LIMITING ENERGY CHARACTERISTICS OF PULSED TEA CO_2 LASERS

A. M. Orishich, A. G. Ponomarenko,
and R. I. Soloukhin

UDC 537.521

The article presents the results of experimental studies on the determination of the characteristics of the process of absorption of large specific electrical energy densities in a wide range of pressures (0.1-0.5 atm $CO_2-2N_2-0.5H_2$). The presence of limitations ($E_0/p \geq 45$ V/cm · torr, $Q/p \leqslant 1$ J/cm^3 · atm) which are responsible for the region of existence of a diffusional discharge was established, which made it possible to determine the relationship between the limiting electrical energy density which can be absorbed in the discharge, the initial parameters of the system, and the amount of radiated energy.

Along with the development of the technology of powerful pulsed lasers of the electroionization type, which use an electron beam to create a uniform discharge in a dense gas, interest continues to be maintained in the most simple laser systems having excitation of an optically active medium at high pressures by means of a double transverse electrical arc (TEA CO_2 lasers) [1-4]. The investigations of such systems have brought out a number of insufficiently studied aspects of the problem of creating an efficient pulsed laser system based on this principle. First of all, there is no clear answer to the question of just what processes are responsible for the limitation in the amount of electrical energy absorbed in the arc without overheating and in a stable mode, what are the limiting values of the amplification factor and energy efficiency of the entire system, etc.

The quenching by electrons of the vibrational excited states of the molecules, which can considerably alter both the electron distribution function and the average energy of the electrons and gas molecules, begins to play an important role at higher densities of applied energy. The results of studies of the dynamics of the absorption of electrical energy in pulsed discharges are presented in the present report, and the relationship between the limiting energy, the initial parameters of the system, and the radiated energy is established.

1. Experimental Apparatus and Measurement Methods. A schematic diagram of the apparatus and an equivalent electrical diagram of the system are presented in Fig. 1. The capacitor C_1 is charged by a rectifier to the voltage $U_0 \simeq 0$–80 kV. When the discharger D is fired through a circuit containing an inductance L_0 the voltage is fed to the arc gap and the initial ionization system. Upon breakdown of the air capacitor C_4 an arc develops which is a powerful source of ultraviolet radiation. The auxiliary capacitors C_2 and C_3 determine the dynamics of the igniting arc and allow the creation of an additional overvoltage on the arc gap, which considerably affects the rate of initial ionization in the main volume. The main arc was produced in a metallic chamber 100 cm long. The specially developed and fabricated storage capacitor $C_1 = 10^{-7}$ F consisted of a compact electrical line for a voltage of about 100 kV with a characteristic impedance $\rho \simeq 0.8\ \Omega$. The total resistance of the current-carrying elements of the capacitor and leads was $R_b \simeq 0.4\ \Omega$. The electrodes were made in the shape recommended by Rogowski with a length of 80 cm and a width of 8 cm. The distance between electrodes was 5 cm. The cathode was built in the form of a shell within which the preliminary ionization system was located. The capacitor $C_2 \simeq 4 \cdot 10^{-9}$ F, in which polyethylene film was used as an insulator, was placed right inside the igniting electrode, which, in turn, was

---

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 1, pp. 3-12, January-February, 1975. Original article submitted September 6, 1974.

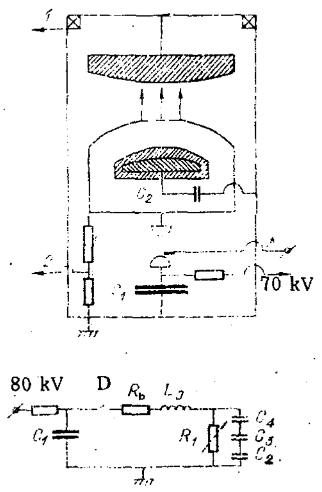

Fig. 1

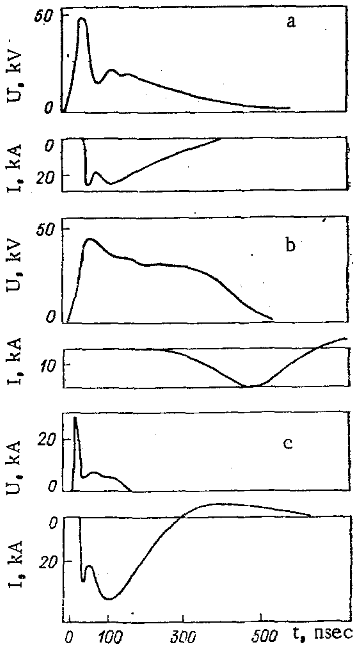

Fig. 2

covered with a Teflon film about 250 μ thick, which created an additional distributing capacitor $C_3 \simeq 8 \cdot 10^{-9}$ F. The middle part of the cathode in the region of the uniform field 2 cm in width was made of a parallel series of thin filaments 0.25 mm in diameter. The distance between the filaments and the dielectric surface of the igniting electrode was 2 mm.

The arc current I_a and the active voltage drop U_a between the electrodes were measured in the experiment with a Rogowski loop (1) and an ohmic divider (2) (see Fig. 1). The Rogowski loop had a characteristic time $\tau \simeq 15 \cdot 10^{-6}$ sec, which made it possible to reliably determine the shape of a current pulse with a duration of $\leqslant 2 \cdot 10^{-6}$ sec. The ohmic divider, consisting of a carefully calibrated water resistance, was connected directly to the cathode of the arc gap. The measured currents and voltages made it possible to determine the basic parameters characterizing the arc: its resistance $R_a(t) = U_a/I_a$, power, and total absorbed energy per unit volume

$$Q(t) = \frac{1}{V_0} \int_0^t I_a U_a \, dt.$$

The average electron concentration was determined from the expression

$$n_e \simeq \frac{I_a}{eSv_d},$$

where S is the average cross section of the arc, and v_d is the effective drift velocity, which was calculated from the equation $\frac{1}{v_d} = \sum_i \psi_i / v_{di}$ (i is the index of a component of the gas mixture, $\varphi_i = p_i/p$; p_i is the partial pressure, and v_{di} is the drift velocity determined with the value of the parameter $E_a/p = U_a/pd$ realized in the arc). The gas mixture $CO_2 : 2N_2 : 0.5H_2$ was used in the majority of experiments.

2. Absorption of Electrical Energy in Arc. The initial electron concentration produced in our experiments using an auxiliary discharge depends on the gas composition. For a $CO_2 : 2N_2$ mixture it can reach values of $n_e < 10^9$ cm^{-3} under the conditions chosen for this experiment [5]. The addition of hydrogen contributes to a certain increase in n_e, although this is still not sufficient to assure the rapid and efficient contribution of energy to the arc. We have established that in order to create a stable volumetric discharge at higher pressures it is necessary to bring about a relatively high rate of growth of the initial ionization, which is determined by the parameter $E_0/p = U_0/pd$, where E_0 is the initial electric field strength, U_0 is the voltage, d is the distance between the electrodes, and p is the pressure of the working mixture. Typical oscillograms of the arc current and voltage for different modes are presented in Fig. 2 (a: p = 0.2 atm, $U_0 = 50$ kV; b: p = 0.23 atm, $U_0 = 40$ kV; c: p = 0.15 atm, $U_0 = 60$ kV). It was found that the minimum value of the parameter $(E_0/p)_-$ required for stable ignition should only exceed by a few percent the value corresponding to the independent breakdown threshold. For the $CO_2 : 2N_2 : 0.5H_2$ mixture it was $(E_0/p)_- \simeq 45$ V/cm · torr. A volumetric discharge does not develop at lower values, but after about 10^{-6} sec a streamer breakdown of the arc gap occurs. This fact is explained by the uneven growth of avalanches in the initial stage of ionization when $E_0/p < (E_0/p)_-$. With the uneven ionization produced by the auxiliary ignition system it is necessary to create an initial overvoltage for the main gap in order to ignite a stable volumetric discharge in a uniform field [6, 7]. It is just this fact that explains the existence of a limiting value $(E_0/p)_-$ (different for different mixture compositions) above which the existence of a volumetric discharge in a wide range of working pressures is possible.

The data on the time dependence of E_0/p and n_e presented in Fig. 3 illustrate the dynamics of the development of a stable discharge (U_0 equals 50, 40, and 30 kV for curves 1-3, respectively, and p = 0.14 atm). The time variation in the resistance of the arc is shown in Fig. 4 (p equals 0.14, 0.21, 0.28, and 0.35 atm for curves 1-4, respectively, and $U_0 = 60$ kV). When $E_0/p > 45$ V/cm · torr a rapid increase occurs

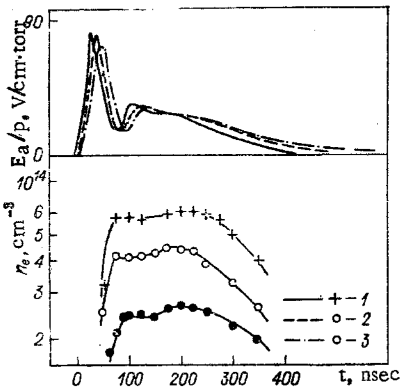

Fig. 3

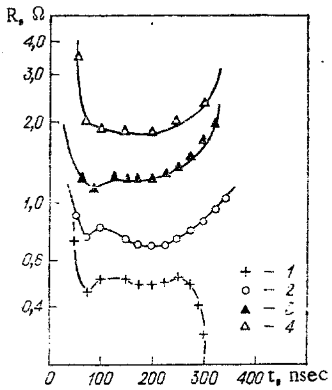

Fig. 4

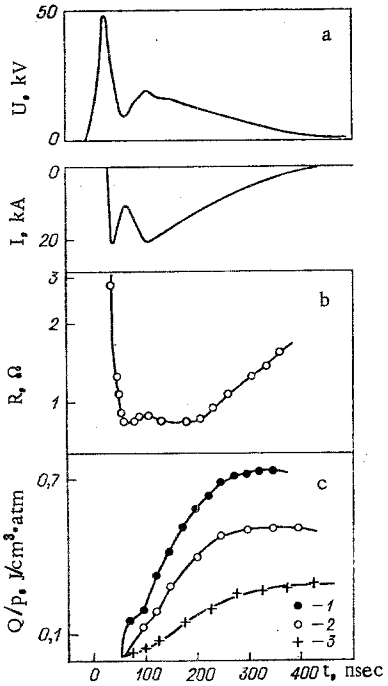

Fig. 5

in the electron concentration in the entire working volume, and there is a redistribution of the initial voltage between the internal resistance of the energy source and the time-varying ohmic resistance of the arc gap (see Fig. 2a and Fig. 3). The first short current pulse corresponds to the moment of intense ionization in the gap and is determined mainly by the discharge of the auxiliary capacitors C_2 and C_3. About $20 \cdot 10^{-9}$ sec after the rapid rise in the electron concentration (the resistance falls!) its stabilization occurs at some almost constant level n_e whose value is determined by the parameters E_0/p, p, and ρ (see Figs. 3 and 4). The electric field strength $(E_a/p)_c \simeq 25$-35 V/cm · torr established by this time in the gap does not depend on the initial voltage or the concentration n_e which is reached. The tendency toward the establishment of some quasistationary value of n_e (and, consequently, of R_a) actually comes down to the realization of the condition $dn_e/dt \simeq 0$ in the arc for different values of n_e (see Fig. 3). Since $(E_a/p)_c$ is also established at some quasiconstant level of ~25 V/cm · torr in this case and does not depend on E_0/p, the fact that the condition $dn_e/dt = 0$ is satisfied for different values of n_e cannot be explained by mutual compensation of two processes: direct ionization of N_2 and CO_2 molecules from the ground state and two-particle recombination. Evidently, at high arc-current densities of ~50-100 A/cm^2 ($n_e > 10^{13}$ cm^{-3}) the determining role may be played by processes of multistage ionization from excited metastable states (such as $A^3\Sigma_u^+$ and $B^3\Pi_g$ for N_2 molecules) and from states of dissociated CO_2 and N_2 molecules. An exact solution of the system of equations describing the kinetics of these processes is complicated because of the absence of reliable data on the dissociation cross sections and, especially, on the ionization cross sections of the excited states of N_2 and CO_2 molecules. Preliminary estimates made with allowance for the known data on the rate of excitation and subsequent ionization of states of the N_2 molecule, $A^3\Sigma_u^+$, $B^3\Pi_g$, and others, which have lifetimes considerably exceeding the duration of the discharge, show that in the quasistationary phase the number of N_2 molecules excited in the initial stage is sufficient to compensate for recombination losses of electrons through multistage ionization. In this case the equilibrium condition $dn_e/dt = 0$, or the equivalent $f(E_a/p, p)n_e^2 = \beta n_e^2$, does not depend on the electron concentration and is determined by the established value of $(E_a/p)_c$, the pressure, and the recombination coefficient. In Fig. 5 we present typical oscillograms of the current and voltage (a: $U_0 = 50$ kV), as well as the time variation in the arc resistance (b: $U_0 = 50$ kV) and the specific density of absorbed energy Q(t)/p (c: U_0 equals 60, 50, and 40 kV for curves 1-3, respectively, and p = 0.21 atm). By the time the quasistationary phase $n_e \simeq$ const has set in, a minor amount of energy (~15-20%) has been released in the gap, and therefore, the following relationship should be valid:

$$U_a = \frac{U_0 R_a}{R_a + R}, \quad R = R_b + \rho$$

or

$$R_a = R\left[\frac{E_0/p}{(E_a/p)_c} - 1\right]^{-1}. \qquad (2.1)$$

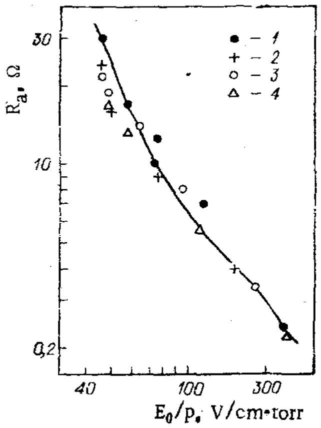

Fig. 6

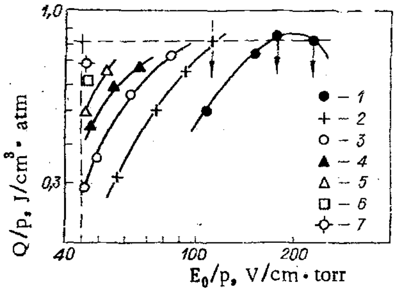

Fig. 7

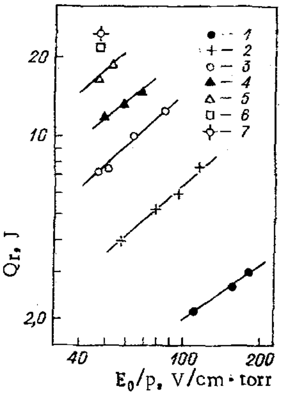

Fig. 8

Considering that $(E_a/p)_c$ is practically independent of U_0 and has a weak dependence on the pressure (35 V/cm · torr at p = 0.07 atm and 25 V/cm · torr at 0.5 atm) one can roughly assume that R_a is a function only of the parameter E_0/p. In Fig. 6 the experimental data on the dependence of the arc resistance R_a on the value E_0/p ($U_0 = 60$, 50, 40, and 30 kV for points 1-4, respectively) are compared with a calculation by the approximate equation (2.1) at $(E_a/p)_c = 30$ V/cm · torr (solid line). The possibility of using Eq. (2.1) $R_a = f(E_0/p)$ was tested experimentally in a wide range of pressures p = 0.1-0.5 atm of the working mixture with variation in the storage capacitance in the range of 0.03-0.6 μF. It was found that the best agreement is observed in the case when the duration of the initial stage of ionization comprises a small fraction of the duration of the phase of a quasistationary electron concentration ($\tau \approx 0.1\tau_c$). In practice, this condition is achieved through the appropriate choice of the capacitance of the main storage capacitor C_1, which must considerably exceed the capacitance of the working gap and that of the auxiliary capacitors C_2 and C_3 ($C_1 \gg 10C_2$).

A series of experiments was conducted on the determination of the limits of existence of the mode of stable discharge. The voltage dependence of the energy absorbed in the arc in the stable mode for different gas pressures is presented in Fig. 7 (p equals 0.07, 0.14, . . ., 0.49 atm for 1-7, respectively). The experiments established that the specific energy density Q/p absorbed in the arc is limited by the formation of an instability manifested in the constriction of the arc and a sharp drop in its resistance (see Fig. 4). The nature of the variation in the current and voltage in such a mode is shown in Fig. 2c. With a main storage capacitance $C_1 = 10^{-7}$ F the limiting values of Q/p are reached in the experiment only when $E_0/p \gg 100$ V/cm · torr. An increase in C_1 to $6 \cdot 10^{-7}$ F made it possible to establish the limiting value of $(Q/p)_-$, which proved to equal about 0.8 J/cm³ · atm in the entire range of the values $E_0/p = 45$-150 V/cm · torr and pressures 0.1-0.5 atm used. Unfortunately, at present one cannot yet present reliable data on the cause and the dynamics of the development of the observed instability. The results published earlier [8, 11] showed that the characteristic time of its development is determined by the rate of energy absorption, the pressure, and the composition of the working mixture. However, it must be noted that constriction of the discharge was not observed when $\tau < 180$ nsec. These facts are in qualitative agreement with the hypothesis advanced in [9, 10] that it is possible for instabilities of the ionization-superheating type to develop in electrical discharges at high absorbed energy densities. Somewhat lower values of $(Q/p)_-$ are presented in [11]. This is explained by the fact that they were obtained under conditions where $E_0/p \approx (E_0/p)_-$, and in this case an instability develops earlier because of the nonuniformity of the initial stage of ionization.

Since almost all the energy of a volumetric discharge is released in the stage of slow variation in its resistance (see Fig. 5), one can establish useful relationships between the value Q/p and the initial parameters of the entire system:

$$\frac{Q}{p} = \frac{C_1 U_0^2}{2} \frac{1}{pSd} \left(\frac{R_a}{R_a + R_b} \right), \tag{2.2}$$

where S is the area, and d is the length of the gap. Using (2.1) we obtain

$$\frac{Q}{p} = p \frac{C_1}{C 8\pi} \left(\frac{E_0}{p} \right)^2 \frac{1}{1 + \left(\frac{E_0}{30p} - 1 \right) \frac{R_b}{R_b + \rho}}, \tag{2.3}$$

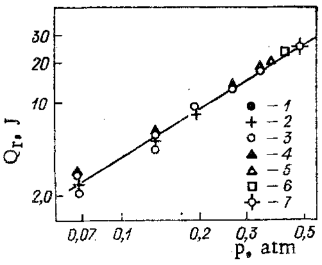

Fig. 9

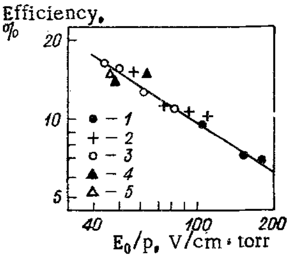

Fig. 10

where $C = S/4\pi d$ is the capacitance of the arc gap. The dependences of the specific energy density Q/p on the parameter E_0/p are represented by the curves in Fig. 7. It is seen that a tendency toward saturation is observed at $Q/p \gtrsim 0.6$ J/cm^3 · atm, while at $Q/p \simeq 0.8$–1.0 J/cm^3 · atm constriction of the arc occurs which limits the process of energy absorption. This limit is shown in Fig. 7 by vertical arrows.

Finally, using these results one can establish the connection between the limiting energy density which is released in a volumetric discharge and the initial parameters which determine its value. If one denotes $(Q/p)_- = q = 0.8$ J/cm^3 · atm and $(E_0/p)_- \simeq \varepsilon = 45$ V/cm · torr, then the region of stable arcing of the volumetric discharge is determined by the two inequalities

$$p\frac{C_1\varepsilon^2}{C8\pi}z \leqslant Q \leqslant qp, \text{ where } z = \frac{1}{1+\left(\frac{\varepsilon}{30}-1\right)\frac{R_b}{R_b+\rho}}, \tag{2.4}$$

and

$$\varepsilon \leqslant \frac{E_0}{p} \leqslant \sqrt{\frac{qC8\pi}{C_1pz}} \quad \underline{\text{when}} \quad \frac{C}{C_1} \ll 1. \tag{2.5}$$

In the conversion of (2.4) and (2.5) into an equality we obtain the following expressions for the limiting energy density and the corresponding limiting pressure of the working mixture:

$$Q_- = \frac{q^2C8\pi}{\varepsilon^2C_1z} = \frac{q^2C}{\varepsilon^2C_1z} \cdot 4.4 \cdot 10^7 \text{ J/cm}^3, \tag{2.6}$$

$$p_- = \frac{qC8\pi}{\varepsilon^2C_1z} = \frac{qC}{\varepsilon^2C_1z} \cdot 4.4 \cdot 10^7 \text{ atm}. \tag{2.7}$$

In the graph (Fig. 7) they are represented by the point of intersection of the boundary lines q = const and ε = const. It is seen from (2.6) and (2.7) that when the initial condition $E_0/p \gtrsim \varepsilon$ is satisfied the absolute values of Q_- and p_- depend only on the ratio of the capacitance of the arc gap to that of the working capacitor and on the ratio R_b/ρ. Thus, by using Eqs. (2.6) and (2.7) one can solve practical problems on the choice of the optimum operating mode for a volumetric electric discharge in a dense gas.

3. Properties of the Mode of Generation and Energy Efficiency at High Densities of Energy Applied to Arc. In the experiments described the parameters of the emerging laser beam were measured simultaneously with the recording of the arc parameters. The radiation was drawn from a volume of ∼0.64 liter through a germanium plane-parallel plate. A spherical metallic mirror with a radius of curvature of 5 m served as the second element of the resonator. The distance between the mirrors was 1 m. To record the radiation with an energy on the order of $Q_r \approx 25$ J/pulse we used a calorimeter with an absorbing element made in the form of an anodized aluminum disk 60 mm in diameter with a thickness d = 1 mm which absorbs 95% of the incident radiation in the wavelength region near 10.6 μ [12]. A study of the dependence of Q_r on the ratio of partial pressures of the working gases showed that the optimum ratio is $p_{CO_2}/p_{N_2} = 1/2$. The addition of 10–20% hydrogen led to an improvement in the uniformity of the arc and an increase in Q_r by approximately 25%. A further increase in the H_2 pressure leads to a decrease in Q_r, which is evidently connected with quenching of the upper laser level.

The dependences of the radiated energy Q_r on E_0/p and the pressure are shown in Fig. 8 (p equals 0.07, 0.14, ..., 0.49 atm for 1–7, respectively) and Fig. 9 (U_0 equals 30, 40, ..., 80 kV for points 1–6, respectively). The energy efficiency of the system was determined by the ratio $\eta = Q_r/V_0Q$ of the energy radiated per unit volume to the applied energy density. The dependence of η on the parameter E_0/p is shown in Fig. 10 (p equals 0.07, 0.14, 0.28, 0.35, and 0.42 atm for points 1–5, respectively). A marked decrease in η is observed with an increase in E_0/p (which corresponds to an increase in Q/p when the other initial conditions are maintained). Since the average effective value of $(E_a/p)_c$ at which the principal energy application and the creation of the optically active medium occur is practically independent of E_0/p, the decrease in efficiency cannot be connected with a decrease in the pumping efficiency to the upper molecular levels of CO_2 (00°1) and N_2 (V = 1). Additional research is evidently needed to explain the observed dependence $\eta = f(E_0/p)$.

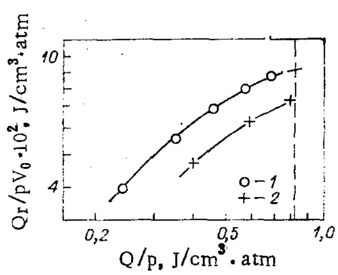

Fig. 11

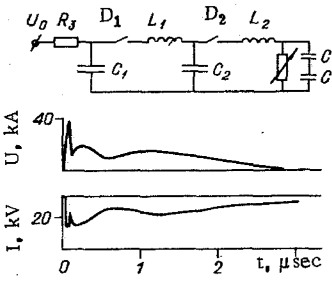

Fig. 12

Finally, the dependence of the specific radiated energy density Q_r/pV_0 on the value Q/p is presented in Fig. 11 (E_0/p equals 47 and 110 V/cm · torr for curves 1 and 2, respectively). At small values $Q/p = 0.2$ J/cm³ · atm and the optimum value $E_0/p = 47$ V/cm · torr the efficiency reaches 17%, but when $Q/p > 0.5$ J/cm³ · atm it decreases, approaching its limiting value of about 14%, which is determined by the upper limit of the region of existence of a volumetric discharge.

With allowance for the dependence of the efficiency on E_0/p, as well as for the limitations which condition the possibility of obtaining a volumetric discharge ($E_0/p \geqslant 45$ V/cm · torr and $Q/p \leqslant 0.8$ J/cm³ · atm), one can determine the region of possible values of the radiated energy density. In Fig. 11, curve 1, corresponding to $E_0/p = 47$ V/cm · torr, determines the maximum values of Q_r/pV_0 which can be obtained at the respective values of Q/p. The intersection of curve 1 with the dashed line $Q/p = q = 0.8$ J/cm³ · atm corresponds to the limiting attainable value $Q_r/pV_0 = 10^{-1}$ J/cm³ · atm. This value must be considered as the optimum limit for TEA CO_2 lasers with a double transverse arc under the conditions usually realized in such systems. When the extreme simplicity of construction of TEA lasers is taken into account the possibility of achieving a high enough energy reserve and efficiency makes them fully competitive with lasers of the electroionization type.

In generally summing up the investigation performed, it should be noted that the experimental results presented in this report made it possible to bring out important relationships which determine the dynamics of the absorption of electrical energy in a double electric arc and to find sufficiently universal equations establishing the connection between the limiting values of the radiated energy and the initial parameters of the system. Their effectiveness is now already sufficient to solve many practical problems connected with the concrete creation of powerful pulsed CO_2 laser systems of the simplest construction. It must also be noted that the absence of constriction of the arc for $\tau < 180$ nsec allows one to rely on an additional increase in the limiting energy applied to the arc owing to a decrease in the duration of the discharge and a corresponding increase in the specific power. The most important drawback of the described method of creating an inverted medium consists in the necessity of having a relatively high initial value of the parameter E_0/p, which requires the use of high-voltage primary energy sources of $\sim 10^6$ V at high pressures. Preliminary studies conducted with the help of an electronic computer and model devices show that there also exists a practical solution to this important problem, which consists in the conversion to two-cascade power-supply systems with a double transverse arc. One possible electrical system allowing one to duplicate the initial voltage on the gap is presented in Fig. 12, and typical oscillograms of the arc current and voltage are given. With the condition that $C_1 > C_2 > C_3$ and with the appropriate choice of L_1 and L_2 one can accomplish the rapid process of initial ionization through the energy of capacitor C_3, and then the main application of energy from the source is achieved in the quasistationary phase at values of $E_a/p =$ 25–30 V/cm · torr or even less, which assures an increase in the total efficiency of such systems. Since the energy required for the preliminary ionization and excitation of the metastable molecular states is comparatively small, the capacitance of the high-voltage storage capacitors C_3 proves to be rather small, which alleviates the problem of their development and fabrication.

The authors are sincerely grateful to S. P. Shalamov, L. N. Puzyrev, and N. P. Davydov for help in constructing the apparatus, and to P. N. Medvedev and D. A. Suvorov for participation in the installation and start-up of the high-voltage equipment.

LITERATURE CITED

1. R. Dumanchin, B. Lavarin, M. Michon, M. Neubauer, and J. Rossa-Sorra, "High-power per unit volume CO_2 lasers in continuous and pulsed operation," IEEE J. Quantum Electron., QE-6, 4 (1970).
2. A. K. Laflamme, "Double discharge excitation for atmospheric-pressure CO_2 lasers," Rev. Sci. Instrum., 41, 1578 (1970).
3. A. M. Robinson, "Afterflow gain measurement in CO_2-N_2-He mixtures at pressures up to 1 atmosphere," Can. J. Phys., 48, 1996 (1970).
4. A. J. Beaulieu, "Transversely excited atmospheric-pressure CO_2 lasers," Appl. Phys. Lett., 16, 504 (1970).

5. H. J. J. Seguin, J. Tulip, and D. Mcken, "UV photoionization density measurements in TEA lasers," Appl. Phys. Lett., 23, No. 6, 344 (1974).
6. G. Reiter, Electron Avalanches and Breakdown in Gases [Russian translation], Mir, Moscow (1968).
7. G. A. Mesyats, Yu. I. Bychkov, and V. V. Kremnev, "A pulsed nanosecond electric discharge in a gas," Usp. Fiz. Nauk, 107, No. 2, 201 (1972).
8. Yu. V. Afonin, A. G. Ponomarenko, and R. I. Soloukhin, "Energy characteristics of an electroionization CO_2 laser," in: Reports to 11th International Conference on Phenomena in Ionized Gases, Prague [in Russian] (1973).
9. E. P. Velikhov, I. V. Novobrantsev, V. D. Pis'mennyi, A. T. Rakhimov, and A. N. Starostin, "Combined pumping of gas lasers," Dokl. Akad. Nauk SSSR, 205, No. 6, 1328 (1972).
10. S. V. Pashkin, "Effect of inelastic energy losses by electrons on the development of an ionization instability in a plasma," Teplofiz. Vys. Temp., 10, No. 3, 475 (1972).
11. A. M. Orishich, A. G. Ponomarenko, and R. I. Soloukhin, "Energy characteristics and instability of a double transverse arc during pumping of a CO_2 laser," Dokl. Akad. Nauk SSSR, 212, No. 5, 1099 (1973).
12. J. H. Jacob, E. R. Pugh, J. D. Daugherty, and D. B. Northam, "An absolute method of measuring energy outputs from CO_2 lasers," Rev. Sci. Instrum., 44, No. 4, 471 (1973).