Advanced materials in experimental equipments for absolute measurement of X and gamma-ray exposure rate with free-air and cavity ionization chambers

M. R. CALIN, M. A. CALIN[a*], S. VLASE[b], I. RADULESCU
„Horia Hulubei" National Institute for Physics and Nuclear Engineering-IFIN-HH, P.O. Box MG-6, 077125, Magurele, Romania
[a]Nationale Institute of Research and Development for Optoelectronics – INOE 2000, P.O. Box MG-5, 077125, Magurele, Romania
[b]Transilvania University of Brasov, Department of Automotives and Mechanical Engineering, 29 Eroilor Blvd, 500036 Brasov, Romania

The problem of radiation doses measurements is important both in research and in practical applications whenever one needs to evaluate the effects of irradiation from the energy deposited by radiation into substance. Among the approaches currently available, the ones using free-air ionization chambers and cavity ionization chambers (developed by the SALMROM laboratory, at IFIN-HH) are the most viable as they constitute primary (reference) standards that are used in national laboratories for the metrology of ionizing radiation. Both types of chamber rely on the electronic balance principle and Bragg-Gray relation. They are basic detectors for measuring exposure rates and/or absorbed dose rates in various materials, including air. The experimental data provided by both chamber types are in agreement with market requirements and international data. Both are used as primary standards in national metrological laboratories. By using these two measuring procedures for gamma, X and beta radiation, one can determine various quantities such as exposure, exposure rate, dose, dose rate, activity, etc. Depending on intended use, radiation field, ambient conditions, kind of radiation, etc., the parameters of both chambers can be improved by varying the types of gas or gas mixture that are introduced in the sensitive volume.

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1. Introduction

The Röentgen has been used for many years as a unit of X-ray exposure. The free air ionization chamber was the instrument employed to determine it. *One Röentgen is an exposure dose of X or gamma radiation such that the associated corpuscular emission per 0.001293 gram of air produces, in air, ions carrying 1 electrostatic unit of quantity of electricity of either sign* [1], [2], [3]. According to this definition, a measurement of the number of röentgens need to take account all charge carriers produced in air by the high speed electrons that are themselves produced within the definite mass of air. According to the principle of electronic equilibrium, within a medium subseated to uniform irradiation the ionization produced outside of a specified mass, m, by high speed electrons generated inside is compensated by ionization produced by high speed electrons generated outside of m [4], [5].

The measuring radiation doses are imported both in research and in practical applications whenever one needs to evaluate the effects of irradiation from the energy deposited by radiation into substance. Among the approaches currently available, the ones using free-air ionization chambers and cavity ionization chambers are the most viable inasmuch as they constitute primary (reference) standards used in national laboratories for the metrology of ionizing radiation. Both types of chambers rely on the electronic balance principle and on the Bragg-Gray relation and are basic detectors for measuring exposure rates and/or absorbed dose rates in various materials, including air [1], [3]. The purpose of this paper is to present results for carrying out the second type ionization chamber detectors and their functional characteristics.

2. Materials and methods

2.1. The free-air ionization chamber method

The general characteristics of free ionization chambers are shown in Fig. 1. This is a cross section of a parallel plate ionization chamber. The plate system is introduced in a radiation shielding box. The X-ray beam is delimited by the diaphragm, D, therefore the photons pass centrally between the plates. A high potential (field strength of the order of 100V/cm) on plate H, sweeps out the ionization produced in the air between the plates [4,5].

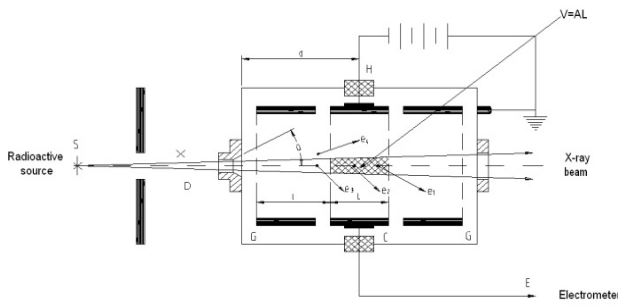


Fig. 1. Schematic plan view of a parallel-plate free-air ionization chamber. S - source of radiation, X - x-ray beam, G – grid, C - collector, E - electrometer, H - High voltage, e_1, e_2, e_3, e_4, - electron trajectories

The ionization is measured for a length, L, determined by the limiting lines of force to the edges of the collector, C. These lines are made straight and perpendicular to the collector by the guard plates, G, and surrounding guard wires or strips, W. The latter are connected to a resistance dividing network to grade the potential uniformly across the gap between C or G, and H. Ionization is collected from the region enclosed by the dashed lines, F [2], [5].

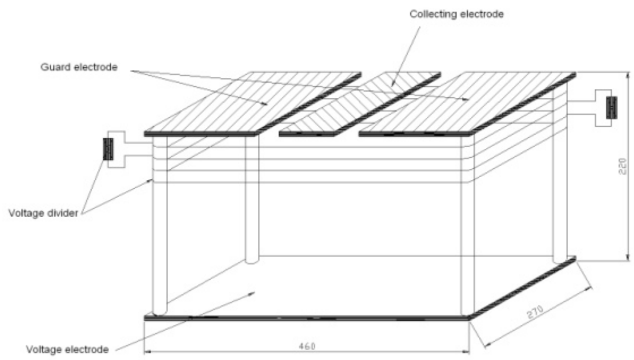
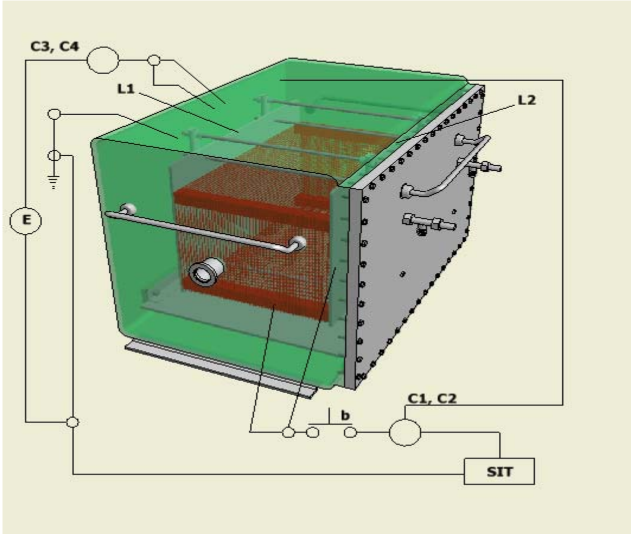


Fig. 2 Electric structure for the free-air ionization chamber.

Its electric structure (Fig. 2) consists of: a voltage electrode; a collecting electrode, guard electrodes, and a voltage divider. The electric system of the ionization chamber was mounted on a duralumin plate (front panel), sliding inside the chamber on two metal runners.

Two diaphragms, made of stainless steel and wolfram alloy, were placed one each on the side walls for the entry and exit of the X or gamma-ray beam. The free-air ionization chamber (Fig. 3), developed for this experiment, was a parallelepiped, 660 mm long, 300 mm wide and 380 mm high, made of metal sheet and lined with 5-mm thick lead plates. [2], [4], [12].



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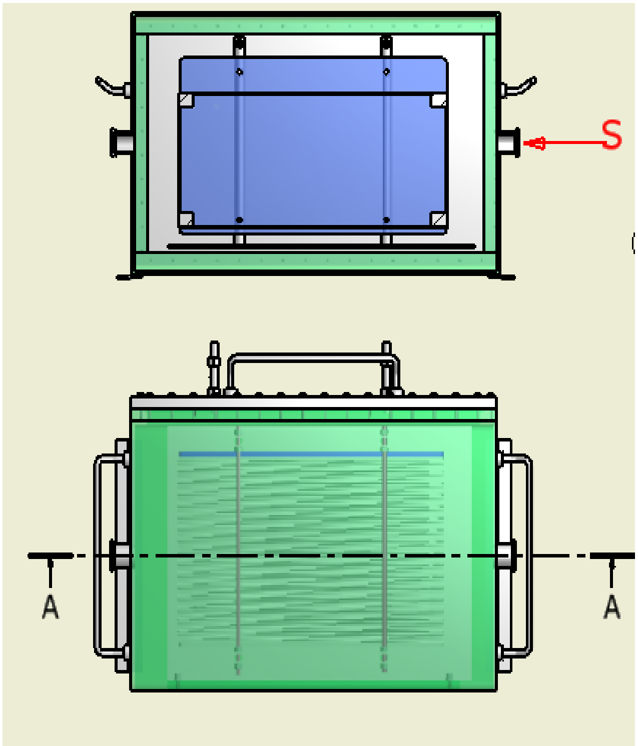

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Fig. 3. (a) Free-air ionization chamber - general view in 3D, B - Switch On/Off, C1, C2, C3, C4 - Coaxial cable, L1 - High voltage electrode,L2 - Collecting electrode, SIT - High voltage supply, E - KEITHLEY 6517A Programmable Electrometer, S - Radioactive source., (b) 1 – body case, 2 - functional structure.

The block-scheme used for the measurement of characteristic parameters for this detector, is shown in figure 4 [12].

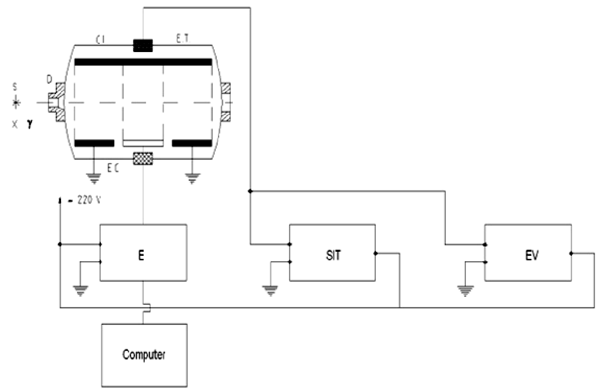

Fig. 4. Block-scheme used for the measurement of characteristic parameters for the free-air ionization chamber E - KEITHLEY 6517A Programmable Electrometer; SIT - High Voltage Supply-CAMBERRA; EV - Electrostatic Voltmeter.

2.2 The Cavity Ionization Chamber Method

For the application of cavity theory in dosimetry, a number of technical and technological conditions have to met, a such as [5]:

• the cavity must be small that only a small fraction of particle energy to be dissipated in it;

• photon radiation absorption by the gas cavity is negligible;

• the cavity must be surrounded by a "equilibrium thickness" of solid particles so that all that one crosses to the environment arises. This thickness is theoretically equal to during high energy particles into the environment;

• dissipation of energy by ionizing particles to be uniform throughout the volume of the environment surrounding the cavity thereby contribute to the electronic balance [6], [9].

Thus, the chamber cavity, as well as outdoor room, are considered primary standards (or secondary) to measure the radiation field with this ionization chamber being able to measure: exposure (*X*), flow exposure ( ) and and activity of sources of radiation (*Λ*), the absorbed dose (*D*), absorbed dose rate ( ), (both X and gamma radiation fields and for beta radiation).

The response of a radiation detector is proportional to the absorbed dose deposited within its sensitive volume, which in general differs from the surrounding medium. A cavity theory is used to relate the radiation dose deposited in the cavity (sensitive volume of the detector) to that in the surrounding medium [7], [8]. The dose to the cavity depends on the size, atomic composition and density of the cavity and the surrounding medium. The size of the cavity is defined relative to the range of the electrons set in motion. A cavity is considered small when the range of the electrons entering the cavity is very much greater than the cavity dimensions. The electron spectrum within a small cavity is solely determined by the medium surrounding the cavity [10]. The ratio of absorbed dose in the cavity to that in the surrounding medium is given by the Bragg-Gray theory or the Spencer-Attix theory [4]. When the cavity dimensions are many times larger than the range of the most energetic electrons, the electron spectrum within the cavity is determined by the cavity material itself. A cavity whose dimensions are comparable to the range of electrons entering the cavity has a spectrum within the cavity that is partially determined by the medium and partially determined by the cavity material. Burlin proposed a general cavity theory to include all cavity sizes. The Burlin [8] theory ignores all secondary-electron scattering effects which results in large discrepancies in dose to the cavity with the experimental results in high atomic number media (Horowitz *et al*, Kearsley) [5], [11]. Horowitz *et al* [11] have proposed a modification of the Burlin cavity theory based on the proof that, in general, the average path length for electrons crossing the cavity is not equal to the average path length for electrons created within the cavity. Although conceptually interesting, the Burlin–Horowitz model did not make any significant improvement on the Burlin model (Kearsley, Horowitz *et al* [5], [11]) also demonstrated that taking electron backscattering into account can improve the Burlin model. Kearsley [11] proposed a new general cavity theory that takes into account secondary-electron scattering at the cavity boundary. An outstanding feature of this model is the ability to calculate dose distributions inside plane parallel cavities surrounded by medium. In the absence of secondary-electron backscattering, the Kearsley [5] cavity theory reduces to Burlin's cavity theory. However, the Kearsley theory has poor correlation with experimental results in high-Z media. The Kearsley theory [5] has numerous parameters and the magnitude of the input parameters is arbitrary at present, and therefore the dose to the cavity depends on the choice of parameters. Here we have developed a new cavity theory that includes secondary-electron backscattering from the interface. The theory contains few parameters and the magnitudes of the parameters are determined experimentally. Our cavity theory can be used to relate the dose in the cavity to the dose in the medium (front wall or back wall) when the front wall medium, cavity medium and back wall medium are all of different atomic composition [10].

An ionization chamber that is designed for the point-by-point measurements of the dose absorbed in an environment will have to meet a number of basic conditions of the cavity theory. [5], [6]. The relation between the energy that radiation yields to an environment and the ionization caused by this same radiation in a gas inside a cavity of this environment [4]. A condition imposed on the ionization chamber, especially on the gas-filled cavity, is that it not be larger than a given size. On the contrary there are no restrictions with respect to low size. They depend only on practical considerations relating to the design and the intensity of ionization currents that would be appropriate to the electrometric system which is used. [1,3].

In order to comply with these conditions, we conducted the cavity ionization chamber (see Fig. 5 and Fig. 6).

3. Experimental results

3.1. The cavity ionization chamber

When constructing the free-air ionization chamber, several main technical, technological and operational problems were taken into account, including: the electronic balance; the air mass, calculated after the chamber diaphragm definition; field distortions; X-ray leaks, electron losses; diaphragm-collector distance; recombination losses; air dampening corrections; protection against stray radiation, etc. The principal technical and operational features of the ionization chamber, as tested in normal operation (test) conditions, were: $\bar{I}_{leakage}$ = 2.97× 10^{-16} A, for rated working voltage: U = -1200 V; $\sigma_{\bar{I}}$ = 0.038× 10^{-16}A (n = 20 values for $\bar{I}_{leak.}$); $\sigma_{rel.} = \sigma_{\bar{I}} / \bar{I}_{leak.}$ = 0.0129; Average ionization current in the presence of a ^{241}Am radiation source having 600 mCi ±10% (2.22× 10^{10}Bq±10%): $\bar{I}_{ioniz.}$=3× 10^{-15} A ±10%; for a voltage U =-1200 V and d = 1.20 m±0.005 m; with standard deviation $\sigma_{\bar{I}}$= 0.0305×10^{-15}A (for n=100 measurements). Considering P* = 95%, n = 100 and k = 2.09, $\bar{I}_{ioniz.}$= (3±0.0638)× 10^{-15}A; Characteristic I-U curve plateau: -1000 V ÷ -2100 V; Relative variation in ionization current when using polarization voltages within the range -1200 V ÷ -2100 V: $\Delta I/I_0$ = 0.5%; Ionization chamber response in terms of radiation energy of the ^{241}Am radionuclide: R = 8.7× 10^{-11} A/R×h^{-1}, [12,13].

3.2. The cavity ionization chamber

By taking into account the principle of electronic balance, the Bragg-Gray relation and the cavity theory, different types of cavity ionization chamber were made; one of graphite-coated Teflon (PTFE), (Fig. 6) [14] order to better illustrate the basic ionometric principles of the cavity theory.

One type of the cavity ionization chamber consisted of a cylinder made of graphite-coated Teflon (in nearly equal proportion with each other), with overall dimensions L=50 mm and Ø=16 mm, and walls about 1 mm thick. The components of the chamber were: a thimble-shaped voltage electrode (the chamber case), made of graphite-coated Teflon; a collecting electrode, of the same material, threaded into the chamber insulation by a collecting pin; and an insulator, made of polystyrene of very high electric resistivity (ρ > 10^{16} Ω×cm), threaded into the case [12, 14].

In normal testing conditions, several technical-operational features were identified:

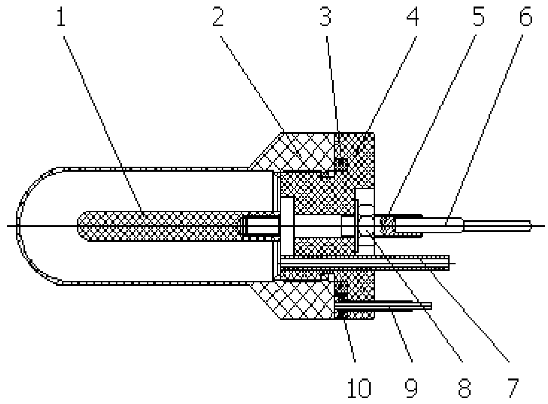

Fig. 5. Cavity ionization chamber made of graphite-coated Teflon; 1 - collecting electrode, 2 - voltage electrode, 3 - O-ring, 4 -insulator, 5 - collecting pin, 6 - gold pin, 7 - inlet pipe, 8 - calmping system, 9 - clip, 10 - elastic system.

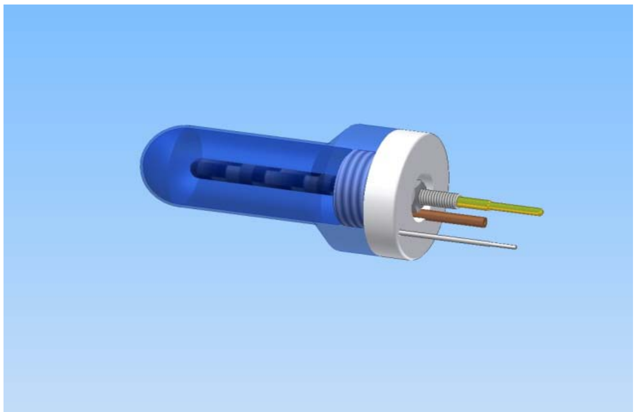

Fig. 6. Cavity ionization chamber - general view in 3D

$\bar{I}_{leakage}$ /$_{U\ =-800\ V}$ = 1× 10^{-15}A ± 5%; with standard deviation: $\sigma_{\bar{I}}$ = 0.0346× 10^{-15}A (n=100 values for $\bar{I}_{leak.}$); $\sigma_{rel.} = \sigma_{\bar{I}} / \bar{I}_{leak.}$ = 0.0346; Characteristic I-U curve plateau: -500 V ÷ -1200 V; Average ionization current in the presence of a ^{241}Am radiation source having Λ= 600 mCi ±10% (2.22× 10^{10} Bq ±10%): $\bar{I}_{ioniz.}$ = 6.49× 10^{-13} A ±10%; for a voltage U = -800V; and d = 0.2 m ±0.005 m; with standard deviation $\sigma_{\bar{I}}$ = 0.160× 10^{-13}A (for n = 100 measurements). Considering P* = 95%, n = 100 measurements and k= 2.09, $\bar{I}_{ioniz.}$ = (6.49±0.074)× 10^{-13}A; Relative variation in ionization current with the polarization voltage within the range -500 V ÷ -1200 V: $\Delta I/I_0$ = 0.1%; The ionization chamber response to the gamma radiation of a radionuclide ^{241}Am, with Λ = 600 mCi ± 10% (2.22× 10^{10} Bq ± 10%) for exposure rate ($\dot{X}$ =103.62 mR/h) was:

$$\frac{I_{ioniz}}{\dot{X}} = 6.2 \times 10^{-8}\ A / R.h^{-1} ; to : d = 20\ cm$$ [12,13].

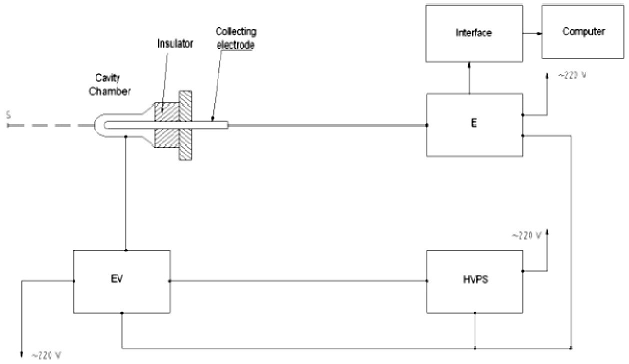

Fig. 7. Block-scheme used for the measurement of characteristic parameters for the cavity ionization chamber.

The block-scheme used for the measurement of characteristic parameters for this detector, is shown in figure 7. Measurement chain is completed with a hardware structure equipped with a specialized interface for measuring characteristic parameters of radiation detectors (*KEITHLEY* company), as well as specialized programs for measuring *"KEITHLEY 2000"* and *"Test Point"* [12].

4. Conclusions

The data resulting from our measurements lead to a number of significant conclusions on how the pressurized-gas ionization chamber works and which further studies on this detector could be necessary.

- The experimental data provided by the three chambers are in agreement with usual requirements and available reported until now.
- Both detectors are used as primary or secondary standards in national metrological laboratories. The detection methods are based on the principle of electronic balance and Bragg-Gray relation. These methods can be used for gamma, X and beta radiation, in order to determine exposure, exposure rate, dose, dose rate and activity.
- As far as structure is concerned, the ionization chamber meets our goal: it is appropriately gastight to ensure a constant gas pressure inside the detector while the measurements are carried out;
- Future researches will provide further opportunities for testing these types of detectors and for conducting differential mode measurements; also, they will make it possible to extend the range of structural variants and uses of such detectors;
- This kind of radiation detectors are very stable in time and relatively easily made; moreover, they have a wide range of applications;
- The results obtained with this type of detectors are in agreement with literature data and in line with similar products in this field manufactured by leading foreign producers (BIPM-Paris, RIV-Utrecht, PTB-Braunsweig, CNEN-Bologna, etc.)

Acknowledgments

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*Corresponding author: micalin@inoe.ro