TRAINING COURSE ON RADIATION DOSIMETRY:

Gas Detectors for Microdosimetry

A.J. Waker, UOIT

Fundamentals of Gas-Filled Detectors

- One of the oldest and most widely used radiation detector types

- Gas-filled detectors respond to the direct ionization created by charged particles set in motion by the interaction of the radiation field with the chamber gas

    – Ion Chambers
    – Proportional Counters
    – Geiger-Mueller Counters

Fundamentals - Ionization in Gases

To create an ion pair, a minimum energy equal to the ionization energy of the gas molecule must be transferred

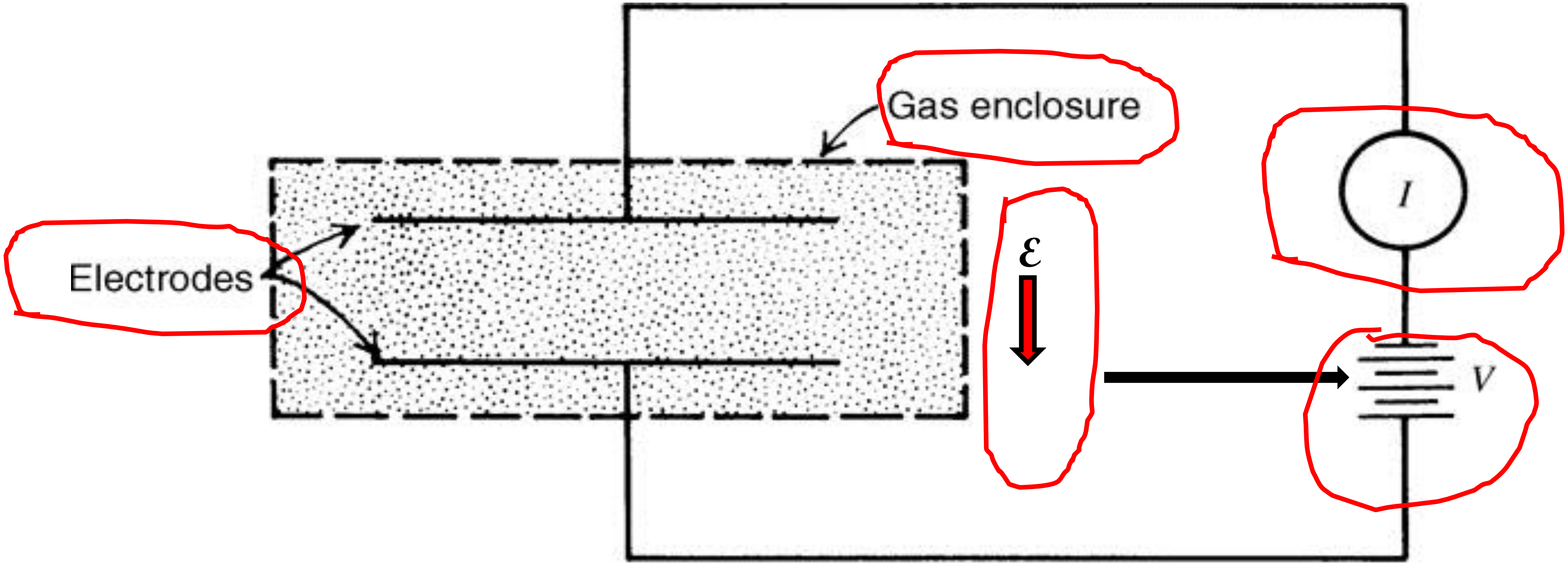
Ionization energy between 10 to 25 eV for least tightly bound electron shells for gases of interest in radiation detection

- **Competing mechanisms such as excitation leads to incident particle energy loss without the creation of ion pair**

W-value: average energy lost by incident particle per ion pair formed

Typical W-values are in the range of 25 – 35 eV/ion pair

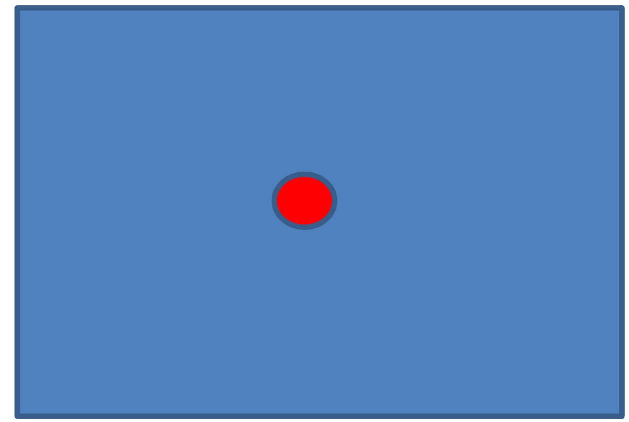
Fundamentals - Basic Components



Common Fill Gases: Ar, He, H_2, N_2, Air, O_2, CH_4, TE

Fundamentals – What is Measured?

$$D_{matter} = D_{cavity} \cdot \left\{\frac{S}{\rho}\right\}_{cavity}^{matter}$$



The charge generated in a gas-filled detector depends on:

- The gas used
- The material surrounding the gas
- The characteristics of the radiation field

Ionization Chambers in Experimental Microdosimetry

Ionization chambers have played an important niche role in experimental microdosimetry particularly for situations where nanometric site-sizes have been of interest or where high dose-rates have excluded the pulse-height measurement technique

- **Variance Methods**
  - Single chamber (variance)
  - Twin chambers (variance – covariance)

Based on the repeated measurement of charged collected in a given time interval and the relationship between the dose mean specific energy for single events, the relative variance for multiple events and the mean specific energy per time interval

$$\bar{Z}_D = V(z).\bar{Z}$$

Kellerer and Rossi: RADIATION RESEARCH 97, 237-245 (1984)
Lillhok, Grindborg, Lindborg et. al. Phys. Med. Biol. 52, 4953-4966, (2007)

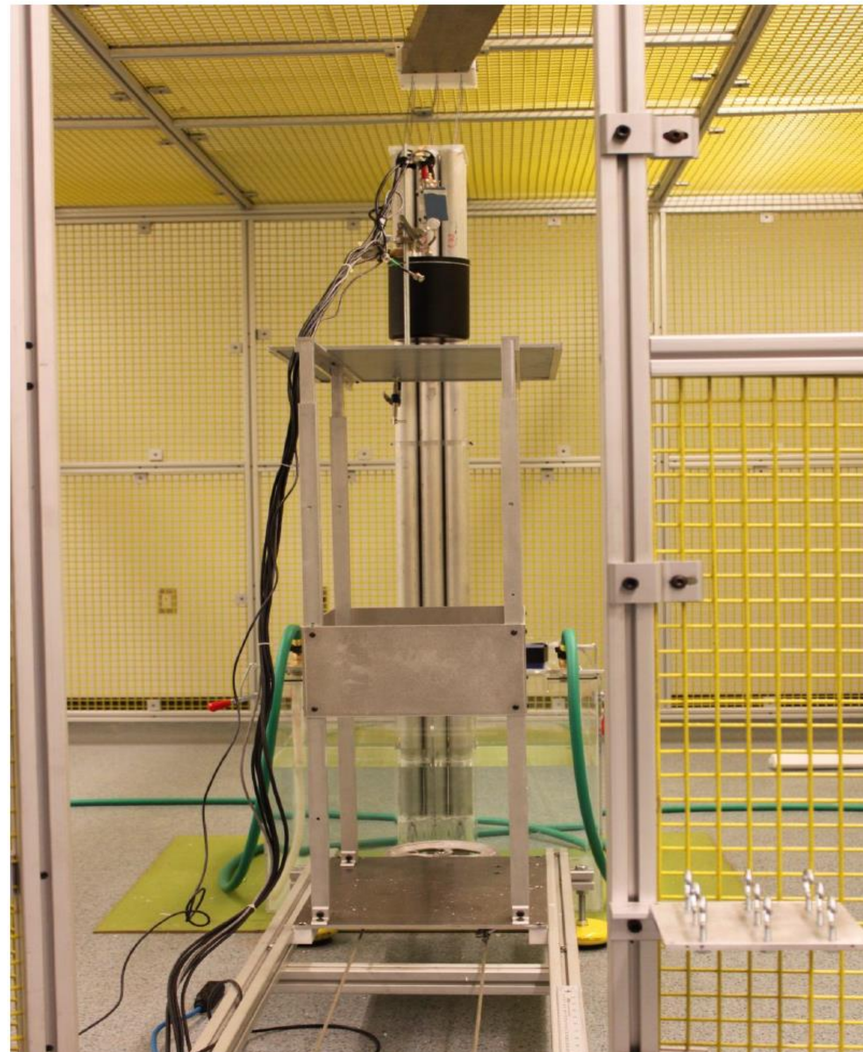
- **Recombination Chambers**
  - High pressure ionization chambers

Based on the difference of ionization current measured at two different collection voltages and the degree of columnar recombination in individual particle tracks.

Makrigiorgos and Waker: Phys. Med. Biol. 31, No 5, 543-554 (1986)
Golnik: Radiat. Prot. Dosim. No 1-4, 211-214 (1997)

Proportional Counters in Experimental Microdosimetry

- Operating Principle
- Tissue Equivalent (TEPC)
- Other Counter Types
  - Multi-element
  - Wall-Less
  - Heterogeneous



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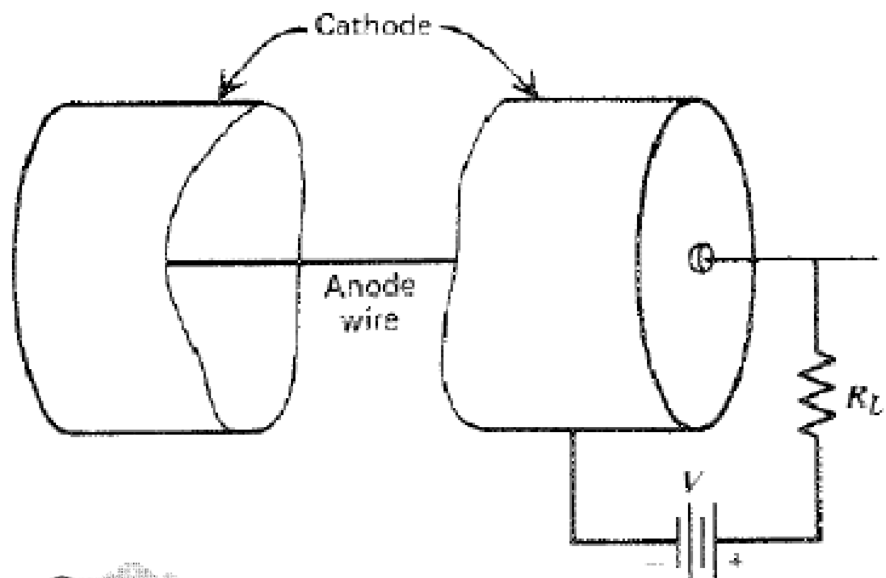
Proportional Counters – Operating Principle

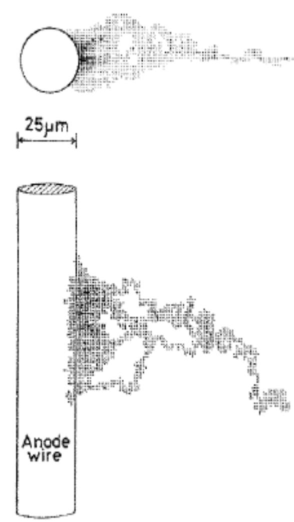
A proportional counter is a gas-ionization device consisting of a cathode, thin anode wire and fill-gas.

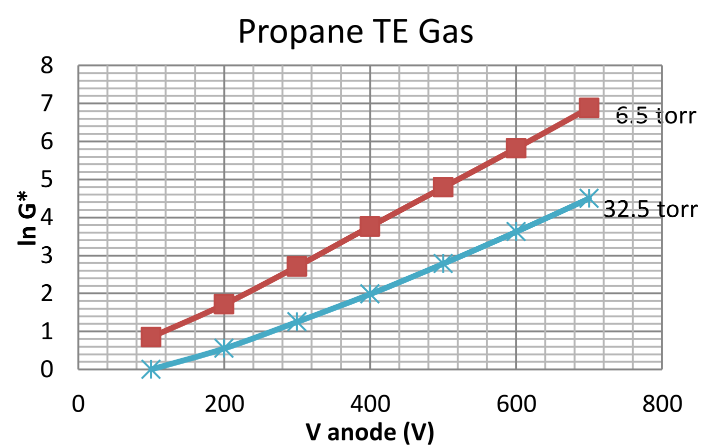
Charge produced by ionization in the fill gas is multiplied providing an amplified signal proportional to the original ionization.

Multiplication (gas-gain) depends on the fill-gas, applied voltage and detector geometry

With sufficient gas-gain the energy deposited by individual charged particle tracks can be recorded as a pulse-height single-event spectrum

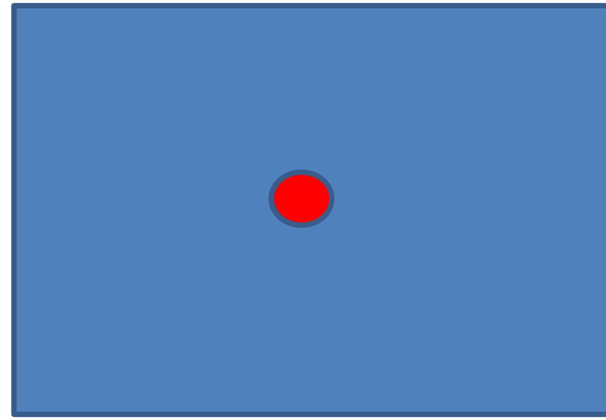






Proportional Counters – Tissue Equivalent Walls

$$D_{matter} = D_{cavity} \cdot \left\{\frac{S}{\rho}\right\}\frac{matter}{cavity}$$



For tissue equivalent walls and gas (homogeneous counters) the stopping power ratio is unity and absorbed dose in wall is given by the absorbed dose to the gas cavity

A150 TE-plastic atomic composition by % weight

H	C	N	O
muscle (10.2)	muscle (12.3)	muscle (3.5)	muscle (72.9)
10.1	**77.6**	**3.5**	**5.2**

Proportional Counters – Tissue Equivalent Gases

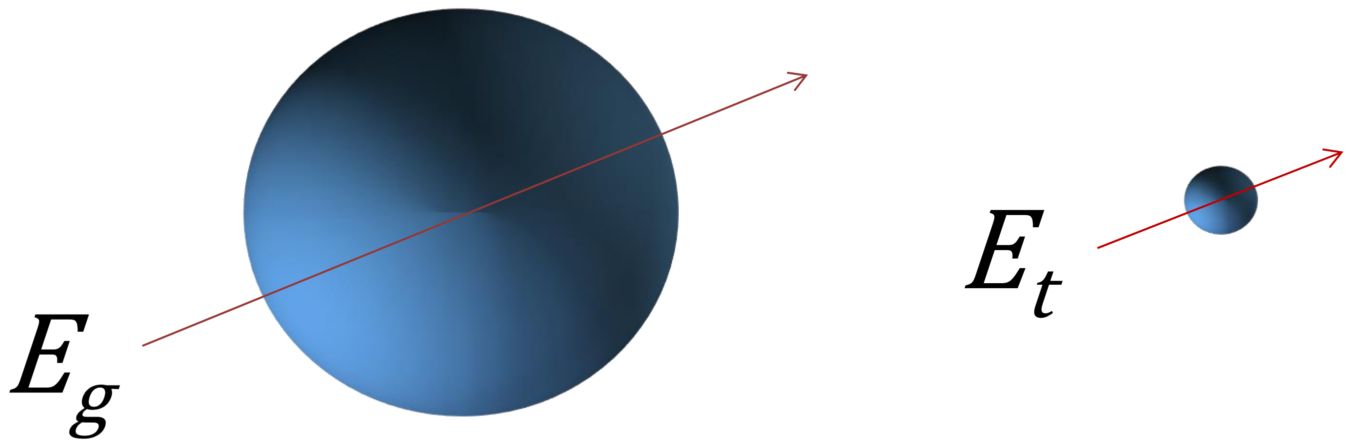
- **Methane based**
  - CH_4 (64.4% partial pressure)
  - CO_2 (32.4% partial pressure)
  - N_2 (3.2% partial pressure)
  - By %weight: **H (10.2); C (45.6); N (3.5); O (40.7)**

- **Propane based**
  - C_3H_8 (55% partial pressure)
  - CO_2 (39.6% partial pressure)
  - N_2 (5.4% partial pressure)
  - By %weight: **H (10.3); C (56.9); N (3.5); O (29.3)**

	H	C	N	O
ICRU Tissue (Muscle) atomic composition by % weight	10.2	12.3	3.5	72.9

Proportional Counters – Microscopic Site-Size Simulation

The density of the gas in the cavity is adjusted to equal the ratio of the tissue site diameter to the gas cavity diameter



Diameter of Tissue Site

$$\rho_g = \left(\frac{\Delta X_t}{\Delta X_g} \right) \rho_t$$

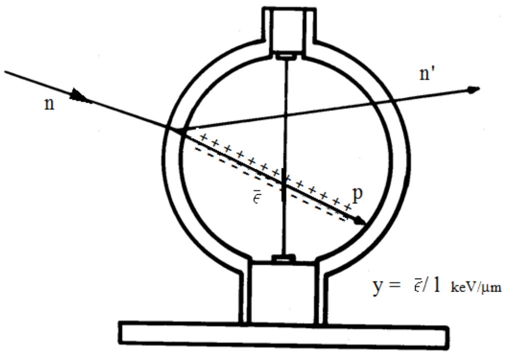
Density of Gas

Density of Tissue Site (1000 kg.m^{-3})

Diameter of Gas Cavity

Proportional Counters – TEPC Applications

- **TEPC - Measurable Quantities**
  - Absorbed dose
  - Mean Quality factor
  - Dose equivalent
  - Microdosimetric averages
- **TEPC - LET Spectrometry**
  - Radiation Field Analysis
  - Charge Particle Identification
- **TEPC - Differential Dosimetry**
  - Measurement of Kerma Factors
  - Boron Neutron Capture Dose



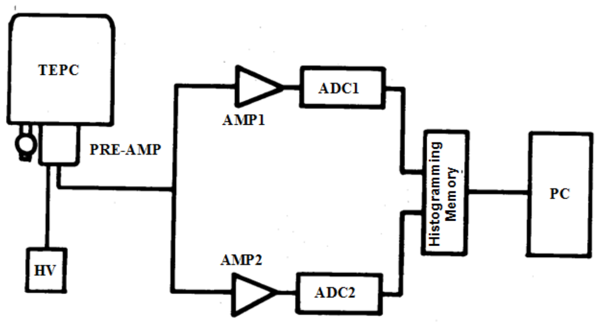


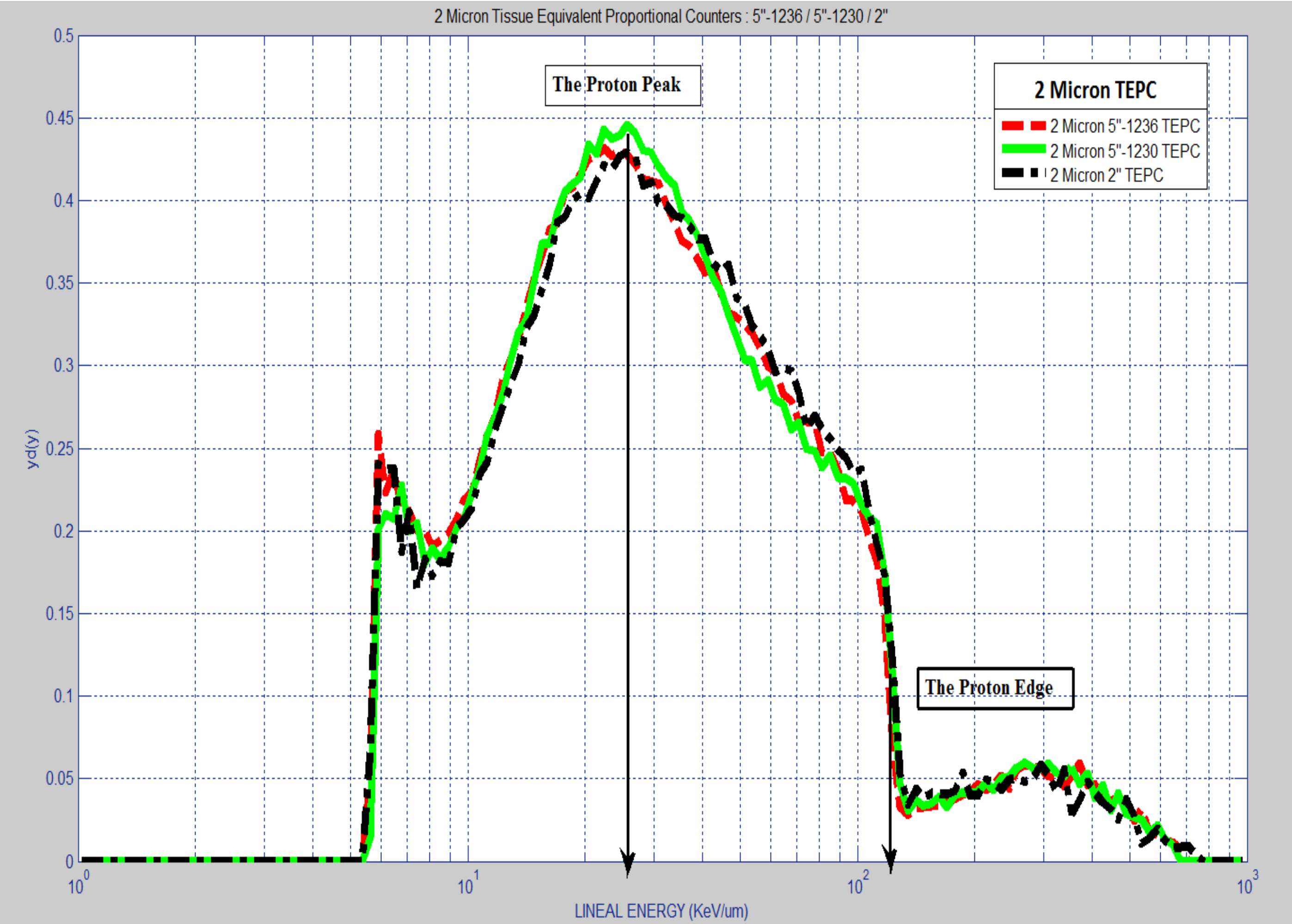
Figure 1. The principles of operation and measurement with TEPCs

TEPC Measureable Quantities – Absorbed Dose

Fraction of dose per log interval of Lineal Energy

yf(y) vs d(logy)

yd(y)



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TEPC Measureable Quantities – Absorbed Dose

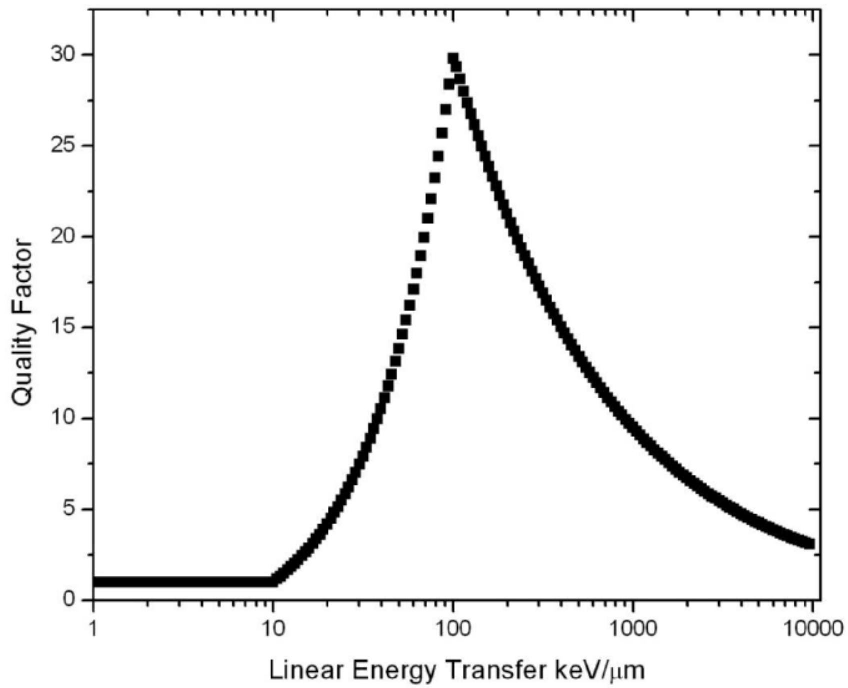
The absorbed dose to the counter gas cavity is derived from the measured *yd(y)* event-size spectrum:

$$D = \frac{energy\ deposited\ [J]}{mass\ of\ gas\ [kg]}$$

$$D = \frac{\sum_i y_i\, d(y)[keV/\mu m]\ x\ \bar{l}\ [keV/\mu m]}{\rho_g\ x\ V}\ 1.602\ \mathrm{E} - 16\ [J/keV]$$

Measureable Quantities – Quality Factors

From ICRP 60



$$Q(L) = \begin{cases} 1, & L < 10\, keV/\mu m \\ 0.32L - 2.2, & 10 \le L \le 100\, keV/\mu m \\ \frac{300}{\sqrt{L}}, & L > 100\, keV/\mu m \end{cases}$$

Measureable Quantities – Dose Equivalent

$$H = D.\bar{Q}$$

Dose to the gas cavity calculated directly from the measured event-size spectrum

Determined from the shape of the event-size spectrum and assuming Q(y) = Q(L)

Measureable Quantities – Dose Equivalent Response

For neutron s the measured quantity, dose-equivalent to the gas-cavity is often compared to the operational quantity Ambient Dose Equivalent H*(10). The dose equivalent response of the TEPC, defined as *H/H*(10),* is a function of neutron energy and is found to be close to unity for neutron fields greater than 1 MeV and for thermal neutrons, but significantly less than 1.0 for neutrons of a few hundred keV and below.

Measureable Quantities – Dose Equivalent Response

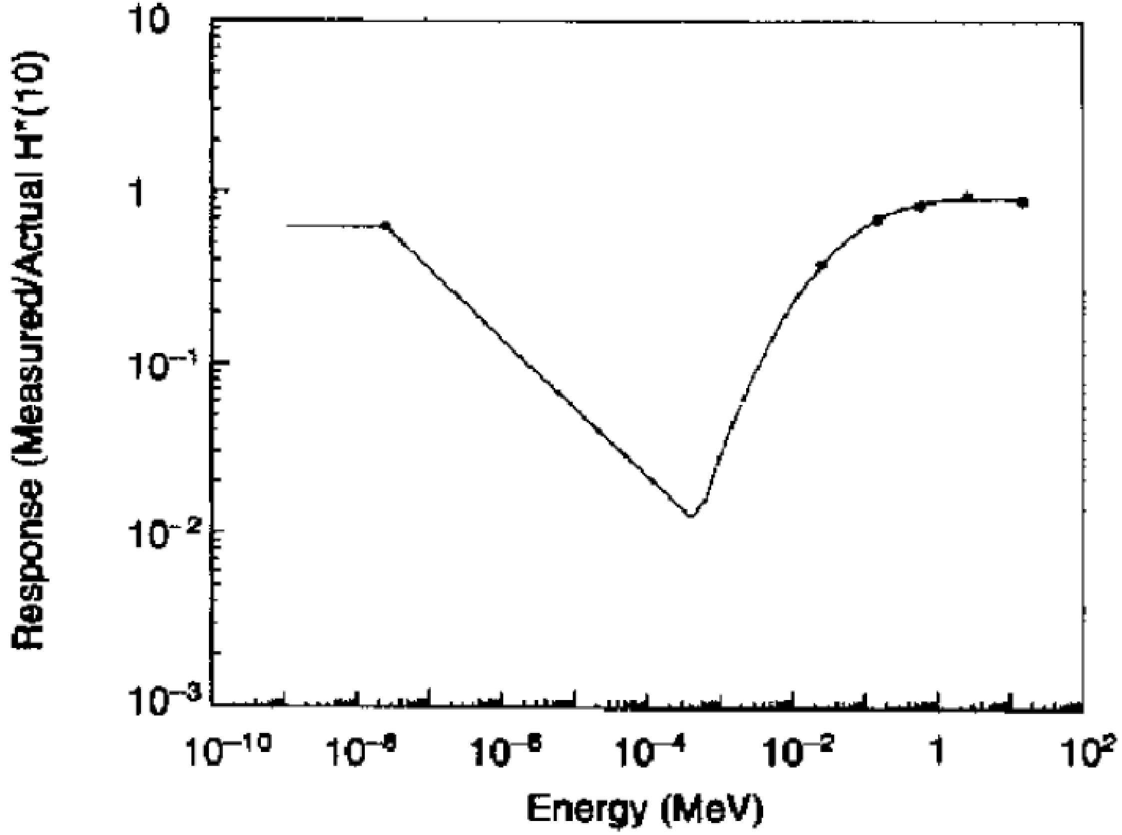


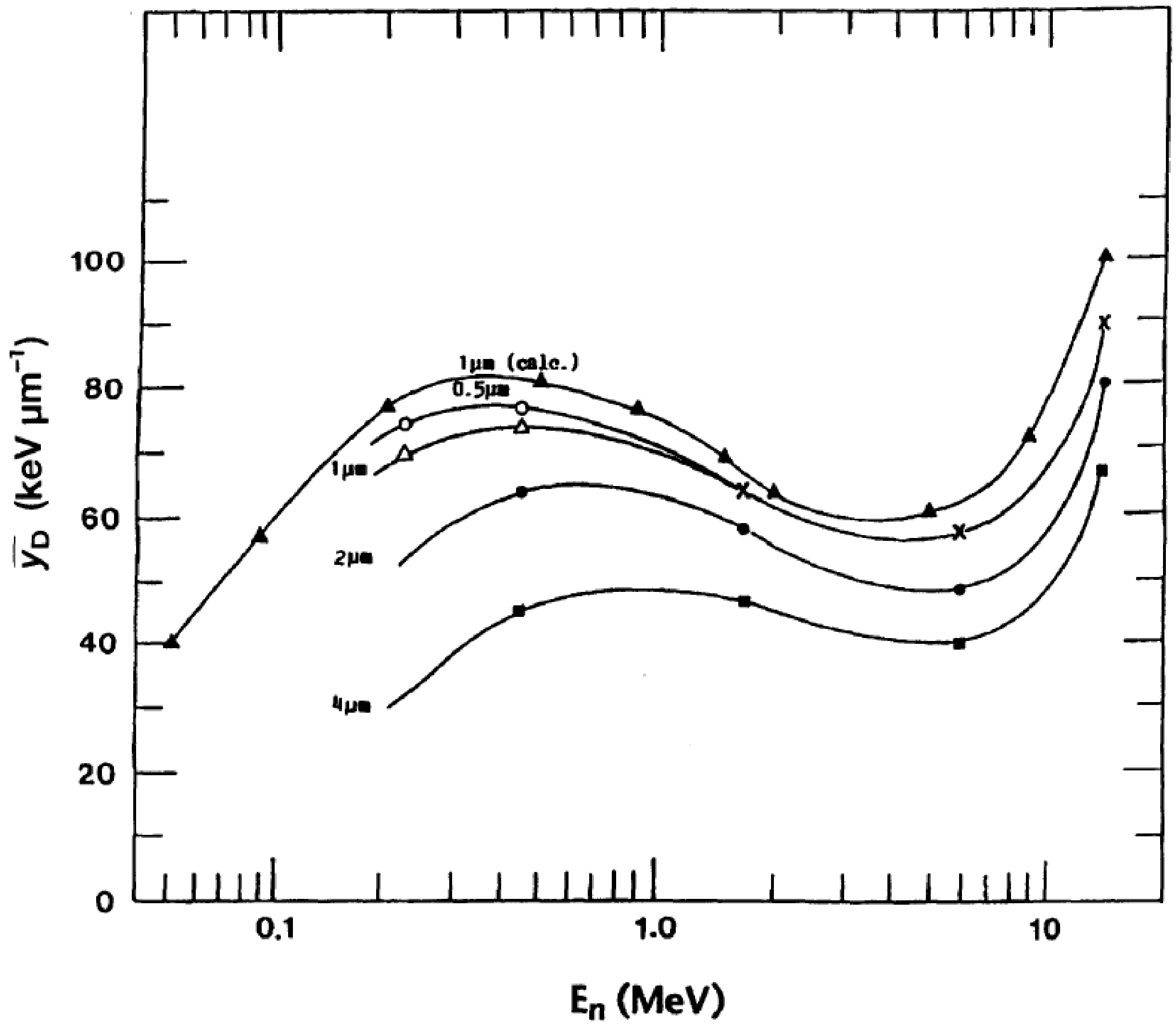
Figure 3. Monoenergetic response of a 5″ TEPC. Response is defined as the fraction of the ambient dose equivalent that is measured by the instrument. Line, analytical fit; symbols, experimental data from Reference 8.

Nunes and Waker, Radiat. Prot. Dosim. 59, No 4, 279-284, 1995

Measureable Quantities – Microdosimetric Averages

Microdosimetric averages such as the frequency mean and dose mean lineal energy are important measures of radiation quality for characterising radiation fields and therapy beams in terms of their potential biological effect. These quantities are directly derivable from measured event-size spectra using TEPCs

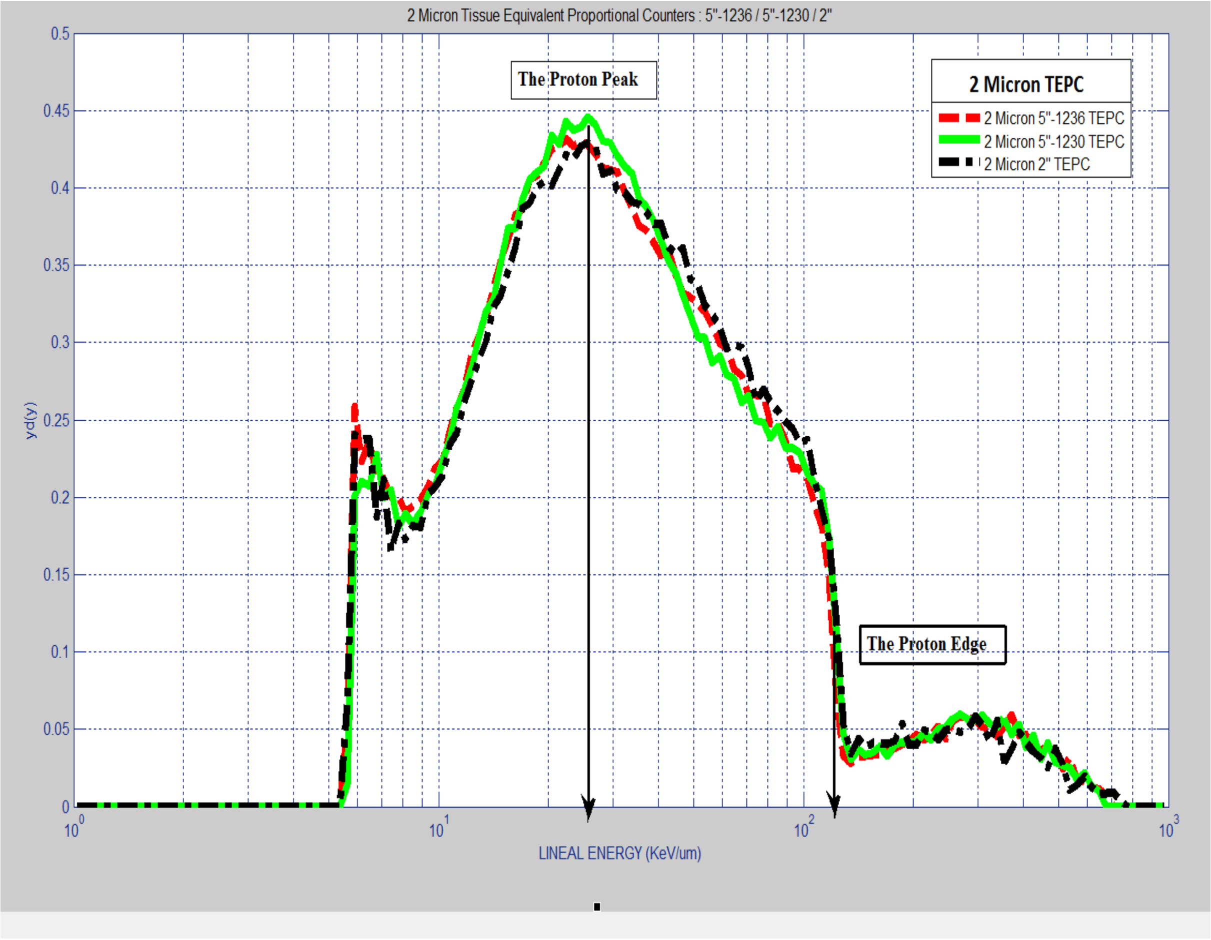
Measureable Quantities – Microdosimetric Averages



Dušan Srdoč*,2 and Stephen A. Marino
RADIATION RESEARCH **146**, 466–474 (1996)

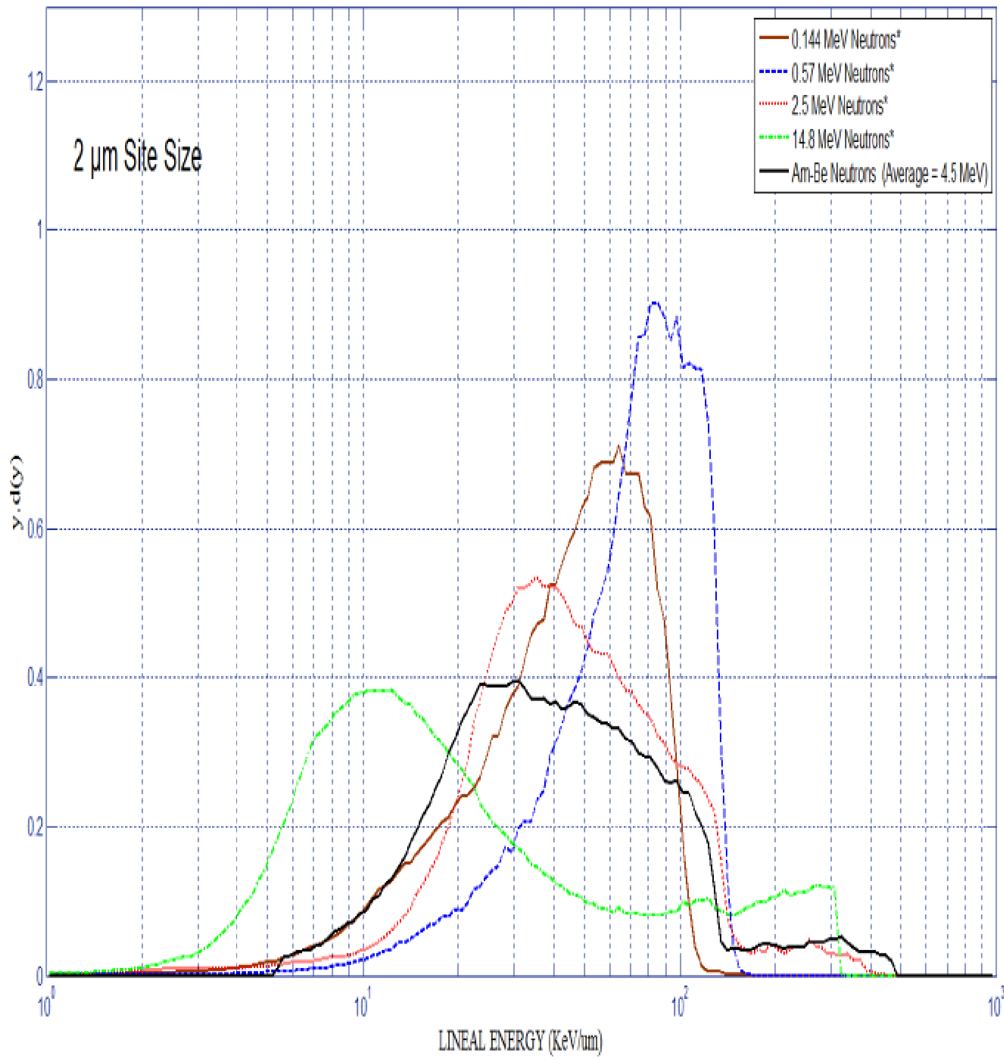
TEPC – LET Spectrometry

Recognizable features of an event-size spectrum enable us to identify and analyse radiation fields



LET Spectrometry– Radiation Field Analysis

The position of 'peaks' and 'edges' can tell us something about the energy of the radiation and gives us fixed event-sizes for calibration



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LET Spectrometry – Radiation Field Analysis

Similarly, photon fields can be identified by the position of ‘peaks’ and ‘edges’ in the event-size spectrum.

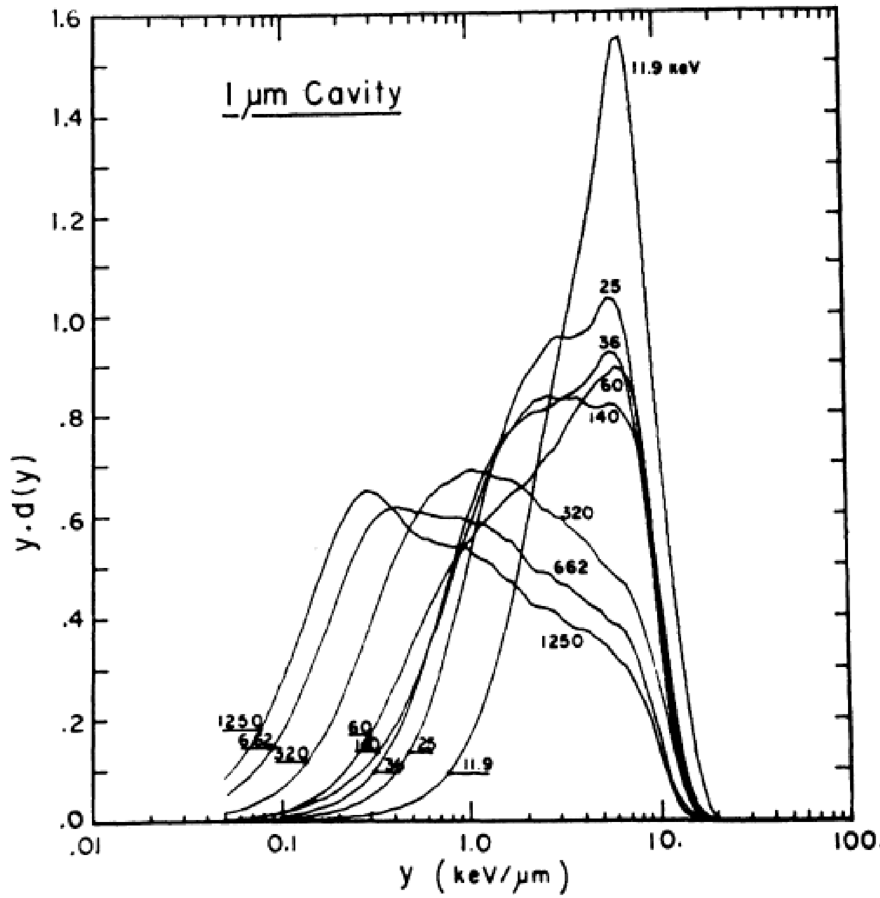
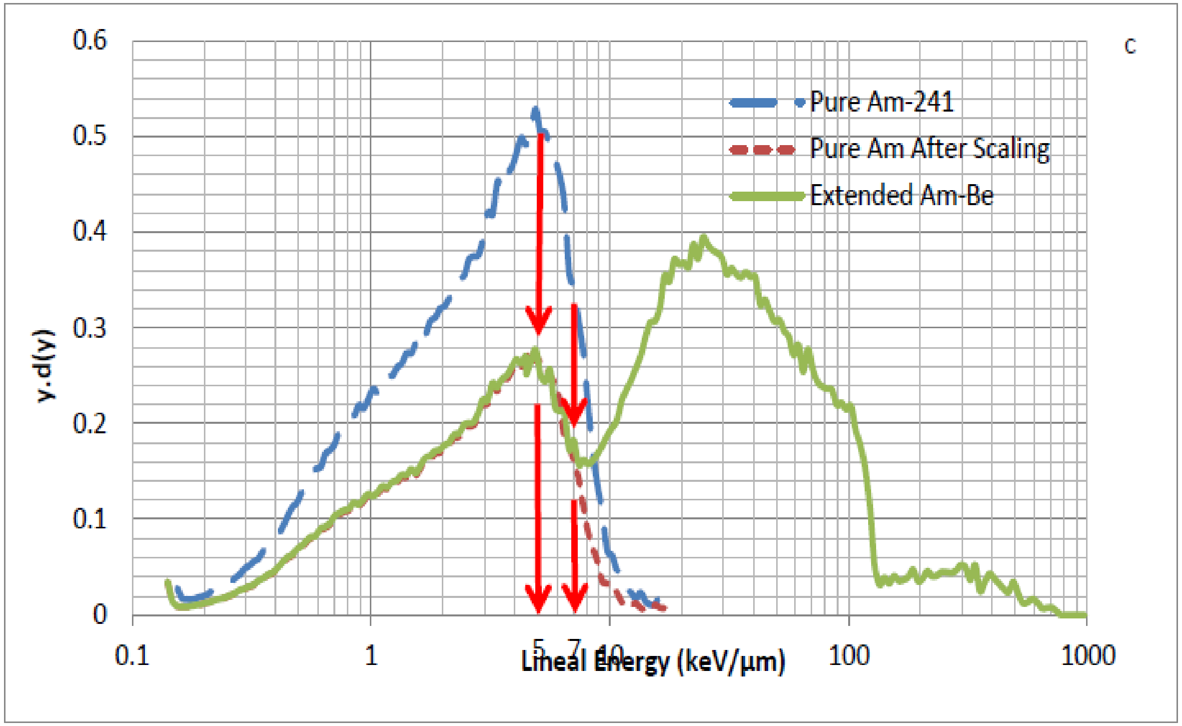


FIG. 10. The distribution $yd(y)$ as a function of y for a 1-μm simulated cavity at eight photon energies.

P. KLIAUGA AND R. DVORAK[2] RADIATION RESEARCH **73**, 1–20 (1978)

LET Spectrometry – Charged Particle Identification

Mixed field neutron - gamma dosimetry can be carried out by the identification of ‘low LET’ electrons and ‘high LET’ protons



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Differential Dosimetry - Kerma Factors

Differences between microdosimetric spectra obtained with counters with wall-materials different in one element can provide information on the kerma per unit fluence for that element

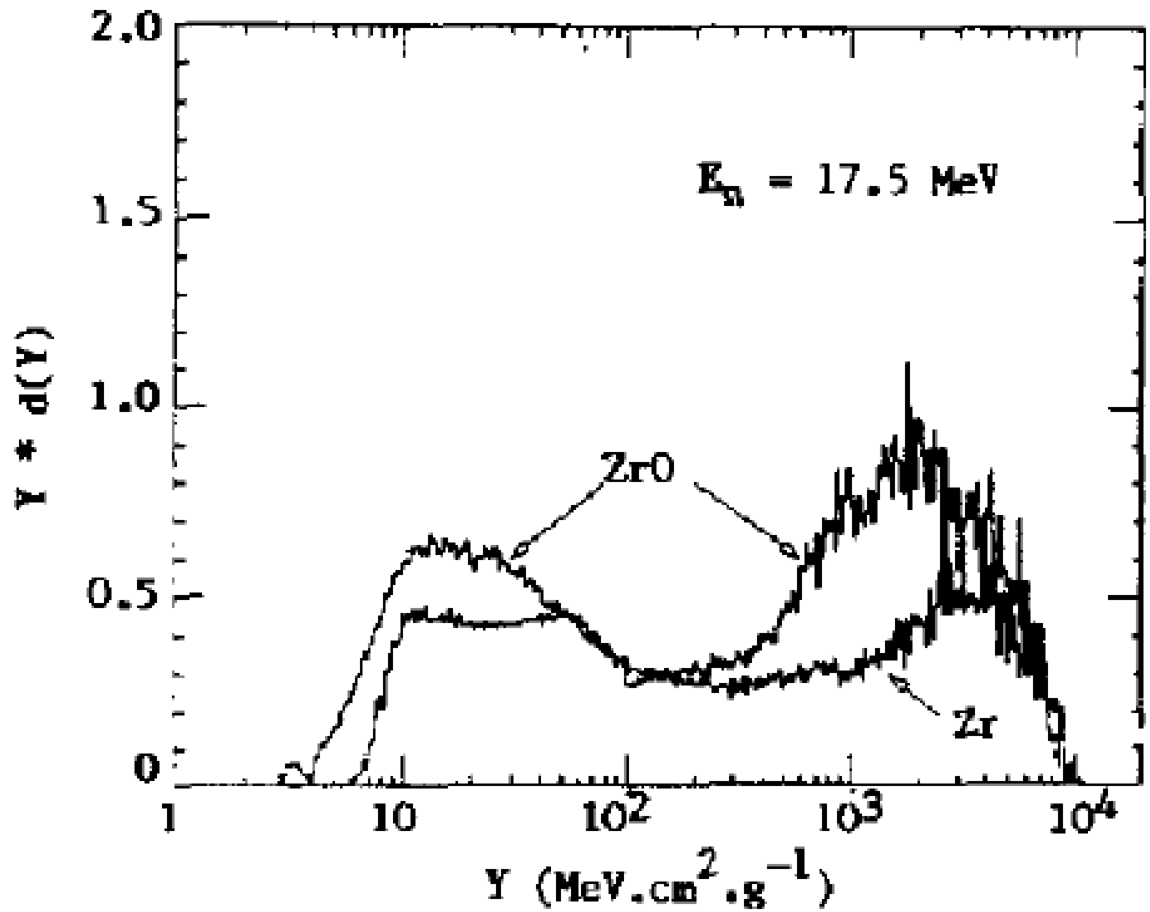
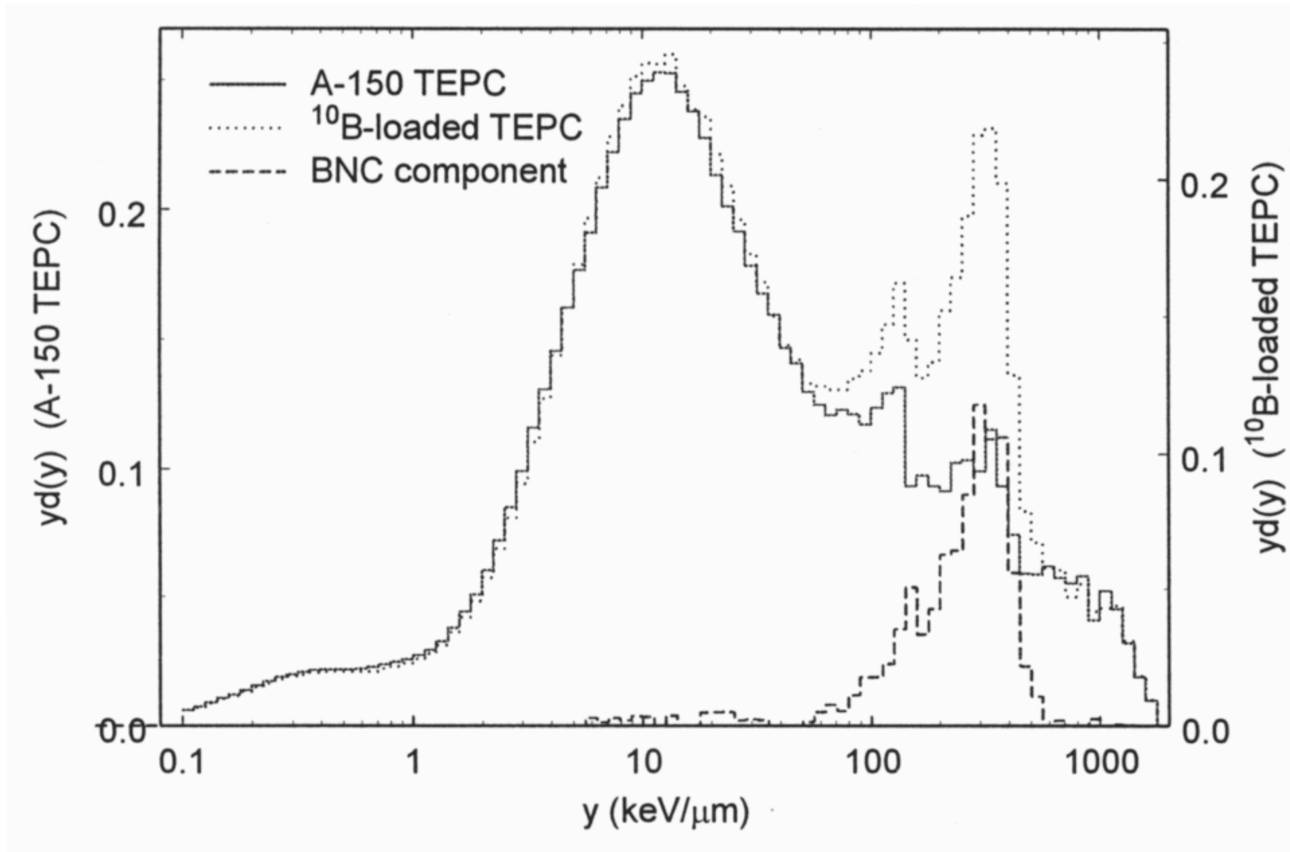


Figure 2. Measured dose distribution plotted against event size for ZrO and Zr walled counters bombarded by 17.5 MeV neutrons.

DeLuca et al. Radiat. Prot. Dosim. 23 Nos 1-4, 27-30, 1988

Differential Dosimetry - BNCT

Differences between microdosimetric spectra obtained with counters with wall-materials having different boron concentrations can provide information on the dosimetric impact of boron capture in a given neutron field

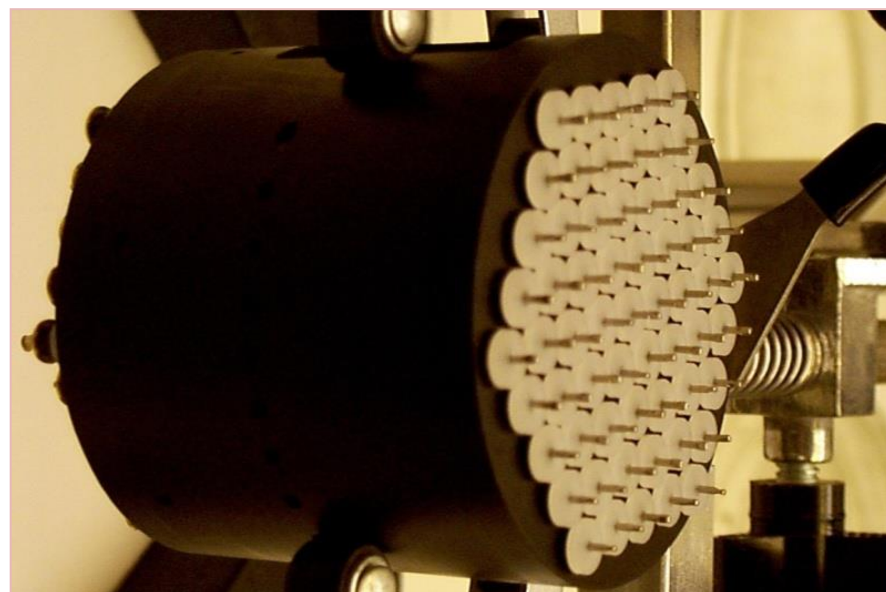


Waker , Burmeister et al, Radiat. Prot. Dosim., 99, No 1-4, 311-316, 2002

Other Counter Types – Multi-Element

To increase the sensitivity of a TEPC we need to increase the surface area of the wall either by:

- Increasing the diameter of the counter
- Constructing a multi-element device



Other Counter Types – Multi-Element Counters

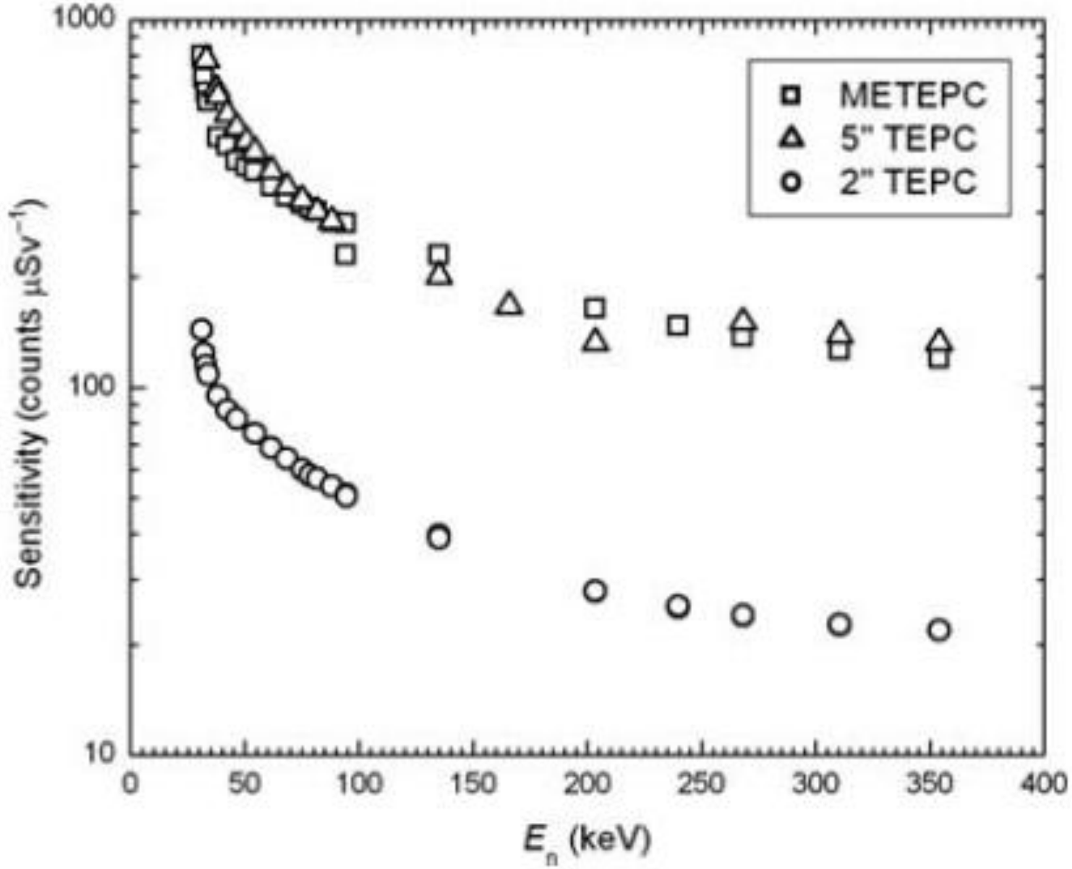
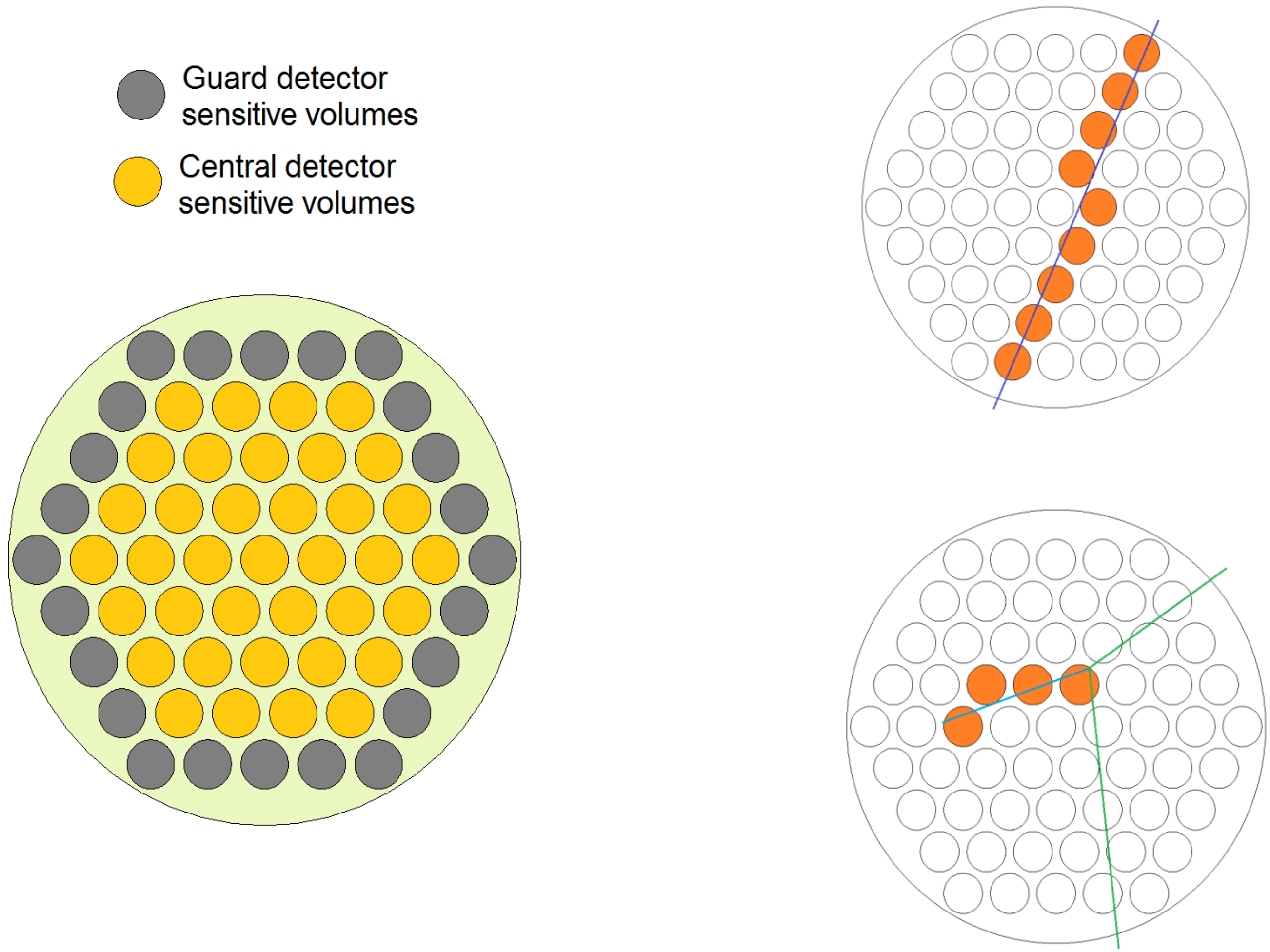


Figure 8. Comparison of the sensitivity of the METEPC as a function of mean neutron energy with that of a 5″ and 2″ diameter spherical TEPC.

Waker, Aslam and Lori; Radiat. Prot. Dosim, 2010

Other Counter Types – Multi-Element

Using coincidence techniques to distinguish between energetic charged particles and neutrons in high energy ion beams or Space radiation environment



Matysiak , Hanu and Waker, PTCOG51, 2012

Other Counter Types– Wall-Less

Measurement of dose mean specific energy avoiding the distortions introduced by 'wall-effects' due to the difference in density between the solid TE wall and the TE gas cavity

250 WILLIAM A. GLASS AND WILLIAM A. GROSS

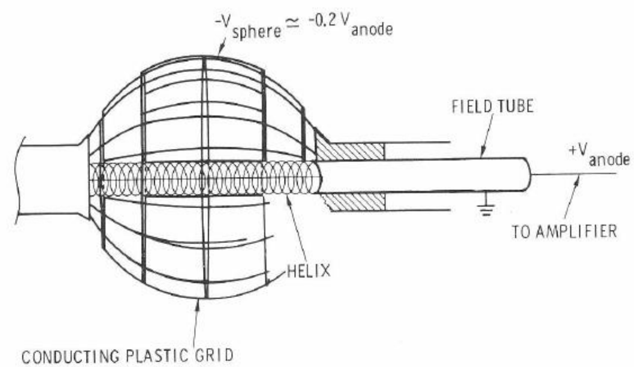


FIG. 8. A spherical grid-walled counter. The spherical ionization chamber is gas coupled to a cylindrical proportional counter (after Gross *et al.*, 1970).

4. WALL-LESS DETECTORS IN MICRODOSIMETRY 251

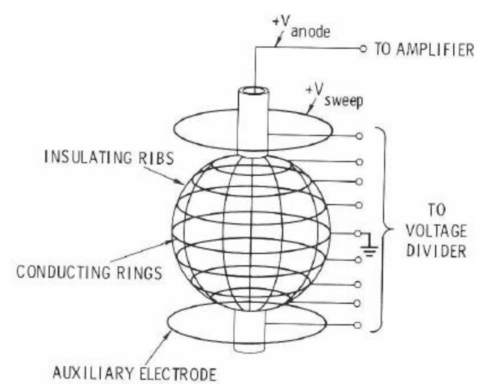


FIG. 9. Spherical grid-wall counter using a series of wall potentials (after Braby, 1971).

Topics in Radiation Dosimetry – Supplement 1. F. Attix, Academic Press, 1972

Other Counter Types– Wall-Less

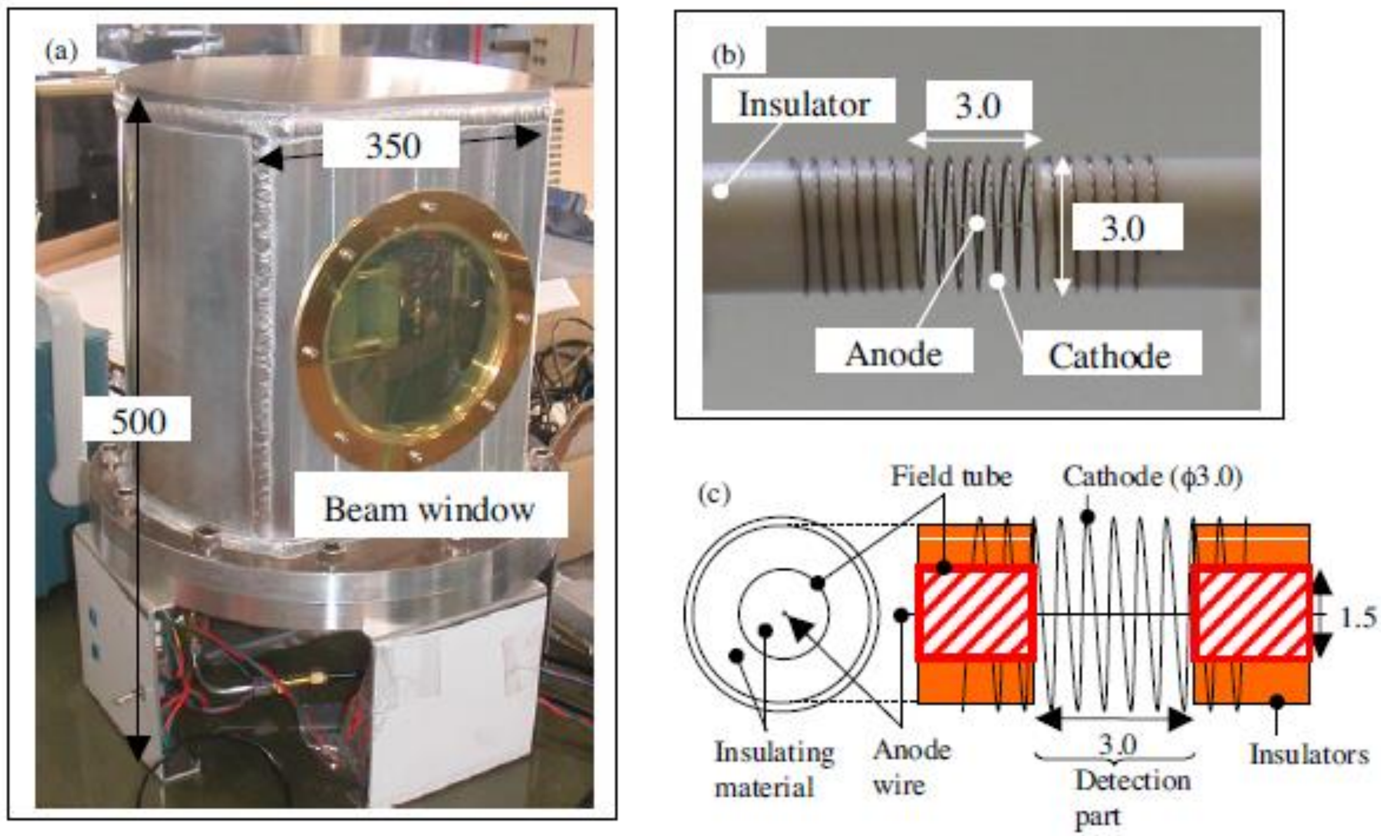
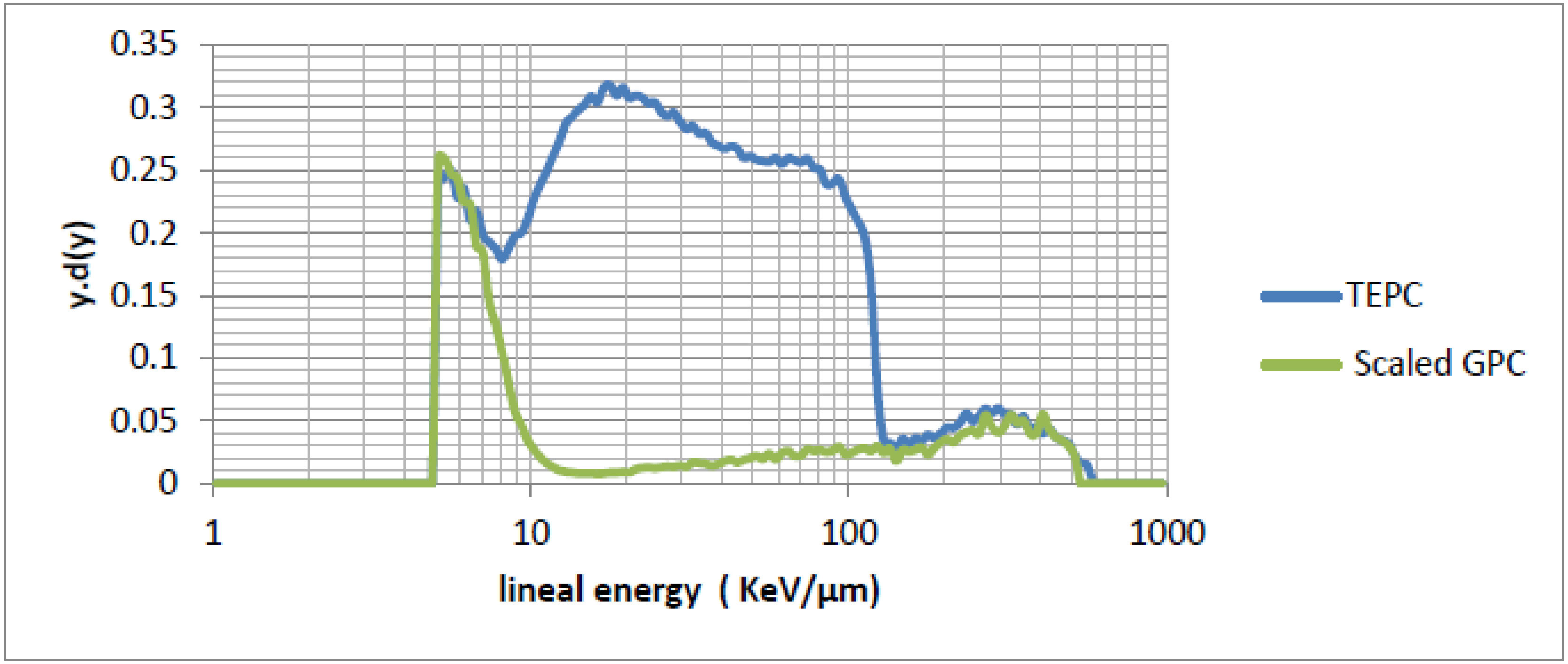


Figure 2. Photographs of the wall-less tissue-equivalent proportional counter (unit: mm). The overview (a) and the detection part (b) are shown. The details of the detection part are illustrated in (c).

Tsuda et. al. Phys. Med. Biol., 55, 5089-5101, 2010

Other Counter Types – Heterogeneous

Graphite counter used in mixed field dosimetry



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Future Needs and Challenges

- Size and sensitivity
- Calibration
- Signal Processing

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