(K)}} \right| + E_i(\mu t' - \mu^{(K)} t') - E_i(-\mu t' - \mu^{(K)} t') \right.
\]

\[ - e^{\mu t'} E_i(-\mu^{(K)} t') - e^{-\mu t'} E_i(-\mu^{(K)} t'') \left. \right| \frac{\mu^{(K)}}{\mu_{en}} \]  

(22)
An exact analytical solution for the isotropic angular distribution photons is not possible for a wall of finite radius $b$ and separation $v$. An approximation has been derived [6] for:

$$b \gg t, \quad \text{and} \quad v = 0$$

or

$$t \ll v \ll b$$

This limitation makes a numerical computation necessary in many practical cases.

5. **FINITE AREA OF THE DOSE METER**

Whereas the scatter contribution at the central axis of the cylinder, for small thickness $t$ ($\mu t \ll 1$), can be computed exactly, this calculation is far more problematical for a flat cylindrical dose meter (see Fig. 1), when the radius, $a$, is
FIG. 2. Multiplication factors for Compton scatter at 1 MeV, for an infinitely thin wall, as a function of the relative distance \((v/b)\).

(1) point dose meter \((a = 0)\); (2) dose meter with radius \(a = b\), computed using Eq. (23).

not very small when compared with the radius of the wall, \(b\). The exact multiplication factor can only be computed for an infinitely small thickness, \(t\). For example, in the case \(a = b\), this yields the following expression:

\[
p = \frac{1}{S} \int_0^e dz \, S(z) \frac{1}{z} \frac{\mu'_\text{en}}{\mu_{\text{en}}} \int_0^a \frac{2\pi y}{\pi a^2} \left(\frac{\phi}{2\pi}\right) \exp\left\{\epsilon (\mu_2 - [\mu'_2/z]) v\right\} \tag{23}
\]

In this expression, \(\phi\) is the angle defined by the intersection of the circles with radius \(a\) \((a = b)\) and \(v\) tan \(\theta\), represented in Fig. 1.
This angle is given by the expression:

$$\phi = 2 \arccos \left( \frac{y^2 - a^2 + v^2 \tan^2 \theta}{2yv \tan \theta} \right)$$

which equals $2\pi$ for $(v \tan \theta) < (a - y)$, and vanishes for $(v \tan \theta) > (a + y)$. For a finite thickness of the wall, the values obtained with Eq. (23) can be integrated over the appropriate range of distance $v$. For small values of $a$, as compared with $b$, an approximation has been derived [6] which makes use of the approximate expression for the angle $\phi$, for large values of $y$:

$$\phi \approx \frac{2}{y} \sqrt{a^2 - (y - (t - x + v) \tan \theta)^2}$$

In the resulting equation, the multiplication factor is computed as a weighted sum of the factors for a point dose meter with wall radii $(b - a)$ and $(b + a)$. The calculations show that the average fluence of secondary photons for small radii, $a$, is not significantly different from the dose on the central axis. (This is illustrated in Fig. 3G, for $(a/b) = 1$.) The true multiplication factor for $a = b$ is, however, much smaller than the plotted values. In Fig. 2 a comparison is made between the multiplication factor for Compton scatter at 1 MeV, as a function of $(v/b)$, for a point dose meter and for $a = b$, calculated using Eq. (23), for an infinitely thin wall.

6. SURVEY OF THE BEHAVIOUR OF THE MULTIPLICATION FACTOR

In Fig. 3, a survey of calculated values of the multiplication factor has been given for different geometrical parameters $b$, $t$, $v$ and $a$. The computations for the Compton effect were performed for energies of 0.1, 1 and 10 MeV, and for the photoeffect for different values of the ratio of the attenuation coefficients $(\mu'/\mu)$: 0.23, 0.63 and 1.56. The plotted values of the multiplication factor for the photoeffect should be multiplied by the ratio of the energy absorption coefficients $(\mu'_en/\mu_en)$, for the energy and material of interest. The values for the Compton effect have been calculated for a carbon wall, but are relevant also for other materials, since the ratios $(\mu'/\mu)$ and $(\mu'_en/\mu_en)$ are not much different from unity, for all materials, in the region where the Compton effect is the dominant process.

The plotted values show that the build-up of secondary photons is nearly proportional to the thickness, $t$. The multiplication factor decreases with increasing thickness, due to the distance effect and to the attenuation of secondary photons (cf. Fig. 3B). For the fluorescence photons, a similar dependence on the
FIG. 3. Multiplication factors for Compton scatter and the photoeffect, as a function of the relative distance (v/b) and of the wall radius expressed in mean-free-path lengths (μ₁b), with parameters as indicated on the graphs.
ratio \( (\mu'/\mu) \) is observed (Fig. 3H). The multiplication factor for Compton scatter increases with decreasing energy, depending on the radius \( b \) (cf. Fig. 3G). This is due to the increasing isotropy of the Compton photons at the lower energy. The decrease in the multiplication factor with distance is consequently less pronounced for higher energies (cf. Fig. 3A).

The multiplication factor increases with increasing radius of the wall (cf. Figs 3G, H, I). A saturation value is reached for \( \mu' b > 10 \). The saturation radius is smaller when the energy (Fig. 3G) or the ratio \( (\mu'/\mu) \) is increased (Fig. 3H). The effect of the attenuation coefficients \( \mu_2 \) and \( \mu'_2 \) in the space between wall and dose meter (Fig. 3C) is small. The values of the multiplication factor, when the materials (1) and (2) are identical but with equal \( (\rho_2 = \rho_1) \) or zero \( (\rho_2 = 0) \) density in space (2), differ significantly only for large distances, \( v \).

The multiplication factor is always much larger than unity, except for a very small radius of the wall, and for distances, \( v \), larger than the radius, \( b \). When the ratio \( (v/b) \) is larger than 10, the scatter or fluorescence contribution becomes negligible, and reduces further with the square of the distance.

7. PRACTICAL APPLICATIONS

The method of computation described above enables a quite exact solution to the problem for thin walls to be obtained. The range of applications may be extended to rather thick walls to obtain the order of magnitude and the evolution of the scatter contribution. This is true also for the photoeffect, since the fluorescence photons are often of such a low energy that tertiary photons are not significant.

An example of the practical application of the theory is the calculation of fluences in the experimental high-pressure cavity chamber, which is described in a separate article [7]. The details of the calculation have been presented in Ref. [6].

As an example of the application of the theory in accurate metrology, the method has been applied to the contribution of scattered photons in the carbon cavity chamber for use with \( ^{60} \text{Co} \) radiation at the BIPM. This contribution has been estimated [8] by extrapolating the measured increase of the ionization current by providing additional carbon walls, corrected for narrow-beam attenuation. The front and back walls, with a thickness of 2.83 mm, were investigated by addition of plates having thicknesses of 1, 2 and 3 mm; this yielded by extrapolation a contribution of 1.85% and 0.18% for the front and back walls, respectively.

For the side wall, a ring of 2.75 mm thickness was added (the same thickness as the actual side wall); this yielded a contribution of 0.39%. The central electrode (1.02 mm) was considered as half a front plate and half a back plate. Extrapolation
of the data for the front and back walls yielded a contribution of 0.23%. The total correction factor was:

$$K_{sc} = 0.9735 \pm 0.002$$

The calculation of the scatter contribution was undertaken for the actual walls and for the additional carbon walls.

The ionization is produced by electrons that originate in the walls of the cavity by energy deposition of the photons. The average radius within which the electrons originate is set equal to the radius of the collecting electrode. Since the angular distribution of the slowing-down electrons from the scattered photons is not fully isotropic, the energy transfers in the different walls must be weighted, depending on the direction of incidence of the photons relative to the cavity. These weighting factors were determined by matching the calculated and experimental values for the additional walls. The fitted weighting factor for inward directions of photons is found to be 0.7 for the added front plates, and 0.5 for the added back plates. The application of these weighting factors to the calculated contributions of the walls and of the central electrode yields the values reported in Table I. These values show that the extrapolation method underestimates significantly the contribution of the actual walls. This is mainly due to the greater distance of the added plates relative to the sites of energy deposition. This conclusion is quite independent of the choice of the weighting factors and of the effective radius of the collecting area (the multiplication factors being computed with the approximate expression given in Ref. [6]). Computation based on the exact expression in Eq. (23), which requires a long computing time, will be undertaken in the near future. It is believed, however, that this will not affect the conclusion regarding the underestimate of the extrapolated values. The underestimate is particularly large for the central electrode.
No accurate calculations can be made based on the present method to determine the contribution of the side wall. For the same reasons, however, the extrapolation method will probably yield an underestimate, particularly if a significant part of the ionization is due to tertiary electrons originating in the side wall. The total underestimate is thus larger than 0.6%, which is larger than the uncertainty of 0.2% given in Ref. [8].

Both the calculated and the extrapolated values may, however, overestimate the scatter contribution, because the true centres of electron production have not been taken into account. The electrons will indeed start, on average, at a small depth as measured from the cavity surface. This will have a negligible effect on the contribution of the additional walls, but will affect directly the contribution of the actual walls, due to the anisotropy of the scattered photons. The size of this effect is difficult to estimate, but is probably less than 0.3%.

The true dose enhancement by secondary photons in this chamber is therefore difficult to estimate without significant error, relative to the total calibration uncertainty of 0.68% [8]. The uncertainty in the calculated values could be reduced by constructing a large guard ring around the collecting electrode to minimize the side wall contribution and to improve the radial homogeneity of the fluence of scattered photons. Such a design would also ensure that the fluence of scattered photons is nearly constant over the air gap between the electrodes, and that it is independent of the spacing. This would allow of ionization measurements of absorbed dose at a standard depth within a broad phantom, and thus facilitate the calibration of dose meters.

8. CONCLUSION

The simple method described in this paper for the calculation of the dose contribution of Compton scattered and fluorescence photons can be valuable in many practical situations. The pilot calculations show the behaviour of this contribution as a function of the radius of the wall and of the relative distance of the measuring point from the wall. These calculations show that the contribution is strongly dependent on the geometry. The fluence of secondary photons is negligible only for distances larger than about ten times the radius of the wall. Within or in close proximity to the wall, the scatter correction can greatly exceed the narrow-beam attenuation correction. The application of the theory to the BIPM $^{60}$Co carbon chamber shows that the scattered fluences cannot be estimated by an extrapolation method. The true scatter contribution should be estimated from the combined photoelectron transport using a more elaborate method.
ACKNOWLEDGEMENTS

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The authors would also like to thank Mrs. B. Van Waeyenberge and Mr. R. Verspille for their assistance in preparing the manuscript and diagrams.

REFERENCES


DISCUSSION

J.C. McDONALD: How was the dose computed from the fluence? Was $\mu_{en}/\rho$ used or $\mu_{tr}/\rho$?

A. JANSSENS: We multiplied the secondary photon fluences by the energy absorption coefficients of the secondary photons, relative to the primary photon energy absorption coefficient. We did not take bremsstrahlung into account since the corrections involved are expected to be negligible.

R. ABEDINZADEH: Did you also try calculations for in-phantom irradiation? About four years ago we calculated the contribution of primary and secondary electrons in water with a $^{60}$Co source by a similar method. The results are published in Strahlentherapie.¹

A. JANSSENS: Thank you for this information. I will certainly look up your paper. We have not performed any calculations for in-phantom irradiation, since this method is restricted to first interactions, and at a depth of about 1 cm, for $^{60}$Co irradiation, multiple scatter should be taken into account.

¹ Strahlentherapie 143 (1972) 90.
STANDARDIZATION AND CALIBRATION OF RADIOACTIVE SOURCES
STANDARDIZED RADIOACTIVE DECAY DATA SETS FOR USE IN RADIATION DOSIMETRY*

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Presented by W.M. Good

Abstract

STANDARDIZED RADIOACTIVE DECAY DATA SETS FOR USE IN RADIATION DOSIMETRY.

A computer-based system for obtaining the energies and intensities of radiations from radionuclide decays in a format suitable for application to radiation dosimetry calculations is described. The system is based on radionuclide decay data written in the format of the Evaluated Nuclear Structure Data File (ENSDF). These data are processed with the computer code MEDLIST, which produces listings of the energies and intensities of the radiations in tabular form and in a decimal, computer-readable format. Collections of radionuclide decay data which have been prepared for publication from ENSDF by the MEDLIST code and applications of these data to radiation dosimetry calculations are discussed.

1. INTRODUCTION

The availability of evaluated decay data for a large number of radionuclides is of fundamental importance for radiation dosimetry. This paper describes a computer-based system for obtaining the energies and intensities of the atomic and nuclear radiations from radionuclide decays in a format suitable for application to radiation dosimetry calculations.

The system described here was developed by the Nuclear Data Project at Oak Ridge National Laboratory. For three decades, the Nuclear Data Project has been a recognized center for the systematic collection and evaluation of data from all types of nuclear structure experiments, including those pertaining to radioactive decay. The process of organizing nuclear structure data into formats suitable for publication in the journal Nuclear Data Sheets [1] has led to the development of a comprehensive, computer-based Evaluated Nuclear Structure Data File (ENSDF) [2]. The radionuclide decay data contained in ENSDF are described in Section 2. The computer code MEDLIST [3], which processes

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FIG. 1. ENSDF Decay Data. Radionuclides for which data sets are included in the computer-based Evaluated Nuclear Structure Data File (ENSDF), plotted as neutron excess (N−Z) v. atomic number (Z).
The radionuclide decay data in ENSDF are organized into data sets, each of which summarizes the state of experimental knowledge for a distinct decay mode (α, β−, β+, γ, and electron capture, or isomeric transition) of a particular radionuclide. At present, ENSDF includes approximately 1450 decay data sets for the radionuclides shown in Fig. 1. Each data set includes a recommended or adopted value for the radionuclide half-life and the decay branching fraction for the particular decay mode, adopted values for the energies and intensities of the nuclear radiations (α, β−, β+, γ, and conversion electron) occurring in the decay mode, and an adopted uncertainty for each quantity. A decay data set may also include information on daughter radionuclides produced in the decay and their relative abundances. Each adopted value is based on a careful evaluation of all available measurements reported in the worldwide literature. All data sets are reevaluated at least every four to five years.

FIG. 2. Data set for 134Cs β− decay written in ENSDF format. The format is described in Section 2.
FIG. 3. Decay scheme for $^{134}$Cs $\beta^-$ decay generated from data set in ENSDF format. The intensity shown with each gamma ray is the number of transitions (photon plus conversion electron) per 100 decays of $^{134}$Cs.
Each decay data set in ENSDF is written in a uniform, standard format. The format is illustrated by means of the data set for $^{134}$Cs $\beta^-$ decay shown in Fig. 2. The corresponding decay scheme is shown in Fig. 3. The data set begins with an identification record giving the daughter nucleus identification, the data set name, and key numbers for the literature references. Following the identification record are optional comment records, denoted by the letter “C” following the nucleus identification. For this data set, these records give descriptive information about the decay branching fraction and the measured intensities for two beta groups. The normalization record, denoted by “N”, gives the factors by which the measured relative photon intensities are multiplied to obtain absolute intensities. Multiplication by the first factor gives the number of photons per 100 $\beta^-$ decays. Multiplication of these intensities by the second factor, the decay branching fraction, gives the number of photons per 100 decays of $^{134}$Cs. The parent record, denoted by “P”, gives the parent nucleus identification, the level energy and spin-parity of the parent, the adopted half-life and its uncertainty, and the adopted decay Q value and its uncertainty. Level records for the daughter nuclide, denoted by “L”, give the level energy and its uncertainty, the spin-parity, and the half-life. Following each level record are $\gamma$ and gamma records, denoted by “B” and “G”, respectively, for the particular level. The first card of each $\beta^-$ record gives the endpoint energy of the beta group feeding the level, the number of betas per 100 decays of $^{134}$Cs, the log $\beta$ value, and their uncertainties. The second card of each $\beta^-$ record gives the average beta energy and its uncertainty. The gamma records describe each gamma-ray transition originating from the decay of the particular energy level. The first card of the gamma record gives the adopted photon energy and relative intensity and their uncertainties, the transition multipolarity, the multipole mixing ratio and its uncertainty, the total internal conversion coefficient and its uncertainty, and symbols denoting measured coincidences. The second card of the gamma record gives internal conversion coefficients for the K, L, M, etc., shells. For this data set, a conversion coefficient is given on a second gamma card only if the resulting conversion-electron intensity is greater than 0.1 per 100 decays.

Tables of recommended Q values and computer codes maintained by the Nuclear Data Project are used to calculate the internal conversion coefficients, normalization factors for obtaining absolute intensities of the nuclear radiations, and energies and intensities of individual beta groups included in a data set. Further information about ENSDF formats can be obtained from Ref. [2].

3. COMPUTER CODE MEDLIST AND TABLES OF DECAY DATA

The radionuclide decay data sets in ENSDF contain information about the nuclear radiations. The energies and intensities of the atomic radiations (X rays and Auger electrons) are calculated by processing the data sets in ENSDF format with the computer code MEDLIST [3]. The code combines the atomic radiations with the nuclear radiations, sorts them according to radiation type, and, within each type, arranges and numerically labels them in order of increasing energy.

The data table obtained as output from the MEDLIST code for the $^{134}$Cs $\beta^-$ decay data set is shown in Fig. 4. The table lists all radiations with intensity greater than 0.1 per 100 decays. Auger and conversion-electron radiations are listed first, followed by the beta radiations for which both endpoint and average energies are given, and then the electromagnetic radiations. Immediately following the beta and gamma listings, the code prints a comment giving the number of radiations omitted from the listing because the intensity is less than 0.1 per 100 decays, the average energy of the omitted radiations, and their summed intensity. The average energy is calculated from the energies of the individual omitted radiations weighted by their respective intensities. The last column in the table gives the equilibrium absorbed-dose constant; i.e., the energy emitted per decay in units of g-rad/$\mu$Ci·h. The data tables produced by MEDLIST are described in detail in Ref. [3].

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1 The conventions used in Fig.3 are described in any recent issue of Nuclear Data Sheets [1]. It is noteworthy that Fig.3 was prepared automatically by computer from the ENSDF data set.

2 The low-intensity cutoff limit is an adjustable parameter in the MEDLIST code.
Table of energies and intensities of atomic and nuclear radiations from $^{134}$Cs $\beta^-$ decay produced by the computer code MEDLIST from the data set in ENSDF format. The table and the code MEDLIST are described in Section 3.

In addition to the data table shown in Fig. 4, the MEDLIST code produces output in a decimal, computer-readable format suitable for use as input to further calculations. The format for this output is available upon request from the Nuclear Data Project.

### 4. APPLICATIONS OF ENSDF AND THE MEDLIST CODE

Several collections of radionuclide decay data have been prepared and published using standardized data sets in ENSDF format and the MEDLIST code. These include a group of 194 radionuclides for users concerned with biological effects of radiation [3], a group of 220 radionuclides of importance in radiation protection [4], and a group of 240 radionuclides of potential importance in routine releases from nuclear fuel cycle facilities [5].
The MEDLIST decimal output for the data in Ref. [5] was used to calculate dose-rate conversion factors for external exposure to electron and photon radiation from radionuclides in the air, in water, and deposited on a smooth ground surface (in units of mrem/h per µCi/cm² or mrem/h per µCi/cm²), and to calculate S factors for internal dose (in units of rem/µCi·d) [6].

The Nuclear Data Project welcomes inquiries from persons interested in using radionuclide decay data sets in ENSDF or decay data produced by MEDLIST.

REFERENCES


DISCUSSION

B.J. JACKSON: Could you indicate the date of the last review of the data on the lists?

D.C. KOCHER: Yes, I myself routinely include the date when a data set has last been updated. In cases such as the one illustrated in Fig.2 of the paper, the date can be given on the first record (the identification record) of the data set following the key numbers for the literature references.

B.J. JACKSON: How often are the data reviewed?

D.C. KOCHER: The Nuclear Data Project re-evaluates its data sets at least every four to five years. For my work in the Health and Safety Research Division, I maintain my own file of radioactive decay data sets in ENSDF format. This file at present contains about 380 decay data sets, and I attempt to update them continuously (i.e., about every three months) as new and significant results are brought to my attention by “Recent References”, which is published quarterly by the Nuclear Data Project.

3 Answers confirmed for the Proceedings by an author.
THE RADIOACTIVITY STANDARDS PROGRAMME OF THE NATIONAL BUREAU OF STANDARDS

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Abstract

THE RADIOACTIVITY STANDARDS PROGRAMME OF THE NATIONAL BUREAU OF STANDARDS.

From nuclear data tables, such as those compiled by the Oak Ridge Nuclear Data Project, the absorbed dose to a homogeneous medium can be calculated from given values of the mean energy per decay, expressed in gram rad per microcurie hour. To make any of these calculations the activities of the various components of radioactive effluents or of the administered radio-pharmaceuticals must be known. For more than ten years the Radioactivity Section of the National Bureau of Standards has been devoting a very considerable part of its effort to the production of radioactivity standards that are needed in environmental and nuclear-medicine measurements. Such standards are also being produced in appropriate environmental matrices and the latest available nuclear-decay data, often produced in the Radioactivity Section, is also supplied. Traceability to the International and National Radioactivity Measurements Systems is discussed.

Absorbed doses of radiation arising from various radiation sources affect the population at large. One of these sources is radioactivity, and the radiation arising from this can be delivered to man through many different paths. There is natural radioactivity and induced, and both interact with man by way of the air, water or food which he assimilates, or in the form of therapeutic or diagnostic radioactive agents with which he is treated.

Natural radioactivity escapes from the earth largely in the form of radon or thoron, or can be injected into the environment as daughters of these families from coal-burning power stations. Radium-226 can be leached by water, and radon-222 is often present in the water from springs and wells.

In assessing the dose to man, either collectively or individually, one starts with the activity of a particular radionuclide and then develops a plausible mathematical model to calculate the dose. Thus, in the case of iodine-131 effluent from a power reactor, one first measures the activity in the stack and then models the flow from the stack to the surrounding countryside as a function of prevailing meteorological conditions. The processing of the iodine
TABLE I. EXAMPLE OF A NUCLEAR DECAY SCHEME TABLE

Taken from Appendix A of A Handbook of Radioactivity Measurements Procedures issued by the NCRP [7]

<table>
<thead>
<tr>
<th>Radiation Type</th>
<th>Energy (keV)</th>
<th>Intensity (%)</th>
<th>Intensity (µCi-h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auger-L</td>
<td>2.72</td>
<td>0.18</td>
<td>3</td>
</tr>
<tr>
<td>β⁻ 1 max</td>
<td>692.9 20</td>
<td>6.3 16</td>
<td>0.0304</td>
</tr>
<tr>
<td>avg</td>
<td>226.2 6</td>
<td>0.08</td>
<td>0.003</td>
</tr>
<tr>
<td>β⁻ 2 max</td>
<td>789.6 20</td>
<td>1.0 3</td>
<td>0.0060</td>
</tr>
<tr>
<td>avg</td>
<td>281.6 6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>β⁻ 3 max</td>
<td>1035.0 20</td>
<td>92.7 16</td>
<td>0.717</td>
</tr>
<tr>
<td>avg</td>
<td>363.3 9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>total β⁻</td>
<td>353.7 9</td>
<td>100.0 23</td>
<td>0.754</td>
</tr>
</tbody>
</table>

3 weak β's omitted (Σβ = 0.04 %)

| γ 1            | 96.75 20    | 0.11 3       | 0.0002           |
| γ 2            | 245.400 20  | 1.1 3        | 0.0057           |
| γ 4            | 342.130 20  | 6.0 16       | 0.0436           |

7 weak γ's omitted (Σγ = 0.04 %)

Deposited on the grass (or of strontium-90 in the case of fall-out), through the benign intervention of the cow, into the milk distributed to the local population, must then be modelled and calculated in terms of potential radioactive deposition, and it is also measured at many sampling stations after the event. In the case of radiopharmaceuticals administered to man, crude models of his organs are assumed, together with their spatial distribution, and the absorbed dose, due to a source of penetrating radiation located in one, is calculated by Monte-Carlo methods for any other organ in the body or for the whole body [1, 2].

If radioactive materials are introduced into man, either from the environment or in the form of a radiopharmaceutical, they will often localize in certain organs; it is important to be able to assess not only the absorbed radiation dose in these organs but also in other parts of the body. Calculations of such doses to other organs are usually based on the concept of absorbed fraction introduced by Ellett, Callahan and Brownell [3, 4] and of specific absorbed fraction used by Loevinger and Berman [5, 6]. If A₀ be the activity ingested by or administered to a man and f is the fraction taken up by one of his organs, then:

\[ A_s = f A_0 \]  

is the activity localized in that source organ. The mean absorbed dose, \( \bar{D} \), in
FIG. 1. "Traceability Tree" for International and National Radioactivity Measurements Systems.

Organizational acronyms are:

**International**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>BIPM</td>
<td>Bureau International des Poids et Mesures</td>
</tr>
</tbody>
</table>

**National**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>NBS</td>
<td>National Bureau of Standards</td>
</tr>
<tr>
<td>NRC</td>
<td>National Research Council of Canada</td>
</tr>
<tr>
<td>NPL</td>
<td>National Physical Laboratory</td>
</tr>
<tr>
<td>LMRI</td>
<td>Laboratoire de Métrologie des Rayonnements Ionisants</td>
</tr>
</tbody>
</table>

**United States organizations**

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Full Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>DOE</td>
<td>Department of Energy</td>
</tr>
<tr>
<td>NRC</td>
<td>Nuclear Regulatory Commission</td>
</tr>
<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
</tr>
<tr>
<td>HEW</td>
<td>Department of Health, Education and Welfare</td>
</tr>
<tr>
<td>FDA</td>
<td>Food and Drug Administration</td>
</tr>
<tr>
<td>BRH</td>
<td>Bureau of Radiological Health</td>
</tr>
<tr>
<td>DOD</td>
<td>Department of Defense</td>
</tr>
<tr>
<td>AIF</td>
<td>Atomic Industrial Forum</td>
</tr>
<tr>
<td>CAP</td>
<td>College of American Pathologists</td>
</tr>
</tbody>
</table>

The International Atomic Energy Agency and International Committee for Radionuclide Metrology also function at the international level in coordinating such activities as low-level environmental radioactivity measurements, applications of nuclear medicine, and the acquisition of nuclear-decay and neutron cross-section data.

another organ, the target organ, due to the source organ can then be given [2, 6] by the expression:

\[
\overline{D}(t \leftarrow s) = \tilde{A}_s \sum_i \Delta_i \frac{\phi_i(t \leftarrow s)}{m_t}
\]  

(2)

where \(\tilde{A}_s (= \int \tilde{A}_0)\) is the time integral of the activity in the source organ taken
over some suitable interval of time, $\Delta_i$ is the energy emitted per decay in the $i$-th radiation of the radionuclide in question, $\phi_i(t \rightarrow s)$ is the fraction of the energy of the $i$-th radiation that is absorbed by the target organ, and $m_t$ is the mass of the target organ. The quantity $\phi_i(t \rightarrow s)$ is known as the absorbed fraction, and the quantity $\phi_i(t \rightarrow s)/m_t$ is usually called the specific absorbed fraction. For radiations of low penetration, $\phi$ is approximately unity and the source organ is also the target organ. The mean absorbed dose can then be calculated if $A_0$, $f$, $\Delta_i$ and the mass of the organ are known. Values of $\Delta_i$ are given for all known transitions of radionuclides of interest in the forthcoming NCRP Handbook of Radioactivity Measurements Procedures [7] (for an example, see Table I).

For penetrating radiations (photons with energies greater than 10 keV) values for the specific absorbed fractions are given in ICRP Publication 23 [2].

In either event, however, fundamental inputs into the calculation of the mean absorbed dose are the value of $A_0$, the activity introduced into the subject, and the nuclear decay data for the radionuclide, or radionuclides, in question.

The accuracies with which these activities are known will also be reflected in the final evaluation of dose, and it is therefore important that additional uncertainties in activity measurements should be kept reasonably small, so that uncertainties may be limited to those of the models themselves.

The National Bureau of Standards (NBS) is the custodian of the United States National Radioactivity Measurements System, one of the National Ionizing Radiation Measurements Systems, the requirements for traceability to which have already been described and discussed by my colleagues Cavallo, Ehrlich and Hutchinson in this Symposium [8]. In Fig. 1 is shown in rather skeleton form that part of the national and international "family tree of traceability" in which the National Bureau of Standards finds itself both as progeny and progenitor. There are many other branches involving other national laboratories and, as in most highly reputable international families, a sibling of perhaps lesser legitimacy may be found in the form of crown companies or atomic energy commissions.

In the United States of America the function of the National Bureau of Standards is to transfer traceability from the international level to the national level and vice versa. In the field of radioactivity we interact internationally with the Bureau International des Poids et Mesures (BIPM), the International Atomic Energy Agency (IAEA), and the International Committee for Radionuclide Metrology (ICRM).

The first international radioactivity standards were those of radium, prepared in 1911 by Marie Curie and Otto Hönigschmid. In 1912 a whole committee appointed by the Congress of Radiology and Electricity met in Paris, not to prepare a report but, shades of a bygone age, to carry out an experiment, namely to compare the two radium standards which were then named the 1911 Paris and Vienna International Standards of radium. In 1934, Professor Hönigschmid
prepared twenty new radium preparations, one of which was compared with the 1911 Paris radium standard [9] and designated as the new BIPM international radium standard. Subsequently in 1959, after many international measurements of the 1934 Hönigschmid standards, it was agreed that all the 1934 Hönigschmid radium standards could represent the international radium standard [10].

After the advent of the nuclear age, with its prolific supplies of radioactive materials, the Tripartite Countries (Canada, the United Kingdom, and the United States of America) initiated in 1957 three-way international comparisons of radioactivity measurements. The organization of such intercomparisons was continued by the International Commission on Radiological Units and Measurements (ICRU) from 1955 until, in the period between 1958 and 1962, it gradually turned over responsibility for such measurements to BIPM.

In 1962 the IAEA also began to distribute activity standards of a number of radionuclides, and in the mid-1960s it organized a series of international measurements of low levels of radioactivity in environmental matrices. NBS participated in those of $^{90}$Sr-$^{90}$Y in rice flour and seaweed, $^{131}$I in powdered milk, and $^{144}$Ce in spinach.

The organization of such international comparisons and the reporting and collating of the data culled from them have, however, begun to demand an almost superhuman effort (see, for example, Ref. [11]).

A simpler method of maintaining international traceability was, however, suggested in 1967, namely to establish a very stable ionization chamber at BIPM for the purpose of measuring national standards of photon-emitting radionuclides so that consistency would be maintained between national laboratories and also within individual national laboratories over extended periods of time. Such a system for maintaining internal consistency had been in operation at NBS for many years and also at other national laboratories. It was also pointed out that such a well calibrated chamber at BIPM, with calibrations derived from standards produced by many national laboratories, could provide other countries having more limited facilities with calibrations for radionuclides that, because of complicated decay schemes, might present serious problems in measurement. This scheme was adopted by the IAEA [12] and first put into operation by the Agency in 1973, and then by BIPM in 1975. If, in the course of the measurement and registration of any photon-emitting radionuclides by IAEA or BIPM, serious discrepancies are revealed between national laboratories, then international measurements can be organized on split samples of the same solution of that radionuclide in the hope of elucidating the nature of the discrepancy.

Another international radioactive metrology effort worthy of note is the monitoring by IAEA of the levels of tritium in water at many hydrological monitoring stations around the world. In this connection we are very gratified that our tritiated-water standards have been adopted as the international standard for such measurements.
Recently a third international body has entered the field of radionuclide metrology, namely the International Committee for Radionuclide Metrology (ICRM). This body burgeoned from the roots laid by the First International Summer School on Radionuclide Metrology held in the late summer of 1972 at Herceg Novi in Yugoslavia [13]. It was nurtured into existence and through its first three years by Boris Grinberg, its chairman for that period. At the first meeting of the members of ICRM at Saclay in 1975 its activities were defined so as to cover only fields in metrology not already covered by BIPM. These new fields initially included the life sciences, low-level radioactivity measurements, alpha-, beta- and gamma-ray spectrometry, nuclear-decay schemes and nuclear energy. All are concerned with the direct or indirect achievement of international accuracy and consistency of radioactivity measurements. Working and information groups were set up in each field and their respective chairmen are M.J. Woods (United Kingdom), J.M.R. Hutchinson (United States of America), K. Debertin (Federal Republic of Germany), J. Legrand (France), and Y. LeGallic (France).

The information group on the life sciences has issued a comprehensive questionnaire seeking to identify problems in nuclear medicine and Janet S. Merritt has written a report dealing with problems encountered in the calibration of dose calibrators. The working group on low-level measurements techniques organized a successful symposium on environmental problems, the proceedings of which are in process of publication in the new International Journal of the Environment. The spectrometry group has organized a very useful intercomparison of the measurement of photon emission rates at energies between 120 keV and 1408 keV with germanium spectrometry systems. This intercomparison involved not only standardizing laboratories, but many other gamma-ray-spectrometry groups. Better values of gamma-ray probabilities for the radionuclide distributed ($^{152}$Eu) should also result from the intercomparison. The activities of the nuclear-decay group may have been rendered somewhat redundant because the IAEA has organized a group with similar aims, and Legrand is participating in the activities of this group. The nuclear-energy information group has been considering the scientific and sociological problems associated with nuclear power production.

BIPM and IAEA representatives have attended both of the last two ICRM annual meetings so that close co-operation between all three international bodies can be assured.

Figure 1 also indicates to whom our radioactivity standards and calibration services are made available on the domestic scene. Many United States Government Agencies, as already described by Cavallo et al. at this Symposium [8], have agreements or working arrangements with NBS for the maintenance of traceability in radioactive metrology. The beginnings of such arrangements were also described at an international summer school at Herceg Novi in 1972 [14]. Essentially the philosophy underlying the arrangements illustrated by Fig. 1 is that NBS can in no way maintain firsthand metrological traceability in radioactivity
to all domestic users of radioactive materials in the USA. The numbers of hospitals and medical laboratories involved in the use of radiopharmaceuticals are in the tens of thousands. Thus we feel that the only way we can establish a strong link with the practitioners of nuclear medicine is through the producers of radiopharmaceuticals, the manufacturers of dose calibrators, and also through the Food and Drug Administration (FDA). This then is the basis of our arrangements with the Atomic Industrial Forum (AIF), described in Volume 1 by Cavallo et al. [8], and with the FDA. In the long term we aim to establish the "dose" of a radiopharmaceutical, so that the manufacturer's stated value of the activity cannot only be accepted at face value, but may even be used to calibrate an ionization-chamber system such as a commercial dose calibrator. In the same way we are carrying out traceability exercises with the Environmental Protection Agency (EPA) and the Nuclear Regulatory Commission (NRC) so that, through them, State health laboratories and the health physics laboratories of nuclear power stations and fuel processing plants may be accountable to each other on the same common scale inherent in the National Radioactivity Measurements System.

As I said at the beginning of this paper, assumed models for the pathway of radioactive material from its source to its potential host and the calculation of the dose delivered may be tenuous and subject to error. But the National Bureau of Standards, like many of its sister national laboratories, is trying to minimize error in that parameter that enters right at the beginning of all calculations based on such models, namely the activity.

REFERENCES


DISCUSSION

M.A.F. AYAD: In your oral presentation, you mentioned the activities of some radioisotopes coming from boiling-water reactors. Is any work being done to estimate the radioactivity associated with pressurized-water reactors?

W.B. MANN: All radioactive effluents from power reactors are monitored and controlled by the Nuclear Regulatory Commission and the Environmental Protection Agency. The National Bureau of Standards is non-regulatory, and the purpose of our quality-control exercises is merely to ensure correct measurements; this is part of our responsibility for tightening up national and international radioactivity measurements systems. If measurements are divergent we try to help the laboratory in difficulty to identify its problem.

M.A.F. AYAD: What is the proper unit to use for absorbed dose?

W.B. MANN: The dimensions of absorbed dose are joules per kilogram, and the unit in the Système International (SI) is the gray.
REALISTIC CALIBRATION OF WHOLE-BODY COUNTERS FOR MEASURING PLUTONIUM*

W.W. PARKINSON Jr., R.E. GOANS, W.M. GOOD
Oak Ridge National Laboratory,
Oak Ridge, Tennessee,
United States of America

Abstract

REALISTIC CALIBRATION OF WHOLE-BODY COUNTERS FOR MEASURING PLUTONIUM.

The low energies and abundance of X-ray photons from $^{239}\text{Pu}$ make its detection in vivo one of the most difficult procedures in low-level radioactive counting. Standard practice is to reduce background by thick shielding, controlled atmospheres and electronic pulse shape discrimination. The natural radioactivity of the human subject, however, sets a lower limit on the quantity of plutonium which can be detected in the lungs and chest. Monte Carlo photon transport calculations have been performed for the 14, 17 and 20 keV L X-ray photons from various distributions of plutonium in a simulated human chest and compared with measured counting rates from a uniform distribution and a point source in a Rando phantom. Agreement is reasonable for a $^{239}\text{Pu}$ calibration factor of 6.5 nCi (240 Bq) per count/min in the average human chest (25 mm tissue) for the paired 127 mm phoswich detectors of the Oak Ridge National Laboratory facility. The counting rate in the plutonium region for the average human subject is about 500 counts in 40 minutes, due largely to the $^{40}\text{K}$ content of natural potassium. The minimum detectable activity (MDA) of $^{239}\text{Pu}$, at twice the standard deviation of this counting rate, corresponds to 6.6 nCi (245 Bq). Furthermore, unless recent uncontaminated counting data on the specific subject are available, it is necessary to allow for the normal $^{40}\text{K}$ radioactivity by deriving a ratio of the counts in the plutonium spectral region (14—25 keV) to some spectral region characteristic of normal human radioactivity. The two regions utilized for this purpose at ORNL have been the 1.46 MeV $^{40}\text{K}$ photopeak and the 80—128 keV upper end of the phoswich spectrum. For an uncontaminated, male population at ORNL, the ratio of the plutonium 14—25 keV band to the 1.46 MeV $^{40}\text{K}$ photopeak has been found to be 0.022 and that of the plutonium to the 80—128 keV band was 0.15 with standard deviations for the population of 23% and 17%, respectively. When these standard deviations among the normal population are taken into account, the MDA for a human subject becomes 14 nCi (520 Bq) of $^{239}\text{Pu}$ at the 2σ level. If common radionuclides such as the fission products $^{137}\text{Cs}$ or $^{90}\text{Sr}$ are present, the MDA, even with accurate spectral stripping can easily become 20—25 nCi (740—925 Bq) depending, of course, on the counting rate of these additional contaminants.

* Research sponsored by the United States Department of Energy under contract with the Union Carbide Corporation.
1. INTRODUCTION

One of the most difficult and demanding areas of low-level counting is the detection of $^{239}$Pu in vivo, since photons are emitted in only 4.6% of the disintegrations, and these have only low energies, 13 to 20 keV. In the case of inhalation of actinide elements it is common practice at many installations to determine the resulting lung burden by external counting of these low-intensity, L x-rays with either a phoswich detector, proportional counter, or Ge detector. Since the purpose of this paper is to examine calibration procedures for Pu counting and to discuss possible uncertainties in the determination of lung burdens, and since essentially all of our operational experience at Oak Ridge National Laboratory has been limited to the use of phoswich detectors, the discussion that follows will deal exclusively with that instrument.

Standard instrumentation for external counting of the actinides at ORNL is a matched pair of 127 mm diameter phoswich detectors. For those unfamiliar with such a system, the phoswich is essentially a thin NaI(Tl) crystal ($\approx$ 1.5 mm thick) optically coupled to a CsI(Na) crystal (25 or 50 mm thick) which serves as an anti-coincidence mantle to suppress those low-energy events arising from high energy encounters. A block diagram of this system is shown in Fig. 1. Basically, pulses from the dual phoswich assembly are summed and routed to a delay line amplifier from which both unipolar and bipolar outputs are available. The bipolar output is used for pulse-shape timing and a time-to-pulse-height analyzer (TPHA) is employed to distinguish pulses arising in the NaI crystal from those arising from dual crystal events. The unipolar signal is delayed $\approx$ 4 $\mu$s while these logic decisions are made. If the analyzed bipolar pulse has the time signature of NaI, the unipolar output is then routed through a linear gate for computer analysis. A cosmic ray

Text continues on page 161
TABLE I. $\mu$ AND CORRESPONDING HALF-VALUE LAYERS FOR L X-RAYS ARISING FROM THE DECAY OF PLUTONIUM

<table>
<thead>
<tr>
<th>Scattering Medium</th>
<th>$\mu$ (cm$^{-1}$)</th>
<th>Half-Value Layers (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>L$_\alpha$</td>
<td>L$_\beta$</td>
</tr>
<tr>
<td>Soft Tissue</td>
<td>1.83</td>
<td>0.968</td>
</tr>
<tr>
<td>Bone</td>
<td>9.53</td>
<td>4.85</td>
</tr>
<tr>
<td>Lung</td>
<td>0.607</td>
<td>0.318</td>
</tr>
</tbody>
</table>

TABLE II. ENERGIES OF PROMINENT L-SERIES X-RAY LINES FOR THE ELEMENTS Th-Cm

<table>
<thead>
<tr>
<th>Element</th>
<th>Z</th>
<th>Line Designation (keV)</th>
<th>L$_k$</th>
<th>L$_{\alpha 1}$</th>
<th>L$_{\beta 1}$</th>
<th>L$_{\gamma 1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Th</td>
<td>90</td>
<td>11.119</td>
<td>12.969</td>
<td>16.202</td>
<td>18.983</td>
<td></td>
</tr>
<tr>
<td>U</td>
<td>92</td>
<td>11.618</td>
<td>13.615</td>
<td>17.220</td>
<td>20.167</td>
<td></td>
</tr>
<tr>
<td>Np</td>
<td>93</td>
<td>11.890</td>
<td>13.944</td>
<td>17.750</td>
<td>20.785</td>
<td></td>
</tr>
<tr>
<td>Am</td>
<td>95</td>
<td>12.384</td>
<td>14.617</td>
<td>18.852</td>
<td>22.065</td>
<td></td>
</tr>
<tr>
<td>Cm</td>
<td>96</td>
<td>12.650</td>
<td>14.959</td>
<td>19.426</td>
<td>22.730</td>
<td></td>
</tr>
<tr>
<td>Bk</td>
<td>97</td>
<td>12.917</td>
<td>15.307</td>
<td>20.006</td>
<td>23.417</td>
<td></td>
</tr>
<tr>
<td>Cf</td>
<td>98</td>
<td>13.174</td>
<td>15.660</td>
<td>20.611</td>
<td>24.116</td>
<td></td>
</tr>
<tr>
<td>Es</td>
<td>99</td>
<td>13.429</td>
<td>16.014</td>
<td>21.234</td>
<td>24.835</td>
<td></td>
</tr>
<tr>
<td>Fm</td>
<td>100</td>
<td>13.685</td>
<td>16.374</td>
<td>21.875</td>
<td>25.574</td>
<td></td>
</tr>
</tbody>
</table>

TABLE III. ABSOLUTE L X-RAY INTENSITIES IN THE DECAY OF SEVERAL ACTINIDE NUCLIDES

<table>
<thead>
<tr>
<th>Parent Nuclide</th>
<th>L$_k$</th>
<th>L$_{\alpha}$</th>
<th>L$_\beta$</th>
<th>L$_\gamma$</th>
<th>% per disintegration</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{238}$Pu</td>
<td>0.26 ±0.01</td>
<td>4.15±0.07</td>
<td>5.61±0.07</td>
<td>1.36±0.02</td>
<td>11.38±0.10</td>
</tr>
<tr>
<td>$^{239}$Pu</td>
<td>0.113±0.005</td>
<td>1.82±0.04</td>
<td>2.16±0.04</td>
<td>0.53±0.01</td>
<td>4.63±0.06</td>
</tr>
<tr>
<td>$^{240}$Pu</td>
<td>0.24±0.01</td>
<td>3.78±0.06</td>
<td>4.84±0.07</td>
<td>1.20±0.03</td>
<td>10.06±0.10</td>
</tr>
<tr>
<td>$^{242}$Pu</td>
<td>0.21±0.02</td>
<td>3.10±0.08</td>
<td>4.15±0.10</td>
<td>1.08±0.04</td>
<td>8.54±0.14</td>
</tr>
<tr>
<td>$^{244}$Am</td>
<td>0.86±0.03</td>
<td>13.2±0.3</td>
<td>19.25±0.60</td>
<td>4.85±0.2</td>
<td>38.2±0.7</td>
</tr>
<tr>
<td>$^{246}$Cm</td>
<td>0.25±0.01</td>
<td>3.86±0.07</td>
<td>4.30±0.07</td>
<td>1.03±0.02</td>
<td>9.44±0.10</td>
</tr>
<tr>
<td>$^{246}$Cm</td>
<td>0.21±0.01</td>
<td>3.33±0.07</td>
<td>3.71±0.07</td>
<td>0.86±0.02</td>
<td>8.11±0.10</td>
</tr>
<tr>
<td>$^{250}$Cf</td>
<td>0.21±0.01</td>
<td>3.27±0.08</td>
<td>3.85±0.08</td>
<td>0.85±0.03</td>
<td>8.18±0.12</td>
</tr>
</tbody>
</table>
### TABLE IV. MONTE CARLO RESULTS: POINT SOURCE IN RIGHT LUNG (MIDPLANE, CENTER)

<table>
<thead>
<tr>
<th>Number of Histories</th>
<th>Total Escapes (%)</th>
<th>Front</th>
<th>Right</th>
<th>Rear</th>
<th>Left</th>
<th>Top</th>
<th>Bottom</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_\alpha$</td>
<td>$0.858 \times 10^6$</td>
<td>8 ($9.3 \times 10^{-4}$)</td>
<td>4</td>
<td>-</td>
<td>4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$L_\beta$</td>
<td>$0.5 \times 10^6$</td>
<td>412 ($8.2 \times 10^{-2}$)</td>
<td>208</td>
<td>77</td>
<td>121</td>
<td>-</td>
<td>6</td>
</tr>
<tr>
<td>$L_\gamma$</td>
<td>$0.25 \times 10^6$</td>
<td>1506 (0.6%)</td>
<td>659</td>
<td>358</td>
<td>449</td>
<td>-</td>
<td>40</td>
</tr>
</tbody>
</table>

### TABLE V. MONTE CARLO RESULTS: UNIFORM SOURCE IN LUNG

<table>
<thead>
<tr>
<th>Number of Histories</th>
<th>Total Escapes (%)</th>
<th>Front</th>
<th>Right</th>
<th>Rear</th>
<th>Left</th>
<th>Top</th>
<th>Bottom</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_\alpha$</td>
<td>$2 \times 10^5$</td>
<td>327 (0.016)</td>
<td>176</td>
<td>7</td>
<td>140</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>$L_\beta$</td>
<td>$2 \times 10^6$</td>
<td>5,302 (0.26)</td>
<td>2,470</td>
<td>339</td>
<td>2,286</td>
<td>112</td>
<td>95</td>
</tr>
<tr>
<td>$L_\gamma$</td>
<td>$2 \times 10^6$</td>
<td>20,008 (1.0)</td>
<td>8,811</td>
<td>2,052</td>
<td>8,014</td>
<td>724</td>
<td>407</td>
</tr>
</tbody>
</table>

### TABLE VI. EXPERIMENTAL CALIBRATION FACTORS FOR VARIOUS DISPOSITIONS OF ACTINIDE ACTIVITY IN A RANDO PHANTOM LUNG*

<table>
<thead>
<tr>
<th>Distribution</th>
<th>Calibration Factor for $^{239}$Pu (counts/min. per nCi)</th>
<th>Ratio of Calibration Factor to that for the Uniform Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uniform (N = 130 points)</td>
<td>0.15</td>
<td>1.0</td>
</tr>
<tr>
<td>Point source; middle of lung at level of 2nd rib</td>
<td>0.13</td>
<td>0.84</td>
</tr>
<tr>
<td>Point source; surface of lung at level of 2nd rib</td>
<td>2.4</td>
<td>16.1</td>
</tr>
<tr>
<td>Point source; back of lung at level of 2nd rib</td>
<td>0.012</td>
<td>7.9 x $10^{-2}$</td>
</tr>
<tr>
<td>Approximate surface distribution in pleura (N = 47 points)</td>
<td>0.38</td>
<td>2.5</td>
</tr>
</tbody>
</table>

*Detector was a 127 mm diameter phoswich; time window was ~ 66 nsec and energy window was 15.5 - 25.5 keV.
### TABLE VII. COMPARISON OF MONTE CARLO CALCULATIONS WITH MEASUREMENTS ON A RANDO PHANTOM

<table>
<thead>
<tr>
<th>Mathematical Phantom (counts/min. per MPLB)*</th>
<th>Rando Phantom (counts/min. per MPLB)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point source $^{238}$Pu; midpoint of upper 1/3 of lung</td>
<td>4.7</td>
</tr>
<tr>
<td>Point source $^{238}$Pu; midplane of lung; center position</td>
<td>2.02</td>
</tr>
<tr>
<td>Uniform source of $^{238}$Pu</td>
<td>~ 6.1</td>
</tr>
</tbody>
</table>

*MPLB = Maximum Permissible Lung Burden = 16 nCi.

### TABLE VIII. SOME SOURCES OF RADIOACTIVITY IN MAN

<table>
<thead>
<tr>
<th>Radioisotope</th>
<th>Source</th>
<th>Primary Medium of Intake</th>
<th>Type of Radiation</th>
<th>Estimated Body Burden 70 kg Man</th>
<th>Estimated Dose Rate (mrad/year) 70 kg Man</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{226}$Ra</td>
<td>Natural (Rocks)</td>
<td>Foods</td>
<td>$\alpha,\gamma, (\beta^-)$</td>
<td>0.1 nCi</td>
<td>4</td>
</tr>
<tr>
<td>$^{222}$Rn</td>
<td>Natural ($^{226}$Ra)</td>
<td>Air and Water</td>
<td>$\alpha, (\beta^-, \gamma)$</td>
<td>--</td>
<td>3-30</td>
</tr>
<tr>
<td>$^{232}$Th</td>
<td>Natural (Rocks)</td>
<td>Foods</td>
<td>$\alpha,\gamma, (\beta^-)$</td>
<td>&lt; 0.1 nCi</td>
<td>--</td>
</tr>
<tr>
<td>$^{228}$Ra</td>
<td>Natural ($^{232}$Th)</td>
<td>Air and Water</td>
<td>$\alpha, (\beta^-, \gamma)$</td>
<td>(same as $^{222}$Rn)</td>
<td></td>
</tr>
<tr>
<td>$^{14}$C</td>
<td>Natural - Cosmic Rays</td>
<td>Normal Carbon Intake</td>
<td>Low Energy $\beta^-$</td>
<td>90 nCi</td>
<td>1.6</td>
</tr>
<tr>
<td>$^{40}$K</td>
<td>Natural (0.0119% of all potassium)</td>
<td>Foods</td>
<td>$\beta^-, \gamma$</td>
<td>120 nCi</td>
<td>19</td>
</tr>
<tr>
<td>$^3$H</td>
<td>Natural - Cosmic Rays</td>
<td>Food and Water</td>
<td>Low Energy $\beta^-$</td>
<td>1 nCi</td>
<td>0.002</td>
</tr>
</tbody>
</table>

### TABLE IX. MINIMUM DETECTABLE ACTIVITIES

<table>
<thead>
<tr>
<th>Radioisotope</th>
<th>Emissions</th>
<th>Minimum Detectable Activity (nCi)</th>
<th>Maximum Permissible Lung Burden (Occupational, nCi)</th>
<th>Maximum Permissible Body Burden (Occupational, nCi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{239}$Pu</td>
<td>$\alpha, X$-Rays (4%)</td>
<td>14</td>
<td>16</td>
<td>40</td>
</tr>
<tr>
<td>$^{238}$Pu</td>
<td>$\alpha, X$-Rays (10%)</td>
<td>6</td>
<td>15</td>
<td>40</td>
</tr>
<tr>
<td>$^{241}$Am</td>
<td>$\alpha, \gamma$-Rays (36%)</td>
<td>1</td>
<td>15</td>
<td>50</td>
</tr>
<tr>
<td>$^{244}$Cm</td>
<td>$\alpha, X$-Rays (10%)</td>
<td>5</td>
<td>14</td>
<td>100</td>
</tr>
<tr>
<td>$^{117}$Cs</td>
<td>$\gamma, X$-Rays, $\beta^-$</td>
<td>2</td>
<td>2 000</td>
<td>30 000</td>
</tr>
<tr>
<td>$^{60}$Co</td>
<td>$\gamma$-Rays, $\beta^-$</td>
<td>0.5</td>
<td>1 200</td>
<td>10 000</td>
</tr>
<tr>
<td>$^{96}$Sr</td>
<td>$\beta^-$</td>
<td>10</td>
<td>760</td>
<td>2 000</td>
</tr>
</tbody>
</table>
FIG. 2. Typical human spectrum.

FIG. 3. Typical human, $^{239}$Pu and $^{241}$Am spectra (low energy).
suppression system is also included in Fig. 1. If an overload pulse appears at the output of the delay line amplifier, the TPHA is disabled for ~1 ms in order to allow all transient effects to disappear. Presently, the phoswich spectrum is analyzed over the region 0-128 keV while the energy chosen for analysis of actinide L x-rays is 14-25 keV. A large (229x229 mm) NaI detector is also employed during subject counts for simultaneous analysis of high energy gamma spectra (≤ 3 MeV). Both the gated phoswich signal and the 229x229 signal are routed to a single 80 MHz analogue-to-digital converter for computer acquisition of the spectrum.

2. CALIBRATION PROBLEMS PECULIAR TO ACTINIDE COUNTING

Calibration problems peculiar to actinide counting have been treated extensively recently.\(^2\) One of the most critical problems in chest counting is the determination of whether or not a given individual's count is statistically within the population of normal, uncontaminated individuals. Determination of the amount of human background (primarily bremsstrahlung from \(^{40}\)K) present in the phoswich spectrum is particularly important in the context of Pu detection since small errors in this quantity may lead to large uncertainties in the calculated actinide chest burden. Another serious uncertainty in the determination of lung burden at ORNL is the occasional presence of both long-term and short-term variations in background in our shielded counting facility. The counting room has excellent shielding with the walls, floor and ceiling being constructed of WW-II naval armor plate. Walls, etc., are 356 mm thick lined on the inside with 3.2 mm of aged, low-radioactivity lead and the floor has an additional graded shielding of 1.0 mm sheets of tin and cadmium and a 0.2 mm thick sheet of copper to absorb characteristic lead x-rays. An attempt to remove natural background from gaseous radon and thoron and their daughters is made by having an aged supply of breathing air and absolute filters to reduce the concentration of atmospheric dust. The detection efficiency and background of the overall system have been found to be among the best in the USA.\(^3\)

3. UNCERTAINTIES IN CALIBRATION FACTORS DUE TO NONUNIFORMITY OF DISTRIBUTION

It is very difficult to assess the uncertainty in the calibration factor due to a lack of uniformity of source distribution. Radiobiological evidence does indicate that the distribution of activity is nonuniform, at least for long times after inhalation of the activity, but we do not at present have an adequate functional dependence for this distribution.

In an effort to investigate some of the variables which affect detector,calibration factors, Monte Carlo photon transport techniques\(^4\) have recently been used to investigate the spatial distribution of unattenuated photons that leave the chest from various distributions of activity within the lung. Macroscopic attenuation factors and the corresponding half-value layers for these photon groups are presented in Table I.

---

1 World War II naval armor plate incorporates no radioactive fall-out contamination.
Absolute L x-ray yields for various heavy elements have also been published recently by Bemis, et al.\textsuperscript{[2]} (Tables II and III). From the data in Table I and from the \textsuperscript{239}Pu yield data of Tables II and III, intensity-weighted half-value layers for soft tissue, bone, and lung are calculated to be 6.05 mm, 1.21 mm and 18.4 mm, respectively.

The Monte Carlo modeling technique has been used in conjunction with a mathematical heterogeneous phantom which closely approximates details of the reference man given in ICRP Report 23. In this model each lung is considered to be one-half of an ellipsoid with an anterior section removed, 24 cm long and 1689 cm\textsuperscript{3} in volume. The photons that leave the body unattenuated, i.e., have suffered no collisions, are counted in 7 mm grids. The distance, 7 mm, matches half the distance between ribs and the grid structure is aligned to coincide with the ribs for ease in orientation.

In Table IV are typical data for a point source of Pu in the center of the lung and in Table V are those for the corresponding uniform distribution. In Table VI, experimentally determined calibration factors for various dispositions of actinide activity in a Rando phantom lung are listed. The theoretical and experimental calibration factors for the Monte Carlo modeling technique and for the Rando phantom, respectively, are compared in Table VII.

From the data presented here, it is evident that there is significant attenuation in all photon groups, with negligible transmission of the L group. In addition, from these and other data it can be shown that there is at least a factor of 100 difference in the point source response function from the front of the lung to the rear of the lung. The error in using a uniform distribution for calibration is possibly not too serious for counting performed soon after an inhalation incident, because long-term lung clearance mechanisms have not yet taken effect. However, the error could be quite significant in continued analysis of those personnel exposed several years ago or for individuals with chronic exposures. The uncertainty in routine monitoring of employees is perhaps not as severe as a factor of 100, but, conservatively, it could be a factor of 2-5. These Monte Carlo results and a more detailed analysis of their implications to whole body counting of Pu will be presented in the near future.

4. ALLOWANCE FOR BACKGROUND AND NORMAL HUMAN RADIOACTIVITY

Since the excess counting rate arising from the maximum permissible lung burden (MPLB) of \textsuperscript{239}Pu, after attenuation through the average human chest, is only one-fifth the gross counting rate of a normal human spectrum, very precise elimination of the spectral contributions of background and normal human radioactivity is required. The standard deviation of the background can be minimized by counting for long periods (800 min at ORNL) since this can be done without inconvenience to the human subject. On the other hand, a convenient counting period for routine measurement of humans must not exceed one hour, and our standard period is 40 min. At the low counting
rates observed, the inherent statistical variation will inject considerable uncertainty into the determination of any possible plutonium which may be present.

The normal human spectrum is shown in two energy regions in Figs. 2 and 3, the higher energy region where common fission and activation radioisotopes emit and the low-energy actinide region. The spectra for relatively intense $^{239}\text{Pu}$ and $^{241}\text{Am}$ sources attenuated by an equivalent chest thickness are also shown in Fig. 3. The normal human spectrum in this energy region, for convenience, can be broken down into four components:

a) $^{40}\text{K}$ from body potassium. This radionuclide contributes background in three principal ways:

i) Bremsstrahlung,

ii) Compton recoil electrons in the detector with energies down to zero, and Compton scattered and energy degraded photons from the source. Both these contributions in their turn relate to the 1.46 MeV $\gamma$-ray that accompanies the electron capture branch of the $^{40}\text{K}$ decay.

b) Low-energy room photons as spectrally modified (increased below 100 keV) by bulk matter in the vicinity of the detector.

c) Room background as determined by the presence of the shielding enclosure and including airborne radioactive daughters in the natural radioactive series.

d) Background intrinsic to the detector itself.

The natural body potassium includes, on the average, about 120 nCi of $^{40}\text{K}$ but varies considerably with age, sex and body build.\[^5\] In addition, there are other contributions from natural radionuclides which are more difficult to define, listed in Table VIII, along with their radiation dose rates to the body. In the ORNL facility typical 40-minute counts with two phoswich detectors (total area 250 cm$^2$) in the 14-25 keV region can be broken down as follows: room + intrinsic = 200 counts; room + intrinsic + bulk matter (70 kg H$_2$O) = 350 counts; room + intrinsic + bulk matter + 120 nCi $^{40}\text{K}$ = 500 counts. In comparison, one lung burden (MPLB) of $^{239}\text{Pu}$ (16 nCi) would contribute to this total an additional 100 counts. Even if the natural radioactivity of the subject could be determined exactly, the inherent statistical variation of the count has a standard deviation ($\sigma$) of 22 counts. At two $\sigma$, the minimum detectable activity of $^{239}\text{Pu}$ would be 6.6 nCi. Unfortunately, the natural radioactivity in the human varies considerably in a typical population, and even varies with time in an individual. Consequently, some means must be employed to estimate the contribution of the normal radioactivity of the individual to the counting rate in the 14-25 keV region.

At ORNL two schemes for elimination of "background" and "normal human" counts in the Pu spectral region (14-25 keV) have been utilized. In both schemes a "bulk matter background" (i.e., a water-filled phantom) is counted to 1% precision (800 minutes).
and the appropriate fraction is subtracted from the individual subject spectrum to yield a net human spectrum. In the first scheme, the 1.46 MeV \(^{40}\)K photopeak is integrated in the high energy spectrum from the 229x229 mm NaI detector. The ratio of counts in the 14-25 keV region to those in the \(^{40}\)K peak has been determined for a large number of normal subjects and the mean ratio is compared with that of the subject. If the ratio of the subject exceeds the mean ratio by twice its standard deviation, the excess content is calculated from the excess counts. Our ratio (14-25 keV/1.46 MeV) is 0.022, \(\sigma = \pm 23\%\). This treatment has the advantage of using an identified, easily definable spectral peak from a known naturally occurring radionuclide as a normalization factor. Unfortunately, other possible radio-nuclides may be present to contribute to bremsstrahlung and Compton degraded photons in the 14-25 keV region without being detected in the 1.46 MeV peak, since many fission products and naturally occurring radionuclides emit only photons of energy lower than 1.46 MeV or no photons at all.

The second scheme, then, utilizes the upper end of the phoswich spectrum, 80-128 keV, to sum all Compton and bremsstrahlung in this energy region and provide a ratio of the Pu region to the 80-128 keV band. For a normal population we have observed (14-25/80-128) = 0.150, \(\sigma = \pm 17\%\). A difficulty in this scheme is that we are comparing the extreme ends of the phoswich spectrum and they are affected oppositely by variations in the parameters of the pulse shape discrimination electronics.

If the standard deviation in these ratios (< 20\%) is converted to an equivalent counting rate for a net human spectrum (150 counts in 40 min), \(\sigma_1 \approx 4 \text{ counts/min} \times 20\% = 1 \text{ count/min} \) for our "normal population." Combining this \(\sigma_1\) for the mean of the ratios for our population with the inherent statistical variation of counting (\(\sigma_2 \sim 0.5 \text{ counts/min}\)) gives an overall resultant standard variation:

\[
\sigma_r = \sqrt{\sigma_1^2 + \sigma_2^2} = 1.1 \text{ counts/min}
\]

At the 2 \(\sigma\) confidence level, then, our MDA is about 14 nCi of \(^{239}\)Pu. It should be emphasized that these counting statistics are for clean, uncontaminated individuals.

A further complication is common at large nuclear energy installations, i.e., the employees are exposed to a host of fission and activation products along with Pu. Fortunately, \(^{241}\)Am usually accompanies \(^{239}\)Pu in known concentrations and, with its greater detectability, can be used as a tracer for Pu. Table IX lists reasonable values for our levels of MDA for \(^{239}\)Pu, \(^{241}\)Am and other nuclides common at large nuclear installations. However, with the notoriously poor resolution of the phoswich detector substantial allowance must be made for low-energy contributions in subjects contaminated with \(^{60}\)Co, \(^{137}\)Cs and especially \(^{90}\)Sr.

For example, in case of contamination with the common, long-lived fission product \(^{137}\)Cs, 10% of the MPLB is 200 nCi and contributes 22 counts/min in the 17 keV band. Even though this can be stripped from the spectrum, utilizing the 0.662 MeV
peak to determine $^{137}$Cs, the additional counting rate at 17 keV raises the MDA by about 7 nCi of $^{239}$Pu at the $2\sigma$ level. Similarly, in the presence of $^{90}$Sr, at the level of one MPLB ($^{90}$Sr) the $\sigma$ for the counts in the 17 keV band is raised to 2 counts/min and the MDA for $^{239}$Pu increased by about 20 nCi.

Clearly, there is a great need for marked improvement in our methods of detecting plutonium. At ORNL we have been investigating the use of large, planar intrinsic Ge detectors. Except for their great expense, we feel that they are practical for arrays large enough to provide a useful counting geometry. We hope to exploit their very high resolution to lower appreciably the levels of detectability of plutonium.

REFERENCES


DISCUSSION

J.E. McLAUGHLIN: What, in your opinion, is the largest area that is practical for the intrinsic germanium detector arrays?

W.W. PARKINSON Jr.: I understand that these detectors are now available in areas up to 13 cm$^2$. As your question implies, arrays will have to be used to improve the geometry of the inherently small germanium detectors for detection of $^{239}$Pu. We have not yet tested such arrays, but we anticipate that critical problems will be, first, to achieve stability of energy calibration of individual detectors to avoid loss of resolution and, secondly, to cope with the increases in background noise that accompany the additional electronics needed for multiple detectors.

M.A.F. AYAD: How many counts per minute are recorded from the $^{40}$K content of an uncontaminated body?
W.W. PARKINSON Jr.: With our 229 mm dia. x 229 mm NaI(Tl) detector, we record a counting rate at the 1.46 MeV photopeak of 25 counts/min in the peak channel (at 12 keV per channel). There is a dependence on resolution, of course, and our resolution is 8% at 0.66 MeV. This corresponds to about 120 nCi of $^{40}$K.

From $^{40}$K in the $^{239}$Pu band (i.e. 14—25 keV) we get about 3.5 counts/min in the phoswich detectors, but this counting rate includes small contributions from other natural radioisotopes in the body.
MULTI-TECHNIQUE CHARACTERIZATION OF NEUTRON FIELDS FROM MODERATED $^{252}$Cf AND $^{238}$PuBe SOURCES

Lawrence Livermore Laboratory,
University of California,
Livermore, California,
United States of America

Abstract

MULTI-TECHNIQUE CHARACTERIZATION OF NEUTRON FIELDS FROM MODERATED $^{252}$Cf AND $^{238}$PuBe SOURCES.

At the Lawrence Livermore Laboratory, $^{252}$Cf and $^{238}$PuBe neutron sources are used for calibration of personnel neutron dose meters and neutron monitoring instrumentation. The sources with emission rates of approximately $2 \times 10^9$ and $2 \times 10^7$ n·s$^{-1}$, respectively, have been calibrated by the United States National Bureau of Standards. The sources are transferred into a 815 m$^3$ concrete calibration cell through a remotely operated pneumatic system. Calibrations can be made without source moderation, or with spherical moderators of aluminium, polyethylene, water or deuterium oxide placed over the end of the pneumatic irradiation tube. The source is located in the tube at one metre above a false floor in the centre of the cell. Nine different moderators are available in sizes up to 56 cm in diameter. Several techniques have been used to characterize the neutron fields produced by each source-moderator configuration to improve the quality of our calibrations. Measurements and calculations have been made to determine neutron flux, kerma rate, neutron spectrum, quality factor, dose equivalent rate and linear energy transfer (LET) spectrum. Neutron spectra are determined by: (1) Calculation using the ANISN discrete ordinates transport code, (2) Bonner sphere measurements using the LOUHI unfolding code, and (3) measurement with proton recoil counters and liquid scintillation detectors. The spectra are then folded into published energy dependent conversion factors to yield kerma, quality factor and dose equivalent values. We obtain LET spectra using a tissue-equivalent LET chamber and the GANDALF unfolding code. Chamber data are used to determine kerma and quality factor. Finally, an 80 cm$^3$ tissue-equivalent ion chamber and neutron-insensitive Geiger counter are used to measure the neutron kerma. Results of the various techniques are presented and compared. In addition, comparisons are made with results obtained from conventional health physics instrumentation such as moderated rem counters.

INTRODUCTION

Bare and moderated neutron sources are used to calibrate survey instruments and personnel neutron dosimeters in the Hazards Control Department radiation calibration facility at the Lawrence Livermore Laboratory(LLL). Specifically, $^{252}$Cf and $^{238}$PuBe sources are used in spheres
of water, polyethylene, deuterium oxide and aluminum. We have used these sources and moderators in the concrete calibration room, of dimensions 12.2 x 9.14 x 7.32 meters (Fig. 1), for more than five years. The sources are moved from storage shields to the irradiation position through a pneumatic system. The end of the transfer tube is one meter above an aluminum false floor in the center of the calibration room. Spherical moderators are placed over the end of the tube by a hydraulic lift. All source to detector distances refer to the separation between the center of the irradiation tube and detector.

The initial calibrations were based on National Bureau of Standards source emission rate calibrations for the bare sources $^{252}\text{Cf} - 3.5217 \times 10^9 \text{n} \cdot \text{s}^{-1}, 28 \text{ Aug 1974}$ and $^{238}\text{PuBe} - 7.895 \times 10^7 \text{n} \cdot \text{s}^{-1}, 28 \text{ Feb 1973})$. Relative dose equivalent rates at fixed distances from the source were initially obtained with an Andersson Braun cylindrical rem meter. However, concern about the energy response of these units prompted us to begin more detailed calibration work.

We felt that characterization of the neutron fields should include information about the neutron spectrum, dose equivalent, kerma, quality
TABLE I. INPUT NEUTRON SPECTRA FOR ANISN SOURCE NEUTRONS/ENERGY BIN

<table>
<thead>
<tr>
<th>Lower Bound Neutron Energy (MeV)</th>
<th>$^{252}$Cf</th>
<th>$^{238}$PuBe</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-10}$</td>
<td>$1.054 \cdot 10^{-10}$</td>
<td>0.0</td>
</tr>
<tr>
<td>$4.00 \cdot 10^{-7}$</td>
<td>$1.087 \cdot 10^{-8}$</td>
<td>0.0</td>
</tr>
<tr>
<td>$3.18 \cdot 10^{-6}$</td>
<td>$2.443 \cdot 10^{-7}$</td>
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<td>$2.52 \cdot 10^{-5}$</td>
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<td>$1.230 \cdot 10^{-4}$</td>
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<td>$1.59 \cdot 10^{-3}$</td>
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<td>0.224</td>
<td>$4.965 \cdot 10^{-1}$</td>
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<td>0.500</td>
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<td>$1.857 \cdot 10^{-2}$</td>
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<td>0.595</td>
<td>$2.378 \cdot 10^{-1}$</td>
<td>$2.210 \cdot 10^{-2}$</td>
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<td>0.707</td>
<td>$2.823 \cdot 10^{-1}$</td>
<td>$2.620 \cdot 10^{-2}$</td>
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<td>0.841</td>
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<td>$5.372 \cdot 10^{-1}$</td>
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<td>1.257</td>
<td>$6.414 \cdot 10^{-1}$</td>
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<td>$7.043 \cdot 10^{-1}$</td>
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<td>2.973</td>
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<td>$4.860 \cdot 10^{-1}$</td>
<td>$1.238 \cdot 10^{-1}$</td>
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<td>$3.888 \cdot 10^{-1}$</td>
<td>$1.667 \cdot 10^{-1}$</td>
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<td>5.000</td>
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<td>$1.550 \cdot 10^{-1}$</td>
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<td>5.765</td>
<td>$1.560 \cdot 10^{-1}$</td>
<td>$8.470 \cdot 10^{-2}$</td>
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<td>$3.570 \cdot 10^{-2}$</td>
<td>$4.719 \cdot 10^{-2}$</td>
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<td>10.19</td>
<td>$1.523 \cdot 10^{-2}$</td>
<td>$2.720 \cdot 10^{-3}$</td>
</tr>
<tr>
<td>11.74</td>
<td>$5.220 \cdot 10^{-3}$</td>
<td>0.00</td>
</tr>
<tr>
<td>13.5</td>
<td></td>
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</tr>
</tbody>
</table>

factor, and linear energy transfer (L.E.T.) spectrum for each of the 20 source-moderator configurations. We selected a distance of one meter from the source as a reference, since that position is commonly used for calibrations.

DISCRETE ORDINATES CALCULATIONS

The discrete ordinates computer code ANISN [1] is available at LLL to make radiation transport calculations. Our first attempt to determine the neutron spectra, kerma, dose equivalent and quality factor was made using ANISN. The geometry we had to simulate was that of a point source...
in the center of a moderating volume surrounded by air and bounded by the concrete room. Because ANISN is a one-dimensional code, the problem statements have to be made in a spherically symmetrical geometry. This meant that we had to ignore the aluminum false floor and the effect of the nonspherical source transfer tube. In addition, the oblong room was simulated by a concrete shell 0.6 meters thick, with an inner radius of 6.1 meters. The source spectra for $^{239}$PuBe and $^{252}$Cf (Table I) were composites of published data [2-8].

ANISN can be used to calculate neutron and gamma spectra in any pre-selected spherical shell or zone. We chose zones 1 cm thick with radii of 0.50, 1.00, 1.50, 2.00, 2.50 and 3.00 meters. The spectra calculated in these zones were used to determine spectrum weighted dose equivalent and kerma rates from published flux to dose conversion factors [9, 10]. We also calculated the total dose in volume element 57 of the cylindrical phantom developed by J. A. Auxier, W. S. Snyder and T. D. Jones [11]. This represents the maximum absorbed dose in the body, and is divided into the dose equivalent to determine the quality factor. The same procedure was used to determine kerma, absorbed dose and dose equivalent rates and quality factor from the neutron spectra determined by other methods.

MULTISPHERE MODERATOR SPECTROMETRY

For some time, we have been working with a set of "Bonner spheres" (Fig 2) for measurement of neutron spectra both at the calibration
FIG. 3. NE213 scintillator positioned for measurement of neutron spectrum.
FIG. 4. 80 cm$^3$ tissue equivalent ion chamber and neutron-insensitive Geiger tube.
facility and for environmental spectrum measurements near neutron producing facilities. The polyethylene spheres are 7.6, 12.7, 20.3, 25.4, 30.5, and 45.7 cm diameter. We obtain a set of data for a spectrum determination by making a count with each sphere placed over the $^6$LiI detector. Additional counts are made with no sphere and with a 0.5 mm thick cadmium thermal shield. Count rate in the peak due to the $^6$LiI (n,$\alpha$) reaction is used as the detector response. The effective detector energy response is characteristic of the moderator size, with large spheres being preferentially more sensitive to more energetic neutrons. The maximum response of the 7.6 and 12.7 cm spheres is to neutrons between thermal and 100 keV. Therefore, 0.5 mm thick cadmium shells were placed over these spheres to suppress the influence of the thermal neutrons.

The effective neutron response of the moderated detector has been calculated by Sanna [12], for each of our sphere sizes. Sanna has shown that detector response also depends on the density of polyethylene in each sphere and we have made appropriate corrections for the response of our spheres. Recently we made measurements with monoenergetic neutrons over the energy range 0.1 to 18 MeV [13], and the measurements confirm Sanna's calculations within the error of the experiment.

The spectral determination is made with the LOUHI computer code to unfold the responses of the moderated and unmoderated $^6$LiI detector. The LOUHI code is a Fortran program written to obtain the solution of Fredholm integral equations of the first kind, by using a generalized least-squares procedure with nonnegative solution [14]. With LOUHI, the spectral solution is not dependent on the choice of initial approximation. If the user has prior knowledge of the fluence in a particular part of the spectrum, the solution in the appropriate energy bin can be "TIED" to that point. We used this feature to restrain the high energy bin to a realistic value which reflected the general lack of source neutrons above 15 MeV. The specific value was chosen as $10^{-5}$ times the count rate from the 12.7 cm sphere which can be used as a rough flux monitor.

**RECOIL PROTON SPECTROMETRY**

We felt that it was important to obtain experimental information about the fast neutrons (energies greater than 0.1 MeV), with a detector system that had sufficient resolution to compare with the ANISN calculations. A pair of detectors - an NE213 liquid scintillator (Fig. 3) and a hydrogen proportional counter - were selected for this purpose.

A $^{22}$Na source is used for energy calibration of the scintillator. The 511 and 1275 keV gamma rays produce Compton electrons in the detector. The Compton distributions have steep slopes at light outputs corresponding to the most energetic Compton electrons - 341 keV and 1062 keV. The light output may be related directly to that produced by recoil protons, so the gamma produced spectrum is used to establish the energy scale for recoil protons in a given measurement.

After calibration, a pulse shape discrimination system is used to eliminate the low LET Compton electron events and accept the high LET pulses from recoil protons. The pulse heights of the high LET events are then analyzed.

The hydrogen proportional counter is calibrated using the $^{14}$N(n,p)$^{14}$C thermal neutron reaction. The counter contains about 5% nitrogen which undergoes this reaction with thermal neutrons. A peak occurs in the
FIG. 5. 80 cm$^3$ tissue equivalent proportional counter used to determine LET spectra.
The spectrum due to the energy deposited by the proton and recoil $^{14}\text{C}$. The energy deposited is equivalent to that of a 606 keV proton, and that establishes the energy scale. After calibration, we wrap the proportional counter with cadmium to eliminate the thermal peak from subsequent pulse height spectra.

To process the liquid scintillation pulse height spectra, we produce two data files from each 2048 channel spectrum. The first, called the "high energy" file contains 256 channels, each of which contains the sum of counts in successive 8 channel segments in the original pulse height spectrum. The second, called the "mid energy" file contains just the first 256 channels of the original pulse height data. Rebinning the NE213 data into two files is required since the energy per channel varies more than a decade over the spectrum due to the nonlinearity in NE213 light output.

Data unfolding is carried out on three data files: the "high energy" and "mid energy" data from liquid scintillators and the "low energy" file obtained with the hydrogen proportional counter. The LLL code NUTSPEC is used for this purpose. A derivative unfolding method is used on the liquid scintillation data to produce two flux files corresponding to the two data sets. The "low energy" file is unfolded using a response function unfolding method. The data from the "high energy" portion of the spectrum is used to calculate the high energy response of the proportional counter. This response is subtracted from the experimental response and the residual is unfolded to determine the low energy spectrum.

**ION CHAMBER, GEIGER COUNTER MEASUREMENTS**

We made independent measurements of the kerma rate using a tissue equivalent ion chamber together with a neutron insensitive Geiger tube (Fig. 4). The ion chamber, with a volume of 80 cm$^3$, has tissue equivalent Shonka plastic walls 5.0 mm thick. The tissue equivalent gas filling was CO$_2$ - 32.32%, N$_2$ - 3.16% and CH$_4$ - 64.52%. The Geiger counter has a flat response for gamma rays (± 10%) from 70 keV to 1.2 MeV. Both detectors were manufactured by EG&G.

The ion chamber is operated at +300 V, with output to a digital electrometer used in the charge collection mode. Our gamma calibration using a $^{60}$Co source was 3.26 x 10$^7$ R/C compared with the value provided by the manufacturer of 3.33 x 10$^7$ R/C. We multiply the exposure calibration factor by 0.957 rads/R [15] to determine the absorbed dose calibration. The composition of Shonka plastic is sufficiently different from tissue, that consideration must also be given to the kerma conversion for each material. A spectrum weighted calculation using fission spectrum neutrons results in a factor of 0.97 tissue rads/Shonka plastic rad. The net neutron sensitivity for the ion chamber becomes 3.01 x 10$^7$ tissue rads/C.

The GM counter, when calibrated with a $^{60}$Co source, yields a sensitivity of 6.56 x 10$^{-7}$ R/pulse compared with the manufacturer's value of 6.66 x 10$^{-7}$ R/pulse. The fast neutron sensitivity of the GM counter is thought to be less than 1%, so we have chosen to ignore the counter neutron response.
FIG. 6. Comparison of $^{252}$Cf neutron spectra at 2 m.
(a) Bare source; (b) through 25 cm $H_2O$ sphere; (c) through 25 cm $D_2O$ sphere; (d) through 20 cm Al sphere.
FIG. 7. Comparison of $^{238}$PuBe neutron spectra at 1 m.
(a) Bare source; (b) through 25 cm $H_2O$ sphere; (c) through 25 cm $D_2O$ sphere; (d) through 20 cm Al sphere.
LET SPECTRUM MEASUREMENTS

We have used a tissue equivalent proportional counter to measure LET spectra to determine kerma and quality factor. The 2 in diameter, single-wire LET proportional counter was manufactured by EG&G (Fig. 5). It was filled with tissue equivalent counter gas (CO₂ - 39.6%, N₂ - 5.4%, and C₃H₈ - 55%) at a pressure of 7.0 mm Hg, to simulate a 0.966 μm diameter tissue sphere. The pulse height spectrum generated by neutrons incident on this detector simulates the lineal energy density distribution (Y-distribution) in tissue and can, therefore, be used to generate LET (D(L)) spectra for each source-moderator configuration. Average quality factors and kerma are then determined by folding together these D(L) spectra and some discrete representation of Q(L), the quality factor as a function of LET.

Energy calibration of the pulse height distribution is provided by a collimated 5.8 MeV alpha source provided in the wall of the detector, which produces a 77 keV pulse in the chamber when operated at 7.0 mm Hg. Because of the low source strength of several of the heavily moderated sources, it was necessary to collect data over periods of up to three days. The resulting pulse height spectra were not accepted if the alpha calibration had drifted more than five channels, about 4%, during the experiment. A 4% shift in alpha calibration causes an insignificant (<1%) change in the calculated quality factors.

We have chosen to treat the gamma contribution to the quality factor as a separate entity, removing gamma induced pulses from the lineal energy distribution by a spectrum stripping technique. Investigations with a variety of gamma ray sources have shown that the pulse height spectrum is almost completely independent of gamma energy down to at least 100 keV. This allows us to simulate the gamma portion of the spectrum with a cobalt source. For each moderator-source combination we measure the gamma dose with the neutron insensitive GM counter and strip the corresponding fraction of the standard gamma spectrum out of the pulse height distribution, leaving only neutron induced pulses. The modified spectra are then used to determine the neutron quality factor, and the gamma dose can be added back with a quality factor of one to give the total average quality factor. Our data indicate that about 95% of the gamma pulses fall below 6.5 keV/μm. Neutron LET spectra were based on pulses ranging down to 3.5 keV/μm after gamma stripping. This technique leaves some of the neutron induced gamma pulses in the spectrum - those that are induced in the detector itself - but because of the small mass of the detector and the small fraction of the gamma pulses included above 3.5 keV/μm it is unlikely that this error is significant.

The total dose was measured for each source-moderator configuration using the 80 cm³ tissue equivalent ionization chamber, whose physical dimensions correspond to those of the LET chamber. Since the neutron dose can be determined independently by the LET chamber, this three detector system provides a redundancy of information on n/y ratios for obtaining total average quality factors. The neutron doses reported here are from single measurements (or averages of two or three measurements) made at one meter with the LET chamber. Our spectra include about 5% room scattered dose and distributed source effects of less than 1.5% of the dose for the largest moderator sphere.

Data are analyzed by GANDALF, a program written to make a triangular approximation to the Y-distribution below the noise limit, smooth the
data and calculate $D(L)$ from the standard unfolding equations \([16]\). GANDALF then folds in the desired $Q(L)$, calculates neutron doses and finally the average neutron quality factor.

**EXPERIMENTAL ERRORS**

The problem of estimating the magnitude of the errors associated with each characterization technique used in this report is extremely complex. We will only identify some sources of error, and estimate the overall error associated with each method.

Sources of errors for the ANISN calculations include errors in selection of input spectra, assumptions about the composition of moderators and room materials, failure to consider the effects of the aluminum false floor and penetration of the moderators by the pneumatic transfer tube, selection of cross sections used in the code, and inappropriate formulations used for the transport calculations. The magnitude of these effects varies with the moderator material and thickness. The error in the differential spectrum at low energies could be a factor of two, decreasing to about 15\% for neutrons above about 0.1 MeV. The effect on the dosimetric quantities is an estimated error of 15\% in kerma and dose equivalent, and 5\% in the quality factor.

Spectral measurements with multisphere or proton recoil counters can be expected to suffer from errors in the response functions, statistical errors from the individual measurements, and errors in formulation of the unfolding process. The overall errors are probably similar in magnitude to those experienced in the ANISN calculations.

The errors experienced in the ion chamber - Geiger counter technique include statistics of measurement, conversion of R to rad, and conversion of rad in tissue equivalent plastic to tissue itself. The expected error in measurement with each detector is about 5\%; however, the error in the neutron dose - the difference between the two measurements - would be as high as 40\% for highly moderated fields with a high gamma component.

The LET measurements can experience statistical errors, errors in the gamma stripping process and errors in the unfolding process. The overall error in kerma is about 10\% and in the quality factor may be near 5\%.

**RESULTS**

All results are normalized to source neutron emission rates for most convenient use of the data. The ANISN calculations do this automatically. All measurement results are referred to the NBS calibration of the source emission rates. The relative agreement between ANISN calculation and measured values of dose and dose equivalent for unmoderated sources indicate that the source calibrations are accurate and make the normalization technique valid.

Although one meter was chosen as a standard source-detector distance, differences in the detector sensitivities caused us to make some measurements at 0.5 and 2.0 meters. We used ANISN results to normalize all results to one meter. In particular, the $^6$LiI detector and liquid scintillator used for spectral measurements were too sensitive for one meter measurements of the high flux $^{252}$Cf source. The tissue equivalent ion chamber, on the other hand, is relatively insensitive and was moved to 0.5 meters for measurement of the lower intensity $^{238}$PuBe source.
All results from the ANISN calculations, Bonner sphere and proportional counter measurements depend on the spectral determinations. A comparison of the spectra for the bare and heavily moderated sources is shown in Figs 6 and 7. The relative agreement is gratifying and will be supported by general agreement between the spectrum weighted conversion factors presented further in the test. In addition to determination of the dose conversion factors, the spectra can be used for measurement of the energy response of dosimeters and survey instruments.

Sample LET spectra are shown in Fig 8. One of the more interesting features of the results is the relative enhancement of the high LET proton peak for neutrons through the aluminum sphere. The reason, of course, is that the scattering in the aluminum results in an enhancement of the number of neutrons between 0.1 and 1.0 MeV. It is these neutrons that are responsible for production of the high LET protons in the hundred keV energy domain. This is reflected in the elevated quality factors for the aluminum attenuated sources.

A summary of the values of kerma, dose equivalent and quality factor is shown in Tables II-V. (The "element 57" absorbed dose can be determined by dividing the dose equivalent by quality factor.) There are some characteristics of the measurement system that should be noted here. The agreement for the dosimetric quantities generally improves with decreasing moderator size. That is not surprising since the more heavily moderated fields spread the neutrons having significant contribution over a wider energy range. This places a greater strain on the energy dependence of the "measurement" system.
### TABLE II. KERMA

1 m distance; 10^{-12} erg/g per source neutron

<table>
<thead>
<tr>
<th>252Cf MODERATOR</th>
<th>ANISN</th>
<th>BONNER^{a} SPHERES</th>
<th>RECOIL PROTON^{a,c}</th>
<th>ION CHAMBER</th>
<th>L.E.T.</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>2.47</td>
<td>2.56</td>
<td>3.07</td>
<td>2.46</td>
<td>2.48</td>
</tr>
<tr>
<td>2cm CH(_2)</td>
<td>1.97</td>
<td>2.01</td>
<td>2.24</td>
<td>1.90</td>
<td>1.66</td>
</tr>
<tr>
<td>5cm</td>
<td>1.27</td>
<td>1.32</td>
<td>1.43</td>
<td>1.28</td>
<td>1.10</td>
</tr>
<tr>
<td>10cm</td>
<td>0.543</td>
<td>0.572</td>
<td>0.586</td>
<td>0.591</td>
<td>0.577</td>
</tr>
<tr>
<td>25cm H(_2)(_O)</td>
<td>0.110</td>
<td>0.128</td>
<td>0.141</td>
<td>0.172</td>
<td>0.115</td>
</tr>
<tr>
<td>5cm D(_2)(_O)</td>
<td>1.62</td>
<td>1.71</td>
<td>1.77</td>
<td>1.58</td>
<td>1.43</td>
</tr>
<tr>
<td>10cm</td>
<td>0.948</td>
<td>1.09</td>
<td>0.984</td>
<td>0.970</td>
<td>0.865</td>
</tr>
<tr>
<td>15cm</td>
<td>0.529</td>
<td>0.648</td>
<td>0.533</td>
<td>0.561</td>
<td>0.458</td>
</tr>
<tr>
<td>25cm</td>
<td>0.184</td>
<td>0.240</td>
<td>0.198</td>
<td>0.360</td>
<td>0.202</td>
</tr>
<tr>
<td>20cm Al</td>
<td>1.88</td>
<td>1.60</td>
<td>1.78</td>
<td>1.52</td>
<td>1.47</td>
</tr>
</tbody>
</table>

| 239PuBe MODERATOR | | | | | |
|------------------|---|---|---|---|
| None             | 3.09| 2.86| 3.33| 3.00| 3.12|
| 2cm CH\(_2\)    | 2.62| 2.49| 2.82| 2.44| 2.50|
| 5cm             | 1.96| 1.90| 2.13| 1.83| 2.08|
| 10cm            | 1.06| 1.10| 1.22| 0.874| 1.12|
| 25cm H\(_2\)\(_O\) | 0.298| 0.375| 0.397| 0.187| 0.385|
| 5cm D\(_2\)\(_O\) | 2.28| 2.24| 2.47| 2.10| 2.33|
| 10cm            | 1.53| 1.60| 1.76| 1.34| 1.44|
| 15cm            | 0.974| 1.10| 1.18| 0.833| 1.03|
| 25cm            | 0.415| 0.544| 0.541| 0.310| 0.523|
| 20cm Al         | 2.22| 1.76| 2.20| 1.80| 1.99|

- ^{a}252Cf results normalized from measurements at 2.0 meters based on ANISN calculations.
- ^{b}239PuBe results normalized from measurements at 0.5 meters based on ANISN calculations.
- ^{c}Includes only neutrons above 0.1 MeV.

ANISN calculations depend on the quality of moderator cross section data available to make accurate calculations. Errors in cross section or the physics of neutron transport become increasingly more important as the neutron penetration depth increases. With the multisphere detectors, the region above 0.1 MeV can be more clearly determined than the "intermediate" energy range because the responses of the moderated detectors are probably more accurately known and are changing more rapidly at the...
TABLE III. DOSE EQUIVALENT FOR NEUTRONS ABOVE 0.1 MeV

1 m distance; $10^{-13}$ rem per source neutron

<table>
<thead>
<tr>
<th>MODERATOR</th>
<th>ANISN</th>
<th>BONNER&lt;sup&gt;a&lt;/sup&gt; SPHERES</th>
<th>RECOIL PROTON&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>252Cf</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>2.87</td>
<td>2.84</td>
<td>3.61</td>
</tr>
<tr>
<td>2cm CH₂</td>
<td>2.26</td>
<td>2.22</td>
<td>2.61</td>
</tr>
<tr>
<td>5cm</td>
<td>1.44</td>
<td>1.43</td>
<td>1.68</td>
</tr>
<tr>
<td>10cm</td>
<td>0.606</td>
<td>0.613</td>
<td>0.680</td>
</tr>
<tr>
<td>25cm H₂O</td>
<td>0.119</td>
<td>0.136</td>
<td>0.159</td>
</tr>
<tr>
<td>5cm D₂O</td>
<td>1.80</td>
<td>1.85</td>
<td>2.07</td>
</tr>
<tr>
<td>10cm</td>
<td>0.999</td>
<td>1.12</td>
<td>1.14</td>
</tr>
<tr>
<td>15cm</td>
<td>0.535</td>
<td>0.645</td>
<td>0.613</td>
</tr>
<tr>
<td>25cm</td>
<td>0.175</td>
<td>0.237</td>
<td>0.227</td>
</tr>
<tr>
<td>20cm Al</td>
<td>2.27</td>
<td>1.80</td>
<td>2.20</td>
</tr>
<tr>
<td>238PuBe</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>3.16</td>
<td>2.86</td>
<td>3.25</td>
</tr>
<tr>
<td>2cm CH₂</td>
<td>2.69</td>
<td>2.51</td>
<td>2.79</td>
</tr>
<tr>
<td>5cm</td>
<td>2.03</td>
<td>1.92</td>
<td>2.13</td>
</tr>
<tr>
<td>10cm</td>
<td>1.10</td>
<td>1.12</td>
<td>1.22</td>
</tr>
<tr>
<td>25cm H₂O</td>
<td>0.304</td>
<td>0.379</td>
<td>0.400</td>
</tr>
<tr>
<td>5cm D₂O</td>
<td>2.33</td>
<td>2.28</td>
<td>2.45</td>
</tr>
<tr>
<td>10cm</td>
<td>1.54</td>
<td>1.63</td>
<td>1.76</td>
</tr>
<tr>
<td>15cm</td>
<td>0.960</td>
<td>1.12</td>
<td>1.18</td>
</tr>
<tr>
<td>25cm</td>
<td>0.399</td>
<td>0.546</td>
<td>0.545</td>
</tr>
<tr>
<td>20cm Al</td>
<td>2.51</td>
<td>1.96</td>
<td>2.46</td>
</tr>
</tbody>
</table>

<sup>a</sup> 252Cf results normalized from measurements of 2.0 meters based on ANISN calculations.

higher energies. The differences in slopes of multisphere responses are not adequate to provide good spectral resolution between $10^{-6}$ and 0.1 MeV. Because the high resolution hydrogen recoil spectrometers were effective only above 0.1 MeV, they could not account for increasing dose contributions at lower energies. Finally, the gamma contributions to the kerma for the largest H₂O and D₂O filled spheres are 82% and 70% respectively for 252Cf neutrons and 82% and 66% for 238PuBe neutrons. Therefore, small errors in dose measurement with either the tissue equivalent ion chamber or Geiger counter will result in large errors in the differences between them - the neutron kerma. The LET spectrometer can accomplish the separation more effectively, but with more effort.
TABLE IV. DOSE EQUIVALENT FOR NEUTRONS ABOVE $2.5 \times 10^{-8}$ MeV

1 m distance; $10^{-13}$ rem per source neutron

<table>
<thead>
<tr>
<th>$^{252}$Cf MODERATOR</th>
<th>ANISN</th>
<th>BONNER$^2$ SPHERES</th>
<th>ANDERSSON BRAUN REMMETER</th>
<th>9&quot; SPHERICAL REMMETER</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>2.89</td>
<td>2.86</td>
<td>2.87</td>
<td>2.87</td>
</tr>
<tr>
<td>2 cm CH$_2$</td>
<td>2.30</td>
<td>2.24</td>
<td>2.30</td>
<td>2.18</td>
</tr>
<tr>
<td>5 cm</td>
<td>1.50</td>
<td>1.48</td>
<td>1.49</td>
<td>1.35</td>
</tr>
<tr>
<td>10 cm</td>
<td>0.640</td>
<td>0.640</td>
<td>0.629</td>
<td>0.631</td>
</tr>
<tr>
<td>25 cm H$_2$O</td>
<td>0.1291</td>
<td>0.142</td>
<td>0.138</td>
<td>0.148</td>
</tr>
<tr>
<td>5 cm D$_2$O</td>
<td>1.88</td>
<td>1.89</td>
<td>1.92</td>
<td>1.92</td>
</tr>
<tr>
<td>10 cm</td>
<td>1.11</td>
<td>1.19</td>
<td>1.19</td>
<td>1.37</td>
</tr>
<tr>
<td>15 cm</td>
<td>0.652</td>
<td>0.723</td>
<td>0.711</td>
<td>0.864</td>
</tr>
<tr>
<td>25 cm</td>
<td>0.291</td>
<td>0.307</td>
<td>0.264</td>
<td>0.382</td>
</tr>
<tr>
<td>20 cm Al</td>
<td>2.32</td>
<td>1.85</td>
<td>1.90</td>
<td>2.45</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$^{238}$PuBe MODERATOR</th>
<th>ANISN</th>
<th>BONNER$^2$ SPHERES</th>
<th>ANDERSSON BRAUN REMMETER</th>
<th>9&quot; SPHERICAL REMMETER</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>3.18</td>
<td>2.86</td>
<td>3.02</td>
<td>3.02</td>
</tr>
<tr>
<td>2 cm CH$_2$</td>
<td>2.72</td>
<td>2.52</td>
<td>2.60</td>
<td>2.59</td>
</tr>
<tr>
<td>5 cm</td>
<td>2.10</td>
<td>1.95</td>
<td>1.83</td>
<td>2.06</td>
</tr>
<tr>
<td>10 cm</td>
<td>1.132</td>
<td>1.138</td>
<td>1.01</td>
<td>1.26</td>
</tr>
<tr>
<td>25 cm H$_2$O</td>
<td>0.318</td>
<td>0.390</td>
<td>0.327</td>
<td>0.452</td>
</tr>
<tr>
<td>5 cm D$_2$O</td>
<td>2.38</td>
<td>2.31</td>
<td>2.09</td>
<td>2.49</td>
</tr>
<tr>
<td>10 cm</td>
<td>1.62</td>
<td>1.68</td>
<td>1.53</td>
<td>2.04</td>
</tr>
<tr>
<td>15 cm</td>
<td>1.063</td>
<td>1.19</td>
<td>1.05</td>
<td>1.41</td>
</tr>
<tr>
<td>25 cm</td>
<td>0.511</td>
<td>0.626</td>
<td>0.491</td>
<td>0.750</td>
</tr>
<tr>
<td>20 cm Al</td>
<td>2.54</td>
<td>1.99</td>
<td>1.86</td>
<td>2.94</td>
</tr>
</tbody>
</table>

a) $^{252}$Cf results normalized from measurements at 2.0 meters based on ANISN calculations.

Our calibration facility is used primarily for calibration of radiation protection instruments. It is of interest to us to know how well these instruments can be used as dose equivalent monitors in unknown calibration fields. Table IV contains a comparison of the dose equivalent estimates obtained with two popular moderated rem meters - the Andersson Braun cylindrical rem meter and the 9" spherical rem meter - in our neutron fields. The response of each rem meter was normalized to the bare source responses. The Andersson Braun unit was exposed with the source on a line perpendicular to the axis of the cylinder. The data in Table IV show us that the spherical rem meter over responds more to heavily moderated spectra than does the Andersson Braun unit. This means
TABLE V. NEUTRON QUALITY FACTORS FOR 1 m DISTANCE

<table>
<thead>
<tr>
<th>252_Cf MODERATOR</th>
<th>En 0.1 to 18 MeV</th>
<th>En Thermal to 18 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ANISN</td>
<td>BONNER SPHERES</td>
</tr>
<tr>
<td>None</td>
<td>9.38</td>
<td>8.96</td>
</tr>
<tr>
<td>2cm C_H_2</td>
<td>9.38</td>
<td>8.99</td>
</tr>
<tr>
<td>5cm</td>
<td>9.29</td>
<td>8.88</td>
</tr>
<tr>
<td>10cm</td>
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<td>8.82</td>
</tr>
<tr>
<td>25cm H_2O</td>
<td>8.81</td>
<td>8.72</td>
</tr>
<tr>
<td>5cm D_2O</td>
<td>9.33</td>
<td>8.94</td>
</tr>
<tr>
<td>10cm</td>
<td>9.17</td>
<td>8.75</td>
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<tr>
<td>15cm</td>
<td>9.08</td>
<td>8.68</td>
</tr>
<tr>
<td>25cm</td>
<td>8.93</td>
<td>8.49</td>
</tr>
<tr>
<td>20cm Al</td>
<td>9.91</td>
<td>9.38</td>
</tr>
<tr>
<td>238_PuBe MODERATOR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>None</td>
<td>8.19</td>
<td>7.97</td>
</tr>
<tr>
<td>2cm C_H_2</td>
<td>8.25</td>
<td>8.04</td>
</tr>
<tr>
<td>5cm</td>
<td>8.35</td>
<td>8.07</td>
</tr>
<tr>
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<td>8.33</td>
<td>8.13</td>
</tr>
<tr>
<td>25cm H_2O</td>
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<tr>
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<td>8.14</td>
</tr>
<tr>
<td>10cm</td>
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<tr>
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<td>8.35</td>
<td>8.24</td>
</tr>
<tr>
<td>25cm</td>
<td>8.30</td>
<td>8.27</td>
</tr>
<tr>
<td>20cm Al</td>
<td>9.19</td>
<td>9.07</td>
</tr>
</tbody>
</table>

a) 252_Cf results normalized from measurements at 2.0 meters based on ANISN calculations.

that the Andersson Braun counter would be more useful for relative calibration of "laboratory fields" from 252_Cf or 238_PuBe neutrons having unknown degrees of moderation. It should be noted however, that Hankins [17] has shown that the directional dependence of moderated rem meters make them less accurate in the relatively uncontrolled conditions of a radiation protection survey.

SUMMARY

The fields from 252_Cf and 238_PuBe neutron sources, each used in nine different moderators, have been characterized. The qualities measured,
include: neutron spectra, kerma, dose equivalent, quality factor and LET spectra. The data thus obtained will be used to improve the accuracy of dosimeter and survey instrument calibrations. This work has also provided valuable information about the advantages and limitations of the various techniques used, as they would apply to other situations.

Discrete ordinate calculations can be used to characterize radiation fields when the geometry is simple and approximates spherical symmetry. Monte Carlo techniques could be used for more complicated geometries, however the accuracy of either technique would suffer for deep penetration calculations. Multisphere spectrometry is instrumentally simple and sensitive, but the resolution is poor. However, it can be used for special field survey problems with good accuracy. Proton recoil spectrometry is sensitive with superior resolution to multisphere techniques, but requires more sophisticated instrumentation and does not provide full energy range information. Use of a tissue equivalent ion chamber with a neutron insensitive Geiger counter is a simple method of determining kerma. However, it has poor sensitivity and the accuracy of neutron measurement suffers if the gamma component is high – greater than about 50% of the total kerma. LET spectrometry can be used effectively in fields having higher gamma dose rates, but the electronics are more complicated and the data requires computer unfolding. However, the LET does provide data which can be used directly to determine the radiation quality factor.

ACKNOWLEDGEMENTS

The authors wish to thank Robert Strout for his assistance in modifying the GANDALF and LOUHI computer codes used for this work, and Thomas Crites for preparing the $^{252}$Cf and $^{238}$PuBe spectra for ANISN. We also thank Roger Kloepping, now of San Jose State College, and Dale Hankins for providing the moderated rem meter response data used for this report.

REFERENCES


SOME IMPROVEMENTS IN LOW-ACTIVITY GAMMA SPECTROMETRY.

In this study the authors have analysed some problems encountered in their experiments. The choice of an optimum geometry is particularly important in the case of low-activity measurements for which the counting rate needs to be maximized; the variations in the radius/height ratio in a Marinelli-type geometry for different detector dimensions are examined, and significant improvements in the counting rate are noted. In addition, two methods of secondary standard preparation are compared: the first, involving a single mixed source (containing a mixture of standards prepared by a primary laboratory), can only cause a shift in the calibration curve; the second, involving several individual (primary) sources, can in addition change the shape of the curve; the consequences of these different deformations were studied with a view to choosing the best method of preparing secondary standards. The measurements apply to various samples: water, milk, crushed vegetable matter, animal tissues, organic sediments, and sand; the gamma absorption in samples of different compositions was compared in order to establish the minimum number of secondary sources to be prepared.
1. OPTIMISATION DE LA GEOMETRIE DE L'ECHANTILLON

1.1. Hypothèses et calculs

Pour des mesures à basse activité, il est important de placer le volume d'échantillon autour du détecteur de façon à ce que le taux de comptage soit maximal.

Nous étudions la géométrie Marinelli pour déterminer quelles sont les valeurs optimales du rayon en fonction de la hauteur pour différents volumes.

Comme critère d'optimisation, nous considérons qu'un récipient a les dimensions idéales lorsqu'une couche supérieure externe de l'échantillon donne une contribution au taux de comptage égale à la contribution d'une couche latérale externe ayant le même volume. Si, par exemple, la couche latérale contribuait plus que la couche supérieure, le même volume placé dans un récipient plus large aurait un taux de comptage plus élevé.

Pour calculer ces contributions au taux de comptage, nous avons considéré que les \( \gamma \) qui sortent des couches en question parcourrent une même distance à l'intérieur du volume actif du détecteur, indépendamment de l'endroit d'où ils sont sortis.

Cette approximation est valable si ces couches ne sont pas très proches du détecteur et si on en tient compte dans les hypothèses d'approximation pour les angles solides. Nous n'avons pas considéré non plus les problèmes de différence d'absorption à l'intérieur de l'échantillon des \( \gamma \) provenant des couches externes; ceci est raisonnable, car la différence des distances des couches latérale et supérieure au centre du détecteur n'est pas très grande.

Avec ces approximations, la condition d'optimisation est que l'intégrale

\[
I = \int_{\Delta V} \Omega \, dV
\]

où \( dV \) est un élément de volume dans la couche, \( \Omega \) l'angle solide selon lequel cet élément de volume voit le volume actif du détecteur, \( \Delta V \) le volume de la couche, ait la même valeur pour les deux couches.

Pour la couche supérieure, nous aurons, d'après la figure 1,

\[
I_s = \int_{0}^{R} 2\pi \, \Delta h \, \frac{\pi a^2}{\cos \alpha} \, \frac{1}{y^2 + (h-b)^2} \, \gamma \, dy
\]
Après quelques transformations, nous arrivons à

\[ I_S = 2\pi^2 \Delta h \frac{a^2}{h-b} \left\{ \sqrt{R^2 + (h-b)^2 - (h-b)} \right\} \]  

Pour la couche latérale, nous avons considéré que celle-ci voit le détecteur comme un rectangle \( 2a \times 2b \) placé au centre du détecteur; donc

\[ I_L = \int_0^h 2\pi R \Delta R \, dx \, 4ab \, \frac{\cos \beta}{R^2 + (x-b)^2} \]

Après quelques transformations, nous arrivons à

\[ I_L = 8\pi \frac{ab}{\sqrt{b^2 + R^2}} \left\{ \frac{h-b}{\sqrt{(h-b)^2 + R^2}} + \frac{b}{\sqrt{b^2 + R^2}} \right\} \]  

La condition d'optimisation, soit \( I_L = I_S \), les équations (1) et (2), et l'équation d'égalité des volumes des deux couches nous permettent d'établir le rapport \( R \) et \( h \) pour des dimensions données (A et B) d'un détecteur.

**FIG.1. Approximations pour les angles solides.**
La figure 2 montre les valeurs optimales que nous avons trouvées pour A et B = 38,1 mm. Sur la même figure, nous montrons les valeurs R et h pour quelques récipients disponibles dans le commerce ainsi que nos valeurs pour des récipients ayant le même volume que ces récipients commerciaux.

Pour le contenant A₁, nous proposons un changement de dimension de façon à placer autrement 28% du total du volume en aplatissant le récipient.

Cette partie du volume, même si elle représente une proportion importante du total, contribue pour beaucoup moins au taux de comptage; ceci est dû à des considérations d'angle solide et d'absorption dans les couches intérieures de l'échantillon. Dans le récipient que nous proposons, cette partie du volume
FIG. 3. Variation des taux de comptage pour des volumes égaux de dimensions différentes.

verrait le détecteur selon un angle solide plus grand et la couche à traverser serait plus mince.

Pour le contenant $A_2$, nous proposons un déplacement de 16% du volume. Cette partie du volume est moindre que dans le cas $A_1$; de plus, elle est séparée du détecteur par une couche intérieure plus épaisse, ce qui réduit les effets d'une amélioration de l'angle solide. De ce fait, l'amélioration totale du cas $A_2$ est moins grande que celle de $A_1$.

1.2. Résultats expérimentaux

Nous avons effectué quelques mesures pour vérifier la validité de nos hypothèses. Nous utilisons pour cela une diode Ge-Li de type coaxial de 95 cm$^3$ de volume actif. La chambre est une chambre cubique de 51 cm de côté dont les murs sont constitués de 10 cm de plomb et d’une feuille de cadmium. Ces mesures consistent essentiellement à placer un même volume d'échantillon dans différents récipients et à comparer les taux de comptage respectifs. Pour éviter
FIG. 4. Variation de deux courbes de calibration (Ge-Li): région de la première parabole.

Les problèmes de variation dans la préparation des échantillons, nous utilisons la même solution. Nous prenons des temps de comptage suffisamment grands pour réduire à moins de 0,3% l’erreur dans les calculs des surfaces des pics.

Afin de vérifier nos hypothèses, nous préparons un récipient ayant les dimensions suggérées par nos calculs. Entretemps, nous avons pu étudier des variations autour des dimensions des récipients disponibles. Nous avons modifié quelques contenants en plaçant sur les parois latérales une couche de 2,5 mm de matériel imperméable ne donnant pas de bruit de fond, et nous avons comparé leurs taux de comptage à différents volumes avec les récipients commerciaux.

Les résultats de ces mesures sont montrés dans la figure 3 pour le césium-137 (661 keV). Nous voyons que, pour un même volume, si nous changeons les valeurs de R et h de façon à se rapprocher des valeurs prévues par nos calculs, nous trouvons une augmentation du taux de comptage. Pour le cas du récipient $A_1$ (de 0,95 litre), nous estimons que nous pouvons augmenter le taux de comptage d’à peu près 10%, et de 5% pour le Marinelli $A_2$ (de 3,7 litres).
2. PROBLEMES D'ETALONNAGE EN EFFICACITE

2.1. Préparation d'étalons secondaires liquides

Pour préparer nos sources d'étalonnage, nous pouvons soit utiliser une seule source mixte (contenant un mélange étalon de plusieurs pics préparé par un laboratoire primaire), soit utiliser plusieurs sources individuelles (primaires). La première méthode peut produire un décalage de la courbe d'étalonnage en efficacité et la deuxième peut non seulement provoquer un décalage, mais aussi modifier la forme de la courbe.

La courbe d'étalonnage en efficacité d'un détecteur Ge-Li de type coaxial se comporte comme deux paraboles dans une échelle log-log.

La première parabole, qui va jusqu'aux alentours de 250 keV, a une courbure très accentuée à cause des effets d'atténuation dans la couche morte de la surface du détecteur et, dans une moindre mesure, dans le terminal métallique du cryostat.
FIG. 6. Pourcentage de γ absorbés par une couche de 6,5 cm d'épaisseur de différents matériaux.

A cause de cette courbure accentuée, il est important de ne pas changer la forme de la courbe. Comme cette région est relativement étroite en énergie, il n'est pas toujours possible d'obtenir plus que les trois pics nécessaires pour établir la parabole. Avec seulement trois pics, si nous faisons des erreurs en plus et en moins alternativement, nous pouvons avoir un changement important de la forme de la courbe d'étalonnage.

La figure 4 montre deux courbes d'étalonnage établies par ordinateur, suivant une méthode des moindres carrés, à partir des trois pics (88, 122 et 356 keV). Dans l'une, nous avons pris les valeurs correctes pour les activités, et dans l'autre, nous avons pris des valeurs supérieures de 5% pour 88 et 356 keV, et inférieures de 5% pour 122 keV. La différence entre les deux calibrations est de plus de 8% entre 140 et 220 keV, et de plus de 15% en deça de 80 keV.

L'utilisation d'une seule source mixte ne provoquerait pas de déformation de ce genre car l'erreur commise serait la même pour toutes les énergies. Donc, pour cette région, il est préférable d'utiliser une seule source mixte.

La région de la deuxième parabole ne présente pas de courbure accentuée. De ce fait, un changement possible de sa forme est moins important. De plus, cette région est beaucoup plus large en énergie et on peut y obtenir plus facilement un grand nombre de pics.
La figure 5 montre la région de la deuxième parabole, dont le premier pic (356 keV) appartient aussi à la première parabole pour deux courbes d'étalonnage faites avec la même méthode que pour la région 1. Pour l'une des courbes, nous avons pris les valeurs correctes des activités et pour l'autre, nous avons pris des valeurs supérieures de 5% pour 356 et 835 keV, et inférieures de 5% pour 661 et 1332 keV. On remarque qu'à l'exception des extrémités, les courbes présentent un écart beaucoup plus petit que les 5% entre 450 et 1050 keV, la différence étant inférieure à 2,5%.

Donc, pour la deuxième région, il est préférable d'utiliser plusieurs sources individuelles qu'une seule source mixte.

2.2. Nombre de sources secondaires de compositions différentes

Nos mesures de routine portent sur divers échantillons: eaux (pluie, neige, eau du fleuve St. Laurent), lait, thyroïdes de bovins, viandes, poissons, mollusques, légumes et plantes aquatiques broyés, sédiments statiques et dynamiques, sables. L'absorption des $\gamma$ à l'intérieur de ces matériaux varie beaucoup d'un échantillon à l'autre. La figure 6 montre l'absorption des $\gamma$ par une couche de 6,5 cm d'épaisseur de ces différents matériaux. Le grand écart entre les absorptions nous oblige à préparer plusieurs sources secondaires de compositions différentes.

La préparation de ces sources pour certains matériaux (par exemple tissus animaux, végétaux broyés, etc.) présente beaucoup plus de problèmes que pour d'autres (par exemple l'eau) à cause de la difficulté de distribuer nos sources radioactives de façon homogène à l'intérieur de ces matériaux. Il serait fort commode d'avoir un moyen de réduire le nombre de sources secondaires à préparer.

Si on utilise un même genre de récipient, les questions d'angle solide sont les mêmes pour tous les échantillons, la différence importante tenant à l'absorption. Actuellement, nous mettons au point un programme d'ordinateur qui, à partir d'un étalonnage fait avec une géométrie donnée, calculerait les effets de la différence dans l'absorption et produirait une courbe d'étalonnage correspondant à chaque matériau utilisant la géométrie en question.

DISCUSSION

A.O. FREGENE: Your counting geometry is obviously not $4\pi$; would you not expect much better results, i.e. smaller deviations with the size of your container, if you had a $4\pi$ arrangement?

Jacqueline CABORET: For a given volume, even if the detector is placed at the centre of the sample, there will be differences in the counting rate depending on the shape of the volume; optimum geometry, we find, is achieved under the conditions outlined in our paper. The results indicate that configurations tending
towards optimum geometry have better counting rates than certain commercially available shapes — according to our calculations.

M.A.F. AYAD: Important work has been done in the United States of America on absolute detection efficiency as related to source and detector geometry. Have you made use of the results of this work?

Jacqueline CABORET: No, our measurements are not concerned with absolute detection efficiency.
ABSORBED DOSE DETERMINATIONS
A TECHNIQUE TO COMPENSATE FOR GEOMETRY-INDUCED ERRORS IN A PHOTON IRRADIATOR CALIBRATION*

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Abstract

A TECHNIQUE TO COMPENSATE FOR GEOMETRY-INDUCED ERRORS IN A PHOTON IRRADIATOR CALIBRATION.

The calibration of the exposure rate instrumentation used at Hanford necessitates the exposure of the instruments to photon beams at various radiation intensities. To simulate the wide variety of photon energies encountered, half a gram of $^{226}$Ra + daughters is used. So that a minimum exposure to Calibrations personnel is assured, the source is contained in an open-topped concrete well about 8 m deep. Instruments to be calibrated are placed in a holder at the top of the well and the source is raised to the prescribed position that gives the desired exposure rate. The primary calibration of the well poses unique problems because the exposure rates vary from place to place across the top surface of the well. Therefore, a transfer standard, being of a different volume and shape from the instruments being calibrated, responds differently to a source position than does a service instrument. To compensate for this variation, a service instrument has been modified to accommodate an integration device and a digital read-out. The instrument is first calibrated, free-in-air, by comparison to the transfer standard, and is then placed over the well in exactly the same position at which all instruments of that type are calibrated. The exposure rate is integrated over a sufficiently long time to eliminate the measurement errors resulting from a rate-only read-out. The calibration accuracy is discussed in this paper and an analysis of the error contributions at each step is provided.

INTRODUCTION

All of the routine photon exposure rate instruments (CPs)¹ used at the Hanford Project at Richland, Washington are calibrated biweekly at the Radiological Calibrations Laboratory. The calibration process requires the adjustment of each of the CP's four ranges at the 40% and 80% points. At these positions, the CP indicates 2, 4, 20, 40, 200, 400, 2000, and 4000 mR/h. On the average, 30 CPs are calibrated daily.

* Based on work performed under Contract EY-76C-06-1830 with the United States Energy Research and Development Administration, the function of which has been transferred to the United States Department of Energy.

¹ Cutie Pie radiation survey instrument.
FIG. 1. External configuration of well.

FIG. 2. Internal view of well.
The 2 mR/h and 4 mR/h points are calibrated free-in-air with a 1-mg source of $^{226}$Ra in equilibrium with its daughters. The other six points are calibrated with 1/2 g of $^{226}$Ra + daughters. To provide maximum personnel shielding, the 1/2 g source is contained in an open topped concrete-lined well approximately 8 m deep (see Figures 1 and 2). The walls of the well and the source positioning mechanisms in the well cause the radiation field strength to be nonuniform across the top of the well where instruments are exposed for calibration. Historically, the calibration of the well (source position versus exposure rate) has been accomplished by using a transfer standard which has calibration points traceable to the National Bureau of Standards at $^{137}$Cs (0.662 MeV) and $^{60}$Co (1.25 MeV).[1] The average energy of the photon radiation of $^{226}$Ra + daughters is 0.83 MeV, when filtered by 0.5 mm of platinum.[2] A calibration factor for the transfer standard has been assigned at our laboratory for $^{226}$Ra + daughters based on the assumption that the energy response of the transfer standard varies in a linear fashion between 0.662 MeV and 1.25 MeV. The problem associated with using the transfer standard directly is that it differs in size and shape from the instruments that are calibrated at the well. Because the beam is nonhomogeneous, the indicated exposure rate for a CP cylinder may be different from that of the transfer standard even though the distance between the source and either detector remains the same. Our new procedure eliminates any errors introduced as a result of these photon field differences.

**PROCEDURE**

Before the well can be calibrated, a CP must be modified to allow external monitoring of its response (see Figure 3). To integrate the exposure rate over a desired period of time, the voltage across the meter of the CP is connected through an isolation amplifier to a voltage-to-frequency converter (VFC). The pulses from the VFC accumulate in a scalar. The frequency of pulses is directly proportional to the meter deflection bias. Scale factors can be generated which accurately relate the counts accumulated over a given time with the dose delivered to the CP during that time.
## TABLE I. WELL CALIBRATION DATA

<table>
<thead>
<tr>
<th>Source Position (cm)</th>
<th>Measured (mR/h)</th>
<th>Previous (mR/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>533.8</td>
<td>13.2</td>
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</tr>
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<td>386.2</td>
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<td>319.7</td>
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<td>4000</td>
</tr>
<tr>
<td>31.3</td>
<td>4200</td>
<td>4500</td>
</tr>
</tbody>
</table>

Once the CP has been connected to a scalar and its scale factor has been measured, it is placed free-in-air along with a transfer standard, and both are exposed simultaneously to the photon radiation from a 1/2 g source of 226Ra + daughters that is the same in all physical dimensions as the one in the well. The calibration controls on the CP are adjusted until the indicated exposures after 100 s agree to within 1% between the CP and the transfer standard. All three upper ranges on the CP are calibrated by varying the source-to-detector distance.

The in-air calibrated CP with its associated readout equipment is then moved to the well and placed in the irradiation assembly for all CPs. The source is raised to the 20, 40, 200, 400, 2000, and 4000 mR/h positions and the exposure rates are integrated for 100 s each. The true exposure rate in mR/h can be calculated from the integrated value as follows:

\[
ER = \frac{(C)(SF)(CF)}{100 \text{ s}} \times 3600 \text{ s/h}
\]

where \( ER \) = exposure rate in mR/h
- \( C \) = counts observed in 100 s
- \( CF \) = correction factor converting counts to mR
- \( SF \) = scale factor (10, 100, or 1000)
Results

The data (see Table I) indicate that on the average, the actual exposure rate delivered to a CP during a calibration is 3% to 11% higher than anticipated on the X10 scale, 2% to 3% higher on the X100 scale, and 5% to 7% higher on the X1000 scale. By redetermining the true exposure rates throughout the length of the well, the accuracy of our calibration technique can be improved for all positions.

Errors Considered

Sources of error can arise at any step in a calibration such as this. Efforts have been made to identify these sources and to determine their effect on the data obtained.

Temperature and pressure correction factors which reference the measurements to 760 mm Hg and 25°C were calculated. The thermometer and barometer used have an accuracy of ±0.5% resulting in a correction factor error of 0.4%. All distances are known to within 2 mm. The maximum error that can be attributed to positioning errors is 1.3%. The scalar uses a crystal controlled-time base which exhibits better than 10 ppm accuracy. Timing errors are negligible. The in-air calibration of the CP was previously stated to agree to within 1% of the transfer standard. The National Bureau of Standards calibrates to an uncertainty of ±2%. Random experimental errors are assumed to be 1%. Therefore, the overall accuracy of this calibration is estimated to be ±5.7% at the closest distances. On the X10 scale, the positioning error is less than 0.1%. Therefore, the X10 calibration error is 4.5%.

CONCLUSION

We feel that our knowledge of our exposure parameters has been improved. Within the limits of experimental error, we can improve the accuracy of our calibration techniques throughout the length of the well.

REFERENCES


GENERAL CAVITY THEORY IN THE DOSIMETRY OF X-RAYS
Experimental study with a high-pressure chamber

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Abstract

GENERAL CAVITY THEORY IN THE DOSIMETRY OF X-RAYS: EXPERIMENTAL STUDY WITH A HIGH-PRESSURE CHAMBER.

Consistent models have been constructed for the calculation of the stopping power ratio in the limiting cases of small and large cavity sizes. The direct application of this theory is inhibited by the lack of data on isotropic backscatter coefficients and the uncertainty in the appropriate interpolation procedure between the limiting cases. An experimental arrangement has been set up to yield confirmation of the theory and to provide the missing information. Measurements have been made of the ionization density in a parallel-plate chamber with gold walls, filled with air pressurized from 1 to 25 atm. The plate separation is 4 mm and the effective energy of the heavily filtered X-rays is 170 keV, such that quite a large range of cavity sizes is covered, from about one tenth of the average electron range to about the maximum range. The collecting plate of the chamber consists of a 10 cm dia. collecting electrode surrounded by a 5 cm guard ring, such that no side wall effects occur. Through attenuation of the X-rays in the walls of the pressure vessel, the air mass and the gold foils, a large fluence of secondary photons is produced, which has been calculated with great accuracy. The experimental data and the calculated values of the stopping power ratio (air to gold) show good agreement, within the limits of confidence of the energy absorption coefficients. Further analysis of the data shows the need to use a 24% smaller value for the ratio of absorption coefficients (air to gold), and determines the energy backscatter coefficient of gold ($b_{en} = 0.49$) and the interpolation procedure. The consequences of applying cavity theory in dosimetry are discussed.

* This work is partially supported by the Interuniversity Institute of Nuclear Sciences.
1. INTRODUCTION

The aim of the cavity theory is to make possible the calculation of the absorbed dose in a cavity surrounded by a medium of different atomic number or composition. The ratio of the cavity dose $D_c$, to the dose when the cavity is filled with medium material, $D_m$, is the stopping power ratio:

$$f_{c,m} = \frac{D_c}{D_m} \quad (1)$$

The need for a cavity theory originally arose from the use of cavity ionization chambers. Since the range of the electrons is in general much greater than the average chord length of the gas volume, cavity theory at first made no allowance for the modification of the electron fluence in the cavity, as compared with the equilibrium fluence in the homogeneous medium. The ratio of the absorbed doses thus reduced to the ratio of the rates of energy deposition of the electrons. In Bragg-Gray theory [1] this equals the ratio of stopping powers:

$$f_{c,m}^{B-G} = \frac{S_c}{S_m} \quad (2)$$

In the theory of Spencer and Attix [2], allowance for the finite range of $\delta$-rays has been made. The $\delta$-rays with energy above or below an energy $\Delta$ are assumed to be absorbed outside or inside the cavity:

$$f_{c,m}^{S-A} = \frac{1}{T_0} \int_\Delta^{T_0} dT I_m(T_0, T) S_c(T, \Delta) \quad (3)$$

The stopping power $S_c$ is thus restricted to energy losses below $\Delta$, and, from the equilibrium fluence $I_m(T_0, T)$ of slowing down electrons including $\delta$-rays, in the homogeneous medium for an initial energy $T_0$, only electrons above $\Delta$ enter the cavity. The Spencer-Attix theory has been widely accepted for application to ionization chambers. The use of solid and liquid dose meters created a need for a general cavity theory, which should allow for the attenuation of the electron fluence due to absorption and scatter. In the theory of Burlin [3], this attenuation yields a weighting factor between the Spencer-Attix stopping power ratio and the ratio of energy absorption coefficients $\mu_{en}/\rho$:

$$f_{c,m}^{B} = f_{c,m}^{S-A} d + \frac{(1-d)(\mu_{en}/\rho)_c}{(\mu_{en}/\rho)_m} \quad (4)$$
This weighting factor $d$ equals the average attenuation in the cavity, assuming
exponential attenuation with coefficient $\beta$, over the average cavity chord length, $g$:

$$d = \frac{1 - e^{-\beta g}}{\beta g} \quad (5)$$

A different approach to the problem for large cavity sizes has led to a theory
[4—6] which consists of a modified form of the Spencer-Attix expression for
small cavities and of a surface method for large cavity sizes. For intermediate
cavity sizes an interpolation is proposed. The full description of the final theory
is given in the following section. The main part of this paper deals with the
description and the results of ionization measurements with a high-pressure cavity
chamber; these yield an experimental verification of the theory.

2. GENERAL CAVITY THEORY

2.1. Theory for small cavities

The fundamental expression for the contribution of electrons with origin in
the medium to the stopping power ratio ($f_{c,m}^m$) has been given in a paper by
Spencer [7]:

$$f_{c,m}^m = \frac{1}{T_0} \left( \int_{\bar{Q}}^{T_0} dT \right) \frac{m}{m} \left( \int_{\bar{Q}}^{T} dT' k(T, T') \langle e(T') \rangle \right)$$

$$- \frac{1}{T} \left( \int_{0}^{T} dT' k(T, T') \langle e(T) \rangle \right)$$

$$- \left( \int_{0}^{T} dT' k(T, T') \langle e(T) \rangle \right)$$

$$+ \left( \int_{0}^{T} dT' k(T, T') \langle e(T') \rangle \right)$$

$$\langle e(T) \rangle = \langle e(T') \rangle \quad (6)$$

The function $D(T)$ is the stopping power restricted to locally absorbed energy
losses (below the binding energy $\bar{Q}$):

$$D(T) = \int_{0}^{\bar{Q}} dT' k(T, T') T'$$

and the function $\langle e(T) \rangle$ is the volume average of the fraction of the energy, $T$, of an
electron which is absorbed in the cavity.
The cavity contribution is simply given by:

\[ f_{c, m}^{c} = \frac{1}{T_0} \langle \bar{\epsilon}(T_0) \rangle \]  (7)

The Spencer-Attix theory can be derived from this fundamental expression by a two-step model for the energy deposition:

\[ \langle \bar{\epsilon}(T) \rangle = T \quad \text{for} \quad T < \Delta \]  (8)
\[ \langle \bar{\epsilon}(T) \rangle = 0 \quad \text{for} \quad T > \Delta \]

The energy, \( \Delta \), is chosen such that the extrapolated range of electrons with this energy equals the average chord length of the cavity. The discontinuity in definition (8) of \( \langle \bar{\epsilon} \rangle \) induces a sharp transition, when \( \Delta \) equals \( T_0 \), between the Spencer-Attix expression and the ratio of energy absorption coefficients. To avoid the unrealistic behaviour for large cavity sizes of the Spencer-Attix theory, a more appropriate definition of the energy deposition function has been introduced:

\[ \langle \bar{\epsilon}(T) \rangle = T(1 - T/(2\Delta)) \quad \text{for} \quad T < \Delta \]  (9)
\[ \langle \bar{\epsilon}(T) \rangle = \Delta/2 \quad \text{for} \quad T > \Delta \]

The use of this model in the basic expression (6) yields, with neglect of terms smaller than

\[ \frac{1}{T} \int_{0}^{\frac{1}{2}T} dT' k(T, T') T'^2 \]

as compared with the stopping power, the expression:

\[ f_{c, m}^m = \frac{1}{T_0} \int_{0}^{T_0} dT I_m(T_0, T) S_c^*(T, \Delta) \]  (10)
with

\[ S^*(T, \Delta) = S(T, \Delta) = \int_{T' \leq T} dT' k(T, T') T' \quad \text{for } \frac{1}{2}T > \Delta \]

\[ = S(T) = \int_{T' \leq T} dT' k(T, T') T' \quad \text{for } \Delta < T \quad \text{and } \frac{1}{2}T < \Delta \]

\[ = \frac{T}{\Delta} S(T) \quad \text{for } \Delta > T \]  

This expression is similar to the Spencer-Attix expression and yields, for small cavities, about the same results [5, 6]. For large cavity sizes Eq. (10) yields quite realistic values.

2.2. Theory for large cavities

In the surface model [5, 6] the cavity dose is computed from the net inward and outward energy currents at the interface. These currents are determined by transmission and reflection of the electrons. A full description of the multiple scatter has been given with an operator formalism [6]. In a first order approximation for the scatter contribution, the contribution of the medium to the stopping power ratio is thus given by the expression:

\[ f_{c,m}^m (g) = f_{c,m}^m, o (g) + \frac{2(b_en - b_en)}{1 - b_en b_en} (f_{c,m}^m, o (g) - f_{c,m}^m, o (2g)) \]  

(12)

the "homogeneous" term being given by:

\[ f_{c,m}^m, o (g) = \frac{1 - b_en}{1 + b_en} \frac{1}{g T_0} \int_{0}^{T_0} dT I_m(T_0, T) (T - t(T, g), \tau(T, g)) \]  

(13)

In this expression, b_en is the energy backscatter coefficient for isotropic incidence on a semi-infinite wall of cavity or medium material, t(T, g) is the transmission coefficient for traversal of a slab of cavity material of thickness g (average chord.
length), and $\tau(T, g)$ is the average energy of the transmitted electrons, which is defined by the condition for the extrapolated range:

$$R_{\text{ex}}(\tau) = R_{\text{ex}}(T) - g$$

Expression (12) is, except for the energy dependence of the scatter coefficients, exact for large cavities ($g > R_{\text{ex}}(T_0)$). The surface model makes no allowance for the escape of $\delta$-rays, and thus overestimates the stopping power ratio for small cavity sizes. Expression (10) is then more appropriate than (13) for the calculation of the homogeneous term. The application of Eq. (12) to the homogeneous term in the theory for small cavities is justified since the energy-deposition model (9) does not take differences between the scatter coefficients of cavity and medium into account.
2.3. Hybrid calculations

A convenient interpolation procedure between expressions (10) and (13) has been retained such that the homogeneous term is given by:

\[
f_{c,m,0}^{m_0} = \frac{1}{gT_0} \int_0^{T_c} dT I_m(T_0, T) \frac{1 - b_{c\text{en}}}{1 + b_{c\text{en}}} (T - t(T, g) \tau(T, g))
\]

\[
+ \frac{1}{T_0} \int_{T_0}^{T_c} dT I_m(T_0, T) S_c^\alpha(T, \Delta)
\]

the cut-off energy \( T_c \) being given by:

\[
R_{\text{ex}}(T_c) = \eta g
\]

The interpolation parameter \( \eta \) is unknown, and has to be derived from the fitting of experimental and theoretical data. The interpolation procedure (15) should also be justified. The experimental programme which is described below is intended to yield this information and to confirm the cavity theories.

3. EXPERIMENT

3.1. Description

Ionization chambers with variable plate separation [8] or gas pressure [9], have been used for investigating the cavity theory. In the experiment of Larsson [9], a broad range of cavity variables was obtained by varying the pressure from \( 3 \times 10^{-3} \) to 1 atm using fluorescence X-rays with energies of 16.1 to 34.4 keV. In the present experiment, using a variable high pressure (from 1 to 25 atm) has been preferred, to allow cavity experiments at energies of about 100 to 200 keV to be made. In this intermediate energy range, the electron transport properties are less energy dependent [10], and thus allow of more general conclusions. This configuration has also the advantage of nearly eliminating the side-wall contribution. A disadvantage of the use of high pressures is the appearance of initial recombination.
The pressure vessel is shown in Fig. 1, and the alignment of the ionization chambers, pressure vessel, collimator and X-ray target in Fig. 2. A full description of the construction is given in Ref. [6]. The pressure vessel has been designed to reduce the attenuation and scatter of the X-rays in the Dural entrance window and the scatter against the steel plates.

A parallel-plate cavity chamber (with thin metal electrodes) and a reference chamber (with carbon-coated electrodes) were inserted at approximately the mid-plane of the vessel. The metal foils and the carbon coating are supported by 1 mm thick Lucite plates. The carbon layer is sufficiently thick (16 µm) to ensure that the contribution of electrons with origin in the Lucite plates is negligibly different from that in a homogeneous carbon plate. The cross-sections of carbon are not significantly different from the cross-sections in air over the energy range of 100 to 200 keV, so that the reference chamber is approximately air equivalent.
The construction of the chambers as used for the actual experiment is shown in Fig. 3. For this experiment a 25 μm thick gold foil was used as the high-atomic-number electrode (i.e. the medium for cavity theory). An effective X-ray energy of 170 keV was obtained by heavy filtering of 200 kV X-rays. The plate separation of 4 mm for the cavity chamber was chosen to yield an appropriate range of cavity dimensions. The plate separation of 12 mm for the reference chamber is sufficiently small to eliminate the side-wall contribution.

More detailed attention is given to the calculation of the side-wall contribution, of the photon fluences in the chamber walls, and of the initial recombination in the paragraphs below. For details of other aspects we refer the reader to Ref. [6].

3.2. Side-wall contribution

The side-wall contribution is the relative difference between the ionization density in the collecting volume of radius a produced by an infinite and uniform
parallel beam, and that due to a beam limited to a radius $b$ (the radius of the guard ring). In the homogeneous case, such as for the reference chamber, an equilibrium fluence of secondary electrons leaves the area $2\pi bd$, $d$ being the plate separation. If the dimensions $a$ and $d$ are much smaller than the distance $b$, then, for an isotropic angular distribution, a fraction $(2da/4\pi b^2)$ traverses the collecting volume, which has an average chord length of $(\pi a/2)$. The energy deposition per unit distance is approximately proportional to $(1 - \{b/R_0\})$, $R_0$ being the extrapolated range of secondary electrons with initial energy $T_0$. The side-wall contribution is thus given by the following expression:

$$\frac{(2\pi bd)(2da/4\pi b^2)(\pi/2a)(1 - \{b/R_0\})}{\pi a^2 d} \tag{17}$$

or:

$$(d/2b)(1 - \{b/R_0\}) \tag{18}$$

For the contribution of the electrons from the medium or from the metal foil, the calculation is similar, but the fluence of electrons is weighted with the cosine of the angle between the normal to the surface and the vector pointing to the collecting volume (cf. Fig. 4) for a point a distance $r$ from the centre. The mean value of this weighting factor equals $(d/2r)$, and the side-wall contribution equals:

$$2 \int_b^R 2\pi r \, dr \frac{(\pi a^2 d/4\pi r^2)(1 - \{r/R_0\})(d/2r)}{\pi a^2 d} \tag{19}$$

or:

$$(d/2b)(1 - \{b/R_0\} + \{b/R_0\} \ln \{b/R_0\}) \tag{20}$$
In the expressions (17) and (19), the energy deposition function can be integrated over the range of chord lengths, but it appears that this induces only terms of the order \((a/R_0)^2\) as compared with unity.

The outer radius of the guard ring is 10 cm. For the carbon chamber, the average range, \(R_0\), is 1.3 cm at 1 atm, so that there is no side-wall contribution. For the gold foil, the electron range is about 20 cm, which yields a side-wall contribution of 0.3%.

To these small contributions, the effect of radial non-uniformity of the beam must be added. This non-uniformity has been measured and it is, within experimental error (± 1%), not larger than the non-uniformity due to the inverse-square-law effect. The ratio of the fluence at a distance \(r\) from the centre to the fluence at the centre, at a distance \(f\) from the target, is \((1 + (r/f)^2)^{-1}\). The relative average fluence for an outer radius of \(b = 10\) cm, and a focus distance of 74 cm, equals 0.991. In fact a weighted average should be calculated, taking the energy deposition of electrons with origin at a radial distance \(r\) into account. For this purpose, the contribution of electrons from beyond a radius \(a = 5\) cm has been computed. In the homogeneous case, this contribution can be evaluated from the calculation of the average chord length \(\bar{x}\), which has been shown [6] to be given by the expression:

\[
\bar{x} \geq \frac{2d}{\pi} \left( \ln \left( \frac{4a}{d} \right) + 0.19 - L(\psi) \right)
\]

with:

\[
L(\psi) = \ln \left[ \tan \left( \frac{\pi}{4} + \frac{\psi}{2} \right) \right] - \sin \psi
\]

and:

\[
\psi = \arccos \left( \frac{R_0}{2a} \right)
\]

The relative deposited energy equals:

\[
\left( \frac{\bar{x}}{a} \right) \left( 1 - \frac{\bar{x}}{2R_0} \right)
\]

The correction for radial non-uniformity is thus equal to 0.3% for the carbon chamber, and less than 0.4% for the gold chamber.

The total correction for the side wall and the radial non-uniformity is thus negligible at 1 atm, and decreases rapidly at higher pressures. The collecting volume of the reference chamber, which is limited by this condition, is about 94 cm³, which yields a sufficiently large ionization current (> \(10^{-11}\) A).
### TABLE I. FLUENCES OF PRIMARY AND SECONDARY PHOTONS

<table>
<thead>
<tr>
<th>Primary photons</th>
<th>Ratio of the fluence in the gold chamber to that in the reference chamber</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>at 1 atm</td>
</tr>
<tr>
<td>Due to attenuation</td>
<td>0.911</td>
</tr>
<tr>
<td>Due to distance</td>
<td>0.925</td>
</tr>
<tr>
<td>Product</td>
<td>0.843</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Secondary photons</th>
<th>Ratio of the fluence to the fluence of primary photons in the two chambers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scatter in</td>
<td>Reference chamber</td>
</tr>
<tr>
<td>Lucite</td>
<td>0.055</td>
</tr>
<tr>
<td>Gold</td>
<td>0.024</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>Air at 1 atm</td>
<td>0.002</td>
</tr>
<tr>
<td></td>
<td>0.050</td>
</tr>
<tr>
<td>Entrance window</td>
<td>0.020</td>
</tr>
<tr>
<td>Steel back plate</td>
<td>(&lt;10^{-3})</td>
</tr>
<tr>
<td></td>
<td>(&lt;10^{-3})</td>
</tr>
<tr>
<td>Steel cylinder</td>
<td>(&lt;0.006)</td>
</tr>
<tr>
<td></td>
<td>(&lt;0.022)</td>
</tr>
<tr>
<td>Total at 1 atm</td>
<td>0.101</td>
</tr>
<tr>
<td>at 25 atm</td>
<td>0.149</td>
</tr>
</tbody>
</table>

### Total fluence Ratio of the fluence in the gold chamber to the fluence in the reference chamber

At 1 atm: 1.048  
At 25 atm: 1.052  
Ratio at 25 atm to ratio at 1 atm = 1.004
For the side-wall contribution in the Larsson chamber [9], the following approximate values were computed using Eqs (21) and (24):

\begin{align*}
\text{at 1 atm: } & 0.09 \\
\text{at 0.1 atm: } & 0.34 \\
\text{at 0.01 atm: } & 0.38. \\
\end{align*}

(25)

Although the side walls are partly covered with metal, these contributions are too large to enable a valid comparison with cavity theory to be made.

3.3. Photon fluences

The photon fluences in the reference chamber and in the cavity chamber differ as a result of their different distances to the target and the attenuation and build-up of fluorescence photons in the gold foils. The fluences of Compton-scattered photons generated in the aluminium entrance window, the air mass and the Lucite supports are also somewhat different in both chambers, but have to be evaluated mainly because of the different ratios for gold to air of the energy absorption coefficients in the two media for the secondary and the primary photons.

The calculation of the fluences of fluorescence and Compton-scattered photons was made using a method described elsewhere [11]. This method yields the fluences of secondary photons generated in cylindrical walls irradiated perpendicularly with a uniform beam. In this experiment the beam is conical, such that the inverse-square-law effect has to be taken into account. For this purpose the air mass and the cylindrical side wall were divided into a number of segments. For the side wall, the length of these segments is equal to the average distance which the primary photons traverse in the steel wall. The contribution of the side-wall segments were computed by making a difference between the calculated contributions for the inner and outer radius of the cylinder, the attenuation of the secondaries being properly corrected for (cf. [6]).

The fluences of secondary photons were computed in the mid-plane of the chambers for a photon energy of 170 kV. The contributions of the Lucite plates and of the gold foils were computed both in the front and the back planes to estimate the homogeneity of the fluences, and, at energies of 150 keV and 200 keV, to estimate the possible error due to an uncertainty in the effective energy. The calculations were performed for a measuring point on the central axis, the average fluence over the collecting area being not significantly different. The fluences were multiplied by the relative energy absorption coefficients in air for the reference chamber, and by the coefficients both in air and in gold for the cavity chamber. The various contributions to the total fluence have been listed in Table I. These fluences are used in the normalization of the currents.
TABLE II. MULTIPLICATION FACTORS FOR THE TRANSFORMATION OF THE RATIO OF THE CURRENT IN GOLD TO THAT IN AIR INTO A STOPPING POWER RATIO

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Plate separations</td>
<td>2.985</td>
</tr>
<tr>
<td>Surfaces</td>
<td>0.984</td>
</tr>
<tr>
<td>Fluences at:</td>
<td></td>
</tr>
<tr>
<td>1 atm</td>
<td>0.954</td>
</tr>
<tr>
<td>25 atm</td>
<td>0.950</td>
</tr>
<tr>
<td>Energy absorption coefficients</td>
<td>0.0287</td>
</tr>
<tr>
<td>Products at:</td>
<td></td>
</tr>
<tr>
<td>1 atm</td>
<td>0.0804</td>
</tr>
<tr>
<td>25 atm</td>
<td>0.0801</td>
</tr>
</tbody>
</table>

delivered by the chambers to yield a stopping-power ratio. The different contributions to the fluence in the gold chamber, and the corresponding photon energies, are used for calculating the yields of different electron energies (§ 4).

3.4. Initial recombination

The disadvantage of ionization measurements with high-pressure gases is the increase in the initial recombination of the ions. The collection efficiency, \( y \), is given by the expression [12]:

\[
y = (1 + cf(x))^{-1}
\]  

(26)

in which \( c \) is a constant, proportional to the ionization density in the track, and thus to the pressure \( p \), and the function \( f(x) \) is given by:

\[
f(x) = e^x \frac{\pi}{2} H_0^{(1)}(ix)
\]  

(27)

(with the Bessel function of the third kind or Hankel function \( H_0^{(1)} \)). The variable \( x \) is proportional to the square of \( (X/p) \), \( X \) being the field strength and \( p \) the pressure.
FIG. 5. Stopping power ratio of air to gold, as a function of the gas pressure.

From measurements of the variation with field strength of the ionization current in the chambers at different pressures, the following approximate best fits for the constants were obtained:

for both chambers: \( \frac{xp^2}{X^2} \approx 4 \times 10^{-5} \)
for the reference chamber: \( (c/p) \approx 5.8 \times 10^{-3} \)
for the cavity chamber: \( (c/p) \approx 4.2 \times 10^{-3} \) \( (28) \)

The first constant \( \frac{xp^2}{X^2} \) is in good agreement with the value reported in Ref. [12]. The constants \( (c/p) \) are, however, about a factor of 10 larger than
TABLE III. RELATIVE CONTRIBUTIONS OF DIFFERENT ELECTRON ENERGIES TO THE ENERGY ABSORPTION IN THE GOLD FOILS

<table>
<thead>
<tr>
<th>Medium (gold) contribution</th>
<th>Cavity contribution (air)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energies (keV)</td>
<td>Yields at 1 atm</td>
</tr>
<tr>
<td>-----------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>157.5</td>
<td>0.199</td>
</tr>
<tr>
<td>128.5</td>
<td>0.042</td>
</tr>
<tr>
<td>89</td>
<td>0.449</td>
</tr>
<tr>
<td>57.5</td>
<td>0.199</td>
</tr>
<tr>
<td>34</td>
<td>0.018</td>
</tr>
<tr>
<td>8.5</td>
<td>0.060</td>
</tr>
<tr>
<td>2</td>
<td>0.030</td>
</tr>
<tr>
<td>Total</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Expected from the constants for α-particles, which suggests that the energy of the secondary electrons is about 2 keV. The difference between the constants for the two chambers is caused by the different electron energies and angular distributions.

The current measurements for pressures above 5 atm were made at a field strength of 667 V/cm. The collection efficiency in the reference chamber equals 0.920 at 8 atm and reduces to 0.645 at 25 atm. At 1 atm, the collection efficiency is almost unity. The saturation currents, calculated with the given constants and normalized to the current at 1 atm and to the pressure, agree to within 1% with the calculated fluences of primary and secondary photons.

The uncertainty in the correction factor for recombination applied to the ratio of the current in the cavity chamber to that in the reference chamber has been estimated to be smaller than:

\[
0.1\% \text{ at 1 atm} \\
1\% \text{ below 15 atm} \\
3\% \text{ below 25 atm}
\]

(29)

3.5. Results

The measured currents, corrected for leakage current and recombination, are divided by the relative fluences of the photons and by the collecting volumes.
The current density in the reference chamber is multiplied by the ratio for gold to air of the energy absorption coefficients in the two media to yield the equilibrium current density in gold. The multiplication factors given in Table II transform the ratio of the current in the gold chamber to that in the reference chamber into the stopping power ratio of air to gold. The uncertainties in these factors are significant only for the ratio of the energy absorption coefficients and for the ratio of the fluences. The limits of confidence of the tabulated values of the absorption coefficients [13] have been set at 20% for gold and 5% for air. The dominating contribution in the ratio of the fluences is the fluence of fluorescence photons in gold (relative yield 0.2), having an uncertainty of about 25%. These errors can be even larger as a result of the width of the energy distribution of the X-rays (homogeneity index 0.99).

The standard deviation of the measured currents is negligibly small (normally less than 0.3%).

The values of the experimental stopping power ratios are shown in Fig. 5 together with theoretical values, which are described in the next section.

4. CALCULATIONS OF THE STOPPING POWER RATIO

The calculation of the stopping power ratio of air to gold has been made using the method described in §2. The average chord length, $g$ (g/cm$^2$), for the plane-parallel plate at a pressure $p$ (atm, normalized to 22°C), equals:

$$g = 2 \times 0.400 \times 0.001197 \times p$$

$$= 0.9576 \times 10^{-3} p$$

(30)

The source energies have been computed for the different photon energies (primary, average Compton, $K_{\alpha \beta}$ and L), and for all interactions of these photons with gold. In order to simplify the calculations, the energy yields $\mu_i$ of electrons with about the same energies $E_i$ have been summed. These groups have been chosen such that the average energies of a group, defined by:

$$\overline{E_1} = \frac{\sum \mu_i}{\sum (\mu_i/E_i)}$$

(31)

and by:

$$\overline{E_2} = \frac{\sum (\mu_i E_i)}{\sum \mu_i}$$

(32)
differ by less than 0.5 keV. The definitions of $E_1$ and $E_2$ are suited to the small and large cavities, respectively. The computations have been performed with electron energies $E_i$, given in Table III, with their relative yields at 1 and 25 atm. The relative contributions of the electrons generated in the cavity (air) are also given in Table III.

The calculated values of the homogeneous terms in the stopping power ratios, $f_0(E_i)$, have been corrected for the difference between the average chord length approximation and the chord length distribution within a plane-parallel cavity. This correction factor has been derived from the approximate function for the energy deposition per unit chord length, at a depth $r$ within the cavity:

$$\frac{dE}{dr} = 1 - \frac{r}{R}$$  \hspace{1cm} (33)

($R$ is the extrapolated range of the source electrons), which yields in the average chord length approximation the following expressions for the weighting factor $d_c$ (wall contribution to $f$, in the homogeneous case):

\begin{align*}
    d_c &= 1 - \frac{g}{2R} \quad \text{for } R > g \\
    d_c &= \frac{R}{2g} \quad \text{for } R < g \\
\end{align*}

\hspace{1cm} (34)

Integration of the energy deposition function $(dE/dr)$ over the chord length distribution in a plane-parallel cavity yields:

\begin{align*}
    d_c &= 1 - \frac{3g}{8R} - \left(\frac{g}{4R}\right) \ln \left(\frac{2R}{g}\right) \quad \text{for } R > g/2 \\
    d_c &= \frac{R}{2g} \quad \text{for } R < g/2 \\
\end{align*}

\hspace{1cm} (35)

The ratio of the weighting factors, (35) to (34), yields the appropriate correction factor.

The weighted sum of the corrected stopping power ratios is corrected for the difference between the energy backscatter coefficients in gold and in air. For the coefficient in air the calculated values in Ref. [14] were used. The mean value of $b_{\text{air}}^{\text{en}}$ is 0.138 for the medium and 0.152 for the cavity contribution. For the coefficient in gold, we have made use of data of the energy backscatter of
FIG. 6. Ratio of the cavity dose to the equilibrium dose in air; experimental values (○) and theoretical curves for:

$\left( \frac{\mu_{en,\text{air}}}{\mu_{en,\text{en}}} \right) = 0.0217; \quad b^{en}_{Au} = 0.49; \quad \eta = 2^{-n}, \text{ where } n = 0 \text{ to } 6.$

electrons in tantalum (Z = 73) and uranium (Z = 92) [15]. For both materials in the vicinity of gold (Z = 79), the increase of the backscatter coefficient for isotropic relative to perpendicular incidence is 0.1 ± 0.01 at 1 MeV; from measurements at 60° incidence it appears that this increase is probably energy independent down to 100 keV. The energy backscatter coefficient in gold for perpendicular incidence, at energies between 50 and 200 keV, is about 0.39, so that a good estimate for $b^{en}_{Au}$ is 0.49. Values smaller than 0.4 or greater than 0.6 have been excluded.
FIG. 7. Ratio of the cavity dose to the equilibrium dose in air, with the partial contributions of the different electron energies.

The stopping power ratios, computed with values $b_{\text{Au}}^{\text{en}}$ equal to 0.4 and 0.6, and values for the interpolation parameter $\eta$ of 0.5 and 2, have been represented in Fig. 5, together with the experimental values. For none of these parameters is the agreement between theory and experiment good, although the curves exhibit a similar behaviour. This implies that the normalization factor (Table II) is too large and thus, in the first place, that the ratio of energy absorption coefficients should be smaller than the value which was obtained from the tabulated cross-sections and fluorescence yields.

To allow a further analysis of the experimental data, the ratio of energy absorption coefficients ($\mu_{\text{en}}^{\text{air}} / \mu_{\text{en}}^{\text{Au}}$) has been omitted from the normalization.
factor, and the calculated stopping power ratios are divided by a factor \( \left( \frac{\mu_{en}^{\text{air}}}{\mu_{en}^{\text{Au}}} \right)_{\text{eff}} \), which is considered as a parameter. This procedure yields values of the ratio of the cavity dose to the dose in a homogeneous air medium, for the same fluence of primary and secondary photons. The parameter \( \left( \frac{\mu_{en}^{\text{air}}}{\mu_{en}^{\text{Au}}} \right) \) has been defined by fitting the experimental and theoretical data at 20 atm. In Fig. 6 the theoretical values have been computed with \( b_{\text{en}}^{\text{Au}} = 0.49, \left( \frac{\mu_{en}^{\text{air}}}{\mu_{en}^{\text{Au}}} \right) = 0.0217 \) and the parameter \( \eta \) ranging over an interval from \( 1/8 \) to 1. The agreement between experiment and theory is within 3% over this range of values for \( \eta \). An increase of the optimum value of \( \eta \) with pressure, or cavity dimension, can be observed. This shows the increasing importance of an evaluation of the balance between the \( \delta \)-electrons in gold and in air for small cavities. The contribution of \( \delta \)-rays is computed accurately only for \( \eta = 0 \).

The irregularities in the slopes of both the theoretical and experimental curves are related to the different electron energies. The partial contributions of the different electron energies are represented in Fig. 7.

5. CONCLUSIONS

The measured values of the stopping power ratio of air to gold have been predicted by the general cavity theory, within the limits of confidence which are given for the tabulated energy absorption coefficients. Since the ratio of the atomic number of the medium (gold) to that of the cavity (air) is much larger than the ratios found in the current dosimetry practice, we conclude that the general cavity theory is sufficiently accurate for most applications.

The scaling of the experimental and theoretical data yields the value 0.0217 for the ratio of energy absorption coefficients, instead of the value 0.0286 derived from the tabulated cross-sections. Since the normalization factor also includes the ratio of photon fluences in the chambers, which is determined by the yield of fluorescence photons in gold, the interpretation of this large deviation (24%) is not straightforward.

In the range of cavity sizes investigated, good agreement with cavity theory has been obtained, with a value of about 0.5 for the parameter \( \eta \). The optimum value seems to decrease for smaller cavity sizes. This small value for \( \eta \) implies that the modified two-step model yields good results even for large cavity sizes. The validity of the surface method seems to be limited to cavity sizes greater than the extrapolated range.

The present experiment provides a relevant argument for the validity of the general cavity theory. Measurements with other metal foils and other gases will be performed to improve the knowledge of the effective energy backscatter coefficients and of the appropriate values of the parameter \( \eta \).
In situations where the cross-sections in the cavity and the medium do not differ very much, the cavity theory can be applied with confidence, and the uncertainty in the stopping power ratio is probably of the same order as the uncertainty in the ratio of energy absorption coefficients. The application of the cavity theory may allow the use of cavity ionization chambers or dose meters in absolute metrology to be extended.

ACKNOWLEDGEMENTS

The authors acknowledge the support of Professor Dr. A.J. Deruytter, Director of the Laboratory of Nuclear Physics, and of Professor Dr. O. Segaert, Director of the Central Service of Radiation Protection.

The authors would also like to thank Mrs. B. Van Waeyenberge and Mr. R. Verspille for their assistance in preparing the manuscript and diagrams.

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A NEW TYPE OF STANDARD FREE-AIR CHAMBER FOR HIGH QUANTUM ENERGIES

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Abstract

A NEW TYPE OF STANDARD FREE-AIR CHAMBER FOR HIGH QUANTUM ENERGIES. The conventional free-air chamber is employed for the exposure standardization of X-rays generated at potentials up to a few hundred kilovolts, i.e. for secondary electron ranges below 1 m. Two methods of attaining higher energies have been published: suppressing electron ranges by operating the chamber under high pressure, and forcing electron trajectories into spirals by a magnetic field parallel to the photon beam. The first method leads to increased ion recombination, causing additional inaccuracy, the second leaves the required chamber length unchanged. The secondary electron trajectories can also be confined by a magnetic field orthogonal to the photon beam. This is achieved by means of a toroidal winding, which is intersected by the beam parallel to the toroid symmetry axis, z. The free-air chamber inside the torus consists of two cylinders (a high voltage electrode and a collector-guard electrode assembly) and two end plates (guard strip assemblies). The magnetic flux density is inversely proportional to the distance r from the axis, the lines of induction being around it. The required chamber cross-section is defined by the secondary electron trajectories in the rz-plane. These are periodic loops with a net drift along z, and can be expressed in terms of Bessel functions. The product, mass of the winding multiplied by power dissipation in it depends on the maximum energy T of the secondary electrons but not significantly on other design parameters. For copper, a value below $10^{-4} \text{kg} \cdot \text{W}$ can be achieved, where T is measured in MeV. Thus this method is feasible, for example, for the $^{60}$Co quantum energies (T = 1.1 MeV). An experimental chamber for X-ray measurements is described. The chamber length is 250 mm and the electrode radii are 85 and 195 mm. The design allows of selection among eight collector electrodes and an adjustable beam-to-axis distance. The winding consists of 36 turns of water cooled copper tubing, carrying a current of 833 A maximum. Measurements of the ionization as a function of the magnetic induction are reported.

INTRODUCTION

The exposure is defined as the quotient $dQ$ by $dm$, where $dQ$ is the absolute value of the total charge of the ions of one sign produced in air when all the electrons liberated by photons in a volume element of air having mass $dm$ are completely stopped in air [1]. The standard instrument for the measurement of the exposure has been the conventional free-air chamber. The ionization $dQ$ produced by a photon beam having a known cross-sectional area, is, with
the aid of an electric field, collected between two planes, which are a known distance apart. The mass dm is defined by these dimensions and the density of air. The planes are perpendicular to the photon beam axis, and sited so that an electron equilibrium is created between them. For the electrons to be completely stopped in air, it is further necessary that the lateral walls of the chamber are unattainable for the electrons. The use of the conventional free-air chamber is limited to quantum energies up to a few hundred keV’s, corresponding to secondary electron ranges below 1 m [2].

Recently, graphite cavity chambers have been adopted as the standard of exposure for the $^{60}$Co and other high energy radiations up to a few MeV’s. These chambers utilize the Bragg-Gray principle, which involves a correction due to the fact that the stopping-powers of air and graphite are different. A conservative value of .5 per cent has been stated as the inaccuracy of this correction [3].

Higher energies are also attainable with free-air chambers operating under a high pressure. The electron ranges are shortened in proportion to the air pressure. The principal source of inaccuracy is the increased ion recombination, which may require an extrapolation correction of more than ten per cent [4].

The electron tracks can also be suppressed with the aid of a magnetic field. The free-air chamber is placed inside a solenoid winding, whose symmetry axis coincides with the photon beam axis. A current in the winding sets up a nearly homogeneous magnetic field, which forces the electron trajectories into helices of radius of curvature:

$$\rho = \frac{p_{tr}}{eB}$$

where $p_{tr}$ is the transverse momentum of an electron, $e$ the elementary charge ($= +.16$ aC), and $B$ the magnetic induction. The longitudinal momentum of electrons is not affected by the magnetic field. Therefore the length required for the chamber is determined by the maximum electron range as in the conventional type. Chambers of thin type have been described both for medium energy x-rays [5,6] and for higher energies (combined with the use of increased air pressure) [7]. It has also been suggested that the length of the chamber could be radically shortened by producing the electron equilibrium with graphite sheets at the ends of the chamber. This design, however, necessitates the stopping-power considerations [8].

One might expect that an orthogonal magnetic field would suppress the electron tracks in a more compact way. The field can be set up by means of
a toroidal winding. The photon beam intersects the winding parallel to the
toroid symmetry axis. The free-air chamber inside the torus consists of two
coaxial cylinders, which form the high voltage electrode and the collector-
guard electrode assembly, together with the end plates (guard stip assemblies).
The objects of the following are to study electron trajectories in the magnetic
field, derive design criteria for an idealized case, give some experimental
results on a prototype, and discuss the feasibility of this design.

THE ELECTRON TRAJECTORIES

Electron trajectories in the magnetic field set up by the toroidal winding, have been studied in connection with the so-called "orange"-type β-spectrometers [9,10,11]. With some modifications, a similar treatise is followed here. For the present, electron slowing-down and scattering will be ignored.

It is convenient to adopt the cylindrical system of coordinates \((rr, \phi, z)\) the \(z\) coordinate coinciding the toroid symmetry axis. Let us define the current \(I\) in the winding as positive, if it runs parallel to \(z\) on the outer surface and antiparallel to \(z\) on the inner surface of the torus. The magnetic induction or flux density inside the toroid of \(N\) turns is:

\[
\mathbf{B} = \frac{\mu_0 NI}{2\pi r} \hat{\phi}
\]

where \(\mu_0 = 4\pi \times 10^{-7} \, \text{V-s/A-m}\) is the permeability of vacuum (practically equal to the permeability of air). \(\mathbf{B}\) can be expressed as the curl of the vector potential \((b\) is an arbitrary constant):

\[
\mathbf{A} = -\frac{\mu_0 NI}{2\pi} \cdot \log(r) \hat{r}
\]

The Lagrangian for the motion of an electron (mass \(m\), rest mass \(m_0\), charge \(-e\), velocity \(v\), \(c\) is the velocity of light) is:

\[
L = -m_0 c^2 \sqrt{1 - \left(\frac{v}{c}\right)^2} - e\mathbf{v} \cdot \mathbf{A}
\]

The constants of motion can now be solved by substituting (4) into the equations:

\[
\frac{d}{dt} \left(\frac{\partial L}{\partial \dot{q}}\right) = \frac{\partial L}{\partial q}, \quad q = r, \phi, z
\]
These are the velocity:

\[ v = \sqrt{z^2 + r^2 \frac{\dot{\gamma}^2}{v^2} + \dot{z}^2} \]  

(6)

the angular momentum:

\[ l = mr^2 \dot{\gamma} \]  

(7)

and the radius, for which \( \dot{z} = 0 \),

\[ a = r \cdot \exp(K\dot{z}/v) \]  

(8)

K is a dimensionless parameter given by:

\[ K = \frac{2mv}{\mu NI} \]

Equations (6-8) together with the initial conditions can be used for the numerical solution of a trajectory.

Trajectories in the rz-plane evidently determine the maximum dimensions of the chamber. Therefore \( \dot{z} \) can be taken as zero. The parameter \( \psi \) defined so that:

\[ \cos \psi = \frac{\dot{z}}{v} \]  

(10)

is convenient for the exact analytic solution of the trajectories (\( \cos \psi = \dot{z}/v_{r_2} \) can be used for an iterative solution, if \( \dot{z} \) is nonzero but small \(|11|\)). Substituting (10) into (8) gives:

\[ a = r_0 \cdot \exp(K\cos\psi_0) \]  

(11)

and:

\[ r = a \cdot \exp(-K\cos\psi) \]  

(12)
Equations (6), (10) and (12) can be used to eliminate the derivation with respect to time, and give for $z$:

$$z' = aK \cdot \cos \psi \cdot \exp(-K \cos \psi)$$

(13)

and for the path length travelled:

$$s' = aK \cdot \exp(-K \cos \psi)$$

(14)

The integrals in (13) and (14) can be evaluated through series expansions.

$$z - z_0 = aK \cdot \{-I_{\frac{1}{2}}(K)(\psi - \psi_0) \cdot \sum_{k=1}^{\infty} \frac{1}{k} (-1)^{k-1} \cdot \left[I_{k-1}(K) + I_{k+1}(K) \right] \cdot (\sin \psi - \sin \psi_0)\}$$

(15)

$$s - s_0 = aK \cdot \left[\sum_{k=1}^{\infty} \frac{1}{k} (-1)^{k-1} \cdot I_{\frac{1}{2}}(K)(\psi - \psi_0) + 2 \sum_{k=1}^{\infty} \frac{1}{k} (-1)^{k-1} \cdot I_{k}(K) \cdot (\sin \psi - \sin \psi_0)\right]$$

(16)

$I_k(K)$ is the $k$'th order modified Bessel function of the first kind. Fig. 1 illustrates the trajectory. It is a periodic function of $\psi$ with a net drift along $z$. The period is $2\pi a K I_{\frac{1}{2}}(K)$. The maximum and minimum radii attained are $a \cdot \exp(\pm K)$. The parameter $a$ acts as a scale factor for a family of trajectories with constant $K$.

DESIGN CRITERIA FOR THE IDEAL CASE

In order to derive the basic design criteria for the chamber, it is necessary to determine the minimum and maximum radii an electron can reach, and the length required to create the electron equilibrium. Since only quantum energies from a few hundred keV to a few MeV are of interest, it is sufficient to restrict to the Compton electrons alone. For simplicity, electron scattering will be ignored and slowing-down will be considered only in connection with the chamber length.
From the energy and momentum considerations of the Compton scattering, it is easy to show that:

\[ 0 \leq \tau \leq \frac{2\alpha^2}{1 + 2\alpha} = \tau_{\text{max}} \]  \hspace{1cm} (17)

and:

\[ \cos \psi_o = \frac{1 + \alpha^2}{\alpha \sqrt{1 + 2}} \]  \hspace{1cm} (18)

where \( \alpha \) and \( \tau \) are the kinetic energies of the incident photon and the recoil electron in units of the electron rest energy, and \( \psi_o \) is the recoil angle.

From equations (9), (11), (12), (17) and (18) it is now possible to derive:

\[ r_{\text{max}} = r_0 \exp\left(\frac{4\alpha(1+\alpha)}{1+2\alpha} \frac{2m_e c}{\epsilon u_o N} \right) \]  \hspace{1cm} (19)
and:

\[ r_{\text{min}} = r_0 \exp \left( \frac{1 + \alpha \sqrt{1 + 2\alpha}}{\sqrt{2\pi\alpha}} \frac{2\mu e}{N} \right) \]  

(20)

If the current in the winding is reversed, the signs of the exponents as well as the indexes for \( r \) must be interchanged. Some values of \( r_{\text{max}}/r_0 \) and \( r_{\text{min}}/r_0 \) are given in Table I.

### TABLE I. MINIMUM AND MAXIMUM RADII RELATIVE TO THE PHOTON BEAM POSITION \((r_{\text{min}}/r_0, r_{\text{max}}/r_0)\) AND THE DISTANCE REQUIRED TO PRODUCE ELECTRON EQUILIBRIUM \((Z)\) FOR COMPTON RECOIL ELECTRONS

<table>
<thead>
<tr>
<th>NI(kA)</th>
<th>20</th>
<th>50</th>
<th>100</th>
<th>200</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>(r_{\text{min}}/r_0)</td>
<td>0.965</td>
<td>0.986</td>
<td>0.993</td>
<td>0.996</td>
<td>0.999</td>
<td>0.999</td>
<td>1.000</td>
</tr>
<tr>
<td>(r_{\text{max}}/r_0)</td>
<td>1.339</td>
<td>1.124</td>
<td>1.060</td>
<td>1.030</td>
<td>1.012</td>
<td>1.006</td>
<td>1.003</td>
</tr>
<tr>
<td>(Z(m))</td>
<td>0.001</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
</tr>
<tr>
<td>(r_{\text{min}}/r_0)</td>
<td>0.930</td>
<td>0.971</td>
<td>0.985</td>
<td>0.993</td>
<td>0.997</td>
<td>0.999</td>
<td>0.999</td>
</tr>
<tr>
<td>(r_{\text{max}}/r_0)</td>
<td>1.694</td>
<td>1.291</td>
<td>1.136</td>
<td>1.066</td>
<td>1.026</td>
<td>1.013</td>
<td>1.006</td>
</tr>
<tr>
<td>(Z(m))</td>
<td>0.025</td>
<td>0.010</td>
<td>0.005</td>
<td>0.003</td>
<td>0.001</td>
<td>0.001</td>
<td>0.000</td>
</tr>
<tr>
<td>(r_{\text{min}}/r_0)</td>
<td>0.892</td>
<td>0.955</td>
<td>0.977</td>
<td>0.989</td>
<td>0.995</td>
<td>0.998</td>
<td>0.999</td>
</tr>
<tr>
<td>(r_{\text{max}}/r_0)</td>
<td>3.113</td>
<td>1.575</td>
<td>1.255</td>
<td>1.120</td>
<td>1.046</td>
<td>1.023</td>
<td>1.011</td>
</tr>
<tr>
<td>(Z(m))</td>
<td>0.186</td>
<td>0.080</td>
<td>0.040</td>
<td>0.020</td>
<td>0.008</td>
<td>0.004</td>
<td>0.002</td>
</tr>
<tr>
<td>(r_{\text{min}}/r_0)</td>
<td>0.850</td>
<td>0.937</td>
<td>0.968</td>
<td>0.984</td>
<td>0.994</td>
<td>0.997</td>
<td>0.998</td>
</tr>
<tr>
<td>(r_{\text{max}}/r_0)</td>
<td>7.721</td>
<td>2.265</td>
<td>1.505</td>
<td>1.227</td>
<td>1.085</td>
<td>1.042</td>
<td>1.021</td>
</tr>
<tr>
<td>(Z(m))</td>
<td>1.040</td>
<td>0.441</td>
<td>0.222</td>
<td>0.111</td>
<td>0.045</td>
<td>0.022</td>
<td>0.011</td>
</tr>
<tr>
<td>(r_{\text{min}}/r_0)</td>
<td>0.786</td>
<td>0.913</td>
<td>0.955</td>
<td>0.977</td>
<td>0.991</td>
<td>0.995</td>
<td>0.998</td>
</tr>
<tr>
<td>(r_{\text{max}}/r_0)</td>
<td>6.412</td>
<td>2.532</td>
<td>1.591</td>
<td>1.204</td>
<td>1.097</td>
<td>1.048</td>
<td></td>
</tr>
<tr>
<td>(Z(m))</td>
<td>5.750</td>
<td>2.820</td>
<td>1.466</td>
<td>0.741</td>
<td>0.297</td>
<td>0.149</td>
<td>0.074</td>
</tr>
<tr>
<td>(r_{\text{min}}/r_0)</td>
<td>0.761</td>
<td>0.896</td>
<td>0.947</td>
<td>0.973</td>
<td>0.992</td>
<td>0.995</td>
<td>0.997</td>
</tr>
<tr>
<td>(r_{\text{max}}/r_0)</td>
<td>5.956</td>
<td>2.441</td>
<td>1.429</td>
<td>1.195</td>
<td>1.093</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Z(m))</td>
<td>9.349</td>
<td>5.240</td>
<td>2.712</td>
<td>1.096</td>
<td>0.549</td>
<td>0.274</td>
<td></td>
</tr>
</tbody>
</table>
The longitudinal motion of an electron can be treated with the continuous-slowing-down-approximation. Since $z$ and $s$ are periodic functions of $\psi$, (15) and (16) give:

$$\frac{dz}{ds} = - \frac{I_1(K)}{I_0(K)}$$

The maximum electron range projected on the z-axis can now be written as:

$$Z = \left| \int_{\tau_{\text{max}}}^{0} \frac{I_1(K(\tau))}{I_0(K(\tau))} \frac{d\tau}{S(\tau)} \right|$$

where $S$ is the stopping-power. $Z$ is the minimum length needed to produce electron equilibrium, and will be along -z for positive $I$, and vice versa. Using published data for $S$ [12], some values for $Z$ have been computed in Table I (at 300 K and 101.3 kPa).
AN EXPERIMENTAL CHAMBER

An experimental chamber for medium energy x-rays was designed. In order to avoid distorting the magnetic field, brass and bronze together with other non-ferrous materials were used for the construction. The chamber has eight collector electrodes each 25 mm in length and 170 mm in diameter. Teflon supports insulate the electrodes and provide .02 mm gaps between them. Any of the electrodes can be selected for measurement, while the others are grounded to the 25 mm end sections to act as guard electrodes. The surrounding high voltage electrode is 250 mm in length and 390 mm in diameter. Guard rings are used to minimize the distortion of the electric field. The end plates are divided into twelve rings at radii proportional to log(r). These are connected to a resistor chain, which brings them to stepwise ascending

FIG. 3. A view of the back end of the experimental chamber.
potentials. Openings in the end plates allow the photon beam to enter the chamber at an arbitrary radius of from 95 to 185 mm (Fig. 2).

The 36 turn toroid winding was assembled from pre-bent sections of Ø 10/7 mm copper tubing. The sections were insulated with heat shrinking plastic and joined by rubber tubing and screw junctions (Fig. 3). The coil resistance is about 17 mΩ. The power supply is of the three-phase full wave rectified type. The output can be adjusted from 0 to a nominal 833 A. For cooling, the coil was divided into four parallel sections, in which water is circulated. A water pressure of 200 kPa is sufficient to limit the temperature rise to less than 6 K at a maximum power dissipation of 12 kW.

A 400 kVp radiography x-ray machine was used as the radiation source. The beam size was limited to 0.5 mm by an external tungsten diaphragm sited 850 mm from the tube focus. Ionization currents from the chamber and a monitor chamber were measured by the current integration method. Typical results of the relative ionization current for different photon beam positions are given in Fig. 4 as a function of the current in the toroid winding.
DISCUSSION

The shape of the curves in Fig. 4 can be explained as follows. At a low current, the magnetic field tends to force the side-recoiled low energy electrons past one of the chamber walls (the high voltage electrode), thus improving the ionization yield. As the current is increased, the forward-recoiled electrons of higher energy are driven towards the other wall (the collector electrode). Additional ionization loss is now produced. Increasing the current further forces the electrons into trajectories of stronger curvature and enables more electrons to pass by the wall. Ultimately, saturation is reached. However, the current sufficient to produce saturation is twice as large or larger than that predicted by Table I. This is due to the effect of electron scattering, and has been observed earlier, too [5]. For higher energies, one might expect the role of scattering to be less important. Further work will be needed to derive practical design criteria that take the scattering into account.

It is of interest to study the chamber dimensions for high energies. If $S(r)$ is replaced by a constant in (22), it is easy to see that $Z$ will behave asymptotically as $\tau_{\text{max}}^2$. Applying this relationship to the figures in Table I, we obtain:

$$Z(m) = \frac{3850 \ldots 9040}{N I(A)} \cdot \tau_{\text{max}}^2.$$  \hspace{1cm} (23)

The toroid winding is characterized by its mass $m$, and the power dissipation $P$ in it. The length of one turn of the winding is made up of twice $Z$, $r_{\text{max}} - r_{\text{min}}$, the collector length, and of the "loss" in the construction. Since, for high energies, $Z$ will be the major part, the length can be denoted as $2 \cdot (1 + \lambda) \cdot Z$. The product $mP$ can now be evaluated. Applying the density and resistivity values of copper gives:

$$m \cdot P(\text{kg-W}) < 50000 \cdot (1 + \lambda)^2 \cdot \tau_{\text{max}}^4.$$  \hspace{1cm} (24)

It is evident that chambers can be designed with $m \cdot P$ less than $10^7 \cdot \tau_{\text{max}}^4$ kg-W, where $T$ is the maximum energy in MeV of secondary electrons. However, above a few MeV, pair production becomes important. Since positron trajectories will be mirror images of the respective electron trajectories, the chamber size will have to be doubled.

Before a chamber of this type can be regarded as a standard instrument, several other factors need to be studied. These include the combined effect
of magnetic and electric fields on the behaviour of electrons and ions, the accurate determination of the collection volume, the temperature distribution inside the chamber, etc.

REFERENCES


H. REICH: Up to 400 kV peak tube potential the conventional method without pressurization is applicable for parallel-plate chambers. At still higher potentials or photon energies we find that in pressurized chambers the effect of transparency of the entrance diaphragm rim together with recombination leads to an increase in the uncertainty of the exposure determination. Did you perform calculations on this effect?

I.K. UOTILA: No, I have not done such calculations yet. I quite agree with your comments, however.

R. ABEDINZADEH: Did you study the effect of combined electrical and magnetic fields on the ions and electrons in determining the exact volume?

I.K. UOTILA: The mass of the ions is four orders of magnitude greater than that of the electrons. Thus, the magnetic fields will have a negligible effect on the motion of the ions; the collection volume is defined by the ion trajectories, as in the zero-magnetic-field case.

L. LINDBORG: Can you give the accuracy obtainable with your chamber?

I.K. UOTILA: The project is still in the experimental stage, and no accuracy analysis has been performed yet. However, the accuracy obtained should not differ much from that of conventional chambers.

L. LINDBORG: Will the heat developed around the chamber give you any trouble?

I.K. UOTILA: Although a power dissipation of 12 kW results in a temperature rise of 6 K in the cooling water, the temperature inside the chamber appears to be very stable, and no problems should arise.
Abstract

Recommendations concerning procedures in radiation therapy dosimetry with high-energy electrons and photons have been given by both international and national physicists’ organizations. Some of these recommendations are now the subject of a revision, mainly for the following reasons: (i) the introduction of The International System of Units (SI) with SI derived units for radiological quantities will have consequences for the recommendations, and (ii) several papers have been published which give new data concerning the influence on ionization chamber measurements of various effects such as perturbation and displacement and those introduced by the chamber wall material. In this paper a new formalism for the absorbed dose determination using ionization chambers in electron and photon beams is suggested. This abandons the exposure calibration factor and the dose conversion factors $C_E$ and $C_\lambda$. Instead, a new calibration factor, the mass calibration factor, $N_c$, is defined, as is also a new conversion factor, $C_u$, independent of chamber type, to be used with both electron and photon radiation. In addition, a correction for the different types of chambers must be applied, the total perturbation factor, $P_u$. The determination of the mass calibration factor is not related to any particular calibration procedure and should, thus, not be influenced by the procedure used by the national standards laboratories. The $C_u$-value includes the water/air

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mass stopping power ratios and the values of the mean energy expended by electrons in the cavity gas per unit charge. The \( p_u \)-value corrects for the disturbance of the particle fluence caused by the introduction of the air cavity and by the chamber wall. Experimental corrections for cylindrical ionization chambers of sizes and constructions often used for absorbed dose measurements have been carried out. A complete set of data needed for the ionization chamber dosimetry based on the suggested procedure is reported.

1. INTRODUCTION

Ionization chamber dosimetry is by far the most common method used for making absorbed dose measurements in beams from medical electron accelerators and \( ^{60}\text{Co} \gamma \)-ray units. Practical dosimetric procedures are well established in international [1,2] and national protocols [3—9]. These protocols should be modified owing to the introduction of SI derived units for certain radiation quantities and because of the likelihood that national standards laboratories will cease to make exposure calibrations. The Nordic Association of Clinical Physics (NACP) decided to make a complete revision of its protocol [7], not only for these reasons, but also because of the present ambiguity in the \( C_E \) and \( C_\lambda \) concepts [10—14] and because of the need to update the data required in ionization chamber dosimetry. The working group on dosimetry of the NACP has recently finished a series of measurements aimed at making the reference literature more complete. The findings will constitute a basis for the new NACP report.

2. BASIC PRINCIPLES

It is expected that the ionization chamber, with or without its measuring assembly, will also in the future continue to be calibrated by national standards laboratories, either in a beam of \( ^{60}\text{Co} \gamma \)-rays or of 2 MV X-rays. It will then be possible to use the calibrated chamber for making absorbed-dose determinations in \( ^{60}\text{Co} \gamma \)-ray beams, or in high-energy photon or electron beams derived from therapy accelerators.

2.1. Calibration of the ionization chamber

The calibration procedure used by the national standards laboratories will probably continue to be developed in the future and is presently under discussion. It is, therefore, worth striving for dosimetric protocols in which the calibration procedures will exert as small an influence as possible on the subsequent dosimetry.
It is therefore suggested by us that the standards laboratory should provide a mass calibration factor, $N_c$, defined by:

$$N_c = \frac{J_{\text{air},c}}{M_c}$$

where $J_{\text{air},c}$ is the mass ionization, i.e. the charge of ions of one sign produced by radiation in the air cavity divided by the mass of air (C·kg$^{-1}$), $M_c$ is the meter reading corrected for temperature, pressure and recombination losses (C·kg$^{-1}$ or in scale divisions), and $N_c$ is the mass calibration factor (kg$^{-1}$ or C·kg$^{-1}$·(scale div.)$^{-1}$). The subscript $c$ stands for calibration quality, i.e. the radiation quality of a well defined irradiation geometry in a beam of 60Co $\gamma$-rays. The calibration is preferably carried out separately for the ionization chamber (in units of kg$^{-1}$) and the measuring assembly (in units of C per scale division). (The alternative units within braces, { }, refer to the case when the calibration is carried out with the ionization chamber connected to its measuring assembly.)

The mass calibration factor, $N_c$, is related to the mean absorbed dose to air in the air cavity, $D_{\text{air},c}$, by:

$$N_c = \frac{D_{\text{air},c}}{M_c \cdot (\bar{W}/e)}$$

where $(\bar{W}/e)$ is the mean energy expended by electrons in the cavity gas per unit charge (J·C$^{-1}$). The dose to the air, $D_{\text{air},c}$, can be determined, for example, from a known exposure free in air, or a known absorbed dose to air free-in-air, or in water under conditions of secondary electron equilibrium.

The calibration factor, $N_c$, is related to the exposure calibration factor by:

$$N_c = \frac{N_c^1 \cdot A_{\text{air}} \cdot A_m \cdot k_1}{R \cdot C^{-1}}$$

where $N_c^1$ is the exposure calibration factor (R·C$^{-1}$ or R·(scale div.)$^{-1}$) (see NACP, Ref.[7]), $A_{\text{air}}$ is the correction factor, less than unity, due to attenuation and scattering of the beam in the wall and the build-up cap, $A_m$ is the factor correcting for the lack of air equivalence of the ionization chamber wall material, and $k_1$ is a conversion constant, equal to $2.58 \times 10^{-4}$ C·kg$^{-1}$·R$^{-1}$.

Equation (3) could be used during a transition period for deriving the mass calibration factor from an exposure calibration factor. It is suggested that the factors $A_{\text{air}}$ and $A_m$ should already be incorporated at an early stage, namely in the national standards laboratories.

These factors have been determined for cylindrical ionization chambers with an inner diameter of 5 mm and a volume of 300 mm$^3$, with wall and build-up
layers of either graphite or tissue-equivalent materials. The results are reported below. Chambers of approximately these types will be recommended in the new Nordic report for all radiation qualities except for electron beams with mean electron energies in the range \(1 \leq E_0 \leq 10\) MeV, where the use of a plane-parallel chamber will be suggested.

### 2.2. Absorbed dose measurements at a given reference depth and radiation quality

In this report, radiation quality, denoted by \(u\), refers to the quality of an electron or photon beam having an energy in the range \(1\) to \(50\) MeV.

The depths of the reference points for electron radiation are still under discussion. The depths chosen by the NACP [7] and the ICRU [2] corresponded approximately to the depths of the peak absorbed dose using large field sizes and an SSD of 100 cm from a betatron. However, the peak absorbed dose can be at much greater depths with some types of accelerators [15, 16]. Therefore alternative depths may be given. With photon radiation, 5 cm will probably be suggested in the new NACP report as the reference depth for \(h\nu_{\text{max}} \leq 10\) MeV and 10 cm for \(h\nu_{\text{max}} > 10\) MeV.

According to the procedure proposed by us, the cylindrical ionization chamber should be placed with its centre at the reference depth in a water phantom. The measurement then gives in reality the mass ionization at a point in front of the chamber centre, i.e. at the effective measuring point [17, 18], because of replacement of water by air. The distance between the centre and the effective measuring point depends on the shape and size of the chamber, and it also varies with the radiation quality and the depth in the phantom. Therefore, for practical reasons, the absorbed dose is determined at the centre of the chamber instead of at the effective measuring point [17, 18]. A correction factor, the displacement factor (see §6), must then be applied to the measured ionization.

The Bragg-Gray equation is used for the assessment of the absorbed dose to water at the reference depth:

\[
D_w = J_{\text{air}, u} \cdot \left( \frac{S}{\rho} \right)_{\text{water}, \Delta u} \cdot \left( \frac{W}{e} \right) \cdot p_u
\]

where \(D_w\) is the absorbed dose in water (Gy) at the centre of the cylindrical chamber when the chamber is replaced by water, \(J_{\text{air}, u}\) is the charge of ions of one sign in the air cavity divided by the mass of air (C·kg\(^{-1}\)), \((S/\rho)_{\text{water}, \Delta u}\) is the mean collision mass stopping power, water to air, and \(p_u\) is the total perturbation correction factor. This factor includes the correction for lack of water equivalence in the wall at a radiation quality \(u\) (see §4), the correction for perturbation of the electron fluence due to the insertion of the air cavity, \(p_{w,g}\) (see §5), and the correction for the displacement, \(d\) (see §6).
It is assumed that:

$$\frac{J_{\text{air}, c}}{M_c} = \frac{J_{\text{air}, u}}{M_u} = N_c$$

(5)

i.e. the mass calibration factor determined at the calibration quality c is also valid at quality u. Equation (4) could thus be rewritten:

$$D_w = M_u \cdot N_c \cdot C_u \cdot p_u$$

(6)

where $M_u$ is the corrected meter reading, and:

$$C_u = \left( \frac{S}{\rho} \right)_{\text{air}, \Delta, u} \cdot \left( \frac{\bar{W}}{e} \right)$$

(7)

The $p_u$ factors were determined in experiments for different beam qualities and for chambers which will probably be recommended in the new Nordic protocol. The factor $C_u$ was calculated using the most recent data (see §7).

2.3. Beam-axis dose distribution measurements

Beam-axis depth dose curves can be measured with different types of dose meters. However, the ionization chamber method is well established and is therefore often recommended as a reference method [7]. The measurements can be carried out with a cylindrical ionization chamber using an effective measuring point displaced from the chamber centre towards the radiation source [7]. It is not experimentally possible to separate the geometrical displacement and the perturbation correction, $p_{w,g}$, at depths different from that of the peak absorbed dose region. In the determination of depth ionization curves, a geometrical displacement which includes the correction for $p_{w,g}$ is therefore used. For electron radiation, the ionization curves have to be corrected for the variation with depth of the $C_u$-values to obtain the beam-axis absorbed dose curves.

3. EXPERIMENTAL FACILITIES

In the experimental investigation, a great effort was made to minimize the influence of different sources of error, e.g. the directional dependence of the chambers, variations in the chamber positioning, variations in the accelerator dose monitors and timers, and variations in field flatness when accelerators were used,
TABLE I. IMPORTANT DIMENSIONS OF THE CHAMBERS

<table>
<thead>
<tr>
<th>Chamber number</th>
<th>Wall material</th>
<th>Approx. volume (mm$^3$)</th>
<th>Cavity diameter (mm)</th>
<th>Wall thickness (mm)</th>
<th>Electrode diameter (mm)</th>
<th>Cavity height (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cylindrical (thimble type)</td>
<td>I</td>
<td>Perspex &amp; graphite plastic</td>
<td>110</td>
<td>3</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>&quot;</td>
<td>II</td>
<td>&quot;</td>
<td>290</td>
<td>5</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>&quot;</td>
<td>III</td>
<td>&quot;</td>
<td>580</td>
<td>7</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>&quot;</td>
<td>IV</td>
<td>Tissue equivalent plastic</td>
<td>900</td>
<td>8</td>
<td>0.5</td>
<td>2.0</td>
</tr>
<tr>
<td>&quot;</td>
<td>V</td>
<td>Graphite</td>
<td>900</td>
<td>8</td>
<td>0.5</td>
<td>2.0</td>
</tr>
<tr>
<td>&quot;</td>
<td>VI</td>
<td>Perspex &amp; graphite</td>
<td>900</td>
<td>8</td>
<td>0.5</td>
<td>2.0</td>
</tr>
<tr>
<td>&quot;</td>
<td>Baldwin Farmer</td>
<td>Graphite</td>
<td>600</td>
<td>6.3</td>
<td>0.375</td>
<td>1.0</td>
</tr>
<tr>
<td>&quot;</td>
<td>Philips</td>
<td>Graphite plastic</td>
<td>3000</td>
<td>13.2</td>
<td>0.65</td>
<td>2.0</td>
</tr>
<tr>
<td>Plane parallel</td>
<td>VII</td>
<td>Graphite plastic</td>
<td>300</td>
<td>100</td>
<td>0.5</td>
<td>19</td>
</tr>
</tbody>
</table>

and the like. The precision of the measurements was within 0.2% (P = 0.95) using cylindrical chambers and within 0.5% (P = 0.95) using the plane-parallel chamber.

3.1. Ionization chambers

Ionization chambers of different types and sizes and with different wall materials were used to determine the $A_{\text{air}}, A_{\text{m}}$ and $p_u$ of Eq.(6). The chamber details are given in Table I.

Chambers I, II and III have the same wall material and shape, but they have different cavity radii. These chambers were used to investigate the displacement effect, $d$, and the perturbation effect, $p_{w,g}$. Chambers IV, V and VI are of the same shape and size, but they have different wall materials, namely tissue-equivalent plastic (A 150), graphite and Perspex, respectively. These chambers were used to investigate the wall-material effects.

The chambers were checked for polarity effects by reversing the bias-voltage. The instrument readings were corrected for recombination, and temperature and pressure variations.
3.2. Electrometers

The chambers were coupled to a two-channel Therados model RDM 2 electrometer with a circuit which gave the ratio of the outputs of the two channels. The power supply provided a bias voltage output with both positive and negative polarity for the ionization chambers [19].

3.3. Calibration and constancy checks

The ionization chambers, together with the electrometers, were calibrated before and after the experiments at the Swedish national radiation standards laboratory. The constancy of the instruments was checked before and after every set of experiments.

3.4. Irradiation sources

A $^{60}$Co γ-ray therapy unit, two travelling wave linear accelerators (5 and 20 MeV) and a 42 MeV betatron were used as irradiation sources.

4. WALL-MATERIAL EFFECTS

It is well known that the medium immediately around the air cavity of an ionization chamber affects the ionization in the cavity. Investigations were carried out to determine the magnitude of any such effects. Measurements were made both free in air and in water, using chambers having different wall materials.

4.1. Wall-material effects at the ionization chamber calibration

The $A_{\text{air}}$-factor has been discussed by several investigators [20–28]. $A_{\text{air}}$ was experimentally determined by us for chambers V (graphite wall) and VI (Perspex wall) and the Baldwin-Farmer chamber. Measured ionizations were plotted against chamber-wall thickness to allow the ionization readings to be extrapolated to zero wall thickness [27]. The value determined from these measurements should be an overestimate by 0.3% to 0.8% [12], since electrons giving rise to ionization in the cavity are generated in front of the cavity by photons traversing only a part of the wall. A correction of 0.5% was applied to the extrapolated value. The mean of the experimentally determined $A_{\text{air}}$-values for the chambers, at a total wall thickness of 0.6 g·cm$^{-2}$, was 0.990. This is compared with the results of different investigators in Table II.
TABLE II. $A_{air}$ VALUES FOR $^{60}$Co $\gamma$-RAY BEAMS, OBTAINED BY DIFFERENT INVESTIGATORS FOR DIFFERENT TYPES OF CHAMBERS

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Wall thickness (g · cm$^{-2}$)</th>
<th>$A_{air}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plans parallel [46]</td>
<td>0.52</td>
<td>0.996</td>
</tr>
<tr>
<td>Cylindrical [46]</td>
<td>0.52</td>
<td>0.991</td>
</tr>
<tr>
<td>Cylindrical (present work)</td>
<td>0.60</td>
<td>0.990</td>
</tr>
<tr>
<td>Spherical [27]</td>
<td>0.60</td>
<td>0.988</td>
</tr>
</tbody>
</table>

TABLE III. THE $A_m$ FACTOR FOR $^{60}$Co $\gamma$-RAY BEAMS, FOR IONIZATION CHAMBERS WITH GRAPHITE AND TISSUE-EQUIVALENT PLASTIC WALLS

<table>
<thead>
<tr>
<th>Wall material</th>
<th>$A_m$</th>
<th>$A_{m, graphite}^{A_{m, A 150}}$</th>
<th>$A_{m, graphite}^{A_{m, A 150}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphite</td>
<td>0.991</td>
<td>1.029</td>
<td>1.032</td>
</tr>
<tr>
<td>Tissue-equivalent plastic (A 150)</td>
<td>0.963</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

TABLE IV. MEASURED IONIZATION NORMALIZED TO THE TISSUE-EQUIVALENT (A150) CHAMBER FOR ELECTRON RADIATION

<table>
<thead>
<tr>
<th>$E_z$ (MeV)</th>
<th>Chamber wall material</th>
<th>Graphite</th>
<th>Perspex</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$A_{150}$</td>
<td>$A_{150}$</td>
<td></td>
</tr>
<tr>
<td>5.5</td>
<td>1.000</td>
<td>1.029</td>
<td>0.909</td>
</tr>
<tr>
<td>8</td>
<td>1.000</td>
<td>1.025</td>
<td>0.908</td>
</tr>
<tr>
<td>14</td>
<td>1.000</td>
<td>1.028</td>
<td>0.908</td>
</tr>
<tr>
<td>Mean value</td>
<td>1.000</td>
<td>1.027 ± 0.002</td>
<td>0.908 ± 0.001</td>
</tr>
</tbody>
</table>
Theoretical $A_m$-values for $^{60}$Co $\gamma$-ray beams were determined from the relation [14]:

$$A_m = \left( \frac{\mu_{en}}{\rho} \right)_{air,c}^m \cdot \left( \frac{S}{\rho} \right)_{m,c}^{air}$$

where $m$ stands for the wall material. These $A_m$-values using recent $(\mu_{en}/\rho)$-values from Hubbel [29] and $(S/\rho)$-values from Berger and Seltzer [30] are given for graphite and tissue-equivalent materials (Table III).

According to the current NACP report, the ionization chambers should be calibrated with an additional Perspex cap, giving a total wall thickness of about 0.5 g·cm$^{-2}$. A common combination is a chamber having a 0.5 mm graphite wall fitted with a Perspex cap. If such a chamber should be used with the procedure described in this paper, the $(A_{air} \cdot A_m)$-value must be known. The $A_{air}$-value for this type of chamber was determined as described above. An $A_m$-value was determined using the method described by Almond and Svensson [14]. A value of 0.974 was obtained for $(A_{air} \cdot A_m)$. This value can be used in Eq.(3) to determine $N_c$ from $N_j$.

The factors $A_{air}$ and $A_m$ may not be relevant to future calibration procedures if the free-in-air calibration is abandoned. However, the factors are needed for the present determination of $N_c$ in Eq.(3).

4.2. Wall-material effects in water-phantom measurements

For photon beams the evaluation of absorbed dose is simplified when a chamber with a tissue-equivalent wall (i.e. approximately water equivalent) is used, as all electrons arriving at the cavity are generated in water or water-equivalent materials. For other wall materials, some electrons giving rise to ionization in the cavity are generated in the water and some in the wall material. This problem has been considered by other authors [12, 14], but additional experimental data were needed.

Chambers IV, V and VI were used for these experiments. They are approximately of the same cavity size and shape but have different wall materials, namely graphite, tissue-equivalent plastic ($A_{150}$), and Perspex with a 50 $\mu$m conducting layer of graphite. All walls have a thickness of 0.5 mm. Calibrations were carried out to determine the relative ratios of cavity air masses using the relation for a given radiation quality, $u$:

$$N_c = \frac{J_{air,u}}{M_u}$$

(9)
The calibration was made in electron beams where the choice of any of these three wall materials should exert a very small influence on the mass ionization in the air cavity [14, 31]. The masses of air in the cavities relative to the tissue-equivalent chamber are given in Table IV. The ratios were not dependent on the electron beam energy.

The relative mass ionization, i.e. the charge divided by mass for a graphite-wall chamber relative to an A150-wall chamber without build-up caps, was then determined in measurements at 2, 5 and 10 cm depth in water for photon beams of different energies (Fig.1a). The ratios were found to be independent of the depth of the measurements, and a mean value was therefore determined for each beam energy. With decreasing energy the relative mass ionization increases. This result can be explained as showing that, at the lower photon energies, more of the electrons giving rise to the ionization in the cavity are generated in the wall.

In a beam of $^{60}$Co $\gamma$-rays, the ratios of mass ionization for the graphite chamber to that for the A150 chamber were measured both in a water phantom and free in air. In the free-air measurements, caps of the same material as the wall were used. A mass ionization ratio of 1.032 was determined free in air, to be compared with 1.023 in water. The difference between the measurements free in air and in water can be explained by the fact that some of the electrons giving rise to ionization in the graphite chamber cavity are still generated in the water.
(the graphite wall was 0.5 mm). This result was verified by measurements in which
the graphite build-up cap for a graphite chamber was replaced by a tissue-
equivalent build-up cap when the irradiations were made free in air.

The ratio of 1.032 should be compared with the theoretical value of 1.029
(Table III): the agreement is just within the precision of the measurements and
proves that consistent mass ionization values are obtained at different beam
qualities with the A150 and graphite chambers when the Am correction is allowed
for in the calibration.

A similar set of measurements was carried out using a chamber with a Perspex
wall having a thin, inner layer of conducting graphite. Again, the relation between
the cavity air masses was determined for electron beams, and mass ionization
ratios were measured for the Perspex relative to the tissue-equivalent chamber for
different photon qualities. The ratios for the measurements in water given in
Fig.1b were, within the uncertainty of measurements, the same as for the pure
graphite to A150 chamber measurements. This result was not expected, since
Perspex and tissue-equivalent plastic are both approximately water equivalent.
It seems that the thin layer of graphite (50 μm) acts similarly to a 0.5 mm graphite
wall. One explanation may involve the elastic scattering of electrons at the inter­
face between the air and the graphite [33, 34]. Measurements in water and in air
for 60Co γ-ray beams gave, within the uncertainty of the measurements, the same
ratios. This result was expected, since Perspex is almost water equivalent.

This experiment shows that the Perspex ionization chamber with a thin, inner
layer of graphite (50 μm) can, in practical dosimetry, be regarded as a homogeneous
graphite-wall chamber. The same conclusion was drawn by Almond and Svensson [14].

The wall-material corrections for measurements in water with radiation
corresponding to the user's radiation quality, u, are included in the total perturba­
tion factor, pu. Tables are given for a graphite and a tissue-equivalent chamber
having 0.5 mm thick walls.

5. PERTURBATION, pw,g

When a gas-filled cavity is inserted into a solid or a liquid phantom irradiated
by electrons, the fluence of electrons within the volume now occupied by the
gas is changed due to the difference in the scattering and stopping properties of
the gas and the phantom material. The perturbation effect depends on the shape
and size of the air cavity and on the radiation quality. Theoretically derived
perturbation factors, pw,g (w = water, g = gas), for cylindrical and plane-parallel
chambers have been published [35].

As experimental data, to our knowledge, are not available for cylindrical
chambers, a series of measurements was carried out to determine pw,g-factors
for such chambers. Cylindrical chambers (I, II and III) and a plane-parallel
chamber were used for the investigation. The cylindrical chambers have the same wall material and cavity length, but have different cavity diameters, namely 3, 5 and 7 mm, respectively. Beams of $^{60}$Co $\gamma$-rays, X-rays between 5 and 42 MV, and electrons of energies, $E_z$, between 2.5 and 22 MeV were used.

A solid phantom material was chosen in order to obtain high reproducibility in the measurements. Perspex was used, since it has almost the same angular scattering power, $(\tilde{\theta}/l)^2$, as water [2]. The measurements were made at depths equal to the peak of the depth ionization curves in Perspex to eliminate any possible displacement effect. The measured ionization was corrected for recombination losses and polarity effects.

For plane-parallel chambers, the $p_{w,g}$-factor has been determined experimentally using an extrapolation method [36, 37]. Morris and Owen [36] reported that the perturbation correction was less than 0.5% at electron energies above 0.5 MeV, while Markus [37] stated that the effect was negligible for electron energies at the point of measurement of 2.2 to 14.3 MeV. Thus, no perturbation correction needs to be applied for plane-parallel ionization chambers using a thin air cavity.

5.1. Photon radiation

Table V shows the measured relative ionization using photon radiation for the 5 and 7 mm diameter chambers normalized to the 3 mm diameter chamber. No difference in the relative ionization as a function of photon energy could be found. This result was expected, as the perturbation effect should be negligible in photon beams at depths where secondary particle equilibrium exists [38]. This condition does not hold completely at the depth equal to the peak of the depth ionization curve, but the error can be neglected. The measured ionization in the cylindrical chambers (I, II, III) was also compared with the ionization in
the plane-parallel chamber (VII), and consistent results were obtained. The conclusion is, therefore, that no perturbation correction factor needs to be applied for photons of energies ranging from that of $^{60}\text{Co} \gamma$-rays to 42 MV X-rays at depths at which approximate secondary particle equilibrium exists. Since there is no perturbation effect for photon radiation and since the chambers have the same wall material, the measured relative ionization (Table V) can be assumed to be equal to the relation between the effective mass of air in the chambers.

5.2. Electron radiation

It was assumed that the differences in the ratios of measured ionization to effective mass of air for the different chambers were solely due to the perturbation effect. It is believed that the variation of stopping power ratios with cavity size is, at most, very small, since the conductive layer of the chambers contains mainly carbon. Thus, Harder [31] showed that carbon walls suppress the boundary effect of an air ionization chamber, resulting in a mass ionization almost independent of the cavity size.

The measured relative mass ionizations (charge divided by mass) for the 5 and 7 mm diameter chambers to that of the 3 mm diameter chamber are shown in Fig.2. In Fig.2 are also shown the theoretically calculated ratios [35]; according to the measurements, the theory underestimates the perturbation effect.

The experimental result indicates that the correction factor could be written:

$$p_{w,g} = 1 + k \cdot r$$

(10)

where $k$ includes an energy-dependent constant and $r$ is the radius of the air cavity (Fig.3). This relation differs from the theoretical relation [35] for cylindrical cavities which contains $\sqrt{r}$ instead of $r$. Equation (10) and the measured, normalized ratios of the mass ionization shown in Fig.2 have been used to determine the perturbation correction factor, $p_{w,g}$, for the three chambers (Fig.4).

The mass ionization in the cylindrical chambers (I, II, III) was also compared with that in the plane-parallel chamber (VII). The photon radiation measurements were used to normalize the response of the cylindrical chambers to that of the plane-parallel chamber. The latter chamber should, according to the experiments referred to above, have a negligible perturbation effect. The ratio of the mass ionization of the cylindrical chambers to that of the plane-parallel chamber should thus give the $p_{w,g}$-values. The result of these measurements is in agreement (to within $\pm 0.7\%$) with the result obtained above (Fig.4).

The experimental results show that rather large corrections for perturbation of the electron fluence have to be made for medium electron energies. Thus the corrections with a Baldwin Farmer 0.6 cm$^3$ chamber are 3.5% at the reference
FIG. 2. Relative mass ionizations: (a) for a 5 mm diameter and (b) for a 7 mm diameter chamber, each relative to a 3 mm diameter chamber, for electron radiation as a function of mean electron energy, $E_z$.

FIG. 3. Perturbation correction factors, $p_{w,g}$, for cylindrical chambers for electron radiation ($E_z = 2.5$ MeV) as a function of the chamber radius. Experimental values were obtained from measurements using plane-parallel and cylindrical chambers. Theoretical values calculated according to Harder [35].
In order to measure the absorbed dose at a point of interest in the medium, some of the medium around this point is replaced by detector material, i.e. the air of an ionization chamber. Thus, the particle fluence in the cavity will no longer be representative of the fluence at the point of interest in the homogeneous medium (see §5). One method of correcting for this effect is to use a displacement factor and regard the centre of the ionization chamber as the measuring point [1]; this factor can only be used for depths larger than that corresponding to the peak absorbed dose. Another method is to define an effective measuring point in front of the centre of the chamber [17, 18, 40].
FIG. 5. Relative depth ionization curves measured with cylindrical chambers in a Perspex phantom irradiated with $^{60}$Co γ-rays and 42 MV X-rays. The ionization is plotted against the depth of the chamber centre.

FIG. 6. Relative depth ionization curves measured with cylindrical chambers and a plane-parallel chamber in a Perspex phantom irradiated with electron beams of various energies. The ionization is plotted against the depth of the chamber centre and against the depth of the front wall of the plane-parallel chamber.
Experiments were made covering a more complete set of beam qualities than those studied before. The displacement effect was investigated using several cylindrical chambers (I, II, III, Baldwin-Farmer and Philips) and a plane-parallel chamber (VII) (see Table I). The cylindrical chambers were irradiated with the axis perpendicular to the direction of the beam. Beam-axis depth ionization curves were measured. The ionization was corrected for recombination losses and polarity effects. The measurements were carried out for photon beams of energies ranging from that of $^{60}\text{Co}$ $\gamma$-rays to 42 MV X-rays and for electron beams with mean energies at the phantom surface of between 4.5 and 30 MeV. Central depth ionization curves for all energies and ionization chambers were plotted versus the depth of the front wall of the plane-parallel chamber and the depth of the chamber centre of the cylindrical chambers. The measurements were carried out in solid Perspex phantoms in order to obtain high reproducibility. Figure 5 shows, as an example, the depth ionization curves for $^{60}\text{Co}$ $\gamma$-rays and 42 MV X-rays, and Fig. 6 those for electron beams with mean energies, $E_0$, of 4.5, 9.5 and 19.0 MeV.

6.1. Radial displacement

The displacement of the effective measuring point from the centre of the cavity in cylindrical chambers, i.e. the radial displacement, was determined from the measured depth ionization curves.

The result for photon beams is given in Fig. 7. In the build-up region and close to the peak absorbed dose, a radial displacement varying between 0.75$r$ and 0.95$r$, where $r$ stands for the cavity radius, was determined. Our results show that the radial displacement decreases with increasing depth in the phantom. Dutreix [40] reported a theoretical value of 0.85$r$ for a cylindrical chamber in a unidirectional beam, and an experimental value in the build-up region in beams of 5 and 25 MV X-rays equal to the theoretical value. Hettinger et al. [18] reported an experimental value of 0.75$r$ for 32 MV X-rays. All of these values agree very well with our results.

With electron radiation, the variation of the perturbation factor, $P_{w,g}$, with depth was not corrected for and is thus included in the radial displacement. This is the most practical procedure, because it will facilitate the use of the results in measurements of relative depth ionization curves. Below 10 MeV, the radial displacement decreases with increasing depth (Fig. 8). No significant variation with depth was found above 19 MeV. The radial displacement was somewhat smaller than that quoted in some data [18], but in good agreement with other data [41]. The use of an effective measuring point should be preferred for electron beams, since the rapid fall-off of the depth dose curve gives an impractically large factor at some depths.
**FIG. 7.** Radial displacement for cylindrical ionization chambers versus depth in a Perspex phantom irradiated with $^{60}$Co $\gamma$-rays and 5 to 42 MV X-rays.

**FIG. 8.** Radial displacement for cylindrical ionization chambers versus relative ionization in a Perspex phantom irradiated with electron beams of various energies.
6.2. Displacement factor

With photon radiation, the ratios of the relative ionizations in the different chambers were determined for depths larger than that of the peak absorbed dose. Figure 9 shows the displacement factors versus the depth in Perspex for photon beams. No significant variation with phantom depth could be seen, but there is a variation with energy. The mean displacement factors are given in Table VI. The factors decrease with increasing energy. The measurements gave a displacement factor for $^{60}$Co $\gamma$-rays of 0.988 for a Baldwin-Farmer chamber, which is in good agreement with the value 0.985 reported by ICRU [1].

The result given for $^{60}$Co $\gamma$-rays in Table VI was checked in an independent experiment using cylindrical chambers of different diameters (3, 5 and 7 mm) but having the same wall material. Measurements were carried out both free in air (with the chambers fitted with build-up caps) and in a Perspex phantom (with the centre of the chambers placed at a depth of 5 cm). The ratios of the ionizations measured in Perspex were determined, corrected for the displacement using data from Table VI. These values were compared with the ratios determined from the measurements free in air. The agreement was within 0.2%, which shows that the displacement corrections applied are reasonable.
**TABLE VI. DISPLACEMENT FACTOR FOR PHOTON RADIATION**

<table>
<thead>
<tr>
<th>Energy</th>
<th>Displacement factor (% · (mm chamber radius)$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{60}$Co $\gamma$-rays</td>
<td>0.40</td>
</tr>
<tr>
<td>5 MV</td>
<td>0.40</td>
</tr>
<tr>
<td>8 MV</td>
<td>0.31</td>
</tr>
<tr>
<td>16 MV</td>
<td>0.24</td>
</tr>
<tr>
<td>42 MV</td>
<td>0.25</td>
</tr>
</tbody>
</table>

**TABLE VII. CALCULATED C$_u$-VALUES AND MEASURED p$_u$-VALUES FOR A 5 mm DIAMETER CYLINDRICAL IONIZATION CHAMBER WITH GRAPHITE OR WATER-EQUIVALENT WALLS, FOR PHOTON RADIATION**

<table>
<thead>
<tr>
<th>Type of radiation</th>
<th>C$_u$ (J · C$^{-1}$)</th>
<th>p$_u$, graphite</th>
<th>p$_u$, water</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{60}$Co $\gamma$-rays</td>
<td>38.8</td>
<td>0.968</td>
<td>0.990</td>
</tr>
<tr>
<td>4 MV</td>
<td>38.7</td>
<td>0.972</td>
<td>0.990</td>
</tr>
<tr>
<td>6 &quot;</td>
<td>38.4</td>
<td>0.979</td>
<td>0.992</td>
</tr>
<tr>
<td>8 &quot;</td>
<td>38.2</td>
<td>0.983</td>
<td>0.993</td>
</tr>
<tr>
<td>10 &quot;</td>
<td>38.0</td>
<td>0.984</td>
<td>0.994</td>
</tr>
<tr>
<td>12 &quot;</td>
<td>37.8</td>
<td>0.985</td>
<td>0.994</td>
</tr>
<tr>
<td>14 &quot;</td>
<td>37.7</td>
<td>0.985</td>
<td>0.994</td>
</tr>
<tr>
<td>16 &quot;</td>
<td>37.5</td>
<td>0.985</td>
<td>0.994</td>
</tr>
<tr>
<td>18 &quot;</td>
<td>37.3</td>
<td>0.994</td>
<td></td>
</tr>
<tr>
<td>20 &quot;</td>
<td>37.2</td>
<td>0.994</td>
<td></td>
</tr>
<tr>
<td>22 &quot;</td>
<td>37.1</td>
<td>0.994</td>
<td></td>
</tr>
<tr>
<td>25 &quot;</td>
<td>37.0</td>
<td>0.994</td>
<td></td>
</tr>
<tr>
<td>30 &quot;</td>
<td>36.7</td>
<td>0.994</td>
<td></td>
</tr>
<tr>
<td>35 &quot;</td>
<td>36.5</td>
<td>0.994</td>
<td></td>
</tr>
<tr>
<td>40 &quot;</td>
<td>36.3</td>
<td>0.994</td>
<td></td>
</tr>
<tr>
<td>45 &quot;</td>
<td>36.1</td>
<td>0.994</td>
<td></td>
</tr>
<tr>
<td>50 &quot;</td>
<td>35.9</td>
<td>0.994</td>
<td></td>
</tr>
</tbody>
</table>
TABLE VIII. CALCULATED $C_u$-VALUES AND MEASURED $p_u$-VALUES FOR A 5 mm DIAMETER CYLINDRICAL IONIZATION CHAMBER, FOR ELECTRON RADIATION

Calculation of $E_z$ according to Brahme [47]

<table>
<thead>
<tr>
<th>$E_0$ (MeV)</th>
<th>Depth (cm)</th>
<th>$E_z$ (MeV)</th>
<th>$C_u$ (J·C$^{-1}$)</th>
<th>$p_u$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1.0</td>
<td>3.0</td>
<td>36.9</td>
<td>0.967</td>
</tr>
<tr>
<td>6</td>
<td>1.4</td>
<td>3.0</td>
<td>36.8</td>
<td>0.967</td>
</tr>
<tr>
<td>8</td>
<td>1.7</td>
<td>4.5</td>
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<td>0.971</td>
</tr>
<tr>
<td>10</td>
<td>2.0</td>
<td>5.5</td>
<td>35.4</td>
<td>0.974</td>
</tr>
<tr>
<td>15</td>
<td>2.0</td>
<td>10.5</td>
<td>34.0</td>
<td>0.984</td>
</tr>
<tr>
<td>20</td>
<td>2.0</td>
<td>15.0</td>
<td>33.2</td>
<td>0.992</td>
</tr>
<tr>
<td>25</td>
<td>3.0</td>
<td>17.0</td>
<td>32.9</td>
<td>0.995</td>
</tr>
<tr>
<td>30</td>
<td>3.0</td>
<td>22.0</td>
<td>32.4</td>
<td>0.996</td>
</tr>
<tr>
<td>35</td>
<td>3.0</td>
<td>26.0</td>
<td>32.0</td>
<td>0.997</td>
</tr>
<tr>
<td>40</td>
<td>3.0</td>
<td>31.0</td>
<td>31.6</td>
<td>0.997</td>
</tr>
<tr>
<td>45</td>
<td>3.0</td>
<td>35.5</td>
<td>31.4</td>
<td>0.998</td>
</tr>
<tr>
<td>50</td>
<td>3.0</td>
<td>40.0</td>
<td>31.2</td>
<td>0.998</td>
</tr>
</tbody>
</table>

TABLE IX. CALCULATED $C_u$-VALUES FOR ELECTRON RADIATION FOR $1 \leq E_0 \leq 10$ MeV

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Mean energy at phantom surface, $E_o$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1  2  3  4  5  6  8  10</td>
</tr>
<tr>
<td>0.0</td>
<td>38.3 37.5 36.7 36.1 35.5 35.0 34.2 33.6</td>
</tr>
<tr>
<td>0.2</td>
<td>38.9 37.9 37.1 36.4 35.8 35.2 34.4 33.8</td>
</tr>
<tr>
<td>0.4</td>
<td>39.1 38.4 37.4 36.7 36.0 35.5 34.6 34.0</td>
</tr>
<tr>
<td>0.6</td>
<td>39.5 38.8 37.8 37.0 36.3 35.7 34.8 34.1</td>
</tr>
<tr>
<td>0.8</td>
<td>39.0 38.2 37.3 36.6 36.0 35.0 34.3 34.3</td>
</tr>
<tr>
<td>1.0</td>
<td>39.1 38.6 37.7 36.9 36.2 35.2 34.5 34.5</td>
</tr>
<tr>
<td>1.2</td>
<td>38.8 38.0 37.2 36.5 35.4 34.6 34.6 34.6</td>
</tr>
<tr>
<td>1.4</td>
<td>39.0 38.4 37.5 36.8 35.7 34.8 34.8 34.8</td>
</tr>
<tr>
<td>1.6</td>
<td>39.1 38.7 37.9 37.1 35.9 35.9 35.9 35.9</td>
</tr>
<tr>
<td>1.8</td>
<td>38.9 38.2 37.4 36.1 35.2 35.2 35.2 35.2</td>
</tr>
<tr>
<td>2.0</td>
<td>39.0 38.5 37.8 36.4 35.4 35.4 35.4 35.4</td>
</tr>
<tr>
<td>2.5</td>
<td>39.1 38.9 38.5 37.1 35.9 35.9 35.9 35.9</td>
</tr>
<tr>
<td>3.0</td>
<td>39.0 38.9 37.8 36.6 35.6 35.6 35.6 35.6</td>
</tr>
<tr>
<td>3.5</td>
<td>38.9 38.4 37.2 36.6 35.6 35.6 35.6 35.6</td>
</tr>
<tr>
<td>4.0</td>
<td>39.7 37.8 36.6 35.6 35.6 35.6 35.6 35.6</td>
</tr>
<tr>
<td>4.5</td>
<td>38.7 38.4 38.4 38.4 38.4 38.4 38.4 38.4</td>
</tr>
<tr>
<td>5.0</td>
<td>38.6 38.6 38.6 38.6 38.6 38.6 38.6 38.6</td>
</tr>
</tbody>
</table>
### Table X. Calculated C\textsubscript{u}-Values for Electron Radiation for 10 \(\leq E_0 \leq 50\) MeV

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Mean energy at phantom surface, (\overline{E}_o) (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>z</td>
<td>15</td>
</tr>
<tr>
<td>0</td>
<td>32.8</td>
</tr>
<tr>
<td>1</td>
<td>33.4</td>
</tr>
<tr>
<td>2</td>
<td>34.0</td>
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<tr>
<td>3</td>
<td>34.6</td>
</tr>
<tr>
<td>4</td>
<td>35.3</td>
</tr>
<tr>
<td>5</td>
<td>36.3</td>
</tr>
<tr>
<td>6</td>
<td>37.2</td>
</tr>
<tr>
<td>8</td>
<td>38.1</td>
</tr>
<tr>
<td>10</td>
<td>38.0</td>
</tr>
<tr>
<td>12</td>
<td>37.2</td>
</tr>
<tr>
<td>14</td>
<td>37.2</td>
</tr>
<tr>
<td>16</td>
<td>37.0</td>
</tr>
<tr>
<td>18</td>
<td>36.8</td>
</tr>
<tr>
<td>20</td>
<td>36.6</td>
</tr>
<tr>
<td>22</td>
<td>36.4</td>
</tr>
<tr>
<td>24</td>
<td>36.2</td>
</tr>
<tr>
<td>26</td>
<td>36.1</td>
</tr>
</tbody>
</table>

### 7. RESULTS

For photon beams the C\textsubscript{u} and p\textsubscript{u}-factors are given as a function of the maximum energy, determined as described by the NACP [7]. For electron beams the values are given as a function of the mean energy at the phantom surface, \(\overline{E}_o\), and the depth, z, in a water phantom. \(\overline{E}_o\) was determined from the energy-range relation \(R_{50} = k\overline{E}_o\), where \(R_{50}\) is the half-value depth (cm) in water measured with large fields and \(k = 0.43\) cm·MeV\(^{-1}\) [15].

#### 7.1. Calculation of C\textsubscript{u}-values

In the calculation of the C\textsubscript{u}-factor for electron radiation, \((S/\rho)_{\text{water, A}}\) values were taken from Berger et al. [42] with \(\Delta = 15\) keV, \(I(\text{water}) = 65.1\) eV and \(I(\text{air}) = 68.8\) eV. \((W/e) = 33.73\) J·C\(^{-1}\). For photon radiation, the stopping power ratios at a depth of 5 cm in water were taken from ICRU data [1] C\textsubscript{u}-values for photon radiation are given in Table VII, and for electron radiation in Tables IX and X.
7.2. Total perturbation correction factor, \( p_u \)

The total perturbation correction factor, \( p_u \), was evaluated from the experiments made using a 5 mm diameter cylindrical chamber for different beam qualities and depths in the phantom (Tables VII and VIII). Thus, as an example, a graphite chamber placed with its centre at a depth of 5 cm in water, irradiated with a beam of \( ^{60}\text{Co} \) \( \gamma \)-rays, will give \( p_{wg} = 1.000 \) (see §5), \( d = 0.990 \) (Table VI), and a wall effect of \( (1/1.023) = 0.978 \) (Fig.1); this gives a \( p_u \)-value of 0.968. Table VII shows \( p_u \)-values using ionization chambers with a 0.5 mm graphite and a 0.5 mm water-equivalent wall. Different sets of \( p_u \)-values for the two materials are obtained with photon radiation, but they agree for the electron beams (Table VIII).

7.3. Application of results

The corrections necessary for the determination of absorbed dose at a reference point using Eq.(6) were tabulated (Tables VII and VIII). The corrections are valid when a cylindrical ionization chamber of 5 mm diameter is placed with its centre at the reference depth in a water phantom.

With photon radiation, the absorbed dose at depths which differ from that of the reference point could be measured using relative depth ionization curves and applying a radial displacement correction; as can be seen from Fig.7, a suitable value for the correction would be 0.7\( r \).

With electron radiation above 10 MeV, the absorbed dose at depths other than that of the reference point could be measured using a cylindrical chamber and relative depth ionization curves, applying a radial displacement correction of 0.5\( r \) and allowing for the variation of \( C_u \) with depth (Table IX).

8. CONSISTENCY

A comparison was carried out between the absorbed-dose determination using the procedure recommended by the NACP [7] and the method described in this report. Cylindrical ionization chambers of 5 mm diameter, with walls of graphite and water-equivalent material, were used. According to the current NACP report, the chambers should have an additional build-up cap of Perspex during the exposure calibration; however, the procedure described in this paper requires an additional cap of graphite or water-equivalent material for chambers having graphite or water-equivalent walls, respectively. The absorbed doses were normalized to the values determined using the procedure described in this paper. The result is given in Table XI. The differences in the absorbed doses determined using the two methods were in most cases less than 1.5%. However, the difference
TABLE XI. COMPARISON BETWEEN ABSORBED DOSES DETERMINED USING THE DOSIMETRIC PROCEDURE DEVELOPED IN THIS REPORT WITH DOSES DETERMINED USING THE $C_E$ AND $C_A$ CONCEPTS RECOMMENDED BY THE NACP [7]

The values are for two chambers identical except for the wall material (Al50 and graphite).

<table>
<thead>
<tr>
<th>Type of radiation</th>
<th>Present work</th>
<th>NACP (1972)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A 150</td>
</tr>
<tr>
<td>Photon $^{60}_{\text{Co}}$ γ-rays</td>
<td>1.000</td>
<td>1.005</td>
</tr>
<tr>
<td>8 MV</td>
<td>1.000</td>
<td>0.997</td>
</tr>
<tr>
<td>16 MV</td>
<td>1.000</td>
<td>1.003</td>
</tr>
<tr>
<td>Electron</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10 MeV</td>
<td>1.000</td>
<td>1.026</td>
</tr>
<tr>
<td>20 MeV</td>
<td>1.000</td>
<td>1.037</td>
</tr>
<tr>
<td>30 MeV</td>
<td>1.000</td>
<td>1.033</td>
</tr>
</tbody>
</table>

could be up to about 3%, solely due to wall-material effects when a water-equivalent chamber was used with electron radiation.

The stopping power ratios of water to air for electron radiation used for the determination of $C_U$ were taken from Berger et al. [42], who used the Spencer-Attix theory. Nahum [43] and Harder [44] recently pointed out that the track-end dissipation is neglected in this theory, resulting in stopping power ratios that were 0.5% to 1.5% too low. This difference is small and was neglected, since it is practically convenient to use the large amount of data available from Berger et al. directly. Furthermore, these data agree very well with experiments [42].

The theoretical stopping power ratios for electron radiation were calculated for a monoenergetic broad beam [42]. Experimental values measured by the Umeå group [25, 45] for 10, 20 and 30 MeV electrons incident on a water phantom agreed with these values to better than 1% at depths greater than 1 cm and less than 0.75 of the extrapolated range [42]. The experiments were carried out with betatron beams. Preliminary results indicated similarly good agreement for beams from travelling wave linear accelerators and microtrons (which have a somewhat different energy distribution) provided that the mean electron energy at the phantom surface is determined with the energy-range relation given above.
The stopping power ratios used for X-rays will probably need a further revision, as will the method for beam-quality calibration. Thus, new ratios based on more rigorous computations than those given by the ICRU [1] will soon be published [43]. The different photon spectral distributions from the different types of accelerators are also considered.

Before suggesting new procedures for ionization chamber dosimetry, we felt it important to make a comparison between the procedure suggested in this paper and the dosimetry of an established dosimetry centre. The National Physics Laboratory (UK) ferrous sulphate mailing service was used. The comparison was made for both $^{60}$Co $\gamma$-ray beams and 20 MeV electron beams. The absorbed dose was evaluated by the NPL using a G-value of 0.155 eV$^{-1}$ for both qualities. The dosimetric procedure described in this paper was used for the ionization chamber measurements. For $^{60}$Co $\gamma$-rays, the absorbed dose determined with the ionization chamber was 1.2% lower than the NPL value, and, for 20 MeV electrons, 1.9% lower than the corresponding NPL value. The differences are within the uncertainty of the comparison.

9. CONCLUSION

We have suggested a simple dosimetric procedure based on the ionometric method of making absorbed-dose measurements in $^{60}$Co $\gamma$-ray beams and in photon and electron beams produced by medical electron accelerators. Some work is under way that is to suggest the making of measurements using a plane-parallel chamber in a solid phantom for electron radiations with energies below 10 MeV. However, it is most important that the national standards laboratories agree on the first step in therapy-level dosimetry, namely on calibrations in a beam of $^{60}$Co $\gamma$-rays.

ACKNOWLEDGEMENTS

The skilful mechanical work by Mr. Ralph Kellgren and Mr. Rune Karlsson is acknowledged.

REFERENCES


DISCUSSION

J.J. BROERSE: In your paper you report a radial displacement between 0.75r and 0.95r for photon beams. In our routine depth dose measurements with fast neutron beams we also apply a similar correction for the displacement of the effective measuring point by 0.75 of the radius towards the inner front wall. You state in your paper that the radial displacement decreases with increasing depth in the phantom. Have you found any explanation for this phenomenon?

L.O. MATTSSON: The decrease of the radial displacement with depth is probably due to a larger contribution from scattered radiation to the absorbed dose at larger depths.

J.-P. SIMOEN: I find your work very interesting. Do your conclusions concerning the validity of the ICRU $C_\lambda$ and $C_E$ coefficients agree with those of Almond and Svensson (your Ref. [14])? In France, this year, we have set up a service for the calibration of dose in water, based on the use of the Fricke dose meter. Examination of the first results, presented by Guiho at this meeting, leads one to the same conclusions as the above-mentioned paper.

L.O. MATTSSON: Perhaps my co-author Mr. Svensson would answer that.

H. SVENSSON: The findings presented in our paper agree very well with the results obtained by Almond and Svensson, and should also agree with the
data given by Guiho\textsuperscript{1} and Simoen\textsuperscript{2}. All the experimental data thus seem to be consistent.

R. LOEVINGER: There are many persons giving attention to this problem; among them is a small Task Group of the American Association of Physicists in Medicine. Their theoretical approach is similar to that you have presented here. Your paper is the most complete and most convincing treatment that has come to my attention. I must, however, express some reservations about the "mass calibration factor" that you have introduced. A proper calibration factor is the quotient of a physical quantity and the signal from the instrument being calibrated. The physical quantity is determined in the absence of the instrument being calibrated and at its reference point. Your mass calibration factor contains terms that depend on the properties of each individual chamber. I doubt whether it is appropriate for a calibration laboratory to provide a calibration factor of the type you have suggested. I believe the chamber-dependent correction factors should be introduced elsewhere in the calculation.

\textsuperscript{1} GUIHO, J.-P., SIMOEN, J.-P., these Proceedings, Vol. 1, page 3.
\textsuperscript{2} SIMOEN, J.-P., these Proceedings, Vol. 1, page 21.
IONIZATION-CHAMBER-DEPENDENT FACTORS FOR CALIBRATION OF MEGAVOLTAGE X-RAY AND ELECTRON BEAM THERAPY MACHINES*

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Department of Physics,
The University of Texas System Cancer Center,
M.D. Anderson Hospital and Tumor Institute,
Houston, Texas
United States of America

Abstract

IONIZATION-CHAMBER-DEPENDENT FACTORS FOR CALIBRATION OF MEGAVOLTAGE X-RAY AND ELECTRON BEAM THERAPY MACHINES.

When exposure-calibrated ionization chambers are used to calibrate megavoltage X-ray and electron beam therapy machines, the calibration factor can be divided into a chamber-dependent and a chamber-independent component. Until recently, only the chamber-independent part, which has been derived theoretically, has been used; the chamber-dependent component has been ignored. Recent experimental and theoretical considerations, however, have indicated that the dependent component must be taken into account and can affect the calibration by as much as 4%. The calibration can change due to (i) the thickness of the chamber wall, (ii) the chamber wall composition, i.e. whether the chamber is constructed of air-equivalent material, or tissue- or water-equivalent material, and (iii) the size of the chamber changing the displacement factor. Theoretical and experimental evidence indicates that the third factor varies from approximately 4.5% for $^{60}$Co $\gamma$-rays to 0.5% for 25 MV X-rays, and that it is also dependent upon the first and second factors. The first and second factors are interrelated. Owing to the nature of the exposure calibration (made with $^{60}$Co $\gamma$-rays), no effect is seen for $^{60}$Co. For 25 MV X-rays, however, the effect increases to 3%. For electron beams, the effect is energy-independent and is about 3%. All measurements and calculations have been made with commercially available ionization chambers with a $^{60}$Co exposure calibration traceable to the National Bureau of Standards (USA). All differences were determined against values obtained using standard calibration procedures recommended in various handbooks and protocols.

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FIG. 1. Characteristic build-up curve for X-rays showing that it consists of two exponential curves (both scales have arbitrary units).

TABLE I. LIST OF CHAMBERS USED IN DETERMINING $(K_{\text{wall}})^{-1}$ DISPLACEMENT AND REPLACEMENT FACTORS

$x$ is the chamber wall thickness corrected for curvature.

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Effective wall material</th>
<th>$\mu_1$</th>
<th>$\mu_2$</th>
<th>$x$ (cm)</th>
<th>$(K_{\text{wall}})^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baldwin-Farmer</td>
<td>Lucite</td>
<td>0.045</td>
<td>13.8</td>
<td>0.564</td>
<td>0.978</td>
</tr>
<tr>
<td>EG&amp;G (57-TG) 1e-17</td>
<td>TE plastic</td>
<td>0.043</td>
<td>11.8</td>
<td>0.610</td>
<td>0.978</td>
</tr>
<tr>
<td>Shonka 0.1 cm$^3$</td>
<td>Lucite</td>
<td>0.045</td>
<td>13.8</td>
<td>0.564</td>
<td>0.978</td>
</tr>
<tr>
<td>X-Radin AE</td>
<td>AE plastic</td>
<td>0.060</td>
<td>17.8</td>
<td>0.609</td>
<td>0.968</td>
</tr>
<tr>
<td>X-Radin TE</td>
<td>TE plastic</td>
<td>0.043</td>
<td>11.8</td>
<td>0.609</td>
<td>0.978</td>
</tr>
<tr>
<td>EG&amp;G (72-TG) 1e-18</td>
<td>TE plastic</td>
<td>0.043</td>
<td>11.8</td>
<td>0.570</td>
<td>0.979</td>
</tr>
<tr>
<td>6 cm$^3$ TE</td>
<td>TE plastic</td>
<td>0.043</td>
<td>11.8</td>
<td>0.656</td>
<td>0.976</td>
</tr>
<tr>
<td>Shonka 3 cm$^3$</td>
<td>AE plastic</td>
<td>0.060</td>
<td>17.8</td>
<td>0.819</td>
<td>0.956</td>
</tr>
</tbody>
</table>

$^a$ TE: tissue-equivalent; AE: air-equivalent.
1. INTRODUCTION

When exposure-calibrated ionization chambers are used to calibrate megavoltage X-ray and electron beam therapy machines, the calibration factors to be applied can be divided into a chamber-dependent and a chamber-independent component. To date, only the chamber-independent part, which has been derived theoretically, has been used. The chamber-dependent components have been ignored.

Recent experimental and theoretical considerations have indicated that these factors must be taken into account because they can affect the calibration by as much as 4%. The calibration can change owing to:

(i) Cobalt-60 X-ray attenuation through the chamber walls at the time of exposure calibration;
(ii) The effect of the chamber wall material upon the calibration in a water phantom as a function of energy;
(iii) Displacement of the water in the water phantom by the chamber.

The approach taken has been to use commercially available chambers according to published protocols, i.e. the calibration procedure is based on using chambers with an exposure calibration traceable to a national calibration laboratory [1–6].

2. COBALT-60 GAMMA-RAY ATTENUATION THROUGH CHAMBER WALLS

Because ionization chambers are made of different materials with different densities, the attenuation of the 60Co γ-rays at the time of chamber calibration will be different for each chamber. This arises because the radiation intensity across the volume from which the ionization-producing electrons originate is not constant but varies because of attenuation. Cormack and Johns [7] define an equivalent uniform radiation intensity, I_e, that would produce the same ionization as that produced by the non-uniform intensity. The ratio of this intensity, I_e, to the incident intensity, I_0, is given by:

\[ \frac{I_e}{I_0} = e^{-\mu_1 t} \cdot \frac{\mu_2 (1 - e^{-(\mu_2 - \mu_1) t})}{(\mu_2 - \mu_1) (1 - e^{-\mu_2 t})} = \frac{1}{K_{wall}} \]

where \( t \) is the thickness of material between the front surface and the point of interest, \( \mu_1 \) is the effective attenuation coefficient in poor geometry for the radiation in the wall material, and \( \mu_2 \) is the attenuation coefficient for the
secondary electrons. The coefficients $\mu_1$ and $\mu_2$ can be experimentally
determined from the build-up curve [8] as shown in Fig. 1.

Studies were done with a thin-window extrapolation chamber using machined
layers of chamber wall material. Corrections were then made for chamber-wall
curvature [9] and the attenuation factors ($1/K_{\text{wall}}$) were calculated (Table I).
Currently, a constant factor of 0.985 is being used for all chambers, which can be seen to lead to uncertainties of 1% to 2%.

3. THE EFFECT OF CHAMBER WALL MATERIAL ON THE CALIBRATION
IN A WATER PHANTOM AS A FUNCTION OF ENERGY

Almond and Svensson [10] have shown for X-rays that the dose in water is
given by:

$$D_{\text{water},0} = M_0 \cdot \frac{1}{K_{\text{wall}}} \cdot A_0 \cdot \left( \frac{\bar{W}}{e} \right) \cdot \beta \cdot \left( \frac{S}{\rho_{\text{air}}} \right)_{\text{water}}$$

$$+ (1 - \beta) \cdot \left( \frac{S}{\rho_{\text{air}}} \right)_{\text{wall}} \cdot \left( \frac{\mu_{\text{en}}}{\rho_{\text{wall}}} \right)_{\text{water}} \cdot d \cdot p$$

where $A_0$ is calculated at the calibration energy, c, and is given by:

$$A_0 = \left[ \alpha \cdot \left( \frac{\mu_{\text{en}}}{\rho_{\text{air}}} \right)^b \cdot \left( \frac{S}{\rho_{\text{air}}} \right)_{\text{air}} - (1 - \alpha) \cdot \left( \frac{\mu_{\text{en}}}{\rho_{\text{air}}} \right)_{\text{wall}} \cdot \left( \frac{S}{\rho_{\text{wall}}} \right)_{\text{air}} \right]_c$$

For a two-component chamber, $\alpha$ is the fraction of the ionization due to
electrons appearing to be generated in the build-up material, b, and $(1 - \alpha)$ is the fraction from the wall itself (wall).

It is assumed that the higher energy X-ray measurements are made with
the thimble ionization chamber without build-up cap in a water phantom, and
that a fraction $\beta$ of the ionization comes from electrons generated in the wall.
The factor $p$ is introduced to correct for the distortion in electron fluence
caused by the differences in electron multiple scattering in the probe and air
cavity compared with that of the phantom material. The factor $d$ corrects
for the reduction of attenuation when the air cavity replaces phantom material. $N_0$ is the exposure calibration factor and $M_0$ is the instrument reading (minor
corrections due to radiation-induced leakage, recombination losses, etc. are not considered).
TABLE II. LIST OF CHAMBERS USED TO DETERMINE THE WALL EFFECT

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Wall material</th>
<th>Volume (cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exradin</td>
<td>tissue equivalent</td>
<td>0.5</td>
</tr>
<tr>
<td>Exradin</td>
<td>air equivalent</td>
<td>0.5</td>
</tr>
<tr>
<td>Baldwin-Farmer</td>
<td>air equivalent</td>
<td>0.6</td>
</tr>
<tr>
<td>Capintec</td>
<td>tissue equivalent</td>
<td>0.6</td>
</tr>
<tr>
<td>EG&amp;G</td>
<td>tissue equivalent</td>
<td>0.1</td>
</tr>
</tbody>
</table>

It was shown [10] that $\alpha = 0$ for most practical cases, and it has been generally assumed that $\beta = 1$, $p = 1$ and $d = 1$.

For a chamber constructed of tissue-equivalent or water-equivalent material, therefore:

$$D_\text{water,} = M_\lambda \cdot N_c \cdot C_\text{water,} \quad \text{(4)}$$

where:

$$C_\text{water,} = \frac{1}{K_\text{wall}} \cdot \left( \frac{W}{e} \right) \cdot \left[ \frac{\left( \frac{\mu_{\text{en}}}{\rho} \right)_\text{water}}{\left( \frac{S}{\rho} \right)_\text{water}} \right] \cdot \left( \frac{S}{\rho} \right)_\text{air,} \quad \text{(5)}$$

Published values of $C_\lambda$ are based on this equation [1–5]. For a chamber with inner walls made of air-equivalent material, the dose is given by:

$$D_\text{water,} = M_\lambda \cdot N_c \cdot C_\text{air,} \quad \text{(6)}$$

where:

$$C_\text{air,} = \frac{1}{K_\text{wall}} \cdot \left( \frac{W}{e} \right) \cdot \left[ \frac{\left( \frac{\mu_{\text{en}}}{\rho} \right)_\text{air,eq}}{\left( \frac{S}{\rho} \right)_\text{air,eq}} \right] \cdot \left( \frac{S}{\rho} \right)_\text{water} \cdot \left( \frac{S}{\rho} \right)_\text{air,} \quad \text{(7)}$$

The square bracket in Eq. (7) should thus be unity for a completely air-equivalent material. For carbon used as an air-equivalent material, the factor
\[ C_{E, \text{Tissue}} = \frac{1}{K_{\text{Wall}}} \left[ \frac{M_{\text{E, Tissue}}}{W} \left( \frac{S_{\text{Tissue}}}{r} \right) \frac{S_{\text{Water}}}{W} \right] r \cdot d \phi \]

\[ C_{E, \text{Air}} = \frac{1}{K_{\text{Wall}}} \left[ \frac{M_{\text{E, Air}}}{W} \frac{S_{\text{Water}}}{W} \right] r \cdot d \phi \]

\[ C_{E, \text{Tissue}} = \frac{M_{E, \text{NClAir}}}{M_{E, \text{NClTissue}}} C_{E, \text{Air}} \]

**FIG. 2.** Theoretical \( C_E \)-values of Exradin air-equivalent and tissue-equivalent chambers, and experimental values for a tissue-equivalent chamber.

\[ C_{\lambda, \text{Air}} = \frac{1}{K_{\text{Wall}}} \left[ \beta \left( \frac{S_{\text{Water}}}{r} \right) \frac{S_{\text{Air}}}{W} + \eta - \beta \left( \frac{M_{\text{E, Air}}}{W} \right) \right] \cdot d \phi \]

\[ C_{\lambda, \text{Tissue}} = \frac{M_{E, \text{NClAir}}}{M_{E, \text{NClTissue}}} C_{\lambda, \text{Air}} \]

**FIG. 3.** Theoretical \( C_{\lambda} \)-values for two conditions, \( \beta = 0 \) and \( \beta = 1 \). Experimental values showing that \( \beta \) varies from 0 to 1. (Baldwin-Farmer air-equivalent chamber.)
should formally be 1.005 for a chamber calibrated at the National Bureau of Standards (NBS, USA), as that value is used in the calculation of exposure from cavity ionization in graphite.

$C_{\text{air},\lambda}$ is approximately 3%, plus 0.5% if graphite is taken as air-equivalent wall material, higher than $C_{\text{water},\lambda}$ according to the foregoing discussion. Experiments were conducted to confirm this difference.

Similar equations were derived for electron beams:

$$D_{\text{water},E} = M_E \cdot N_c \cdot C_{\text{water},E}$$  \hspace{1cm} (8)

where

$$C_{\text{water},E} = \frac{1}{K_{\text{wall}}} \cdot \left( \frac{\bar{W}}{e} \right) \cdot \left[ \frac{(\mu_{en})_{\text{water}}}{\rho_{\text{air}}} \right] \cdot \left( \frac{S}{\rho_{\text{air}}} \right)_{\text{water}} \cdot \left( \frac{S}{\rho_{\text{air}}} \right)_{\text{water}}$$  \hspace{1cm} (9)
Published values of $C_E$ are based on this formula [4–6].

Table II lists the chambers used in this investigation. Matched pairs of chambers were used so that displacement and perturbation effects were equal. Measurements were made at the same position in a water phantom with each chamber for each radiation beam.

Figure 2 shows the effect of wall material on the $C_E$ correction factors. Both theoretical and experimental values are shown, indicating a constant $2^\frac{1}{2}\%$ difference.

Figure 3 shows the effect of increasing the X-ray energy on chamber response. The top curve assumes all electrons come from the water phantom ($\beta = 1$), while the bottom curve assumes they all come from the chamber wall.
(\(\beta = 0\)). The experimental data shows the transition from the latter case to the former case as the X-ray energy increases.

Figure 4 shows recommended \(C_\lambda\)-values for two Farmer-type chambers built of different materials. Also shown are the protocol-recommended values, which are close to the values for the tissue-equivalent chamber.

Figure 5 shows the correction factors that should be applied to the published \(C_\lambda\)-values when air-equivalent chambers are used. As expected, the correction factors vary with energy. Close to the calibration energy at which the wall of the chamber dominates, its response varies rapidly with energy, but the response levels off at higher energies when the phantom material becomes important.

4. DISPLACEMENT FACTOR (FOR THE CALIBRATION RADIATION OF \(^{60}\text{Co} \gamma\)-RAYS)

It might be thought that, since the energy of \(^{60}\text{Co} \gamma\)-rays is that at which the chamber is calibrated for exposure, the determination of absorbed dose in a phantom would be straightforward. Unfortunately, at the present time it is still not clear what the best approach is, because the chamber can be used in at least three different ways [3]:

(a) The chamber can be used as an exposure meter to determine the exposure at a point in air, from which the dose in the phantom can be calculated. The calculation requires an application of the tissue-to-air ratio at the position of the maximum dose (backscatter factor).

(b) The chamber can be used as an exposure meter to determine the exposure in the phantom, from which the absorbed dose can be calculated.

(c) The exposure calibration of the instrument can be used to determine the cavity ionization per mass of gas, so that the chamber can be used as a Bragg-Gray cavity with the appropriate corrections.

If the ionization chamber is used to determine exposure in free air, then:

\[
X_{\text{air},c} = M_c \cdot N_c \tag{12}
\]

and the dose at maximum depth (0.5 cm) will be given by:

\[
D_{\text{water},c} = M_c \cdot N_c \cdot \left( \frac{W}{e} \right) \cdot \left( \frac{\mu_{\text{en}}}{\rho} \right)_{\text{air},c} \cdot A_{\text{eq}} \cdot (\text{TAR})_{0.5\text{cm}} \tag{13}
\]

where \(A_{\text{eq}}\) is the attenuation of the photons through the first 0.5 cm of the water phantom and \((\text{TAR})_{0.5\text{cm}}\) is the tissue-to-air ratio at 0.5 cm. In this case,
### TABLE III. CALCULATION OF MISSING PHANTOM MATERIAL FOR REPLACEMENT CALCULATIONS

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Centre electrode radius, $R_E$ (cm)</th>
<th>Inside radius, $R_I$ (cm)</th>
<th>Outside radius, $R_O$ (cm)</th>
<th>Symmetry</th>
<th>Missing phantom material (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baldwin-Farmer</td>
<td>0.038</td>
<td>0.356</td>
<td>0.813</td>
<td>Cylindrical</td>
<td>0.209</td>
</tr>
<tr>
<td>EG&amp;G (57-TG)</td>
<td>0.237</td>
<td>0.635</td>
<td>1.143</td>
<td>Spherical</td>
<td>0.381</td>
</tr>
<tr>
<td>Shonka 0.1 cm³</td>
<td>0.075</td>
<td>0.225</td>
<td>0.738</td>
<td>Cylindrical</td>
<td>0.066</td>
</tr>
<tr>
<td>X-Radin AE</td>
<td>0.230</td>
<td>0.450</td>
<td>0.977</td>
<td>Cylindrical</td>
<td>-0.226</td>
</tr>
<tr>
<td>X-Radin TE</td>
<td>0.230</td>
<td>0.450</td>
<td>0.977</td>
<td>Cylindrical</td>
<td>0.199</td>
</tr>
<tr>
<td>EG&amp;G (72-TG)</td>
<td>0.095</td>
<td>0.229</td>
<td>0.739</td>
<td>Cylindrical</td>
<td>0.090</td>
</tr>
<tr>
<td>6 cm³ TE</td>
<td>0.750</td>
<td>1.250</td>
<td>1.750</td>
<td>Spherical</td>
<td>0.567</td>
</tr>
<tr>
<td>Shonka 3 cm³</td>
<td>0.095</td>
<td>0.920</td>
<td>1.590</td>
<td>Spherical</td>
<td>0.636</td>
</tr>
</tbody>
</table>

### TABLE IV. CALCULATION OF MISSING PHANTOM MATERIAL FOR DISPLACEMENT CALCULATIONS

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Outside diameter (cm)</th>
<th>Symmetry</th>
<th>Missing phantom material (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baldwin-Farmer</td>
<td>1.626</td>
<td>Cylindrical</td>
<td>0.690</td>
</tr>
<tr>
<td>EG&amp;G (57-TG)</td>
<td>2.286</td>
<td>Spherical</td>
<td>0.857</td>
</tr>
<tr>
<td>Shonka 0.1 cm³</td>
<td>1.476</td>
<td>Cylindrical</td>
<td>0.626</td>
</tr>
<tr>
<td>X-Radin AE</td>
<td>1.953</td>
<td>Cylindrical</td>
<td>0.829</td>
</tr>
<tr>
<td>X-Radin TE</td>
<td>1.953</td>
<td>Cylindrical</td>
<td>0.829</td>
</tr>
<tr>
<td>EG&amp;G (72-TG)</td>
<td>1.478</td>
<td>Cylindrical</td>
<td>0.627</td>
</tr>
<tr>
<td>6 cm³ TE</td>
<td>3.500</td>
<td>Spherical</td>
<td>1.312</td>
</tr>
<tr>
<td>Shonka 3 cm³</td>
<td>3.180</td>
<td>Spherical</td>
<td>1.192</td>
</tr>
</tbody>
</table>
the chamber is used with the build-up cap on and the determination of absorbed dose is independent of the chamber size and the constructional material of the chamber and build-up cap.

If the chamber is used as an exposure meter in the phantom, then the dose will be given by:

\[ D_{\text{water},c} = M_c \cdot N_c \cdot \left( \frac{\bar{W}}{e} \right) \cdot \left( \frac{\mu_{en}}{\rho} \right)_{\text{air}}^{\text{water}} \cdot d' \cdot p \]  

(14)

where \( d' \) is a displacement correction factor and \( p \) is the perturbation factor, taken as unity. In this case, the small differences in scatter and beam spectrum for the chamber in air versus the chamber in the phantom will be ignored so that the same exposure factor may be used and the determination of \((\mu_{en}/\rho)_{\text{air}}^{\text{water}}\) will be the same. Although this method is not strictly correct, if the measurement is made near the depth of maximum dose, the errors introduced should be small. Since the instrument is used as an exposure meter, the build-up cap must be left on and the exposure is determined at the centre of the air cavity left when the chamber and cap are removed. This cavity, however, fills with water and the calculated absorbed dose must be reduced to take into account the additional attenuation in this volume of water (Fig. 6). The factor \( d' \) is therefore less than unity and will depend only on the external dimensions of
### TABLE V. DISPLACEMENT AND REPLACEMENT VALUES

<table>
<thead>
<tr>
<th>Chamber</th>
<th>Missing phantom material, Table IV</th>
<th>(d^*) based on 4.5% per cm</th>
<th>Missing phantom material, Table III</th>
<th>(d) based on 4.5% per cm for Co-60</th>
<th>((K\text{\textsubscript{wall}})^{-1})</th>
<th>(d \cdot (K\text{\textsubscript{wall}})^{-1})</th>
<th>(d) based on 2% per cm 25 MV X-rays</th>
<th>(d \cdot (K\text{\textsubscript{wall}})^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baldwin-Farmer</td>
<td>0.69</td>
<td>0.97</td>
<td>0.209</td>
<td>0.99</td>
<td>0.978</td>
<td>0.968</td>
<td>0.996</td>
<td>0.974</td>
</tr>
<tr>
<td>Capintec</td>
<td>0.69</td>
<td>0.97</td>
<td>0.209</td>
<td>0.99</td>
<td>0.978</td>
<td>0.968</td>
<td>0.996</td>
<td>0.974</td>
</tr>
<tr>
<td>EG&amp;G (57-TG) 1c-17 1 cm³</td>
<td>0.857</td>
<td>0.963</td>
<td>0.381</td>
<td>0.983</td>
<td>0.978</td>
<td>0.961</td>
<td>0.992</td>
<td>0.961</td>
</tr>
<tr>
<td>Shonka 0.1 cm³</td>
<td>0.626</td>
<td>0.973</td>
<td>0.066</td>
<td>0.997</td>
<td>0.978</td>
<td>0.975</td>
<td>0.999</td>
<td>0.977</td>
</tr>
<tr>
<td>X-Radin AE</td>
<td>0.829</td>
<td>0.964</td>
<td>-0.226</td>
<td>1.01</td>
<td>0.968</td>
<td>0.978</td>
<td>1.005</td>
<td>0.972</td>
</tr>
<tr>
<td>X-Radin TE</td>
<td>0.829</td>
<td>0.964</td>
<td>0.199</td>
<td>0.991</td>
<td>0.978</td>
<td>0.969</td>
<td>0.996</td>
<td>0.974</td>
</tr>
<tr>
<td>EG&amp;G (72-TG) 1c-18 0.1 cm³</td>
<td>0.627</td>
<td>0.972</td>
<td>0.090</td>
<td>0.996</td>
<td>0.979</td>
<td>0.975</td>
<td>0.998</td>
<td>0.977</td>
</tr>
<tr>
<td>6 cm³ TE</td>
<td>1.312</td>
<td>0.944</td>
<td>0.567</td>
<td>0.975</td>
<td>0.976</td>
<td>0.952</td>
<td>0.989</td>
<td>0.965</td>
</tr>
<tr>
<td>Shonka 3 cm³</td>
<td>1.192</td>
<td>0.949</td>
<td>0.636</td>
<td>0.972</td>
<td>0.956</td>
<td>0.929</td>
<td>0.987</td>
<td>0.944</td>
</tr>
</tbody>
</table>
the build-up cap and not on the constructional material or the internal structure of the chamber.

Using the chamber as a Bragg-Gray cavity will depend on the determination of \( J_c \).

\[
D_{\text{water},c} = J_c \cdot \left( \frac{\bar{W}}{e} \right) \cdot \left( \frac{S}{\rho} \right)_{\text{wall}} \cdot \left( \frac{\mu_{en}}{\rho} \right)_{\text{water}} \cdot d \cdot p \tag{15}
\]

\[
J_{c,\text{air}} = M_c \cdot N_c \cdot \frac{1}{K_{\text{wall}}} \cdot A_m
\]

\[
D_{\text{water}} = M_c \cdot N_c \cdot \left( \frac{1}{K_{\text{wall}}} \right) \cdot A_m \cdot \left( \frac{\bar{W}}{e} \right) \cdot \left( \frac{S}{\rho} \right)_{\text{wall}} \cdot \left( \frac{\mu_{en}}{\rho} \right)_{\text{water}} \cdot d \cdot p \tag{16}
\]
This equation is very similar to Eqs (13) and (14), except that now \((1/K_{\text{wall}})\) appears in the equation and \(d\) is a factor that takes into account the fact that the phantom material has been replaced by a chamber made of a different material, including air spaces, with the net result that either more or less phantom-equivalent material is in the beam. This factor has been called the replacement factor.

All three approaches should yield the same dose for a given situation. Therefore, if \(A_{\text{eq}}\) and \((\text{TAR}_{0.5\text{cm}})\) are known and \(p = 1\), the ratio of Eq. (14) to Eq. (13) should yield information about the displacement factor, \(d'\). If \((1/K_{\text{wall}})\) for each chamber is known, then the ratio of Eq. (17) to Eq. (13) should yield information about the replacement factor, \(d\).

Since a number of different chambers were used, some way of correlating the results with a specific chamber parameter had to be found. It was decided to use the missing phantom material calculation of Shapiro [11] as the parameter of interest. In this calculation, the net amount of material (g/cm\(^2\)) displaced by the ion chamber is calculated. The dependence of the displaced material on the radiation path in the ion chamber is taken into account by weighting the displaced material along each path by the path length in the cavity, and averaging over all the path lengths in this cavity, assuming that the incident radiation is parallel. Cylindrical and spherical symmetry of the chamber can be taken into account. These calculations should correlate with replacement. The calculation, however, can also be modified to determine the missing phantom material when the space occupied by the chamber is filled with air and should correlate with displacement. The results of such calculations are shown in Tables III and IV.

Experimentally, a \(^{60}\text{Co}\) \(\gamma\)-ray beam 10 cm \(\times\) 10 cm at 80 cm SSD was used. The percentage depth dose curve and \((\text{TAR})_{0.5\text{cm}}\) were very carefully measured using ion chambers and thermoluminescent dosimetry. The depth-dose was found to agree very closely with published results [12] and the \((\text{TAR})_{0.5\text{cm}}\) was found to be 1.035, again in close agreement with the published result of 1.036 [12].

For each chamber, the dose on the central axis was measured for depths between 2 cm and 20 cm. Equations (14) and (17), with \(d\), \(d'\) and \(p\) equal to
IAEA-SM-222/20

25 MV X-Ray
10 x 10 cm² Field Size
SSD = 100 cm

unity, were used to calculate the dose, which was then compared with the dose obtained using Eq. (13), the standard depth dose tables being used to obtain the dose at a given depth. For any particular chamber, the ratios were constant with depth, and so the average value for all depths was used. For each chamber, the experiment was repeated at least three times.

Figure 7 shows the results of such measurements. The spread in the data indicates the difficulty of doing those experiments, but the trends are quite clear. For the chambers used as Bragg-Gray cavities, the reciprocal of the ordinate gives the replacement factor, d. For the chamber used as an exposure meter, the reciprocal gives the displacement factor, d'.

Using the average slope and the computed missing phantom material for each chamber, displacement and replacement factors have been computed and are listed in Table V. Also listed are the factors (1/Kwall) and the product of (1/Kwall) times the replacement factors, which should be numerically very close to the displacement factor. In most cases, this was the case, except for two chambers, the Shonka 3 cm³ and X-Radin AE, made of air-equivalent plastic.
In no instance was the value of displacement or replacement times \((1/K_{\text{wall}})\) equal to 0.985, the value currently in use. It is therefore not surprising that differences between calibrations in air and in phantoms have been found for \(^{60}\text{Co}\) calibrations and that this difference was as large as 3%.

5. HIGH-ENERGY X-RAYS

Experiments were also done with 25 MV X-rays (Fig. 8). In this case, since no measurements in air could be done, results (using the Bragg-Gray approach) were normalized to the response for the Farmer chamber. The slope indicates a 2.0% replacement factor per 1 cm of missing phantom material.

6. CONCLUSIONS

A number of different situations can be considered for determination of absorbed dose. For the calibration energy of \(^{60}\text{Co}\) gamma rays:

\[
\alpha = \beta = 0
\]  

(18)

Therefore, Eq. (2) reduces to:

\[
D_{\text{water}} = M_{\text{c}} \cdot N_{\text{c}} \cdot \frac{1}{K_{\text{wall}}} \cdot \left(\frac{\mu_{\text{en}}}{\rho}\right)_{\text{water}} \cdot d' \cdot p
\]  

(19)

and is independent of the wall material. As pointed out above, most protocols and handbooks take the equation to be:

\[
D_{\text{water}} = M_{\text{c}} \cdot N_{\text{c}} \cdot \left(\frac{\mu_{\text{en}}}{\rho}\right)_{\text{water}} \times 0.985
\]  

(20)

But from Table V, it can be seen that \(d' (K_{\text{wall}})^{-1}\) varies from 0.978 to 0.929 for the chambers we used, resulting in uncertainties of 1% to 6%.

If the chambers had been used as exposure meters, then:

\[
D_{\text{water, c}} = M_{\text{c}} \cdot N_{\text{c}} \cdot \left(\frac{\mu_{\text{en}}}{\rho}\right)_{\text{water}} \cdot d' \cdot p
\]  

(21)

But \(d'\) varied between 0.973 and 0.944, resulting in uncertainties of 1.2% to 4%.
6.1. Higher X-ray energies

For higher energy X-rays, a correction for the chamber wall must be applied, as indicated in Figure 5 for air-equivalent chambers; this factor is a function of energy. Corrections also have to be made for the variation from 0.985 of \( d \cdot (K_{\text{wall}})^{-1} \). Fortunately, these two factors tend to offset each other and, for most cases above 4 MV X-rays, the overall correction is only about 1%.

A correction should be applied for electron beams if the chamber wall is tissue- or water-equivalent. The difference between an air chamber and a tissue chamber is 2.5%.

In clinical situations, the current recommendations in handbooks and protocols should be followed and changes should not be made until new official recommendations are published. The above discussion is given, however, to indicate that, when using commercially available chambers in the recommended manner and with the standard factors, differences in the calculated absorbed dose of several percentage points can be observed. Fortunately these differences do not appear to be large, up to 4%; in the future, however, handbooks and protocols should take the chamber-dependent factors into account.

REFERENCES


DISCUSSION

Y. NISHIWAKI: In your paper you give a number of commercial names for the chambers used in the USA which are sometimes difficult for participants from other countries to understand. May I ask you, for clarification, whether the tissue-equivalent or air-equivalent plastics listed under different commercial names are different types of plastic or the same plastic?

P.R. ALMOND: All the commercial tissue-equivalent plastics used in our work were Shonka A150.

A.O. FREGENE: You are right to take wall thickness into account in your treatment, and to allow for wall material and composition. However, in Eq. (13) of your Ref. [10] an expression is given for \( D_{\text{water},E} \) which fails to do this:

\[
D_{\text{water},E} = M_E \cdot N_c \cdot \left( \frac{W}{e} \right) \cdot A_{eq} \cdot \left( \frac{S}{\rho} \right)_{\text{water}} \cdot d \cdot p
\]

This cannot therefore give correct results for electrons.

P.R. ALMOND: Any derivation of \( C_\lambda \) or \( C_E \)-factors must include factors that take into account the effect of the wall material at the calibration energy, and this must be done through mass energy absorption coefficients. If chamber-independent \( C_u \)-factors are used, then the effect must be taken into account in the chamber-dependent part, and \( C_u \) will be essentially just stopping power ratios.

The equation you mention is for calculating the dose in water when an air-equivalent chamber is used. In the same paper we give an equation to be applied when the chamber wall is tissue-equivalent.

All the derivations so far are correct, including those of ICRU Reports 14 and 21, which are often quoted as being inconsistent, but the basic assumptions are different and these must be specified; that is, it must be stated whether the chamber is water-equivalent or air-equivalent.
A.O. FREGENE: Your paper contains a statement that as long as one takes measurements at maximum depth (0.5 cm) with the cap on, the determination of absorbed dose is independent of the chamber size and constructional material of the chamber and build-up cap. This statement is not reconcilable with what you say in the first part of your paper.

P.R. ALMOND: Such an assumption is valid only when the absorbed dose is calculated from the exposure in free air. When an ionization chamber is used as an exposure meter, the structure and material of the chamber is not taken into account because of the way the exposure calibration factors are derived. The exposure is determined in the absence of the chamber and all that is required is the chamber response relative to that exposure.

A.O. FREGENE: The cavity displacement factor of 0.985 given by ICRU in respect of a particular cavity size and shape and depth for $^{60}$Co would appear to be correct. However, your cavity displacements, presented for different sizes and shapes of cavities and for differing materials, and plotted graphically (displacement versus volume), do not seem to be altogether satisfactory.

P.R. ALMOND: In our work, spherical and cylindrical symmetry have been taken into account.
A SIMPLE METHOD OF ENERGY DETERMINATION FOR ELECTRON ACCELERATORS USED IN MEDICINE

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Abstract

A SIMPLE METHOD OF ENERGY DETERMINATION FOR ELECTRON ACCELERATORS USED IN MEDICINE.

Electron accelerators operating in the energy range of 5 to 50 MeV may be used for therapeutic purposes. ICRU has published suggestions for making energy calibrations for such accelerators — a necessary routine procedure at clinical installations. A simple method, but as yet rarely used, is based on the Cerenkov effect in gases. The method is described and its practical application discussed. Corrections to and errors in the energy determination are considered.

1. INTRODUCTION

A necessary routine procedure with clinically used electron accelerators is energy calibration. Several methods of undertaking this have been proposed in ICRU Report 21 [1]. A simple and inexpensive method, capable of covering a wide range of energies — from 15 MeV to 45 MeV, is based on the Cerenkov effect in gases, a method already considered by a number of authors [1—7].

2. EXPERIMENTAL ARRANGEMENT

The experimental arrangement is shown in Fig.1. The electron beam of the accelerator passes through a collimator, a thin walled transmission-type of monitor ionization chamber and then enters the gas filled Cerenkov detector pipe. A mirror at 45° to the incident beam deflects the light to an eleven-stage photomultiplier tube. The pipe has a length of about 1 m and a diameter of 10 cm. Shielding with about 10 cm of lead is necessary to protect the multiplier
FIG. 1. Experimental arrangement for the energy determination using the Cerenkov effect. 1: Betatron; 2: Cerenkov detector; 3: Mirror; 4: Monitor ionization chamber; 5: Lead shield; 6: Photomultiplier; 7: Beam entrance window; 8: Perspex window; 9: Perspex and lead collimator. All dimensions are in millimetres.

from background radiation. A more detailed description of the experimental arrangement has been published [7].

If a charged particle traverses a transparent medium with a speed \( v \) greater than the velocity of light in that medium, \( c/n \), Cerenkov radiation of intensity \( I \) will be emitted:

\[
I = A \left(1 - \frac{1}{\beta^2 n^2}\right) \Phi
\]

(1)

where \( \beta (= v/c) \) is the ratio between the particle velocity and the speed of light in vacuo, \( n \) is the refractive index of the medium, \( \Phi \) is the electron fluence, and \( A \) is a characteristic constant for the experimental set-up. Cerenkov light is emitted if the term in parentheses \( (1 - (1/\beta^2 n^2)) \) is greater than zero or if the threshold at:

\[
\beta = 1/n
\]

(2)
Fig. 2. Cerenkov light yield in air and methane as a function of gas pressure for a fixed electron energy, $E$, of 24 MeV (temperature, $T = 297.6 \pm 0.1$ K).

has been passed. In a gaseous medium, the refractive index $n$ is a well-known function of the parameters pressure ($p$), absolute temperature ($T$) and wavelength ($\lambda$) [8, 9]:

$$n - 1 = (n_0 (\lambda) - 1) \frac{T_0}{p_0} \frac{p}{T}$$

For a given electron energy and a corresponding $\beta$, the threshold condition of Eq.(2) can easily be obtained by varying the pressure. For a typical measurement,
FIG. 3. Threshold energies for air and methane as a function of pressure, using an AVP 153 photomultiplier ($T = 296.6 \, K$).

FIG. 4. The influence of different variables on the total uncertainty of the energy determination (Cerenkov tube length, 30 cm).
the Cerenkov light intensity (in relative units) is shown as a function of gas pressure in Fig.2. The thresholds for a given electron energy but for two different gases, air and methane, have been plotted. Starting at low pressures, there is only the dark current of the photomultiplier and a background-radiation component. Exact extrapolation of the threshold value is facilitated by the fact that the beginning of the curve, after the threshold, is a straight line — to a very good approximation. Figure 3 shows the calculated threshold energy, $E_t$, as a function of pressure for air and methane. For air we determined a simple-fit formula:

$$E_t = 34.437 \left( \frac{p}{T} \right)^{-0.5104}$$

(4)

where the energy is determined in MeV when the pressure, $p$, is in torr and the temperature, $T$, is in kelvin.

3. CORRECTIONS

Various factors influence the accuracy of the energy determination. The uncertainties have been described in detail elsewhere [7]; they are summarized in Fig.4, where the total relative uncertainty in energy has been plotted as a function of electron energy. Curve (a) has a pronounced minimum at 25 MeV. In the energy range between 14 and 45 MeV, the total uncertainty for the energy determination can be kept below 1%.

Curve (a) comprises a number of contributions that are discussed below.

3.1. Energy loss in the gas and in the entrance foil of the Cerenkov tube

Because of the thinness of the entrance foil, the influence of the energy loss in the foil is negligible compared with the energy loss in the gas. The curve plotted in Fig.4 corresponds to a pipe length of only 30 cm; in our case, using a pipe length of about 1 m, the loss would be some three times greater.

3.2. Dependence of the energy determination on the accuracy of pressure and temperature determinations

The temperature in the gas during the measurement can easily be kept constant to ± 1 K; the corresponding energy resolution, curve (d), is constant over the whole energy range. Care must be taken to avoid temperature changes resulting from rapid pressure variations.
Experimentally we have found that the threshold pressure readings of many independent runs differed by \( \pm 1 \) torr; curve (c) shows the influence of this pressure variation on the accuracy of the energy determination.

3.3. Corrections due to water vapour in the filling gas

To avoid this error, we recommend that commercially available compressed gases, taken from cylinders, be used.

3.4. Dependence of the energy determination on the photomultiplier spectral sensitivity

For a precise energy determination, not only the factors considered in §§3.1–3.3 have to be considered, but the spectral sensitivity of the photomultiplier also.
It is usually assumed in calculations of the electron energy that the photomultiplier is only sensitive to one single wavelength, i.e. the maximum of the sensitivity curve of the photomultiplier. This ignores the fact that a photomultiplier cathode has a rather wide spectral sensitivity range. Figure 5 shows the quantum efficiency $S(\lambda)$ for an S-11 cathode in an AVP 153 PM tube. The sensitivity of the quantum efficiency curve ranges from about 300 nm to 640 nm, with a maximum at 400 nm. Accordingly, the simple equation for the Cerenkov light yield, Eq.(1), has to be replaced by an integral form:

$$ I = A \Phi \int_{\lambda_1}^{\lambda_2} \frac{S^*(\lambda)}{\lambda^2} \left( 1 - \frac{1}{\beta^2 [n(\lambda)]^2} \right) d\lambda \quad (5) $$

where $\lambda$ is the wavelength, $\beta = v/c$, and $n(\lambda)$ the wavelength-dependent refractive index of the gas. The integral has to be extended over the whole spectral sensitivity range of the photomultiplier. Further, the quantum efficiency $S(\lambda)$ has to be folded with the optical transmission $T(\lambda)$ of the Perspex window (see Fig.1) to obtain the net quantum efficiency function for the experiment, $S^*(\lambda)$:

$$ S^*(\lambda) = S(\lambda) \cdot T(\lambda) \quad (6) $$

The transmission curve of Perspex has a sharp cut-off at 380 nm, which strongly depends on the manufacturer (see Jelly [10]). We have performed a numerical integration of Eq.(5) with the aid of Simpson's rule. As a result of these integrations, for a given electron energy, $E$, we found there to be a linear dependence of light intensity on gas pressure after the threshold, which is in good agreement with the experimental findings (see Fig.2).

The corresponding threshold pressure, $p$, has been calculated by a least-squares fit. To check the validity of Eq.(4), derived from the simpler Eq.(1), we inserted the calculated threshold pressure into Eq.(5) and obtained a threshold energy, $E_t$, somewhat different from the energy, $E$, assumed for the calculation. The difference $(E_t - E)/E$ has been plotted as curve (a) in Fig.6 as a function of the energy, $E$. In the energy range between 20 and 55 MeV the correction is $< \pm 0.3\%$ for air. This result shows that the simpler Eq.(1) can be used, with our experimental arrangement, instead of that involving a complex integration, inserting the refractive index for a wavelength of 420 nm.

So far we have checked the validity of Eq.(1) for our particular arrangement (photomultiplier, air, Perspex window). In order to have generally definable conditions, we propose that suitable optical filters having a narrow pass bandwidth in the range of the maximum of the sensitivity of the photomultiplier be
used. We therefore also performed experiments with a filter for \( \lambda = 418 \text{ nm} \) (half-width 13 nm, transmission 40\%) placed in front of the multiplier window. The use of this filter did not change our original results, except that the light intensity decreased appreciably — by a factor of 25.

A similar numerical integration procedure to that described above yielded a curve shown as (b) in Fig. 6. Using an optical filter with a narrow bandwidth, the energy determination will not be affected by the sensitivity of the photomultiplier cathode (cathode type, changes with time) or by the transmission of the Perspex window.

4. INTERCOMPARISON OF THE RESULTS FOR METHANE AND AIR

As a first check that the results for methane and air are consistent, we measured the threshold for both gases with the same energy setting of the accelerator. The results are plotted in Fig. 2. The mean value of eight measurements for these thresholds are \( p_{\text{air}} = 619 \text{ torr} \) and \( p_{\text{CH}_4} = 407 \text{ torr} \). According to the theory expressed by Eq. (3), we find the correlation:

\[
\frac{p_{\text{air}}}{p_{\text{CH}_4}} = \frac{(n_0 - 1)_{\text{CH}_4}}{(n_0 - 1)_{\text{air}}}
\]
Experimentally, we obtained for the left-hand side, $p_{\text{air}}/p_{\text{CH}_4} = 1.521$. This is in good agreement with the calculated value of 1.520 for the right-hand side. The refractive indices have been evaluated for $\lambda = 420$ nm.

5. COMPARISON WITH OTHER METHODS

The "MeV-meter" of the betatron has been calibrated independently using the energy-range relation and using the activation threshold method over the range from 10 to 31 MeV. Over this range the energy determinations obtained with the Cerenkov method differed by less than $\pm 1.5\%$ from the values read from the MeV-meter.

More exact energy comparisons with results from a magnetic spectrometer system will be performed in near future. We also aim to investigate the influence of the spectrum shape on the accuracy of the energy determination.

REFERENCES


DISCUSSION

H. SVENSSON: You have a linear part in the curve when you increase the pressure over that of the threshold. If you have a beam with an energy spread, the light output increase should be supralinear. Have you considered this problem, and can you comment on the possibility of using this first part of the curve to analyse the energy spread?
H. LIESEM: The first part of the curve after the threshold is, of course, correlated with the energy spectrum of the electrons. An analysis is difficult because of the sensitivity of the photomultiplier and the energy loss in the Cerenkov tube. Since we find the threshold pressure by extrapolation, the shape of the curve in the vicinity of the threshold is of no importance for the determination of the (mean) electron energy.
EFFET DU RAYONNEMENT DIFFUSE SUR LE RAPPORT DES DOSES ABSORBÉES DERIVÉES DE MESURES D’IONISATION ET OBTENUES PAR DOSIMÈTRE DE FRICKE

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Abstract–Résumé

EFFECT OF DIFFUSE RADIATION ON THE RATIOS OF ABSORBED DOSES DERIVED FROM IONIZATION MEASUREMENTS AND THOSE OBTAINED BY FRICKE DOSIMETRY.

An NPL secondary standard chamber (type NE-2561), two 0.6 cm$^3$ Baldwin chambers (type NE-2505/3) and a Baldwin soft X-ray chamber (type NE-2536/3) were irradiated in Plexiglas and in water with Fricke dose meters from the National Physical Laboratory (NPL), Teddington, and from the laboratory where this work has been carried out. Within the experimental margins of error, no effect of field size or of depth in Plexiglas or in water on the absorbed dose ratios derived from measurements with both types of dose meter was found. Nevertheless, when the contribution of backscattered radiation to the absorbed dose at the point of measurement is removed, these absorbed dose ratios decrease by about 4% to 4.8% as the field size increases. Comparison of the absorbed dose ratios obtained with and without backscattered radiation shows that this secondary radiation component is responsible, with increasing field size, for a progressive increase in the ratios of the absorbed doses derived from measurements with Baldwin and NPL chambers and those obtained by ferrous sulphate dosimetry; when the soft X-ray chamber is used, the absorbed dose ratios vary differently. The study shows that, merely by increasing the number of measurements taken, it is possible, with the limited means available in a radiotherapy department, to define a correction factor for an ionization chamber with an accuracy better than 1%, and to specify its limits of validity.

EFFET DU RAYONNEMENT DIFFUSE SUR LE RAPPORT DES DOSES ABSORBÉES DERIVÉES DE MESURES D’IONISATION ET OBTENUES PAR DOSIMÈTRE DE FRICKE.

Une chambre étalon secondaire NPL (type NE-2561), deux chambres Baldwin de 0,6 cm$^3$ (type NE-2505/3), et une chambre Baldwin pour rayons X mous (type NE-2536/3) ont été irradiées dans le plexiglas et dans l’eau avec des dosimètres de Fricke du National Physical Laboratory (NPL) de Teddington et du laboratoire où ce travail a été effectué. Aux erreurs expérimentales près de ce travail, aucun effet des dimensions de champ ou de la profondeur dans le plexiglas ou l’eau n’est mis en évidence sur les rapports de doses absorbées déduites des mesures par ces deux types de dosimètres. Toutefois, lorsque la contribution du rayonnement rétrodiffusé à la dose absorbée au point de mesure est éliminée, les rapports de ces doses absorbées diminuent d’environ 4 à 4,8% à mesure qu’augmentent les dimensions du champ.
La comparaison des rapports de doses absorbées obtenues avec et sans rayonnement rétrodiffusé montre que cette composante de rayonnement secondaire est responsable, à mesure qu'augmentent les dimensions du champ, d'un accroissement progressif des rapports des doses absorbées dérivées de mesures par chambres Baldwin et NPL et obtenues par dosimètre en sulfate ferreux; lorsque la chambre à rayons X mous fournit les mesures d'ionisation, la variation des rapports de dose absorbée est différente. Ce travail montre qu'avec les moyens disponibles restreints d'un service de radiothérapie il est possible de préciser à mieux de 1%, en répétant davantage les mesures, un facteur de correction d'une chambre d'ionisation et d'en déterminer les limites de validité.

1. INTRODUCTION

Les contrôles dosimétriques réguliers nécessaires dans un service de radiothérapie visent la comparaison entre la réponse des chambres d'ionisation utilisées pour la surveillance de la routine des irradiations cliniques ainsi que pour des expériences de mise au point de traitements, et la réponse d'un dosimètre de référence. Ce dosimètre de référence est encore bien souvent un dosimètre à chambre d'ionisation, tel un étalon secondaire du National Physical Laboratory de Londres, étalonné en exposition; maintes comparaisons à un niveau international ou entre institutions font un usage développé du dosimètre de Fricke au sulfate ferreux. La comparaison dosimétrique dans un service de radiothérapie bénéficie avantageusement d'un faisceau de radiations stable et reproductible, tel un faisceau de rayons gamma de $^{60}$Co.

Ces comparaisons dosimétriques se heurtent à deux problèmes:

a) l'étalonnage des chambres est réalisé en exposition alors que l'effet biologique est directement lié à la dose absorbée;

b) le spectre d'énergie des photons d'un faisceau de rayons gamma de $^{60}$Co n'est pas identique dans l'air libre et au sein d'un milieu diffusant comme l'eau, le plexiglas ou le polystyrène, ainsi que le montrent les travaux de Guiho et al. [1] et de Jessen [2].

Il est bien connu que l'intensité des photons diffusés sur l'axe du faisceau dépend de la section de ce faisceau (ou de la dimension du champ d'irradiation), ou mieux du volume irradié de milieu diffusant (Faw et Glenn [3]): Weiss et Rizzo [4] ont rapporté qu'à 15 cm de profondeur dans l'eau irradiée par les rayons gamma du $^{60}$Co, niveau où le rendement est de l'ordre de 1/3, près de la moitié de la dose absorbée peut être due à des photons diffusés.

Quant à la forme du spectre d'énergie des photons diffusés, elle se modifie progressivement avec la profondeur atteinte par le faisceau dans l'eau: Goldstein et Wilkins [5] ont montré qu'en deçà de 15,5 cm, une composante de photons de faible énergie présentant une intensité maximale vers 70 keV se forme progressivement avec un faisceau de photons de 1 MeV issus d'une source ponctuelle isotrope.
Alors que Guiho [6] a pu préciser l'énergie effective des photons de faisceaux de $^{60}\text{Co}$ et $^{137}\text{Cs}$ soigneusement étudiés au Laboratoire de mesure des rayonnements ionisants à Saclay et, par conséquent, établir avec plus de rigueur les facteurs de conversion de l'exposition en dose absorbée pour ces faisceaux, nous ne pouvions, à notre niveau, dans l'ignorance des spectres d'énergie des photons composant le faisceau utilisé de rayons gamma de $^{60}\text{Co}$ dans l'air et dans le milieu diffusant, que prendre la convention d'adopter tout au long le facteur de conversion de l'exposition en dose absorbée relatif aux photons de 1,25 MeV. Encore sommes-nous conscients que de tels facteurs de conversion ont été obtenus avec des faisceaux de rayons gamma de $^{60}\text{Co}$ comportant des composantes plus ou moins importantes de photons dégradés.

La disponibilité relativement restreinte de l'installation d'irradiation, jointe aux durées assez longues d'irradiation requises des dosimètres de Fricke, n'a pas permis de répéter suffisamment les mesures pour leur affecter une précision statistique valable. Nous nous bornerons à signaler, à titre indicatif, à propos de chaque ensemble de mesures, l'intervalle total de variation en pourcents de la moyenne arithmétique ainsi que cette moyenne.

Le but de ce travail ne visant que l'évolution éventuelle des rapports en cause de doses absorbées en fonction de deux paramètres d'irradiation, il ne nous a pas paru indispensable de préciser, pour les dosimètres de Fricke, le rapport de la dose centrale à la dose moyenne, le facteur d'atténuation du tube de verre, l'effet de paroi de ce tube, la correction pour manque de diffusion à partir du volume d'air, ainsi que, pour les chambres d'ionisation, les facteurs de correction pour recombinaison des ions et pour non-linéarité de la réponse. En première approximation, nous pouvons adopter les coefficients définis par Day et Rasoul [7]; les produits des facteurs relatifs d'une part au tube de solution ferreuse, et d'autre part aux chambres, sont égaux à l'unité ou très proches de celle-ci à 0,1% près.

2. TRAVAIL EXPERIMENTAL

Le faisceau exploité de rayons gamma de $^{60}\text{Co}$ est issu d'un appareil Picker C8M/80 muni d'un diaphragme permettant d'obtenir des champs d'irradiation de $40 \times 40 \text{ cm}$ à $80 \text{ cm}$ de la source.

2.1. Plan

Nous avons proposé de:

a) comparer la réponse de chambres d'ionisation Baldwin (type NE-2505/3) de 0,6 cm$^3$ avec celle de l'étalon secondaire du NPL dans des conditions expérimentales apportant aux points de mesure une contribution aussi faible que possible
**FIG. 1.** Dispositif expérimental choisi pour la comparaison des chambres d'ionisation en exposition.

**TABLEAU I. RAPPORTS DES EXPOSITIONS X MESURÉES PAR CHAMBRE D'IONISATION BALDWIN (n° 454 et n° 1112) ET PAR CHAMBRE NPL, POUR 4 DIMENSIONS DE CHAMP CARRE**

<table>
<thead>
<tr>
<th>Côté du champ carré (cm)</th>
<th>X ch. Baldwin 454 X ch. NPL</th>
<th>X ch. Baldwin 1112 X ch. NPL</th>
</tr>
</thead>
<tbody>
<tr>
<td>11,4</td>
<td>1,007</td>
<td>1,015</td>
</tr>
<tr>
<td>14</td>
<td>1,005</td>
<td>1,018</td>
</tr>
<tr>
<td>20</td>
<td>1,007</td>
<td>1,015</td>
</tr>
<tr>
<td>28,6</td>
<td>1,003</td>
<td>1,023</td>
</tr>
</tbody>
</table>

1,005 (5) ← Moyenne → 1,023
0,4% ← Plage de variation → 1,8%
du rayonnement diffusé, selon nos moyens propres dans le service pour une bonne reproductibilité;

b) comparer la réponse des mêmes chambres ainsi que d'une chambre Nuclear Enterprises à parois plan parallèles de 0,3 cm³ (NE-2536/3) pour rayons X mous et celle du dosimètre de Fricke du NPL dans le fantôme d’eau recommandé par le NPL\(^1\) ainsi que du dosimètre de Fricke de notre laboratoire dans une masse de plexiglas\(^2\);

c) essayer de déterminer l’importance de l’influence des photons diffusés sur la comparaison des réponses des chambres d’ionisation et du dosimètre de Fricke.

2.2. Comparaison des chambres d’ionisation dans l’air

Une plaque de polystyrène de 21 X 21 cm, épaisse de 2 cm, reçoit bout à bout la chambre NPL et une chambre Baldwin (soit n° 454, soit n° 1112) de sorte que les axes des chambres se situent dans le plan médian de la plaque et les extrémités des chambres soient séparées de 3 mm l’une de l’autre, l’axe du faisceau passant par le milieu de cette séparation.

La surface de la plaque est disposée à 1 m de la source; la plaque repose à ses bords sur deux blocs de plexiglas de 10 cm d’épaisseur.

Les champs d’irradiation sont des carrés de 11,4, 14, 20 et 28,6 cm de côté (les axes des chambres sont disposés selon les médianes des carrés) (fig.1).

Les rapports des expositions X mesurées par une chambre Baldwin et par la chambre NPL sont donnés par le tableau I: il ne s’en dégage pas d’influence de la surface du champ.

2.3. Comparaison des doses absorbées dérivées de mesures d’ionisation et obtenues par dosimètre de Fricke

2.3.1. Nous nous sommes servi du dosimètre de Fricke du NPL, ainsi que de tubes à essai de pyrex d’un diamètre extérieur de 15,6 mm et d’épaisseur de 1 mm contenant 6 cm³ de solution ferreuse.

Nous avons utilisé le dosimètre de Fricke du NPL et irradié ce dosimètre et les chambres dans le fantôme d’eau recommandé par le NPL.

Pour cette expérimentation, nous employons les chambres utilisées précédemment et une chambre Nuclear Enterprises pour rayons X mous de 0,3 cm³ type NE-2536/3. Le point de mesure est défini sur l’axe des chambres cylindriques.

\(^1\) Dimensions du fantôme NPL: surface d’entrée 25,4 X 25,4 cm, épaisseur totale 26 cm.
\(^2\) Présentant au faisceau une surface de 20 X 20 cm.
TABLEAU II. RAPPORTS DES DOSES ABSORBEES DERIVEES DE MESURES D'IONISATION ET OBTENUES PAR DOSIMETRE DE FRICKE DANS LE DISPOSITIF EXPERIMENTAL DE LA FIGURE 2 POUR 3 DIMENSIONS DE CHAMP ET 5 PROFONDEURS DANS L'EAU

*Distance source-surface de la cuve d'eau: 70 cm*

<table>
<thead>
<tr>
<th>Côté du champ carré (cm)</th>
<th>Profondeur dans l'eau (cm)</th>
<th>Moyenne</th>
<th>Plage de variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>D ch. NPL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0,998</td>
<td>1,003</td>
<td>1,018</td>
</tr>
<tr>
<td>14</td>
<td>0,9985</td>
<td>1,004</td>
<td>1,013</td>
</tr>
<tr>
<td>20</td>
<td>0,997</td>
<td>1,001</td>
<td>-</td>
</tr>
<tr>
<td>D Fricke NPL</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>1,010</td>
<td>1,012</td>
<td>1,014</td>
</tr>
<tr>
<td>14</td>
<td>1,009</td>
<td>1,009</td>
<td>-</td>
</tr>
<tr>
<td>20</td>
<td>1,008</td>
<td>1,014</td>
<td>-</td>
</tr>
<tr>
<td>D ch. rX mous</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>-</td>
<td>1,003</td>
<td>1,011 (5)</td>
</tr>
<tr>
<td>14</td>
<td>0,995</td>
<td>1,004 (5)</td>
<td>-</td>
</tr>
<tr>
<td>20</td>
<td>0,994</td>
<td>1,001</td>
<td>-</td>
</tr>
<tr>
<td>D ch. Bald. 454</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>1,001</td>
<td>0,986</td>
<td>1,013</td>
</tr>
<tr>
<td>14</td>
<td>0,992</td>
<td>1,000</td>
<td>-</td>
</tr>
<tr>
<td>20</td>
<td>0,989</td>
<td>0,995</td>
<td>-</td>
</tr>
<tr>
<td>D ch. Bald. 1112</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>-</td>
<td>1,003</td>
<td>1,011 (5)</td>
</tr>
<tr>
<td>14</td>
<td>0,995</td>
<td>1,004 (5)</td>
<td>-</td>
</tr>
<tr>
<td>20</td>
<td>0,994</td>
<td>1,001</td>
<td>-</td>
</tr>
</tbody>
</table>
et des ampoules de solution ferreuse ainsi qu'à mi-épaisseur de la cavité de la chambre à rayons X mous: chambres et ampoules sont ainsi irradiées sur l'axe du faisceau à des profondeurs de 2, 6, 12, 16 et 19 cm.

La surface de la cuve d'eau est placée à 70 cm de la source et au niveau de cette surface les champs choisis sont des carrés de 8, 14 et 20 cm de côté (fig.2).

Pour la conversion de l'exposition en dose absorbée, nous utilisons le coefficient $C_x$ de 0,95 recommandé [8].

Les rapports des doses absorbées ainsi obtenues des mesures d'ionisation et par dosimétrie chimique sont rassemblés dans le tableau II: il ne s'en dégage pas un effet de la dimension de champ ni de la profondeur du point de mesure.

2.3.2. Les tubes à essai contenant la solution ferreuse ont été irradiés dans un bloc de plexiglas de 20 $\times$ 20 cm de masse volumique de 1,18 $\text{g} \cdot \text{cm}^{-2}$ de telle sorte que leur axe se trouvât à 70 cm de la source et en amont d'une épaisseur de 12 cm de plexiglas; des plaques de même surface que le bloc porteur des tubes ont été empilées contre la face d'entrée de ce bloc porteur.

Les champs d'irradiation sont définis à la distance de 70 cm de la source: ce sont à nouveau des carrés de 8, 14 et 20 cm de côté.
TABLEAU III. RAPPORTS DES DOSES ABSORBÉES DERIVÉES DE MESURES D'IONISATION ET OBTENUES PAR DOSIMETRE DE FRICKE DANS LE DISPOSITIF EXPERIMENTAL DE LA FIGURE 3 POUR 3 DIMENSIONS DE CHAMP CARRE ET 3 EPAISSEURS DE PLEXIGLAS

Distance source—axe des dosimètres: 70 cm

<table>
<thead>
<tr>
<th>Côté du champ carré (cm)</th>
<th>Epaisseur du plexiglas (cm)</th>
<th>Moyenne</th>
<th>Plage de variation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
<td>12</td>
<td>19</td>
</tr>
<tr>
<td>D ch. NPL</td>
<td>8</td>
<td>0,997</td>
<td>0,998</td>
</tr>
<tr>
<td>D Fricke</td>
<td>14</td>
<td>1,007</td>
<td>1,011</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0,999</td>
<td></td>
</tr>
<tr>
<td>D ch. rX mous</td>
<td>8</td>
<td>0,997</td>
<td>0,985</td>
</tr>
<tr>
<td>D Fricke</td>
<td>14</td>
<td>1,005</td>
<td>0,995</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0,998</td>
<td></td>
</tr>
<tr>
<td>D ch. Bald. 454</td>
<td>8</td>
<td>0,998</td>
<td>0,993</td>
</tr>
<tr>
<td>D Fricke</td>
<td>14</td>
<td>1,003</td>
<td>1,007</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0,996</td>
<td></td>
</tr>
<tr>
<td>D ch. Bald. 1112</td>
<td>8</td>
<td>1,000</td>
<td>0,994 (5)</td>
</tr>
<tr>
<td>D Fricke</td>
<td>14</td>
<td>1,000</td>
<td>1,004</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>0,991</td>
<td></td>
</tr>
</tbody>
</table>
TABLEAU IV. RAPPORTS DE DOSES ABSORBÉES DÉRIVÉES DE MESURES D'IONISATION OBTENUES PAR DOSIMETRE DE FRICKE À LA PROFONDEUR DE 2 CM DANS L'EAU

Distance source—surface de la cuve: 48 cm

<table>
<thead>
<tr>
<th>Côté du champ carré (cm)</th>
<th>D ch. NPL D Fricke</th>
<th>D ch. rX mous D Fricke</th>
<th>D ch. Bald. 454 D Fricke</th>
<th>D ch. Bald. 1112 D Fricke</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>1,008</td>
<td>1,000</td>
<td>1,004 (5)</td>
<td>1,004 (5)</td>
</tr>
<tr>
<td>10</td>
<td>0,995</td>
<td>0,991</td>
<td>0,998</td>
<td>0,991 (5)</td>
</tr>
<tr>
<td>15,6</td>
<td>0,997</td>
<td>1,007</td>
<td>0,996</td>
<td>1,001</td>
</tr>
<tr>
<td>Moyenne</td>
<td>1,000</td>
<td>0,999</td>
<td>0,996</td>
<td>0,999</td>
</tr>
<tr>
<td>Plage de variation (%)</td>
<td>1,3</td>
<td>1,6</td>
<td>1,7</td>
<td>1,3</td>
</tr>
</tbody>
</table>

Mesures rapportées sous 2.3.1

| Moyenne                 | 0,998                | 1,009                  | 0,994 (5)                | 0,994                    |
| Plage de variation (%)  | 1,5                  | 0,2                    | 1                        | 1,2                      |

Mesures rapportées sous 2.3.2

| Moyenne                 | 1,001                | 1,000                  | 1,001                    | 0,997                    |
| Plage de variation (%)  | 1                    | 0,8                    | 0,7                      | 0,9                      |
TABLEAU V. RAPPORTS DE DOSES ABSORBÉES OBTENUS PAR DOSIMÈTRES PLACÉS SOUS 3 CM DE PLEXIGLAS, SANS MILIEU DIFFUSANT DERrière CEUX-CI  

*Distance source—surface: 48 cm*

<table>
<thead>
<tr>
<th>Côté du champ carré (cm)</th>
<th>D ch. NPL D Fricke</th>
<th>D ch. rX mous D Fricke</th>
<th>D ch. Bald. 454 D Fricke</th>
<th>D ch. Bald. 1112 D Fricke</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>1,010</td>
<td>1,051</td>
<td>1,007</td>
<td>1,012</td>
</tr>
<tr>
<td>10</td>
<td>0,977</td>
<td>1,026</td>
<td>0,973</td>
<td>0,974</td>
</tr>
<tr>
<td>15,6</td>
<td>0,967</td>
<td>1,023</td>
<td>0,967</td>
<td>0,967</td>
</tr>
</tbody>
</table>

Moyenne                  | 0,985              | 1,033                  | 0,982                    | 0,984                     |
Plage de variation (%)    | 4,8                | 2,7                    | 4                        | 4,6                       |
TABLEAU VI. VARIATION DES RAPPORTS DE DOSES ABSORBÉES DUE À LA CONTRIBUTION DU RAYONNEMENT RETRODIFFUSE AU POINT DE MESURE

<table>
<thead>
<tr>
<th>Côté du champ carré (cm)</th>
<th>D ch. NPL</th>
<th>D ch. Bald. 454</th>
<th>D ch. Bald. 1112</th>
<th>D ch. rX mous</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>D Fricke</td>
<td>D Fricke</td>
<td>D Fricke</td>
<td>D Fricke</td>
</tr>
<tr>
<td>6</td>
<td>- 0,002</td>
<td>- 0,002</td>
<td>- 0,007</td>
<td>+ 0,051</td>
</tr>
<tr>
<td>10</td>
<td>+ 0,016</td>
<td>+ 0,014</td>
<td>+ 0,016</td>
<td>+ 0,035</td>
</tr>
<tr>
<td>15,6</td>
<td>+ 0,028</td>
<td>+ 0,027</td>
<td>+ 0,032</td>
<td>+ 0,016</td>
</tr>
</tbody>
</table>

Le point de mesure est défini pour les tubes et les chambres comme précédemment; les épaisseurs utilisées de plexiglas se rapportent à l'épaisseur comprise entre ce point de mesure et la surface d'entrée des plaques empilées sur le bloc porteur des dosimètres: ce sont 2, 12 et 19 cm (fig.3).

Les rapports des doses absorbées dérivées des mesures d'ionisation et obtenues par dosimétrie chimique sont repris au tableau III: ils ne mettent en évidence d'effet ni de la dimension du champ, ni de l'épaisseur du plexiglas surmontant le point de mesure.

2.4. Contribution du rayonnement rétrodiffusé

Nous avons essayé de rechercher si la contribution du rayonnement rétrodiffusé au point de mesure pouvait avoir une influence sur les rapports de doses absorbées dérivées de mesures d'ionisation et obtenues par dosimétrie chimique.

2.4.1. Nous avons d'abord irradié les chambres d'ionisation déjà utilisées et les tubes contenant la solution ferreuse dans le fantôme d'eau recommandé par le NPL: ces dosimètres y sont placés à la profondeur de 2 cm, selon la convention définie ci-avant, et à 50 cm de la source. Les champs d'irradiation sont définis à ce niveau: ce sont des carrés de 6, 10 et 15,6 cm de côté correspondant à peu de choses près aux carrés de 8, 14 et 20 cm de côté déterminés à 70 cm de la source.

Dans ces conditions, nous reproduisons aux erreurs expérimentales près des rapports de doses absorbées dérivées des mesures d'ionisation et obtenues par dosimétrie chimique identiques à ceux que nous avons observés ci-avant.

Ces rapports, leurs plages de variation et leurs moyennes sont rassemblés dans le tableau IV, avec les données analogues obtenues dans les expériences précédentes.

Alors que les plages de variation des rapports n'excèdent pas 1,7% de la valeur moyenne, ces moyennes diffèrent au plus de 1,4—1,5%.
TABLEAU VII. ACCROISSEMENT (en %) DE LA DOSE DUE AU RAYONNEMENT RETRODIFFUSE

<table>
<thead>
<tr>
<th>Côté du champ carré (cm)</th>
<th>Ch. NPL</th>
<th>Ch. Bald. 454</th>
<th>Ch. Bald. 1112</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>2,9</td>
<td>2,9</td>
<td>2,5</td>
</tr>
<tr>
<td>10</td>
<td>4,5</td>
<td>3,8</td>
<td>4,7</td>
</tr>
<tr>
<td>15,6</td>
<td>5,3</td>
<td>4,7</td>
<td>5,6</td>
</tr>
</tbody>
</table>

2.4.2. Nous avons vidé la cuve d’eau tout en déplaçant les dosimètres à 3 cm de profondeur et en gardant du plexiglas entre les dosimètres et la surface de la cuve : ces valeurs des rapports de doses absorbées deviennent celles que reprend le tableau V. Les rapports de doses absorbées obtenus avec les chambres NPL, Baldwin 454 et 1112 présentent systématiquement des moyennes inférieures de 1% et des plages de variation 3 fois supérieures à celles du tableau IV.

Par contre, avec la chambre à rayons X mous, la moyenne des rapports paraît significativement plus élevée de près de 5%.

2.4.3. Le passage des conditions reprises sous 2.4.2 à celles reprises sous 2.4.1, manifestant l’influence du rayonnement rétrodiffusé au point de mesure, se traduit par les variations de rapports de doses absorbées reprises au tableau VI, confirmant les résultats que nous avions obtenus précédemment avec deux autres chambres Baldwin de 0,6 cm³.

La contribution du rayonnement rétrodiffusé à la dose absorbée entraîne une augmentation régulière avec les dimensions du champ des rapports de doses absorbées obtenues par chambres d’ionisation NPL et Baldwin 454 et 1112 et par dosimètre de Fricke; par contre, le surcroît du rayonnement diffusé provoque une diminution régulière avec la dimension du champ des rapports de doses absorbées obtenues par chambres pour rayons X mous et par dosimètre de Fricke.

Nous avons mesuré avec les chambres NPL et Baldwin l’augmentation de la dose due au rayonnement diffusé (tableau VII).

3. CONCLUSIONS

3.1. La comparaison des expositions lues dans l’air par deux chambres d’ionisation ne fait pas apparaître dans les conditions de notre expérience d’effet des dimensions de champ.
3.2. Lorsque nous dérivons les doses absorbées moyennant le facteur constant 
$C_X = 0.95$ des mesures d'ionisation dans un faisceau de rayons gamma de $^{60}$Co issu 
d'une source de radiothérapie, nous ne remarquons pas, aux erreurs expérimentales 
près de notre travail, d'influence des dimensions du champ d'irradiation et de la 
profondeur dans un milieu diffusant, sur les rapports de doses absorbées dérivées 
des mesures d'ionisation et obtenues par dosimétrie au sulfate ferreux.

3.3. Lorsque le point de mesure choisi pour la comparaison dosimétrique ne 
bénéficie pas entièrement de la composante de rayonnement rétrodiffusé qu'il 
trouverait dans un milieu diffusant condensé, nous observons une diminution des 
rapports de doses absorbées dérivées de mesures par chambres NPL ou Baldwin de 
0,6 $\text{cm}^3$ et par dosimètre de Fricke de l'ordre de 4 à 4,8% à mesure qu'augmentent 
les dimensions de champ.

3.4. La comparaison des rapports de dose absorbée obtenus avec et sans rayonne-
ment rétrodiffusé montre que cette composante (d'intensité augmentant avec les 
dimensions du champ) entraîne, à mesure qu'augmentent les dimensions du champ, 
un accroissement progressif des rapports des doses absorbées dérivées de mesures 
par chambre Baldwin et NPL et obtenues par dosimétrie au sulfate ferreux. 

Par contre, ce supplément de rayonnement rétrodiffusé provoque, pour des 
champs relativement faibles, un accroissement de 5% du rapport des doses 
absorbées dérivées de mesures par chambre pour rayons X mous et obtenues par 
dosimètre de Fricke; cet accroissement diminue quand augmentent les dimensions 
du champ.

Si une chambre est utilisée pour des irradiations thérapeutiques avec un 
facteur de correction résultant d'une comparaison avec le dosimètre de Fricke dans 
un porte-dosimètre peu épais, il pourrait en résulter une erreur allant jusqu'à 3,2% 
selon la dimension du champ.

3.5. Les résultats obtenus dans ce travail avec un nombre relativement restreint de 
mesures indiquent qu'il est possible dans le cadre d'un service de radiothérapie et 
avec des moyens disponibles restreints de préciser un facteur de correction d'une 
chambre d'ionisation à mieux de 1% en répétant davantage les mesures et en 
faissant intervenir toutes les corrections d'usage [7] et d'en déterminer les limites 
de validité.

**REMERCIEMENTS**

Ce travail a été mené à bien grâce à la collaboration technique de 
MM. H. Fraikin, A. Hubert, J. Breyre, A. Martial et Chr. Delfosse.
REFERENCES


[3] FAW, F., GLENN, D., «Dose distributions if the field is larger than the patient», Digest 3rd Int. Conf. on Medical Physics, Including Medical Engineering (Göteborg, 1972), communication 34.8.


DISCUSSION

M.N. VARMA: In ionization chamber absorbed-dose measurements I think you should apply an appropriate correction for the variation of $\bar{W}$ with energy, similar to the correction to the G-value that you have applied for dose determination by Fricke dose meter.

J.L. GARSOU: The variations in the absorbed dose ratios due to the contribution of backscattered radiation when passing from the measurement point conditions described in §2.4.2 to those indicated in §2.4.1 are also dealt with in Table VI; I should like to attempt at least a qualitative explanation.

When a thimble chamber provides the ionization measurements, the absorbed dose ratio increases with field size; on the other hand, when a soft X-ray chamber is used to measure ionization, the absorbed dose ratio decreases.

The absorbed dose measured by Fricke dose meter is proportional to G$^{-1}$. Let the absorbed dose derived from the ionization measurements be proportional to what we may call the “response” of the chamber in the medium, according to cavity theory. The ratio of the absorbed doses derived from the ionization measurements to those given by the FeSO$_4$ dose meter will be proportional to the product of this chamber response and G.

It is well known that G increases as a function of photon energy: the G-value for backscattered radiation is lower than that for primary radiation. Let us call
the difference between the G-values for primary and scattered radiation $\Delta G$ (e.g. let $\Delta G$ equal 3 for photon energies of 1.25 keV and 5 keV, to keep a clear picture, Fig.A).

If, in relation to 1.25 MeV photons, the chamber responses increase when the photon energy is reduced, and if the thimble chamber response shows a greater increase than the soft X-ray chamber, the difference in "response", $\Delta_{\text{response}}$, for primary and scattered photons will thus be greater for the thimble chamber than for the soft X-ray chamber (Fig.A).

The greater difference in response to primary and scattered radiation of the thimble chamber as compared with the variation in the G-value explains the increase observed in absorbed dose ratios with field size when the thimble chamber is used for ionometric measurements. The smaller difference in response of the soft X-ray chamber as compared with the variation in the G-value explains the

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**FIG.A. Variation of chamber "response" and G-value with energy.**
reduction observed in absorbed dose ratio with field size when this chamber provides the ionization measurements.

H. REICH: The application of the Fricke chemical dose meter method at energies below that of $^{60}$Co is of questionable value when you are looking for effects of the order of a few per cent. What uncertainty do you attribute (a) to the G-value and (b) to the chemical method as a whole, at energies below that of $^{60}$Co?

J.L. GARSOU: I have used the values given in the literature, together with the quoted uncertainties. I have not myself used the Fricke dose meter at energies below the energy of $^{60}$Co gamma rays.
DISCREPANCIES IN MOLAR EXTINCTION COEFFICIENTS OF Fe$^{3+}$ IN FRICKE DOSIMETRY*

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Abstract

DISCREPANCIES IN MOLAR EXTINCTION COEFFICIENTS OF Fe$^{3+}$ IN FRICKE DOSIMETRY.

Values of the chemical yield, G, and of the molar extinction coefficient, e, for Fricke dosimetry, have been recommended by ICRU. For e, the recommended value was $2196 \pm 5$ l·mol$^{-1}$·cm$^{-1}$ in ICRU Report 14, in conformity with the value previously proposed by Fricke; the value was slightly changed in ICRU Reports 17 and 21, to $2205$ l·mol$^{-1}$·cm$^{-1}$, based on an analysis of 83 reported values. It was suggested that, where neither a careful wavelength calibration nor absorbance linearity checks had been performed, a standard error of 1.5% should be assumed; otherwise 0.15% could be accepted. Alternatively, the accuracy in applying this chemical dose meter was considered improved if there was an independent determination of e with the same spectrophotometer as was used for the determination of the optical density of irradiated Fricke solution. The accuracy claimed for both methods remains questionable, since no complete argumentation could be given for the differences of up to 13% in the published values. This spread could only partially be explained by instrumental differences. Taking into account the discussion of the sources of error by Bryant, Broszkiewicz and Ellis, we tried systematically to elucidate this problem using a high-performance spectrophotometer, while following a precise measuring procedure and using carefully prepared standard solutions. The quantitative results indicated that discrepancies of up to 10% can occur due to the effect of residual oxidizing agents, such as peroxide. This source of error is rarely, and then only qualitatively, mentioned in the literature; it could explain the differences in the values published by a number of laboratories. A spectrum analysis of both absorbance peaks of ferric-ion solutions was made, taking into account different physical and instrumental factors. Special attention was given to the optical density dependence of e and to the absorbance calibration. In order to standardize all parameters influencing e, a complete discussion of the errors in determining the molar extinction coefficient is presented and some conclusions are drawn regarding Fricke dosimetry and, especially, the G-values.

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1. INTRODUCTION

The calibration of a ferrous sulphate dose meter in a standard radiation beam corresponds to the determination of the product $e \cdot G$, where $e$ is the molar extinction coefficient and $G$ is the chemical yield of Fe$^{3+}$ ions. Alternatively, one may use the Fricke dose meter without calibration if the values of $G$ and/or $e$ recommended by ICRU are used. The value for the molar extinction coefficient $e$ given in ICRU Report 14 [1] is $2196 \pm 5 \text{ l}\cdot\text{mol}^{-1}\cdot\text{cm}^{-1}$ at 304 nm, in agreement with the value previously proposed by Fricke [2]. This value was slightly changed in ICRU Report 17 [3] and ICRU Report 21 [4] to $2205 \pm 3 \text{ l}\cdot\text{mol}^{-1}\cdot\text{cm}^{-1}$, which is based on an analysis of 83 published $e$-values [5]. If, however, this value is used with an uncalibrated spectrophotometer, a standard error of about 1.5% should be assumed [3]. In standard dosimetry, this error is usually reduced by an independent determination of $e$ with the same instrument as is used for the measurement of the optical density of the irradiated Fricke solutions. This procedure eliminates errors in the optical density scale of the spectrophotometer.

The accuracies claimed for both methods and for many $G$-value determinations are, however, of questionable validity as long as the differences of up to 13% [5] in the published $e$-values have not been elucidated. Sources of error have been discussed by Ellis [6, 7], Broszkiewicz [5], and Bryant [8]. The spread of the data could only partially be explained by spectrophotometric errors and by differences in the chemical preparation of the standard solution.

The value of $e$ has been measured in our laboratory with a high-performance instrument, following a precise procedure and using standard solutions prepared in conformity with the suggestions of Broszkiewicz. We found that discrepancies of up to 10% could be due to the effect of peroxide. The influence of residual oxidizing materials has only rarely been mentioned in the literature as a possible source of error [9]; most publications have not paid any attention to this problem.

In order to contribute to a standardization of all parameters influencing $e$, a discussion of the errors in a molar extinction coefficient determination is presented, and some conclusions regarding Fricke dosimetry are drawn.

2. DISCUSSION OF THE DETERMINATION OF THE MOLAR EXTINCTION COEFFICIENT

The Fe$^{3+}$ ion formed in Fricke dosimetry by oxidation of Fe$^{2+}$ by irradiation produces an absorbance spectrum characterized by two peaks, one at 223 nm and one at 303 nm (Fig.1). The absorbed dose can be determined by making spectrophotometric absorbance measurements at 303 nm, comparing
FIG. 1. Absorbance spectrum of irradiated Fricke solution.

data for irradiated and non-irradiated solutions, and using the formula given by Fricke [2]:

\[
D = \frac{\Delta_1 \cdot N_A \cdot A}{\varepsilon \cdot G \cdot \xi \cdot \rho} \tag{1}
\]

where:
- \( D \) is the dose in grays;
- \( \Delta_1 \) is the change in absorbance in optical density units (ODU);
- \( G \) is the molecular yield of Fe\(^{3+}\) per 100 eV of absorbed energy for a specific beam quality;
- \( A = 1.602 \times 10^{-17} \) (a factor converting the 100 eV of the G-value into joules);
- \( N_A \) is Avogadro's number (6.022 \( \times \) 10\(^{23}\) mol\(^{-1}\));
- \( \rho \) is the density of the Fricke solution (g \( \cdot \) cm\(^{-3}\))
- \( \varepsilon \) is the molar extinction coefficient (1 \( \cdot \) mol\(^{-1}\) \( \cdot \) cm\(^{-1}\)) at the peak (303 nm), determined from:

\[
\varepsilon = \frac{\Delta_2}{c \xi} \tag{2}
\]

where \( \Delta_2 \) is the change in optical density measured with a spectrophotometric cell of length \( \xi \), containing a standard Fe\(^{3+}\) solution of concentration \( c \) mol\( \cdot \)l\(^{-1}\), with the solvent as reference solution.
Errors in the absorbance scale are eliminated by making a measurement of $e$ on the same spectrophotometer. The values of $e$ published in the literature vary by 13%, from 2057 to 2343 l·mol$^{-1}$·cm$^{-1}$ [8], while 66% of all hitherto reported values lie within the range 2185 to 2231 l·mol$^{-1}$·cm$^{-1}$ [5], with a mean value of 2205 ± 3 l·mol$^{-1}$·cm$^{-1}$, the value proposed by the ICRU since 1970.

Bryant [8] indicates the spectrophotometric design as the main source of divergency (up to 9%); minor divergencies are attributed to Fe$^{2+}$ absorbance disturbances, or to errors in wavelength and band-width selection. Bryant omitted to discuss the solution preparation procedure.

Broszkiewicz [5] noticed that the majority of investigations studying the effect of the spectrophotometer yielded a range of values within ±2% of the mean. He stressed the importance of the applied chemical procedure, preferring standard iron solutions prepared from pure metallic iron to solutions made using iron compounds, in which the amount of water of crystallization can change ($e$ deviation of 3%).

The value of 2205 for the molar extinction coefficient, $e$, cannot be generally accepted as long as the causes of the remaining discrepancies have not been established. Although Broszkiewicz and Ellis explicitly mentioned different aspects of a recommended procedure, an even more complete standardization is necessary. This should include the choice and treatment of iron (metallic or compound form) and the H$_2$SO$_4$ solvent, the detailed oxidation procedure, the dilution of the stock solution, the treatment of the measuring cells, the spectrophotometric precautions and the art of measurement. Before presenting the experimental data on $e$, the experimental procedure used in our laboratory is discussed.

3. EXPERIMENTAL PROCEDURE

The procedure described below sets out our actual, improved practice, which yields our final result for $e$. Any deviation from this procedure during a particular experiment is noted.

3.1. The preparation of a standard Fe$^{3+}$ solution

The standard Fe$^{3+}$ solution is prepared by dissolving 100 mg of metallic iron (99.998%, Koch-Light Labs Ltd) in 200 ml H$_2$O and 22 ml H$_2$SO$_4$ (suprapur, Merck). The water is distilled four times (the third distillation is performed over acidic K$_2$Cr$_2$O$_7$ and the last over alkaline KMnO$_4$ to eliminate organic impurities).

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1 In order to allow of experimental comparisons, some trade names have been mentioned. This identification has no commercial purpose nor does it imply that this product is the best available for that purpose.
It has the same purity as the water used for the Fricke solution. The iron is cut from a 1 mm thick sheet into small turnings (0.1 mm). After cleaning with benzene (reinst, Merck) and methanol (p.a.)², and after rinsing with doubly-distilled water, the surface impurities are removed in a bath of 12N HCl (p.a.)² over a period of 30 minutes. Subsequently, the iron is rinsed with doubly-distilled water and dried for 30 minutes at 100°C. The pieces of iron are weighed and then dissolved at 75°C. Thermogravimetric analysis of the iron in air from 20°C to 200°C was performed over a period of 100 minutes. No change in weight due to oxidation of the iron was observed. The warm solution is oxidized by adding pure H₂O₂ (Carlo Erba RSE 30 vol.%) and is boiled after 5 minutes for half an hour in order to eliminate H₂O₂. Quadruply-distilled water is added at 20°C to make 1 litre of 0.8N stock solution. All flasks used are calibrated with doubly-distilled water at 20°C. All concentrations are calculated after correcting the weights to vacuum. Further dilution is performed at 20°C with 0.8N H₂SO₄ using calibrated pipettes of 10, 25 or 50 ml. The absence of Fe²⁺ and H₂O₂ is checked using the 'O-phenantroline' and the 'perchromic acid' tests, respectively.

3.2. The spectrophotometric procedure

Two types of measuring quartz cells (cuvettes), of length 10 mm, are used: micro-cells of 2.5 mm width together with 2.5 mm masks, and the standard 1 cm cells. All cells are measured with an optical comparator (Zeiss). The cells are carefully cleaned with ‘permanganic acid’ (KMnO₄ dissolved in H₂SO₄) to eliminate impurities. They are further cleaned with dilute H₂O₂ and by frequent rinsing with quadruply-distilled water. The outsides of the cells are wiped with lens-cleaning paper; they are stored in a dust-free area. The transmission of the cells lies between 85% and 90% at 240 nm [10]. For a set of measurements, the cells remain in the thermostatically controlled cell holder in the thermostat compartment of the Cary 118 C spectrophotometer. The water temperature of the thermostat is set at 25.0°C. The water temperature is measured with a standard mercury-in-glass thermometer and a temperature correction of 0.7% °C⁻¹ is applied. The cell remains in the cell holder during each group of measurements. The cell is filled and emptied seven times with the liquid to be measured using micropipettes (Finn) and a suction device. Before measuring, the solution is left in the cell for 10 minutes in order to attain temperature equilibrium within ±0.07°C.

The spectrophotometer is a double-beam Cary 118 C with a maximum zero drift of 0.0004 ODU·h⁻¹. Stray light is controlled to be less than 0.001%. No cell is placed in the reference beam. The cell is first filled with reference liquid (0.8N H₂SO₄) and the zero is established. Afterwards it is filled with sample liquid. The reference measurement is subsequently repeated [11]. For Fricke

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² Analytical reagent grade.
4. EXPERIMENTAL RESULTS

4.1. Spectrum measurements

In Fig.2 is shown a spectrum of an oxidized Fe$^{2+}$ solution. The experiments were performed with 1 mm and 0.05 mm slit widths. The peak shift was
less than 0.5 nm and difficult to observe owing to the broadness of the peak; the difference in peak height was about 0.1 to 0.2%. The noise at 303 nm for a 0.05 mm slit width is 0.0033 ODU peak-to-peak and precludes a more accurate determination of the experimental peak height. A theoretical correction was derived to be 0.16%, in agreement with the experimental value. Therefore the natural band width (NBW) was measured at the smallest slit width. The observed band width (OBW) at 303 nm is then 68 ± 2 nm. The 223 nm peak has an OBW of 104 nm. Table I gives the spectrum band width (SBW) of our apparatus for various slit widths.

Using a computer program which fits two Gauss distributions to the experimental data, the spectrum in Fig. 2 was unfolded. This yielded the real peak wavelength of 308 nm and the real natural band width of 57 nm.

The determination of the molar extinction coefficient should, theoretically, take place at the real peak wavelength, but for practical, quantitative work a measurement at the observed peak wavelength is sufficient. No slit widths greater than 1 mm were allowed. Based on the dispersion data of our specific instrument and using the table in Ref. [7] (or given in most manuals [12]), relative band widths (RBW = SBW/NBW) were derived, and corrections of observed-to-true peak height were calculated. These are listed in the last line of Table I. The use of the OBW instead of the real natural band width in the derivation of the correction only changes the result by <0.1% for 1 mm slit width. These theoretical corrections were applied to the absorbance measurements in the final e-value determination.

The scan speed is carefully selected to fully resolve the absorption spectrum at speeds lower than 0.1 NBW per period (0.1 nm/s for Fig. 2).

The wavelengths were calibrated with a mercury-arc assembly and found to be accurate to within 0.1 nm at the 302.75 nm and 226.2 nm lines.

In the literature, peak maxima are mentioned ranging from 300 to 305 nm. This spread could be due to a lack of wavelength calibration or to the use of too large a slit width.

It is an essential condition that SBW « NBW to satisfy the Lambert-Beer assumption of monochromaticity [13]. The influence of impurities or residual oxidizing agents in the iron solution can also result in a peak shift. The 303 nm peak is asymmetrical due to a slight contribution of the 223 nm peak at 303 nm. If any far-UV absorbing specimen is present, a greater disturbance may occur. As a sensitive means of preventing such errors, Denman [14] suggested that the ratio of the two peak absorbances, which normally remains constant for the same instrument, should be measured. Our ratio is 0.483 and corresponds to the spectral data of Scharf and Lee [15]. Denman obtained 0.496 and 0.491 on a Beckman DB and 0.500 ± 0.02 on a Unicam Sp. Any influence of impurities may shift the ratio by more than 10% [14]. We noticed that an excess of peroxide in the Fe³⁺ solution strongly absorbs shorter wavelengths and shifts the peak maximum.
FIG. 3. The influence of residual H$_2$O$_2$ on the determination of the ε-value. ○, ▼ experimental mean ε-values for one dilution of Fe$^{3+}$ solution made using iron turnings and Mohr’s salt, respectively; ○, V experimental results corrected for H$_2$O$_2$ contribution for a solution made using iron turnings or Mohr’s salt, respectively: — mean of ε-data (○) with standard deviation; ——— mean of ε-data (▼) with standard deviation.

up to 298 nm (the minimum is at 289 nm instead of 275 nm, as illustrated in Fig.2 for a 1.8 mg H$_2$O$_2$·ml$^{-1}$ solution). The molar extinction coefficient variation of a solution of 9 ml H$_2$O$_2$ (30%) per litre of 0.8N H$_2$SO$_4$ varies from ±0.7 l·mol$^{-1}$·cm$^{-1}$ at 305 nm to ±1.2 l·mol$^{-1}$·cm$^{-1}$ at 293 nm.

4.2. The effect of residual H$_2$O$_2$ on the determination of ε

Three methods of oxidizing Fe$^{2+}$ to Fe$^{3+}$ are mentioned in the literature: using KMnO$_4$, H$_2$O$_2$ or irradiation. Two authors have analysed possible interfering effects [9, 16]. Davies and Law [9] conclude that KMnO$_4$, with some H$_2$O$_2$ added, yields a better reproducibility ($ε = 2172 ± 2$ l·mol$^{-1}$·cm$^{-1}$) than does H$_2$O$_2$ ($ε = 2164 ± 6$ l·mol$^{-1}$·cm$^{-1}$), while irradiation results in unacceptably high ε-values. They suspect the possible formation of H$_2$O$_2$-Fe$^{3+}$ complexes.

Holm [16] finds that a varying H$_2$O$_2$ concentration of 3.2 to 16 ml perhydrol per litre does not influence the result for ε. He, however, clearly specifies that he refluxed for 1 hour. His result is 2187 ± 5 l·mol$^{-1}$·cm$^{-1}$ for Mohr’s salt (Fe(NH$_4$)$_2$(SO$_4$)$_2$·6H$_2$O) and 2197 ± 6 l·mol$^{-1}$·cm$^{-1}$ for ferric ammonium sulphate.
Most authors give no detailed oxidation procedures. Broszkiewicz [5] adds 12 ml of 30% H₂O₂ per litre of final stock solution under boiling conditions. The solution is then left to cool to room temperature [17]. Prolonged boiling is considered suspect in different laboratories as bringing with it the risk of removing minor quantities of iron during evaporation; this has never been systematically studied. We have determined the molar extinction coefficients for different iron concentrations in the stock solutions made using iron turnings (4.8 mg·L⁻¹ to 250 mg·L⁻¹, or 0.8 × 10⁻⁵ to 5 × 10⁻³ M), each diluted to different concentrations (1:20 to 1:1). All stocks were oxidized with 9 ml H₂O₂ (perhydrol; 30 wt%; Merck, p.a.), without boiling, in order to analyse the influence on ε of varying residual H₂O₂. All measurements were performed at 25.0°C, with a 1 mm slit at 302 nm, the peak value determined in the first series of measurements. The wavelength dependence was established as already illustrated. The results are presented in Fig.3. Each data point is the mean of at least three absorbance measurements.

An apparently strong dependence of ε on the primary iron concentration of the stock solution is caused by residual, non-destroyed H₂O₂, with a considerable contribution to the spectrum in the far UV extending to 305 nm.

The molar extinction coefficient in Fig.3 could also be represented as a function of the ratio of iron to peroxide concentration. For a high ratio, or at high iron concentrations or small residual H₂O₂, the measured value of ε tends to our original ε-value for boiled solutions (2162 l·mol⁻¹·cm⁻¹).

4.2.1. H₂O₂ correction

For each concentration of iron, the quantity of H₂O₂ consumed in the reaction:

\[
2\text{Fe}^{2+} + \text{H}_2\text{O}_2 + 2\text{H}^+ \rightarrow 2\text{Fe}^{3+} + 2\text{H}_2\text{O}
\]

was calculated and used to evaluate the residual H₂O₂; this ranged from 40 to 2000 times the quantity consumed. The absorbance contribution of H₂O₂ dissolved in 0.8N H₂SO₄ was experimentally determined for the range 0.004M to 0.4M H₂O₂. A linear relationship was found that determined ε(H₂O₂) approximately for a specific quality (ε = ±0.95). Deviations from linearity only occur at low concentrations (<0.005 ODU). Using the expression:

\[
ε_{\text{exp}} = \frac{\text{Abs(Fe)} + \text{Abs(H}_2\text{O}_2)}{λ \cdot d \cdot ε(\text{Fe})}
\]
where \( d \) is the dilution factor and \( \epsilon_{\text{exp}} \) the experimental value of \( \epsilon \), the experimental absorbance corrections for \( \text{H}_2\text{O}_2 \) were applied to the 44 data points in Fig.3, yielding the 38 + 6 data points that are represented in the same figure by:

\[
\begin{align*}
\epsilon(\text{Fe}) &= 2160 \pm 5(\sigma) \text{ mol}^{-1} \cdot \text{cm}^{-1} \quad \text{for metallic iron turnings} \\
\epsilon(\text{Fe}) &= 2165 \pm 2(\sigma) \text{ mol}^{-1} \cdot \text{cm}^{-1} \quad \text{for Mohr's salt}
\end{align*}
\]

Using Eq.(3), the correction can also be represented by:

\[
\Delta \epsilon = \epsilon_{\text{exp}} - \epsilon(\text{Fe}) = \epsilon(\text{H}_2\text{O}_2) \frac{c(\text{H}_2\text{O}_2)}{c(\text{Fe})}
\]

Since \( c(\text{H}_2\text{O}_2) \) and \( c(\text{Fe}) \) are the concentrations in the stock solution, it is interesting to notice that the correction is independent of the dilution factor, \( d \). As a consequence the possible influence of \( \text{H}_2\text{O}_2 \) on \( \epsilon(\text{Fe}) \) cannot be noticed by comparing different dilutions of one stock solution or by following one preparation procedure [5].

It also explains the good standard deviation of all measurements of the same stock solution (max. \( \sigma = 0.4\% \)), which can easily be seen in Fig.3 for Mohr's salt. Additional experiments were performed for slight excesses of \( \text{H}_2\text{O}_2 \) (3 to 10 times the \( \text{H}_2\text{O}_2 \) quantity consumed). A shift in the peak wavelength from 303 nm downwards was difficult to observe.

The result was \( \epsilon = 2164.5 \pm 3.01 \text{ mol}^{-1} \cdot \text{cm}^{-1} \) for ten measurements, while \( \epsilon = 2163.5 \pm 0.91 \text{ mol}^{-1} \cdot \text{cm}^{-1} \) was determined on six boiled solutions. The standard deviation of the value obtained with the boiling method is significantly smaller than that obtained with the correction method. This is due to the poor accuracy of the correction (measured at low absorbances) and due to the increased uncertainty of peak wavelength selection. The general agreement between both methods, however, guarantees that no considerable quantities of iron are removed by boiling. This conclusion is only valid for slow dissolution at 75°C, followed by prolonged boiling, as used in our laboratory.

Residual \( \text{H}_2\text{O}_2 \) can be detected in most cases by performing the perchromic acid test on stock solution (positive for limited, instantaneous boiling), but a systematic control of the Denman ratio seems to us to be very valuable (0.441 for an \( \text{H}_2\text{O}_2 \) excess of 10). The duration of \( \text{H}_2\text{O}_2 \) destruction or oxygen formation can be checked visually by observing the small, distinct bubbles; the process can continue for several minutes. We also evaluated the use of \( \text{H}_2\text{O}_2 \) in the reference solution followed by boiling; we found, however, that \( \text{H}_2\text{O}_2 \) could be fully destroyed; we explain this as due to a catalytic influence of \( \text{Fe}^{3+} \) on \( \text{H}_2\text{O}_2 \) destruction in the stock solution.

It may be concluded that, in determinations of \( \epsilon \) in solutions disturbed by residual \( \text{H}_2\text{O}_2 \), the \( \epsilon \)-value can be markedly overestimated. Since neither
instrumental nor preparational error considerations [5, 8] could fully explain
the spread in ε-values, between 2160 and 2250 l·mol⁻¹·cm⁻¹ in 90% of all
hitherto published values [5], the possible systematic error we have described,
which can raise the ε-value upwards from 2160, has to be taken into account.

The higher values for ε are only a relative indication, since no systematic
corrections were applied for wavelength (0.3%) or true peak height (0.2%). The
H₂O₂ concentration values, too, provide only a relative indication, being based
on the specifications of the manufacturer. No accurate H₂O₂ content deter­
minations were made. The absolute ε-value determined at that time (1975) for
boiled solutions was 2168.5 ± 4 l·mol⁻¹·cm⁻¹ at 303 nm.

This value was confirmed by 25 measurements in 1976, yielding
2167 ± 3 l·mol⁻¹·cm⁻¹, and is in agreement with the measurements of Davies
and Law (ε = 2164 ± 6 l·mol⁻¹·cm⁻¹) [9], the only authors who discussed the
possible effect of H₂O₂. The values of Holm (2187—2197 l·mol⁻¹·cm⁻¹) [16]
were based on other iron preparations.

A possible slight H₂O₂ contribution in the results of Broszkiewicz cannot
be excluded; however, most of the H₂O₂ will have been destroyed.

4.3. Absorbance linearity

Fricke [2] noticed that Beer’s law [2], which states that the proportionality
constant, ε, is independent of concentration, is respected in Fricke dosimetry
to within 0.5% up to 0.01M FeSO₄. Perfect linearity in the relationship of
absorbance to concentration was confirmed by, for example, Scharf and Lee [15].
In our experimental study some aspects appear which may influence the
discussion of errors.

4.3.1. Experimental results

Assuming obedience to Beer’s law, the ratio of absorbance to concentration
should be a constant. The standard deviation of this ratio for 16 mean absorbances
in the concentration range of 6 × 10⁻⁵ mol·l⁻¹ to 4.5 × 10⁻⁴ mol·l⁻¹ is 0.06%,
thus confirming linearity (1975). The same ratio for 38 measurements corrected
for excess H₂O₂ yielded a deviation of 0.23%.

In Fig.4 all measurements made during the last year are illustrated as a
function of absorbance. A specific symbol is used for each group of measurements
made using one particular solution preparation.

The essential feature of this figure is the constant behaviour of ε over the
absorbance range 0.3—1.0, with a small incidental decrease (<0.35%) at low con­
centrations. Ellis [7] measured an unexplained dependence of ε on concentration
over the whole range, but also essentially a decrease of ε at 0.2 ODU. The ε-
value (2187 l·mol⁻¹·cm⁻¹) of NPL was derived from a linear fit to the absorbance/
concentration relation.
A possible explanation could be that the spectrum is composed of different contributions of complexes (FeOH\(^{2+}\), FeSO\(_4\) etc.), of which the fractions could change slightly with concentration, as was noticed for K\(_2\)Cr\(_2\)O\(_7\) by Burke [18]. Applying the Lambert-Beer law to complex peaks assumes independence of absorbing species and absorbance additivity [13].

For each group of \(\epsilon\) measurements (Fig.4), a linear absorbance/concentration relation of the form shown in Eq.(5) was fitted [19]:

\[ A = \epsilon c + a \]  

(5)

The weighted \(\epsilon\)-value derived from Eq.(5) was compared with a weight mean \(\epsilon\)-value assuming no intercept. Weighting of the absorbance or molar extinction coefficient was performed using the standard deviation of all absorbance measurements of the same distribution. This procedure corrects for larger uncertainties at low absorbances. The results are tabulated in Table II. The minor systematic differences between some groups are due to small variations in experimental parameters, studied to establish their (minor) effects, i.e. \(<0.1\%\); these parameters include cell dimension, ultra-purity of products, perfection of temperature stabilization.

The differences between the two \(\epsilon\)-value columns are caused by the varying absorbance intercept for zero concentration (a in Eq.(6)), illustrated in column 4.

Since the intercept was negative as well as positive, and since both column mean \(\epsilon\)-values are equal, the intercept variation could represent essentially a statistical effect in our case. It is very important that \(\epsilon\)-values based on a linear absorbance-to-concentration relationship should be supported by a generally
TABLE II. WEIGHTED MEAN MOLAR EXTINCTION COEFFICIENTS
(1·mol⁻¹·cm⁻¹)

<table>
<thead>
<tr>
<th></th>
<th>( \epsilon_1 )</th>
<th>( \epsilon_2 )</th>
<th>Intercept⁴ (ODU)</th>
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<tbody>
<tr>
<td>1</td>
<td>2164.5</td>
<td>2163.0</td>
<td>+6.0 \times 10^{-4}</td>
</tr>
<tr>
<td>2</td>
<td>2165.2</td>
<td>2166.9</td>
<td>-5.7 \times 10^{-4}</td>
</tr>
<tr>
<td>3</td>
<td>2161.3</td>
<td>2158.9</td>
<td>+5.1 \times 10^{-4}</td>
</tr>
<tr>
<td>4</td>
<td>2161.5</td>
<td>2159.5</td>
<td>+7.7 \times 10^{-4}</td>
</tr>
<tr>
<td>5</td>
<td>2160.3</td>
<td>2158.4</td>
<td>+7.3 \times 10^{-4}</td>
</tr>
<tr>
<td>6</td>
<td>2162.0</td>
<td>2164.5</td>
<td>-9.2 \times 10^{-4}</td>
</tr>
<tr>
<td>7</td>
<td>2165.1</td>
<td>2170.6</td>
<td>-11.9 \times 10^{-4}</td>
</tr>
<tr>
<td>8</td>
<td>2164.0</td>
<td>2163.5</td>
<td>+3.0 \times 10^{-4}</td>
</tr>
</tbody>
</table>

\( \bar{\epsilon}_1 = 2163.0 \)
\( \bar{\epsilon}_2 = 2163.1 \)

\( \sigma = 1.9 \)
\( \sigma = 4.2 \)
\( \bar{\sigma} = 0.7 \)
\( \bar{\sigma} = 1.5 \)

\( \epsilon_1 \): zero intercept;
\( \epsilon_2 \): from absorbance-concentration fitting with absorbance intercept.

\( a \) ODU: optical density units.

constant behaviour of the \( \epsilon \)-value as a function of the absorbance or be accompanied by a properly-specified small intercept, else practical application of the \( \epsilon \)-value in Fricke dosimetry is questionable. The otherwise careful determination of the \( \epsilon \)-value by Scharf and Lee did not specify the magnitude of any possible intercept, nor were details of their use of \( \text{H}_2\text{O}_2 \) given.

5. DETERMINATION OF MOLAR EXTINCTION COEFFICIENT

The last two groups of measurements in Table II were selected for the final determination of the \( \epsilon \)-value. Between measurements 6 and 7, a complete instrumental check of the spectrophotometer, including the photometric calibration procedure, was undertaken by the manufacturer. Afterwards absorbance intercomparisons were performed at the NPL (UK) on a Cary 16 spectrophotometer with \( \text{KNO}_3 \) (303 nm) and \( \text{K}_2\text{Cr}_2\text{O}_7 \) (313 nm) standard solutions prepared in our laboratory. Perfect agreement was found within the limits defined in the specifications of the instrument (maximum deviation 0.2% over the range 0.14 ODU to 0.9 ODU). Earlier measurements on \( \text{KNO}_3 \) had deviated by 0.2% from actual values.
### Table III. Detailed Uncertainties of the Molar Extinction Coefficient Determination

\[ \varepsilon = 2164.3 \text{ l} \cdot \text{mol}^{-1} \cdot \text{cm}^{-1} \]

<table>
<thead>
<tr>
<th>Components</th>
<th>Actual uncertainty, ( \bar{\sigma} ) (%)</th>
<th>Potential uncertainty (max) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Random uncertainty</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concentration</td>
<td>0.01</td>
<td>0.2</td>
</tr>
<tr>
<td>Absorbance</td>
<td>0.04</td>
<td>0.3</td>
</tr>
<tr>
<td>Wavelength (±0.1 nm)</td>
<td>0.016</td>
<td></td>
</tr>
<tr>
<td>Cell length</td>
<td>0.01</td>
<td></td>
</tr>
<tr>
<td>Temperature (±0.07°C) (T)</td>
<td>0.01</td>
<td>0.3</td>
</tr>
<tr>
<td></td>
<td>±0.05</td>
<td></td>
</tr>
<tr>
<td>2. Systematic uncertainty</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preparation procedure</td>
<td>0.05</td>
<td>0.1 [5]</td>
</tr>
<tr>
<td>Concentration</td>
<td>0.12</td>
<td>0.5</td>
</tr>
<tr>
<td>Temperature measurement</td>
<td>0.1</td>
<td>0.5</td>
</tr>
<tr>
<td>Wavelength (0.1 nm)</td>
<td>0.016</td>
<td>0.7 [7]</td>
</tr>
<tr>
<td>Correction, weight (vacuum)</td>
<td>–</td>
<td>0.1</td>
</tr>
<tr>
<td>Correction, true peak height</td>
<td>0.01</td>
<td>0.05–0.5</td>
</tr>
<tr>
<td>Length of cell</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Purity of products</td>
<td>0.1</td>
<td>(?)</td>
</tr>
<tr>
<td>Microcells</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Linearity (Lambert-Beer)</td>
<td>0.06</td>
<td>0.5</td>
</tr>
<tr>
<td>Absorbance calibration</td>
<td>0.2 (!)</td>
<td>0.2 [5]</td>
</tr>
<tr>
<td>Exponential non-linearity</td>
<td>0.2 (?)</td>
<td>0.2 (?)</td>
</tr>
<tr>
<td>Photometric calibration</td>
<td>–</td>
<td>0.2</td>
</tr>
<tr>
<td></td>
<td>0.38</td>
<td></td>
</tr>
<tr>
<td>3. Oxidation procedure</td>
<td>+3. (0–10)</td>
<td></td>
</tr>
<tr>
<td>4. Different preparations</td>
<td>( \sigma = 1. \ [5] ) max 3%</td>
<td></td>
</tr>
</tbody>
</table>

[ ] Denotes reference citations.
5.1. Discussion of errors

A detailed discussion of errors applicable to this particular determination of the \( \epsilon \)-value is presented in Table III. The statistical uncertainty is much lower than the systematic uncertainty. The whole preparation procedure was standardized as described in §3.1. Balance, flasks and pipettes were calibrated. The temperature in the cell and the thermostatic circuit was controlled, and the temperature accuracy checked with a mercury-in-glass thermometer and a thermocouple.

The wavelengths are periodically calibrated by a mercury arc assembly and the reproducibility of the setting has been established. The uncertainty due to the preparation procedure, which is in fact included in the random experimental uncertainty and concentration uncertainty, was also estimated separately, and it was conservatively inserted into the systematic error analysis. We compared all subsequent pairs of measurement groups, which only differed from each other by having the solutions separately prepared. A maximum systematic difference of 0.05% was noticed.

Measurements were performed with 1 cm standard cells, and compared with micro-cell determinations. Solutions prepared from analytical reagent grade products (\( \text{H}_2\text{SO}_4, \text{H}_2\text{O}_2 \)) were also compared with those made with ultrapure products. The differences between the mean \( \epsilon \)-values were greater than the standard deviation of the mean in each group, revealing minor systematic differences (<0.1%).

A periodical check of the photometric calibration of the spectrometer was necessary. A long-term drift of up to 0.2% was noticed.

The absorbance scale of the spectrophotometer was not compared with a standard. The indicated error (\( ! \)) only gives the agreement with the spectrophotometer of NPL, which was also within the absorbance accuracy specification of the manufacturer. Exponential non-linearity, as discussed by Hawes [20], was not measured on our instrument.

Since the two last factors dominate the error discussion, future improvements will essentially concentrate on such calibrations.

In the last column of Table III, estimates are given of the possible errors which could arise from the effects listed if the appropriate corrections or calibrations have not been made, if the procedures recommended in this paper are not followed, or if the quality of the apparatus is worse. These errors are believed to occur unrealized in the reporting of work. In some cases the errors have been reported as part of a more systematic error discussion, to which the reader has been referred.

Finally, the error due to residual \( \text{H}_2\text{O}_2 \) is estimated to be a maximum of +3%. Larger errors are possible but improbable due to the easily detectable wavelength shift. The preparation procedure has been fundamentally studied by Broszkiewicz and this has been essentially followed in this work, with a slightly
better reproducibility. Preparations not starting from iron turnings should be disregarded since larger uncertainties arise [5]. A complete standardization seems to be an essential condition for reaching international agreement on an $\varepsilon$-value.

6. CONCLUSION

A value for the molar extinction coefficient of Fe$^{3+}$ of $2164 \text{ L} \cdot \text{mol}^{-1} \cdot \text{cm}^{-1}$, with a ±1 statistical uncertainty ($\sigma$) and ±8 systematic uncertainty, has been presented, together with a detailed error discussion.

This value is 2% smaller than that recommended by ICRU, the latter having been based on a statistical mean of all hitherto reported values. As a result of an investigation of the possible influence of residual H$_2$O$_2$ on the $\varepsilon$-value, some evidence is provided that, in a number of measurements published in the literature, $\varepsilon$ could have been overestimated by up to 3%, or even more under less appropriate experimental conditions. This makes a purely statistical evaluation of the $\varepsilon$-value based on various authors' results a questionable procedure. Owing to the lack of information on the oxidation procedure used in work described in most publications, the magnitude of any possible error is not determinable.

A possible systematic error in the determination of $\varepsilon$ could change some determinations of the G-value and influence the error in some Fricke dosimetry practice.

Other parameters that have only a minor influence have been discussed, especially a possible concentration-dependence of $\varepsilon$. Some instrumental and preparational aspects slightly extend the error discussion in Refs [5, 8].

Considering the importance in dosimetry of a correct procedure for determining $\varepsilon$, or of an exact recommendation for $\varepsilon$, complete standardization of all experimental procedures is necessary. For the final determination of $\varepsilon$, a new series of $\varepsilon$-value measurements by a number of standards laboratories is preferable to a statistical mean as presented in Ref. [5].

ACKNOWLEDGEMENTS

The authors acknowledge the support of Professor Dr. A.J. Deruytter, Director of the Laboratory of Nuclear Physics, and of Professor Dr. O. Segaert, Director of the Central Service of Radiation Protection. The interesting discussions with Dr. A.J. Deruytter, and with Dr. S.C. Ellis of the National Physical Laboratory (UK) and Dr. H. Feist of the Physikalisch-Technische Bundesanstalt (Fed. Rep. Germany), as well as the valuable intercomparison at NPL were very much appreciated.

The authors would also like to thank Mrs. B. Van Waeyenberge and Mr. R. Verspille for their assistance in preparing the manuscript and diagrams.
REFERENCES


DISCUSSION

S.C. ELLIS: Firstly I should like to compliment the Ghent University group on a particularly careful piece of work.

The influence of hydrogen peroxide may be not only from residues in the solution but also from the formation of peroxyl complexes with the iron. Residual \( \text{H}_2\text{O}_2 \) could be destroyed by addition of potassium permanganate; the additional absorption at 303 nm resulting from any excess of the latter could be corrected
for by measurement of a permanganate peak in the visible region. Did you try this?

R. JACOBS: No, we preferred to eliminate the peroxide by boiling the solution for half an hour. No residual peroxide was detected.

S.C. ELLIS: Bryant and co-workers took aliquots of the same stock solution of ferric iron to the individual spectrophotometers; thus they essentially intercompared instruments. It is difficult to perform a satisfactory intercomparison of high-precision spectrophotometers by means of solutions; potassium dichromate seems to be most satisfactory, and we have found excellent agreement with this solution, not only between NPL and Ghent but also with the Physikalisch-Technische Bundesanstalt (Fed. Rep. Germany). Earlier attempts with aqueous potassium nitrate were much less successful.

J.-P. GUIHO: I find your work interesting, and your paper is an excellent guide in such matters. It is important, I think, that you have determined the molar extinction coefficient for your own use; at the same time, I should like to stress the danger of another laboratory’s making direct use of your value. The molar extinction coefficient depends on a large number of parameters, in particular on the characteristics of the spectrophotometer used. When we determined G-values for the energies of $^{60}$Co and $^{137}$Cs some years ago, we compared several spectrophotometers and found molar extinction coefficients differing by several per cent for the same solution. Users of the Fricke dose meter should therefore be urged to determine their own $\varepsilon$-value.

R. JACOBS: Yes, I agree with you.

A.O. FREGENE: In your molar extinction coefficient of 2164, you are claiming a measurement error of less than 0.1%. I wonder if the manufacturers of the commercial spectrophotometer can guarantee that the error will be so small?

R. JACOBS: The spectrophotometer we use is of sufficient quality to guarantee the errors specified.

A.O. FREGENE: In routine use of the Fricke dose meter, it is certainly more sensible to use the average of the several published $\varepsilon$-values with various systematic and random errors than to rely on individually estimated values.

R. JACOBS: We would agree with the use of a mean value resulting from measurements by standards laboratories.
GAMMA-RAY DOSIMETRY ERRORS WITH THERMOLUMINESCENT DOSE METERS*

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Lawrence Livermore Laboratory,
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Livermore, California,
United States of America

Abstract

GAMMA-RAY DOSIMETRY ERRORS WITH THERMOLUMINESCENT DOSE METERS.

Gamma-ray dosimetry errors can occur when thermoluminescence dose meters (TLDs) are irradiated in thin-walled containers. An over-response has been observed for LiF TLDs, irradiated by an isotropic source, of approximately 25% for $^{24}$Na; 20% for $^{60}$Co, and 2% for $^{137}$Cs. The over-response for CaF$_2$ TLDs was found to be less than the over-response of LiF TLDs. Under-response errors can occur for TLDs in thin-walled containers irradiated under narrow-beam geometry conditions because electron equilibrium is not established, but this error is well known and is not discussed in this paper. The observed over-response is attributable to electrons originating in the radiation source holder and the surrounding air that are scattered into the TLD material. This over-response is less pronounced for $^{137}$Cs gamma rays because few scattered electrons have sufficient energy to penetrate the TLD; however, for higher energy gamma rays, more electrons can penetrate the TLD, resulting in a greater dose. This effect will also be observed with any dose meter that has a small sensitive volume surrounded by a thin wall. The over-response of a dosimetry film in its paper wrapping was measured to be approximately 25% for $^{60}$Co gamma rays and 3% for $^{137}$Cs gamma rays, although this would rarely introduce an error since film dose meters are usually irradiated in a thick-walled badge. This paper presents the measured over-responses of various TLD chips for several exposure conditions and experimental results which demonstrate the cause of the over-response.

INTRODUCTION

The use of thermoluminescence dosimeters (TLDs) has become widespread in gamma-ray dosimetry. The small size into which thermoluminescence material can be fabricated makes it ideal for many dosimetry applications. However, as a result of these small sizes, significant gamma-ray dosimetry errors can occur when TLDs are exposed under broad-beam conditions. Under such conditions, TLDs located in holders with insufficient wall thickness to establish electron equilibrium, for the gamma energy being measured, can receive more dose than would be determined with a primary or secondary standard (calibrated ionization chamber). This overresponse is not limited to TLDs, and can occur with any thin-walled detector with a small sensitive volume. It should be noted that any overresponse errors occurring only during dosimetry calibration will result in underestimating the true dose in subsequent measurements.

This paper investigates the dependence of the overresponse error on several parameters, and discusses the origins of the error.

QUANTIFICATION OF DOSIMETRY ERRORS

A calibration facility was used to quantify the overresponse errors that occur when TLDs are irradiated in thin-walled containers. The facility consists of a 9x9x7-m room with an aluminum grid floor suspended midway between the floor and ceiling. Irradiations with $^{60}$Co or $^{137}$Cs sources, encapsulated in small aluminum cylinders, were conducted using a pneumatic transfer system. This system consists of two concentric 1.6-mm-thick aluminum cylinders, with outside diameters of 35 and 63 mm, and positions the sources 1 m above the aluminum floor.

In addition to $^{60}$Co and $^{137}$Cs, measurements were performed using $^{24}$Na and $^{226}$Ra sources suspended by a thin wire from an aluminum ring stand. To ensure the absorption of the 1.4-MeV $E_{\text{max}}$ of $^{24}$Na, the source was encapsulated in a 3-mm-thick aluminum container with an outer diameter of 25 mm and a height of 41 mm. The $^{226}$Ra source was encapsulated in an approximately 5-mm-thick aluminum cylinder with an outer diameter of 30 mm and a height of 100 mm.

Three types of TLDs were used in these studies: 3.2x3.2x0.89 mm $^{7}$LiF [$\text{LiF}(0.89)$], 3.2x3.2x0.51 mm $^{7}$LiF [$\text{LiF}(0.51)$], and 3.2x3.2x0.89 mm $[\text{CaF}_2(0.89)]$. These TLDs are commercially available from the Harshaw Chemical Company¹ as TLD-700 for the LiF TLDs and TLD-200 for the CaF$_2$ TLDs. TLD luminescence was measured with an automatic TLD reader developed at the Lawrence Livermore Laboratory (LLL).

The LiF(0.89), LiF(0.51), and CaF$_2$(0.89) TLDs were used to observe the effect of TLD thickness and material on the overresponse. Kodak type-3 x-ray film, a typical film used in personnel dosimeters, was also studied.

¹ Reference to a company or product name does not imply approval or recommendation of the product by the University of California or the United States Department of Energy to the exclusion of others that may be suitable.
The TLD holders shown in Fig. 1 were used to study the effect of various holders on the overresponse error. The bayonet (Fig. 1a) has a wall thickness approximately 60 mg/cm², and is a common TLD holder at LLL. The TLD holder shown in Fig. 1b is used for personnel dosimetry at LLL and has a plastic window, 32 mg/cm². The Lucite (composition C₅H₇O₂) holder in Fig. 1c is 9 mm thick and has a 8.5-mg/cm² paper cover to hold the TLDs in place.

The dosimetry overresponse error in this paper is the ratio of a dosimeter's readings with and without an equilibrium thickness of Lucite positioned directly in front of the dosimeter. All ratios have been adjusted for gamma attenuation by the Lucite equilibrium thickness.

Each ratio was determined with a minimum of 12 TLDs, and most ratios were determined with 24 TLDs. The error for the TLD ratios considers only the counting statistics, and is reported at the 95% confidence level.

RESULTS

TLD overresponses for various TLD holders

Table I shows the effect of various TLD holders on the overresponse for both 60Co and 137Cs gamma rays. The TLDs were positioned at a source-to-TLD distance of 1 m (see Fig. 2), and the Lucite equilibrium cover was 4.8 mm thick.
FIG. 2. Pneumatic transfer system with aluminum disc and positioning bar in place.

TABLE I. TLD overresponses for several holders. The source-to-TLD distance was 1.00 m.\(^{a}\)

<table>
<thead>
<tr>
<th></th>
<th>Bayonet</th>
<th>Personnel dosimeter</th>
<th>Lucite holder</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(^{60})Co</td>
<td>(^{137})Cs</td>
<td>(^{60})Co</td>
</tr>
<tr>
<td>LiF(0.51)</td>
<td>1.16 ± 0.03 0.98 ± 0.02</td>
<td>1.16 ± 0.03 0.99 ± 0.04</td>
<td>1.16 ± 0.03 1.03 ± 0.03</td>
</tr>
<tr>
<td>LiF(0.89)</td>
<td>1.11 ± 0.02 1.00 ± 0.02</td>
<td>1.11 ± 0.01 0.99 ± 0.02</td>
<td>1.16 ± 0.02 1.01 ± 0.01</td>
</tr>
<tr>
<td>CaF(_2)(0.89)</td>
<td>1.06 ± 0.01 0.99 ± 0.02</td>
<td>1.07 ± 0.02 0.99 ± 0.04</td>
<td>1.09 ± 0.01 1.00 ± 0.02</td>
</tr>
</tbody>
</table>

\(^{a}\)Errors are reported at the 95\% confidence level.

For TLD irradiations with \(^{60}\)Co the error can be significant, while for \(^{137}\)Cs the error is not appreciable. The overresponse was greatest for the LiF(0.51) TLDs and least for the CaF\(_2\)(0.89) TLDs. The TLD holder thickness did not significantly affect the TLD overresponse (i.e., the error was approximately the same whether the TLDs were packaged in a 60-mg/cm\(^2\)-thick container or had a 8.5-mg/cm\(^2\) window).
Dosimetry overresponses for personnel dosimetry film

Kodak type-3 x-ray film was exposed to $^{60}$Co and $^{137}$Cs gamma rays at a source-to-film distance of 1.00 m. To observe the overresponse with the film, a 4.8-mm-thick Lucite equilibrium cover with a 13-mm-diam hole in the center was positioned directly in front of the film. The hole allowed a comparison to be made of the film response with and without the Lucite cover, using a single film to minimize errors introduced by differences in film emulsions and developing techniques. The overresponse is expressed as the ratio of the film density directly behind the 13-mm hole to the film density behind the 4.8-mm-thick Lucite cover. The overresponses were 1.03 and 1.25 for $^{137}$Cs and $^{60}$Co, respectively. A standard film densitometer was used for the measurement of film density.

TLD overresponse as a function of distance

The effect of source-to-TLD distance on the overresponse for $^{60}$Co and $^{137}$Cs gamma rays was investigated using the LiF(0.89) TLDs. The Lucite holders were used in tandem so that the first TLD array had only the paper cover (8.5 mg/cm$^2$) between the TLDs and source, and the second TLD array used the first Lucite holder to provide an equilibrium cover. To minimize scatter, an aluminum ring stand was used to position the TLDs, and all unnecessary material was removed from the area near the source (see Fig. 3). All the ratios were adjusted for gamma attenuation by the first 0.9-mm-thick holder and for the 0.9-mm difference in the source-to-TLD distance.

The overresponse is shown in Fig. 4, and reaches a maximum of about 11% and 2% for $^{60}$Co and $^{137}$Cs, respectively. For $^{60}$Co, the maximum occurs at about 1 m and decreases to approximately 7% at 0.5 m. For source-to-TLD distances greater than 1 m, the overresponse slowly decreases.

TLD overresponses for other gamma-ray energies

To investigate the overresponse with other gamma-ray energies, additional irradiations of LiF (0.89) TLDs in the tandem Lucite holders were made with $^{24}$Na and $^{226}$Ra gamma-ray sources. The sources and holders were positioned on ring stands with a source-to-TLD distance of 1.00 m.

To ensure that the results obtained with the pneumatic transfer system could be directly compared with the ring-stand results, a comparison study was performed. TLDs were irradiated in the tandem Lucite holders at 1.00 m from a $^{60}$Co source which was suspended from a ring stand by a thin wire. The source was contained in a 3-mm-thick aluminum capsule approximately 16 mm in diameter and 70 mm long. The measured overresponse was $1.13 \pm 0.03$ which is in good agreement with the ratio at 1 m, as shown in Fig. 4.

The results are given in Table II and show that the overresponse only becomes appreciable for gamma rays greater than 0.66 MeV, but the overresponse does not continue to increase with increasing gamma energy. It should be noted that the average gamma-ray energy for $^{226}$Ra is approximately 0.8 MeV, and only about 35% of the dose is from gamma energies greater than 1.7 MeV.
DETERMINATION OF THE CAUSE FOR TLD OVERRESPONSES

It has been shown that overresponse errors can occur when a thin-walled dosimeter of small sensitive volume is irradiated by an isotropic source. The observed overresponse is attributable to electrons which have been generated at the gamma source holder and scattered toward the detector. Some electrons would also be generated in the air, but since the mass of air near the source is much less than the source holder, most of the electrons are from the holder. The overresponse is not significant for 137Cs gamma rays because fewer electrons have sufficient energy to reach the detector and penetrate the sensitive volume. This overresponse is also a function of source-to-detector distance, gamma beam size, wall
FIG. 4. TLD overresponse as a function of distance for $^{60}$Co and $^{137}$Cs. Error bars are shown at the 95% confidence level.

TABLE II. Overresponses for several radionuclides at a source-to-TLD distance of 1.00 m for LiF(0.89) TLDs.$^a$

<table>
<thead>
<tr>
<th>Radionuclide</th>
<th>Gamma energy (MeV)</th>
<th>TLD overresponse</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{137}$Cs</td>
<td>0.66</td>
<td>$1.02 \pm 0.02$</td>
</tr>
<tr>
<td>$^{226}$Ra</td>
<td>aver. -0.8</td>
<td>$1.06 \pm 0.03$</td>
</tr>
<tr>
<td>$^{60}$Co</td>
<td>1.17, 1.33</td>
<td>$1.12 \pm 0.02$</td>
</tr>
<tr>
<td>$^{24}$Na</td>
<td>1.37, 2.75</td>
<td>$1.08 \pm 0.02$</td>
</tr>
</tbody>
</table>

$^a$Errors are reported at the 95% confidence level.
thickness, and sensitive volume. Experimental results are presented below to demonstrate the above explanation.

**Effect of beam size**

To demonstrate the effect of an isotropic gamma source, LiF(0.89) TLDs were irradiated in the tandem Lucite holders (Fig. 1c) at approximately 1.5 m using two $^{60}$Co beam sizes. The beam was collimated by inserting a small aluminum-encapsulated $^{60}$Co source in a hole drilled into the end of a lead brick, and the beam size was adjusted by positioning the source at different depths in the hole. The ratios, given in Table III, have been corrected for gamma attenuation by the first Lucite thickness and for the difference in source-to-TLD distance for the front and rear TLD array.

As expected from narrow-beam conditions, the first ratio is significantly less than unity because the paper-covered TLDs do not have sufficient mass surrounding them to establish electron equilibrium. When the solid angle of the beam is increased to approximately $\pi$ steradians, the ratio is only about 15% less than the ratio for the isotropic exposure previously shown to be approximately 1.1. These results indicate that the number of electrons which are scattered into a detector increases when the beam divergence increases.

**Determination of scattered electron dose fraction**

The TLD overresponse is increased when the TLDs are shielded from the direct gamma rays. A lead brick (200 x 50 x 100 mm), supported by an aluminum ring stand to minimize electron and gamma scatter, was positioned between the gamma source and the LiF(0.89) TLDs. The tandem Lucite holders were at 1.00 m, and the center of the brick was at 0.50 m with the TLDs being shielded by 200 mm of lead. Table IV presents the results with and without the lead shielding. The results have been normalized to the Lucite-covered TLDs irradiated without the lead shielding.

The lead brick decreased the dose to the Lucite-covered TLDs by 98% for $^{60}$Co and 97% for $^{137}$Cs, the remaining 2% and 3% being from gamma scatter in the room, in good agreement with other measurements of room scatter. When the TLDs were not shielded from the scattered electrons by the 9 mm of Lucite, the brick decreased the TLD dose by only 53% for $^{60}$Co and 87% for $^{137}$Cs. It should be noted from Table IV that for the paper-covered TLDs, approximately 40% of the dose is due to scattered electrons.

<table>
<thead>
<tr>
<th>Approximate beam solid angle (steradians)</th>
<th>Response ratio:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lucite covered TLDs</td>
</tr>
<tr>
<td>$\pi/5$</td>
<td>$0.61 \pm 0.03$</td>
</tr>
<tr>
<td>$\pi$</td>
<td>$0.96 \pm 0.03$</td>
</tr>
<tr>
<td>$4\pi$</td>
<td>$1.10 \pm 0.03$</td>
</tr>
</tbody>
</table>

aThe response observed with the isotropic source ($4\pi$ steradians) is included for comparison. Errors are reported at the 95% confidence level.
TABLE IV. TLD responses for $^{60}$Co and $^{137}$Cs irradiations with and without a lead shield.\(^a\)

<table>
<thead>
<tr>
<th></th>
<th>$^{60}$Co</th>
<th>$^{137}$Cs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lucite-covered</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No lead brick</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Lead brick at 0.5 m</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td>Paper-covered</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No lead brick</td>
<td>1.11</td>
<td>1.02</td>
</tr>
<tr>
<td>Lead brick at 0.5 m</td>
<td>0.47</td>
<td>0.13</td>
</tr>
</tbody>
</table>

\(^a\)Responses are normalized to the unshielded Lucite-covered TLDs.

For $^{60}$Co exposures \((0.47 - 0.02)/1.11 = 0.4\). For $^{137}$Cs exposures approximately 10% is due to scattered electrons \((0.13 - 0.03)/1.02 = 0.1\). These results are confirmed by the narrow-beam (\(\pi/5\) steradians) results given in Table III. TLDs with a paper cover have a ratio of 0.61, which is from the direct radiation and presumably little scattered electron dose. Thus, the TLD dose contributions for $^{60}$Co exposures are approximately:

- 0.61 direct radiation
- 0.02 scattered gamma
- 0.45 scattered electrons
- 1.08 total

The value of 1.08 is in good agreement with the measurement of 1.1 for the overresponse for $^{60}$Co given in Fig. 4.

Although the lead brick was in direct line with the source and TLDs, scattered electrons from the source easily reach the TLDs by air scatter. The degree of electron scatter in air was measured with a thin-end-window (2 mg/cm\(^2\)) G-M tube which was positioned 1.00 m from a 30-mm-diam $^{90}$Sr-$^{90}$Y beta source. A 58-mm-diam Lucite disk, of sufficient thickness to stop all source betas, was positioned between the source and detector. This irradiation was repeated using a 89-mm-diam Lucite disk. The results are presented in Fig. 5. The disks appreciably attenuate the betas only when placed near the detector or source; similarly, most of the electrons generated near the gamma source are not affected by the lead brick.

Scattered electron dose as a function of distance and determination of the source of scattered electrons

The previous studies indicate that the TLD overresponse is from scattered electrons. Low-energy gamma or x-ray contributions are not involved since the CaF\(_2\) and LiF TLD overresponses are similar (CaF\(_2\) TLDs have a large overresponse to low-energy photons).

Another indication that the overresponse is primarily due to electrons originating from the source holder can be seen in Fig. 6. Various thicknesses of aluminum absorbers were placed in front of a thin-end-window ion chamber which was irradiated at various distances with the thin window facing the $^{60}$Co and $^{137}$Cs isotropic sources. This chamber, which has a 6.6 mg/cm\(^2\) window and a 0.9 cm\(^3\) sensitive volume, was used because it has a small response to gamma rays and a high sensitivity to electrons due to its small sensitive volume and thin window. The results in Fig. 6
FIG. 5. Count rate as a function of source-to-Lucite distance, d. Thin-end-window probe was positioned 1.00 m from the $^{90}$Sr-$^{90}$Y source.

have been normalized to measurements made without an aluminum absorber. The ion chamber reading decreases as the aluminum absorber thickness increases, indicating that electrons were absorbed in the aluminum. If scattered electrons were not present, the ion chamber reading would increase because of the establishment of electron equilibrium. Figure 6 also shows that the scattered electron dose contribution is greater for $^{60}$Co than $^{137}$Cs gamma rays, and the contribution decreases for increasing distances from the source. Figure 4 shows that the overresponse for $^{60}$Co reaches a maximum at approximately 1 m and decreases for greater distances. Attenuation by air of the electrons originating at the source holder causes the decrease in overresponse for distances greater than 1 m. The decreased overresponse at distances less than 1 m is probably due to fewer electrons being generated in the air between the source and TLDs (i.e., a greater departure from electron equilibrium). This reasoning is supported by the overresponse observed for $^{24}$Na which increased from 1.02 at 0.5 m to 1.12
at 2.0 m (i.e., more electrons are generated in the air, and absorption by air is not significant at these distances for the high-energy electrons generated by the $^{24}$Na gamma rays).

TLD overresponse errors presented in this paper are considered to be a minimum because the TLDs were irradiated in air (suspended from a ring stand). The exception is the exposure condition shown in Fig. 2 where the aluminum disc and positioning bar were present. Overresponse errors can increase if TLDs are irradiated near objects. For example, TLDs were irradiated at 0.5 m on Styrofoam ($1.5 \times 0.4 \times 0.05$ m and density $0.03 \text{ g/cm}^3$) and while suspended from a ring stand. The results obtained on the Styrofoam were the same for $^{137}$Cs, but for $^{60}$Co the overresponse increased from 1.07 to 1.19, and for $^{24}$Na, 1.02 to 1.25.
It was shown in Table I that the overresponses vary for the three types of TLDs discussed in this paper. The overresponse is greatest for LiF(0.51) and least for CaF$_2$(0.89), and the difference can be explained by the effective thickness of the TLD. To show this, the three types of TLDs were irradiated in various holders at 1.00 m to a $^{60}$Co source. The holders were made of aluminum, titanium, copper, zirconium, cadmium, tantalum, lead, and Lucite. A typical metal holder is shown in Fig. 7. Figure 8 presents the overresponse as a function of holder atomic number, the results having been normalized to the TLD readings in the Lucite holder. Corrections which varied from 2% to 5% have been made to account for gamma attenuation by the front layer of each holder.

Since the electron mass stopping powers of CaF$_2$ and LiF are nearly equal, all three of the TLD response curves would approach the curve predicted by the Bragg-Gray cavity theory, provided the TLDs were very thin (i.e., the response is only a function of the TLD electron mass stopping
power). It must also be concluded from Fig. 8 that since the TLD response curves are not flat, the TLDs are too small to consider their response only has a function of the TLD mass energy absorption coefficients. For this intermediate case, the Burlin cavity theory [1],[2] must be used to predict the TLD response curves. The theory would predict the TLD responses by accounting for the effective thicknesses of the TLDs. Although the dimensions of the CaF$_2$(0.89) and LiF(0.89) TLDs are equal, the response difference is explained by the greater density of CaF$_2$ (approximately 25%). Similarly, the overresponse differences for the three types of TLDs are due to variations in effective thickness. That is, the TLD dose from scattered electrons is less for thicker TLDs because the electrons penetrate a smaller fraction of a thick TLD.

It should be noted that large dosimetry errors can occur when TLDs are irradiated within a material of high atomic number. As seen in Fig. 8 for $^{60}$Co, the LiF(0.51) TLD lead/Lucite response is 1.55. The lead/Lucite response ratio was measured as 1.83 for $^{137}$Cs.

**SUMMARY**

Gamma-ray detectors which have dimensions small compared to the range of the most energetic secondary electron can exhibit overresponse errors when exposed in broad-beam conditions. The TLD overresponse is appreciable for gamma rays greater than 0.66 MeV, and the overresponse decreases with increasing TLD thickness.

Overresponses are probably most common in TLDs because the dimensions of the TLDs and TLD holders are often not large in comparison to the secondary electron range. The overresponse error can be eliminated by ensuring that the TLDs are irradiated in holders which have an electron equilibrium thickness for the gamma-ray energy in question.

**ACKNOWLEDGMENTS**

The authors wish to thank Carl W. Sundbeck for reading the many TLDs used in this study.

**REFERENCES**


**DISCUSSION**

A.O. FREGENE: Since the size of your sources and the distances used were finite (1 m), I am not convinced that the effect of geometry on your LiF response is completely eliminated. This view is strengthened by the reduction you reported in the LiF over-response with increasing distance.

C.L. GRAHAM: The over-response reduction at increasing distance is due to electron attenuation by air.
J.F. SOMMERS: Did you irradiate the dose meters in various orientations in the beam?

C.L. GRAHAM: No, we did not.

J.F. SOMMERS: Did you irradiate the badges with paired dose meters (open-window and chamber)?

C.L. GRAHAM: Yes, the tandem Lucite holders had the thin window and also a 9 mm thick Lucite cover.

J.F. SOMMERS: We have noted some very large shielded-position over-responses (relative to open-window) in some field experiments with paired cadmium and aluminium absorber badges. The over-response, when it occurs, appears on both badges. Can you suggest any reason for these observations?

C.L. GRAHAM: No, I cannot.

L.F. PHILLIPS: At Brookhaven National Laboratory we have performed similar studies using several different thin-wall dose meters exposed to various high-energy gamma-ray fields under both "free-in-air" and collimation conditions. Our results support the data that you report here. In radiation protection work we are more concerned with under-response than over-response; however, both are important. Your work shows some of the problems that can arise:

1. In attempting to estimate surface dose to radiation workers operating in complex, mixed radiation fields including high-energy gamma and beta rays;

2. In calibration-testing standards for both hard gamma ($^{60}$Co) and beta ($^{90}$Sr-$^{90}$Y) radiation without agreement as to the over-response effect from "angular divergence" for free-in-air gamma exposures or the under-response effect for collimated gamma exposures.

Have you had the opportunity to apply the results that you have reported here to practical exposure conditions confronting radiation workers in mixed, high-scatter radiation fields?

C.L. GRAHAM: No, we have not.
SYNOPSIS OF THE SYMPOSIUM
1. INTRODUCTION

Traditionally, a synopsis such as this has followed the chronological order of the Symposium. However, due to the nature of the material presented, especially the overlap of much of the subject matter, I've chosen to categorize my remarks into four main subject areas. These include: primary standardization; personnel dose meter standardization; basic physical data; and a few general observations.

2. PRIMARY STANDARDS AND CALIBRATION

It became clear during the course of the Symposium that the world-wide emphasis on primary standardization is directed to traditional instrumentation, especially the detection elements. Ionization chambers (including extrapolation chambers), calorimeters and chemical systems — especially the ferrous sulphate — are all being used as basic elements in primary standardization. More work with these detectors was reported than at any international symposium that I can remember. The overall accuracy of the various national standards should be, and indeed appears to be, excellent; in general the uncertainty is not greater than two percent at one standard deviation. Those working in the national standards laboratories exhibit a high professional competence and a familiarity with earlier work.

3. PERSONNEL DOSE METER STANDARDIZATION

In the general area of personnel monitoring the accuracy requirements have necessarily been greatly relaxed; we learned, for example, that the HPSSC draft recommendations include ± 50% for the accuracy of measurement in the low-dose range. Further, this was for a standardized irradiation geometry. Under actual
field conditions the accuracy can be much less; for example, the detector's position relative to the body may vary from less than a centimetre to more than five centimetres, there can be significant angular and spectral dependence, etc. For this application of detectors the emphasis should be and has been increasingly upon intercomparisons and testing under as realistic field conditions as practical.

4. BASIC PHYSICAL DATA

In the study of basic physics phenomena related to dosimetry, some superb data were reported. It is imperative that this work continue because, without it, real progress on basic standards cannot be made. Unfortunately, there was some evidence of work toward applied goals by basic researchers wherein the work did not reflect a knowledge of the superb work of the 1930s and 1940s by some of the "giants" in the field of dosimetry or of all current standards and guides. I believe that the increasing pressure on basic researchers to produce readily applicable results is a fundamentally bad concept.

5. GENERAL OBSERVATIONS

5.1. There was almost no work reported on new dosimetry systems or concepts.

5.2. Rather, the emphasis was on refinement of techniques of calibration, testing, and intercomparisons of systems developed long ago and widely accepted.

5.3. Intercomparisons generally show a great effectiveness in reducing uncertainties and in serving as an education and training mechanism, at least when there is repeated participation by specific individuals.

5.4. Standardization and calibration functions in the USA are much less formalized, organizationally, than in most of the countries represented. In the western European countries there is evidence of both much more formal organization and greater financial support for new facilities and equipment than in some other countries, notably the USA. I will not attempt to analyse the apparent correlation of formal organization and financial support.

5.5. The role of the secondary standards laboratories, not always clearly understood, is now demonstrated to be that of serving as a necessary service link between the primary standards laboratories and the health physicist in the workplace.

5.6. Testing functions are really related to the individual using the dose meter rather than the dose meter per se; i.e. the user should be tested, in general, rather than the detector.
5.7. There was little attention given to neutron dosimetry. The problem of personnel dosimetry for personnel working in the low-energy neutron fields in transuranium facilities and in power reactors needs attention now. For example, persons making routine inspections inside containment of some PWRs may work in neutron fields of hundreds of millirems per hour, i.e. a few millisieverts per hour. It is clear that good personal dose meters for the neutron energy range from epithermal to about 1 MeV are not at present available. Of course, standardization facilities cannot be effective without instruments, hence the paucity of work on standardization of such instruments.

A different but similar problem is developing rapidly in relation to heavy-ion facilities. Several accelerators are being built or modified for research in heavy-ion physics; some of these will produce copious amounts of a variety of radiations.

5.8. The shift to SI units is going ahead much more rapidly than I would have expected, and it will probably be nearly complete within another three to five years. It was amusing to note in some individuals the pride evidenced at having made the change to SI units followed shortly by their inadvertent return to rads, rems or curies! Most of us at this stage appear to think in the old units and then translate to SI.

Finally, I am pleased with the quality of the content of this Symposium and I find this happy state reflected in many comments from delegates. There is a general awareness of the present and projected problems in radiation dosimetry standardization and of the roles of the various standards laboratories in developing solutions.
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The following conversion table is provided for the convenience of readers and to encourage the use of SI units.

**FACTORS FOR CONVERTING SOME OF THE MORE COMMON UNITS TO INTERNATIONAL SYSTEM OF UNITS (SI) EQUIVALENTS**

**NOTES:**
1. SI base units are the metre (m), kilogram (kg), second (s), ampere (A), kelvin (K), candela (cd) and mole (mol).
2. ▶ indicates SI derived units and those accepted for use with SI.
3. Indicates additional units accepted for use with SI for a limited time.
5. The correct abbreviation for the unit in column 1 is given in column 2.
6. -ft indicates conversion factors given exactly; other factors are given rounded, mostly to 4 significant figures.
7. = indicates a definition of an SI derived unit: (J in column 3 enclose factors given for the sake of completeness.

<table>
<thead>
<tr>
<th>Column 1</th>
<th>Column 2</th>
<th>Column 3</th>
<th>Column 4</th>
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<tr>
<td><strong>Radiation units</strong></td>
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<td>becquerel</td>
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<td>(has dimensions of s (^{-1}))</td>
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<tr>
<td>disintegrations per second (= dis/s)</td>
<td>1 s (^{-1})</td>
<td>(= 1.00 \times 10^9) Bq</td>
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<tr>
<td>◄ curie</td>
<td>1 Ci</td>
<td>(= 3.70 \times 10^{10}) Bq</td>
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</tr>
<tr>
<td>◄ roentgen</td>
<td>1 R</td>
<td>(= 2.58 \times 10^{-4}) C/kg</td>
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</tr>
<tr>
<td>◄ gray</td>
<td>1 Gy</td>
<td>(= 1.00 \times 10^0) J/kg</td>
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<tr>
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<td>(= 1.00 \times 10^{-2}) GY</td>
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<tr>
<td>sievert (radiation protection only)</td>
<td>1 Sv</td>
<td>(= 1.00 \times 10^0) J/kg</td>
<td></td>
</tr>
<tr>
<td>rem (radiation protection only)</td>
<td>1 rem</td>
<td>(= 1.00 \times 10^{-2}) J/kg</td>
<td></td>
</tr>
</tbody>
</table>

| **Mass** | | | |
| ▶ unified atomic mass unit (\(\frac{1}{12}\) of the mass of \(^{12}\)C) | 1 u | \[\approx 1.66057 \times 10^{-27}\] kg, approx. |
| ▶ tonne (= metric ton) | 1 t | \[= 1.00 \times 10^3\] kg |
| pound mass (avoirdupois) | 1 lbm | \(= 4.536 \times 10^{-1}\) kg |
| ounce mass (avoirdupois) | 1 ozm | \(= 2.835 \times 10^{-1}\) g |
| ton (long) (= 2240 lbm) | 1 ton | \(= 1.016 \times 10^3\) kg |
| ton (short) (= 2000 lbm) | 1 short ton | \(= 9.072 \times 10^2\) kg |

| **Length** | | | |
| statute mile | 1 mile | \(= 1.609 \times 10^0\) km |
| nautical mile (international) | 1 n mile | \(= 1.852 \times 10^0\) km |
| yard | 1 yd | \(= 9.144 \times 10^{-1}\) m |
| foot | 1 ft | \(= 3.048 \times 10^{-2}\) m |
| inch | 1 in | \(= 2.54 \times 10^{-1}\) mm |
| mil (= 10\(^{-3}\) in) | 1 mil | \(= 2.54 \times 10^{-2}\) mm |

| **Area** | | | |
| ▶ hectare | 1 ha | \[= 1.00 \times 10^4\] m\(^2\) |
| ▶ barn (effective cross-section, nuclear physics) | 1 b | \[= 1.00 \times 10^{-28}\] m\(^2\) |
| square mile, (statute mile)\(^2\) | 1 mile\(^2\) | \(= 2.590 \times 10^6\) m\(^2\) |
| acre | 1 acre | \(= 4.047 \times 10^3\) m\(^2\) |
| square yard | 1 yd\(^2\) | \(= 8.361 \times 10^{-1}\) m\(^2\) |
| square foot | 1 ft\(^2\) | \(= 9.290 \times 10^{-2}\) m\(^2\) |
| square inch | 1 in\(^2\) | \(= 6.452 \times 10^{-2}\) mm\(^2\) |

| **Volume** | | | |
| ▶ litre | 1 ltr | \[= 1.00 \times 10^{-3}\] m\(^3\) |
| cubic yard | 1 yd\(^3\) | \(= 7.646 \times 10^{-1}\) m\(^3\) |
| cubic foot | 1 ft\(^3\) | \(= 2.832 \times 10^{-2}\) m\(^3\) |
| cubic inch | 1 in\(^3\) | \(= 1.639 \times 10^{-6}\) mm\(^3\) |
| gallon (imperial) | 1 gal (UK) | \(= 4.546 \times 10^{-3}\) m\(^3\) |
| gallon (US liquid) | 1 gal (US) | \(= 3.785 \times 10^{-3}\) m\(^3\) |

| **Velocity, acceleration** | | | |
| foot per second (= fps) | 1 ft/s | \(= 3.048 \times 10^{-1}\) m/s |
| foot per minute | 1 ft/min | \(= 5.08 \times 10^{-3}\) m/s |
| mile per hour (= mph) | 1 mile/h | \(= 1.609 \times 10^0\) km/h |
| knot (international) | 1 knot | \(= 1.852 \times 10^0\) km/h |
| free fall, standard, g | 1 g | \(= 9.807 \times 10^0\) m/s\(^2\) |
| foot per second squared | 1 ft/s\(^2\) | \(= 3.048 \times 10^{-1}\) m/s\(^2\) |

This table has been prepared by E. R. A. Beck for use by the Division of Publications of the IAEA. While every effort has been made to ensure accuracy, the Agency cannot be held responsible for errors arising from the use of this table.
Multiply data given in: | Column 2 | Column 3 | Column 4 
---|---|---|---
Density, volumetric rate | | | 
- pound mass per cubic inch | 1 lbm/in³ = 2.768 x 10⁴ kg/m³ | | 
- pound mass per cubic foot | 1 lbm/ft³ = 1.602 x 10¹ kg/m³ | | 
- cubic feet per second | 1 ft³/s = 2.832 x 10⁻² m³/s | | 
- cubic feet per minute | 1 ft³/min = 4.719 x 10⁻⁴ m³/s | | 

Force | | | 
- newton | 1 N = 1.00 x 10⁹ m·kg·s⁻³ | | 
- dyne | 1 dyn = 1.00 x 10⁻⁴ N | | 
- kilogram force (= kilopond (kp)) | 1 kgf = 9.807 x 10⁰ N | | 
- poundal | 1 pdl = 1.383 x 10⁻¹ N | | 
- pound force (avoirdupois) | 1 lbf = 4.448 x 10⁹ N | | 
- ounce force (avoirdupois) | 1 ozf = 2.780 x 10⁻¹ N | | 

Pressure, stress | | | 
- pascal | 1 Pa = 1.00 x 10⁶ N/m² | | 
- atmosphere⁹, standard | 1 atm = 1.013 25 x 10⁵ Pa | | 
- bar | 1 bar = 1.00 x 10⁵ Pa | | 
- centimetres of mercury (0°C) | 1 cmHg = 1.333 x 10⁻¹ Pa | | 
- dyne per square centimetre | 1 dyn/cm² = 1.00 x 10⁻¹ Pa | | 
- feet of water (4°C) | 1 ftH₂O = 2.989 x 10⁵ Pa | | 
- inches of mercury (0°C) | 1 inHg = 3.386 x 10⁵ Pa | | 
- inches of water (4°C) | 1 inH₂O = 4.387 x 10⁴ Pa | | 
- kilogram force per square centimetre | 1 kgf/cm² = 9.807 x 10⁴ Pa | | 
- pound force per square foot | 1 lbf/ft² = 4.788 x 10⁴ Pa | | 
- pound force per square inch (= psi) b | 1 lbf/in² = 6.895 x 10⁴ Pa | | 
- torr (0°C) (= mmHg) | 1 torr = 1.333 x 10⁵ Pa | | 

Energy, work, quantity of heat | | | 
- joule (≡ W·s) | 1 J = 1.00 x 10⁶ N·m | | 
- electronvolt | 1 eV = 1.602 19 x 10⁻¹⁹ J, approx. | | 
- British thermal unit (International Table) | 1 Btu = 1.055 x 10⁶ J | | 
- calorie (thermochemical) | 1 cal = 4.184 x 10⁶ J | | 
- calorie (International Table) | 1 calₜₐₜ = 4.187 x 10⁶ J | | 
- erg | 1 erg = 1.00 x 10⁻⁷ J | | 
- foot-pound force | 1 ft·lbf = 1.356 x 10⁶ J | | 
- kilowatt-hour | 1 kW·h = 3.60 x 10⁶ J | | 
- kiloton explosive yield (PNE) (≡ 10¹² g-cal) | 1 kt yield = 4.2 x 10¹⁵ J | | 

Power, radiant flux | | | 
- watt | 1 W = 1.00 x 10⁶ J/s | | 
- British thermal unit (International Table) per second | 1 Btu/s = 1.055 x 10⁶ W | | 
- calorie (International Table) per second | 1 calₜₐₜ/s = 4.187 x 10⁶ W | | 
- foot-pound force/second | 1 ft·lbf/s = 1.356 x 10⁶ W | | 
- horsepower (electric) | 1 hp = 7.46 x 10² W | | 
- horsepower (metric) (= ps) | 1 ps = 7.356 x 10² W | | 
- horsepower (550 ft·lbf/s) | 1 hp = 7.457 x 10² W | | 

Temperature | | | 
- temperature in degrees Celsius, t | t = T - T₀ | | 
- where T is the thermodynamic temperature in kelvin and T₀ is defined as 273.15 K | | | 
- degree Fahrenheit | °F | | 
- degree Rankine | °R | | 
- degrees of temperature difference c | ΔTₜₐₜ (= ΔTₚ) = 5.192 x 10¹ W·m⁻¹·K⁻¹ | | 
- Thermal conductivity c | 1 Btu·in/(ft²·°F) (International Table Btu) = 5.192 x 10¹ W·m⁻¹·K⁻¹ | | 
- 1 Btu/ft²·°F (International Table Btu) = 6.231 x 10² W·m⁻¹·K⁻¹ | | 
- 1 cal/°C·cm·°C (International Table Btu) = 4.187 x 10² W·m⁻¹·K⁻¹ | | 

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a atm abs, ata: atmospheres absolute; atm (g), atü: atmospheres gauge. 
b lbf/in² (g) (= psig): gauge pressure; lbf/in² abs (= psia): absolute pressure. 
c The abbreviation for temperature difference, deg (= degK = degC), is no longer acceptable as an SI unit.
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