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NUCLEAR PUMPING IN MOLECULAR GAS LASERS

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The mechanism of populating vibrational levels of molecules by electrons produced during the ionization of a gas by the byproducts of nuclear reactions or by a charged particle beam is considered. It is shown that the mode containing the lowest excited level of the molecule is strongly populated by the diffuse flux of electrons produced in the energy space due to the high negative gradient of the electron energy distribution at the excitation threshold of the level. The conditions for producing inverted populations by nuclear pumping are established and it is shown that mixtures based on CO_2 do not satisfy these conditions.

1. The possibility of using the energy of nuclear reactions for pumping gas lasers has recently been discussed in the literature.[1-4] Promising results have been obtained in experiments using atomic gases, namely, mercury vapor, argon, and xenon.[3,4] However, both in experiments simulating nuclear pumping by the use of charged-particle beams[1,5,6] and in direct experiments using nuclear reactors[4,7] the inverted population has not been produced in molecular mixtures

We have also undertaken attempts to excite a CO_2-He^3 laser by a pulsed flux of thermal neutrons (flux density $\sim 5 \times 10^6\,cm^{-2}\cdot sec^{-1}$, pulse length ~1 msec). The diameter and length of the laser tubes are restricted by the dimensions of the channel in the active zone of the neutron source, and amount to 2–4 cm and 20–60 cm, respectively. Shielding arrangements impeded the alignment of the working reactor with the laser radiation receiver, so that infrared radiation exceeding 20 mW was recorded. The experiments were carried out at $CO_2 - He^3$ and $CO_2 - N_2 - He^3$ pressures between 0.01 and 3 atm for different relative concentrations. Generation was not observed.

The fundamental possibility of nuclear pumping of a CO_2 laser would appear to be ensured by the fact that the lifetime of the lower laser state (100) is much shorter than the lifetime of the upper level (001), the electron excitation cross section for which is several times greater than that for the lower level.[8] The main process through which electrons lose energy in the range 0.3– eV is the excitation of the (001) level of CO_2 (or the vibrational levels of nitrogen which produce resonance excitation of CO_2). Higher-energy electrons generated during the ionization of the gas by the nuclear reaction products are slowed down and, after passing through this energy range, can excite the upper levels. Moreover, the rate of excitation should be of the order of the rate of ionization.[1] The absolute values of the ionization rates can always be increased by correspondingly increasing the neutron flux density (or the intensity of the charged-particle beam when the excitation of the laser is produced with the aid of an accelerator).

The lack of success of the experiments performed so far shows that it would be very desirable to carry out a more careful analysis of the mechanism responsible for the excitation of molecular gases during nuclear pumping.

2. Let us consider the stationary excitation of a gas by nuclear reaction products. We shall use the following assumptions: a) the molecular levels are excited by electrons produced during the ionization of the gas by the charged products of nuclear reactions [for example, (n, p), (n, α), or fission] which are slowed down as a result of inelastic collisions with the molecules; b) the levels are depopulated by intermolecular collisions; c) the electrons are generated and recombine within the volume; d) diffusion processes in energy space have no effect on the electron energy distribution above the threshold for the excitation of the lower level.

We shall begin by considering the population of the two-level model. All the parameters characterizing the lower and upper levels will be denoted by the subscripts 1 and 2, respectively. Excitation thresholds of the vibrational levels of the molecules are, as a rule, quite low in comparison with the width of the energy band, which is important for the excitation of these levels. Consequently, practically throughout this energy band, with the exception of a small interval near the first threshold, the electron current j(E) in the energy space above level 1, which is determined by the rate G(E) of creation of electrons with an energy E, can be related to the electron energy distribution function f(E) as follows:

$$j(E) = -G(E) = f(E)\dot{E}. \tag{1}$$

In this expression, $\dot{E} = -Nv\Sigma\sigma_i E_i$ is the rate of loss of energy by the electrons, σ_i is the cross section for the excitation of the level with energy E_i, v is the electron velocity, and N is the gas concentration.

Since $\dot{E} < 0$ for $E > E_1$, the current j(E) is negative and the electrons build up largely above the threshold E_1. The electron concentration n is given by the balance equation

$$G(0) = \alpha n^2 \tag{2}$$

where α is the coefficient of dissociative recombination which is usually the dominating process in molecular gases. The electron distribution under the threshold can be assumed to be Maxwellian, since the Maxwellization time τ_{max} is practically always smaller than the recombination time τ_{rec}:

$$\frac{\tau_{\max}}{\tau_{\mathrm{rec}}}=\frac{\alpha}{\sigma_C\bar{v}(1+\gamma/\xi)}<1;\quad \gamma=\frac{m}{M}\frac{\sigma_e}{\sigma_C}.$$

In these expressions $\sigma_C \sim \pi e^4/T_e^2$ is the Coulomb cross section, $\bar{v}$ is the mean velocity of electrons over the threshold, σ_e is the cross section for the elastic scattering of electrons, m and M are the masses of the electron and molecule, respectively, and $\xi = n/N$ is the degree of ionization. The electron temperature T_e was assumed to be equal to the gas temperature T when the ratio $\tau_{\max}/\tau_{\mathrm{rec}}$ was estimated.

As the electron concentration in the region of the excitation threshold for level 1 increases, there is an increase in the negative gradient of the electron energy distribution function. This leads to an increase in the diffusion current of electrons from under the threshold into the region over the threshold:

$$j_{\mathrm{diff}} \sim -D_E df/dE.$$

The electron diffusion coefficient in the energy space $D_E = D_M + D_e$ is due to collisions with molecules and electrons (diffusion coefficients D_M and D_e, respectively). When D_e is estimated in the region near E_1 we shall assume that $E_1 \gg T$, and the electron temperature will be taken to be equal to the gas temperature (in general, $T_e \geq T$). The diffusion current deduced in this way will be an underestimate. To within numerical coefficients of the order of unity, we have the following approximate formulas for the diffusion coefficients near E_1:

$$D_e \sim \frac{E_1 T}{\tau_C}\,[^9],\quad D_M \sim \frac{m}{M}\frac{E_1 T}{\tau_e},$$

where

$$\tau_C = 1/n\sigma_C v,\quad \tau_e = 1/N\sigma_e v.$$

The current penetrates the threshold to a depth of the order of the diffusion "length" in energy space, which is traversed by an electron during the time τ_{in} of one inelastic collision: $\delta E \sim \sqrt{D_E \tau_{\mathrm{in}}}$. In the energy band δE near E_1 the distribution function differs from both the distribution above the threshold [given by Eq. (1)] and from the Maxwell distribution by an additional term which mixes the tail of the Maxwell distribution with the distribution above the threshold.

It is readily shown that if the degree of ionization does not exceed $E_1\sigma_{\mathrm{in}}/T\sigma_C$, the width δE does not exceed the difference between the excitation thresholds for the upper and lower levels, $E_2 - E_1 \sim E_1$. The diffusion current therefore populates only the lower level and the corresponding rate of population is

$$j_{\mathrm{diff}} \sim nD_E\frac{\Phi}{\delta E} \approx nN[\beta(\gamma+\xi)]^{1/2}, \tag{3}$$

where $\beta = \Phi^2(E)E^2T\sigma_{\mathrm{in}}\sigma_C$, σ_{in} is the inelastic cross section for collisions between electrons and molecules, and $\Phi(E)$ is the Maxwell distribution function normalized to unity. All the quantities which depend on energy are taken at $E = E_1$.

Assuming that the population of the lower level is of purely diffusion origin, and the rate of population of the upper level is equal to the rate of ionization, i.e., assuming that each electron will excite only one molecule to the upper level as it slows down, we find that the populations of the upper and lower levels are respectively given by

$$N_1 = j_{\mathrm{diff}}\tau_1,\quad N_2 = G(0)\tau_2. \tag{4}$$

In these expressions τ_1 and τ_2 are the collisional relaxation times of the two levels. The efficiency does not exceed $(E_2 - E_1)/J$ under these assumptions, where J is the energy necessary to form an electron-ion pair.

It follows from Eqs. (2)—(4) that the inverted population ($N_2 > N_1$) is impossible if the degree of ionization does not have a lower limit defined by

$$\xi > \frac{\beta}{2\delta}\left[1+\left(1+4\frac{\gamma\delta}{\beta}\right)^{1/2}\right], \tag{5}$$

where $\delta = (\alpha\tau_2/\tau_1)^2$. For values of β, γ, and δ characteristic for molecular gases, we have $\gamma\delta/\beta \ll 1$. From Eq. (5) we then have

$$\xi > \xi_1 = \beta/\delta. \tag{6}$$

On the other hand, the degree of ionization has also an upper limit. In fact, as it increases, the point at which the spectrum of decelerating electrons becomes mixed with the Maxwell spectrum becomes shifted toward higher energies (this is analogous to the mixing of the Fermi and Maxwell spectra in the thermalization of neutrons). When the degree of ionization is

$$\xi > \xi_2 \sim \sigma_n(E_2)/\sigma_c(E_2), \tag{7}$$

where $\sigma_C(E_2)$ and $\sigma_{\mathrm{in}}(E_2)$ are, respectively, the Coulomb cross section and the total cross section for the excitation of both levels in the region of the E_2 threshold, the mixing boundary turns out to lie above the excitation threshold for the level E_2 and both levels are excited by electrons with the Maxwellian energy distribution. If, at the same time, the depletion of levels is, as before, determined by assumption c), i.e., by intermolecular collisions, inversion may persist for a favorable difference between the cross sections for the excitation of the levels by electrons and the relaxation times of the levels. However, if collisions of the second kind involving electrons predominate in the relaxation of the excited molecules, both levels will be found to be populated with equal temperatures because of the principle of detailed balancing, and inversion will not be possible. This will occur when $n\sigma'\bar{v} > N/\tau^*$, i.e.,

$$\xi > \xi_3 \sim 1/\sigma'\bar{v}\tau^*, \tag{8}$$

where σ' is the cross section for collisions of the second kind, $\tau^* = N\tau$, and $\tau = \max(\tau_1, \tau_2)$.

It is important to note that the inequality given by (8) is not critical for the relative population of the levels when $\xi < \xi_2$. When an electron deexcites a molecule in a collision of the second kind, it enters the region above the threshold, where for $\xi < \xi_2$ the only energy loss process is the excitation of the same level. (It can be shown that, in this case, collisions of the second kind can be excluded on the basis of the balance equation for the level population.)

Thus, the essential prerequisite for an inverted population is the following restriction on the degree of ionization of the gas:

$$\xi_1 < \xi < \max(\xi_2, \xi_3). \tag{9}$$

We note that ξ_1, ξ_2, and ξ_3, which limit the range of admissible values of the degree of ionization of the gas, are determined only by the properties of the gas (excitation cross sections, level relaxation rates, recombination coefficients, and so on), but are independent of the concentration of the gas and the parameters of the source of excitation (for example, the flux density of the neutrons, the reaction energy, and so on). It follows from Eqs. (9) and (2) that the excitation source and the gas density must satisfy the condition

$$\xi_1 < N^{-1}(G/\alpha)^{1/2} < \max(\xi_2, \xi_3). \qquad (10)$$

The rate of ionization G depends on the experimental conditions: in the case of the nuclear reactor, it depends on the neutron flux density, the reaction cross section and energy, the ratio of the dimensions of the excited volume and the ranges in it of the reaction products, and on the concentration and method of distribution of the fissile nuclei in the working volume; in the case of excitation by a charged-particle beam, it depends on the beam intensity and particle energy. In particular, if the relative concentration remains constant and the distribution of fissile nuclei is uniform throughout the working volume

$$G = \begin{cases} Ng_1 & d > R, \\ N^2 g_2' & d < R. \end{cases} \qquad (11)$$

In these expressions g_1 and g_2 are constants independent of the gas density, d is a characteristic dimension of the working volume, $R = R_0/N$ is the range of a charged particle, and R_0 is a constant determined by the properties of the gas. When $d \sim R = R_0/N$ we have $g_2 = g_1 d/R_0$.

Figure 1 shows the surface $\xi = \xi(N, d)$ constructed by using Eqs. (2) and (11), cut by two planes parallel to the (N, d) plane and passing through the points $\xi = \xi_1$ and $\xi = \max(\xi_2, \xi_3)$. (The region of small densities and dimensions, when volume recombination of electrons is replaced by diffusion to the walls, and the dependence of ξ on N and d differs from that shown in the figure, is not of practical interest.)

The projection of the intersections of these planes with the $\xi(N, d)$ plane onto the (N, d) plane, which forms the region of gas densities and working-volume dimensions which are admissible for inversion, is shown in Fig. 2. It is clear that the degree of ionization of the gas can remain within the limits necessary for inversion and defined by the inequality (9) only if, at the same time,

$$N < N_{\max} = g_1/\alpha\xi_1^2, \qquad d > d_{\min} = R_0/N_{\max}. \qquad (12)$$

The quantities d′ and N′ are given by

$$d' = R_0/N', \qquad N' = g_1/\alpha\mu^2, \qquad \mu = \max(\xi_2, \xi_3).$$

3. We shall now generalize the above analysis to the case of a molecular gas with a few types of normal oscillation.

When the populations of the vibrational levels are calculated, we shall use the concept of the vibrational temperature which defines the population distribution within a given mode.[10] For the sake of simplicity, we shall consider the case of two nondegenerate modes. By analogy with the two-level model, the mode with the smaller quantum (mode 1, quantum E_1) is populated by the diffusion current of electrons through the threshold for the excitation of the lower level of this mode [see Eq. (3)], whilst mode 2 with quantum E_2 is populated by the decelerating electrons.

The vibrational energy of a model relaxes, as a rule, through the exchange of large vibrational quanta for smaller ones with the minimum conversion of vibrational energy into translational energy. We shall assume that this relaxation channel for mode 2 (which is also an additional channel for the population of mode 1) is the only one, and that each relaxation event brings k quanta E_1 to the first mode.

The balance equation for the vibrational energy of the modes will be written in the form

$$E_j(F_j + N^2\langle\sigma_j v\rangle) = \bar{E}_j/\tau_j = N\bar{E}_j/\tau_j^*, \qquad j = 1, 2, \qquad (13)$$

where $F_1 = j_{\text{dif}} + kG$, $F_2 = G$, and $\tau_j = \tau_j^*/N$ is the relaxation time for the vibrational energy of the mode. The second term in the brackets represents the population of the mode during collisions between the molecules, which is important for low degrees of ionization. The quantity $\bar{E}_j$ is the specific store of vibrational energy in the mode:

$$\bar{E}_j = N_0 \sum_{\nu=0}^{\infty} \nu E_j \exp\left(-\frac{\nu E_j}{T_j}\right) = N\frac{E_j y_j(T_j)}{1 - y_j(T_j)}. \qquad (14)$$

In these expressions N_0 is the concentration of unexcited molecules, ν is the level number, and T_j is the vibrational temperature of the mode. The quantity y_j is the population of the lower level ($\nu = 1$) at the corresponding temperature (T_j or T) referred to the concentration of unexcited molecules. The population of level ν of mode j is $N_0 y_j^\nu$.

To ensure that in the absence of pumping (F = 0) the vibrational and kinetic temperatures are equal, we must have

$$\langle\sigma_j v\rangle = y_j(T)\,/\,[\tau_j^*(1 - y_j(T))]. \qquad (15)$$

Substituting Eqs. (2), (3), (14), and (15) in Eq. (13), we obtain

$$y_1(T_1) = \frac{y_1(T) + \xi[k\alpha\xi + (\beta(\gamma+\xi))^{1/2}]\tau_1^*(1 - y_1(T))}{1 + \xi(k\alpha\xi + (\beta(\gamma+\xi))^{1/2}]\tau_1^*(1 - y_1(T))}, \qquad (16)$$

$$y_2(T_2) = \frac{y_2(T) + \xi^2\alpha\tau_2^*(1 - y_2(T))}{1 + \xi^2\alpha\tau_2^*(1 - y_2(T))}. \qquad (17)$$

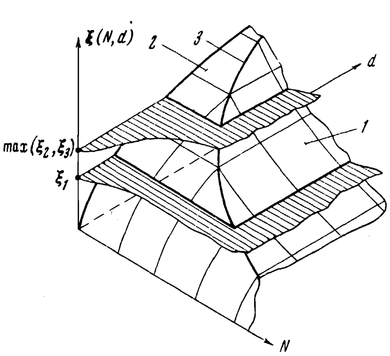

FIG. 1

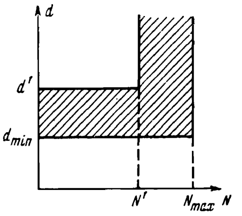

FIG. 2

FIG. 1. Degree of ionization as a function of gas density and characteristic dimensions of the excited volume for a uniform distribution of the fissile nuclei throughout the volume and constant relative density. 1—Surface $\xi \sim N^{-1/2}$; 2—surface $\xi \sim d^{1/2}$; along the edge 3 the range R_0/N is equal to d.

FIG. 2. Region of gas densities and working-volume sizes in which population inversion is allowed.

Hence, it is clear that, when $\xi \to 0$ (because of the increase in the gas density or in the size of the working volume; see Fig. 1), the distribution over the levels tends to the equilibrium state. On the other hand, when $\xi > \xi_2$, both levels are populated with Maxwellized electrons and, consequently, Eqs. (16) and (17) are invalid. Therefore, the values of ξ for which inversion between the vibrational level of number ν_2 of the second mode and level ν_1 of the first mode is possible are given by the inequality

$$y_2^{\nu_2}(T_2) > y_1^{\nu_1}(T_1). \tag{18}$$

The ranges of the admissible values of the degree of ionization in their turn determine the range of the admissible gas densities and dimensions of the working volume(see Figs. 1 and 2).

The diffusion population of the first mode turns out to be the predominant nonthermal population process for this mode for $\xi < \xi' = \beta/k^2\alpha^2$ [see Eq. (16); we note that, in the case of CO_2-based mixtures, $\xi' > \xi_2$]. One of the ways of deforming the electron distribution function and reducing the electron density with a view to preventing diffusion population may be the introduction of electronegative impurities into the mixture with a large attachment coefficient for electrons in the energy region below the threshold E_2. We shall suppose, for simplicity, that attachment determines only the concentration of electrons above the threshold, but does not affect the distribution function. The negative gradient of the distribution function which governs the diffusion population will not be present if [see Eqs. (1) and (3)]

$$G(E)\,/\,\dot{E}\,|_{E=E_1} \gtrsim n\Phi(E_1). \tag{19}$$

Substituting for the electron density from the equation of balance, we have

$$N\chi n\eta = G(0),$$

where χ is the fraction of the electronegative impurity and η is the attachment coefficient, so that Eq. (19) is satisfied when

$$\chi\eta > \Phi\sigma_n vE\,|_{E=E_1}.$$

The reduction in the population of the first mode can be achieved both by preventing diffusion population from taking place and by shortening its relaxation time τ_1. However, even in this case, restrictions such as that given by (12) remain in force. Even in the limiting case $\tau_1^* = 0$, we have from (12), after substituting for ξ_1 from Eqs. (16)—(18) (for example, $\nu_1 = \nu_2 = 1$):

$$N_{max} \sim g_1\tau_2^* \exp\left(\frac{\dot{E}_1}{T}\right); \qquad d_{min} \sim \frac{R_0}{g_1\tau_2^*}\exp\left(-\frac{E_1}{T}\right). \tag{20}$$

We note that R_0, which characterizes the energy losses in the gas mixture, can be reduced by introducing heavy-gas impurities. Formulas analogous to (20) can be obtained for the two-level model if it is assumed that the lower level is populated at the gas temperature.

4. The above results can be used to analyze the excitation of the $CO_2 - He^3$ mixture. Despite the fact that the CO_2 molecule has three vibrational modes the distribution over the levels can be described by two vibrational temperatures because the symmetric and deformation modes have a common vibrational temperature as a result of the Fermi resonance between the (100) and (020) levels.[10]

In the case of CO_2, we shall assume in Eqs. (16)—(18) that $\nu_1 = 2$, $k = 3$, $\nu_2 = 1$, $E_1 = 0.08$ eV, $E_2 = 0.29$ eV, $T = 300°K$, $\sigma_{in} = 10^{-12}$ cm^2, and $\alpha = 3 \times 10^{-7}$ cm$^3 \cdot$sec^{-1}, and that the cross sections[8,11] are $\sigma_e = 5 \times 10^{-15}$ cm^2, $\sigma_{in}(E_2) = 4 \times 10^{-16}$ cm^2, and $\sigma_{in} = 10^{-16}$ cm^2. Finally, the mode relaxation constants will be[12] $\tau_1^* = 3 \times 10^{13}$ sec $\cdot$ cm^{-3} and $\tau_2^* = 10^{14}$ sec $\cdot$ cm^{-3}. The recombination coefficients reported in different papers are very different. The value which we have adopted is close to the recombination coefficient for the CO_2^+ ions at $T = 300°K$, as given in[13].

Figure 3 shows the populations calculated from Eqs. (16) and (17) for the lower deformation level (010), the upper laser level (001), and the total population of the lower laser levels (100) and (020). It is important to recall that a number of assumptions were made in the analysis of the population mechanism, which were favorable for producing the inverted population. In particular, the diffusion population of the first mode was underestimated by the assumption that $T_e = T$ above the threshold E_1. We have also ignored the heating of the gas during the pumping process. However, it is clear from the figure that, despite these assumptions, the inversion condition $y_2 > y_1^2$ is not satisfied when $\xi < \xi_2 \sim 4 \times 10^{-4}$.

The upper limit for the degree of ionization in our experiments at high pressures of the $CO_2 - N_2 - He^3$ mixture can be estimated from the experiments on the combined nuclear-electric pumping of lasers[14] carried out at comparable neutron fluxes and mixture pressures. The degree of ionization calculated from the gas conductivity during the initial stages of current flow, when the discharge is not self-supporting and uniformly fills the working region, turns out to be $\sim 10^{-7}$.

The criterion for inversion in CO_2, $y_2 > y_1^2$, can be made less stringent by comparing the population of the upper level with the populations of each of the lower levels separately. These populations differ by the factor $\exp(-\Delta E/T) \sim {}^2/_3$ at $T = 300°K$, where ΔE is

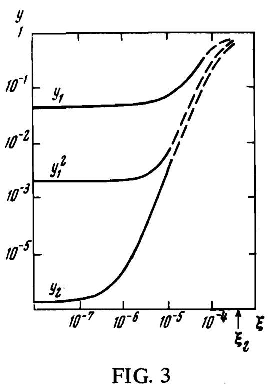

FIG. 3

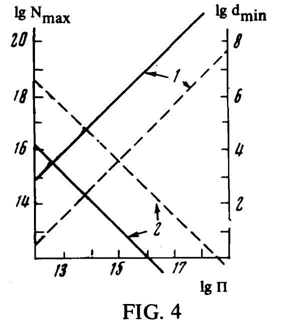

FIG. 4

FIG. 3. Population of CO_2 levels referred to the density of unexcited molecules and calculated from Eqs. (16) and (17): y_1—(010), y_1^2—(100) + (020); y_2—(001). When $\xi > \xi_2$, Eqs. (16) and (17) are invalid.

FIG. 4. Critical parameters as functions of neutron flux density Π in cm$^{-2}\cdot$sec^{-1}: 1—N_{max} in cm^{-3}; 2—d_{min} in cm. Solid line—U^{235}, broken line—He^3.

the energy difference between the levels. The y_1^2 curve in Fig. 3 is then split into two curves. However, it is clear from this figure that, when $\xi \lesssim 10^{-5}$, this would not affect the above conclusion that inversion is impossible in this region. For $10^{-5} < \xi < \xi_2$, where the curves are shown broken, the inversion conditions are not altogether meaningful because, as a result of the approximate nature of the calculation, the relative positions of the y_1^2 and y_2 curves [and for $10^{-4} < \xi < \xi_2$ the position of the y_1 curve too] are indeterminate.

Moreover, in the case of nuclear pumping, this region of the degree of ionization corresponds either to neutron fluxes which cannot be produced at present, or to low pressures and enormous sizes, which cannot be realized in practice. In the case of excitation by strong charged-particle pulses which could produce the necessary degree of ionization at high gas pressures, we must take into account the effect of the intrinsic electric fields of such beams on the electron energy distribution function.

We shall now consider the dependence of the critical values of the gas density and the dimensions of working volume as functions of the thermal-neutron flux for the $CO_2 - He^3$ mixtures (ratio of components 1 : 1, $R_0 \sim 10^{19}$ cm^{-2}), using the formulas given by Eq. (20) (Fig. 4, broken lines). It is clear that even for this idealized case (instantaneous relaxation of the lower laser state), nuclear pumping can be produced with existing neutron sources only for gas densities which are of no practical interest: for a tunnel diameter in the reactor zone of 10 cm, the thermal neutron flux density should exceed 3×10^7 cm$^{-2}\cdot$sec^{-1} and the mixture density should be less than 50 mm Hg.

The critical value of the neutron flux can be reduced by using nuclear reactions with a considerable release of energy (fission of heavy nuclei such as U^{235}, Pu^{239}, and so on). This is clear from Fig. 4, where the solid lines show N_{max} and d_{min} as functions of the thermal-neutron flux in the case of U^{235} deposited on the walls in the form of a layer of optimum thickness (~5 μ). As before, it is assumed that $R_0 \sim 10^{19}$ cm^{-3} and $\tau_1^* = 0$. We note that the effective use of the parameter $d > d_{min}$ is possible only for densities $N < N_{max}$, which satisfy the condition $Nd < R_0$. However, because of the relatively slow increase in the neutron flux in pulsed reactors (characteristic time ~10^{-3}–10^{-2} sec), the heating of the mixture in sealed-off systems to the temperature at which inversion in CO_2 is definitely known to be possible ($T \sim 700$°K) occurs well before the critical flux level is reached.

In principle, the premature heating of the gas can be avoided by fast pumping. If the rate of replacement of the gas is ~d/Mc, and the time of its overheating is $(T_{ov} - T)/gJ$, where $T \approx 300$°K [g measured the rate of pumping, c is the velocity of sound, and M is the Mach number], there will be no overheating provided

$$Mc/gd > J/(T_{ov} - T).$$

For example, to prevent the overheating of the CO_2 mixture at a pressure of 1 atm in a channel with $d \sim 1$ cm, whose walls are coated with U^{235}, when the thermal neutron flux is $\sim 5 \times 10^{16}$ cm$^{-2}\cdot$sec^{-1}, one needs enormous pumping rates: $M \sim 5$ (for $c \sim 10^5$ cm/sec).

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