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Design and Performance of Flowing-Gas Electrical-Discharge CO_2 Lasers

D. T. HODGES and F. B. FOOTE
Electronics Research Laboratory
The Ivan A. Getting Laboratories
The Aerospace Corporation
El Segundo, Calif. 90245

27 December 1978

Interim Report

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Los Angeles Air Force Station
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Los Angeles, Calif. 90009

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This report has been reviewed by the Information Office (OI) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication. Publication of this report does not constitute Air Force approval of the report's findings or conclusions. It is published only for the exchange and stimulation of ideas.

Gerhard E. Aichinger
Project Officer

FOR THE COMMANDER

Frank J. Bane
Frank J. Bane, Chief
Contracts Management Office

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

This report describes the design and construction details of flowing-gas electric discharge CO_2 lasers capable of 750 W TEM_{00} output power in the 10 μm spectral range. Amplitude and frequency stability, lifetime considerations, and general maintenance of the laser are discussed. Detailed engineering drawings, optics requirements, and a parts list are included to facilitate replication.

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SUMMARY

Flowing-gas, single-line, TEM_{00}-mode CO_2 lasers that can deliver up to 50 W per meter of discharge length are described. Long-term amplitude stability of less than 3% P-P is observed and operating lifetimes approaching 1000 hr are possible with proper care. Frequency stability of a few MHz has been measured, and with adequate isolation from environment perturbations, the stability should be less than 2 MHz without dynamic feedback.

PREFACE

The authors acknowledge the valuable technical assistance of Mr. R. D. Reel and thank M. L. Lachuk for his assistance in the preparation of Appendix A.

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CONTENTS

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FIGURES

I. INTRODUCTION

The design features and performance characteristics of flowing-gas, single-mode CO_2 lasers constructed in the Electronics Research Laboratory are discussed (Fig. 1). The specific parameters of this design are dictated by a desired cw output power and beam quality of 50 W in a far-field Gaussian (TEM_{00}) mode. For most electric-discharge CO_2 lasers,[1,2] a gas mixture of CO_2:N_2:He (2:3.4:10) at a pressure of 10 to 50 Torr is flowed longitudinally through a water-cooled cylindrical precision-bore pyrex tube and excited by a high-voltage longitudinal dc discharge. This configuration is capable of generating greater than 50 W cw (TEM_{00}) of P(20) 10.6-μm laser power per meter of discharge length at an overall efficiency of greater than 10%, or 550-W pulses of 150-μsec (FWHM) duration in the same mode also at an overall efficiency greater than 10%. If a dispersive element is included in the laser cavity, any one of approximately 100 separate vibrational-rotational transitions can be selected in the 9 to 11-μm spectral region. However, for any particular line, the power generated per unit length scales approximately as the small signal gain of the particular line relative to the P(20) 10.6 μm line; this distribution is shown in Fig. 2.

[1] P. K. Cheo, "CO_2 Lasers," in Lasers, Vol. 3, eds., A. K. Levine and A. J. DeMaria, Marcel Dekker, Inc., New York (1971).

[2] D. C. Tyte, "Carbon Dioxide Lasers," in Advances in Quantum Electronics, ed., D. W. Goodwin, Academic Press, New York (1970).

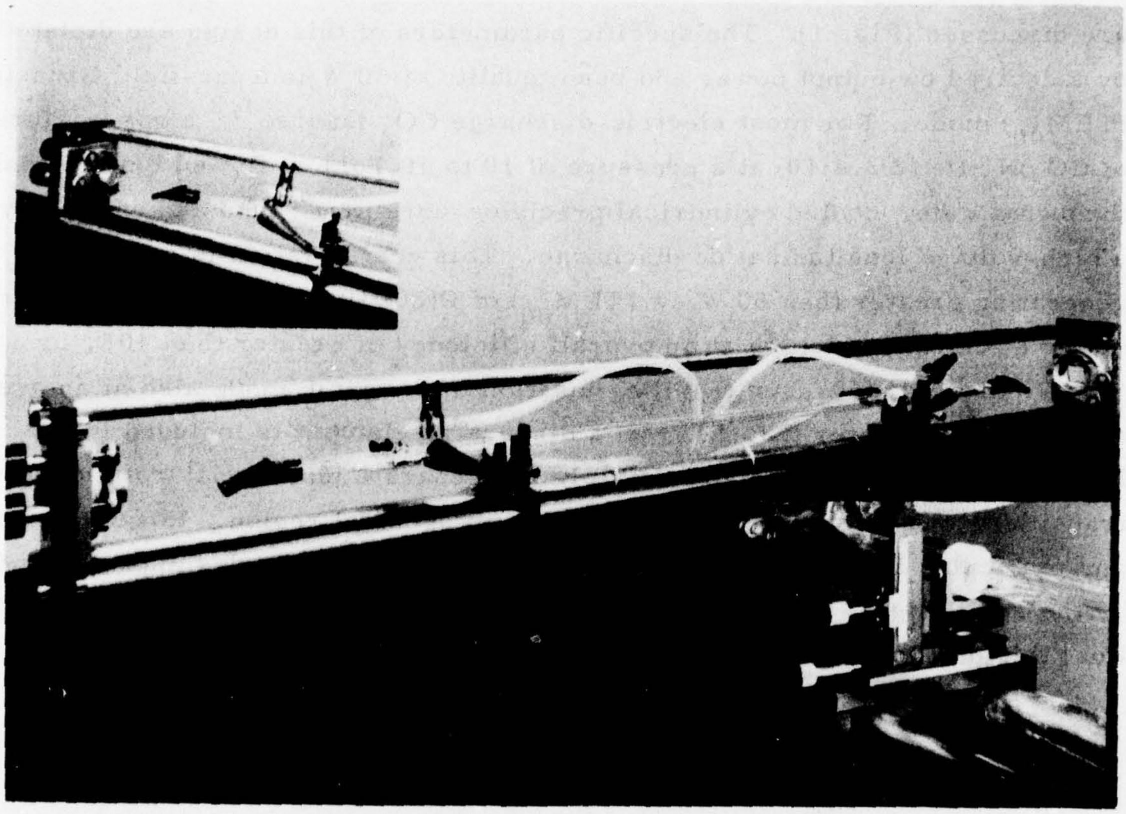

Figure 1. Typical CO_2 Laser as Assembled in the Laboratory. Upper insert, the PZT and front reflector mounting; lower insert, the modified microscope slide stage used as a tube mount adjuster. The main cavity is a rigid structure composed of two end plates and 1-in. diam. Invar rods about 50 cm longer than the planned pyrex discharge tube length.

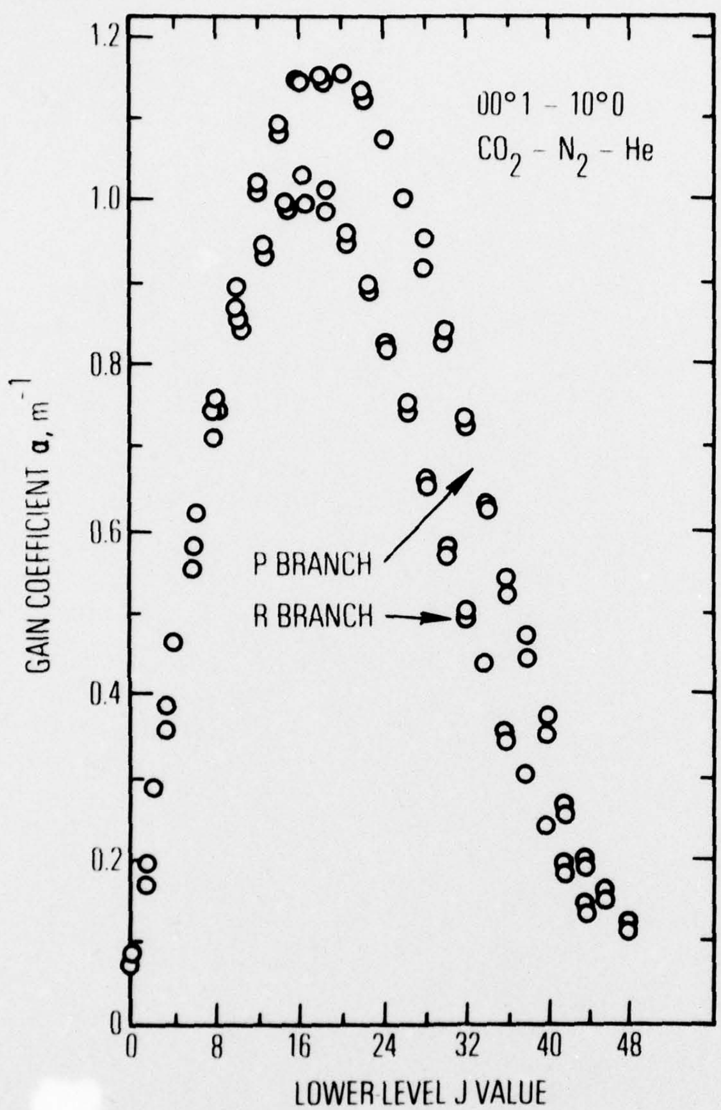

Figure 2. Gain Distribution for Individual Vibrational-Rotational Transitions in P and R Branches of 00°1-10°0 (9.6 μm) Band[1]

II. DESIGN GUIDELINES FOR SINGLE-MODE OPERATION

The intensity profile, or mode, of the CO_2 laser is determined by the dimensions of the discharge tube and the optical cavity parameters. The transverse dimensions of the laser modes are a function of wavelength, the radii of curvature of the optical-cavity elements, and the cavity length. Since the radial dimension of the TEM_{mn} modes increases with the mode numbers m and n, the proper choice of tube diameter will eliminate all but the lowest order mode TEM_{00}. Selection of the laser cavity optics is straightforward. If the CO_2 laser is to operate on selected vibrational-rotational transitions, a diffraction grating is usually included as one of the cavity elements. In the Littrow configuration, the diffraction grating behaves as a flat mirror, and the partially transmitting output mirror is chosen with a spherical surface to give a stable optical cavity with tolerance to angular misalignment. The radius should exceed the cavity length; radii values of 4 to 10 m are standard with CO_2 laser optics suppliers. The mirror mounts have angular adjustment capabilities of several deg for the correction of angular misalignment.

The optical cavity formed from a flat mirror and spherical mirror is referred to in the literature as a half-symmetric cavity. The diffraction losses for the various modes have been calculated by Li[3] for a wide range of bore diameters, cavity lengths, and mirror radii; the pertinent curves have been reproduced in Fig. 3. A desired maximum cw output power of approximately 50 W dictates that the discharge tube length be approximately 1.0 m or greater and the optical cavity length to be approximately 1.5 m in order to accommodate the Brewster-angle windows and an intracavity work space. After the selection of a value for the radius of curvature of the output mirror (10 m is typical), the bore diameter is established from the diffraction loss necessary to suppress modes other than the TEM_{00}. The loss is expressed as a function of Fresnel number $N = d^2/4\lambda L_c$, where d is the discharge tube

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[3] T. Li, "Diffraction Loss and Selection of Modes in Maser Resonators with Circular Mirrors," <u>Bell Syst. Tech. J.</u> <u>44</u>, 917 (1965).

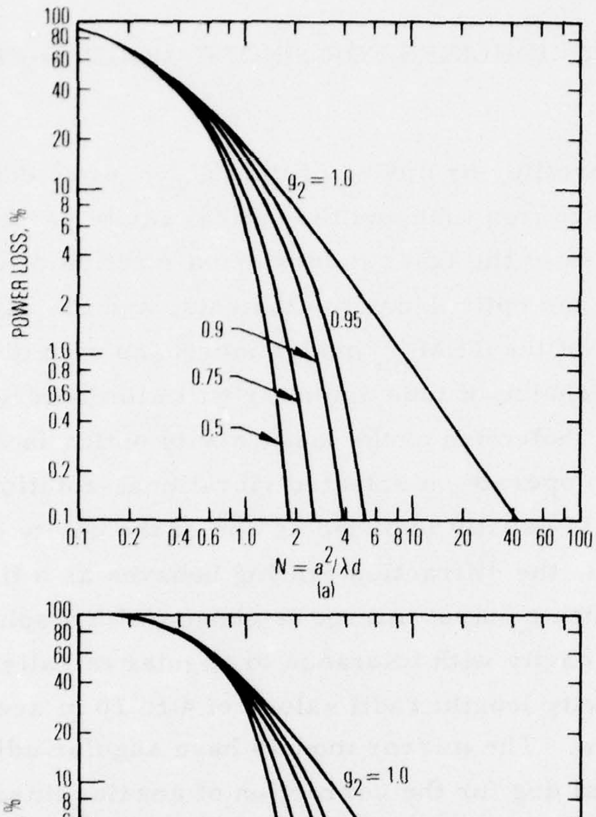


Figure 3. Power Losses as a Function of Fresnel Number for TEM_{00} (a) and TEM_{01} (b) Modes. These curves are computed for the half-symmetric cavity, $g_1 = 1$, $g_2 = 1 - Lc/R_2$, where L_c is the cavity length and R_2 is the mirror radius.

diameter, λ is the laser wavelength, and L_c is the optical cavity length. The design parameters and performance characteristics of a series of lasers constructed in accordance with the above guidelines are summarized in Table 1. At present, there is a considerable amount of literature on CO_2 lasers,[1,2] which includes data on the optimum operating relationship between current, pressure, and bore diameter. The curves given in Fig. 4 reflect the optimum operating conditions observed for our CO_2 lasers.

The observed mode pattern from the CO_2 lasers described in Table 1 confirms the fact that, for a smooth, concentric bore, most of the energy is, indeed, contained in a central lobe with a Gaussian distribution in the far-field. A typical mode scan is shown in Fig. 5. Close to the output mirror (within 0.5 m), however, there is considerable structure in the mode pattern, as observed on a thermal image plate. (It is surprising that the intensity profile transforms so quickly into a single Gaussian lobe at distances greater than 0.5 m from the output mirror. This particular feature of "single-mode" CO_2 has been noted elsewhere, but a definitive experimental study has not yet been published.) Imperfections and slight bends in the glass bore will tend to produce mode distortion with increased losses at the walls, which results in a lower power output and, possibly, a shortened tube life. Mode patterns are also distorted by the use of ZnSe Brewster angle windows with large amounts of optical wedge. Windows should have a maximum optical wedge of less than 30 arc sec for a laser 1 to 2 m in length to minimize this effect. Window specifications are given in Appendix B, and wedge determination methods are described in Appendix C.

The water-cooling requirement is best satisfied with high-impedance (750 Ω-cm) water flowing at $\sim$2 liters/min at $\sim$25°C. (Any other cooling system used as a substitute must be able to dissipate $\sim$600 W of power.) Low-impedance water may be used, but is not recommended because it can drastically shorten the discharge tube life, as noted in Section IV.

Table 1. Typical Parameters for a Variety of CO_2 Lasers, Constructed in The Aerospace Corporation Electronics Research Laboratory. A half-symmetric cavity is used for all the lasers.

L_c, cm	L_d, cm	d, mm	L_d/d, cm	$N = \frac{d^2}{4\lambda L_d}$	I_{opT}, ma	Tube Voltage, kV	P_{in}, W	P_{Torr}	P_{out}
137	81	7.0	116	0.9	28-30	13	~400	30	40 W, 10 mR/c, 65% R, P(20) 10.6, flat hr
175	81	8.0	100	0.9	25			~25	{40 W, P(20) 9.6, / 25 W, P(36) 9.6,} 10 mR/c, 60% R, grating
175	107	8.0	134	0.9	30	15	450	30	65 W, 10 mR/c, 65% R, flat hr
175	107	8.0	134	0.9	30	15	450	30	50 W, 10 mR/c, 65% R, grating
200	137	8.5	161	1.32	20	18	.475	28	55 W, 10 mR/c, 60% R, P(36) 9.6, grating

L_c = cavity length
L_d = discharge length
d = plasma tube diameter
N = Fresnel number
I_{opt} = optimized current
P_{in} = wall-plug power
P_{Torr} = optimum gas pressure
P_{out} = output power with notes on reflectors

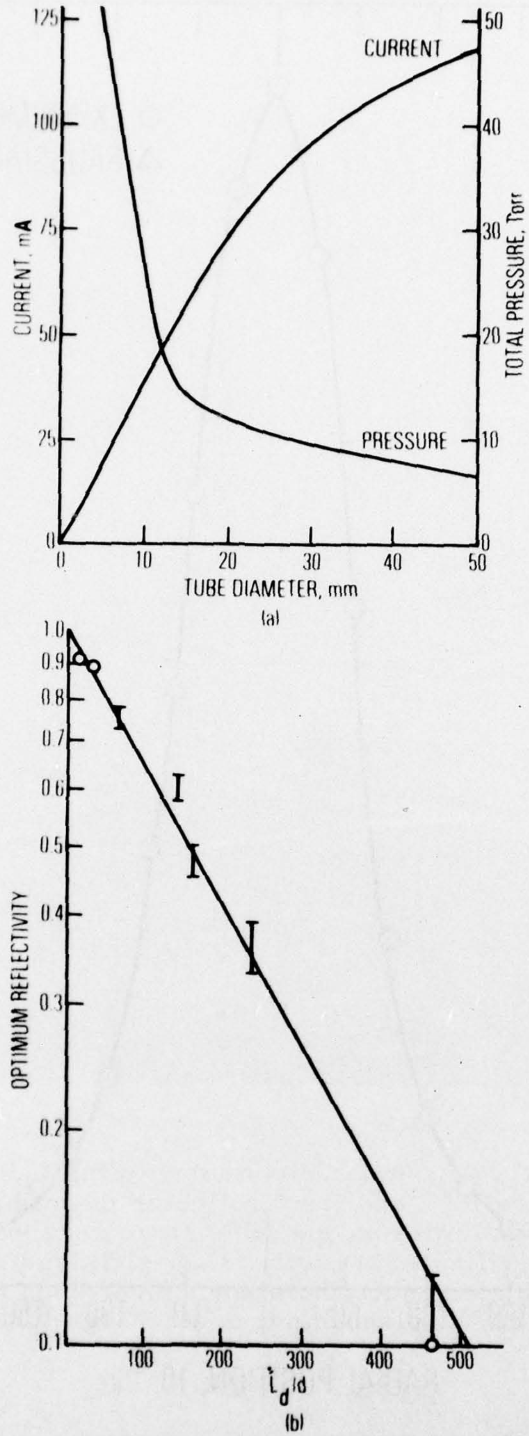


Figure 4. Operating Parameters for CO_2 Laser. For a tube diameter of 8 mm, a pressure of ~ 30 Torr and current of ~ 25 mA are optimum. For L_d of 80 cm and d of 0.8 cm, optimum reflectivity of the front partial output coupler is 60%.

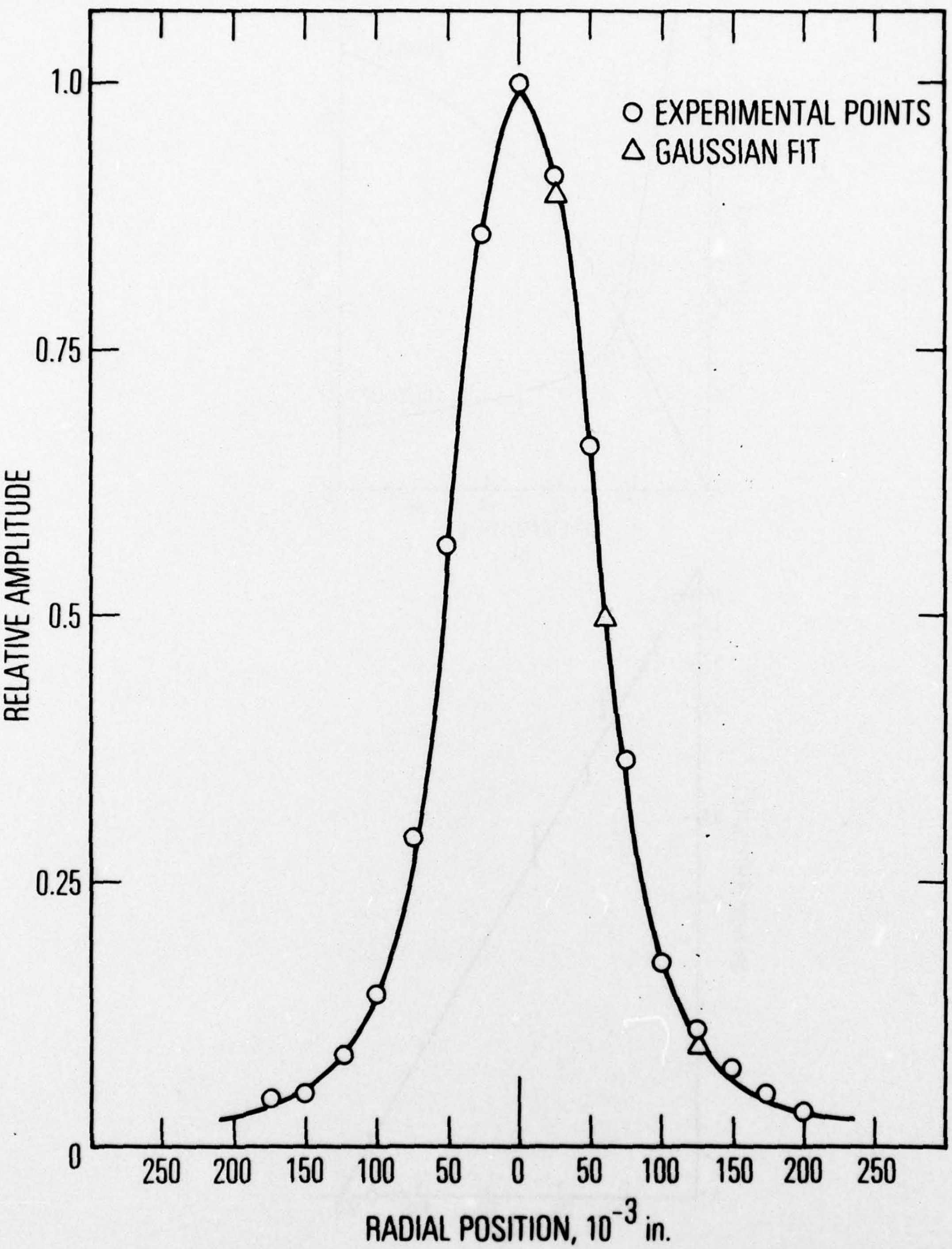


Figure 5. **Intensity Profile of 40-W Beam Across Beam Waist at ~1 m from Output Mirror. A 7-mm-diam tube with an active region of 81 cm was used. L_c was 1.4 m.**

III. LASER AMPLITUDE AND FREQUENCY STABILITY

In addition to output power and mode quality, the amplitude and frequency stability of the laser output are of fundamental importance. The long-term frequency stability is governed by thermal drift and distortion, which can be reduced by the use of low expansion materials such as Invar (for spacing the mirror mounts), the use of such low-absorption infrared materials as ZnSe ($\alpha \lesssim 0.005$ cm) for the Brewster angle windows and mirror substrates, and regular cleaning of optics exposed to high-energy fluxes (Appendix B). Our lasers, which were constructed with Burleigh end plates and mirror mounts assembled on 1-in.-diam Invar rods, operated with fluctuations of less than 3% P-P for tens of minutes without any adjustment. With periodic cavity length tuning by a piezoelectric translation (PZT) element, this stability was maintained for hours. A sample output stability recording is shown in Fig. 6. Encouraged by the amplitude stability, two lasers were heterodyned with a Cu:Ge photoconductor used as a mixer. Each laser operated on a single line [P(20) 10.6-μm band] at approximately 30 W. The total frequency excursion of the beat was approximately 10 MHz in a 20-sec period. The distribution of beat frequencies, however, was clearly bunched with a 1σ of approximately 4 MHz (Fig. 7). By controlling each laser with the PZT, one can maintain this beat-frequency excursion, or jitter, indefinitely. Refinements, such as using a pump ballast on the laser tube and acoustically isolating the optical table (by air suspension), did not appear to reduce the jitter, a result that is somewhat surprising. The jitter can be reduced by sealing the laser cavity to isolate it from air currents and dust in the room. Also, a dedicated, temperature-controlled cooling system would provide a better environment for reduced jitter. These improvements should be incorporated in any serious attempt to frequency stabilize in-house fabricated CO_2 lasers.

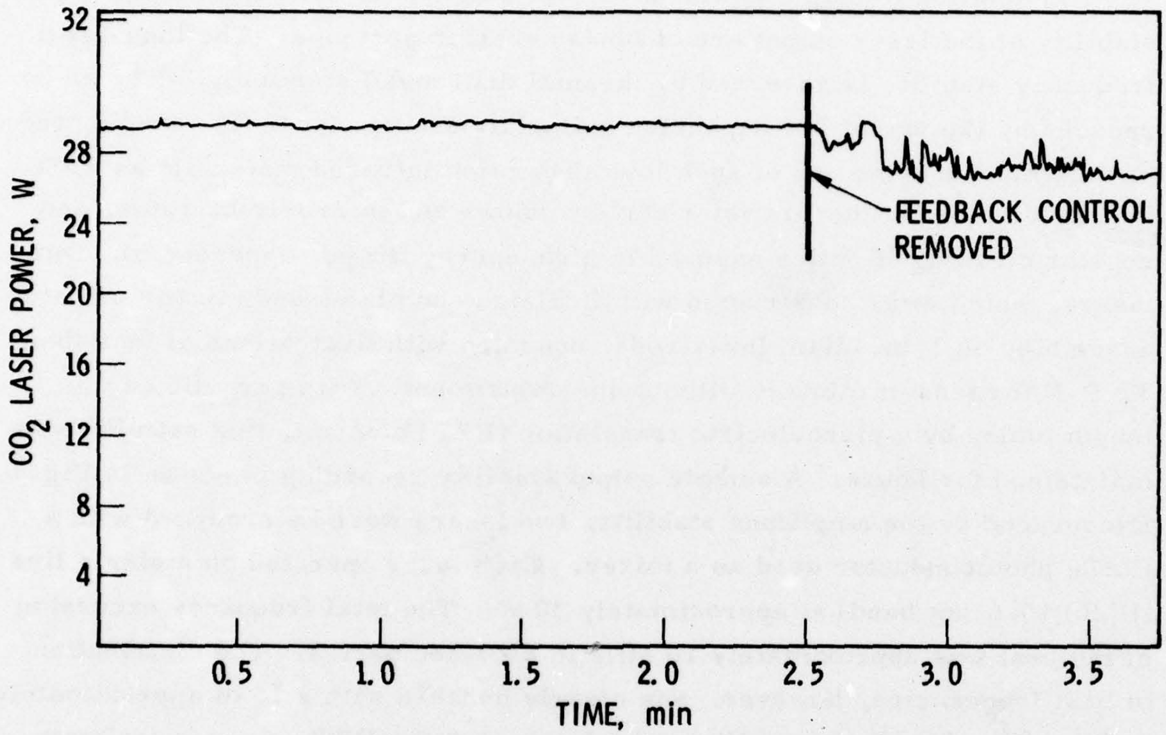


Figure 6. **Output Power Stability for Extended Periods with Active Feedback Loop Used to Control PZT. Removal of the feed-back control precipitates immediate drift in the power and frequency. Fluctuations of <3% P-P are achieved with active feedback methods.**

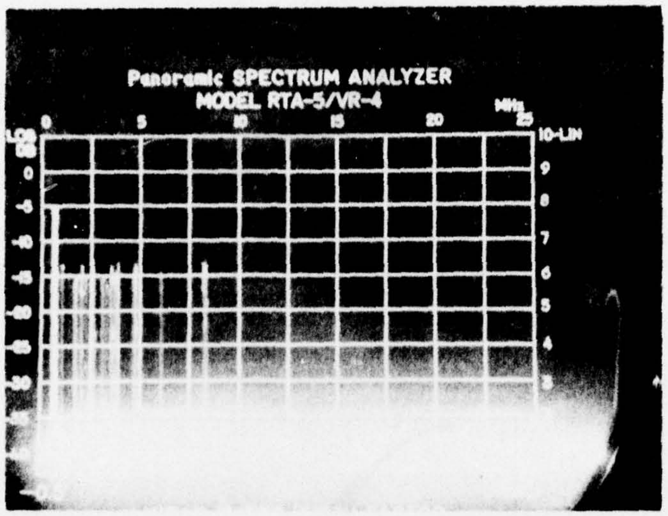


Figure 7. Heterodyne Spectrum of Two Free-Running CO_2 Lasers Operating at 30-W Level. Frequency stability of each laser appears to have a standard deviation of less than 5 MHz over a one-minute period.

IV. LIFETIME CONSIDERATIONS

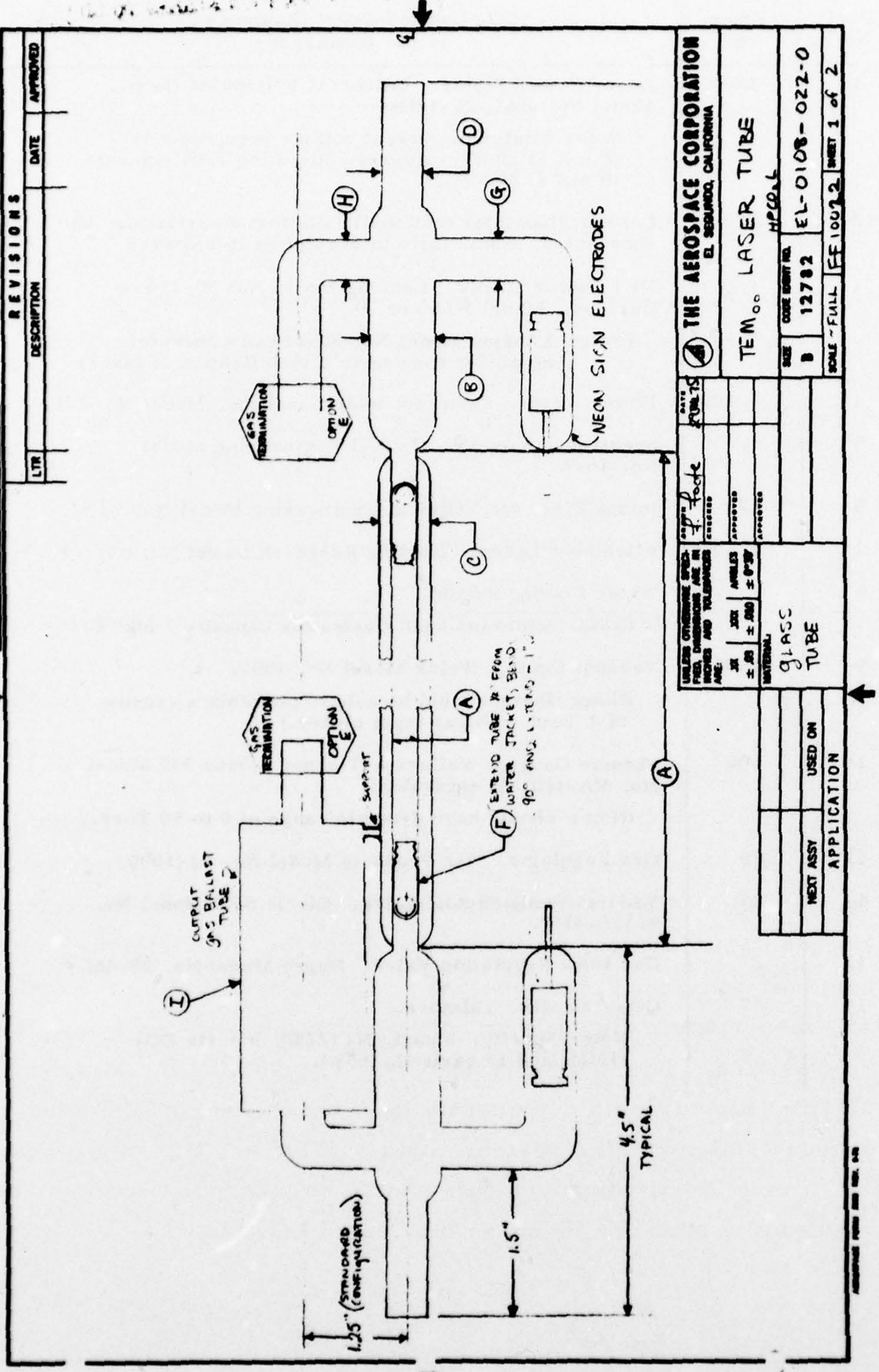
The normal lifetime of the lasers depends heavily on the care and attention they receive. With daily cleaning of the ZnSe optics and daily mirror alignment, more than 100 hr of service between grating cleanings is typical. (A grating should be removed and washed when it becomes too hot to touch while the laser is running. ZnSe windows and reflectors should be removed and replaced when pitted or scratched, usually evident by diffraction of the central spot.) The tube life can be jeopardized by use of low-impedance cooling water because breakdown can occur between the gas at high voltage and the water jacket through the glass ring seals. Also, air cooling the electrodes will help prevent excessive thermal stress.

APPENDIX A. ENGINEERING DRAWINGS AND PARTS LIST

Part No.	Quantity	Price, $	CO_2 Parts List
1	1	~200	CO_2 Laser Tube. In-house manufactured. (Refer to Aerospace Drawing No. EL-0108-022-0.)
2	4	12/ft	Invar Rod. Approx. 6 to 7-ft lengths 1-in. diam. Allen Fry Steel Co. or Carpenter Steel
			Note: The length of the rod is dependent upon length of CO_2 discharge tube. Specify length of rod in feet. Add 1.5 ft to discharge tube length.
3	2	90 ea	Rod Plate. Burleigh Instruments SG-309.
4	2	215 ea	Star Gimbal Mounts. Stainless. Burleigh Instruments SG-201.
5	2	37 ea	Short Clamp Bar. Burleigh Instruments SG-320.
6	1	42	Long Clamp Bar. Burleigh Instruments SG-321.
7	1	385	PZT Aligner-Translator. Burleigh Instruments PZ-80.
8	1	37	2-in. Mounting Adaptor for PZ-80. Burleigh Instruments PZ-80-1
9	2	60 ea	Precision Mechanical Stage. McBain Instruments or Edmund Scientific.
			Note: Specify 27 by 30-mm travel with 30-mm axis worm gear.
10	2		Laser Tube Mounting Assembly. In-house manufactured. (Refer to Aerospace drawings EL-0108-109-0, EL-0108-095-0, EL-0108-053-1, and EL-0108-047-1.)
			Part No. EL-0108-109-0 is designed to match a bolt hole pattern on the precision mechanical stage, Part No. 9 on this list. Since stages vary even with the same supplier, some modification of drawing EL-0108-109-0 may be necessary between shipments of stages.
11	2		Brewster Angle Window Assembly. In-house manufactured. (Refer to Aerospace drawings EL-0108-100-0, EL-0108-101-0, and EL-0108-102-0.)

Part No.	Quantity	Price, $	CO_2 Parts List (Cont.)
12	2	165 ea	ZnSe Brewster Angle Windows. II-VI Inc., Glenshaw, PA 1.820 by 0.700 by 0.080 in. with less than 12 arc sec mechanical wedge.
13	1	230	ZnSe Output Coupler. I"-VI Inc. 60% reflective at 10.6 μm, 1.000-in. diam by 0.120 in. thick.
14	1	600	Master Metal Grating. PTR Optics, Inc. ML303 or Perkin Elmer. Note: Specify 75 Groves/MM, Blaze for peak reflectivity 9.6 to 10.6 μm perpendicular polarization.
15	1		Grating Adaptor to Burleigh Gimbal Mount. *In-house* manufactured.
16	4	3.00/12	Parker O-Ring 2-026
17	4	3.00/12	and 2-206

	Part No.	Price, $	CO_2 Laser Support Equipment (1 ea. Required)
	1	1500	Laser Power Supply. Universal Voltronics Corp., Model No. BAL-20-125A Note: Minimum current voltage requirements = 40 mA at 20 kV. Average operating requirements = 30 mA at 20 kV.
	2	500	Current Regulator (optional). Ballast resistor may be substituted. Some form of regulation is required.
	3	1,200	PZT Power Supply. Lansing Model No. 80-214 or Burleigh, Model PZ60 or 70 (Note: Lansing Model No. 80-214 is a lock-in amplifier for dynamic stabilization of laser)
	4	1,400	Power Meter. Coherent Radiation Labs, Model No. 201.
Optional Items	5	1,250	Spectrum Analyzer. Optical Engineering Model No. 16-A.
Optional Items	6	173	Image Plate Kit. Optical Engineering Model No. 22-K.
Optional Items	7	1,500	Alignment Laser. Lansing Research Model No. 35-101.
Optional Items	8		Water Cooling System. (Note: Minimum heat dissipation capacity = 600 W.)
	9	1300	Vacuum Pump. Welch Model No. 1397. (Note: Pump should be able to maintain a vacuum of 1 Torr with gas input closed.)
	10	300	Vacuum Gauge. Wallace & Tiernan Series 300 Model No. FA-160, or equivalent. (Note: should have dynamic range of 0 to 50 Torr.)
	11	70	Gas Regulator. Air Products Model No. 02-1000.
	12	25	Vacuum Pump Shutoff Valve. Circle Seal Model No. 9232B-4PP.
	13	27	Gas Flow Regulation Valve. Nupro Model No. SS-4M
	14	37	CO_2 Gas Mix. Gilmore. Note: Specify: 5 parts N_2 (22%), 3 parts CO_2 (13%), and 15 parts H_e (65%).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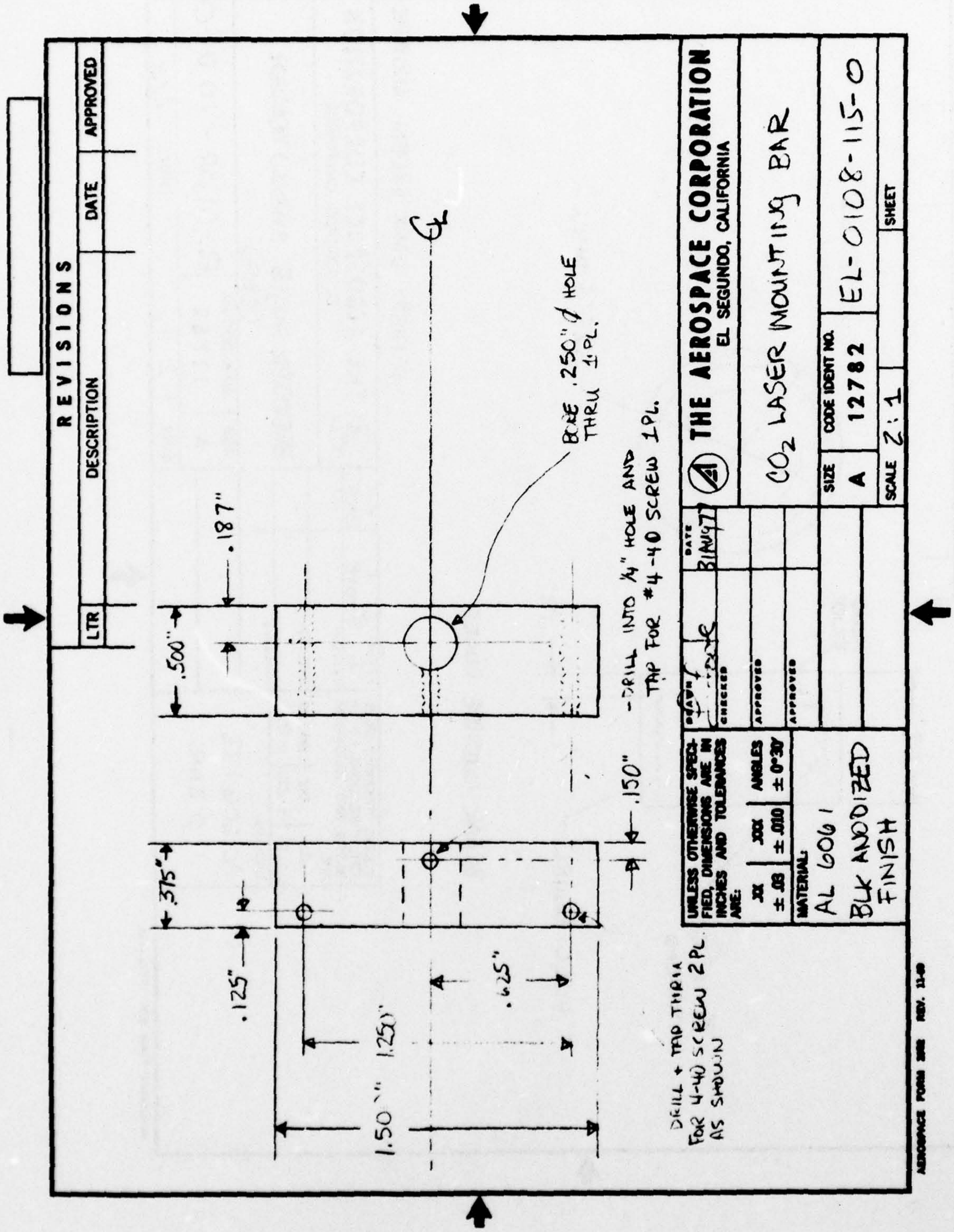
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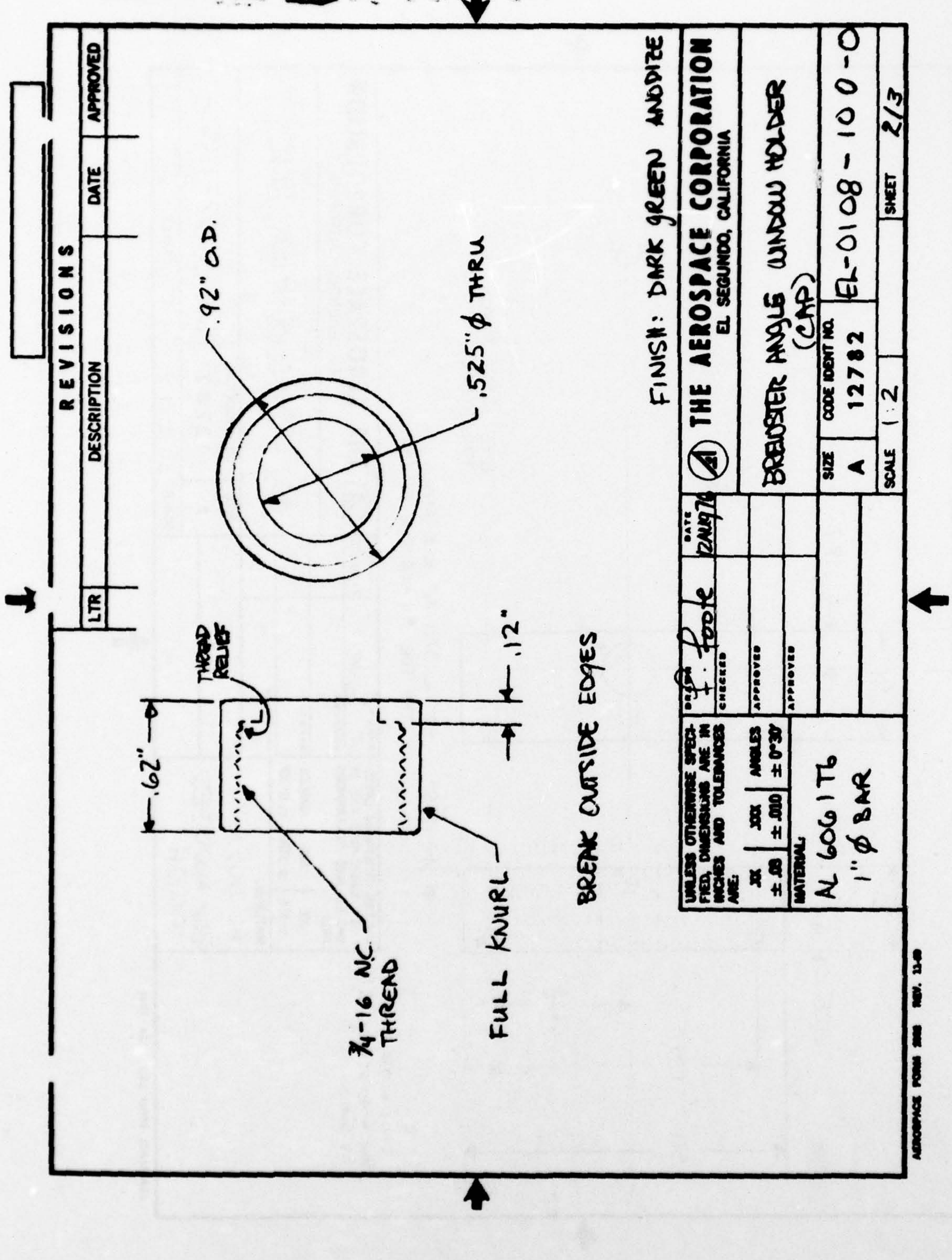
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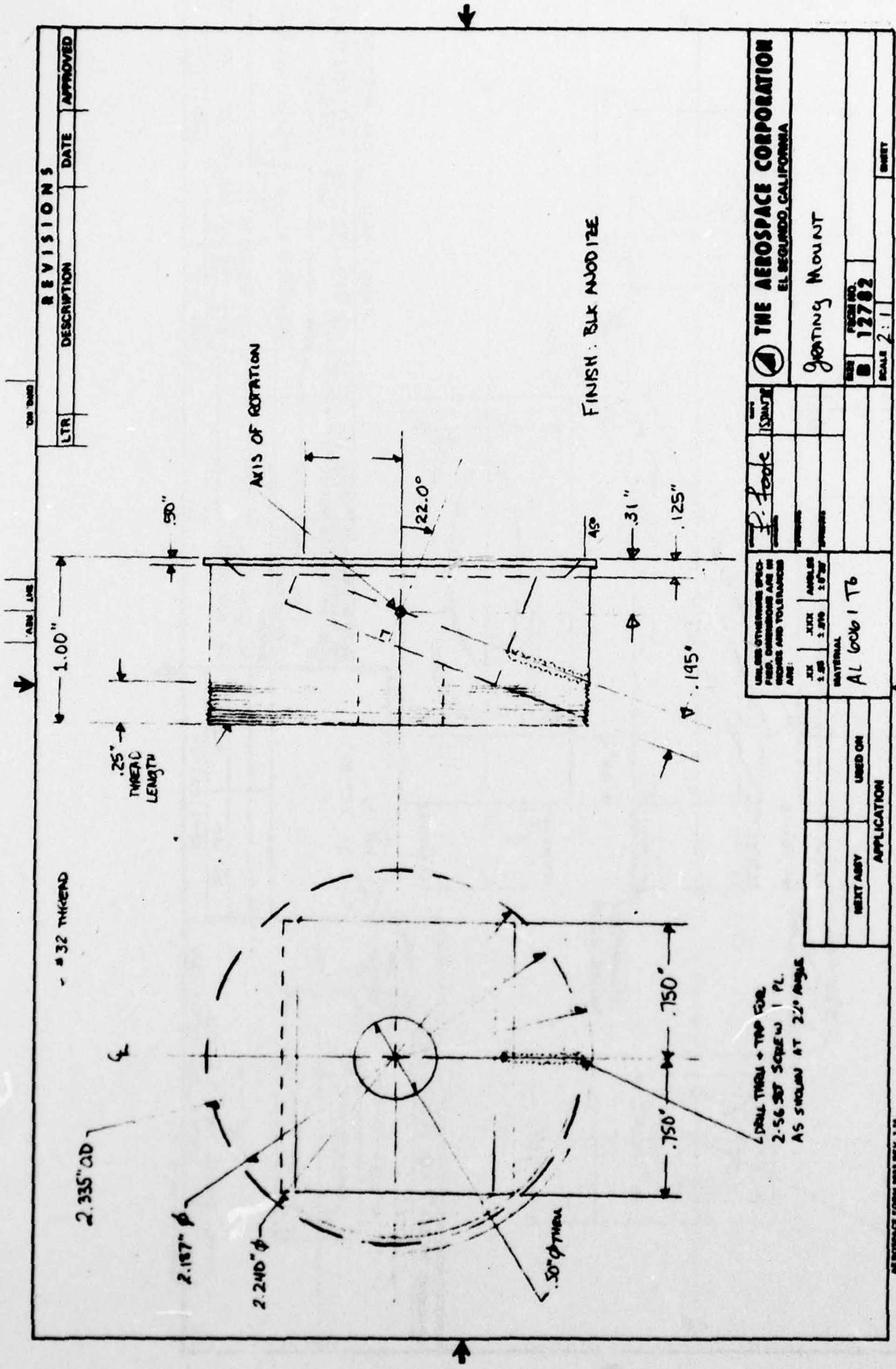

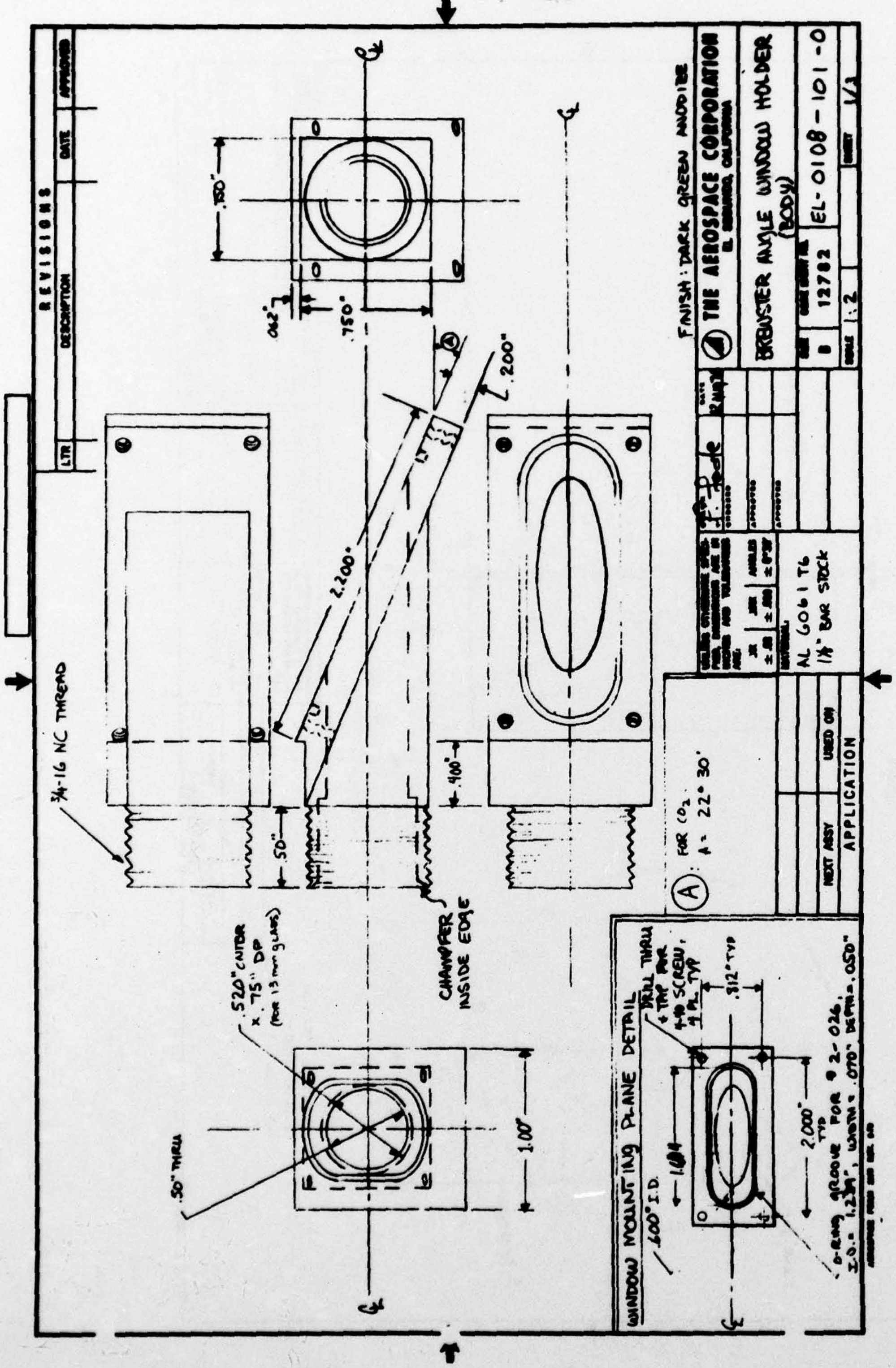
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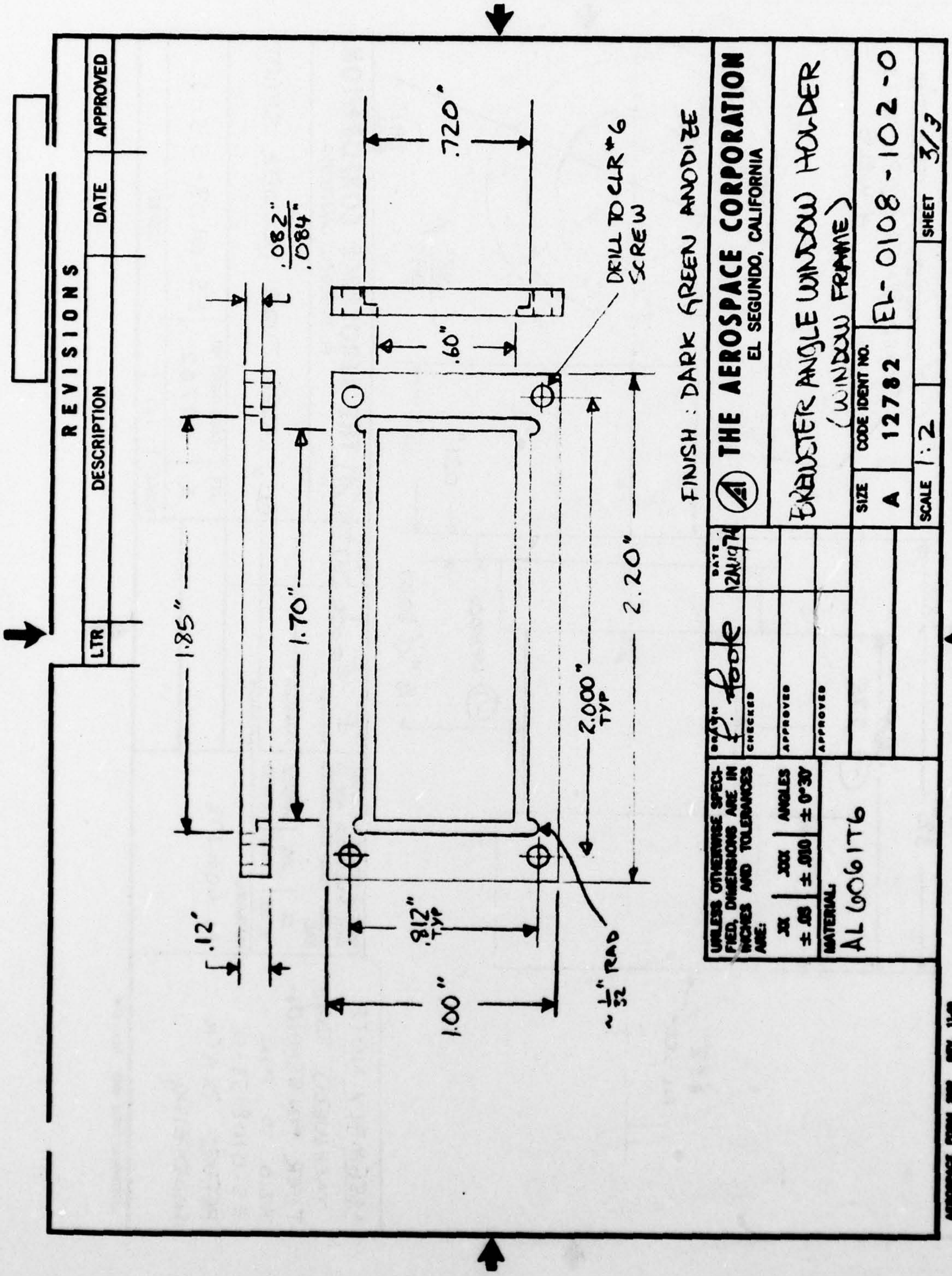

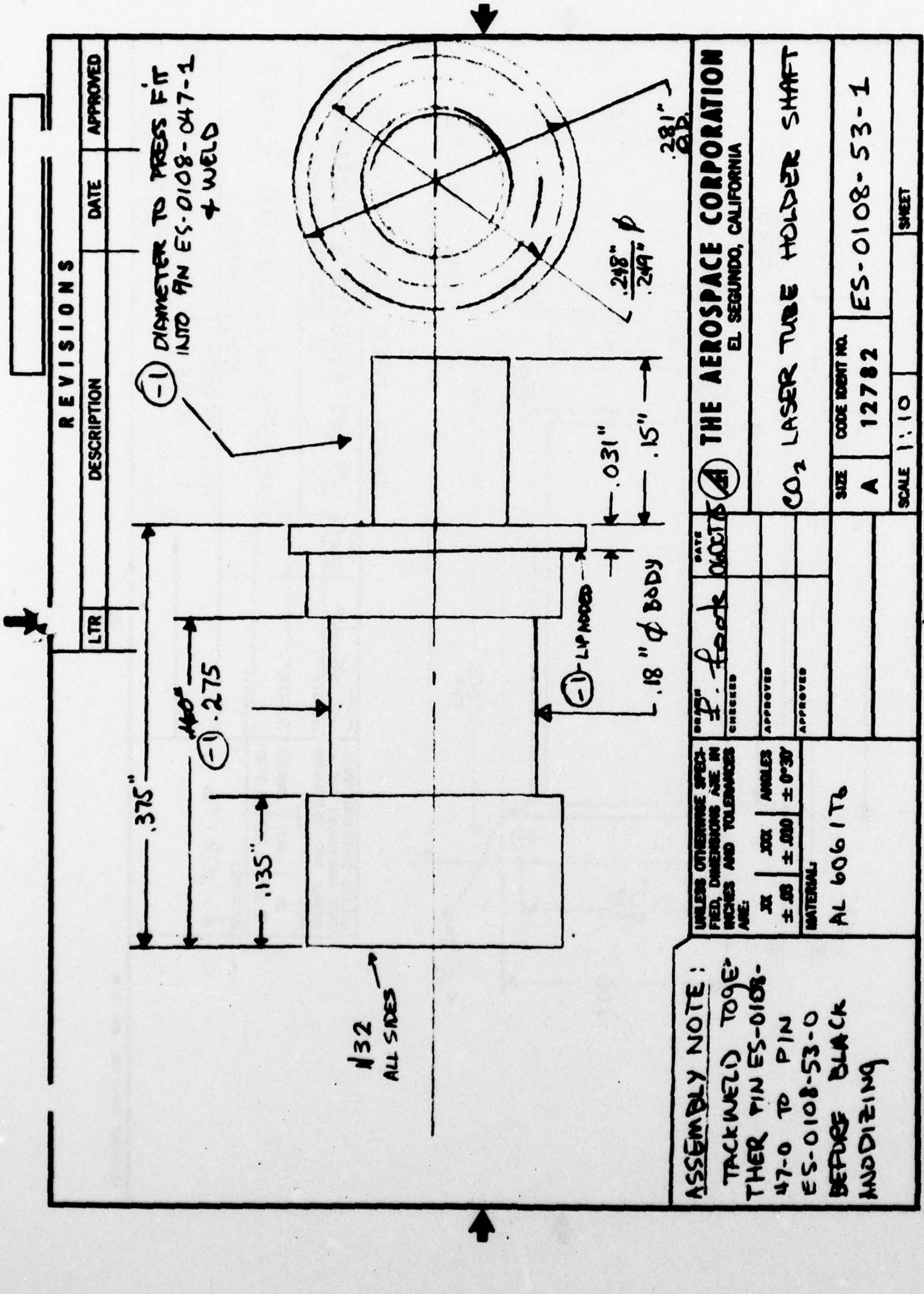
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SCALE 1:10
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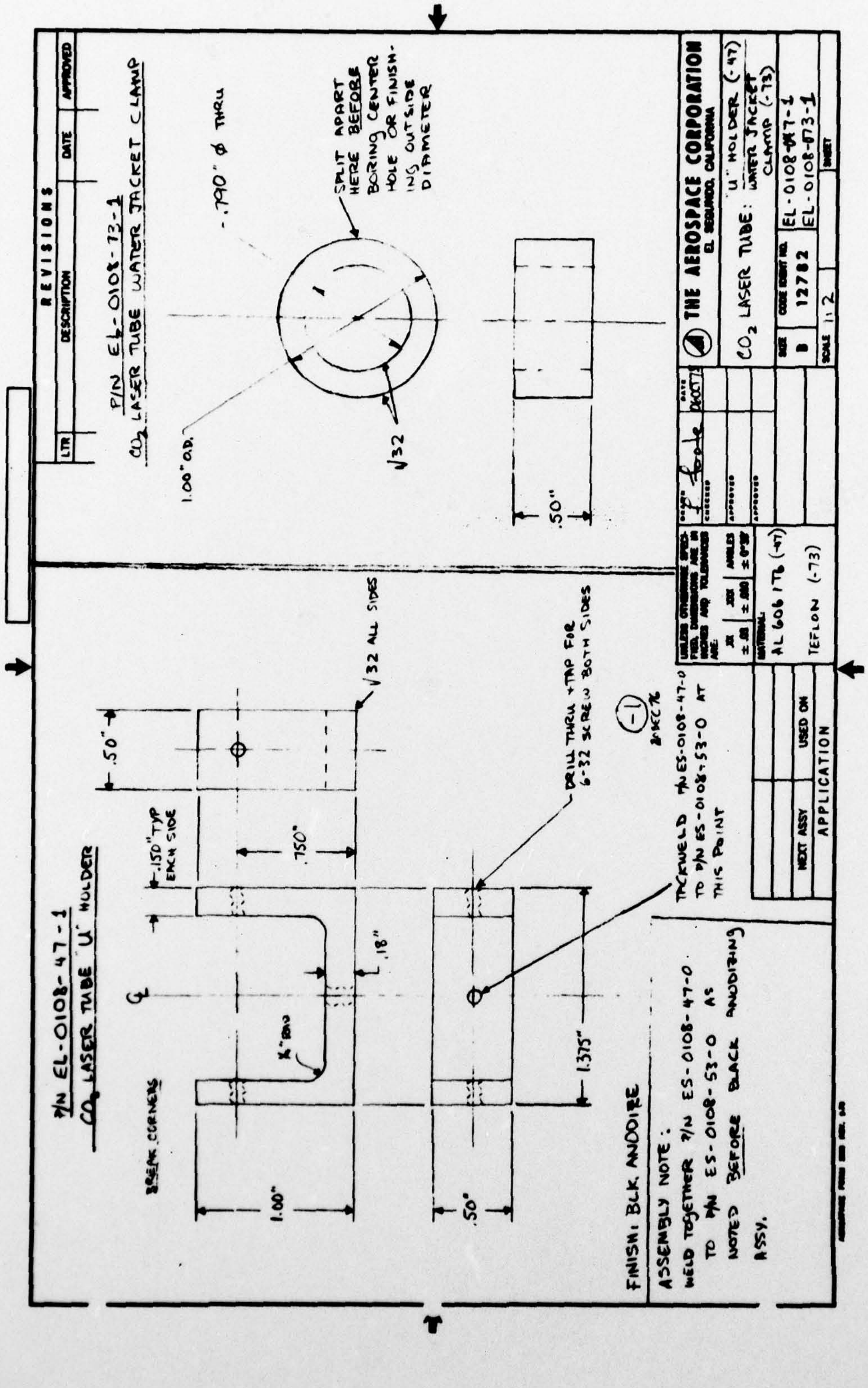
UNLESS OTHERWISE SPECIFIED, DIMENSIONS ARE IN INCHES AND TOLERANCES ARE:
.XX ±.03
.XXX ±.010
ANGLES ±0°30'
MATERIAL: AL 6061T6
DRAWN
CHECKED
APPROVED
APPROVED
DATE
ASSEMBLY NOTE:
TACKWELD TOGETHER PIN ES-0108-47-0 TO PIN ES-0108-53-0 BEFORE BLACK ANODIZING

THIS PAGE IS BEST QUALITY PRACTICABLE
FROM COPY FURNISHED TO DDC



APPENDIX B. OPTICS REQUIREMENTS

The optical components required for this laser include:

A. An output coupler (coated ZnSe, partially reflecting in the wavelength region 9 to 11 μm).

B. Two Brewster-angle windows (ZnSe).

C. A rear reflector [a high-reflectance flat (non-dispersive) or a grating (dispersive, for single-line operation)].

D. A precision-bore pyrex discharge tube.

A. OUTPUT COUPLERS

The output coupler used in a 50-W laser 1 to 2 m in length is a ZnSe substrate 1.0 in. diam by 0.125 in. thick, plano-convex with the convex radius of curvature (R/C) of approximately 10 m, antireflection-coated on the plano side, and coated for partial reflection on the 10-m R/C side. With a reflectivity of approximately 60%, output power greater than 50 W is obtainable. For weaker lines a higher reflectivity output coupler is needed. P(4) is easily obtainable with an 80% reflectance (R) output coupler, as is P(50) and most R branch lines in both the 9.6- and 10.6-μm CO_2 bands. The output coupler should be cleaned with methenol or acetone and air dried every day before operation.

B. BREWSTER-ANGLE WINDOWS

Two Brewster-angle windows are required. These windows are ZnSe, 1.82 by 0.70 by 0.080 in. thick, uncoated, with an optical wedge of less than 30 arc sec (Appendix C). This tight requirement on the wedge is necessary to prevent significant mode distortion by the windows. The wedge on new windows is usually checked by an autocollimator in the Aerospace Optics Laboratory. Dirty windows, or windows with large wedges, will significantly perturb the output mode, and, hence, the output power by shifting energy into the higher order modes or by increased diffraction loss.

Windows should be cleaned with methanol or acetone and air dried before operation of the laser. Window holders that become too hot to comfortably touch after approximately 30 min of laser operation indicate that the windows should be cleaned or replaced.

> WARNING: These windows float at lethal voltages during laser operation. Ensure that high voltage is off before cleaning or replacing.
>
> CAUTION: Because of the toxic nature of ZnSe powder, windows must be returned to manufacturer for repolishing.
>
> Note: A filter on the gas input line is recommended to prevent foreign matter in the gas bottle from depositing onto the windows during laser operation. Do not overtighten window retainer plate as ZnSe windows are fragile and will crack easily.

C. REAR REFLECTORS

The use of a high reflectance mirror in preference to a grating for the rear reflector depends on the application of the laser. For multiline operation, a gold-coated copper or molybdenum mirror with a radius of curvature of 10 m or greater is normally used. Silicon with a high-reflectance coating also works well. Since the beam is only approximately 1 cm in diameter at the mirror, only a small reflector (e.g., 1 in. diam) is necessary. Cleaning of these mirrors should be the same as for any polished optical surface.

A grating can be installed so that only one of the approximately 100 transitions in the 9-11 μm region can be selected. The grating is normally an aluminum or copper substrate with 75 lines/mm (e.g., PTR series ML 301). This grating has an angular dispersion of approximately 245 A/mrad and is mounted in the Littrow configuration at an angle of 22 deg from the incoming k vector. Reflection should be greater than 92% (El) in the first order in the 9- to 11-μm range. When the grating becomes so hot that it cannot be comfortably touched, it should be cleaned or replaced, as it has become excessively lossy, and power output will drop significantly. This grating is cleaned by rinsing it with acetone, then swirled in warm soapy water (a mild laboratory soap solution is used). Immediately after removal from the soap bath, it is rinsed with warm distilled water, then xylene, acetone, again with distilled water, and blown dry with dry nitrogen or air.

> Note: The surface of the grating should not be touched with hands or materials such as Kimwipes or Kaydry. It is highly recommended that the optical shop personnel do this cleaning.

D. PRECISION GLASS BORE TUBING

The precision glass bore tubing, usually pyrex, in the CO_2 laser serves to confine the plasma discharge. The diameter-to-length ratio of the tube should be such that the Fresnel number is 1.0, or slightly less, to ensure a TEM_{00} far-field mode. Since the tube bore is the limiting aperture, its diameter is used as the value of d in the Fresnel expression

$$N = \frac{d^2}{4\lambda \ell}$$

where

N = Fresnel number

λ = wavelength of interest

ℓ = length of the cavity

d = limiting aperture diameter

For a Fresnel number of 1.0, λ of 10 μm, and ℓ of 1.3 m,

$$d = (4\lambda\ell/N)^{1/2} = 7.2 \text{ mm}$$

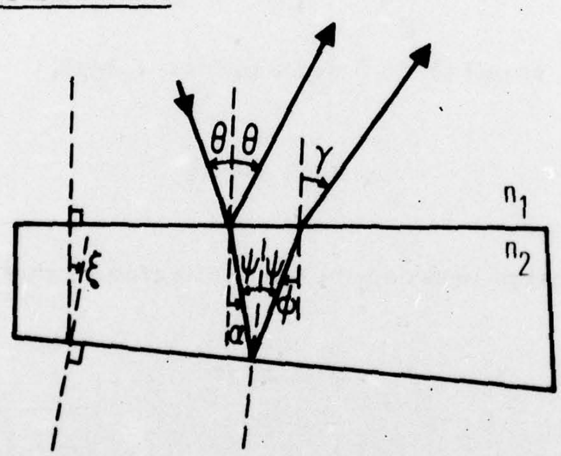
In this design, 8-mm tubes were used with success because of the self-converging effect of the energy in the far-field; 9-mm tubes produced a pronounced TEM_{01} mode and lost power in the far-field as a result of divergence.

It is essential that the tube be straight. When viewing a light source down the axis of the bore, concentric rings should appear. If these rings are not concentric, the tube will not produce the desired power distribution (TEM_{00}), and hence, less energy. Straightening of the tube may be attempted by a glass blower if the tube is not warped significantly. Otherwise, the tube should not be used. When ordering precision bore tubes, the order should specify that the tubing is to be used for laser applications and that it be as straight as possible.

APPENDIX C. METHODS OF MEASURING MECHANICAL AND OPTICAL WEDGE

Because significant diffraction losses may be introduced into a cavity by Brewster-angle windows with measurable wedge, the specifications for these windows are important. Two methods are introduced here by which the actual optical wedge[4] may be determined in either transparent or opaque window substrates. Both use a small visible laser (e.g., He-Ne) incident on the sample at a near normal angle of incidence. As shown below in Method 1, the wedge is computed from the reflection of the beam from the window surface. In Method 2, the wedge angle is computed from the duration of the transmitted beam.

A. METHOD 1: REFLECTION



$$\alpha = \sin^{-1}\left(\frac{\eta_1}{\eta_2} \sin\theta\right) \tag{C-1}$$

$$\psi = \alpha + \xi \tag{C-2}$$

[4]J. W. Erler, Private Communication

$$\phi = \psi + \xi = \alpha + 2\xi \qquad \text{(C-3)}$$

and

$$\gamma = \sin^{-1} \frac{\eta_2}{\eta_1} \sin \phi \qquad \text{(C-4)}$$

where

$$\xi = \text{mechanical wedge}$$

Combine Eqs. (C-4), (C-1), and (C-3).

$$\gamma = \sin^{-1} \frac{\eta_2}{\eta_1} \sin \left[\sin^{-1} \frac{\eta_1}{\eta_2} \sin \theta + 2\xi \right] \qquad \text{(C-5)}$$

Since all angles are small ($\theta \ll 5$ deg and $\xi \ll 1$ deg),

$$\gamma \cong \theta + \frac{\eta_2}{\eta_1} 2\xi \qquad \text{(C-6)}$$

$$\Phi = \text{deviation between the two reflected beams} = \gamma - \theta \qquad \text{(C-7)}$$

$$\Phi = \frac{\eta_2}{\eta_1} 2\xi \qquad \text{(C-8)}$$

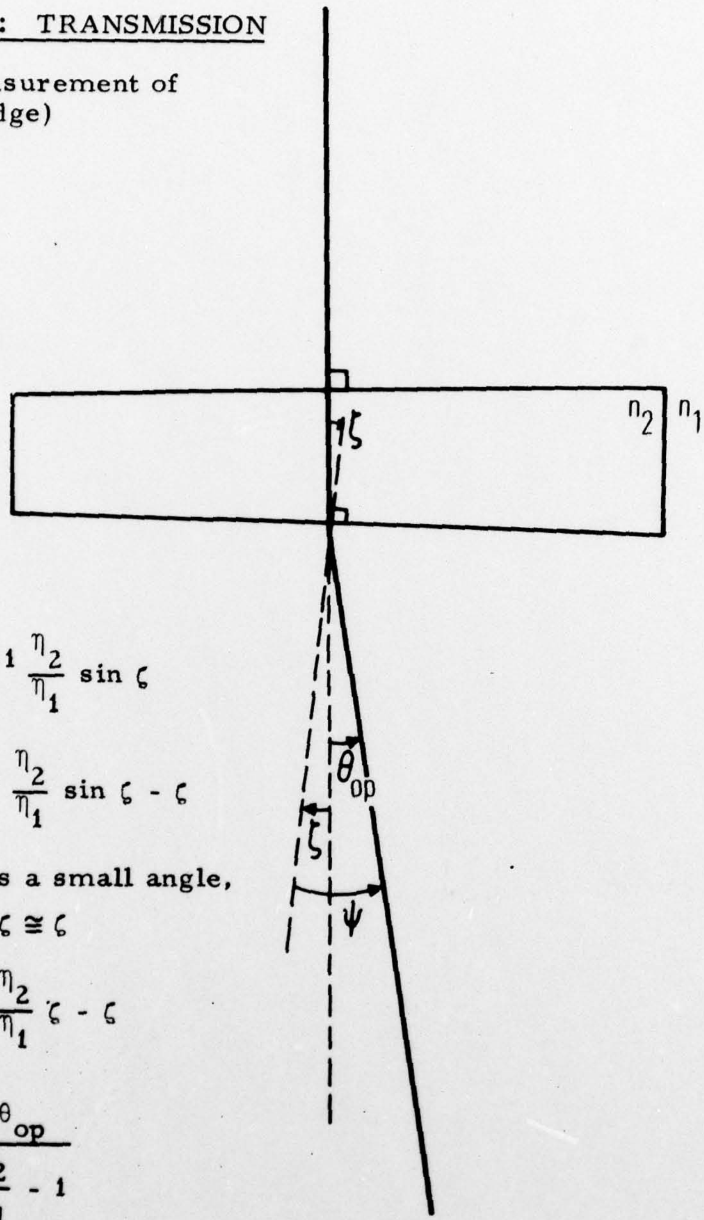
$$\text{Mechanical Wedge} = \xi = \frac{\frac{\eta_1}{\eta_2} \Phi}{2} \qquad \text{(C-9)}$$

$$\text{Optical Wedge} = \theta_{op} = \left(\frac{\eta_2}{\eta_1} \xi \right) - \xi$$

See Method 2 for derivation.

B. <u>METHOD 2: TRANSMISSION</u>

(direct measurement of optical wedge)



$$\psi = \sin^{-1}\frac{\eta_2}{\eta_1}\sin\zeta$$

$$\theta_{op} = \sin^{-1}\frac{\eta_2}{\eta_1}\sin\zeta - \zeta$$

Again since ζ is a small angle,

$$\sin\zeta \cong \zeta$$

$$\Rightarrow \theta_{op} = \frac{\eta_2}{\eta_1}\zeta - \zeta$$

$$\Rightarrow \zeta = \frac{\theta_{op}}{\frac{\eta_2}{\eta_1} - 1}$$

θ_{op} must be in radians.

Overall the direct measurement of θ_{op} will give ζ also. Reflection measurement of Φ will give θ_{op} and ζ.

With an auto collimator,

$$\theta \times \frac{1.5}{\eta_2} = \theta_{op} \quad \text{(for ZnSe } \eta_2 = 2.5,\ \frac{1.5}{2.5} = 0.60\text{)}$$

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