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Laser Cavity Optics

Pratt and Whitney Aircraft Group West Palm Beach Fla

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)				
<p>This program was a cooperative effort, between Pratt & Whitney Aircraft/Florida and United Technologies Research Center (UTRC) to provide a DF wavelength chemical laser beam from a stable resonator to a designated target area for use by Naval Research Laboratory personnel. This final report covers only work completed under the P&WA/Florida contract, which included design and fabrication of a hole coupler mirror and miscellaneous optical hardware and support during the test program which was conducted at the UTRC, East Hartford, Connecticut.</p>				

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ILLUSTRATIONS

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I. INTRODUCTION AND SUMMARY

This program consisted of a cooperative effort between Pratt & Whitney Aircraft/Florida and United Technologies Research Center (UTRC). The purpose of this combined effort was to provide a DF wavelength chemical laser beam from a stable resonator for a materials evaluation program conducted by Naval Research Laboratory (NRL) personnel. Separate contracts were awarded to both P&WA/Florida and UTRC. Basically, P&WA/Florida was responsible for providing the device operating conditions and the stable resonator optical system while UTRC was responsible for operation of the test facility and directing of the beam to the target from downstream of the material window. This final report covers work completed under the P&WA/Florida contract only.

The P&WA/Florida contract was divided into 5 Tasks. The schedule at which these tasks were completed is shown in figure 1. During Task I, an analysis was performed to determine the best operating conditions for the Contractor furnished chemical laser device to achieve outcoupling of the laser beam to the target area. Task II covered the design of a cooled outcoupling mirror and redesign of the contractor furnished chemical laser optical system to allow transmission of the laser beam exterior to the device through a material window. Task III covered fabrication of all parts and flow testing of the outcoupling mirror. Task IV consisted of P&WA/Florida engineering follow-up during set-up and testing of the chemical laser device at UTRC. Because the amount of the P&WA/Florida participation was less than originally expected, the work performed under this task was reduced. Task V covered the work required for submittal of all reports generated during this program.

The UTRC effort consisted of set-up and operation of the Contractor furnished DF chemical laser and preparation of a work area for NRL personnel in the Laser Device Development (LDD) laboratory located at East Hartford, Connecticut. Fifty-two tests were conducted during the test program which began on June 29, 1976 and was completed on July 15, 1976. The stable resonator optical system performed as anticipated and there were few testing delays due to problems or failures associated with this system.

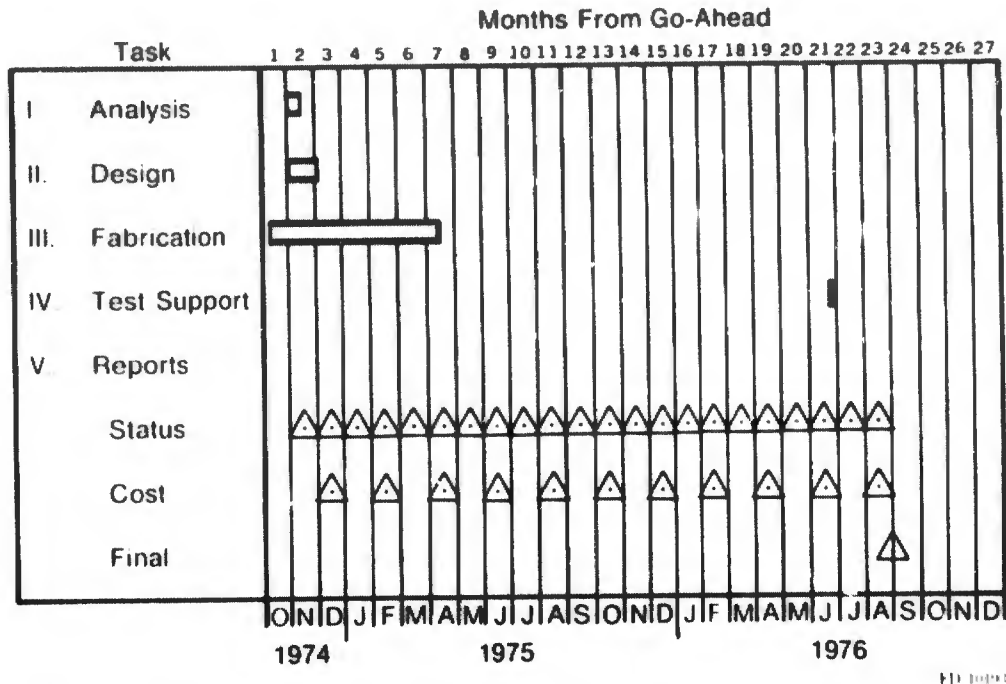


Figure 1. Program Schedule

II. TECHNICAL APPROACH

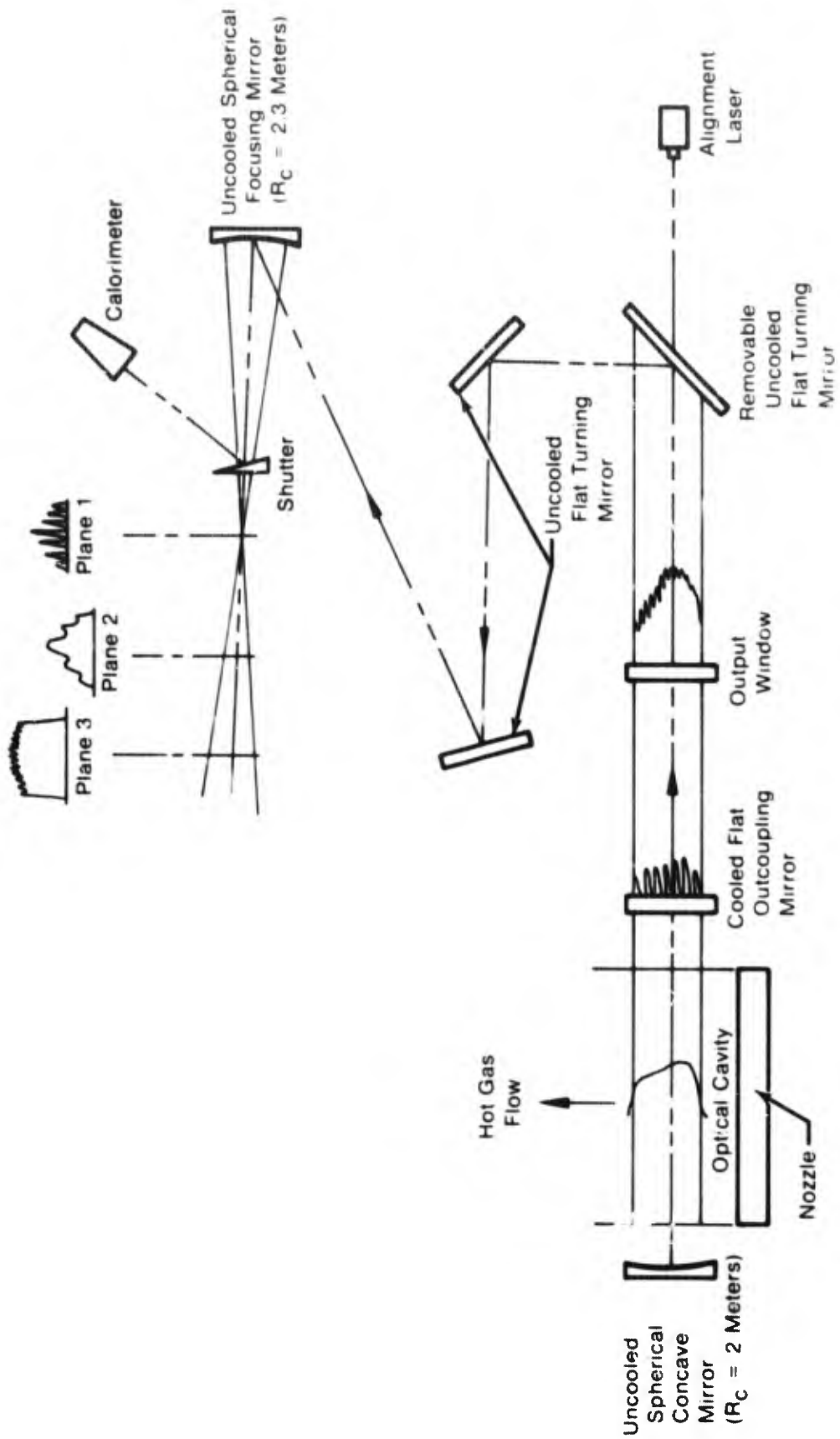
The contractor furnished Chemical Laser was operated at conditions to produce a DF wavelength laser beam of approximately round shape and symmetrical intensity distribution. A stable resonator allowed outcoupling of the laser beam through a material window.

The stable resonator cavity consisted of an uncooled copper curved ($R_c = 4$ meter, spherical) mirror and a water cooled flat hole coupler mirror separated by a distance of 1 meter. The planned high intensities generated during operation of the closed cavity resonator in the Chemical Laser precludes the use of a conventional partially transmitting mirror. Therefore, the approach taken was to provide an array of holes in a flat mirror to allow the beam to be outcoupled. A sketch of the optical train is shown in figure 2.

The flat hole coupler mirror was configured to make an apparent uniform couple with the concave mirror. The approach taken to satisfy the uniform coupling requirement is based on an extension of the Rayleigh criterion, which establishes the ability of an optical system to resolve discontinuities in a wave signature. In other words, the hole size is such that the cavity length is much greater than the Rayleigh range of a single output hole. In addition, the hole size and spacing must provide the desired percentage of geometric output coupling.

Due to the high Fresnel number of the stable resonator and the gain of the active medium, the field inside the optical cavity was expected to completely fill the active region resulting in a nearly uniform intensity distribution over the face of the flat hole coupler mirror. The power was extracted from the resonator through the array of holes in the output mirror. Therefore, immediately downbeam of the output mirror, the intensity profile contained high intensity spikes or effectively a grating sample of the field incident upon the hole coupler mirror. To avoid potential damage to the material output window by exposing it to this highly nonuniform flux, the beam must be propagated a distance sufficient to smooth these spikes before passing through the output window. This distance is governed by the effective Rayleigh range of the individual holes.

The beam was directed to the target through a series of folding optics, the last of which focused the beam to the desired size on the target. The focal length of this latter mirror was approximately 1 meter which provided a maximum intensity spot size. A wide range of intensity levels, depending upon the distance between the target and the focal point, was achieved.



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Figure 2. Optical Train

Estimates of the beam intensity profile at the focal point are difficult because of the unknown quality of the output beam. In the absence of any aberrations, however, one would expect to obtain a well defined multiholed grating diffraction pattern. A typical pattern is illustrated schematically in figure 3. The envelope of the diffraction pattern is governed by the diameter of each small hole in the output mirror. A large percentage of the total power in a beam is contained within a $(1)f\lambda/d_0$ radius of this envelope. Also present in this envelope is a series of secondary spots whose location and size depend upon the hole spacing and the size of the illuminated array of small holes.

In the presence of aberrations (or poor quality) the picture of the intensity distribution (figure 3) in the focal plane remains qualitatively correct. However, it is known from diffraction theory, that the size of these secondary spots depend upon the quality of the beam. Each spot is a replica of the focused diffraction pattern of the beam resulting from the hole coupler mirror hole pattern. Therefore, due to the anticipated poor optical quality of a high Fresnel number stable oscillator these secondary spots will spread sufficiently to somewhat fill the low intensity regions thereby reducing the intensity spiking at the focal plane. High Fresnel number stable resonators are known to operate in many modes simultaneously thus resulting in reduced beam quality. In addition, since the output beam will probably not be monochromatic, but instead contain several wavelengths, dispersion effects will be induced by the grating which also tends to smear out the intensity profile in the focal plane.

Based on the above consideration, the intensity profile on the target was expected to be governed primarily by the size of the holes in the coupling mirror with most of the power contained within a diameter of $2f\lambda/d_0$. In order to provide a more uniform intensity beam on the target, the target was positioned downbeam of the focal plane (such as plane 3 in figure 2).

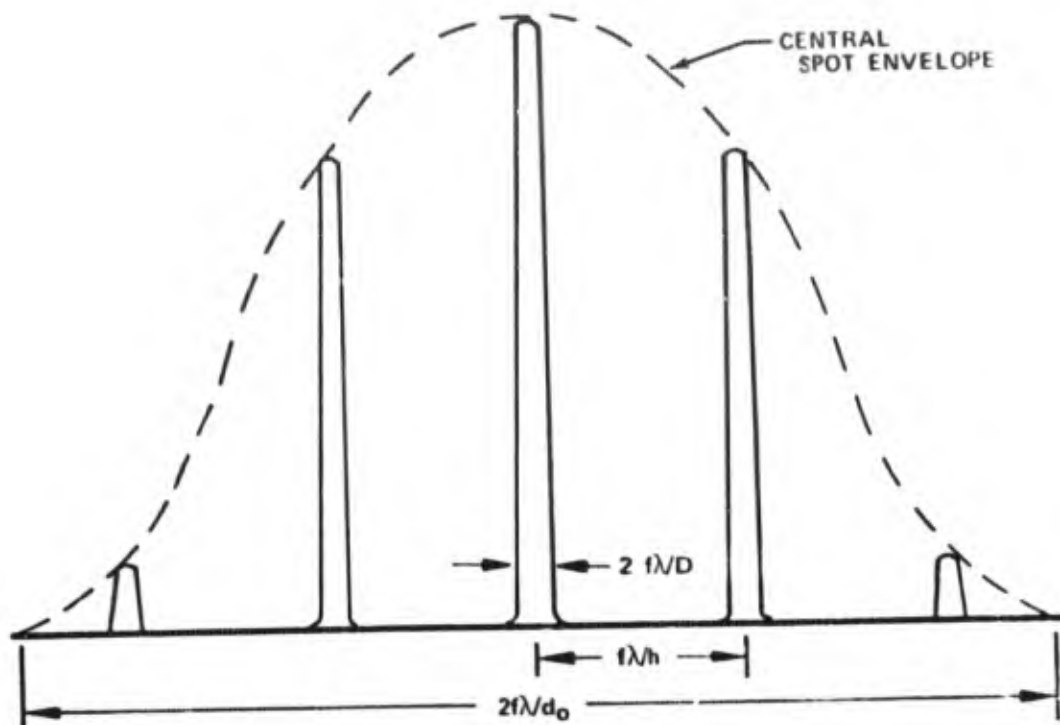


Figure 3. Focused Intensity Pattern Without Aberrations

III. ANALYSIS

Using existing computer programs, the necessary analysis to determine the best chemical laser operating conditions to achieve delivery of 10 Kw DF power to the target area for two different nozzle configurations was completed. This analysis included a study to predict the outcoupled power as a function of coupling. The results of this analysis, using the best coupling, are given in table 1. As shown, the predicted power output for the nozzle No. 1 is 7 Kw. However, this power was expected to be higher because the presented information is based on extrapolated low pressure test data with the device operating at off-design conditions.

Since nozzle No. 1 might not have satisfied the targeted power level of 10 Kw, use of a second nozzle was considered as an alternative. As shown, this nozzle has a predicted power output of 23 Kw at the design point. Ten Kw could be achieved for the materials effect testing by "clipping" the beam exterior to the laser device.

Table 1

Condition	Nozzle No. 1	Nozzle No. 2
Combustor Operating Pressure (atm)	10.00	12.00
Mole % of Helium in the Combustor	0.75	0.50
Combustor Molar Flow Ratio (Oxidizer/Primary Fuel)	2.28	2.00
Cavity Molar Flow Ratio (Secondary Fuel/Oxidizer)	2.00	3.80
Cavity Diluent Molar Flow Ratio (Secondary Diluent/Oxidizer)	6.00	13.60
Power (Kw)	7.00	23.00
Coupling	0.13	0.13

Based on subsequent testing at the UTRC, neither of the above nozzles were used during the "materials effect" testing program. Therefore, the laser nozzle hardware and test conditions for the test program were somewhat different than originally planned. The stable resonator configuration was basically unchanged.

IV. DESIGN

A sketch of the stable resonator optical system is shown in figure 4. This system included the design of a new cooled hole coupler mirror and redesign of the existing contractor optical system. The redesign effort consisted of a modification to mount the new mirror and provisions for the use of a material window.

A detailed sketch of the flat hole coupler mirror containing 2 plates (face plate and back plate) and a substrate with 700 outcoupling holes is shown in figure 5. The back plate, or closure plate, was incorporated to simplify fabrication. This design incorporates a nominal coupling of 0.13 which allows a specified amount of the laser beam to pass through the mirror from the lasing cavity. The coupling is accomplished with 0.052 in. diameter holes spaced in a triangular array. The hole pattern was arranged such that only one end of the mirror was needed for testing. Should problems be experienced during testing the mirror could be rotated 180 degrees and testing could continue with a minimum delay.

Cooling of the single pass hole coupler mirror is accomplished by ambient temperature water entering through 2 inlet holes on the top of the substrate. The water then enters into an inlet manifold for distribution around the beam output holes. After cooling the area around the output holes, the water is then collected into another manifold where it passes through 2 exit holes on the bottom of the substrate. The design coolant flow rate for the single pass mirror is 0.7 lbm/sec at an inlet pressure of 250 psig and a pressure differential of 160 psi.

A heat transfer and structural analysis of the hole coupler mirror indicated that the cooling configuration, shown in figure 6, was acceptable. All parts shown are molybdenum which has the following material properties:

Allowable Tensile Strength	- 68,200 psi
Allowable Yield Strength	- 55,900 psi
Modulus of Elasticity	- 45×10^6 psi
Coefficient of Linear Expansion	- 0.27×10^{-6} in./in./°F

Material stresses calculated due to thermal growth, face plate bending due to thermal gradient, and the effect of coolant passage water pressure on the manifold wall and brazed surfaces were well within the allowable stress limits.

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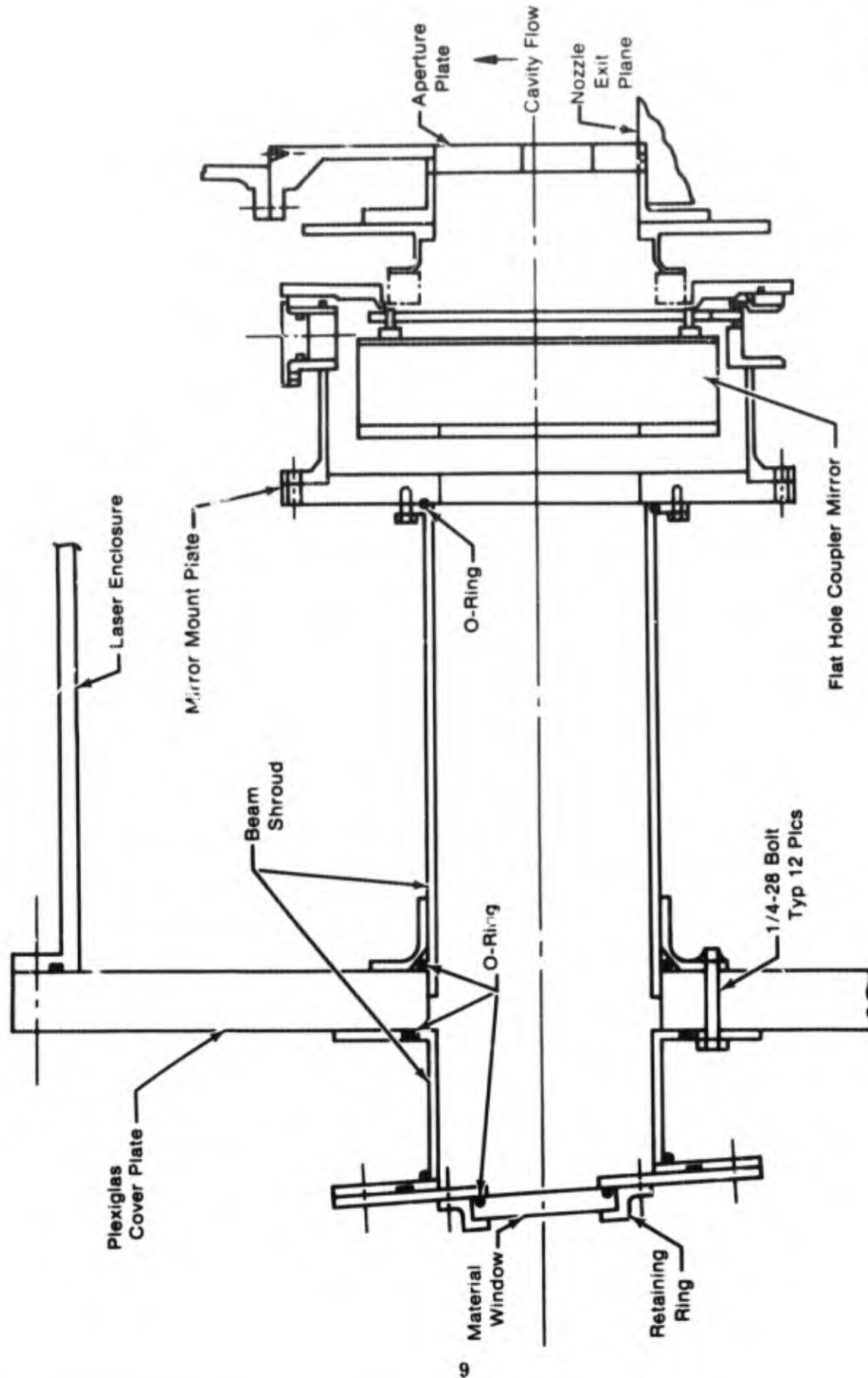


Figure 4. Stable Resonator Optical System

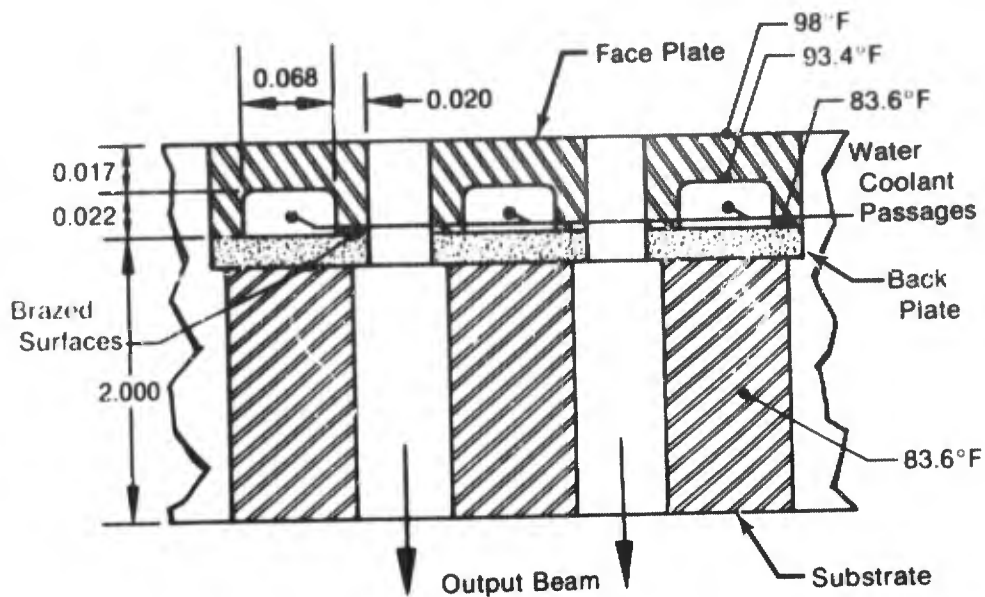


Figure 6 Hole Coupler Mirror Cooling Configuration

The multihole mirror concept used in this design allows dispersion of the laser power concentration so that the beam can be satisfactorily transmitted through a material window. As shown in figure 4, an aluminum shroud is attached downbeam of the hole coupler mirror. The function of this shroud is to maintain vacuum conditions between the hole coupler mirror and the material window and to absorb the reflected component of the beam from the window which was mounted at a 7° angle. Absorption of the reflected component is accomplished by black anodizing the inside surface of the shroud. The length of the shroud was designed to avoid potential damage to the material window from high intensity spikes. By locating the material window approximately two meters away from the outcoupling mirror, the small beams exiting through the many holes will diffract and fill the void between them, thus reducing the peak intensity on the window.

Calcium fluoride (CaF_2) was selected as the material window. This material was chosen because of its superior properties for operation at the chemical laser wavelength, good moisture resistance, availability, and cost. In an effort to reduce window power losses, an anti-reflection material was coated to both sides of the window. The purpose of this coating was to reduce moisture absorption and parasitics. It was estimated that the coating would increase the $3.8 \mu\text{m}$ laser radiation transmitted by approximately 8%. The window was attached to the shroud with a retaining ring and sealed with a soft gasket material. The removable retaining ring allows the window to be easily cleaned or replaced.

Redesign of the mirror mount plate consisted of provisions to attach the beam shroud and the addition of an opening to allow removal of the beam exiting the hole coupler mirror.

V. FABRICATION

Fabrication of the optical system began on October 9, 1974 and was completed on April 18, 1975. This fabrication consisted of a flat mirror assembly, 3 material windows, a beam shroud, one set of aperture plates and associated attachment hardware. The mirror assembly was flow calibrated prior to the use in the test program.

After fabrication was completed, all parts were sent to the UTRC; the hole coupler mirror was sent on June 17, 1975 while the remaining hardware was sent on April 24, 1975.

A. MIRROR ASSEMBLY

The mirror assembly as shown in figure 5 contains a substrate, back plate, and face plate. These parts were machined in detail at outside vendors and subsequently brazed into an assembly and final machined at the P&WA/Florida facility. The assembly was then inspected, leak checked, pressure checked, optically polished, and coated.

The two detail plates were both fabricated from molybdenum. Each plate was machined to the overall dimensions then ground to the desired thickness. The coolant channels were etched into the face plate, then optically inspected to insure that adequate braze area would be maintained when line drilling the seven hundred 0.052 in. diameter holes. The 0.052 in. diameter holes were located on 0.120 in. centers in 40 rows which were located on 0.130 in. centers and alternately staggered 0.060 in. The back plate holes were drilled at the same time as the face plate holes.

The mirror substrate was also fabricated from molybdenum. The overall dimensions, internal water manifolds, inlet and outlet ports, and the seven hundred 0.072 in. diameter holes were all machined in the substrate in detail.

The details shown in figure 7 were final inspected, assembled, and brazed into a semi-finished assembly. This assembly was helium leak checked to 50 psig, hydro-proof tested to 500 psig, and water flow calibrated prior to final machining. The water flow calibration is given in figure 8. As shown, this curve falls slightly below the design point, but was considered to be acceptable. Three spherical mount pads were installed to the back of the mirror assembly. These pads were designed to give low mirror distortion.

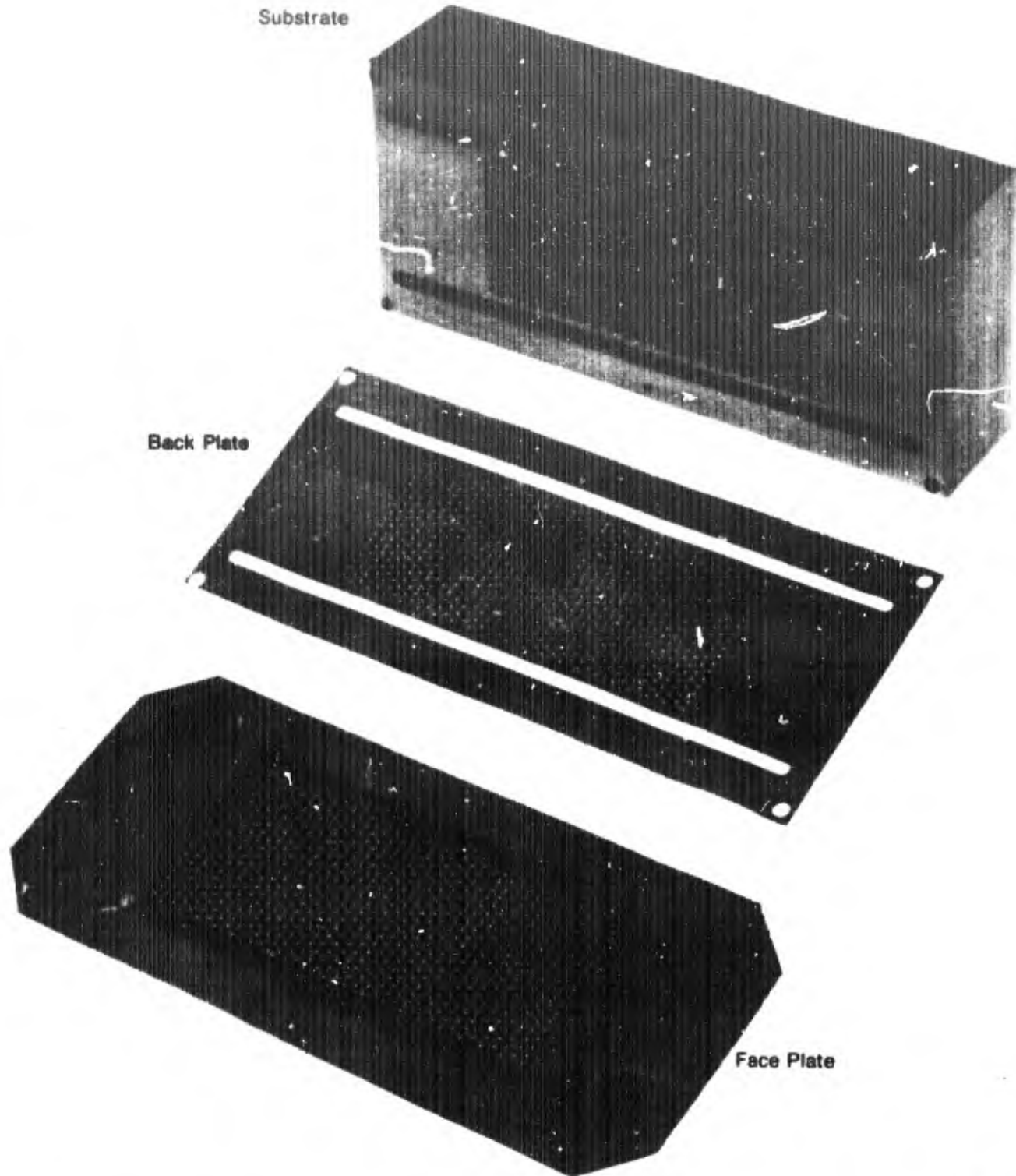


Figure 7. Hole Coupler Mirror Details

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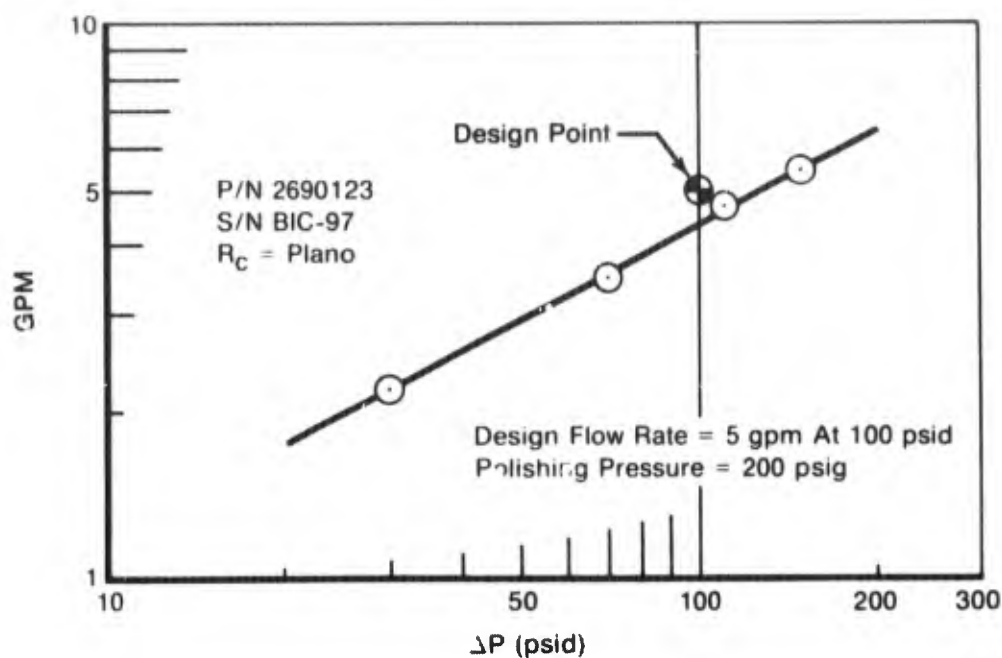


Figure 8. Mirror Water Coolant Flow Calibration

The optical features were obtained initially by machine grinding excess material from the face plate to a nominal hotwall thickness of 0.017 in. Free abrasive final grinding and polishing of the optical surface was performed in a polishing fixture as shown in figure 9. The mirror was polished with the coolant passages static pressurized to 200 psig over the 2.40×8.00 in. active area.

The optical surface was final inspected for flatness and optical surface quality. The optical figure is shown interferometrically in figure 10. The mirror was then coated with a silver (1500°A) coating and overcoated with thorium fluoride (1300°A) to enhance the reflectivity characteristics and to protect the optical surface. An aluminum protective cover was supplied to protect the optical surface during installation and shipment. The completed mirror assembly is shown in figure 11.

B. MATERIAL WINDOWS

Three calcium fluoride (CaF_2) material windows (3 in. diameter×0.320 in. thick) was procured for this program from an outside vendor. Purchasing specifications required that this material be able to withstand a pressure differential of 15 psid, all surfaces be polished flat within 1 wave in the visible, and the crystal should be prepared such that its attenuation for single pass be 8-9% including both reflection and absorption losses.

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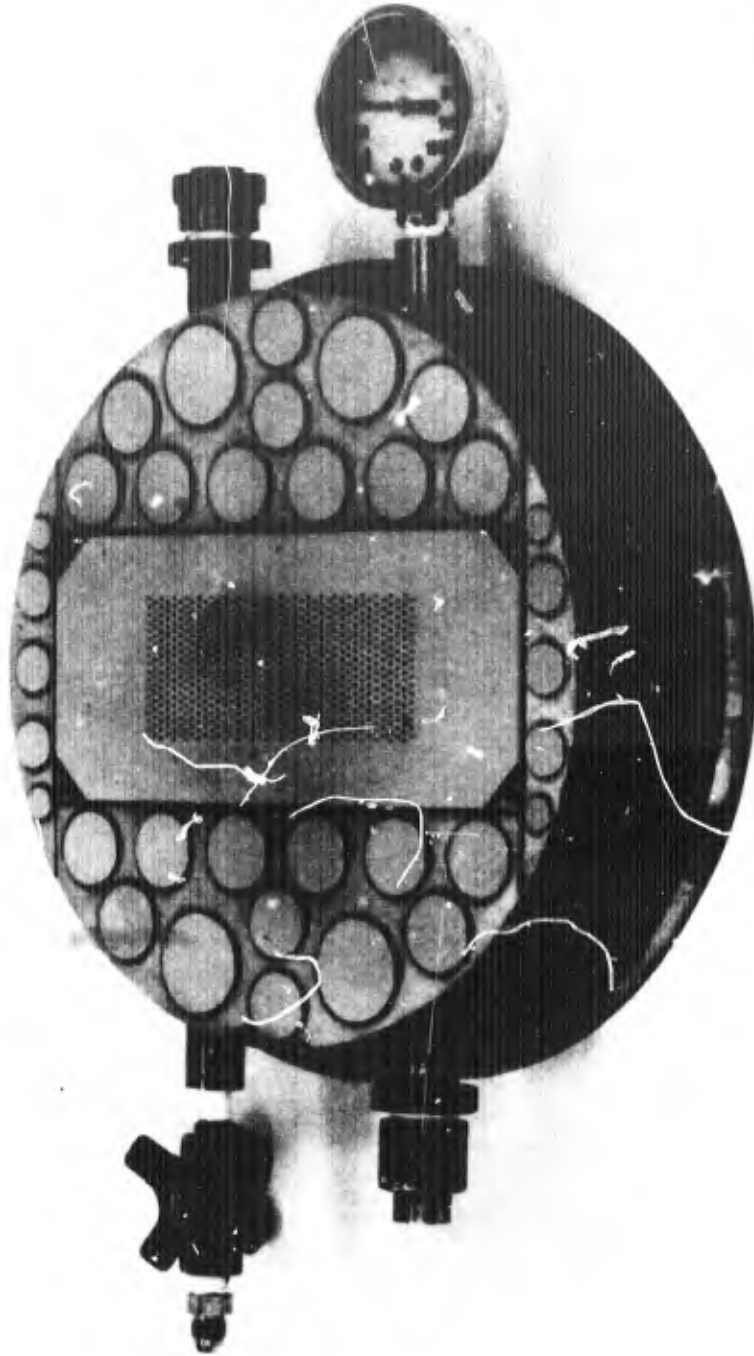
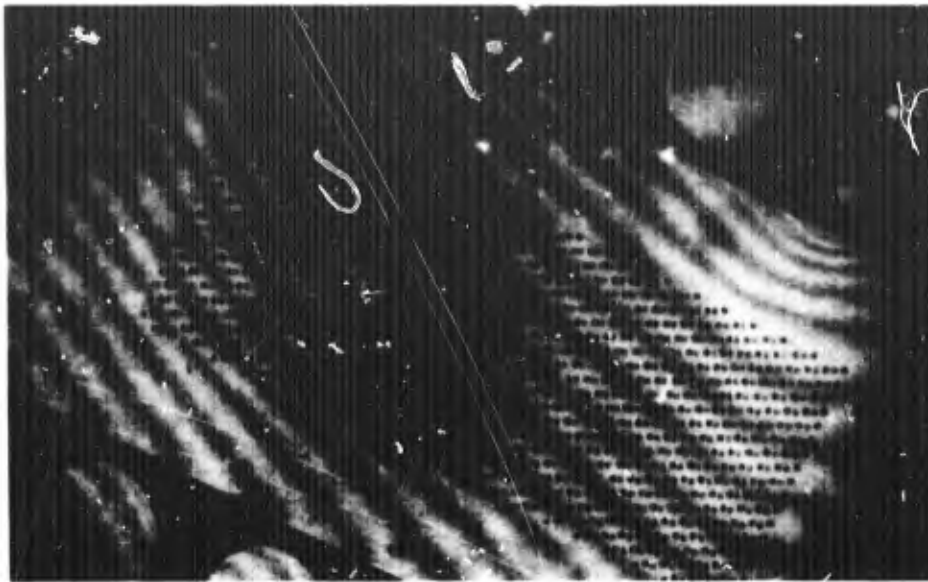


Figure 9. Hole Coupier Mirror Mounted in Polishing Fixture



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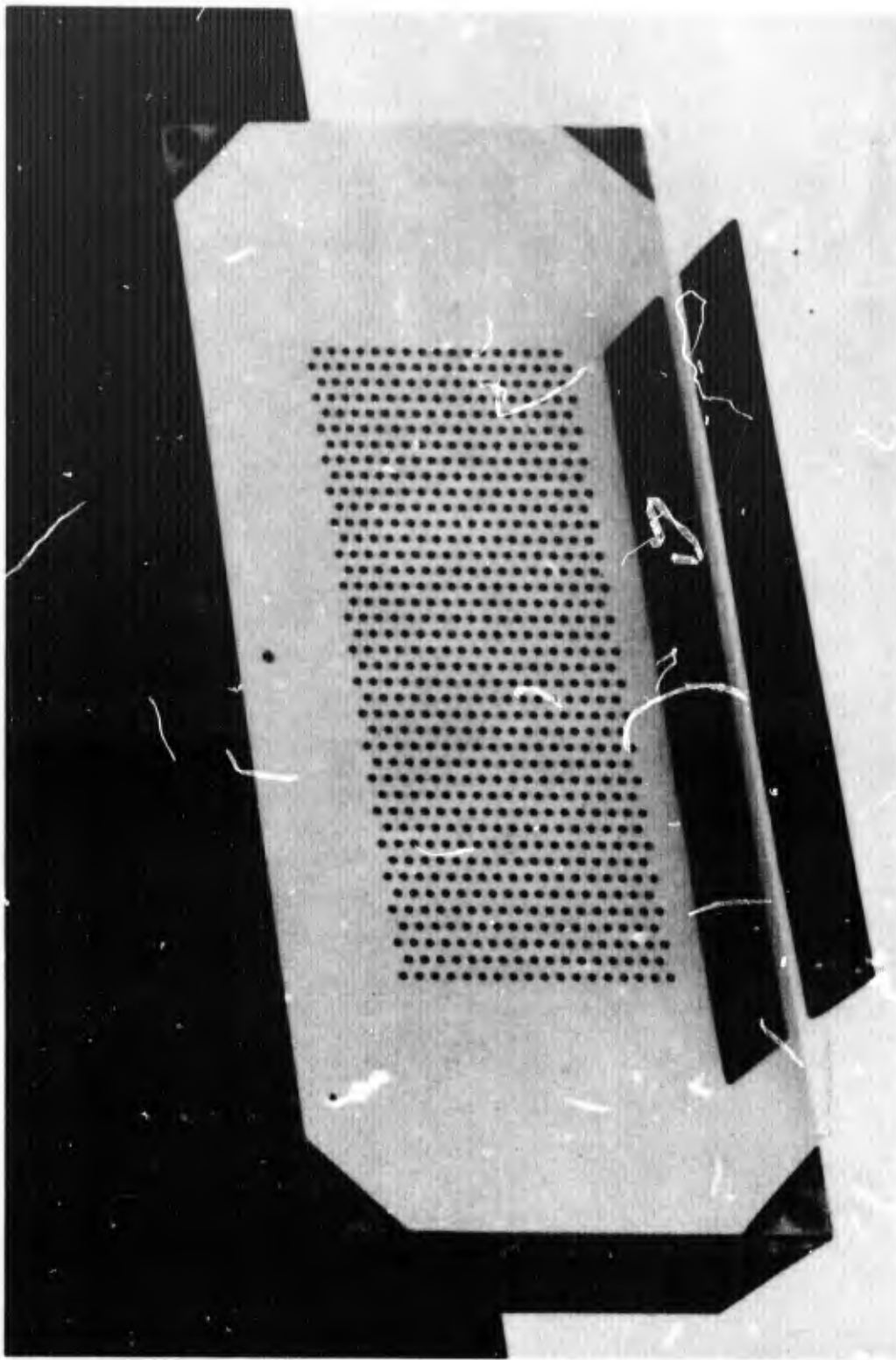
Figure 10. Interferogram of the Hole Coupler Mirror Optical Surface

After receipt at P&WA/Florida, all windows were tested for uniformity of index of refraction and birefringence.

Each window was tested on the Twyman-Green interferometer as shown in figure 12. All windows were found to transmit a wavefront with deviations less than 1λ at $0.633 \mu\text{m}$ (including surfaces and bulk inhomogenities).

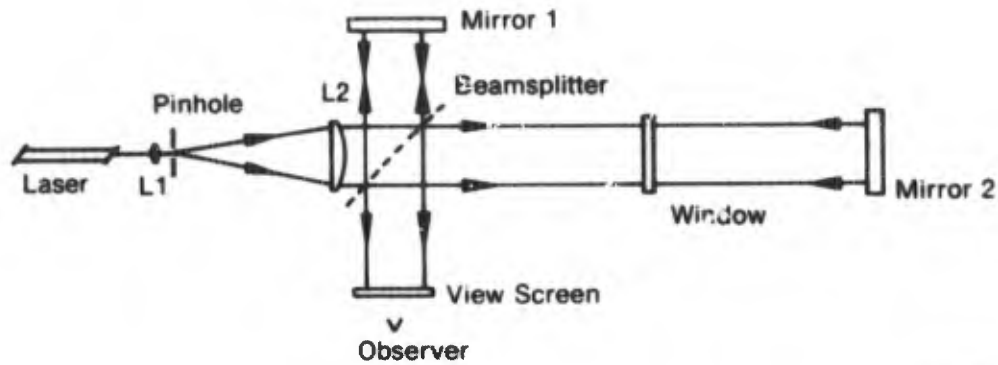
A common "optical shop" quality control technique for transmitting materials is to test for the presence of stress induced birefringence as shown in figure 13. The windows tested were placed between two crossed polarizers such that the polarizers' "transmission-planes" were rotated 90° with respect to each other. Incident light, which is plane polarized by the first polarizer, will be totally attenuated by the second polarizer if the polarization is not changed by transmission through the windows. If the window is stressed, the polarization state will be changed and a region of increased transmission will occur in the stressed area when the test material is viewed through the second polarizer.

Two of the three windows delivered showed areas containing several possible "stress-planes" (figure 14). The vendor who supplied the windows was contracted and he reported that these were "growth planes" and that their presence should not significantly reduce the thermal or mechanical properties of the windows. However, a window failure did occur duringg the material effect test program (Test No. 15) and it was necessary to replace the 3 in. diameter \times 0.320 in. thick CaF_2 window with a larger (5 in. diameter \times 1 in. thick) NaCl window. This new window performed satisfactorily for the remainder of the test program.



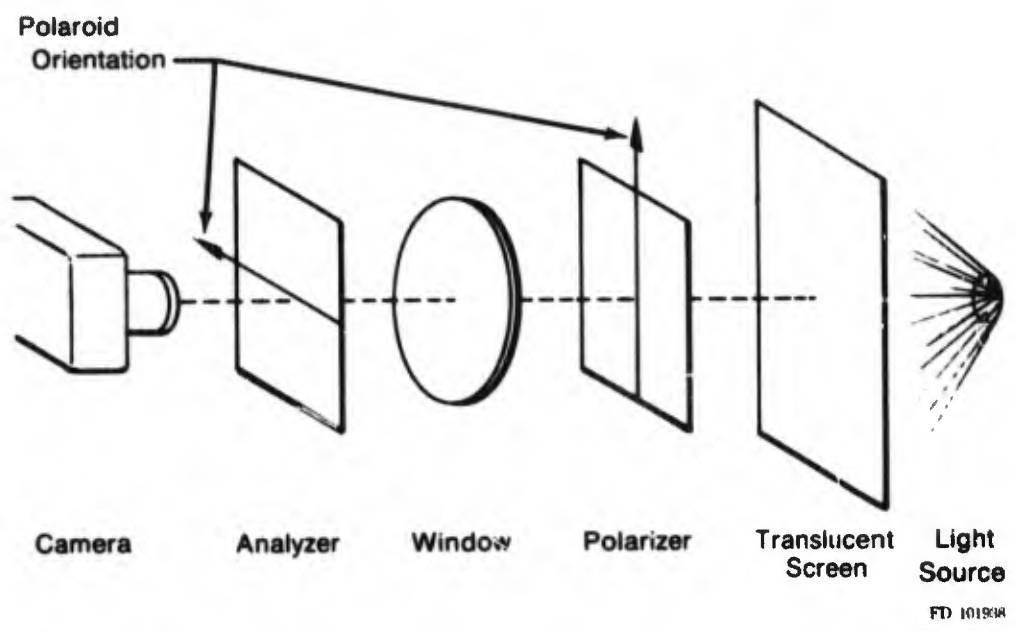
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Figure 11. Hole Coupler Mirror Assembly



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Figure 12. Twyman-Green Interferometer



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Figure 13. Test for Birefringence

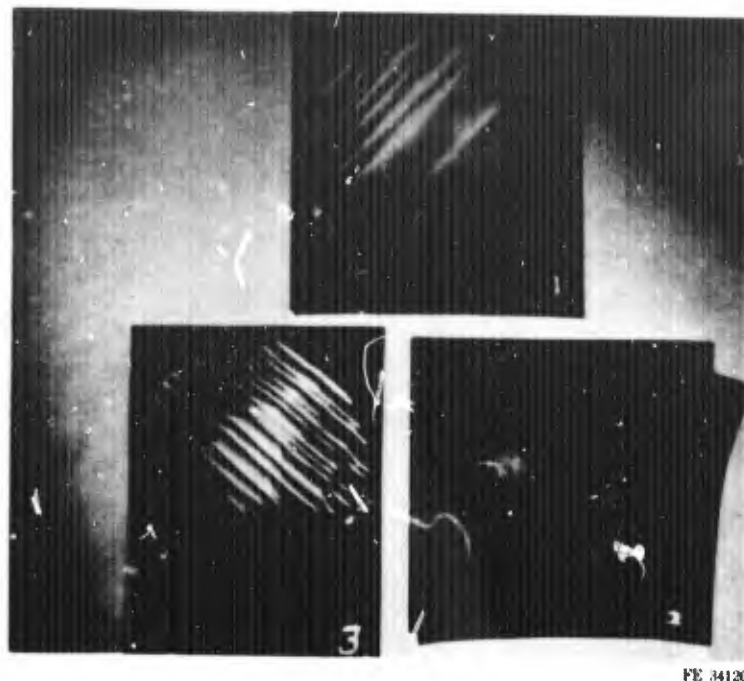


Figure 14. CaF_2 Window Birefringence

After completion of the above tests, the best two windows were sent to an outside vendor for antireflection (AR) coating. The purchase specifications required that both surfaces for each piece be coated for a reflectivity $< 0.5\%$ per coated surface at $\lambda = 3.8\mu\text{m}$.

C. MISCELLANEOUS HARDWARE

One set of two aperture plates were fabricated using annealed nickel raw material. These apertures, which are attached directly to the existing device endwalls, control the beam size and output location relative to the nozzle exit plane.

The beam shroud was fabricated from 6 in. diameter schedule 40 aluminum pipe. The inside diameter of the duct was black anodize coated for stray radiation suppression.

One set of stainless steel attachment hardware (bolts and nuts) and viton o'rings were procured. These items were standard off-the-shelf parts.