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SCALING LAWS FOR PULSED CHAIN-REACTION CHEMICAL LASERS.(U)

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Scaling Laws for Pulsed Chain-Reaction Chemical Lasers

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normalized output energy from a saturated HF laser can be expressed as $2E/\phi H_{2,0} = \phi$, where $\phi \sim (F/F_2)_0^{1/2} (F_2/H_2)_0 [1 + 0.094(F_2/H_2)_0]^{-1/2}$. In the latter regime the product $E t_e$ is a constant for a saturated laser (t_e = pulse length). Corrections for multiple vibrational levels are given in an Appendix.

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I. INTRODUCTION

Pulsed chemical lasers can be characterized as cold-reaction or chain-reaction devices. For the case of pulsed HF chemical lasers excited species are created by the cold reaction $F + H_2 \rightarrow HF(v)$ in the former and by the chain reaction $F + H_2 \rightarrow HF(v) + H$, $H + F_2 \rightarrow HF(v) + F$ in the latter. (The terms cold and hot are used for the reactions $F + H_2$ and $H + F_2$, respectively, because the former is less energetic than the latter.)

Numerous computer codes have been developed that model many of the complex features of pulsed chemical lasers, e. g., multilevel-multicomponent media,¹ rotational nonequilibrium,² and pressure broadening.³ The accuracy of these models primarily is dependent upon the accuracy of the rate coefficients employed therein.

A simplified closed-form analytical solution has been obtained for the performance of cold-reaction HF pulsed lasers.⁴ Analytic solutions for the performance of cw cold-reaction HF chemical lasers^{5,6} can also be applied to cold-reaction pulsed lasers by consideration of the limiting case of infinitely fast lateral diffusion. The development of simplified analytical models for the pulsed chain-reaction chemical laser has received less attention. Skifstad⁷ obtained an analytical solution with the use of a "steady-state" approximation for the chain reaction. The emphasis was on obtaining numerical estimates for chain-reaction laser performance; the parametric nature of the solution was

not examined. In subsequent studies of the chain-reaction chemical laser the emphasis was on numerical codes. For example the steady-state approximation is used in Reference 8 to simplify a numerical code.

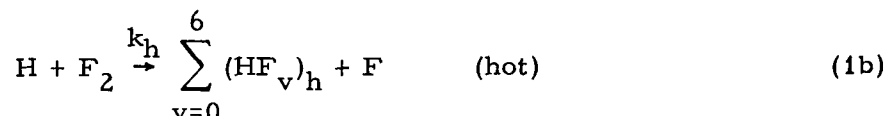
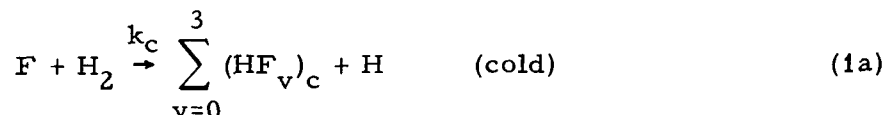
The simplified models of cw cold-reaction chemical lasers^{5,6} have yielded useful scaling laws that characterize laser performance. It is desirable to deduce the equivalent scaling laws for pulsed chain-reaction chemical lasers. This is done herein by means of the steady-state approximation for the chain reaction and a simple two-level vibrational energy model. A pulsed chain-reaction HF chemical laser is considered, in order to fix ideas, and mean kinetic rate coefficients, based on Reference 9, are employed. Corrections for the effect of multiple vibrational levels are given in Appendix A. The case $(F_2/H_2)_0 \geq 1$, where the subscript zero denotes initial concentrations, is of primary interest^{10, 11} and is treated in the body of the report. The case $(H_2/F_2)_0 > 1$ is discussed in Appendix B.

II. THEORY

A pulsed HF laser is considered. A mixture of F_2 - H_2 and a diluent is subjected to an electrical or flash discharge at time $t = 0$, which partially dissociates the F_2 . Typical initial conditions are given in Eq. (29). A chain reaction is initiated, which creates vibrationally excited HF. An approximate solution for the latter ("pumping") process is given in the following section. The solution for the pumping process is used in a simple two vibrational level model to obtain scaling laws for pulsed HF lasers operating under a chain reaction.

A. CHAIN REACTION

The creation of HF by the chain reaction can be expressed as



where k_c and k_h denote the overall rate coefficients for the cold and hot reactions, respectively. Reverse reactions are negligible. Henceforth such symbols as F , H_2 , and F_2 will denote both species and concentration in moles per cubic centimeter. Rate coefficients are in units of cubic centimeter per mole seconds.

The notation

$$HF_{T,c} \equiv \sum_{v=0}^3 (HF_v)_c, \quad HF_{T,h} \equiv \sum_{v=0}^6 (HF_v)_h \quad (2a)$$

$$HF_T \equiv HF_{T,c} + HF_{T,h} \quad (2b)$$

is introduced, where HF_T denotes the total HF concentration. The rate equations can be expressed

$$\frac{dF}{dt} = k_h F_2 H - k_c H_2 F \quad (3a)$$

$$\frac{dH}{dt} = k_c H_2 F - k_h F_2 H \quad (3b)$$

$$\frac{dH_2}{dt} = -k_c H_2 F = -\frac{dHF_{T,c}}{dt} \quad (3c)$$

$$\frac{dF_2}{dt} = -k_h F_2 H = -\frac{dHF_{T,h}}{dt} \quad (3d)$$

with the initial conditions ($t = 0$)

$$F = F_0, \quad F_2 = F_{2,0}, \quad H_2 = H_{2,0} \quad (3e)$$

$$H = HF_{T,c} = HF_{T,h} = 0 \quad (3f)$$

In general $H_{2,0} \leq F_{2,0}$ and $F_0 \ll F_{2,0}$

The following particular integrals can be deduced

$$F + H = F_0 \quad (4a)$$

$$H_2 + HF_{T,c} = H_{2,0} \quad (4b)$$

$$F_2 + HF_{T,h} = F_{2,0} \quad (4c)$$

However a general solution of Eq. (3) cannot be obtained in closed form. Therefore an approximate solution is sought. The temperature dependence of k_c and k_h is ignored.

In general F_0 is small compared to $F_{2,0}$ and $H_{2,0}$. Then for early times a "transient" solution can be obtained in the form

$$F_2 \doteq F_{2,0}, \quad H_2 \doteq H_{2,0} \quad (5a)$$

$$\frac{H}{F_0} = 1 - \frac{F}{F_0} = (1 - R)(1 - e^{-t/t_t}) \quad (5b)$$

where

$$R = [1 + (k_c H_{2,0} / k_h F_{2,0})]^{-1} \quad (5c)$$

$$t_t = (k_c H_{2,0} + k_h F_{2,0})^{-1} = R / (k_h F_{2,0}) \quad (5d)$$

Here t_t is the characteristic time for the transient solution and is generally small compared to the time for the chain reaction to go to completion.

For $t/t_t \gg 1$ Eq. (5b) indicates that H and F approach steady-state concentrations given by

$$\left(\frac{H}{F_0}\right) = 1 - \left(\frac{F}{F_0}\right) = 1 - R \quad (6)$$

From Eq. (6) it is implied that $dH/dt = dF/dt = 0$ and $dH_2/dt = dF_2/dt$ in Eq. (3). Equation (6) can be used to characterize H and F concentrations during the remainder of the chain reaction. Thus for $H_{2,0} \leq F_{2,0}$ (i.e., a chain reaction terminated by the disappearance of H_2) Eqs. (3c) and (6) yield

$$\left(\frac{H_2}{H_{2,0}}\right) = e^{-t/t_p} \quad (7)$$

where $t_p \equiv (k_c R F_0)^{-1}$ is the characteristic time for the chain (pumping) reaction to go to completion. (For $F_{2,0} < H_{2,0}$ the characteristic pumping time is $t_p' = (F_{2,0}/H_{2,0}) t_p$.) It also follows that

$$\frac{1}{2} \frac{HF_T}{H_{2,0}} = \frac{HF_{T,c}}{H_{2,0}} = \frac{HF_{T,h}}{H_{2,0}} = \frac{F_{2,0} - F_2}{H_{2,0}} = 1 - e^{-t/t_p} \quad (8)$$

The present solution, Eqs. (6) to (8), characterizes the chain reaction if

$H_2 \leq F_2$ and

$$\frac{t}{t_p} \equiv R^2 \frac{k_c}{k_h} \left(\frac{F}{F_2}\right)_0 \ll 1 \quad (9)$$

The latter is satisfied when $(F/F_2)_0$ is small, as is generally the case.

The present solution is exact when $F_{2,0} = H_{2,0}$ and $(F/H)_0 = k_h/k_c$.

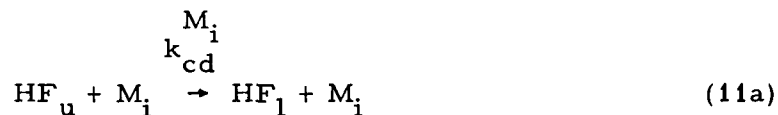
B. PULSED HF LASER MODEL

A two-vibrational-level model is assumed. Upper and lower lasing levels are denoted by HF_u and HF_l , respectively. It is assumed that the pumping reaction creates HF_u only, and that $H_{2,0} \leq F_{2,0}$.

From Eq. 8 HF_u is created by the pumping reaction at the rate

$$\left(\frac{d\text{HF}_u}{dt}\right)_p \equiv \frac{d\text{HF}_T}{dt} = \frac{2H_{2,0}}{t_p} e^{-t/t_p} \quad (10)$$

Collisional deactivation by species M_i can be expressed



The overall collisional deactivation rate is then

$$\left(\frac{d\text{HF}_u}{dt}\right)_{cd} = - \sum_i k_{cd}^{M_i} M_i \text{HF}_u \quad (11b)$$

$$= - \text{HF}_u / t_{cd} \quad (11c)$$

where $t_{cd} \equiv \left(\sum_i k_{cd}^{M_i} M_i\right)^{-1}$ is the characteristic collisional deactivation time.

Radiative deactivation is characterized by

$$\left(\frac{d\text{HF}_u}{dt}\right)_r = - \frac{gI}{\epsilon} \quad (12)$$

where g is the gain

$$g \equiv \sigma(HF_u - HF_l) \quad (13)$$

ϵ is the energy per mole of photons, and I is local intensity. From Eqs. (10), (11b), and (12) the net rate of production of HF_u is

$$\frac{dHF_u}{dt} = \frac{2H_{2,0}}{t_p} e^{-t/t_p} - \frac{HF_u}{t_{cd}} - \frac{gI}{\epsilon} \quad (14)$$

The combination of Eqs. (13) and (14) yields

$$\frac{dG}{d\tau} + G \left(1 + \frac{2\sigma t_{cd}}{\epsilon} I \right) = \frac{1+K}{K} \left[(1+K)e^{-K\tau} - 1 \right] \quad (15a)$$

where

$$G \equiv \frac{g}{2\sigma H_{2,0} K(1+K)^{-1}}, \quad K \equiv \frac{t_{cd}}{t_p}, \quad \tau \equiv \frac{t}{t_{cd}} \quad (15b)$$

It will be shown that $2H_{2,0} K(1+K)^{-1}$ characterizes the value of HF_T during the lasing process so that G is an order one quantity. In the absence of lasing the temporal variation of gain is, from Eq. (15a) with $I = 0$,

$$\begin{aligned} \frac{K}{1+K} G &= \frac{2K}{K-1} e^{-\tau} - \frac{K+1}{K-1} e^{-K\tau} - 1 & K \neq 1 \\ &= e^{-\tau} (1 + 2\tau) - 1 & K = 1 \end{aligned} \quad (16a)$$

The variation of G with τ is shown in Fig. 1. For $K \leq 1$ the variation is relatively insensitive to K .

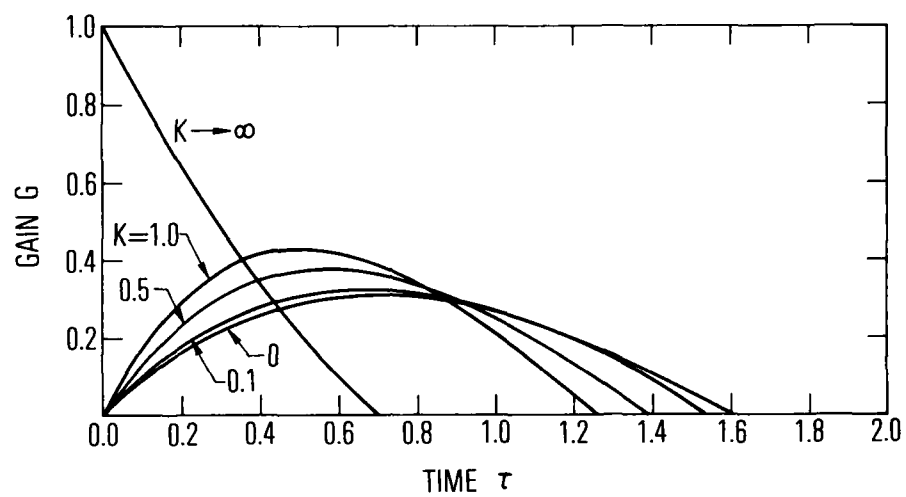


Fig. 1. Variation of zero-power gain with time

For small K the zero-power gain equals

$$G = 2 - \tau - 2e^{-\tau} + \frac{K}{2} \left[(4 - \tau)(2 - \tau) - 8e^{-\tau} \right] + O(K^2) \quad (16b)$$

The zero-power gain is maximum at time

$$\begin{aligned} \tau_m &= \frac{1}{1-K} \ln \left(\frac{2}{1+K} \right) & K \neq 1 \\ &= \frac{1}{2} & K = 1 \end{aligned} \quad (16c)$$

Values of peak zero-power gain G_m are found by substitution into Eq. (16a).

For $K \leq 1$

$$\begin{aligned} G_m &= 0.307 + O(K) & K \ll 1 \\ &= 0.426 & K = 1 \end{aligned} \quad (16d)$$

Lasing is initiated when the zero-power gain reaches the threshold value. For a Fabry-Perot resonator with mirror reflectivities R_1 and R_2 and a mirror separation L , the threshold gain is $g_c = -\ln(R_1 R_2)/2L$ or

$$G_c = \frac{-\ln(R_1 R_2)}{4\sigma H_{2,0} L K (K + 1)^{-1}} \quad (17)$$

The lasing medium is saturated when $G_c = 0$ and is essentially saturated when $G_c/G_m \ll 1$, which for small K corresponds to $G_c \ll 0.307$. Under the latter conditions lasing is initiated at time

$$\tau_i = \frac{G_c}{1+K} \left[1 + 0(G_c) \right] \quad (18)$$

which is small compared to the pulse length. For an unsaturated laser τ_i is found by substituting G_c into Eq. (16a).

During lasing $G = G_c$. Let $E(\tau)$ denote the temporal variation of output energy per unit volume. The intensity of the output from a unit lasing volume is $dE/dt = g_c I$. The latter can be expressed, from Eq. (15a) with $G = G_c$, as

$$\begin{aligned} \frac{(1+K)}{K} \frac{d}{d\tau} \left(\frac{E(\tau)}{\epsilon H_{2,0}} \right) &\equiv \frac{2\sigma t_{cd}}{\epsilon} G_c I \\ &= \frac{(1+K)e^{-K\tau} - 1}{K(1+K)^{-1}} - G_c \end{aligned} \quad (19)$$

which is plotted in Fig. 2 for the case $G_c = 0$. (The quantities C_1 , C_2 , and C_3 in Figs. 2 and 3 represent corrections for multiple vibrational levels as discussed in Appendix A.) The intensity decreases exponentially. (The initial transient is not deduced herein.) For small K the decrease of I with τ is nearly linear. Lasing ends when $I = 0$, which occurs at

$$\tau_e = \frac{1}{K} \ln \left[\frac{1+K}{1 + G_c K(1+K)^{-1}} \right] \quad (20a)$$

$$= 1 - \frac{K}{2} + \frac{K^2}{3} - \dots \quad (G_c = 0, K < 1) \quad (20b)$$

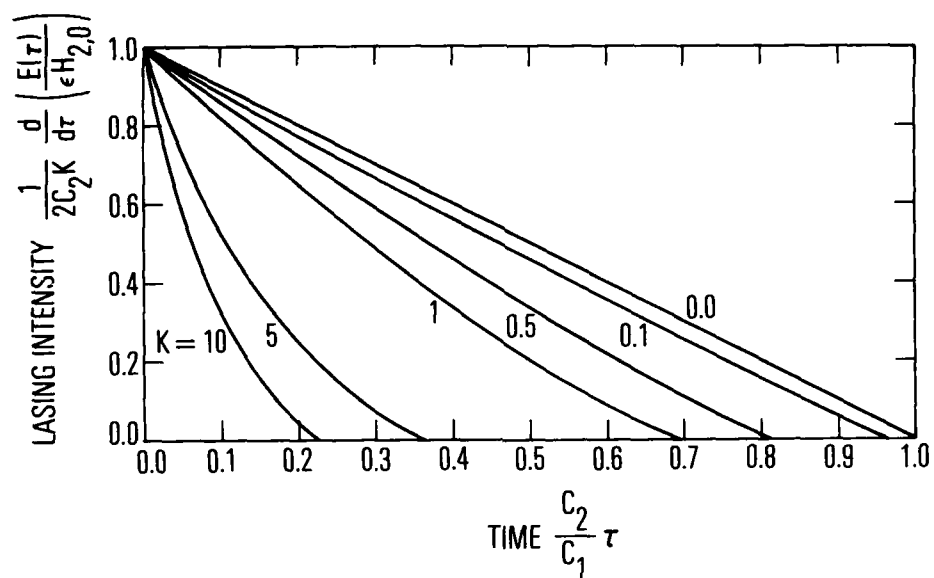


Fig. 2. Variation of lasing intensity with time for $G_c = 0$

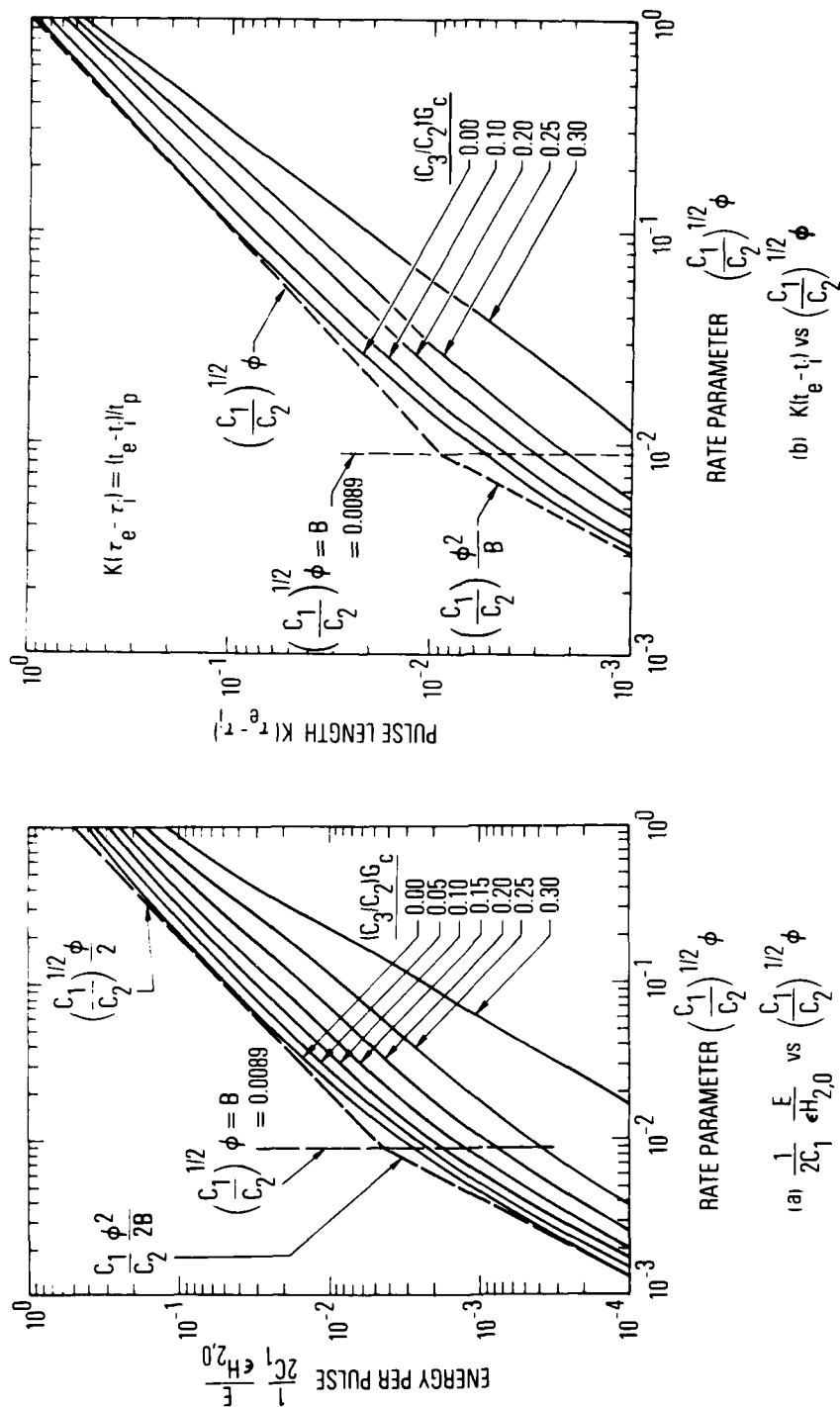


Fig. 3. Variation of output energy per pulse and pulse length with rate parameter ϕ .
 (a) $\frac{1}{2C_1} \frac{E}{\epsilon H_{2,0}}$ vs $(C_1/C_2)^{1/2} \phi$, (b) $K(\tau_e - \tau_i)$ vs $(C_1/C_2) \phi$.

For small K , t_e is of the order of t_{cd} . The pulse length is found from $t_e - t_i$ and is equal to t_e for a saturated laser. The value of HF_T , at the end of the pulse, is

$$\begin{aligned}\frac{(HF_T)_e}{2H_{2,0}} &= \frac{K}{1+K} \left(1 - \frac{G_c}{1+K}\right) \\ &= \frac{K}{1+K} \left[1 + O(G_c)\right]\end{aligned}\quad (20c)$$

The value of HF_T given in Eq. (20c) has been used in Eq. (15b) to characterize the concentration of HF_T during the lasing process.

The net output energy per unit volume per pulse is

$$\begin{aligned}E &\equiv \int_{t_i}^{t_e} g_c I dt \\ &= \epsilon H_{2,0} \left[\frac{1+K}{K} e^{-K\tau} + \left(1 + \frac{KG_c}{1+K}\right) \tau \right]_{\tau_e}^{\tau_i}\end{aligned}\quad (21)$$

For a saturated laser, i.e., $G_c = 0$, Eq. (21) becomes

$$\frac{E}{\epsilon H_{2,0}} = 1 - \frac{\ln(1+K)}{K} \quad (22a)$$

$$= \frac{K}{2} - \frac{K^2}{3} + \frac{K^3}{4} - \dots \quad (K < 1) \quad (22b)$$

The quantity $E/\epsilon H_{2,0}$ is a measure of the chemical efficiency of the laser. Equations (16) through (22) define the performance of pulsed chain-reaction lasers.

III. RESULTS AND DISCUSSION

The performance of a pulsed chemical laser operating on a chain reaction depends on the parameters K and G_c . For a saturated medium $G_c \rightarrow 0$, and the performance depends only on K . The dependence of K and G_c on initial conditions is deduced herein. Simplified expressions for laser performance are given and discussed.

A. SIMPLIFIED SCALING LAWS

The characteristic pumping rate t_p^{-1} and the characteristic collisional deactivation rate t_{cd}^{-1} can be expressed, respectively, as

$$t_p^{-1} \equiv k_c R F_0 = \frac{k_h H_{2,0} (F/F_2)_0 (F_2/H_2)_0^2}{1 + (k_h F_{2,0}/k_c H_{2,0})} \quad (23a)$$

and

$$t_{cd}^{-1} = k_{cd}^{HF} [2H_{2,0} K(1 + K)^{-1}] + k_{cd}^{H_2} H_{2,0} + \sum_i k_{cd}^{\bar{M}_i} \bar{M}_i \quad (23b)$$

where $\bar{M}_i$ denotes collisional deactivation partners other than HF and H_2 , e.g., $\bar{M}_i = H_e, F, H$, and $F_{2,0}$. The rate coefficients are given in Table I. The characteristic value of HF, in Eq. (23b), was taken to be $(HF_T)_e$ as given in Eq. (20c). The characteristic values of F and H are given by Eq. (5b). The relation $K t_{cd}^{-1} = t_p^{-1}$ can be expressed in the form

Table I. Rate Coefficients Based on Reference 9^a

T, K	$k_c \times 10^{-13}$	$k_h \times 10^{-12}$	$k_{cd}^{HF} \times 10^{-12}$	$k_{cd}^{H_2} \times 10^{-10}$	$k_{cd}^{H_e} \times 10^{-6}$	$k_{cd}^{F_2} \times 10^{-6}$	$k_{cd}^H \times 10^{-11}$	$k_{cd}^F \times 10^{-11}$
300	1.092	1.022	1.014	1.80	3.74	1.87	1.39	1.73
400	2.14	2.56	0.777	2.40	15.8	7.89	1.87	5.35
500	3.20	4.43	0.644	3.00	48.1	24.0	2.22	10.6
600	4.18	6.40	0.566	3.60	119.8	59.9	2.50	16.6
700	5.06	8.31	0.523	4.20	259	129	2.72	23.0
800	5.85	10.1	0.502	4.80	505	252	2.90	29.3
900	6.54	11.8	0.500	5.40	909	455	3.04	35.4
1000	7.15	13.3	0.511	6.00	1540	770	3.16	41.1

where

$$k_c = 1.6 \times 10^{14} \exp(-805.2/T)$$

$$k_h = 4 \times 10^{13} \exp(-1100/T)$$

$$k_{cd}^{HF} = 3 \times 10^{14} T^{-1} + 3.5 \times 10^4 T^{2.26}$$

$$k_{cd}^{H_2} = 6 \times 10^7 T$$

$$k_{cd}^{H_e} = 2k_{cd}^{F_2} = 15.4 \times 10^{-7} T^5$$

$$k_{cd}^H = 4.5 \times 10^{11} \exp(-352.3/T)$$

$$k_{cd}^F = 1.6 \times 10^{13} \exp(-1359/T)$$

Overall Rate

HF(1) → HF(0)

^a Coefficient k_h modified per communication with N. Cohen.

$$K \left(\frac{K}{1+K} + B \right) = \phi^2 \quad (24a)$$

where

$$\phi^2 = \frac{k_h}{2k_{cd}^{HF}} \left[\frac{(F/F_2)_0 (F_2/H_2)_0^2}{1 + (k_h F_{2,0}/k_c H_{2,0})} \right] \quad (24b)$$

and

$$B = \frac{k_{cd}^{H_2}}{2k_{cd}^{HF}} \left(1 + \frac{\sum_i k_{cd}^{\bar{M}_i} \bar{M}_i}{k_{cd}^{H_2} H_{2,0}} \right) \quad (24c)$$

The summation term in Eq. (24c) is generally negligible. Inversion of Eq. (24a) yields

$$2K = \left\{ [4\phi^2 + (B + \phi^2)^2]^{1/2} + \phi^2 - B \right\} / (1 + B) \quad (25)$$

which provides an explicit relation between K and the initial conditions. The quantity ϕ can be considered the basic parameter, rather than K, which describes pulsed chemical laser performance. Corresponding values of K and ϕ are given in Table I, and the variation of output energy and pulse length with ϕ is given in Fig. 3.

It will be shown that in general $B \ll 1$, $\phi \ll 1$, and $K \ll 1$ for pulsed chain-reaction chemical lasers. Hence K can be expressed in the form (from Eq. 24a)

$$K = \frac{\phi^2}{B} \left[1 - \left(\frac{\phi}{B} \right)^2 + o\left(\frac{\phi}{B} \right)^4 \right] \quad \phi < B \quad (26a)$$

$$= \phi \left[1 - \frac{B}{2\phi} + o\left(\frac{B}{\phi} \right)^2 \right] [1 + o(\phi)] \quad B < \phi < 1 \quad (26b)$$

Examination of Eqs. (23b) and (24a) indicates that for $\phi \ll B$ collisional deactivation by HF is negligible, whereas for $\phi \gg B$, HF is the major collisional deactivator. The region near $\phi = B$ is the region where collisional deactivation by HF is of the order of the collisional deactivation by the other collisional partners (primarily H_2). It follows from Eqs. (20b) and (22b) that for $G_c = 0$

$$K\tau_e = \frac{2E}{\epsilon_{H_2,0}} = \frac{\phi^2}{B} \left[1 - \left(\frac{\phi}{B} \right)^2 + o\left(\frac{\phi}{B} \right)^4 \right] \quad \phi < B \quad (27a)$$

$$= \phi \left[1 - \frac{B}{2\phi} + o\left(\frac{B}{\phi} \right)^2 \right] [1 + o(\phi)] \quad B < \phi < 1 \quad (27b)$$

The error terms are largest in the vicinity of $B = \phi$. The following expressions agree with the exact solution to within about 20%.

$$K\tau_e = \frac{2E}{\epsilon H_{2,0}} = \frac{\phi^2}{B} \quad \phi \leq 0.5 B \quad (28a)$$

$$= \phi \quad 2B \leq \phi \ll 1 \quad (28b)$$

The upper limit in Eq. (28b) is chosen so as to satisfy the requirement $t_t/t_e \ll 1$, as will be discussed. Equations (28a) and (28b) provide simplified expressions for saturated laser performance. The departure of these expressions from the exact solution [i.e., Eqs. (20a) and (22a)] can be observed in Fig. 3. It is shown in Appendix B that Eq. (28) applies for $(H_2/F_2)_0 > 1$ as well as for $(F_2/H_2)_0 \geq 1$.

B. TYPICAL CONDITIONS

Typical initial conditions for pulsed chain-reaction chemical lasers are¹⁰

$$H_{2,0}/F_{2,0}/He = 1/2/7$$

$$(F/F_2)_0 \lesssim 10^{-2}$$

$$p_0 = 1 \text{ atm}$$

$$T_0 = 300 \text{ K} \quad (29)$$

The value of HF_T at the end of the lasing pulse is given by Eq. (20c). A typical gas temperature at the end of the pulse is then (neglecting energy in vibration) in degrees Kelvin

$$T_e - T_0 = \frac{(6.5 \times 10^4)(HF_T)_e}{\sum_i (C_v M)_i} = \frac{2.6 \times 10^4 K(1+K)^{-1}}{1 + (F_2/H_2)_0 + (3/5)(He/H_{2,0})} \quad (30)$$

where the heat of reaction is 6.5×10^4 cal/mole, and specific heat at constant volume is 3 and 5 cal/mole-K for monatomic and diatomic gases, respectively.

For $T = 300$ K

$$\frac{\phi}{0.710} = \left(\frac{F}{F_2}\right)_0^{1/2} \left(\frac{F_2}{H_2}\right)_0 \left[1 + 0.094 \left(\frac{F_2}{H_2}\right)_0\right]^{-1/2} \quad (31a)$$

$\equiv \psi$

and

$$B = 0.0089 \quad (31b)$$

where the rate coefficients in Table II have been used and the summation term in Eq. (24c) is neglected, i. e., H_2 is the major collisional deactivator other than HF. It follows that $\phi \lesssim 10^{-1}$ and that Eqs. (28a) and (28b) describe the performance of practical pulsed chain-reaction chemical lasers. For these cases $T_e - T_0 \lesssim 400$ K such that the use of $T = 300$ K as a characteristic temperature is a reasonable first estimate. An improved estimate for characteristic temperature can be deduced from Eqs. (30) and (25). Temperature effects become important as the amount of diluent is decreased.

C. CORRELATION WITH EXPERIMENTS AND
NUMERICAL STUDIES

Equation (28) provides simple scaling laws for pulsed chain-reaction chemical lasers, which apply for $(H_2/F_2)_0 > 1$, as well as for $(F_2/H_2)_0 \geq 1$ (Appendix B). These equations have been deduced by means of a two-vibrational level model. The effect of multiple vibrational levels is to introduce additional coefficients, as discussed in Appendix A. Improved numerical estimates of laser performance can be obtained by evaluating these coefficients to agree with available experimental data and with numerical code calculations. The latter procedure is discussed herein.

In References 10 through 12 are presented experimental pulsed chemical laser performance data, which is summarized in Table II. The initiation level $(F/F_2)_0$ reported in References 10 and 12 have been increased by a factor of four (Table II) in accordance with the recommendations of Reference 13. Numerical code calculations reported in Reference 3 are included in Table II. The initiation level $(F/F_2)_0$ in Reference 3 has been increased by a factor of two (Table II) in order to compensate for the fact that the overall hot-reaction pumping rate k_h in Reference 3 is twice the value used herein. That is, the product $k_h (F/F_2)_0$ in Eq. 24b has been kept constant. The value of $(F/F_2)_0$ in Reference 11 has also been increased by a factor of two to account for the effect of the revised value of k_h on the evaluation of initiation strength in Reference 11. The range of ψ in Table II is somewhat limited in that $0.09 \leq \psi \leq 0.33$. Equations (28b) and (A-3) are applicable and indicate that $E/(\psi p_{H_2,0})$ and Et_e should be constant. The data in Table II indicate

Table II. Correlation of Experimental¹⁰⁻¹² and Numerical³ Studies of Pulsed Chemical Laser Performance

Ref.	Initial Conditions				Performance		Correlation Parameters		
	$(F/F_2)_0$	$P_{F_2,0}$ atm	$P_{H_2,0}$ atm	P_{total} atm	E , J/cm^3	t_e μsec	ψ	$E/(\psi P_{H_2,0})$, $J/cm^3 \cdot atm$	$E t_e$, $\mu sec/cm^3$
3	0.016	0.022	0.022	1.1	0.010		0.122	3.8	
	0.016	0.044	0.044	1.1	0.028	4.7	0.122	5.2	0.13
	0.016	0.088	0.088	1.1	0.068		0.122	6.4	
	0.024	0.063	0.032	1.05	0.051	2.5	0.280	5.7	0.13
10	0.0048	0.08	0.03	1.0	0.010	8.0	0.166	2.0	0.08
	0.0044	0.10	0.03	1.0	0.010	7.0	0.192	1.8	0.07
	0.0044	0.12	0.04	1.0	0.016	5.0	0.166	2.3	0.08
	0.0032	0.20	0.06	1.0	0.027	4.3	0.164	2.8	0.12
11	0.0020	0.30	0.08	1.0	0.050	2.0	0.144	4.8	0.10
	0.024	0.063	0.032	1.05	0.042	2.4	0.280	4.7	0.10
12	0.032	0.02	0.02	1.0	0.014		0.172	4.1	
	0.032	0.02	0.04	1.0	0.019		0.088	5.4	
	0.032	0.04	0.02	1.0	0.033		0.328	5.0	
	0.032	0.04	0.04	1.0	0.040	4	0.172	5.8	0.16
	0.032	0.04	0.08	1.0	0.033		0.088	4.7	
	0.032	0.08	0.08	1.0	0.068		0.172	5.0	
	0.032	0.08	0.12	1.0	0.068	2	0.116	4.9	0.14
	0.032	0.08	0.16	1.0	0.080		0.088	5.7	

$$\frac{E}{(\psi P_{H_2,0})} = 4.6 [(1 \pm 0.5)] \quad J/cm^3 \text{-atm} \quad (32a)$$

$$Et_e = 0.11 \times 10^{-6} [(1 \pm 0.5)] \quad J\text{-sec/cm}^3 \quad (32b)$$

Note that the data of Reference 12 includes cases with $(H_2/F_2)_0 > 1$, as well as $(F_2/H_2)_0 > 1$ and is correlated to within about 20%. Substitution of the mean values from Eqs. (32) into Eq. (A-5) yields $C_1 = 2.57$ and $C_2 = 1.32$. Thus the abscissa $(C_1/C_2)^{1/2} \phi$ in Fig. 3 can be replaced by ψ to within an accuracy of about 1%. Substitution of the latter values of C_1 and C_2 into Eqs. (A-2) and (A-3) yield for $\psi \leq 0.004$

$$\frac{E}{P_{H_2,0}} = 510 \psi^2 \quad J/cm^3 \text{-atm} \quad (33a)$$

$$P_{H_2,0} t_e = 2.7 \times 10^{-6} \quad \text{atm-sec} \quad (33b)$$

$$Et_e = 1.4 \times 10^{-3} \psi^2 \quad J\text{-sec/cm}^3 \quad (33c)$$

and for $0.02 \leq \psi \ll 1$

$$\frac{E}{P_{H_2,0}} = 4.6 \psi \quad J/cm^3 \text{-atm} \quad (34a)$$

$$P_{H_2,0} t_e = 0.11 \times 10^{-8} / \psi \quad \text{atm-sec} \quad (34b)$$

$$Et_e = 0.11 \times 10^{-6} \quad J\text{-sec/cm}^3 \quad (34c)$$

Equations (33) and (34) define the performance of pulsed chain-reaction HF chemical lasers for both $(F_2/H_2)_0 \geq 1$ and $(H_2/F_2)_0 > 1$ and are the major results of the present study. Equation (33) correspond to weak initiation (where the assumption $G_c \gg 1$ may be violated). In the latter regime $E \sim (FF_2/H_2)_0$ and $t_e^{-1} \sim H_{2,0}$. Equation (34) correspond to relatively strong initiation and is the regime of practical interest. In the latter regime $E \sim t_e^{-1} \sim (FF_2)_0^{1/2}$ and $Et_e = \text{constant}$.

As previously discussed, Eqs. (33) and (34) represent regimes in which collisional deactivation by HF is negligible and dominant, respectively. The numerical coefficients are considered first estimates, and further correlations with numerical codes and experimental data should result in improvements.

D. REGION OF VALIDITY

In the present solution for the chain reaction pumping process it is assumed that the initial transient time t_t is small compared to the characteristic pump time t_p . This assumption was shown to be valid for $(F/F_2)_0 \ll 1$ [Eq. (9)]. The resulting solution for laser performance is valid provided the relation $t_t/t_e \ll 1$ is also satisfied. Eqs. (5d) and (20a) indicate that for $G_c = 0$

$$\frac{t_t}{t_e} = \frac{R^2(k_c/k_h)(F/F_2)_0}{\ln(1+K)}$$

$$= 0(B) \quad \phi \ll B$$

$$= 0(\phi) \quad B \ll \phi \ll 1$$

$$= 0(1) \quad \phi = 0(1)$$

Hence in order for the present solution to be consistent it is necessary that $\phi \ll 1$. The latter relation provides an upper bound on the validity of the present theory [e.g., Eq. (28b) and Fig. 3].

E. COMPARISON WITH COLD-REACTION LASER

Initial concentrations in pulsed HF cold-reaction chemical lasers are characterized by F_0 , $H_{2,0}$, H_e , ... , where $F_0/H_{2,0} \ll 1$. By virtue of the latter inequality, the pumping reaction is

$$\frac{HF_T}{F_0} = 1 - e^{-t/t_p} \quad (35a)$$

$$t_p^{-1} \equiv k_c H_{2,0} \quad (35b)$$

The concentration of HF_T , during the lasing process, can be shown to be characterized by F_0 so that the collisional deactivation rate is

$$t_{cd}^{-1} = k_{cd}^{HF} F_0 \left[1 + \frac{2H_{2,0}}{F_0} B \right] \quad (36)$$

Hence

$$K \equiv \frac{t_p^{-1}}{t_{cd}^{-1}} = \frac{k_c H_{2,0}}{k_{cd}^{HF} F_0 \left[1 + \frac{2H_{2,0}}{F_0} B \right]} \quad (37)$$

Since $k_c/k_{cd}^{HF} = 0(10)$ and $H_{2,0}/F_0 \gg 1$, K is large for pulsed cold-reaction lasers. Consideration of Eqs. (35a), (10), and (14) indicates that Eqs. (14) to (22) describe pulsed cold-reaction laser performance provided that $2H_{2,0}$ is replaced by F_0 therein. Thus for these lasers $K \gg 1$, $(HF_T)_e = F_0$ [see Eqs. (20a) and (35a)], and the energy output per pulse from a saturated laser is $E/\epsilon F_0 = 1/2$. In contrast the pulsed chain-reaction laser is characterized by $K \ll 1$, $(HF_T)_e = 2KH_{2,0}$, and $E/\epsilon H_{2,0} = K/2$.

IV. CONCLUDING REMARKS

Scaling laws for pulsed chain-reaction chemical lasers have been derived. Equations (33) and (34) provide simple expressions for the case of saturated HF chain reaction lasers. The results are applicable for $(H_2/F_2)_0 > 1$ as well as $(F_2/H_2)_0 \geq 1$. It is hoped that these results will be useful for the correlation of data from experimental and numerical studies of pulsed chain-reaction chemical laser performance. Such correlations should provide improved estimates of the numerical coefficients in Eqs. (33) and (34).

Mean kinetic rates have been used, and the numerical coefficients in Eqs. (33) and (34) have been based on values corresponding to $T = 300$ K. The present approach is applicable when the amount of diluent in the system is sufficient to limit the temperature rise during the lasing pulse [e.g., Eq. (30)]. With decrease in diluent, it may be necessary to modify the coefficients in Eqs. (33) and (34) to account for an increased mean temperature during the lasing pulse.

APPENDIX A

MULTIPLE VIBRATIONAL LEVELS

The results of the two-vibrational-level model can be generalized to account for multiple vibrational levels. The generalization, based on Reference 6, is indicated herein for power-on ($I \neq 0$) conditions.

The definitions $K = t_{cd}/t_p$ and $\tau = t/t_{cd}$ and the definition of ϕ [Eq. (24b)] are retained. The scaling laws deduced from the two-level model are generalized by making the following substitutions:

<u>Two Level</u>		<u>Multiple Level</u>	
K	→	$(C_1/C_2)K$	
τ	→	$(C_2/C_1)\tau$	
G_c	→	$(C_3/C_2)G_c$	
E	→	$E/(2C_1)$	
ϕ	→	$(C_1/C_2)^{1/2}\phi$	(A-1)

The quantities C_1 , C_2 , and C_3 are defined in Reference 6. In particular C_1 equals the number of photons liberated per lasing molecule formed for the case of a saturated laser with no collisional deactivation. The quantity C_2 is the ratio of the net collisional deactivation rate in a saturated laser to the value that would exist if all the lasing species molecules were in the first vibrational level. The quantity C_3 provides for a correction to the net

collisional deactivation rate for the case of a lack of optical saturation. For a given lasing species the quantities C_1 , C_2 , and C_3 are functions of $\exp(-2JT_R/T)$, where J is the lower lasing level rotational energy quantum number and T_R is the characteristic rotational temperature (≈ 30.16 K for HF). These quantities can be considered constants of order one in the present scaling relations.

Substitution of Eq. (A-1) into Eq. (28) and taking $t_p^{-1} \equiv 2 k_{cd}^{HF} H_{2,0} \phi^2$ into consideration yields for $(C_1/C_2)^{1/2} \phi \leq 0.5B$

$$\frac{E}{\epsilon H_{2,0}} = \frac{C_1^2}{C_2} \frac{\phi^2}{B} \quad (A-2a)$$

$$H_{2,0} t_e = \frac{1}{2} \frac{C_1}{C_2} \frac{1}{B k_{cd}^{HF}} \quad (A-2b)$$

$$Et_e = \frac{\epsilon}{2} \frac{C_1^3}{C_2^2} \frac{\phi^2}{B^2 k_{cd}^{HF}} \quad (A-2c)$$

and for $2B \leq (C_1/C_2)^{1/2} \phi \ll 1$

$$\frac{E}{\epsilon H_{2,0}} = \frac{C_1^{3/2}}{C_2^{1/2}} \phi \quad (A-3a)$$

$$H_{2,0}^{t_e} = \frac{1}{2} \left(\frac{C_1}{C_2} \right)^{1/2} \frac{1}{k_{cd}^{HF} \phi} \quad (A-3b)$$

$$Et_e = \frac{\epsilon}{2} \frac{C_1^2}{C_2} \frac{1}{k_{cd}^{HF}} \quad (A-3c)$$

Estimates for C_1 , C_2 , and C_3 are needed. For the present two-level model⁶

$$C_1 = C_2 = C_3 = \frac{1}{2} \quad (A-4)$$

Estimates for a multilevel model can be obtained with the use of the expressions in Reference 6. An alternative approach is to compare the present results with numerical multilevel code solutions or with experimental data. The latter approach is used herein. In the regime wherein Eq. (A-3) are valid

$$C_1 = \frac{\epsilon}{2k_{cd}^{HF}} \left(\frac{E}{\epsilon H_{2,0} \phi} \right)^2 \frac{1}{Et_e} \quad (A-5a)$$

$$C_2 = \frac{2\epsilon C_1^2 k_{cd}^{HF}}{Et_e} \quad (A-5b)$$

Substitution of mean values from Eq. (32) into Eq. (A-5) yields

$$C_1 = 2.57 \quad (A-6a)$$

$$C_2 = 1.32 \quad (A-6b)$$

where it has been assumed that $T = 300 \text{ K}$ and $\epsilon = 44.3 \times 10^3 \text{ J/mole}$. (The latter corresponds to radiation at a wavelength of $2.7 \times 10^{-6} \text{ m.}$) Equation (A-6) indicates that the present two-level model underestimates outputs power by about a factor of 5 (as a result of the neglect of multiple levels and partial inversions). Equation (A-6) should be viewed as a first estimate. Improved correlations can be deduced by further comparisons with numerical code results and experimental data.

APPENDIX B

CASE $H_{2,0} > F_{2,0}$

It has been assumed in the body of the report that $F_{2,0} \geq H_{2,0}$. The case $H_{2,0} > F_{2,0}$ is considered herein.

In the latter case the amount of reactant is characterized by $F_{2,0}$, rather than $H_{2,0}$, and the characteristic times are $t'_p = (F_2/H_2)_0 t_p$ and

$$t'_{cd} = \left[2F_{2,0} k_{cd}^{HF} \left(\frac{K'}{1+K'} + B' \right) \right]^{-1} \quad (B-1)$$

where $K' \equiv t'_{cd}/t'_p$ and $B' \equiv (H_2/F_2)_0 B$. The resultant solution is the same as that in the body of the report with $F_{2,0}$ replacing $H_{2,0}$ and prime quantities replacing the corresponding unprimed quantities. Note that $\tau' \equiv t/t'_{cd}$, $\phi' \equiv (H_2/F_2)_0 \phi$, and

$$G' = \frac{G}{2\sigma F_{2,0} K' (1+K')^{-1}} \quad (B-2)$$

For $K' \ll 1$ it is found that $t'_{cd} = t_{cd}$ and $K' = (H_2/F_2)_0 K$. As a result the expressions for output energy E and pulse time t_e for a saturated chain-reaction laser in the limit $K \ll 1$, given in the body of the report [e.g., Eqs. (20b), (22b), (27), (28), (33), (34)] are applicable for $H_{2,0} > F_{2,0}$ as

well as $F_{2,0} \geq H_{2,0}$. This result is a consequence of the fact that for a saturated chain-reaction HF laser in the limit $K \ll 1$, the quantities K , K' , $H_{2,0}$, and $F_{2,0}$ appear only as the products $H_{2,0} K$ and $F_{2,0} K'$, and the latter are equal.

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