# Simulation of a Compact Multi Element Tissue Equivalent Proportional Counter Response in Low Energy Monoenergetic Neutron Fields

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## Summary

A Tissue Equivalent Proportional Counter (TEPC) directly measures dose equivalent delivered by a radiation field to human tissue. TEPC technology has great potential for use in low energy neutron fields, such as those in nuclear power plants, however, what hinders its use as a portable or personal dosimeter in such fields is its large physical size. To address this technology gap, a Compact Multi Element Tissue Equivalent Proportional Counter (CMETEPC) has been developed. This paper describes the process of designing the CMETEPC and discusses how this counter performs in low energy monoenergetic neutron fields relative to established TEPC designs.

## 1. Introduction and Theory

Tissue Equivalent Proportional Counters (TEPCs) are devices used to measure **dose equivalent** in low energy mixed radiation fields such as those present in nuclear power plants. A typical TEPC design consists of a spherical gas cavity surrounded by a solid wall, both of which are composed of tissue-equivalent material. The gas cavity of the counter seeks to replicate a microscopic tissue volume in which energy deposition by secondary charged particles is measured. This is made possible through the use of the following equation [1]:

$$\rho_{\mathrm{g}} = \left(\frac{\Delta X_{\mathrm{t}}}{\Delta X_{\mathrm{g}}}\right)\rho_{\mathrm{t}} \tag{1}$$

Where:
$\rho_g$ = gas density in TEPC cavity (unit: g cm$^{-3}$) $\rho_t$ = density of tissue (1 g cm$^{-3}$)
$\Delta X_g$ = TEPC gas cavity diameter (unit: cm) $\Delta X_t$ = microscopic site diameter (unit: μm)

Equation (1) states that the diameter of the microscopic tissue volume will dictate the density of gas used to fill the TEPC cavity. TEPC technology is capable of measuring the kinetic energy deposited in the gas cavity by each secondary charged particle that traverses it, however it is desired to know the **lineal energy** of each such particle which quantifies how much energy these particles deposited per unit distance they would have travelled in the corresponding microscopic tissue volume. This distance travelled on the microscopic scale is represented by the mean chord length of the microscopic tissue volume and it represents the average distance each secondary charged particle that traversed the gas cavity will travel in the microscopic site. Knowledge of the lineal energy of each secondary charged particle that traverses the TEPC gas cavity is used to calculate its quality factor using guidelines provided by the International Commission on Radiological Protection [2]. The tabulation of the lineal energy of each traversing charged particle coupled with their quality factors enables the calculation of the dose equivalent delivered by the radiation field to the TEPC and to the simulated microscopic site.

There are two metrics used to quantify the response of a TEPC in a particular radiation field [1]. The first is the **sensitivity** and it is defined as the number of incident radiation particles detected per unit dose equivalent measured and the second is the **dose equivalent response** and is calculated using the following equation:

$$R_H = \frac{\text{measured dose equivalent}}{\text{ambient dose equivalent}} = \frac{D \cdot \langle Q \rangle / \Phi}{H^*(10) / \Phi} \tag{2}$$

Where:

| | | | |
|---|---|---|---|
| $R_H$ = | dose equivalent response of TEPC | D = | absorbed dose delivered to TEPC gas cavity (unit: Gy) |
| $\langle Q \rangle$ = | mean quality of secondary charged particles traversing TEPC gas cavity | $H^*(10)/\Phi$ = | ambient dose equivalent for radiation field per unit fluence |

For any radiation field, an optimum TEPC performance will result in a high sensitivity, which will result in a lower standard deviation associated with the measured dose equivalent and a dose equivalent response close to unity. Standard spherical TEPC designs may provide such a performance for polyenergetic neutron radiation fields in nuclear power plants however their large physical size prohibits its use as a portable and personal radiation dosimeter. To address this technology gap, a Multi Element Tissue Equivalent Proportional Counter (METEPC) was developed by Waker and Aslam [3] and consists of 61 cylindrical gas cavities (known as *elements*) machined into a hexagonal array. For a variety of low energy neutron fields, it was found that the METEPC yielded response metrics that was identical or slightly better than those provided by a standard 5 inch spherical TEPC despite the METEPC having an overall volume that is 90% smaller than the aforementioned standard design. Given the strides made by the METEPC, the current form of this counter design is still too large to be deemed suitable for use as a portable and personal dosimeter. The work presented in this paper documents the design of a new, truncated METEPC design and its performance in several monoenergetic neutron fields.

## 2. Compact Multi Element Tissue Equivalent Proportional Counter

The foremost design goal associated with the truncated METEPC design (herein known as the Compact Multi Element Tissue Equivalent Proportional Counter or CMETEPC) is to provide similar or better sensitivity and dose equivalent response for any radiation field relative to that offered by the existing METEPC design, albeit with a smaller physical volume. The CMETEPC, just like the METEPC, will consist of small cylindrical elements machined into a hexagonal array. However, in order for the CMETEPC to provide the same performance as the METEPC, the following design requirements must be met:

(1) The total surface area of the CMETEPC's cylindrical elements must be equal to that in the METEPC

(2) The mean chord length of each CMETEPC cylindrical element must be similar to that offered by each cavity in the METEPC

Fulfilling the two design requirements above will enable both counter designs to measure similar lineal energy spectra of secondary charged particles that traverse its gas cavities thereby resulting in both instruments providing comparable sensitivity and dose equivalent response for a given radiation field. The figure below illustrates the two counter designs along with their respective radial and axial dimensions:

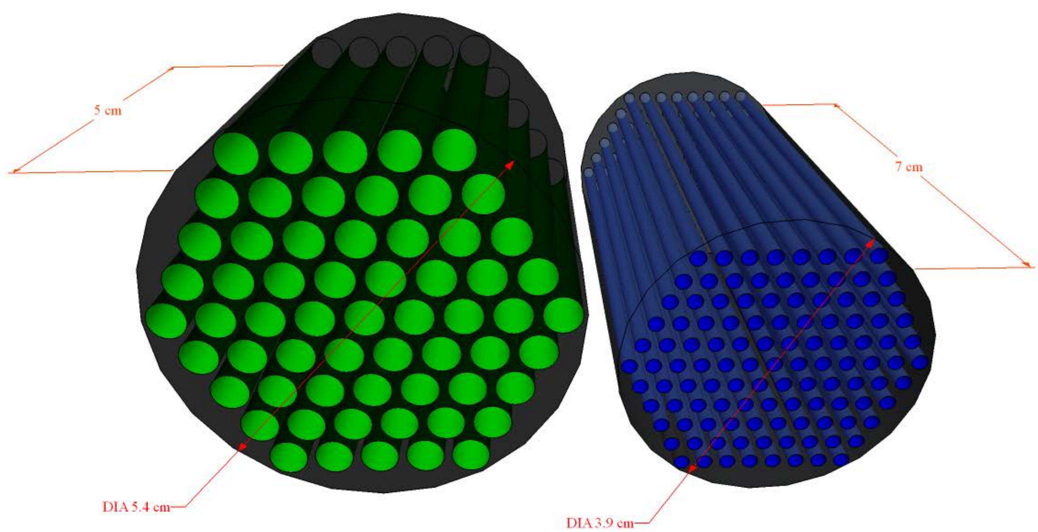


Figure 1 Illustration of METEPC (left) and CMETEPC (right) Instrument Designs

The table below compares several attributes of the counters illustrated above.

| Design Feature | METEPC | CMETEPC |
|---|---|---|
| Number of Elements | 61 | 113 |
| Dimension of Each Element | Diameter = 0.5 cm<br>Length = 5 cm | Diameter = 0.2 cm<br>Length = 7 cm |
| Total Element Surface Area | 503.05 $cm^2$ | 504.10 $cm^2$ |
| Overall Volume of Counter | 114.5 $cm^3$ | 83.6 $cm^3$ |
| Dimension of Corresponding Microscopic Volume | Diameter = 2 μm<br>Length = 20 μm | Diameter = 2 μm<br>Length = 70 μm |
| Mean Chord Length of Each Element | 1.90 μm | 1.97 μm |
| Gas Density Used to Fill Each Element | $4 \times 10^{-4}$ g $cm^{-3}$ | $1 \times 10^{-3}$ g $cm^{-3}$ |

Table 1 Comparison of Instrument Design Features

The next section will describe three-dimensional Monte Carlo radiation transport simulations used to simulate the performance of the METEPC and CMETEPC designs in monoenergetic neutron fields.

## 3. Simulation Method

For a given radiation field, it is necessary to verify that the METEPC and CMETEPC provide comparable sensitivity and dose equivalent response. This is made possible by performing three-dimensional Monte Carlo radiation transport simulations which simulate the transport of neutrons and the secondary charged particles they create within each counter design. From this simulation, a histogram of frequency as a function of kinetic energy deposited is extracted and it is this spectrum that is used to quantify the two abovementioned response metrics. The Particle and Heavy Ion Transport code System (PHITS) version 2.24 is the Monte Carlo code used to perform the required simulations. In the simulations performed, the two instruments were respectively irradiated with planar monoenergetic neutron beams of 204 keV, 354 keV, and 423 keV energy.

## 4. Results

The table below lists the values of the response metrics calculated for each counter design for the three neutron fields mentioned above.

| **Incident Neutron Energy** | **Sensitivity (Counts μSv$^{-1}$)** | | **Dose Equivalent Response** | |
|---|---|---|---|---|
| | METEPC | CMETEPC | METEPC | CMETEPC |
| 204 keV | 313.76 ± 2.96 | 363.15 ± 3.24 | 0.5583 ± 0.0050 | 0.5722 ± 0.0048 |
| 354 keV | 167.85 ± 1.43 | 190.11 ± 1.54 | 0.6585 ± 0.0052 | 0.6802 ± 0.0051 |
| 423 keV | 150.26 ± 1.21 | 169.06 ± 1.30 | 0.6542 ± 0.0049 | 0.6770 ± 0.0048 |

Table 2 Instrument Response Metrics for Monoenergetic Neutron Fields

The results shown in the table above indicate that for each of the three neutron fields, the CMETEPC is able to provide a higher dose equivalent response and sensitivity than the existing METEPC. The latter finding is attributed to the fact that as per the details provided in table 1, the CMETEPC has the same total element surface area as the METEPC, however the density of gas used to fill each element in higher. These two characteristics will enable more incident neutrons to interact with the truncated counter, thereby leading to a higher sensitivity.

## 5. Conclusions

A Compact Multi Element Tissue Equivalent Proportional Counter design has been developed. This instrument provides increased sensitivity and dose equivalent response, relative to the existing METEPC, albeit with a smaller physical size. The CMETEPC represents a potential portable dosimeter that can be used to directly measure dose equivalent delivered to nuclear power plant workers exposed to low energy neutron fields. Further simulation studies will be conducted which will focus on quantifying the response metrics of the METEPC and CMETEPC in realistic nuclear power plant neutron fields such as those offered by Americium-Beryllium, Californium-252, and Californium-252 $D_2O$ moderated neutron sources.

## 6. References

[1] Waker, A. J., “Principles of Experimental Microdosimetry”, *Radiation Protection Dosimetry*, 61, 4, 1995, 297-308.

[2] International Commission on Radiological Protection, “ICRP Publication 60”, 1991.

[3] Waker, A. J., Aslam. “A Preliminary Study of the Performance of a Novel Design of Multi-Element Tissue Equivalent Proportional Counter for Neutron Monitoring”, *Radiation Measurements*, 45, 10, 2010, 1309 – 1312.