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Development of a High Pressure Xe Ionization Chamber for Environmental Radiation Spectroscopy

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A High Pressure Xenon ionization chamber is a promising radiation detector for environmental radiation measurement due to its radiation hardness, its physical rigidity, and its capability of operation at a high temperature up to about 170 ℃. A cylindrical high pressure xenon ionization chamber, which was configured with a shielding mesh to improve its energy resolution, was designed on the basis of an electron transfer simulation code (EGSnrc) to extract an optimal density of Xe gas and a thickness of the chamber wall. An electron drift simulation code, Garfield, which was coupled with a Maxwell electric filed calculator, was also employed for the electron drift simulations due to the geometry of the shielding mesh. Shielding inefficiency was also calculated. A spherical ionization chamber was also designed and fabricated to monitor environmental radiation. A noble gas system was constructed to create a noble gas with a high purity and to inject the noble gas up to 60 atm. The combination of an oxygen absorbent (Oxisorb), a molecular sieve, and a high temperature getter can minimize the electro-negative impurities, such as the O_2 and N_2 gas, to below about several ppb levels. Preliminary tests such as leakage currents, saturation currents, and gas leak test were performed. The performance of the two fabricated ionization chambers at a low dose rate was tested by using a conventional shadow technique with a NIST certified 33.52 MBq ^{226}Ra source in the calibration room at KAERI.

KEY WORDS: high-pressure Xe, ionization chamber, environmental radiation, shadow shielding technique, EGSnrc, Garfield, shielding mesh

I. Introduction

An ionization chamber is still widely used in many fields such as environmental radiation monitoring and industrial application due to its operational stability for a long period and its simple design for its applications[1)]. Pressurized ionization chambers, which are usually made of metal such as stainless steel, have radiation hardness for a long period of time in a comparison with other radiation detectors. Ionization chambers for environmental radiation monitoring are requested to detect a low dose rate at below several μSv/h.

High-pressure xenon (HPXe) gas is attractive gamma-ray detection medium due to its physical and nuclear properties. HPXe has a large detection efficiency for gamma-ray energies, due to its large atomic number (Z = 54), which translates into a high photoelectric absorption and Compton scattering cross sections. In addition, the Fano factor for HPXe is quite good, measured near 0.13 to 0.1[2)]. HPXe ionization chambers are ideal for use in uncontrolled environments, as this detector's response has been shown to be uniform over large temperature ranges up to 170 ℃. Unlike solid detection media that derive their radiation detection capabilities from their crystal structure, the HPXe performance is not degraded by high radiation fluences.

An HPXe ionization chamber, which was equipped with a shielding mesh, was designed on the basis of the results from EGSnrc, a Maxwell electric field calculator and a Garfield electron drift simulator. Shielding inefficiency was also calculated.

A spherical ionization chamber, which was pressurized with Ar up to 25 atm, was also constructed to apply it to environmental radiation monitoring. A gas system was constructed to eliminate the electro-negative impurities and to inject the noble gas up to 60 atm. A conventional shadow shielding technique was incorporated to test the performance of the two ionization chambers at a low dose rate.

II. Experimental

1. Gas Purification and Injection System

The purity of Xe is essential in an HPXe ionization chamber due to the electron attachment by electro-negative gases, which become negative ions after the liberated free electrons being attached. The purification and injection system was designed and constructed to eliminate the electro-negative impurities such as O_2, N_2 and hydro-carbon gases. The combination of an Oxisorb, a molecular sieve, and a high temperature getter can minimize these impurities. The circulation of Xe gas was based on the difference in the temperature of a liquid nitrogen and a high temperature getter (about 350℃). **Fig. 1** shows a diagram of the gas system. Two gas cylinders were incorporated to improve the electron drift velocity of Xe by an addition of 17 % of helium gas[3)]. Xenon and helium mixture will be stored in a reservoir and circulated for several days to reach several ppb

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impurity levels.

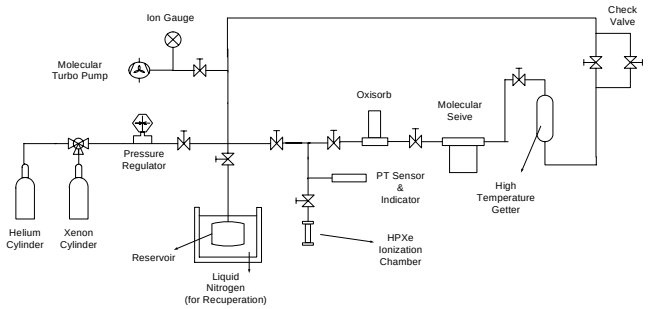

Fig. 1 The gas purification and injection system for an HPXe ionization chamber

2. Design of a cylindrical HPXe Ionization Chamber

A cylindrical HPXe ionization chamber was designed on the basis of the results of the EGSnrc simulation code[4]. A dosrznrc, which simulates the passage of an electron or photon beam in a finite, right cylindrical geometry, was used in the simulation. The considered parameters were the densities of the xenon gas, the thicknesses of an outer shell, and the initial gamma energies. The calculated efficiencies versus the considered parameters are shown in **Table 1**. The simulated energy spectrum at 662 keV is also shown in **Fig. 2**.

Table 1. The calculated percentile efficiency attainable with the given detector parameters by using the EGSnrc code

Initial Energy	Thickness of outer shell	Density of Xenon gas		
		0.4 g/cm^3	0.55 g/cm^3	0.65 g/cm^3
60 keV	1 mm	77.72	78.90	79.38
	2 mm	76.61	77.73	78.38
	3 mm	75.89	76.85	77.27
145 keV	1 mm	72.62	76.22	77.91
	2 mm	68.56	72.24	73.93
	3 mm	65.46	69.02	70.69
662 keV	1 mm	11.24	13.56	14.89
	2 mm	10.30	12.49	13.74
	3 mm	9.53	11.53	12.70
1.17 MeV	1 mm	3.60	5.00	5.86
	2 mm	3.37	4.61	5.44
	3 mm	3.08	4.29	5.08
1.33 MeV	1 mm	2.68	3.85	4.63
	2 mm	2.53	3.64	4.37
	3 mm	2.33	3.45	4.10

The efficiencies throughout the initial energies can be improved when the xenon density is high. Thin outer shells also contribute to higher peak efficiencies. But the density of the xenon gas conflicts with the outer shell thickness. For a cylindrical shape, allowable thickness of an outer shell to endure the pressure is expressed by

$$t = \frac{Dps}{\sigma\eta\times 100} + C \qquad (1)$$

where D represents the diameter of a cylinder in mm, p is the pressure in kg/mm^2, σ is the tension intensity in kg/mm^2, s is 1 as the safety rate, η and C are 0.8 and 1 in Korea. When the material of an outer shell is stainless-steel and the diameter of a cylinder is 76 mm, the thickness of an outer shell must be over 2 mm at a 60 atm pressure for a safe operation.

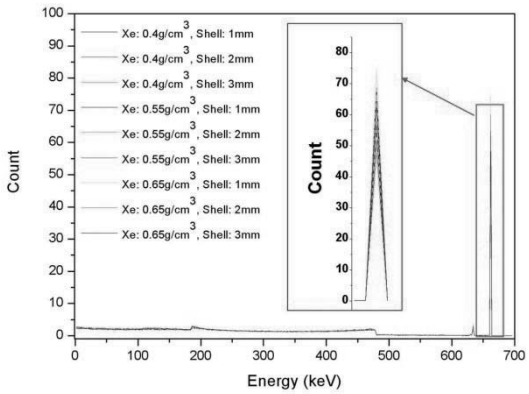

Fig. 2 The 662 keV gamma spectrum obtained by simulation of a dosrznrc of EGSnrc code.

The design of a cylindrical ionization chamber is shown in **Fig. 3**. The diameter and the total length of the ionization chamber were 76 and 170 mm, respectively. The active volume was 450.5 cm^3. Ceramic was chosen for the insulators. The use of a shielding mesh to screen the collecting electrode from the effect of positive ions was suggested by O. R. Frish[5]. A shielding mesh, which eliminates the charge contribution of the slow positive ions, was inserted between the collecting electrode and the potential electrode to increase the energy resolution. Three feed-through connectors were welded onto the flange of the ionization chamber to connect the electrodes. To extract the optimal parameters for the shielding mesh such as the mesh thicknesses, mesh diameters, and the distance from the anode, a Maxwell electric field calculator and a Garfield electron drift simulation were incorporated. The applied voltages of the shielding mesh and the potential electrode were set at -2500V and -5000V, respectively. Mesh spacing was also set at 1 mm. Mesh thicknesses of 0.5, 0.2 and 0.1 mm were simulated. And the distances from the anode was either 7.5 or 5.5 mm. Electron drift lines were not distorted when the mesh thickness and distance from the anode were 0.5 mm and 7.5 mm, respectively. The simulated drift lines are shown in **Fig. 4**. Shielding inefficiency was calculated by using these parameters. In order to purge any gases emanated from the chamber materials, the chamber was kept at 100℃ in vacuum for two weeks before a gas filling. High purity Ar gas was injected by using the constructed gas system up to 40 atm after purification for the preliminary tests.

3. Design of a Spherical Ionization Chamber

A Pressurized Ionization Chamber (PIC) was designed in consideration of an isotropy for an incident radiation and

consideration of an isotropy for an incident radiation and compared with the HPXe ionization chamber. A drawing and a picture are shown in **Fig. 5**. The tri-axial connector, welded on the chamber surface, serves as a terminal for the potential electrode, collector and guard electrode.

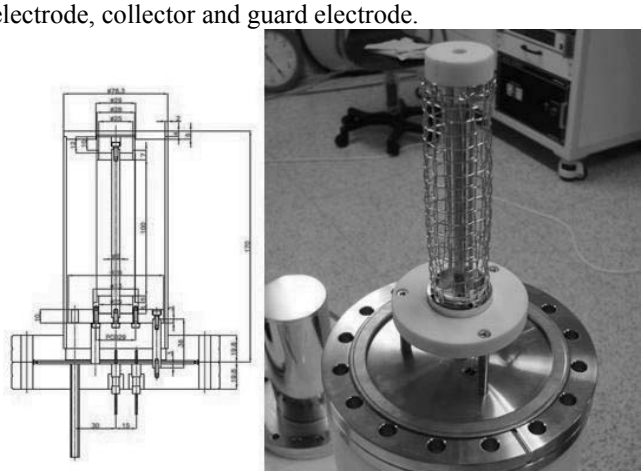

Fig. 3 The designed HPXe ionization chamber for environmental radiation monitoring and spectroscopy (left). And the inner view of the fabricated HPXe ionization chamber with a shielding mesh (right)

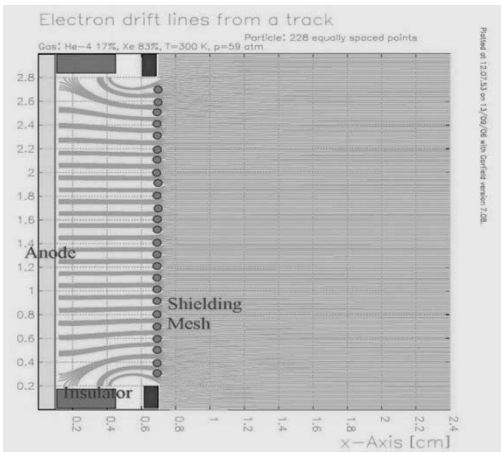

Fig. 4 The simulated shielding mesh by using a Maxwell electric field calculator and a Garfield electron drift simulation when mesh thickness and the distance from the anode were 0.5 and 7.5 mm, respectively

The chamber was fabricated by welding together two 304 stainless steel hemisphere. Purified argon gas was injected up to the pressure of 25 atm. The wall thickness was 0.12 inch. The ionization charge was collected by a spherical aluminum electrode with 2 inch diameter. The sphere was held in place at the center of the chamber shell by a thin aluminum rod. Electrodes were fused to the shell by a metal-to-ceramic tri-axial seal in which the outmost electrode was connected to the chamber shell. The middle or guard electrode was connected to the inner collecting sphere. The center or collecting electrode was completely isolated from the high voltage chamber by a ceramic insulator, which had a minimum resistance of 10^{18} ohms. The assembled chambers were baked in a vacuum at 100 ℃ for four hours and then filled to a known pressure with high purity argon.

4. Measurements of the Fabricated Ionization Chambers at a Low Dose Rate

A Keithley 6517A, an Ortec 673 high voltage supplier, and the LabVIEW program were incorporated to test the performance of the fabricated ionization chambers at a low dose rate. The leakage currents throughout the experiments were kept in the range of 200 fA and the plateaus were observed.

Calibration was also performed by using a conventional shadow technique[6] in a calibration room. Schematic view of the experiments is shown in **Fig. 6**. Linearity against low dose rates was also measured. The source was placed in a low mass holder at a height of about 1 m above the floor and at a distance of 4, 5, 6 m from the ionization chambers, which were at the same height on a low mass stand. A 30-cm thick lead shield with a cross section measuring 10-x-10 cm was interposed on a low mass stand so as to intercept all the primary rays from the source to all parts of the ionization chambers through a full thickness of the shield. Alignment was checked with a string with a dummy source in place. Slight over-shielding in the order of 1-2 cm was used as these results in a negligible error as opposed to an under-shielding which could produce a significant error.

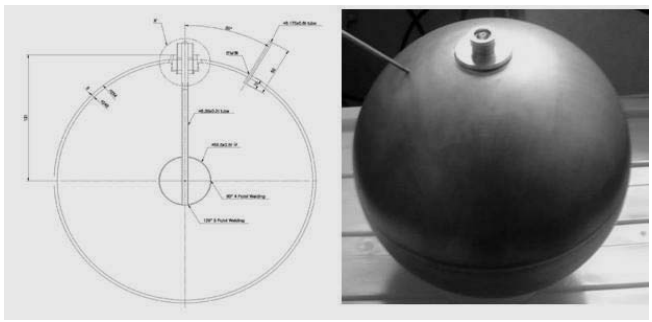

Fig. 5 A spherical ionization chamber for environmental radiation monitoring

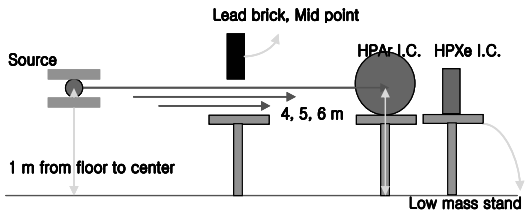

Fig. 6 Experimental setup for the measurement of ionization currents of the fabricated ionization chambers at a low dose rate

The source was placed in its holder and the output signal of the PIC was averaged over a 10- to 30-min time period. The lead shield was removed and the ionization chamber output signal was averaged again over a 10- to 30-min time period. The difference between the average signals was divided by the exposure rate delivered by the source at that a distance to yield the ^{226}Ra primary beam calibration factor.

Fig. 7 and **8** show the linearity of the chamber current change with respect to the dose rate, as measured with the HPXe ionization chamber and the spherical ionization chamber, respectively. Root-mean-square linearities were 0.991 and 0.995, respectively.

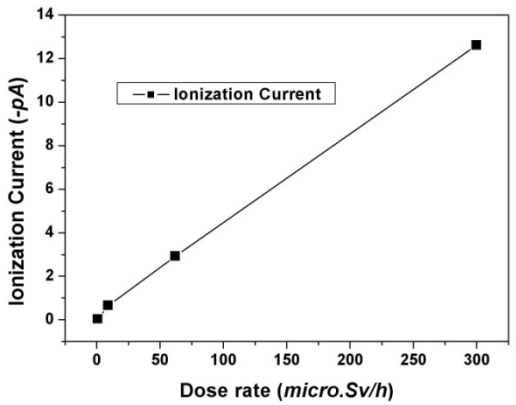

Fig. 7 linearity of ionization currents from the HPXe ionization chamber against low dose rates. Root-mean square linearity was 0.991.The error bars are smaller than the sizes of symbols

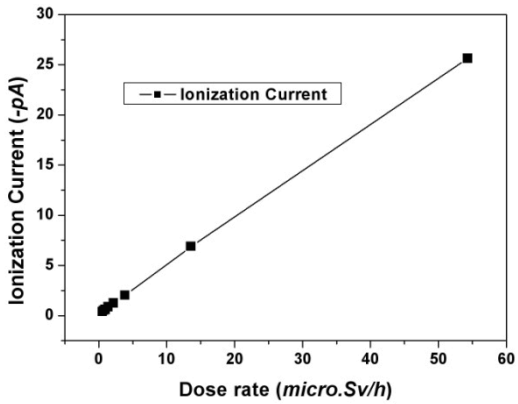

Fig. 8 Linearity between the ionization currents from the PIC and the low dose rates. Root-mean square linearity was 0.995. The error bars are smaller than the sizes of symbols

III. Results and Discussion

The two fabricated ionization chambers for environmental radiation monitoring revealed a linear response against low dose rates from the results by using a conventional shadow shielding technique.

The efficiency of the shielding mesh is measured by the extent to which the charge is induced on the collecting electrode. The shielding inefficiency can be calculated as a function of two geometrical ratios[7]. The electrostatic field and induced charge inside a cylindrical ionization chamber can be calculated by using the expressions obtained for a parallel plate chamber from Bunemann[7] and making logarithmic transformations to a cylindrical geometry. From this transformation, the shielding inefficiency can be estimated by[8]:

$$\delta_0 = 1 - (1/N)\ln(R_g / Nr_0)/\ln(R_g / R_a) \quad (2)$$

where R_a and R_g are the radii of the anode and the shielding mesh, respectively. N and r_0 are the number of wires and the radius of the wires. From this formula, the shielding inefficiency of the fabricated HPXe ionization chamber, which had a 0.5 mm mesh thickness ($2r_0$) and a 7.5 mm radius of a shielding mesh, was 6.8 %.

IV. Conclusions

In this study, two types of pressurized ionization chambers were fabricated and tested with a ^{226}Ra source in a low gamma ray dose range. These two ionization chambers, in current mode operation, showed an excellent linear relationship between the chamber current and the dose rate. The good performance in the low dose range of the ionization chambers suggests that they can be successfully used for low-dose environmental radiation measurement. The shielding inefficiency of an HPXe ionization chamber, which was configured with a shielding mesh to measure an energy spectrum, was calculated. In a future work, energy spectra with the fabricated HPXe ionization chamber will be compared with the simulated energy spectra.

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