A new plate-like tissue equivalent proportional counter (TEPC) based on the gas electron multiplier (GEM) is being developed for use as a neutron rem meter. The advantage of a plate-like TEPC over a conventional spherical TEPC is that several of the plate-like TEPCs can be stacked together as one unit to increase sensitivity to neutrons. A GEM-based TEPC consists of four layers of materials in a series: the front cover made of polyethylene, the cathode made of A-150 plastic, the gas region containing 1/3 atm of P-10 and 1/3 atm of nitrogen and the anode made of a copper-coated printed circuit board. The dimensions of the TEPC are 10 cm x 10 cm x 1.8 cm. The computer simulation shows that the neutron response function of the TEPC closely resembles the response curve of $H^*(10)$ for neutrons with energies between 0.25 eV and 10 MeV. The corresponding sensitivity for such a TEPC for a bare $^{252}$Cf neutron source was calculated to be 5.0 cpm per $\mu$Sv h$^{-1}$. This sensitivity can be increased many times by simply stacking several TEPCs together as one unit.

INTRODUCTION

As recommended by the International Commission on Radiation Units and Measurements (ICRU), the operational quantity for area monitoring of external penetrating radiations is called the ambient dose equivalent, $H^*(10)$, defined as the dose equivalent measured at the depth 10 mm inside a tissue-equivalent phantom$^1$. Several techniques have been developed to measure $H^*(10)$ for gamma rays satisfactorily. However, the measurement of $H^*(10)$ for neutrons has not been satisfactory.

Traditional real-time neutron rem meters are based on the neutron moderation method—i.e. a slow neutron detector (e.g. a $^{10}$BF$_3$ proportional counter or a $^6$LiI scintillation detector) is placed inside a large polyethylene sphere or cylinder. Incident neutrons are moderated (or slowed down) in the polyethylene and then detected by the slow neutron detector. It was noted that the response of a 12-inch-diameter polyethylene sphere surrounding a small $^6$LiI (Eu) scintillator could be used for neutron dose equivalent measurements$^2$. Such a system, however, is too bulky and heavy for an individual to maneuver under field conditions.

Several low-weight neutron rem meters have been commercialized in the last decade: Health Physics Instruments REM 500, Canberra Dineutron, and Ludlum Measurements PRESCILA. REM 500 uses a spherical tissue-equivalent proportional counter (TEPC) to measure the frequency distribution of lineal energy, $f(y)$, which is then used to obtain $H^*(10)$ via the formulas described in ICRU-40$^3$. The neutron signals are derived from the recoil protons originating in the tissue-equivalent wall. While it is indeed low-weight (2.2 kg), REM 500 suffers from a low neutron sensitivity of 0.8 cpm per $\mu$Sv h$^{-1}$. Dineutron is based on the traditional moderating method except it uses two small polyethylene spheres, 2.5 and 4.2 inch in diameter, respectively$^5$. Consequently, Dineutron significantly under-responds to neutrons with energies above 10 MeV. The PRESCILA employs a blended mixture of ZnS(Ag) scintillating grains and hydrogenous Lucite powders. The neutron signals are derived primarily from proton recoils that originate in Lucite and pass through the ZnS(Ag) grains. The neutron sensitivity was reported to be 26 cpm per $\mu$Sv h$^{-1}$ for a bare $^{252}$Cf neutron source. The response function of PRESCILA, however, is quite non-uniform with respect to neutron energy. For instance, the response to epithermal neutrons with energies between 1 eV and 10 keV is more than an order of magnitude greater than the response to neutrons with energies between 100 keV and 1 MeV$^6$.

In this paper, we describe a new neutron rem meter that is based on a plate-like TEPC. The plate-like geometry for a TEPC is made possible because of the recent invention of the gas electron multiplier (GEM)$^7$. Farahmand successfully built and operated a small-cavity TEPC based on a GEM$^8$. Recently, we proposed a large-cavity GEM-based TEPC with the plate-like geometry for use in neutron protection$^9$. The advantage of the plate-like geometry is that several TEPCs can be stacked together as one device to increase sensitivity to neutrons. The following sections present the geometric configuration of a plate-like GEM-based TEPC and the computational results of its performance as a neutron rem meter.
GEOMETRIC CONFIGURATION

The geometric configuration of the new GEM-based TEPC for measuring $H^*(10)$ for neutrons is shown in Figure 1. It consists of four layers of materials in a series. The front layer is made of a 1-cm thick polyethylene plate. The next layer is made of 2 mm of conducting plastic A-150, which serves as the cathode of the detector. The third layer is the gas region, which is further divided by the GEM foil into the upstream region and the downstream region. The upstream region is the electron/ion drift region, which is 4-mm thick, and the downstream region is the electron collection region, which is 2-mm thick. The fourth layer consists of a copper-coated printed circuit board (PCB), which serves as the anode. Also shown in Figure 1 are two Rexolite guard rings used as electrical insulators to separate the GEM foil from the A-150 and the PCB. The gas cavity is filled with a special gas mixture containing $1/3$ atm P-10 and $1/3$ atm nitrogen, which helps make the detector’s response function uniform with respect to neutron energy (see next section). The size of the TEPC is $10 \text{ cm} \times 10 \text{ cm} \times 1.8 \text{ cm}$.

During operation, the A-150 cathode will be held at the ground potential and the PCB anode will be held at a positive voltage. The total voltage between the cathode and anode will be $\sim 700 \text{ V}$, of which 100 V is applied between the A-150 and the upside of the GEM, 500 V is applied between the upside and downside of the GEM, and the remaining 100 V is applied between the downside of the GEM and the anode. As shown in Figure 1, the proper voltages are provided via a voltage divider that is made of a series of three resisters. The neutron counts are derived from the recoil protons, which originate in either the polyethylene layer or the A-150 layer, make their way into the gas cavity, and cause ionizations. The electrons produced in the upstream region of the gas cavity will drift into the holes of the GEM, multiply by many folds, and be collected at the anode. To increase the neutron detection efficiency, one may stack together several GEM-based TEPCs as a single unit. Since each additional TEPC only adds 2 mm of A-150, the neutron attenuation should be negligible. In other words, the detection efficiency of the stacked unit should be approximately proportional to the number of TEPCs in the unit.

COMPUTER SIMULATION AND RESULTS

Two types of (n,p) reaction have been simulated to produce neutron signals in the GEM-based TEPC for neutrons with energies between 0.025 eV and 10 MeV. The reaction types include the neutron elastic scatterings with hydrogen nuclei in both the A-150 and the gas mixture, and the $^{14}\text{N}(n,p)^{14}\text{C}$ reactions in the gas mixture. The neutron transport code MCNP-4C was used to generate the position and direction data for the recoil protons of a large number of (n,p) reactions. The position and direction data were then fed into a special-purpose Monte Carlo program, which uses the proton energy-versus-range table to trace the recoil protons and their energy depositions in the gas cavity. The recoil carbon ions from neutron elastic scatterings are ignored in the simulation because the probability of a carbon ion making into the gas cavity is negligibly small. The (n,a) reactions are also ignored in the simulation because they have negligible effect for neutrons with energies less than 10 MeV.

Figure 2 shows the calculated neutron response functions that are derived from the recoil protons originating in the A-150 for various thresholds of energy deposition. The energy deposition thresholds...
can be used to adjust the neutron response of the TEPC to make it better resemble the response curve of $H^*(10)$. Figure 3 shows the calculated neutron response functions of the GEM-based TEPC derived from the three (n,p) reactions of different origins. The curve corresponding to recoil protons originating in the A-150 shown in Figure 3 is that of Figure 2 with 15 keV as the energy deposition threshold. The other two curves are based on a gas mixture containing 1/3 atm P-10 and 1/3 atm nitrogen. The energy deposition threshold and the gas mixture contents were chosen in such a way that the total neutron response function best resembles the response curve of $H^*(10)$. Figure 4 shows the total
neutron response function of the GEM-based TEPC along with the response curve of $H^*(10)$. Figure 5 shows that the neutron response per unit $H^*(10)$ is indeed relatively independent of neutron energy. This neutron response function is, in fact, better (i.e. varies less with respect to neutron energy) than the response functions of all the existing neutron rem meters. The ideal neutron response function is a

Figure 4. The comparison of the neutron response function of the GEM-based TEPC with the $H^*(10)$ curve.

Figure 5. The neutron response per unit $H^*(10)$ as a function of neutron energy for the GEM-based TEPC.
perfect horizontal line with respect to neutron energy; therefore, the number of counts recorded by the TEPC is exactly proportional to $H^*(10)$ regardless of the incident neutron energy.

According to Figure 5, the sensitivity of the GEM-based TEPC for a bare $^{252}$Cf neutron source was calculated to be 5.0 cpm per $\mu$Sv h$^{-1}$, which is a factor of 5 smaller than the sensitivity of the PRESCILA neutron probe. However, as mentioned earlier, one can increase the sensitivity many times by simply stacking several TEPCs together as one unit. The neutron response of a stacked unit should be directly proportional to the number of TEPCs in the unit. As far as the detector’s weight is concerned, it can be shown that a stacked unit of five GEM-based TEPCs would still weigh <2 kg.

CONCLUSIONS

A new plate-like tissue equivalent proportional counter (TEPC) based on the GEM is being proposed for use as a neutron rem meter. It consists of four layers of materials in a series: the front cover made of polyethylene, the cathode made of A-150 plastic, the gas region containing 1/3 atm of P-10 and 1/3 atm of nitrogen and the anode made of a copper-coated printed circuit board. The dimensions of the TEPC are 10 cm $\times$ 10 cm $\times$ 1.8 cm. The computer simulation shows that the neutron response function of the TEPC closely resembles the response curve of $H^*(10)$ for neutrons with energies between 0.25 eV and 10 MeV. The corresponding sensitivity for such a TEPC for a bare $^{252}$Cf neutron source was calculated to be 5.0 cpm per $\mu$Sv h$^{-1}$. This sensitivity can be proportionally increased many times by simply stacking several TEPCs together as one unit.

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