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HIGH POWER CO LASER
QUARTERLY TECHNICAL REPORT (U)

Period Covering:
September 1, 1973 - November 31, 1973

January, 1974

Prepared by

Northrop Research and Technology Center
W. B. Lacina, G. L. McAllister, V. G. Draggoc

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Northrop Research and Technology Center
Laser Technology Laboratories
3401 West Broadway
Hawthorne, California 90250

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

(U) Effort on the High Power CO Laser Program is reviewed. The program is directed toward the development of the required CO laser technology, the required component technology, and the design and construction of intermediate power laser devices. The results of analytical and experimental investigation of the basic characteristics of the laser and data from a high pressure electrically excited CO laser device are discussed.

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PROGRAM IDENTIFICATION (U)

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Program Scientist:	Dr. G. L. McAllister (213) 675-4611, Ext. 4975
Scientific Officer:	Director, Physics Program Physical Sciences Division Office of Naval Research Department of the Navy 800 North Quincy Arlington, Virginia 22217

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1.0 SUMMARY

(S) The long range objective of this program is to develop the necessary technology for a 1 - 2 MW average power, repetitively pulsed, diffraction limited CO laser operating at an electrical efficiency of 50% or more. The work covered in this contract involves the design of intermediate power CO laser devices, the development of the required CO laser technology, and the construction of an intermediate power CO laser device.

(U) This program encompasses, on a best effort basis, the following major tasks:

(U) 1. The development of both steady state and transient kinetic models in order that realistic theoretical predictions of high energy device characteristics can be made.

(U) 2. Measurements of basic parameters of the CO laser at low pressures including: gain, saturation intensity, rates of vibrational cross-relaxation between CO molecules, transfer rates of CO and N_2, discharge characteristics, and spectral characteristics.

(U) 3. Measurements and characterization of a high pressure E-beam excited pulsed laser to experimentally determine transient operating parameters for high energy extraction.

(U) 4. The design and construction of a 500J/pulse diffraction-limited CO laser oscillator.

(U) 5. The development of line selection techniques for controlling the oscillator spectral output.

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(U) Basic studies directed toward investigation of the physics of CO laser devices were continued during this period. Experimental work on the effects of addition of N_2O to a low pressure longitudinal discharge CO laser was undertaken, following the observations of Jeffers and Wiswall[1] that this technique can be used to enhance output on lower vibrational bands. Results of these experiments are reported and discussed in Section 2.1. Further work has been completed on data collection and theoretical comparison of transient gain relaxation in the three-laser configuration described in previous reports.[2-5] Although several open questions remain in the interpretation of this data, an improved understanding of possible origins of the discrepancies between theory and experiment is evolving. Some data is presented, with a discussion of theoretical and experimental problems, in Section 2.2. The possibility of rotational nonequilibration is discussed, and even if it is not important for interpretation of the present gain relaxation data, it suggests a region of intensities and operating pressures for which rotational cross relaxation effects may be observable.

(U) Mode control and resonator design studies are continuing, both experimentally and theoretically, and are described in Section 3.0. Results of this work were useful in designing the unstable optical resonator successfully employed in the (nominally 10-liter) Device No. 2. Experimental mode shape studies with a high gain 3.5μ Xe laser produced intensity profiles which were successfully interpreted on the basis of approximate geometrical optics considerations. This fact may have important consequences for simplifying the analysis of the effects of gain variation or index variations on unstable mode properties. The relationships between mode loss, number of intensity peaks, and equivalent and effective Fresnel numbers have been studied experimentally (confirming theoretical predictions) and are reported in Section 3.1, 3.2.

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(U) One of the most significant achievements has been the successful operation of the 10-liter device at energies above 500J/pulse, which has been an objective milestone of the program. Conversion efficiency was 32% (based upon total volume) or 42% (based on estimated extraction volume). In addition, the device has been operated at energies greater than 300J/pulse with unstable resonator optics, and preliminary measurements indicate good beam quality. Several experimental device problems have been solved that permit operation at higher sustainer voltages without arcing. Results are reported in Section 4.0.

2.0 BASIC STUDIES AND MEASUREMENTS -(V. G. Draggoo and W. B. Lacina)

(U) A variety of basic measurements for investigation of CO laser physics are continuing, some of which have been described in previous reports. In the previous quarter, studies of VV cross-relaxation, gain saturation, and effects of N_2O have been pursued, and current results are reported below.

2.1 Enhanced Low Band Operation of a Longitudinal Discharge Laser -

(V. G. Draggoo). (U) Jeffers and Wiswall[1] have reported on increase in the efficiency at low V-bands in a room temperature, chemically excited CO laser. They find that the addition of dilute quantities of nitrous oxide (N_2O) to the gas mixture doubles the multiline output. Nearly all of this increase is associated with enhanced output on the low V-band side of the output spectral profile. We report here similar enhancement in a single line longitudinal discharge laser. We observe that the strength of the effect depends principally on the CO partial pressure and the discharge current. We find that the output at low bands (5-4) doubles in intensity (from 10 mW to 20 mW approximately) with the addition of .01 torr of N_2O to a gas mixture optimized for high V-band operation (9-8). Typical parameters for optimum 9-8 operation are: P_{CO}: .4 torr, P_T = 15 torr, I = 7.5 mA. However, addition of N_2O to the gas mixture of a laser optimized for low V-band operation (5-4) results in little if any increase in intensity. Typical parameters in this case are: $P_{CO} \approx .1$ torr, $P_T \approx 15$ torr, I = 3.0 mA. In this case the output was typically 400 - 600 mW at 5-4.

(U) Jeffers and Wiswall attribute the effect to a depopulation of the low V-levels due to near resonant VV transfer collisions between CO and N_2O. In CO-N_2O collisions the VV transfer probability monotonically decreases with increasing V, which therefore suggests the possibility of more efficient depopulation at lower V-bands. This explanation is not inconsistent with our observations. In our experiments the discharge current has the dominant

effect on laser output, particularly at low V-bands. The deactivation of the lower levels due to addition of N_2O probably compensates for the heating due to electrical energy input. This vibrational cooling effect is most pronounced at the high discharge current where thermal input energy is maximum. From these experiments we conclude that the addition of N_2O to the laser gas mixture could be important in multiline and/or line selected operation. However, little or no benefit is achieved in single line operation.

2.2 VV Cross Relaxation Measurements - (W. B. Lacina and V. G. Draggoo)

(U) Transient gain relaxation data for study of VV cross relaxation has been accumulated for a variety of experimental conditions in order to make comparison with theoretical predictions from the molecular kinetics computer model. These experiments utilize the three laser configuration, described in previous reports, [2-5] in which the effects of cross-relaxation are studied by probing the gain of one transition in a CO amplifier which is simultaneously being driven by a pulsed train of saturating radiation on a neighboring transition. The improvement in measurement accuracy and signal to noise quality has made it possible to concentrate additional effort on investigation of the effects of varying the pairs of transitions and other parameters of the experiment. However, there remain certain problems to be discussed below that need to be resolved in order to obtain a definitive and successful comparison of the data with the theory.

(U) Figures 2.1 and 2.2 show experimental/theoretical curves for the gain relaxation on the transition 10-9 P(10), with saturating radiation driving 9-8 P(11), for two different CO partial pressures. Since the experimental data is not calibrated in absolute magnitude, comparison with theory in Figures 2.1 and 2.2 was obtained by constructing a least squares fit with two constants, corresponding to amplitude and dc level. With this

$P_{CO} = .3$

$P_T = 10.5$

$I_S = 4.8 \ W/cm^2 \ 9-8P(11)$

Experimental

Theoretical

m sec
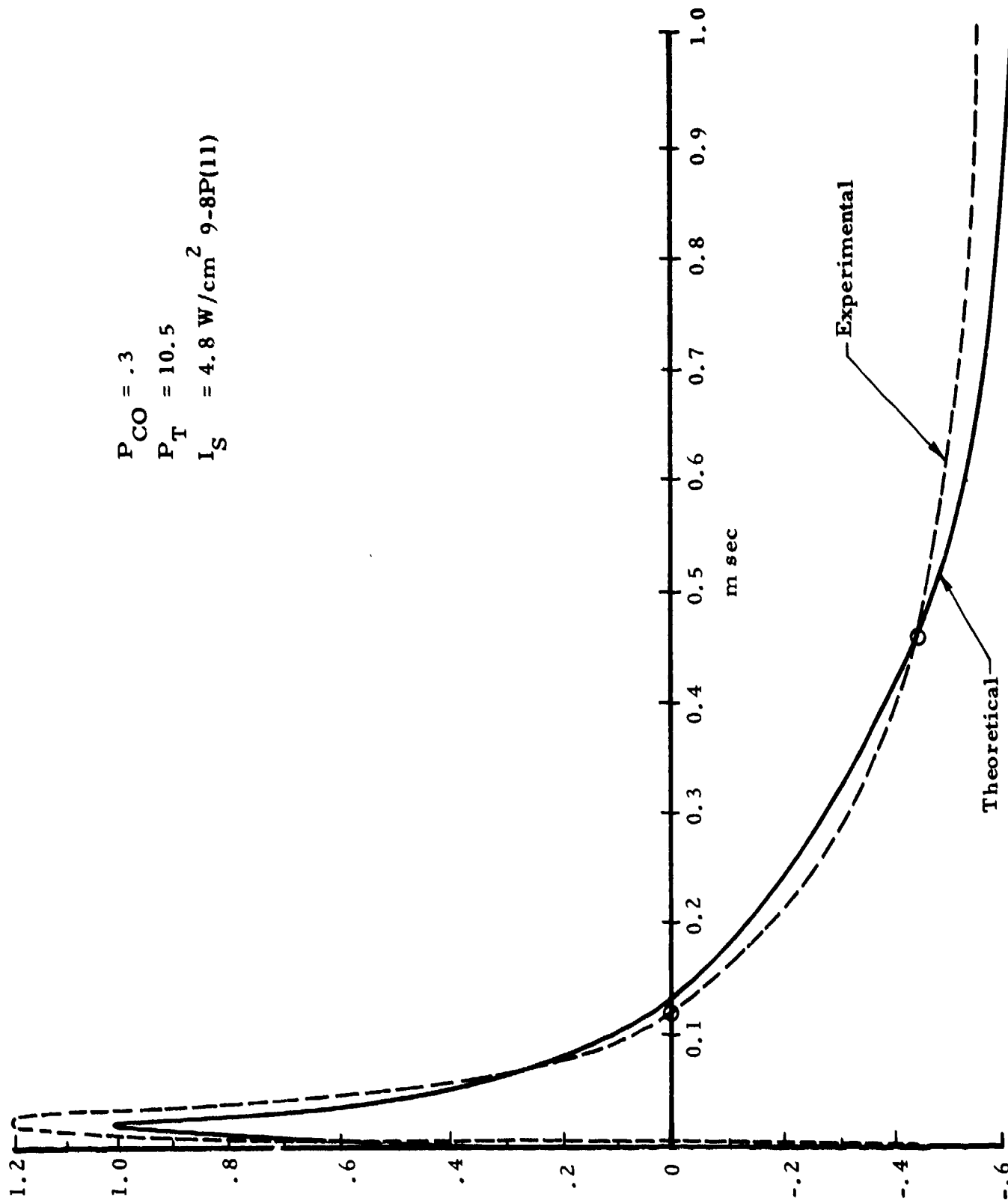
Figure 2.1.   (U) AC Gain Relaxation 10-9 P(10) (U)

Figure 2.2. (U) AC Gain Relaxation 10-9 P(10) (U)
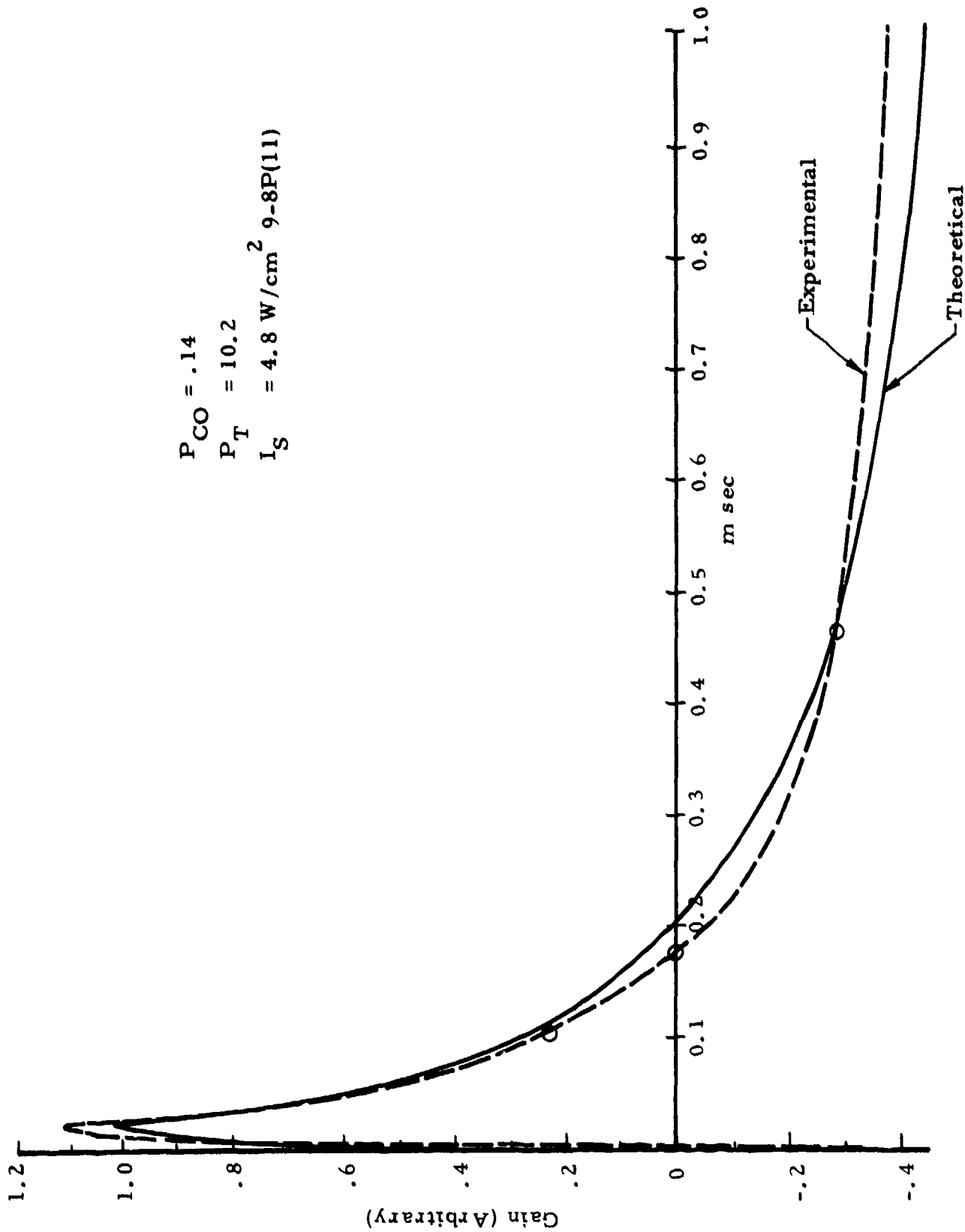
interpretation of the data, there is a reasonably good agreement of the relaxation time constant, although there remains some uncertainty in the explanation of the relatively poor agreement in fitting the final curve to the initial and final steady state points. It is believed that adjustments may be required either in the parameters of the model or in the rate processes included in the analysis to achieve a better calculation of the initial steady state distribution. If the initial steady state level and the magnitude of the gain peak are regarded as important parameters which must be preserved in the comparison of theory with experiment, the results of Figure 2.3 are obtained. In this figure, the least squares criterion for the fit was dropped, and the experimental data was renormalized to reproduce the correct initial point and maximum. It is seen that, with this interpretation, agreement between theory and experiment appears to be poor. In every set of theoretical and experimental comparisons obtained in this way, experimental data produced a final steady state which lies significantly above that predicted by the molecular kinetics model. Adjustment of several input parameters to the computer calculations (particularly molecular temperature, electron density, and radiation input intensity) effected changes in the steady state levels, although the range over which they could reasonably vary was not sufficiently large to account for the experimental values. (Since electrical efficiency of vibrational excitation is not well known, choice of the electron density is not well defined, even though the electrical power/volume of the discharge is known. Molecular temperature is not known accurately at the center of the tube, and focussing and beam steering in the amplifier make it difficult to estimate the saturating intensity precisely.) One possibility that needs to be explored is that the predicted relaxation may be in error due to a failure of the model to adequately calculate the initial steady state distribution. It should be recalled at this point that cw small signal gain measurements, which were reported in a previous report,[2] were undertaken to obtain experimental measurement of vibrational population

$P_{CO} = .14$

$P_T = 10.2$

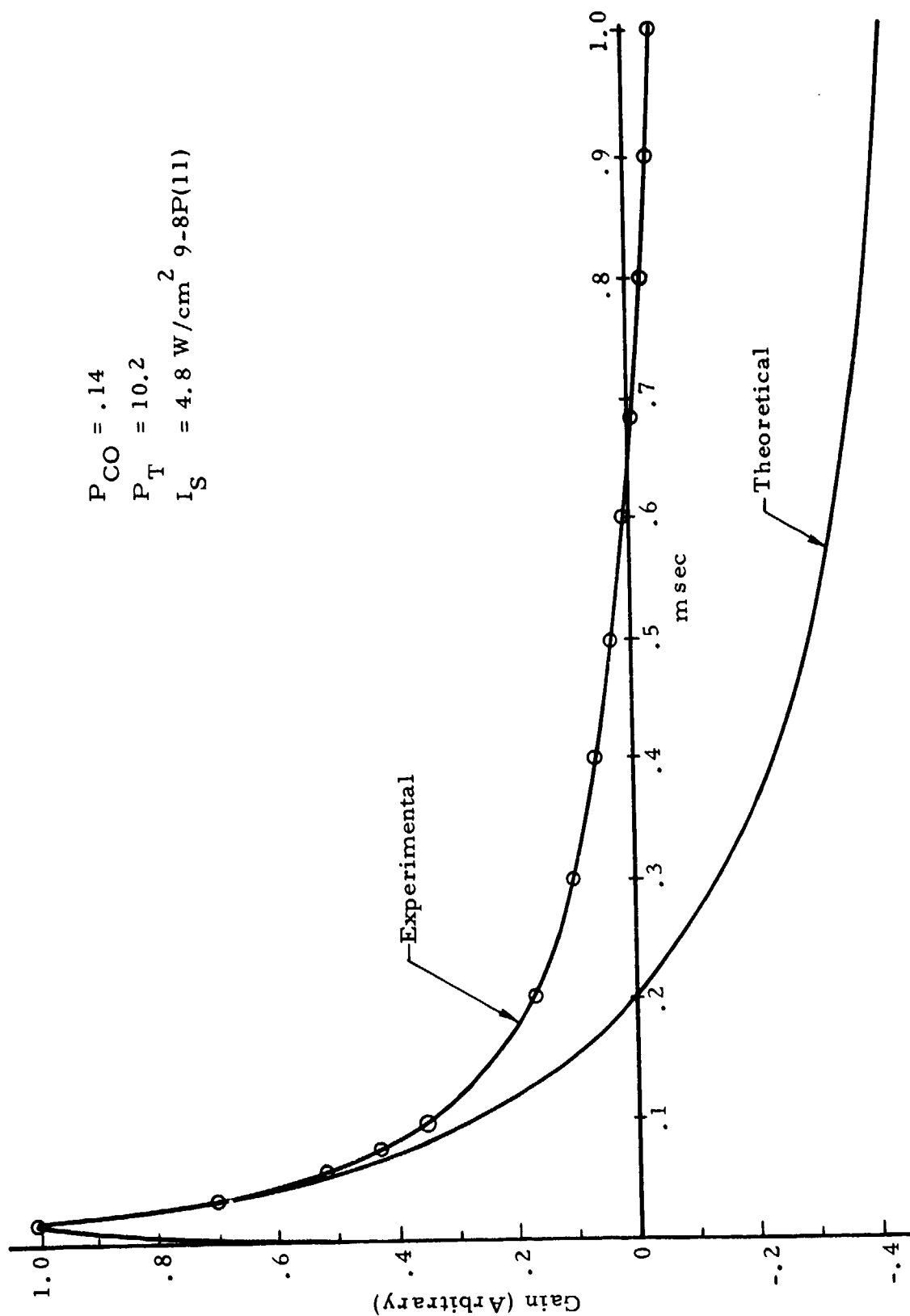$I_S = 4.8 \, W/cm^2 \; 9\text{-}8P(11)$

Experimental

Theoretical

m sec

Gain (Arbitrary)

Figure 2.3. (U) AC Gain Relaxation 10-9 P(10) (U)

distributions. Reasonable comparison of the data with theory[3] required invoking the hypothesis that the optical broadening cross section increased with vibrational level, or the theoretical distribution for the steady state would not be in good agreement with experiment.

(U) Another possibility, which may have important implications for the basic physics of CO laser devices, is that rotational cross relaxation is slow and that the effect of the saturating radiation is to burn a hole in the rotational level distribution. If rotational cross relaxation is infinitely fast (as the molecular kinetics computer model assumes) the effect of a saturating pulse for $v \rightarrow v-1$ P(J) will be to reduce the total populations of all of the upper vibrational levels $\geq v$ in order to drive down the gain on that transition, as shown in Figure 2.4. This reduction of total level populations (in which rotational levels continue to remain in thermal equilibrium) results in a lower steady state gain after the saturating pulse is switched on for gains on all higher transitions. This phenomenon is consistently observed in all of the theoretical plots of transient gain relaxation, although experimental results are often characterized by a higher final steady state level. If rotational cross relaxation is not infinitely fast, a possible explanation for this observation (as well as for discrepancies in initial and final levels for all of the comparisons) is illustrated in Figure 2.5. In this case, it is assumed that the saturating transition is driven down in gain by reducing the population difference only in the J levels involved--i.e., by rotational hole burning. This hole (and bump) in the rotational distributions is smoothed out by rotational cross relaxation, but if the rate for stimulated emission is comparable (i.e. if the saturating radiation intensity is high enough and the total pressure low enough) the levels can never thermally equilibrate. Thus, the final steady state level need not correspond to that predicted by the model. In fact, the nearer the P(J) transition of the probe laser is to the P(J) of the
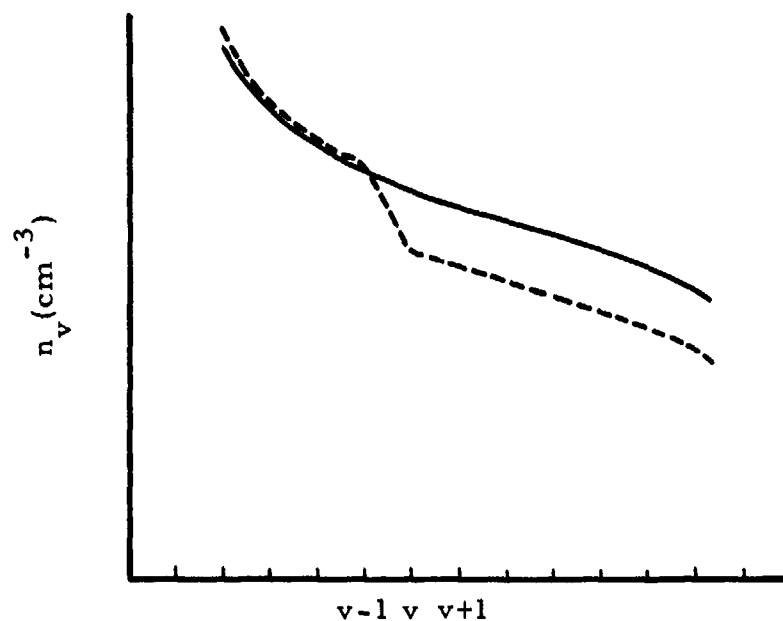
Figure 2.4. (U) Effect on population densities of saturating radiation on transition $v \rightarrow (v-1)$ (dashed curve) compared with initial steady state distribution (solid curve). (U)
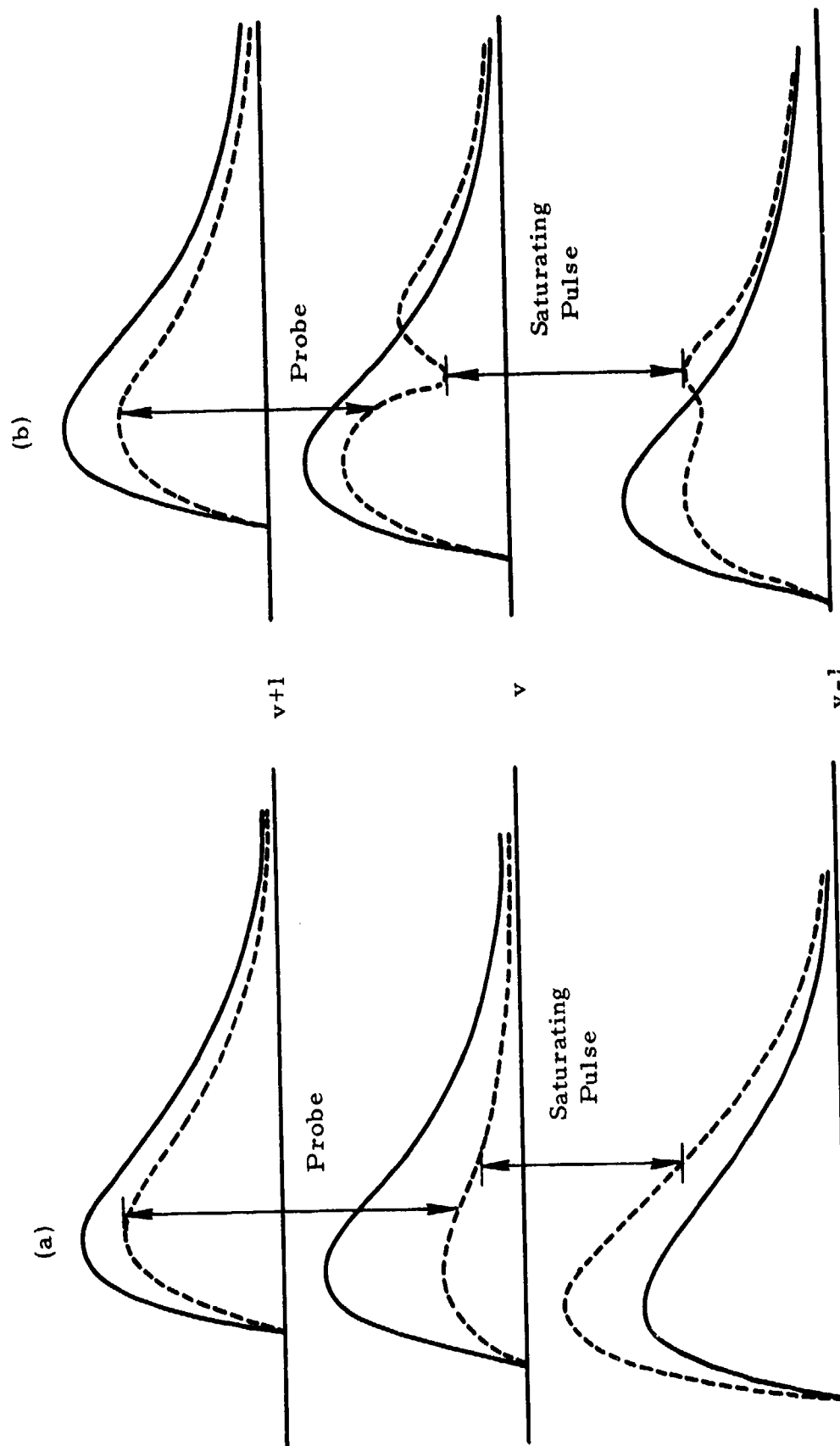
Figure 2.5. (U) Vibrational-rotational population distributions displayed as a function of J for three adjacent v levels at some arbitrary time to show the difference in probe gain for (a) infinitely fast rotational cross relaxation, and (b) rotational cross relaxation comparable to stimulated emission rates. (U)

saturating laser, the poorer the comparison between experiment and present theory is likely to be. The stimulated emission rate for the transition $(v, J-1) \rightarrow (v-1, J)$ is given by

$$\Gamma_{v, J-1 \rightarrow v-1, J} = (I/c)S(\nu_o) \, 8\pi^3 J \left| R_{v \rightarrow v-1} \right|^2 / (3h^2 g_{J-1}) \tag{1}$$

For a (CO, He) mixture of (0.1, 10) torr at 150°K, the resonance line shape factor $S(\nu_o)$ is $\sim 5.6 \times 10^{-9}$ s, so the stimulated emission rate for depopulation of $n_{10}(J=9)$ is $\sim 2 \times 10^5$ S^{-1} $(W/cm^2)^{-1}$. At that temperature and pressure, the kinetic (hard sphere) collision rate is $\sim 2 \times 10^8$ s^{-1}. Thus, if rotational cross relaxation required 100 collisions and if the saturating intensity were $I \sim 10$ W/cm^2, the rates for these competing processes would be equal and rotational thermal equilibrium would be disturbed. For a dilute CO mixture, and on the time scale of VV collision processes, both the rotational cross relaxation and stimulated emission rates are very fast. Thus, the distribution of the J levels in each of the vibrational levels can always be assumed to be instantaneously "frozen," but the assumption employed by the present model that these distributions are all thermal is valid for the levels $(v, v-1)$ only if stimulated emission processes are much slower than the rotational processes. The theoretical expression for the gain employed by the code is taken to be

$$\alpha_{v+1 \rightarrow v}^{P(J)}(t) = C\big(n_{v+1}(t) \, B_{v+1} \, \exp[-B_{v+1} J(J-1)/kT]$$

$$- n_v(t) \, B_v \, \exp[-B_v J(J+1)/kT]\big). \tag{2}$$

However, if the neglect of stimulated emission is not a valid assumption, then the gain on the probe line (lying on that transition immediately above the one being saturated by intense radiation) will be given by

$$\alpha^{P(J)}_{v+1 \to v}(t) = C\left(n_{v+1}(t) \, B_{v+1} \, \exp[-B_{v+1} \, J(J-1)/kT]\right.$$

$$\left. - n_v(t) \, B_v \, f_J \, \exp[-B_v J(J+1)/kT]\right), \tag{3}$$

where $F_J \equiv f_J \exp[-B_v J(J+1)/kT]$ is the relative fraction of molecules with quantum level J in level v (refer to Figure 2.5). Since the rotational distribution is extablished on time scales short compared with vibrational kinetics, the values f_J (which measure the departure from thermal equilibrium) remain frozen in time as the transient gain relaxation phenomenon proceeds. (Furthermore, the stimulated emission rates in the model have to be modified to include the factor f_J in order to make the analysis consistent) There are two important implications that slow rotational cross relaxation would have on the interpretation of the experimental data. The first would be that comparison with theory should not be made in either of the ways discussed above to produce Figure 2.3, since both of these approaches were based on the expression of Equation (2) for the gain as a function of time. Rather, a least squares fit with two parameters (C, f_J) should be made using Equation (3). The constant C will account for the uncalibrated magnitude of the experimental data, and f_J will account for effects of rotational non-equilibration. Secondly, assuming that good values for f_J could be obtained to consistently interpret a wide class of gain relaxation data, an independent model for competition between rotational relaxation and stimulated emission on much shorter time scales can be constructed. This model, which would require only a two level system, each with a manifold of J levels, might then be used to relate the parameters f_J to a rotational relaxation time constant. By scanning the P(J) branch of the probe laser over a range of J values, it may (at least in principle) be possible to construct the rotational distribution of level v. These ideas will be pursued to resolve some of the remaining discrepancies in the experimental measurements.

(U) There also remain certain experimental questions that must be investigated as possible sources of error. For example, in the present configuration, the probe beam essentially fills the amplifier volume, although the saturating beam must be tightly focussed by a telescope in order to obtain adequate intensity. There is an aperture at both ends of the amplifier that restricts the observation of the probe beam. There is the possibility that diffusion processes can result in molecules entering and leaving the saturated region on time scales less than (or at least comparable to) the periods over which transient gain relaxation is experimentally observed (typically 200-300 µs). This cross filling of one region to another may result in some third steady state between the "saturated" and "unsaturated" steady states predicted by the theory. In addition to pursuing some of the theoretical approaches discussed above for resolving discrepancies with the data, experimental techniques will be re-examined to eliminate this or other possible sources of error.

2.3 <u>Saturated Gain Measurements</u> - (V. G. Draggoo). (U) Experimental determination of the gain characteristics of the CO laser in the presence of intense saturating fields is important in assessing the performance of the laser and the role stimulated emission plays in the gas kinetics. Previous experimental determination of the saturation intensity used an input intensity of 1 to 5 W/cm^2. Since then, improvements in the experimental apparatus have yielded single line intensities as high as 10-12 W/cm^2, which prompted further measurements of the saturation intensity in a (CO, He) amplifier at 150° and (0.1, 10) torr. The experimental configuration is similar to that used in previous experiments.[2] Figure 2.6 is a plot of the saturated gain $\alpha(I)$ versus intensity for the 10-9 P(10) and the 8-7 P(12) transitions. The theoretical expression[2] at line center is given by

$$\alpha(I, \nu_o) = \alpha_o \frac{\exp\left(\frac{\Delta\nu_c^2}{\Delta\nu_D^2} \frac{I}{I_S}\right) \operatorname{erfc}\left[\frac{\Delta\nu_c}{\Delta\nu_D}(1 + I/I_S)^{1/2}\right]}{(1 + I/I_S)^{1/2} \operatorname{erfc}(\Delta\nu_c/\Delta\nu_D)},$$ (4)

which asymptotically approaches zero as $I \to \infty$. However, as shown in Figure 2.6, the experimental curves level off at about 4-5 W/cm^2. This deviation from the theoretically expected response is attributed to the diffusion of "unsaturated" molecular constituents into the "saturated" region. To compensate for diffusion effects, the elevated gain should probably be subtracted out. Assuming a definition of I_S as that intensity required to reduce the gain to $\sim\sqrt{2/3}$ (Doppler broadening) the corresponding saturation intensities are ~ 1.0 W/cm^2. These measurements were not intended to establish a set of detailed experimental values for the saturation intensity but only to verify previously reported data.[2,3]
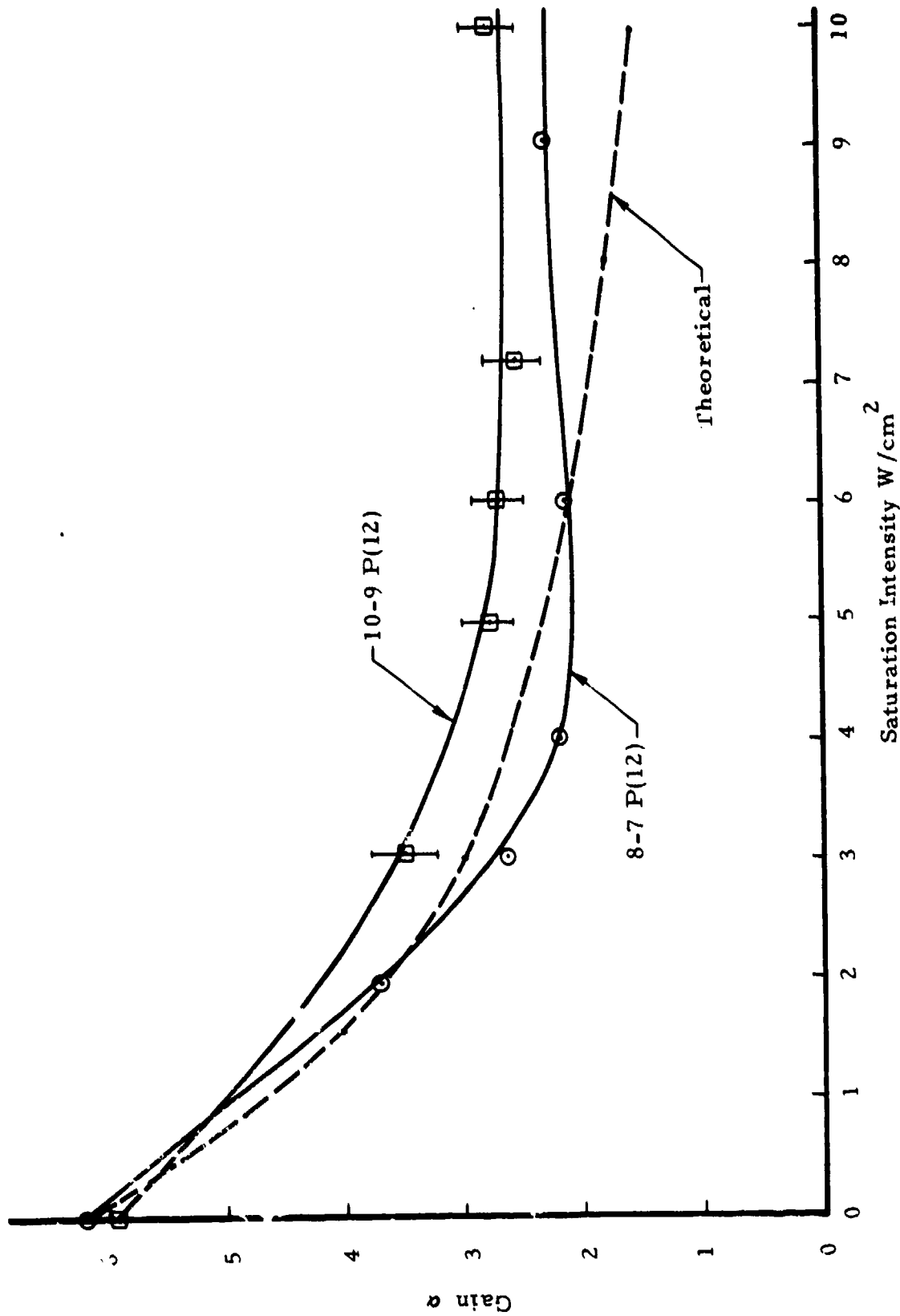
Figure 2.6. (U) Gain vs Intensity (U)

3.0   <u>MODE CONTROL AND RESONATOR DESIGN STUDIES</u> - (G. L. McAllister)

(U) A description of the 3.5µ xenon cw laser used for experimental mode studies was given, along with some of the experimental results of aperture shaping, in the previous report.[5] The results described there were used in designing the unstable resonator optics for the nominal 10-liter device. Preliminary beam diagnostic studies were performed during this reporting period and the results are discussed in Section 4.0. In addition, experimental studies continued with the 3.5µ xenon laser and the results are described below. Numerous mode intensity profiles were measured and the general shapes are always predictable on the basis of a fundamental geometrical optics mode. Also, the mode loss follows N_{eq} as theoretically expected and varies periodically with the intensity at the virtual focus.

3.1   <u>Experimental Mode Shape Studies</u>. (U) The mode intensity profiles

of the xenon laser were observed by making one of the resonator mirrors slightly transmitting and then scanning the output beam past a Ge:Au detector with a rotating mirror. One of the three unstable resonator configurations and the observation p_.nts which were studied are illustrated in Figure 3.1. In addition, the resonator illustrated in Figure 3.1 was studied with coupling through the opposite mirror and finally, a symmetric resonator was studied. A variable-diameter leaf aperture was placed near the mirror opposite the output end and the output mirror was left unapertured. Thus an equivalent symmetric unstable resonator exists as described, for example, by Siegman and Miller[8] so the results can be compared with these theoretical studies.

(U) It was found that the general shape of the mode intensity profile can be predicted by assuming that a fundamental geometrical optics mode exists at the apertured mirror. That is, a uniform intensity spherical phase front appears to emanate from the virtual focus behind the apertured mirror. An effective Fresnel number can then be defined, as shown in Figure 3.2,

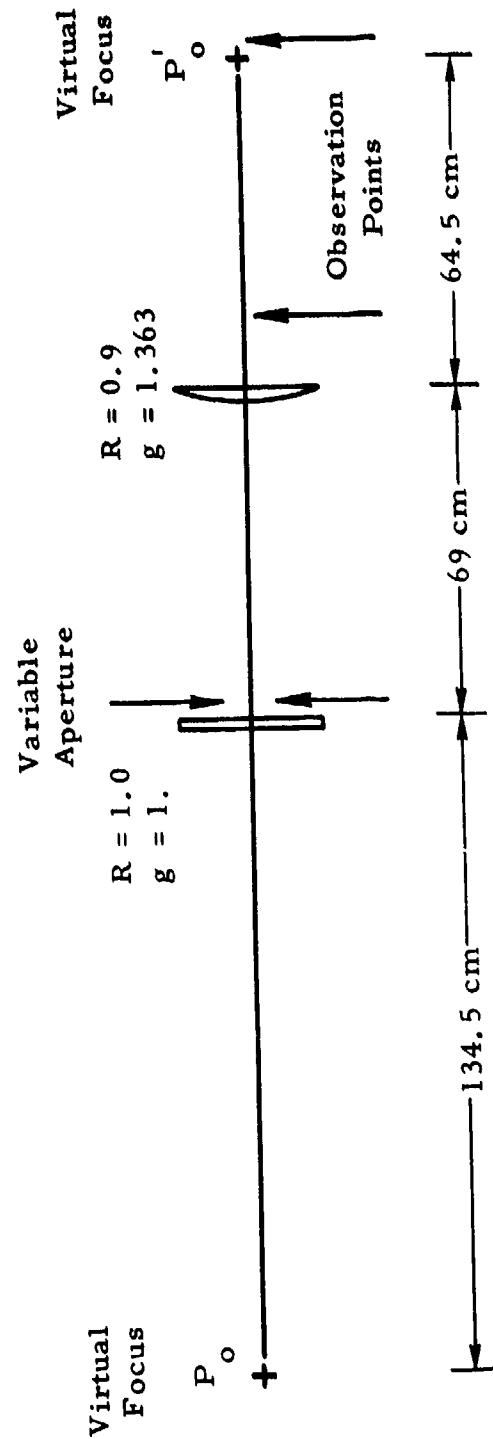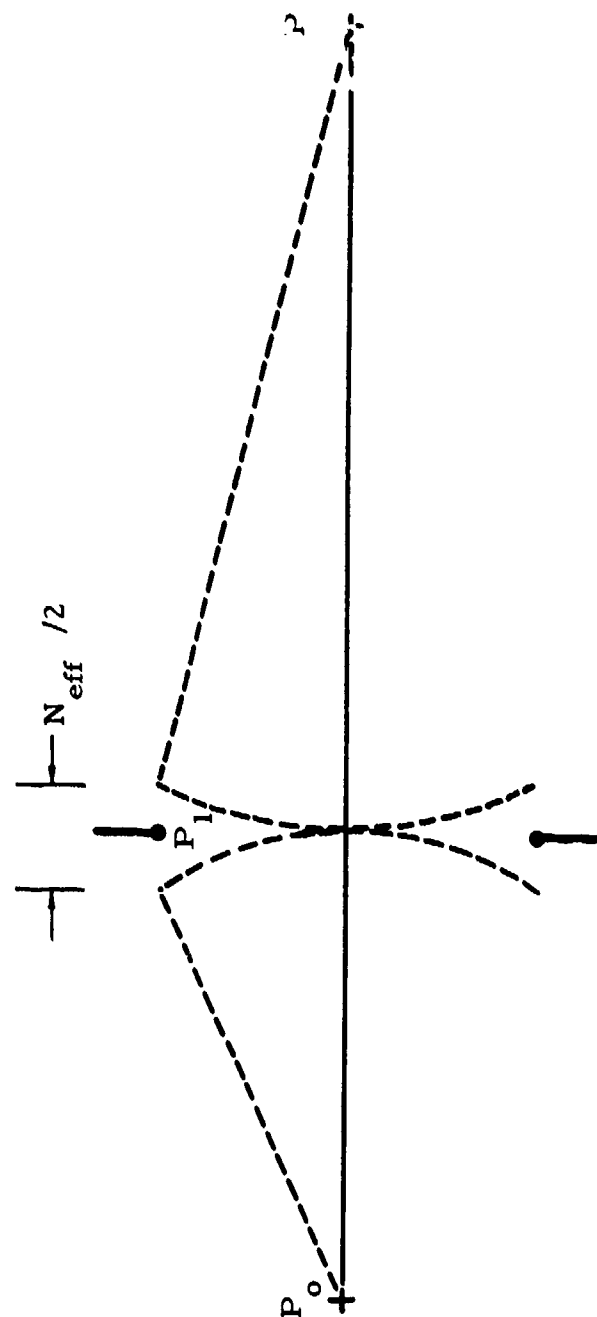Figure 3.1. (U) Cavity Configuration for Mode Observations (U)

Figure 3.2. (U) Schematic Diagram for Computing N_{eff} (U)

to be the number of half wavelengths difference between the path P_oP from the virtual focus P_o to the observation point P, and the path P_oP_1P from the virtual focus to the aperture edge P_1, and then to the observation point. This N_{eff} is just the normal Fresnel number based on a curved phase front.

(U) When a circular aperture is illuminated by a uniform plane wave the total number of bright and dark rings observed is equal to the Fresnel number[9]. Similarly if the mode profile is approximately uniform then the number of bright and dark rings should follow the value of N_{eff}. Equivalently, when the Fresnel number (or N_{eff}) is odd there is an intensity peak on axis at the observation point and when N_{eff} is even there is a null. This is significant because, as discussed below, the resonator loss follows the periodicity of the on-axis intensity at the virtual focus.

(U) The fundamental mode intensity profiles do indeed follow the behavior pattern described above. As the aperture radius is increased (increasing N_{eff}) the number of peaks on the mode profile changes systematically with N_{eff}. Typical mode shapes are illustrated in Figure 3.3. As the distance to the observation point is increased, N_{eff} decreases (for a constant aperture radius) but the behavior is otherwise similar. Figure 3.4 illustrates these results for two observation points, one near the mirror and one near the virtual focus. Note that uniform illumination would result in a straight line with 45° slope. It should be mentioned that the theoretical mode shapes for a medium free cavity show considerable deviations from a spherical phase front and exact correspondence is, therefore, not necessarily to be expected.

(U) From results such as described abov   it is felt that the general mode shapes can be estimated based on geom   :al optics. It may therefore be
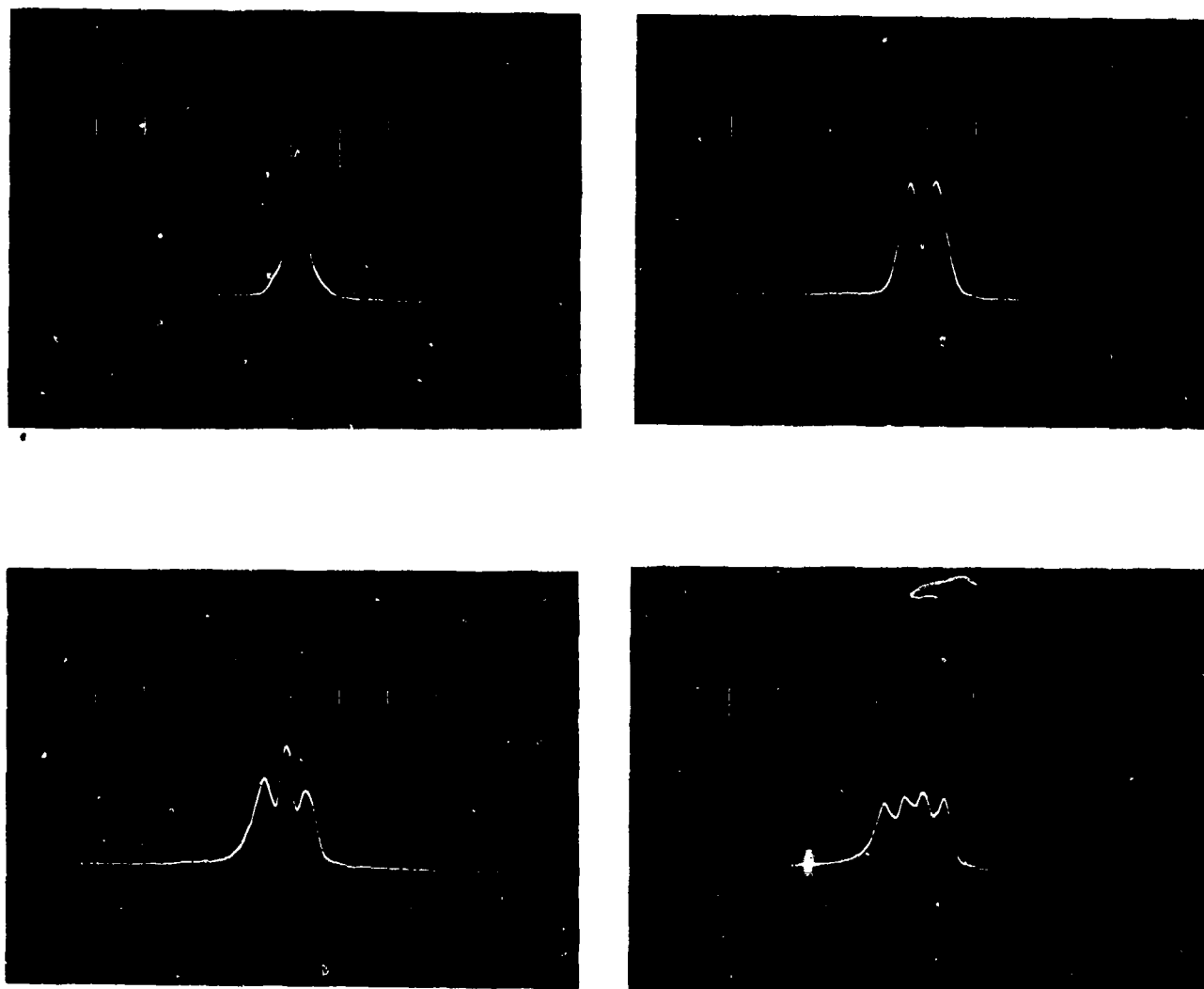
Figure 3.3. (U) Mode Intensity Profiles for N_{eff} = 1, 2, 3, 4. (U)
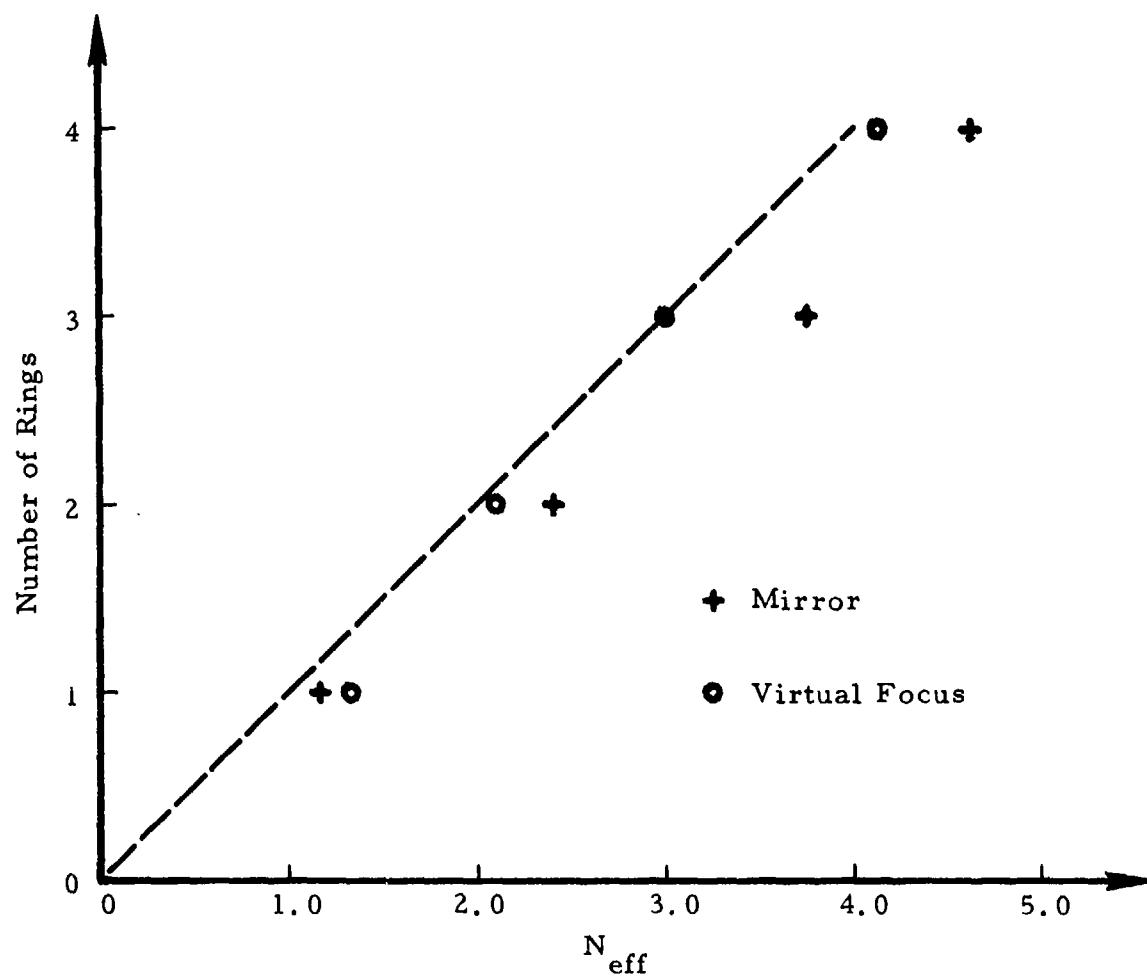
Figure 3.4. (U) Number of bright and dark rings in the mode profiles as a function of N_{eff} (U)

possible to estimate the effects of gain variations or index variations on a mode using these geometrical optics approaches and reduce the numerical calculations needed for parametric mode studies. This approach will be pursued further in the future.

(U) When the observation point is taken to be the same point as the virtual focus then N_{eff} is identical to $2N_{eq}$. That is, except for the factor of two in the definition, N_{eq} is just a normal Fresnel number based on a curved phase front. The importance of this unique point, the virtual focus, has already been pointed out by several investigators (e. g. Reference 10, 11). The diffraction from the sharp mirror edges significantly alters the modes and a criterion for improving the mode shape has been derived based on the diffraction contribution at the virtual focus. We have found that the mode shape at the virtual focus follows $2N_{eq}$ as expected from the discussion above and that the mode loss follows the intensity at this point as discussed below.

3.2 <u>Experimental Mode Loss Studies</u>. (U) Theoretical calculations of Siegman and Miller[8] have indicated that the loss per pass for unstable resonators oscillates in value and the loss curves for all of the dominant modes interleave as N_{eq} is varied. Freiberg, <u>et al</u>[12] have given experimental evidence agreeing with these calculations for the fundamental mode loss. The exact value for the resonator loss was not measured in our experiments; however, the maximum loss points (as a function of N_{eq}) were found by reducing the gain until these points fell below the threshold for lasing. These points occurred near N_{eq} = 1.0 and 2.0 as predicted by the theory and as the laser tube gain is decreased, the region over which lasing will not occur gets larger indicating that a significant change in the loss occurs as N_{eq} is varied.

(U) The mode intensity profiles at the virtual focus beyond the output mirror (see Figure 3.1) also correlate with the loss maxima. Each time the loss reaches a maximum the intensity profile at the virtual focus has an on-axis minimum. Correspondingly, when the loss reaches a minimum, the on-axis intensity at the virtual focus reaches a peak. This is additional evidence that the intensity at the virtual focus is very important in determining the mode properties. Furthermore, it is again suggestive that considerable information about the theoretical modes can be obtained from geometrical optics considerations. As stated above, this approach will continue to be pursued.

4.0 THE NOMINAL 10-LITER LASER SYSTEM -(G. L. McAllister)

(U) The design and construction of the 10-liter device has been described in detail in previous reports along with a discussion of the associated problem areas. During this reporting period solutions to the major problem areas have been achieved and the device has been operated at energies above the 500 J/pulse milestone. In addition, the device has been operated at energies greater than 300 J/pulse with unstable resonator optics and preliminary measurements of the beam quality indicate that it is quite good.

4.1 Laser Modifications.
(U) Arcs behind the Lexan walls which confine the electrical discharge have been a problem and we e discussed in the previous reports. This problem area has been successfully eliminated by eliminating the dead space between these sidewalls and the liquid nitrogen cooled chambers behind them. A second problem area that prevented operation at high sustainer voltages was electrical breakdown through the thin fiberglass cylinders that hold the CaF_2 windows and provide the transition from cryogenic to room temperature. A 3 mil layer of insulating material (Capton) was bonded to the cylinders to improve their dielectric strength and no further breakdown problems have occurred.

(U) The seals for the CaF_2 windows are still a problem area and, after repeated cycling to liquid nitrogen temperature, the seals have a tendency to develop leaks or small fractures in the windows.

4.2 Experimental Results.
(U) After incorporating the above modifications the device was operated with sustainer voltages exceeding 13 kV without failure. The maximum energy obtai ned was 506 J/pulse and numerous pulses were obtained with output energies at approximately the 500 J/pulse level which is one of the program milestones. The

maximum energy was obtained with a $CO/N_2/Ar$ gas mixture at 175 torr in the ratio 1/6.7/10. The sustainer current density was approximately $2A/cm^2$ and the electrical energy input was 1600 J. The resulting conversion efficiency was 32% based on the total volume or, if only the optical extraction volume is considered, the conversion efficiency was 42%. Rather than going to higher energies at this point the unstable resonator optics were installed and preliminary measurements of the beam quality were made.

(U) A confocal unstable resonator with a geometrical magnification of 2.5 was used for the beam quality measurements. The energy extraction for a given set of conditions was at least equal to that for the stable optics and, as expected, depended more sensitively on the electrical pumping rate than the optics used. A typical example of the rise in efficiency with increased pumping rate is shown in Figure 4.1 where the output energy versus input energy is plotted for a 1/6.5 mix of CO/N_2 at 75 torr. As mentioned before, the optical extraction volume was only about 75% of the total discharge volume. Taking this factor into account the conversion efficiency rises from ~15% to 50% as the pumping rate is tripled.

(U) Preliminary measurements of the beam quality were based on the beam patterns in thermofax paper and lucite. The laser output is focused with a 5.5 meter focal length CaF_2 lens onto a diagnostic table as illustrated in Figure 4.2. A small fraction (2.7%) of the incident beam is split off to a Hadron calorimeter so the output energy is measured on each shot. A similar beam splitter is used to reflect 2.7% to the focal plane and the rest of the energy is deposited in a sand-filled dump box.
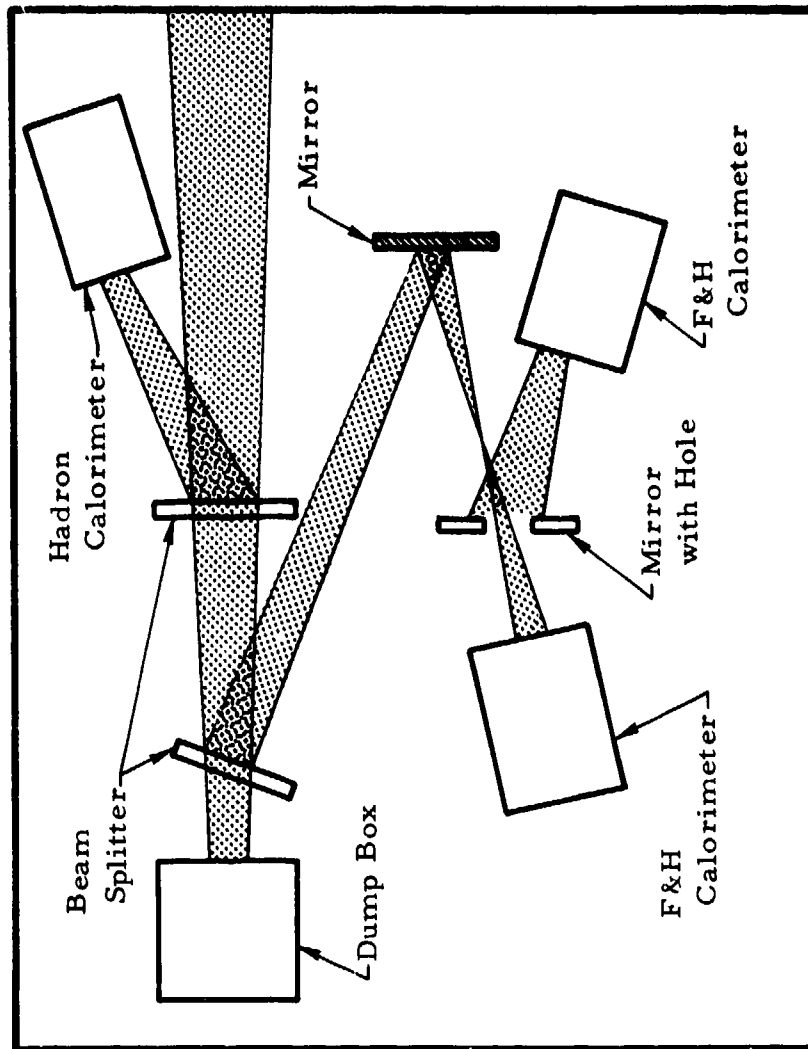
$P_{CO} = 10$ torr
$P_{N_2} = 65$ torr N_2

Input Energy (J)
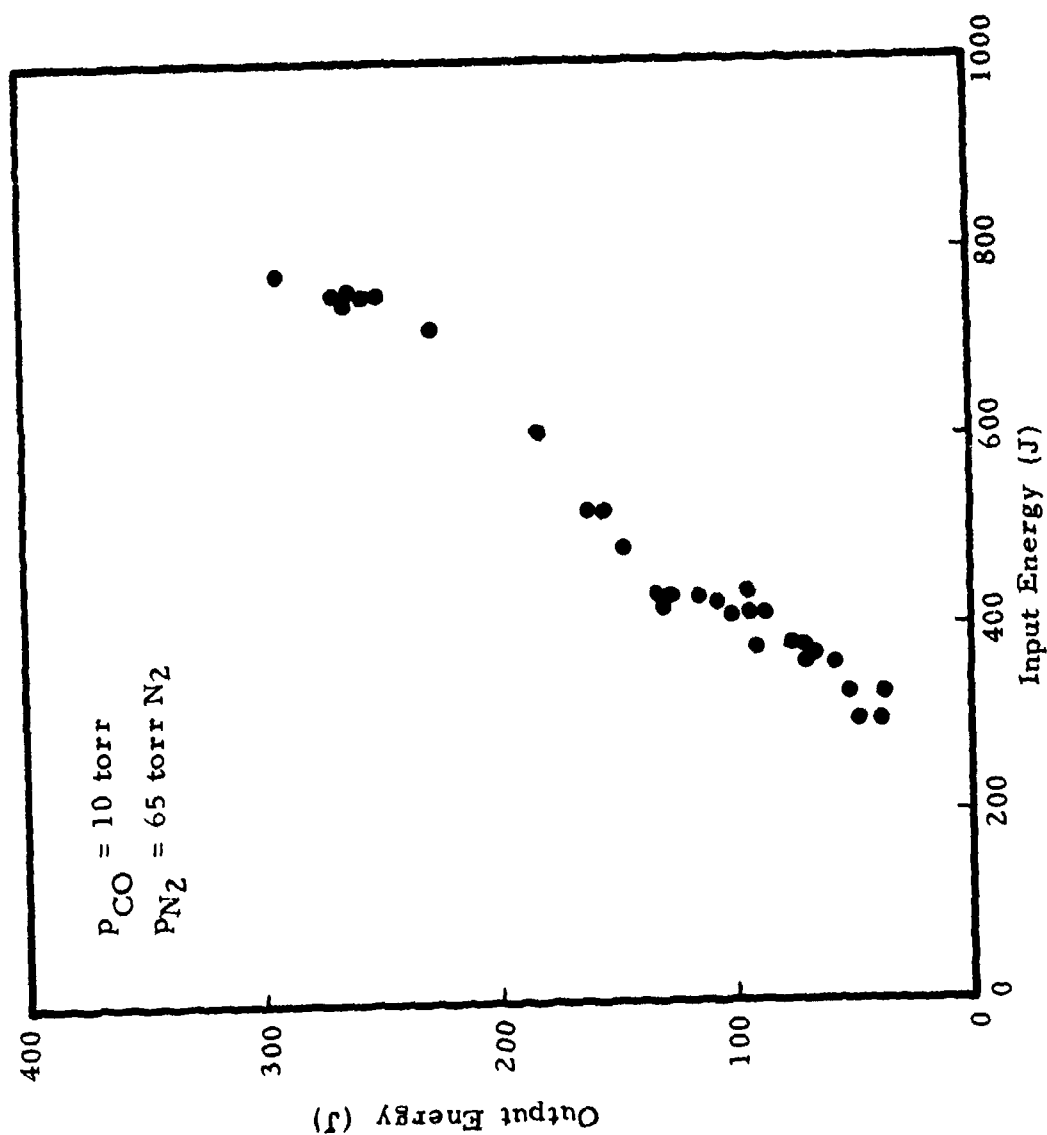
Output Energy (J)

(U) Figure 4.1. Output energy versus input energy with unstable resonator. (U)

(U) Figure 4.2. Beam diagnostic configuration. (U)

(U) The theoretical diameter for the spot size at the focal plane is $D = 0.7$ mm. Experiments with the stable optics indicated, as expected, a very large divergence angle of ~20 mrad which is several hundred times the theoretical diffraction limit. This divergence angle is reduced drastically with the unstable optics and when ~5J pulses are focused on lucite a hole approximately 1.5 mm deep is created with a diameter less than 1 mm as shown with the edge view illustrated in Figure 4.3. A much smaller amount of energy exists at larger radii and the lucite is marked out to a diameter of 1.5 mm. Pulses of 40 J incident at the focus create a much larger burn spot but the depth increases only by a factor of ~2. The resulting flash indicates that much of the energy is absorbed and reflected at this level, and hence, the depth is probably not representative of the energy profile. For energies greater than ~50J the lucite damage reduces, and in air spark which is generated grows in size until, at 150J, it is about 12 inches in length.

(U) The measurements described above are not very quantitative and more accurate measurements are in progress. The "power-in-the-bucket" measurement illustrated in Figure 4.2 has been set up and will be used during the next reporting period. One of the concerns in using this approach is the repeatability of the focused spot location. Burn measurements have shown that the location is consistently repeatable to 0.2 mm or less, which was the experimental resolution of the measurement.
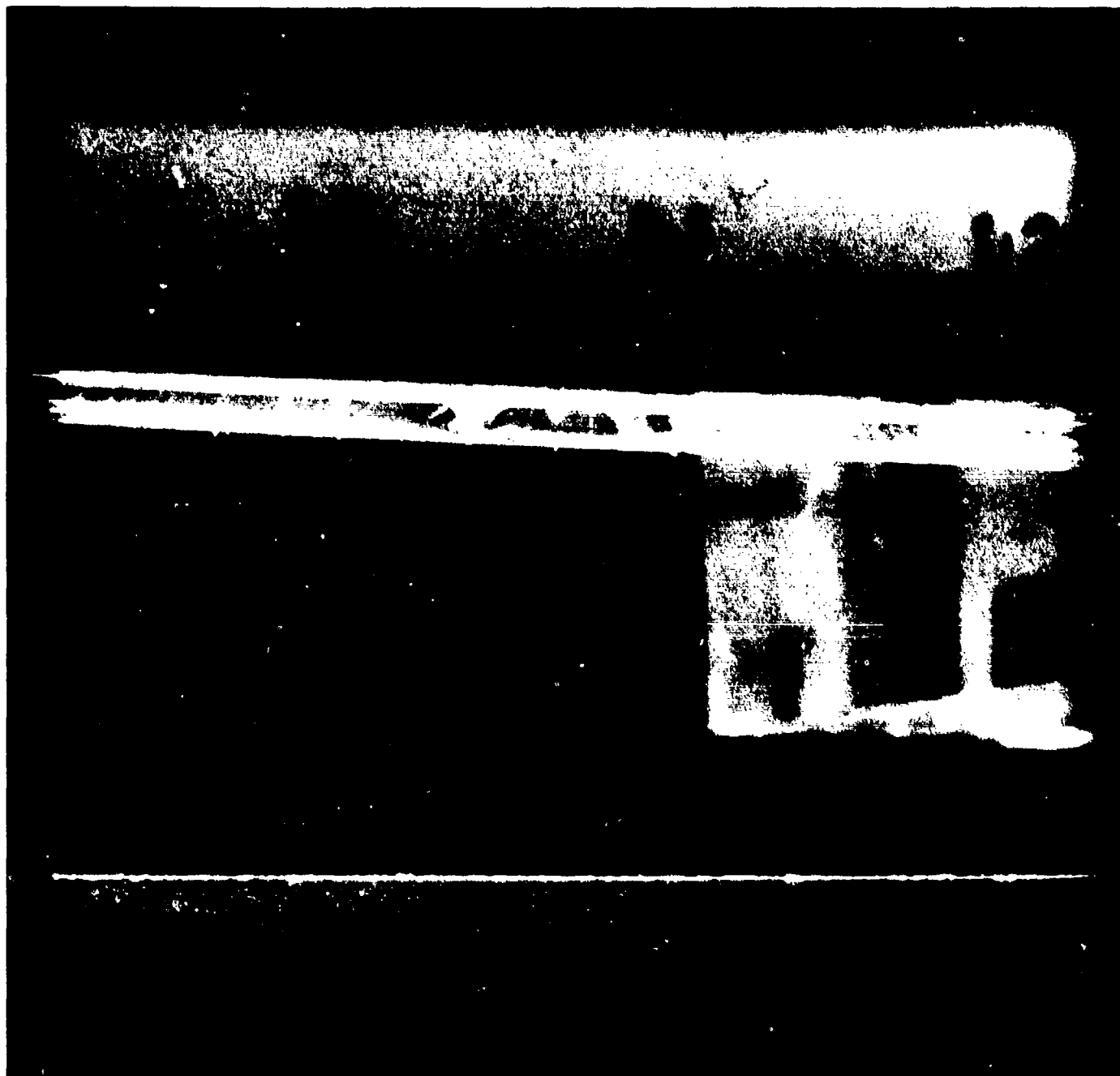
Figure 4.3. (U) Cross-sectional view of focused beam burn
pattern in 1/16" lucite. (U)

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