integrating this equation we obtain that when $\beta = 1$ $Q = Q_0 \exp(\eta)$ and when $\beta \neq 1$

$$Q = [Q_0^{1-\beta} + \eta(1-\beta)]^{1/(1-\beta)}, \text{ where } \eta = \frac{ha^2}{4\pi} \frac{t^{2\alpha+1}}{2\alpha+1} \frac{1}{R^2};$$

in particular, when $\beta < 1$ the relation $Q = Q(t)$ is approximately a power relationship, when $\beta = 1$ it is exponential, and when $\beta > 1$ it is hyperbolic, and as one approaches the corresponding asymptote the whole conductor explodes.

In conclusion we note that these results are also applicable to the following cases. First, when the field is derived from a conductor: We can consider a model in which the initial field $H(x) = \text{const}$, the field is measured from this value, and we use $H = -\alpha t^{\alpha}$ as the boundary condition. Second, when the heating occurs at constant pressure, we can assume that Q is the enthalpy and x is a coordinate which moves with the material.

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BREAKDOWN VOLTAGES OF INERT GASES AT TEMPERATURES OF 300-2000°K

I. V. Bozhko, N. I. Glazkov,
S. R. Troitskii, and N. I. Fal'kovskii

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We may assume that as temperature increases, the dielectric strength of inert gases begins to deviate from Paschen's law

$$U_{br} = f(ps/T) \quad (1)$$

at lower temperatures than, for example, the dielectric strength of electronegative gases [1]. This may be due, in particular, to the fact that in the inert gas there is no capture of the thermal electrons emitted by the cathode at high temperatures, i.e., there is no factor which will retard the development of breakdown. A confirmation of this may be found in the results of an investigation of currents in unheated inert gases at pressures $p < 40$ kPa [2], which disclosed the phenomenon of early breakdown, attributed by the authors to the thermal ionization of the gas near the cathode filament, which is incandescent above 2400°K.

George and Messerle [3] obtained breakdown voltages for argon and helium at isothermal conditions, T = 1600-2500°K, but in a nonuniform field, and therefore no generalized conclusions can be drawn from their results. Measurement of the dielectric strength of argon in a shock tube [4] showed that the breakdown of the gas under such conditions is determined by the colder boundary layer; this makes interpretation of the results more difficult. Direct measurements of the pulsed dielectric strength when a stream of gas is heated in a plasmotron were carried out in [5]. The results show that up to 2100°K in argon and helium Paschen's law remains valid in investigations using unaged electrodes, while investigations with aged electrodes yield much higher values than Paschen's law. Since no conclusion con-

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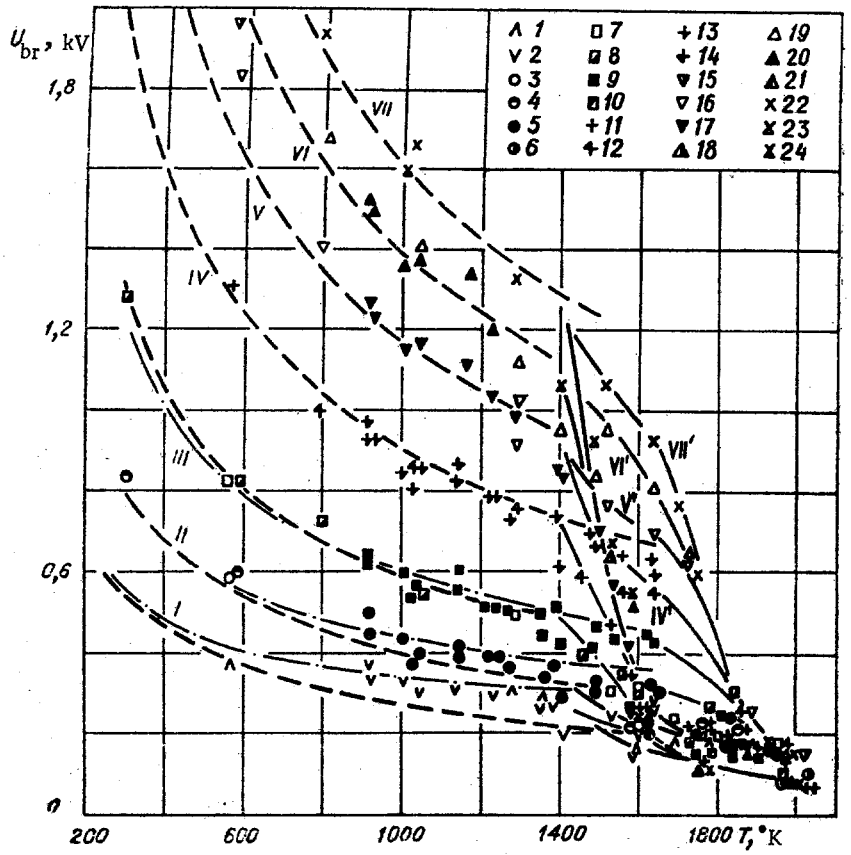

Fig. 1

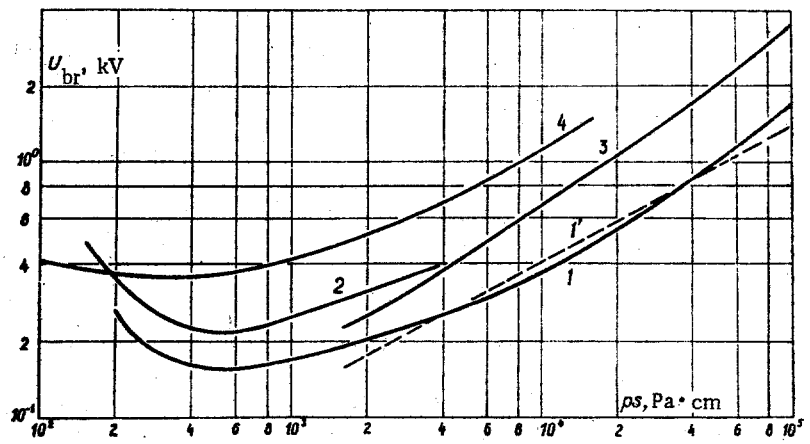

Fig. 2

cerning the value of T_{br} for Ar and He can be drawn from [2-5], it is of interest to carry out investigations under the most idealized conditions.

In what follows, we give the results of an investigation of the dielectric strength of argon and helium in a motionless gas in uniform electric and thermal fields in the 300-2000°K range. The technique and principles of the investigation are analogous to those described in [1]. We used electrodes with a diameter of 20-30 mm, made of platinum and platinum–rhodium alloys (PtRH-10, PtRH-30), as well as of zirconium dioxide (at 900-2000°K in Ar) and aluminum oxide (at 1600-2000°K in Ar). In the investigations we used first-grade argon (99.98%) and highly pure helium (99.99%). The pressure of the gases in the discharge chamber was atmospheric pressure. Beginning at T ∿ 1000°K, we used a two-coordinate recorder to plot the volt–ampere characteristics (VAC) of the discharge.

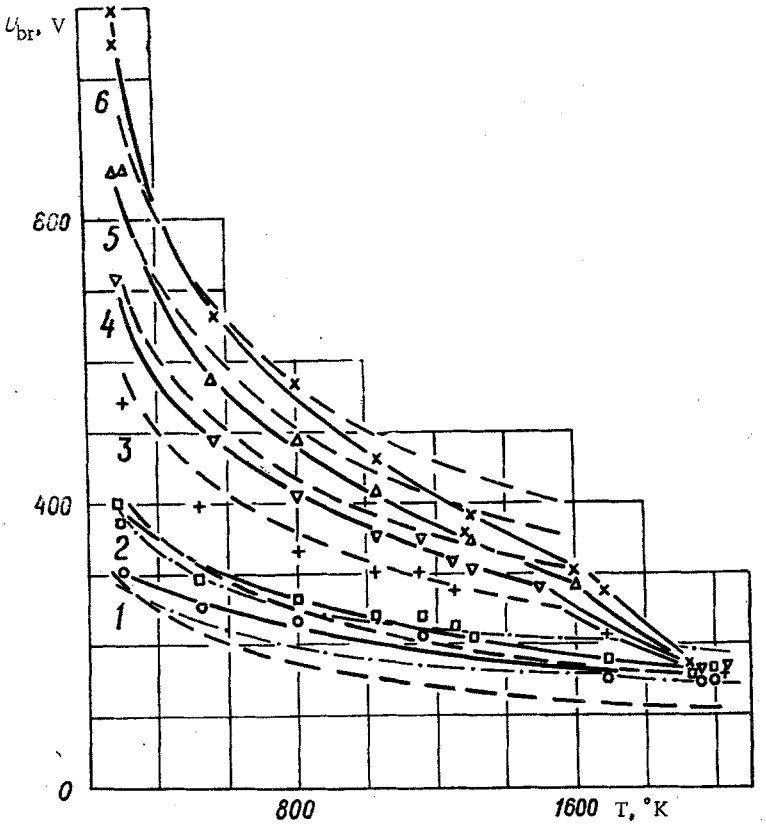

Fig. 3

The variation of the breakdown voltage U_{br} in argon with increasing temperature for different lengths of the interval s is shown in Fig. 1 (curves I-VII correspond to s = 0.25, 0.5, 1, 2, 3, 4, 5, and 5 mm: for Pt, points 1, 3, 7, 11, 15, and 18; for PtRH-10 and PtRH-30, points 4, 8, 12, 16, 19, and 22; for ZrO_2, points 2, 5, 9, 13, 17, 20, and 23; for Al_2O_3, points 6, 10, 14, 21, and 24). Each point was obtained by averaging the values for five or more breakdowns. The dispersion of the breakdown voltages in each such series is no more than 3-5%.

A function of the form (1), according to the experimental results of the present study up to 1400°K (in the range ps = $1.2 \cdot 10^3$-10^5 Pa·cm, where $p = p_0T_0/T$), together with the curve given in [6], can be approximated to within ±7% by the expression

$$U_{br} = 3.36\delta s + 2.93\sqrt{\delta s}. \quad (2)$$

Here s is in cm, δ is the density of the gas, referred to its density at normal conditions; $p_0 = 1.013 \cdot 10^5$ Pa, $T_0 = 293$°K. The functions $U_{br} = f(T)$, calculated in accordance with (2), are shown by dashed curves in Fig. 1. It should be noted that in this range of ps the expression (2) agrees more closely with the data of [6] and Fig. 1 than the expression given for argon in [7]. The deviation of the experimental points from the curves obtained by using (2) when T < 1400°K and ps > $1.2 \cdot 10^3$ Pa·cm is no more than −8 to +15%.

The dot–dash curves indicate the functions $U_{br}(T)$ constructed on the basis of an experimental Paschen curve for normal temperature [6]. The dispersion of the breakdown voltages when T < 1400°K with respect to these curves lies between −10 and +8%. As can be seen from Fig. 1, heating argon to T ∿ 1400°K does not lead to any substantial deviation from Paschen's law. A further increase in temperature leads to a sharp decrease of U_{br} in such a way that when T = 2000°K, for all the gaps investigated, $U_{br} \approx 80$, 90, and 155 V for cathodes made of ZrO_2, Al_2O_3, and Pt and its alloys, respectively. For the temperature range T = 1400-2000°K the variation of U_{br} as temperature increases is shown by solid curves in Fig. 1. The electrode material has no effect on the limiting temperature T_{br} above which Paschen's law fails. However, when $T > T_{br}$, the function $U_{br} = F(T)$ is affected by the emission properties of the cathode. The higher the work function of the cathode, the higher will be the breakdown voltages for this interval. The curves marked with numbers are the ones obtained with platinum electrodes. Experimentation with anodes and cathodes made of different materials showed that the anode material has no effect on the discharge characteristics.

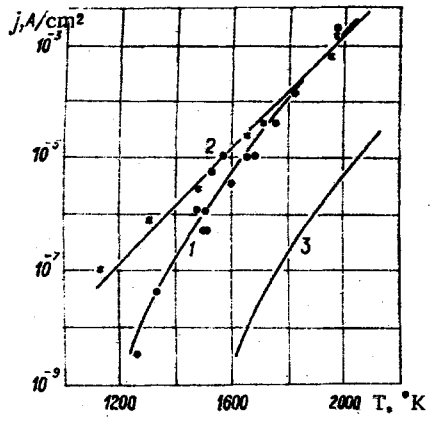

Fig. 4

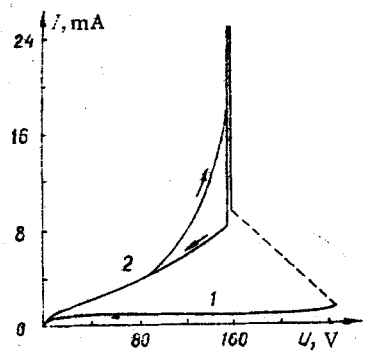

Fig. 5

Investigations of the dielectric strength of helium showed that even at normal temperatures the breakdown voltages are much lower than those given in the literature. The value of the difference increases with increasing values of the parameter ps. This can be seen in Fig. 2, where curve 1, obtained in the present study at normal temperature, is compared with functions 2 and 4 taken from [6] and [5], respectively. Curve 3 is obtained by calculation using the expression [7]

$$U_{br} = 2.01\delta s + 1.53\sqrt{\delta s}. \quad (3)$$

The fact that the experimental curve 1 was found to lie considerably below curves 2 and 3 is due to the fact that the highly pure helium was not contaminated with electronegative impurities whose presence would bind the free electrons into the low-mobility negative ions, thereby retarding the development of breakdown. To verify this, we carried out experiments in which small amounts (∿0.5%) of oxygen or water vapor were introduced into the helium under investigation. In both cases the breakdown voltage increased by 15-20% and the experimental points lay in the vicinity of curve 2 (Fig. 2).

Analytically, curve 1 (Fig. 2), in the range $3\cdot10^3 \leqslant ps \leqslant 6\cdot10^4$ Pa·cm can be described to within ±8% by the expression

$$U_{br} = 0.14\delta s + 1.26\sqrt{\delta s}. \quad (4)$$

Function (4) is shown by curve 1' in Fig. 2.

When helium is heated, its dielectric strength (Fig. 3, solid curves) decreases smoothly. When the temperature rises above $T_{br} \sim 1600$°K, there is a sharp decrease in U_{br} for intervals s > 1 mm. When T ∿ 2000°K, U_{br} no longer depends on the magnitude of the interelectrode gap, and for all the intervals investigated it amounts to about 155 V. In Fig. 3, curves 1-6 correspond to s = 0.5, 1, 2, 3, 4, and 5 mm (electrodes made of Pt). The curves calculated in accordance with (4) are shown in Fig. 3 by dashed curves. For s = 0.5 mm, when T = 500°K, the experimental data lie 20-30% above the calculated data, since above this temperature the parameter ps lies beyond the limits of applicability of formula (4). However, as in the case of Ar (see Fig. 1), the high-temperature results in the case of He for small intervals are in good agreement with the results obtained at normal temperatures (dot–dash curves in Fig. 3). When $T < T_{br}$, the dispersion of the magnitudes of U_{br} (Fig. 3) with respect to the Paschen curve 1 (Fig. 2) is ±12%, and with respect to (4) the dispersion ranges from −6 to +11% (in the range ps = $3\cdot10^3$–$6\cdot10^4$ Pa·cm).

A characteristic feature of the breakdown of these gases at high temperatures is that at atmospheric pressure a normal glow discharge may burn constantly in the interelectrode space. This is somewhat unexpected, since under ordinary circumstances a glow discharge in gases is found only at pressures of no more than a few kilopascals [6]. At higher pressures the glow discharge is very unstable and passes into an arc. However, if we can achieve sufficiently strong free ionization of the gas, then it is possible to have a volume discharge between the electrodes at pressures of the order of atmospheric pressure [8]. This discharge has the cathode and anode parts typical of a glow discharge and also has a nonindependent conductivity in the middle zone of the space [9]. As has been shown by calculations [10] and experiments [8], for a volumetrically homogeneous discharge, the minimum required initial electron density n_{e0} created in the interelectrode space by one or another method must be 10^4–10^6 cm^{-3}.

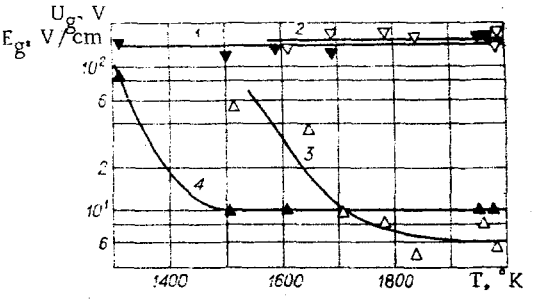

Fig. 6

At high temperatures, thermal-ionization processes in the volume and at the electrodes and thermal emission from the electrodes may serve as the equivalent of the preionization ensuring the initial electron density in the space. The value of n_{e0} can be estimated from the initial currents of the volt–ampere characteristics. The initial segment of the VAC of the discharge at voltages not exceeding a few volts is linear. Since at such low voltages there is practically no amplification resulting from ionization, the initial current is determined by the above-mentioned phenomena. If we consider that the initial current through the space, j_e, is mainly an electronic connection current, $j_e = en_{e0}\mu_e E$, where e is the charge of an electron, and n_{e0} and μ_e are the concentration and mobility of the electrons, we find that the initial electron density is

$$n_{e0} = j_e/(e\mu_e E). \tag{5}$$

The experimental curves for the initial current densities as functions of temperature, taken in argon and helium for U ∿ 2 V, and the emission current for platinum cathodes are shown in Fig. 4 (curves 1-3, respectively). The values of the electron mobilities μ_e in argon and helium at a field of E ∿ 80 V/cm, corresponding to the experimental conditions of Fig. 4, are $3.7\cdot10^3$ and $6.2\cdot10^3$ cm²/(V·sec) [6]. In order to satisfy the condition $n_{e0} > 10^4$-10^6 cm^{-3}, in accordance with (5), the initial current density must be $j_e > 10^{-9}$-10^{-7} A/cm². It can be seen from Fig. 4 that the current density reaches a value of $j_e > 10^{-7}$ A/cm² when T ∿ 1200°K for He and when T > 1400°K for Ar, i.e., at these temperatures a diffuse discharge of the glow type may exist in the interelectrode space. Under the conditions described, a glow discharge of undetermined duration was observed in He when T ⩾ 1300°K and in Ar when T ⩾ 1500°K. At lower temperatures the discharge was highly unstable, and when these were low current-limiting resistances in the circuit, the discharge passed into an electric arc. It should be noted that in the investigations of [11], for pulsed voltages, a momentary glow discharge (lasting several microseconds) in helium at atmospheric pressure was observed beginning at T ∿ 900°K.

The volt–ampere characteristics of the transition to a glow discharge in argon are shown in Fig. 5 (s = 5 mm, cathode made of Pt). As the temperature increases, the jump transition to a glow discharge (T = 1850°K, curve 1) is replaced by a smooth transition (T = 1950°K, curve 2). In the entire temperature range of the existence of a glow discharge, as the discharge current increases and decreases, we observe hysteresis phenomena (Fig. 2). At currents of several hundred milliamperes there is a contraction, and an electric arc is created. The voltage established in the discharge gap after breakdown is the voltage for the ignition of the glow discharge, U_g. Its value depends only slightly on the magntidue of the discharge gap. This indicates that the main potential drop takes place at the cathode layer, and for small values of s we may assume that $U_g \approx U_c$. The average value of U_g for s = 1 mm and electrodes made of Pt in He, in the 1300-2000°K range, is about 150 V (curve 1 in Fig. 6), and in argon for 1600-2000°K it is 155 V (curve 2). For comparison, we may note that the cathode potential drop U_c in a normal glow discharge with cold platinum cathode is 131 V for He and 165 V for Ar [12].

From the variation of the ignition voltage ΔU_g as the discharge gap length Δs varies, for unchanged discharge current j_d, we can determine the value of the longitudinal potential gradient E_g in the positive column of the glow discharge: $E_g = \Delta U_g/\Delta s$. The electric field intensity $E_g(T)$ in Ar and He calculated in this manner, for j_d = 10 mA/cm², is shown by curves 3 and 4, respectively, in Fig. 6.

When T ∿ 2000°K, we have E_g ∿ 6 V/cm for argon and E_g ∿ 10 V/cm for helium, which is close to the values of E_g in these gases in a glow discharge at low pressure with a cold

cathode: For p = 0.65 kPa we have E_g = 1.5 and 6 V/cm [12]. When the gas temperature is reduced, there is a sharp increase in $E_g = f(T)$ at T ∿ 1700°K in Ar and at T ∿ 1500°K in He, indicating that we are observing a transition to an intermediate temperature range, which will be followed by a region in which the stable glow discharge disappears.

As mentioned above, the reason for the initial electron concentration at a level of 10^4-10^6 cm^{-3} may be ionization in the volume and thermal emission from the cathode.

According to the Saha equation, the thermal ionization of the principal gases Ar and He when T < 2000°K is negligibly small. However, vapors from the chember walls, containing metal elements, including a small number of atoms of alkali metals, have an ionization energy much smaller than the gases under investigation, and the calculated ionization in the interelectrode space becomes substantial [13].

The limiting thermal-emission currents from a platinum cathode in a vacuum, calculated by the Richardson-Dashman formula $j_{th} = AT^2\exp(-e\varphi/kT)$, are also substantially less than the experimentally observed values (see Fig. 4). However, as is known [14], in a gaseous medium there is a substantial change even in the work function of platinum, which decreases under the effect of adsorption of the gases (for example, by 0.5-0.7 eV when oxygen is adsorbed), and especially when alkali-metal vapors are adsorbed. If we assume that the initial currents (see Fig. 4) are due only to emission, we can find from the VAC, using the Richardson straight-line method with lines $k \ln j_{th}/AT^2 = e\varphi/T$ [15], that the work function for a platinum cathode under the conditions described would be $e\varphi \sim 4.3$ eV, as opposed to 5.6 eV in a vacuum [14]. Naturally, the initial current in the space is determined by the total effect of the increased thermal emission and thermal ionization in the volume. It does not seem possible at present to estimate the effect of each factor individually.

Thus, the investigations of electrical discharges in inert gases enable us to conclude that when argon is heated to T ∿ 1400°K and helium to T ∿ 1600°K, the variation in the dielectric strength will be described by the generalized Paschen law. When these temperatures are exceeded, there will be a sharp decrease in the breakdown voltages. At high temperatures, breakdown corresponds to ignition in the discharge space of a stable glow discharge.

It has been established that highly pure helium has a dielectric strength lower than the value previously known and that even slight impurities may substantially increase its breakdown voltage. The results also indicate that inert gases (Ar, He), contrary to expectations, have a limiting temperature for Paschen's law which is not lower but higher than some electronegative gases. This indicates that the processes of attachment and detachment of electrons in high-temperature gases play a different role in the development of breakdown than in the development of such breakdown in unheated gases [16].

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