

The instability of gas-filled electronic components in the presence of gamma radiation

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Abstract— The investigations present experimental results dealing with the low doses of gamma radiation impact to breakdown voltage of gas-filled electronic components. It was shown that dynamic breakdown voltage is statistical property which experimental results can be described using Weibull's probability distribution function, in the case when components were not subjected to ionizing radiation. The results have also shown that breakdown voltage is very sensitive to gamma radiation even for such a low doses, slightly higher than natural radioactivity. The paper also present the study dealing with possibility for application of gas-filled components as low doses gamma radiation sensors. In this case, mean value of breakdown voltage was used as dosimetric parameter.

I. INTRODUCTION

Electrical breakdown represent gas transition from insulating state, with resistance of about 10^{14} Ω m, into conducting state, with resistance reduced for several orders of magnitude [1]. After breakdown, constant current flows through the gas (self-sustaining discharge) and current value is determined by external electronic circuit. Various types of technologies are based on the electrical breakdown principle, such as plasma processing [2, 3], surface sputtering [4, 5], nitrating [6], material deposition process [7], medical instruments sterilization [8]. In addition, the operation of many gas-filled components is based on electrical breakdown and self-sustaining discharge. Those are for example, gas-filled surge arresters [9], gas switches [10], plasma display panels [11], light sources [12] and gas lasers [13]. It should be pointed out, that some gas-filled components operate in so called non-self-sustaining regime. Those are ionization chambers [14], proportional counters [15] and Geiger-Muller (GM) counters [16]. The operational principle of these components is based on ionization, induced by ionizing radiation, which further leads to the formation of electron-ions pairs in gas. Under the influence of electrical field of a relatively low intensity, these charges move toward the corresponding electrodes, what is manifested through the constant current flow (ionization chamber current mode), or a pulse in external circuit (ionization chamber pulse mode) that correlate with radiation dose. The operation of proportional and GM counters is based on the multiplication of charge in working gas.

The aim of this paper is to investigate the impact of gamma radiation to gas-filled components breakdown voltage, as well as to conduct analysis of possibility for application of

these components as sensors of low doses of gamma radiation. Breakdown voltage was used as dosimetric parameter in presented investigations.

II. BREAKDOWN CONDITION AND BREAKDOWN VOLTAGE

If the voltage applied to gas-filled component is sufficient enough, so that electrons on their way toward anode, have enough energy to perform ionization collisions, the number of charge carriers increases, further forming avalanche. In that case the current grows exponentially [17]:

$$i = i_0 \exp(\alpha d), \quad (1)$$

where i_0 is the electron current originating due to the external ionization source, while α is the first Townsend's coefficient (α is the number of electron-ion pairs formed by an electron per unit of length) [18].

For breakdown development in low pressure gases, so called secondary or γ processes are very important. Positive ions, metastable atoms and molecules as well as photons in interaction with cathode can induce the emission of secondary electrons (SEE) from its surface. The coefficient of secondary emission γ , represent the number of electrons emitted from cathode in collision with some of above mentioned particles.

When electrical field in inter-electrode space has certain intensity, that electrons emission from the cathode, due to positive ions impact, is sufficient enough the number of electrons in inter-electrode space increases. The current in that case is given by:

$$i = i_0 \frac{\exp(\alpha d)}{1 - \gamma \exp(\alpha d) - 1}, \quad (2)$$

During transition from non-self-sustaining to self-sustaining discharge current rapidly increases. The voltage increase lead to the formation of a large number of avalanches in inter-electrode space. In that case the ionizations and electron emissions from the cathode increases.

The condition for breakdown appearance, i.e. for transition between non-self-sustaining to self-sustaining discharges, can be expressed as following for homogenous field [1]:

$$\gamma \exp(\alpha d) - 1 = 1, \quad (3)$$

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where d is the inter-electrode distance.

The coefficients α and γ are not constant for non-homogenous field, they depend on the inter-electrode position. In that case, the expression for breakdown condition gets more complex. If one assumes that γ coefficient depends only on electrical field in near vicinity of the cathode, the breakdown condition can be expressed as [19]:

$$\gamma \left\{ \exp \left[\int_0^d \alpha(r) \cdot dr \right] - 1 \right\} = 1. \quad (4)$$

The voltage for which breakdown occur, U_b (breakdown voltage), is related to the product of gas pressure p and inter-electrode distance d ($p \cdot d$). Mathematical formulation of that relation is known as Paschen's law:

$$U_b = \frac{B \cdot p \cdot d}{\ln(A \cdot p \cdot d) - \ln[\ln(1 + 1/\gamma)]} \quad (5)$$

where A and B are constants dependent on gas type. This expression shows good agreement with experimentally obtained Paschen's curves with the minimum point which position correspond to most convenient ionization conditions.

The breakdown appearance is not deterministic. Will it occur or not, depends on the ration between the processes of charge creation and loss. For example, if the loss processes in gas are dominant, the breakdown will not occur even when the applied voltage is higher than breakdown voltage.

The nature of breakdown is statistical and so called breakdown probability W , is introduced as a term. This probability is different for each initial electron, and it has complex dependence with respect to electron position, electrical field, gas pressure and coefficients α and γ [20, 21].

The calculation of W for low pressure gas, when space charge influence is neglected, secondary electrons are released from the cathode and when each avalanche is considered independent with respect to previous one, it is shown that $W = 0$ for $q < 1$ and $W = 1 - 1/q$ for $q \geq 1$, where $q = \lambda \exp(\alpha d) - 1$ [22, 23].

Breakdown voltage for gas-filled component is the voltage value for which breakdown in gas occur. Usually, in practical applications, so called dynamic breakdown voltage U_b , is used as well as static breakdown voltage U_s . U_b is statistical quantity, so it is necessary to perform large number of measurements under the same conditions and acquire mean value \bar{U}_b .

The true value of static breakdown voltage U_s cannot be preciously determined, but only estimated. There are several methods for U_s estimation. One of them uses Townsend's plateau of current-voltage characteristics [24]. In this case, the U_s value is obtained by extrapolation of the Townsend's plateau until the intersection with voltage axis. The main disadvantage of this method is the neglecting the statistical nature of processes in gas that lead to breakdown initiation. Due to this fact, we have developed so called discretized dynamic method, which take into account the statistical nature of gas processes [25]. This method require the increase of voltage applied to gas-filled component in steps U_p for a strictly defined time between two steps t_p . In this case, voltage increase rate is defined as $k = U_p/t_p$. Using this method, a large number of U_b measurements is performed for different voltage increase rates k . Further, for each value of voltage increase rate k , \bar{U}_b is found. The static breakdown

voltage U_s can be found by fitting the $\bar{U}_b = f(k)$ dependence and finding its intersection with U_s axis ($k = 0$).

The value of breakdown voltage U_b depends on many parameters. Most important are voltage increase rate k , the relaxation time τ (τ is the time interval between two consecutive breakdowns when there is no voltage on gas-filled component), product $p \cdot d$ [26] and presence of external ionizing radiation [27, 28].

III. EXPERIMENTAL DETAILS

The measurement of dynamic breakdown voltage U_b was performed on custom designed experimental samples with glass housing enclosing two spherical metal electrodes filled with nitrogen at 6.6 mbar pressure. Interelectrode space was 2 mm (Fig. 1).

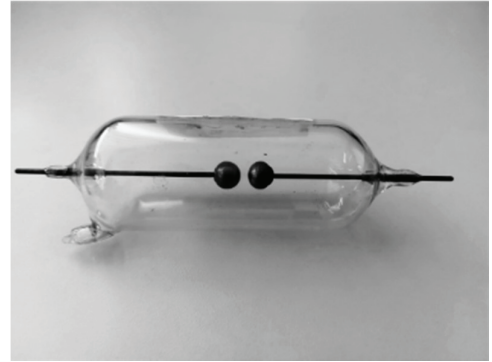


Fig. 1. Glass housing nitrogen-filled component.

In addition, the measurement of this quantity is also performed for GM chamber produced by PHILIPS, (Fig. 2).



Fig. 2. PHILIPS GM chamber

The cathode of this component is of a cylindrical shape, made of 28% Cr and 78% Fe. The chamber contain mica material

window that allow alpha and beta particles transition. The wire-shaped anode is placed along the cylindrical shaped cathode axis. The chamber is filled with argon or neon as a basic gas at low pressure with the addition of several percentages of a halogen gas (chlorine or bromine), which serve as quenching gas. This mixture is working gas for non-self-extinguishing counters.

U_b measurements were performed without and with the presence of gamma radiation, originating from ^{226}Ra with activity $A = 10$ kBq. Exposed dose rate was calculated according to $De = A\Gamma r^2$, where $\Gamma = 1.7 \cdot 10^{-18}$ C·m²/kg [29] is a constant and r is the distance from radioactive source to inter-electrode distance. The U_b values were obtained using discretized dynamic method. Measurement cycle is presented in Fig. 3.

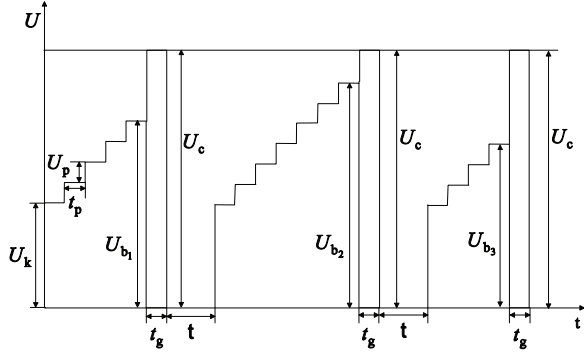


Fig. 3. Measurement procedure: U_{b1} , U_{b2} and U_{b3} are measured data of dynamic breakdown voltage, U_p is the voltage step, t_p is the time interval between two voltage steps, τ is the relaxation time, t_g is the duration of self-sustaining discharge and U_c is the voltage required for maintaining self-sustaining current I_g .

Initial voltage U_k , lower than breakdown voltage is connected to gas-filled component. Voltage value is further increased for predefined voltage step value U_p , every predefined time interval t_p . The voltage value for which breakdown occur is breakdown voltage U_b . After every breakdown, the self-sustaining discharge current $I_g = 0.5$ mA flows through the gas for the time $t_g = 1$ s. Consequently, the component is disconnected from the supply during the predefined relaxation time τ . The whole procedure repeats for desired number of measurements. The mentioned measurement procedure couldn't be performed using conventional commercially available equipment. Due to this, custom made system was realized. Block diagram is presented in Fig. 4 [30]. The system has two main parts, analog and digital. Analog part incorporates programmable DC power supply, which aims to deliver stepped voltage signal on the component. Digital part incorporated microcontroller with D/A converter. The whole system is controlled from PC application which controls various measurement parameters mentioned above.

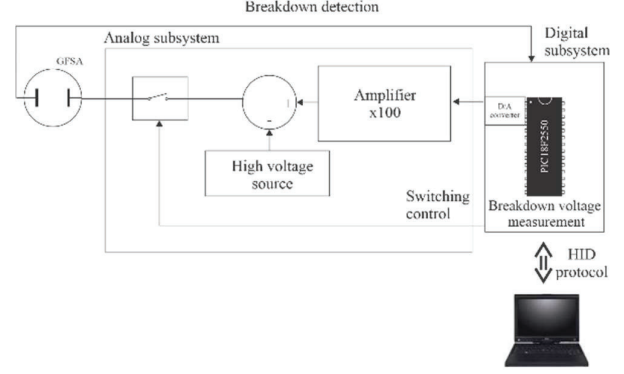


Fig. 4. Block diagram of system for automatic measurement and data acquisition of dynamic breakdown voltage.

IV. RESULTS AND DISCUSSION

A. Statistical analysis of dynamic breakdown voltage data

It is known that during the measurement of dynamic breakdown voltage U_b , under the same conditions, obtained values are different. On the basis of such behavior, it can be concluded that U_b is statistical property. It is very important to find adequate distribution law that describes this property. Recent researches have shown that U_b data obtained for component with glass housing, filled with nitrogen at 6.6 mbar pressure can be very well described using Weibull probability distribution function [31]:

$$f(U_b) = \frac{\beta}{\eta} \left(\frac{U_b - \delta}{\eta} \right)^{\beta-1} \exp \left[- \left(\frac{U_b - \delta}{\eta} \right)^\beta \right], \quad (6)$$

where β is the curve slope parameter or Weibull's slope, η is the scaling parameter and δ is the location parameter.

This paper present Weibull's probability distribution function applied to U_b experimental data obtained for GM chamber. Fig. 5 present distribution for 100 U_b values obtained when GM chamber wasn't subjected to gamma radiation. Fig. 6 present the same distribution for 100 U_b values, when during measurement GM tube was subjected to gamma radiation with exposed dose rate $4.1 \cdot 10^{-12}$ C/(kgs). Voltage increase rate in both cases was $k = 5$ V/s. In both cases Weibull's distribution can be applied. For higher values of exposed dose rates, obtained values doesn't obey any distribution due to low data dispersion (see Fig. 7 obtained for GM chamber irradiated with exposed dose rate $5.7 \cdot 10^{-12}$ C/(kgs)).

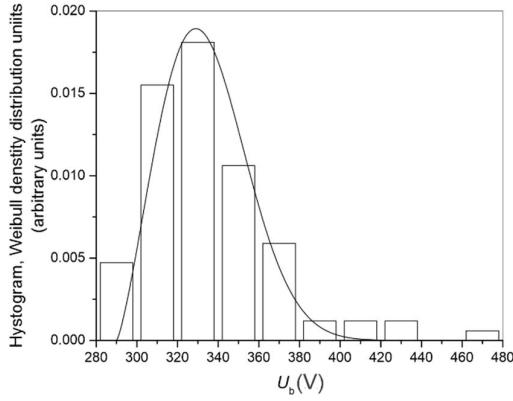


Fig. 5. Weibull's probability distribution function with histogram for non-irradiated GM chamber. Histogram was obtained using U_b 100 data for voltage increase rate $k = 5$ V/s. After every breakdown the self-sustaining discharge current $I_g > 0.5$ mA was flowing through the gas for the time $t_g = 1$ s.

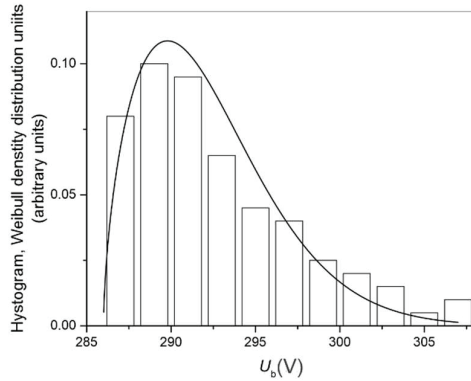


Fig. 6. Weibull's probability distribution function with histogram when GM chamber was irradiated with exposed dose rate of gamma radiation $4.1 \cdot 10^{-12}$ C/(kg.s). Histogram was obtained using U_b 100 data for voltage increase rate $k = 5$ V/s. After every breakdown the self-sustaining discharge current $I_g > 0.5$ mA was flowing through the gas for the time $t_g = 1$ s.

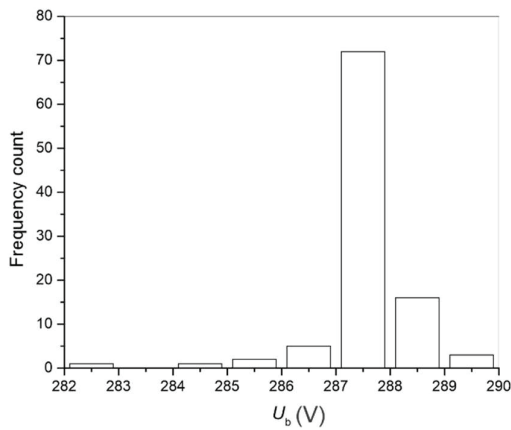


Fig. 7. Weibull's probability distribution function with histogram when GM chamber was irradiated with exposed dose rate of gamma radiation $5.7 \cdot 10^{-12}$ C/(kg.s). Histogram was obtained using U_b 100 data for voltage increase rate $k = 5$ V/s. After every breakdown the self-sustaining discharge current $I_g > 0.5$ mA was flowing through the gas for the time $t_g = 1$ s.

B. The influence of voltage increase rate to the mean value of dynamic breakdown voltage

Fig. 7 present the dependence between mean value of dynamic breakdown voltage, \bar{U}_b and voltage increase rate k , for GM chamber. Presented results were obtained when GM chamber wasn't subjected to gamma radiation as well as when the chamber was subjected to gamma radiation with exposed dose rates $4.1 \cdot 10^{-12}$ C/(kg.s) and $5.7 \cdot 10^{-12}$ C/(kg.s). Every point on the graph present mean value of 100 U_b values. It can be seen that in all three cases linear function very well fits experimental data and intersection of all three lines with \bar{U}_b axis ($k = 0$) give the value of static breakdown voltage U_s . It can be seen from the figure that increase in voltage increase rate lead to the increase in the value of \bar{U}_b . In addition, \bar{U}_b value is very sensitive to gamma radiation because even the small exposition dose rates lead to significant decrease of this property. Also, for exposed dose rate of $5.7 \cdot 10^{-7}$ Gy/h \bar{U}_b value is practically independent from voltage increase rate.

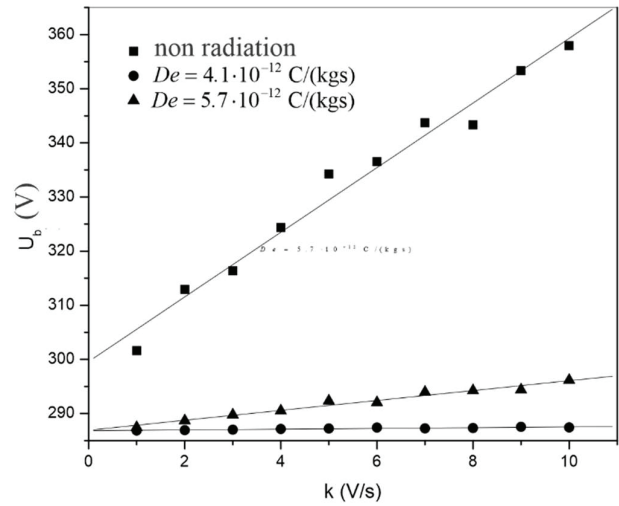


Fig. 8. Dependence between mean value of dynamic breakdown voltage and voltage increase rate k , for the cases when GM chamber was not irradiated during U_b measurement as well as when GM tube was irradiated with gamma radiation with exposed doses of $De = 4.1 \cdot 10^{-12}$ C/(kg.s) and $De = 5.7 \cdot 10^{-12}$ C/(kg.s). After each breakdown, self-sustaining discharge current $I_g = 0.5$ mA was flowing through the gas for the time $t_g = 1$ s.

C. The possibility for application of gas-filled components in gamma radiation dosimetry

Our investigations have shown that breakdown voltage of gas-filled components is very sensitive to gamma radiation. That was the starting point that lead to the idea to use mean value of breakdown voltage as dosimetric parameter for determination of low values of exposed dose rate. Fig. 8 present $\bar{U}_b = f(De)$ dependence for nitrogen-filled component at 6.6 mbar pressure with glass housing. \bar{U}_b was the mean value of 100 U_b data for each value of De . Two distinct areas can be observed on the figure. The first one, up to $De = 2 \cdot 10^{-12}$ C/(kg.s) show significant decrease in \bar{U}_b , and second one from $2 \cdot 10^{-12}$ C/(kg.s) to $8 \cdot 10^{-12}$

$C/(kg \cdot s)$ doesn't exhibit such decrease. It can be concluded that this component can be used as exposed dose detector up to $De = 2 \cdot 10^{-12} C/(kg \cdot s)$. In this range there is approximately linear dependence between \bar{U}_b and De .

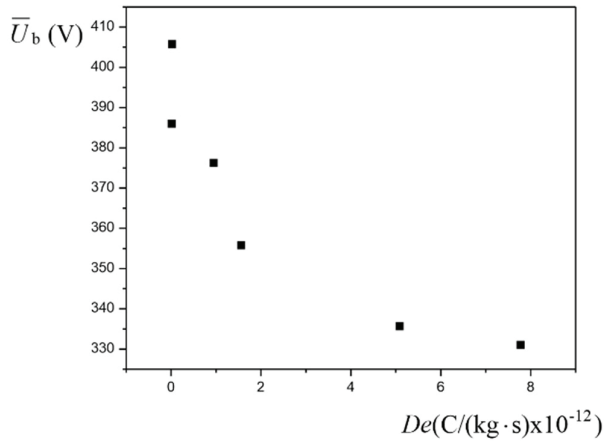


Fig. 9. Mean value of dynamic breakdown voltage as a function of exposed dose rate for nitrogen-filled component at 6.6 mbar pressure with glass housing. The U_b data were obtained for voltage increase rate $k = 5$ V/s.

The possibility for application of static breakdown voltage as dosimetric parameter for the same component was also considered. Fig. 10 present $U_s = f(De)$ dependence. For each value of De , $\bar{U}_b = f(k)$ was obtained (\bar{U}_b represent mean value of 100 data for each value of k) and linear fitting was performed until the intersection with \bar{U}_b axis ($k = 0$). These intersections correspond to the U_s values. The behavior of this dependence is similar to those at Fig. 9.

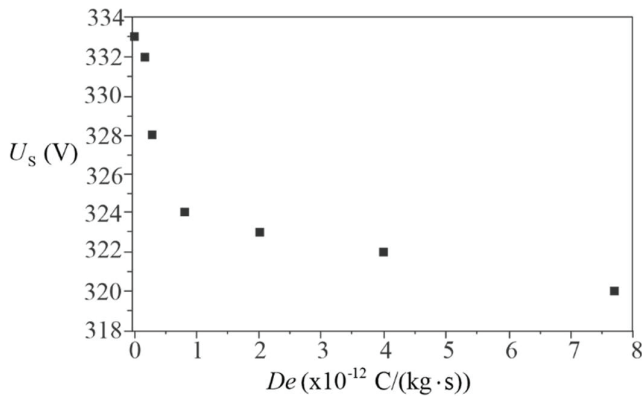


Fig. 10. Static breakdown voltage as a function of exposed dose rate De for nitrogen-filled component at 6.6 mbar pressure with glass housing. The U_s data were obtained from $\bar{U}_b = f(k)$ dependence.

GM chamber was also tested with the aim for possible application in gamma radiation dosimetry. Dosimetric parameter was also the value of \bar{U}_b . Results are presented in Fig. 11. Each point on the figure is mean value of 100 experimentally obtained U_b values. It can be seen that the behavior is similar to those presented in Fig. 9. There is decrease in \bar{U}_b value up to $De = 7 \cdot 10^{-12} C/(kg \cdot s)$. For higher De values \bar{U}_b remain

approximately constant. It can be concluded that GM chamber can be used in gamma radiation dosimetry, with \bar{U}_b as dosimetric parameter, for doses up to $De = 7 \cdot 10^{-12} C/(kg \cdot s)$.

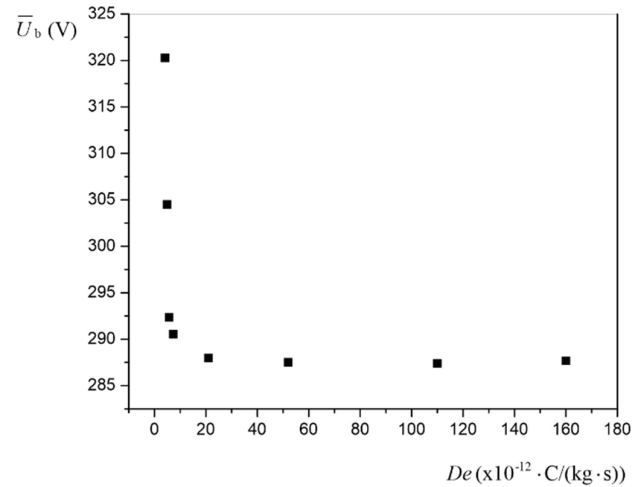


Fig. 11. Mean value of dynamic breakdown voltage as a function of exposed dose rate De for GM chamber. The U_b data were obtained for voltage increase rate $k = 5$ V/s.

The comparison between Figs. 9 and 11 lead to a conclusion that irradiation, glass housing nitrogen-filled tube component and GM chamber behave in a similar way. Namely, \bar{U}_b value rapidly decreases with the increase in exposed dose rate up to a certain value when $\bar{U}_b \approx \text{const}$. Such behavior is a consequence of increase in electron yield (electrons number in inter-electrode space per area unit) with the increase in exposed dose rate. Due to increased electron yield, the breakdown probability W also increases. When $\bar{U}_b \approx \text{const}$ breakdown probability $W \approx 1$. In this case these components cannot be used as ionizing radiation detectors for higher values of exposed dose rates.

V. CONCLUSION

On the basis of experimental data of dynamic breakdown voltage for gas-filled components, obtained under same conditions it was concluded that it is a property of a statistical nature. Due to that fact, in practical applications it is necessary to use mean value of a large number of measurements. The system for automatic measurement and data acquisition of breakdown voltage was designed. It was shown that data set can be very well described using Weibull's probability distribution function for the case when components were not subjected to gamma radiation. It was also shown that there is a linear dependence between mean value of dynamic breakdown voltage and voltage increase, regardless if the component was subjected to gamma radiation, as well as that even low exposed dose rates lead to significant decrease in breakdown voltage. Due to this, analysis incorporated the dependence between mean value of dynamic breakdown voltage, as well as static breakdown voltage and gamma radiation exposed dose for glass housing component and GM chamber. It was shown that these components are very sensitive to exposed dose rate slightly higher than natural radioactivity. For higher values of exposed dose rates, components exhibit low sensitivity due to high

electron yield in inter-electrode space induced by gamma radiation. On the basis of such behavior, it can be concluded that these components can be very efficiently used as sensors of gamma radiation for low doses where dosimetric parameter can be mean value of dynamic breakdown voltage or static breakdown voltage as well.

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