NASA CONTRACTOR REPORT

NASA CR-1664

RESEARCH DIRECTED TOWARD PERFECTING A DESIGN FOR A SPACE QUALIFIED He-Ne LASER

Phase II

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • SEPTEMBER 1970

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA CR-1664 *Call no.*		

4. Title and Subtitle	5. Report Date
Research Directed Toward Perfecting A Design For A Space Qualified He-Ne Laser, Phase II.	~~September 1~~970
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
William P. Kolb *Omit*	
9. Performing Organization Name and Address	10. Work Unit No.
Electron Dynamics Divi~~sion~~	740-21-02-05-25 *Omit*
Hughes Aircraft Co.	11. Contract or Grant No.
~~3100 W. Lomita Blvd.~~	NAS 12-579 *Omit*
~~Terrance California 90509~~	13. Type of Report and Period Covered
12. Sponsoring Agency Name and Address	Contractor Report
National Aeronautics and Space Administration Washington, D. C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

None

16. Abstract

The research and development toward perfecting a space-qualified 5 mW He-Ne laser is reported. The laser and power supply, which are integrated into a single package, provide a rugged, lightweight, compact unit. The design details of the unit are presented. The results of special studies conducted in cold cathode geometry and lifetests; internal mirrors; mirror and window seals; and environmental testing are reported. Fundamental design problems were encountered in testing lasers of this design. Problem investigations and proposed solutions are discussed and results from testing a modified laser are reported. The entire space laser program, Phase I and II, is summarized and presented along with recommendations for design modifications and future investigations.

17. Key Words (Selected by Author(s))	18. Distribution Statement
Space-Qualified Helium Neon Laser	Unclassified-Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	99	$3.00

FOREWORD

This report is the Final Report summarizing the work performed on Phase II (development phase) of NASA Contract NAS 12-579 entitled "Research Directed Toward Perfecting a Design for a Space Qualified He-Ne Laser," covering the period July 1968 to January 1970. This report was prepared by the Electron Dynamics Division of Hughes Aircraft - Torrance, California. It describes work performed in the Laser Department of the Research and Development Laboratory, headed by Dr. A. Stevens Halsted. Mr. William P. Kolb was the principal investigator on the program and served as the Program Manager.

Dr. William B. Bridges, Department Manager of the Laser Department of the Hughes Research Laboratories - Malibu, California, was Program Manager of this program during Phase I (design phase).

All the work performed under this contract was administered by the Chemical Physics Branch, NASA - Electronics Research Center, Cambridge, Massachusetts. Dr. Philip L. Hanst, Branch Chief, Dr. Roy A. Paananen and Dr. W. Horace Furumoto, Staff Members, were the principal technical representatives for NASA during both phases of this program.

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SECTION I INTRODUCTION

This document summarizes work performed by the Hughes Aircraft Company, Electron Dynamics Division for the National Aeronautics and Space Administration under Contract NAS-12-579, "Research Directed Toward Perfecting a Design for a Space-Qualified Laser." It is intended to cover the results of the contractual study performed in Phase II. Phase I is covered in a NASA Report[1] "Design for a Space Qualified Laser - Oral Presentation Data, " which is a summary of the pertinent data presented verbally by Hughes personnel to NASA/ERC personnel at Cambridge, Massachusetts, on 1 February 1968.

The objectives of Phase I are briefly outlined below:

ITEM 1: Perfect a design for a space-qualified laser in accordance with the general specifications (see Appendix B). This shall include, but is not limited to, the following:

a. Calculations of the interaction of all critical parameters.

b. Laboratory experiments intended to support calculations of critical parameters.

c. Literature review.

d. Investigation of the state-of-the art in commercial lasers, including foreign ones.

e. Visits to NASA centers for elucidation of the spacecraft configurations and environmental conditions.

f. Visits to universities or non-NASA government laboratories for information exchange purposes.

ITEM 2: Upon completion of Item 1 an oral presentation and review will be held at NASA/ERC, Cambridge, Massachusetts. Four (4) copies of all pertinent data shall be made available to the contract monitor one week before said review. This shall include a set of design specification requirements which meet all the performance environment needs, and a list of materials.

The objectives of Phase II of the program are best set forth in the Statement of Work:

> "The Contractor shall supply the necessary personnel, facilities, services, and materials to accomplish the work set forth below:"

PHASE II

Item 3

Modify the design perfected under Item 1, to comply with the several specifications outlined in Exhibit A, attached hereto and made a part hereof (included as Appendix B).

Item 4

Upon approval by the Contract Monitor of the design developed under Item 3, and in accordance therewith, fabricate four laser plasma tubes, two power supplies in packages, and laser mounts. This fabrication shall include, but is not limited to, the following:

a. The operation of these laser plasma tubes in the so-called "burn-in" mode.

b. The performance of environmental testing on subassemblies and the complete unit to establish the design in accordance with Exhibit A.

c. The analysis and correction of failures occuring at any point.

d. The generation of sufficient and adequate documentation to permit an orderly transition to the subsequent procurement of fully space-qualified lasers.

e. The implementation of special or separate testing of critical items in the laser design. This can include cathode life tests on dummy tubes, assessment of UV damage to internal mirrors in test fixtures, etc.

Item 5

Upon completion of Items 3 and 4, an oral presentation and review will be held at NASA/ERC, Cambridge, Massachusetts. Five (5) copies of all pertinent data shall be made available to the contract monitor one week before said review. This shall include all the documentation generated on the program as well as a cost and delivery schedule for possible future procurement of fully space-qualified lasers. Two of the laser packages developed and tested under this contract shall be delivered to NASA/ERC at the time of the oral presentation and review.

Item 3 of the Statement of Work, as given previously, has been fulfilled. The modified design of a Space Qualified Laser (SQL) required under Item 3 is presented in Section II of this document. The results of special tests and evaluations of critical items of the laser design are covered in Section III.

SECTION II

SPACE QUALIFIED LASER DESIGN

In this section are presented the details of the laser design developed under the present contract. This basic design, which was presented at the end of Phase I[1] has been modified to incorporate the results of the special test and evaluations which are documented in Section III.

A. DISCHARGE TUBE DESIGN

The construction details of the metal-ceramic discharge tube are shown in Figure II-1 along with the optical cavity support and adjustment structure. This design is basically the same as presented at the end of Phase I except for the modification of the cathode and output mirror as discussed in Section II of this report. A prototype discharge tube of this design has been fabricated with no unexpected difficulties. The items shown in Figure II-1 are named in Table II-1 and are described below.

High purity Al_2O_3 is used for the ceramic bore (7). The active bore dimensions for the prototype tube are 10 in by 1.5 mm i.d. The bore is metallized and sealed to the internal bore support (9) and the end bore supports (21) and (22). The cathode vacuum jacket (6) with ends (21) and (22) form a gas reservoir with approximately 350 cm^3 volume. The cathode consists of two processed tantalum cylinders (30) with end caps. (29) slipped inside the vacuum envelope (6) . A dielectric separator (8) made of Al_2O_3 ceramic is held in place by three stainless steel pins (23) which are heliarced to the cathode vacuum jacket cylinder (6).

The anodes of this dual discharge design are formed by the snouts on the flange adapter (25) which extend into the bellows (13) at each end of the discharge tube. Each bellows is brazed to an adapter ring (12)

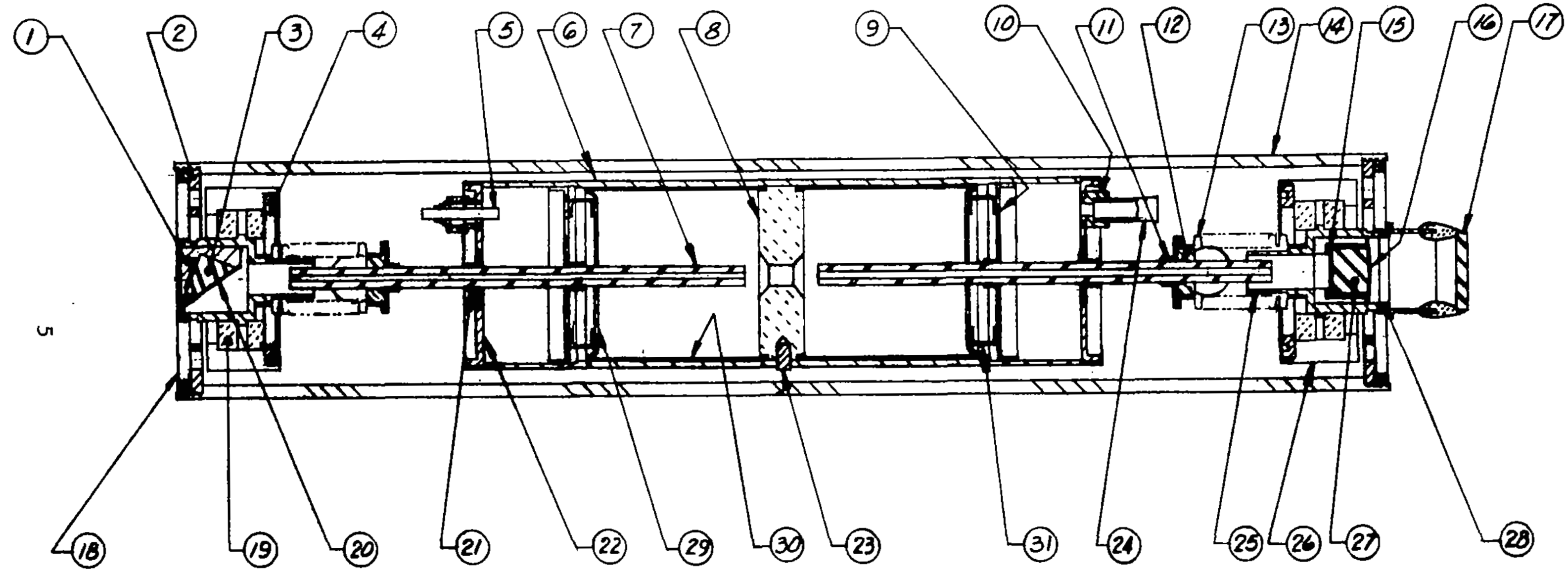

Figure II-1   Metal-ceramic tube cross sectional view.

TABLE II-1 Legend for Figure II-1

1. Prism Holder
2. Mirror Support
3. Brewster's Angle Reflectance Prism
4. Mirror Mount Retainer
5. Getter Feed Thru Assembly
6. Cathode Vacuum Jacket
7. Ceramic Bore
8. Dielectric Separator
9. Internal Bore Support
10. Pumpout Adapter
11. Heliarc Flange Adapter
12. Bellows Adapter
13. Bellows
14. Cavity Support Cylinder
15. Output Mirror Holder
16. Mirror Clamp
17. Output Window Assembly
18. Mirror Support Retainer
19. Insulator
20. Prism Clamp
21. Adapter End Cap
22. Cathode Bore Support
23. Separator Pin
24. Pinch-off Tube
25. Flange Adapter
26. Adjusting Mirror Support
27. Output Mirror
28. Output Window Flange Adapter
29. Cathode End Cap
30. Processed Tantalum Cathode
31. Cathode Loading Spring

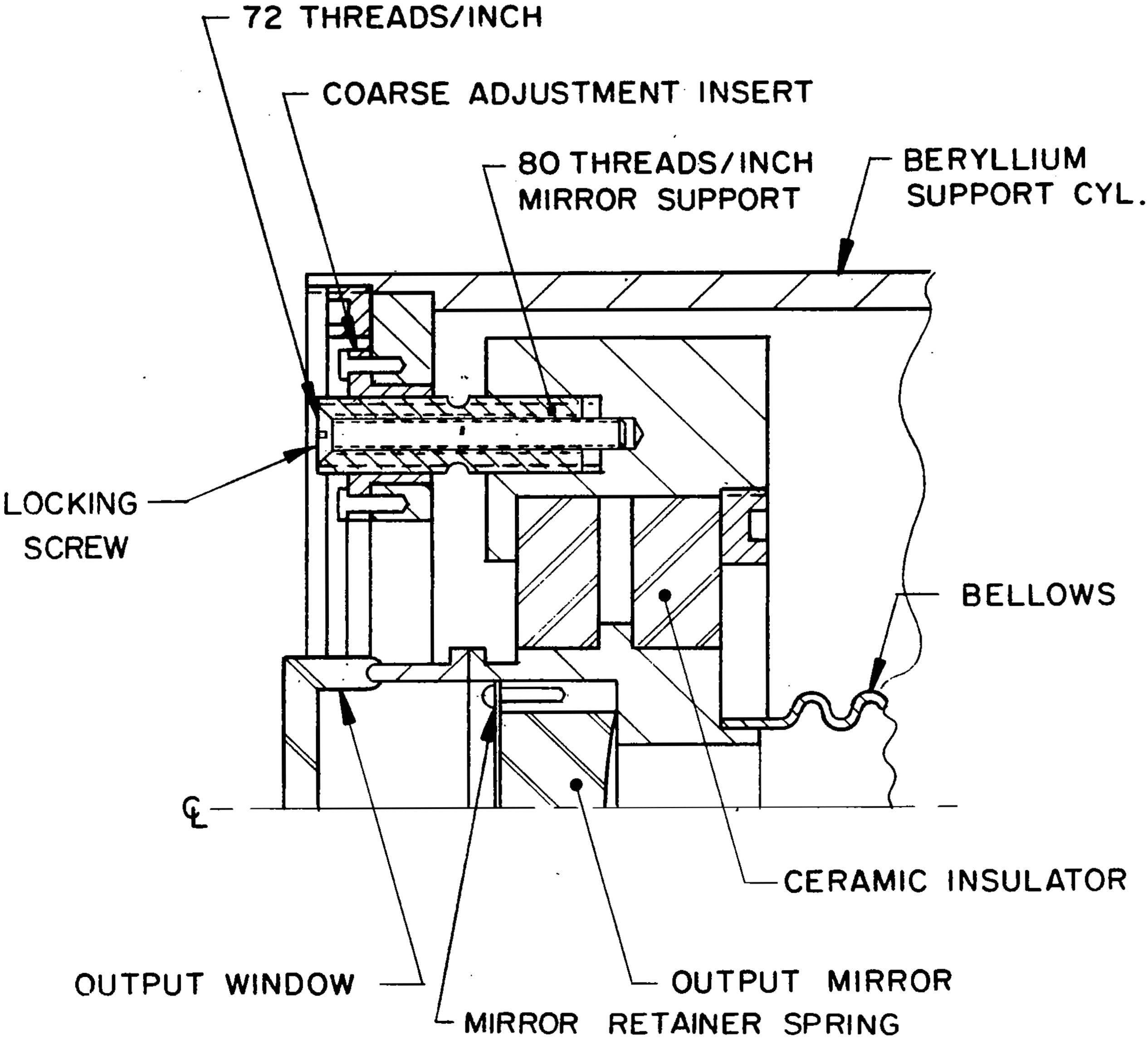

Figure II-2 Detailed view of differential screw tuning mechanism.

which is, in turn, heliarced to the flange (11) brazed to the metallized ceramic bore. The vacuum envelope is completed by the prism holder (1) and the output window assembly (17) . The Brewster's angle prism (3) is held mechanically in part (1) by a clamping mask-spring (20). The output mirror (27) is also held mechanically in the mirror holder (5) by a clamp (16).

Electrical connection to the getter is made through a ceramic feed-through insulator (5). The vacuum tipoff (24) is made by pinching the copper vacuum pump out tube.

B. OPTICAL CAVITY DESIGN

The optical cavity support structure is shown in the cross sectional drawing in Figure II-1. It consists of a simple beryllium cylinder (14) that is 2.50 inches in diameter with a .125 inch wall thickness and 13.50 inches long. The vacuum envelope (6) is held rigidly to the optical cavity support cylinder (14) with a layer of potting compound suitable for use in spacecraft. The mirrors are held rigidly with respect to the outer cylinder by adjustable mounts (See Figure II-2). The mirror holder assemblies are held in the adjusting mirror supports (26) via insulators (19), necessary to allow the optical support structure to remain at ground (cathode) potential while the mirror holder floats at anode potential. The adjusting mirror support (26) is positioned with respect to the support structure end plate by differential screw mechanisms.

The cavity support tube is held over the central 4.00 inches in an aluminum mounting bracket which is dip brazed to the bottom and one side of the laser/power supply package. This mounting bracket provides both mechanical support and a thermal path to the heat sink (spacecraft).

The optical cavity is basically a long radius-flat configuration. The output mirror (27) has a spherical radius of 200 cm and is coated for 1.0% transmission at 6328 Å. A coated Brewster's angle half prism (3) is used for the high reflectance flat mirror. The prism also provides the polarization reference for the beam. The mirror spacing is 33 cm.

C. POWER SUPPLY DESIGN

The detailed design of the laser power supply is presented in another NASA Report[1]. The prototype power supply which was constructed during Phase I of the present contact has been tested to verify this design. In addition, this unit has been life tested for over 5,500 hours with absolutely no problems.

Figure II-3 shows a block diagram of the dual power supply which is made up of the following seven subcircuits:

- Control logic
- Current regulator
- Dc to dc converter
- High voltage filter
- Current sensing
- Starting circuitry
- Telemetry monitoring circuitry

With the exception of the starting circuitry and telemetry monitoring circuitry no major design changes or additions have been made except for the use of MIL Spec or equivalent parts. These changes are detailed below.

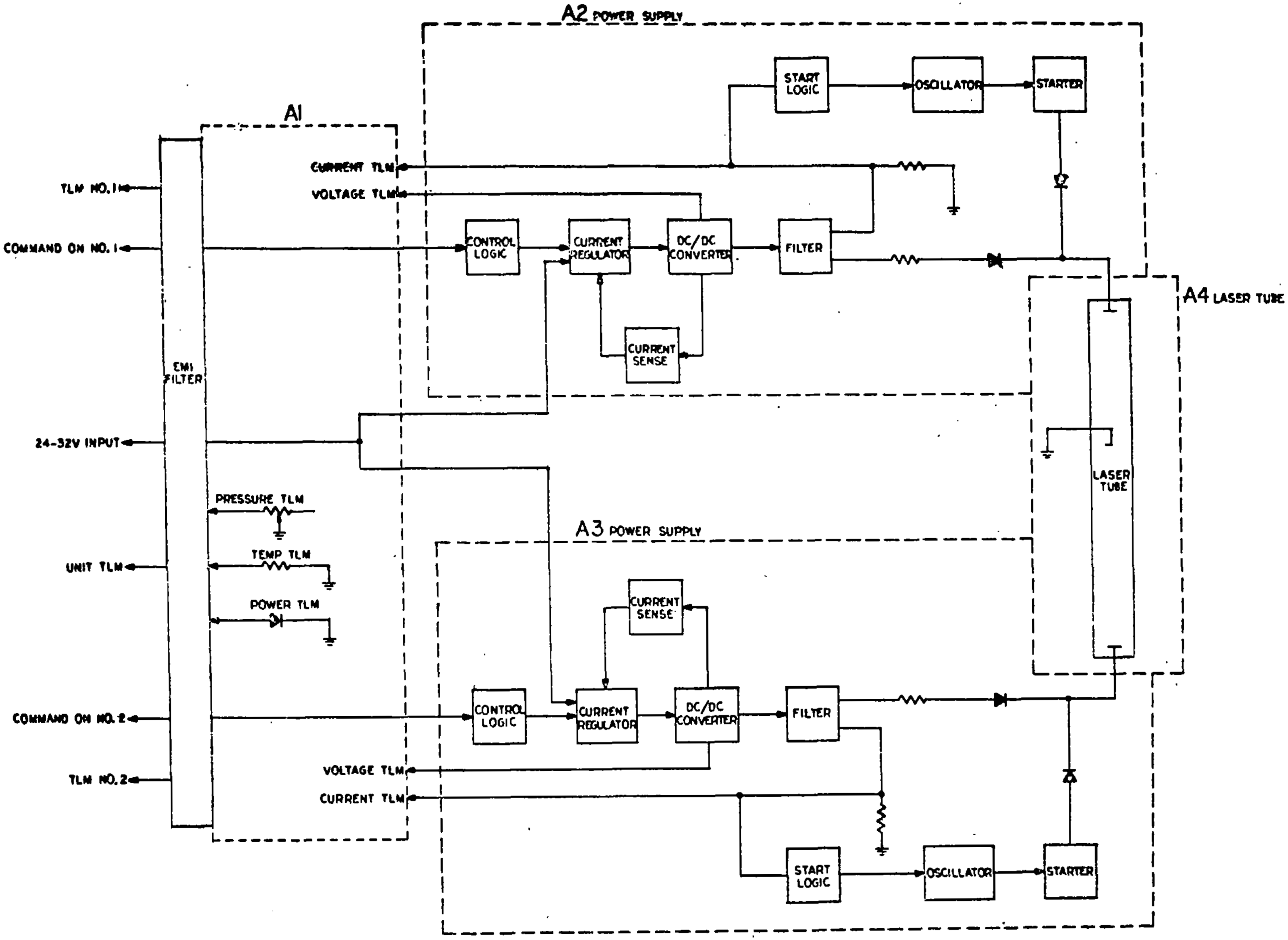

Figure II-3 Block diagram of SQL power supply.

1. Starting Circuitry

The initial starting circuit design employed a silicon control rectifier which was switched allowing a capacitor to discharge through the primary of the trigger transformer to provide the starting voltage pulse to the anode of the discharge tube. However, SCR's are not generally space approved components. A design change is being considered to replace the SCR with a transistor switching circuit.

2. Telemetry

Standard telemetry outputs (0 - 5 VDC) are provided for monitoring both anode voltages and currents as well as the package pressure, laser temperature and laser output power. The following changes or additions have been made in the telemetry circuitry. A solar cell was tested and found to have sufficient output to use a a laser output power detector. The characteristics of this solar cell are shown in Figure II-4. An operational amplifier circuit to provide the 0 - 5 volt telemetry output is shown in Figure II-5. The solar cell has a temperature coefficient of approximately 0.1% current change per degree centigrade with a constant light input.

A pressure sensor has been selected for monitoring the package pressure. It is manufactured by Bourns Instrument and has been tested to or above the required environmental specifications for the SQL. This device provides a resistance that varies linearly with the absolute pressure. An operational amplifier will be used with this sensor to obtain the proper level output.

A thermistor has been selected as the temperature sensor. It too will be used in conjunction with an operational amplifier. This will be used to monitor the laser mounting bracket temperature.

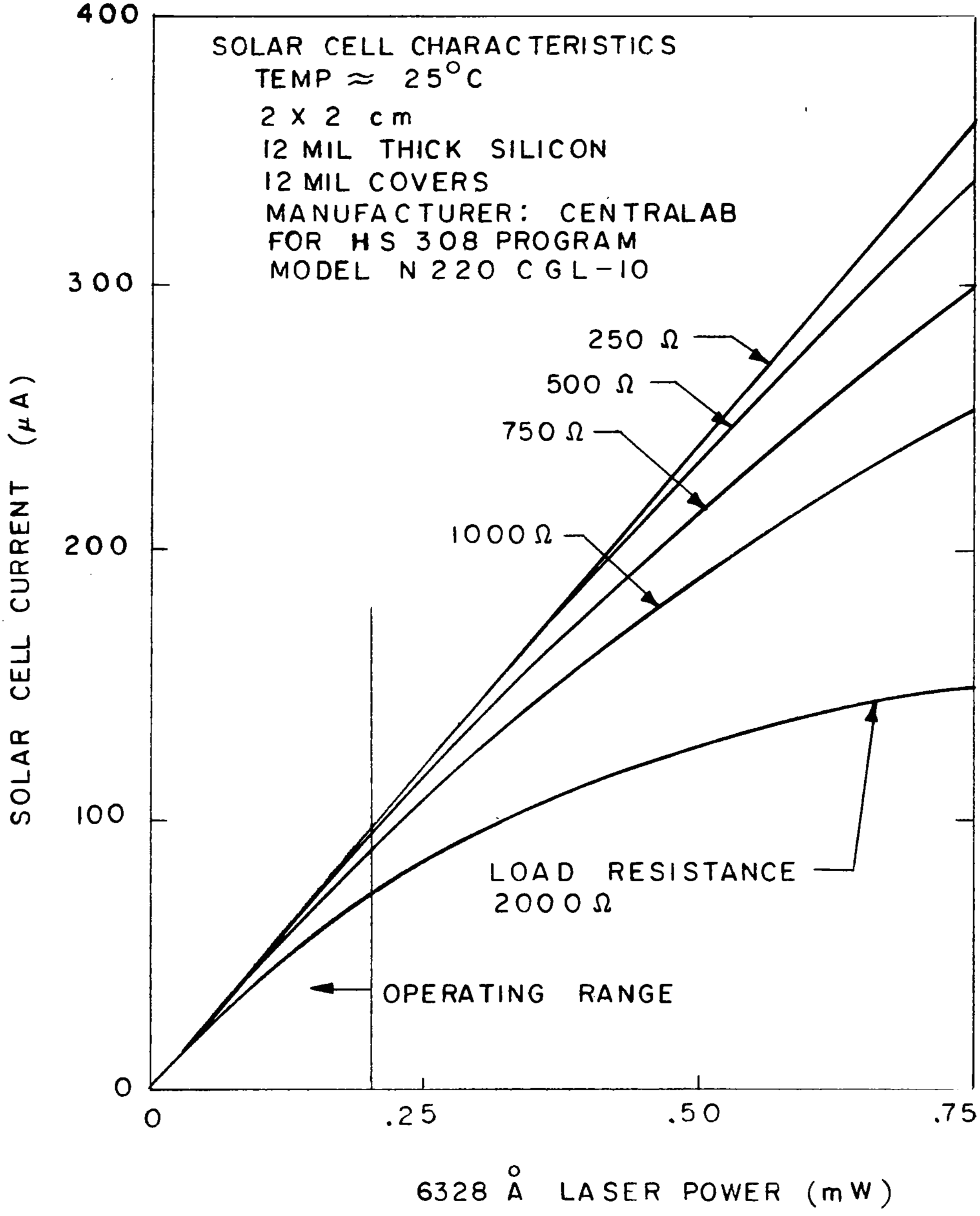

Figure II-4 Solar cell characteristics.

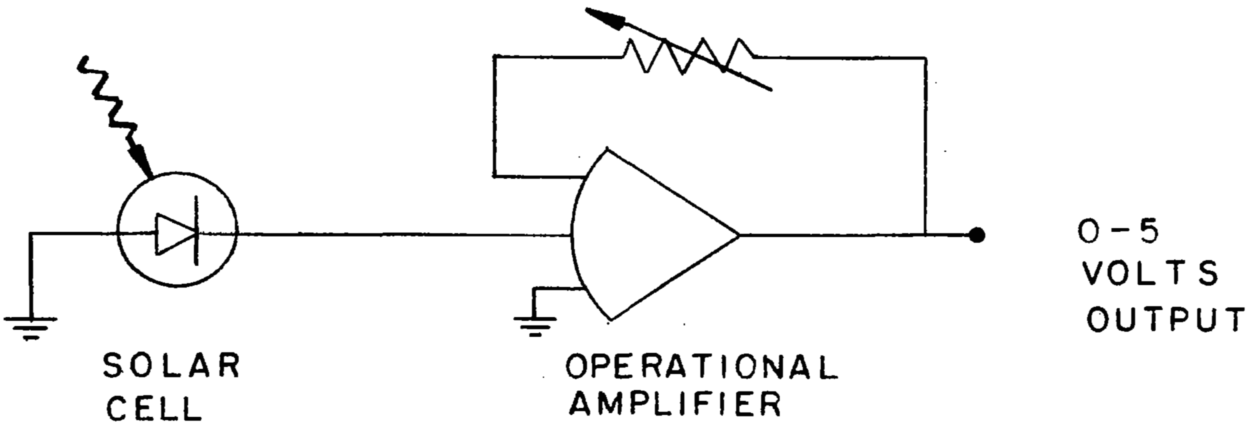

Figure II-5 Telemetry circuit for monitoring laser output power.

D. PACKAGE DESIGN

The integrated laser/power supply package design is shown in Figure II-6. This hermetically sealed helium-filled package is made of aluminum alloy (6061-T6) parts dip brazed together. The electrical connector for the 28 V prime power and the telemetry is a helium-leak tight assembly that is soldered to the package. The output window/beam splitter assembly is shown in Figure II-7. The output window will be sealed with a butyl rubber "O" ring. The assembly housing is dip brazed to the package. A pressure relief valve is provided for evacuating and back filling. A channel which is located around the top of the package, holds a gasket to which the top is sealed. This gasket seal can be used repeatedly if necessary.

An adjustable precision edge is provided for beam alignment. The two independently adjustable surfaces will both be aligned parallel to the beam axis. The surfaces are made of hardened tool steel ground to the required flatness.

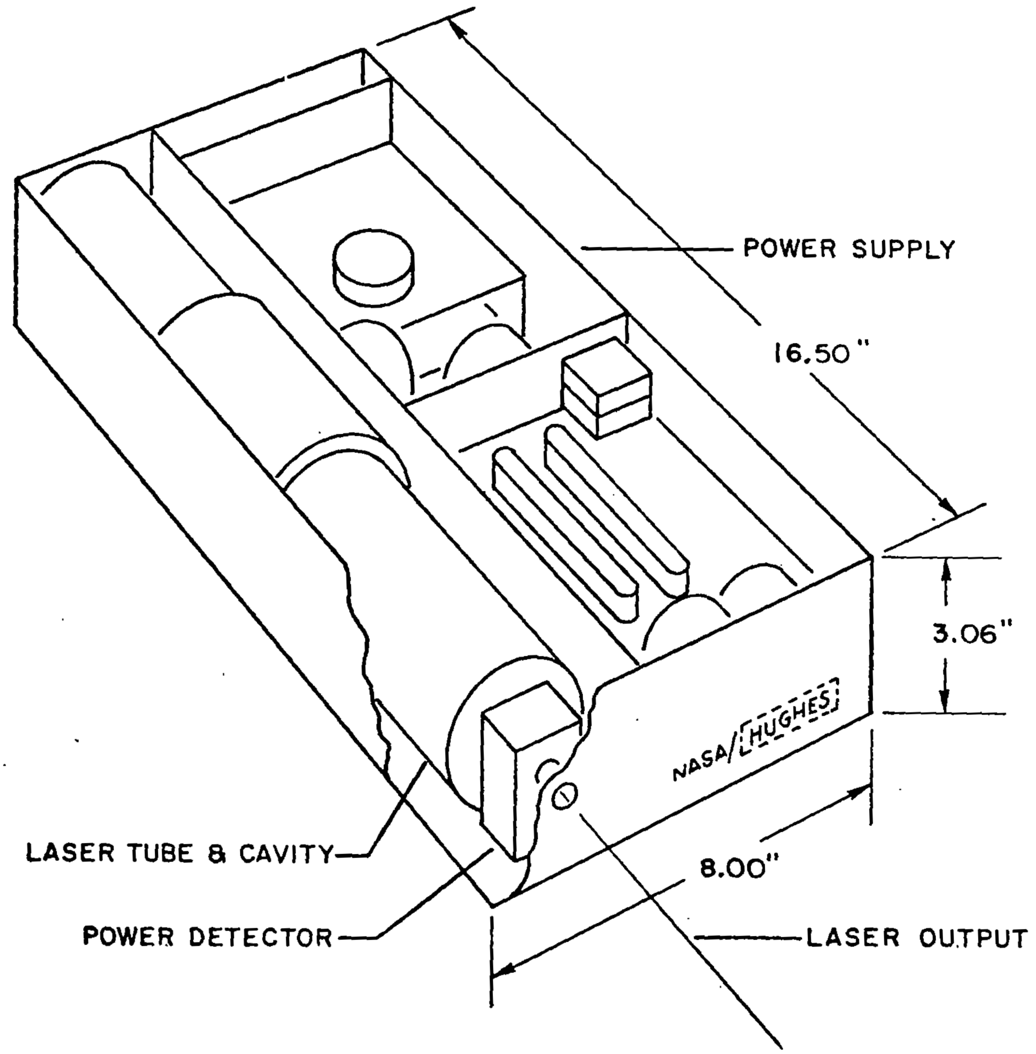

Figure II-6   Laser/power supply package

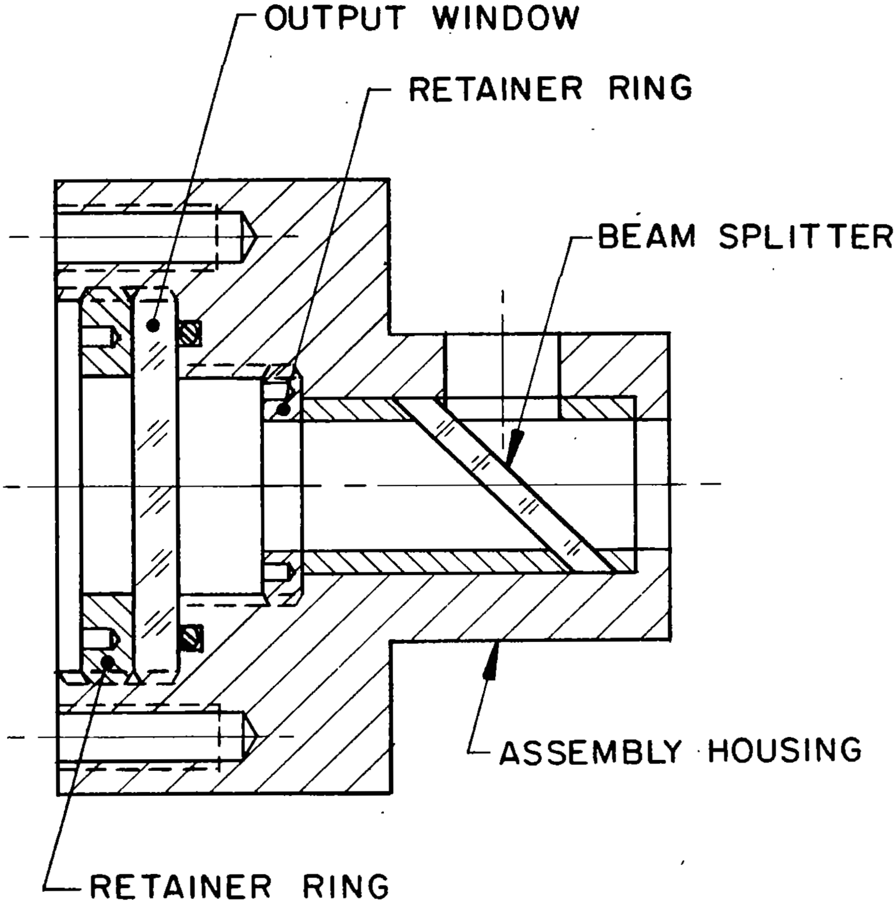

Figure II-7 Output window/beam splitter assembly.

E. RELIABILITY PREDICTION

This prediction updates the prediction of Section J of Reference 1. The reliability of the integrated laser and power supplies is expressed as the product of the probability of mission success for each of its subassemblies. The reliability model of Phase I remains valid as the overall laser unit has two discharge sections within a common metal-ceramic envelope. Each section has separate power supplies which provide the anode and starting voltages and required telemetry circuits. The model is expressed as a series-parallel model and is diagrammed in Figure II-8. This model recognizes two modes of operation. One mode is the probability that the integrated laser provides full power output of 5 mW (i.e., no failures). The probability of success for mode 1 may be expressed by equation 1, which assumes that all subassemblies operate.

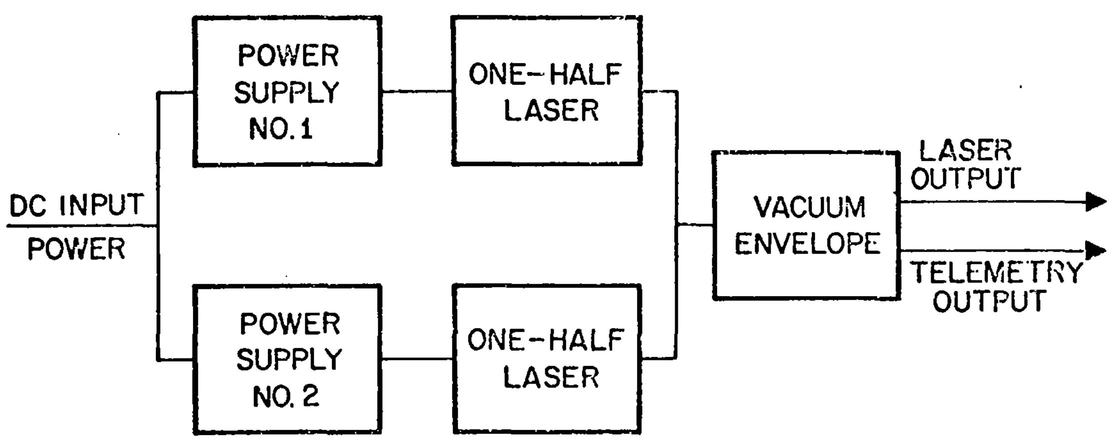

Figure II-8 Reliability diagram.

$$R_{laser} = R_{PS}^{2} \times R_{LDS}^{2} \times R_{VEP} \quad (1)$$

where

R_{laser} = Reliability of the integrated laser and its power supplies (probability everything works).

R_{PS} = Reliability of one power supply

R_{LDS} = Reliability of one discharge section

R_{VEP} = Reliability of the common laser tube vacuum envelope and package.

The second mode for which the probability of success is evaluated allows performance at approximately 35% of the power output; that is, mode 2 assumes the failure of one power supply or discharge element. The probability of success for mode 2 operation is expressed by equation 2.

$$R_{DL} = 1 - (1 - R_{PS} R_{LDS})^{2} \quad R_{VEP} \quad (2)$$

The predicted reliability of the integrated laser unit is shown in Figure II-9. This figure shows the reliability for no failures (5 mW output) and for the degraded mode of operation which provides 35% of the power output.

In addition, curves are provided for the effect on reliability using MIL-spec parts (Phase II) and the use of high reliability parts which will be utilized on the flight unit program (Phase III). This analysis of reliability is based upon actual Hughes laser life test experience and failure rate data of electronic parts selected from MIL-HDBK-217A, "Reliability Stress and Failure Rate Data for Electronic Equipment".

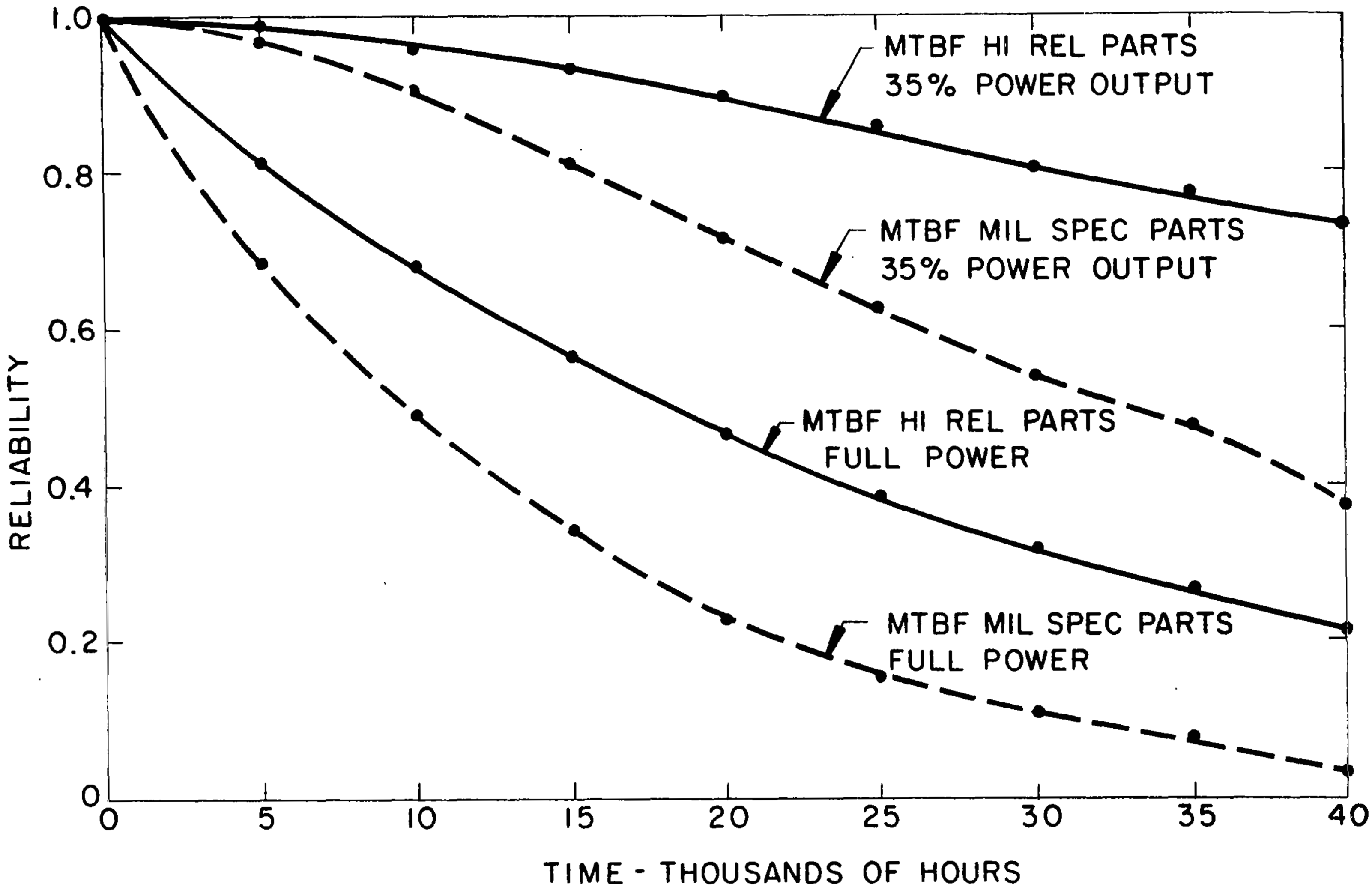

Figure II-9 Reliability as a function of time for MIL Spec parts and high reliability parts.

Hughes Electron Dynamics Division has accrued over 55,200 hours of life test operation on the cold cathode 3082H and 3083H He-Ne (CW) family of lasers. These data indicate to date a demonstrated MTBF of 27,600 hours with two failures. This statement of laser MTBF is only limited by the amount of data accrued to date. As little as ten months ago, Hughes Aircraft Company, Electron Dynamics Division had demonstrated for this family of He-Ne lasers of MTBF of 15,000 hours and was conservatively estimating the actual MTBF to be in the range of 25,000 hours. In the subsequent ten month period the Electron Dynamics Division had demonstrated the actual MTBF to be almost 2 times greater than demonstrated ten months ago. All this points up the rapidly changing state of the art and the rapidly increasing confidence in the He-Ne lasers built at the Electron Dynamics Division. As a comparison, the initial predicted levels for the Hughes medium power traveling-wave tubes were 20,000 hours MTBF based upon similar limited test data. Subsequent life tests have shown that these metal ceramic tubes exhibit an inherent MTBF of greater than 1.5 million hours.

Many of the techniques used in these high reliability space traveling-wave tubes are used in this metal ceramic He-Ne laser. For example, the Hughes metal ceramic seal techniques used in the space traveling-wave tubes will be used for the laser vacuum envelope. This type of vacuum seal has accrued over 1.5 million hours of failure free performance on such space programs as Surveyor, Syncom, ATS, Early Bird, Intelsat, Pioneer and Lunar Orbiter. Therefore, for this estimate the laser MTBF is conservatively estimated to be 50,000 hours.

The reliability parts count prediction for each power supply is contained in Table II-2. The reliability prediction for each power supply does not include the telemetry circuits. The telemetry portion of the laser and power supply is designed to be failsafe; i.e. failure of any telemetry point will not cause a catastrophic failure of the power supply or laser and therefore will not alter the mission success of the integrated power supply and laser.

Table II-2 Power supply parts count and failure rate data (one power supply).

PART TYPE	QTY	MIL SPEC $\lambda/10^{-6}$	HIGH RELIABLILITY $\lambda/10^{-6}$
Transistor			
NPN, Power	4	1.76	.4
NPN, G.P.	1	.56	.015
NPN, G.P.	8	1.75	.304
Diode			
G.P.	24	5.03	.120
Hi Voltage	2	.66	.036
Power	4	1.46	.072
Zener	3	1.64	.06
Resistors			
Metal Film	11	1.77	.027
Power W-W	4	.072	.032
Carbon Corp.	16	.064	.032
Capacitors			
Ceramic	4	.044	.004
Solid Tant.	14	.67	.067
Feed Thru	2	.4	.2
Magnets	7	1.4	.14
TOTAL $\lambda/10^{-6}$		17.55	1.52

SECTION III

SPECIAL TESTS AND EVALUATIONS

There were several problem areas which existed at the end of Phase I of the present contract. The results of special tests which have been conducted to investigate these problems are documented in this section.

A. CATHODE STUDIES AND LIFE TESTS

A continuing company supported cold cathode lifetest program is the basis of the SQL cold cathode design. This program began almost three years ago at Hughes Research Laboratories. Early experiments were made with oxidized aluminum, following Hochuli[2] but this approach was abandoned in favor of oxidized tantalum also built as a hollow structure. Tantalum has more desirable properties as a vacuum tube material and the layer of Ta_2O_5 formed by proper processing should, in theory, have even higher sputtering resistance than Al_2O_3, because of the higher heat of sublimation of Ta_2O_5.

The results of the initial cold cathode life tests for the dual bore design of the SQL discharge tube is discussed on page 46 of reference 4. These life tests, which were performed during Phase I of this program, all failed due to gas clean up caused by cathode sputtering. This problem was initially thought to be due to improper oxidation of the inside of the tantalum cathode in the area where the current density is the highest. More recent tests indicate that the sputtering problem is also associated with the cathode geometry. These tests were conducted on discharge tubes that differed only in cathode geometry. One tube, "A", was identical to SQL, Serial Number 2 and 6 except the cathode was processed by a method which insured proper oxidation of the inside surfaces.

The other tube, "B", had a dielectric septum in the center of the cathode between the two bores which causes an electric field configuration that insures a more uniform current density distribution. This cathode more nearly duplicates the conditions that exist in the 3082H cathode. Both tubes were initially filled to 1.5 torr. Tube "A" failed after 1187 hours, while tube "B" did not fail until it had operated 4120 hours. End of life was determined when the tube pressure reached 1.10 torr. The pressure versus time curve from tube "B" is shown in Figure III-1.

Hochuli[3] has shown that this pressure time curve can be approximated by

$$\frac{P}{P_o} = \left(1 - \frac{t}{\tau}\right)^{1/x}, \quad 0 \leq t \leq \tau$$

where $\frac{P}{P_o}$ is the pressure at time t divided by the initial pressure. The exponent x and lifetime τ for a given cathode material and surface treatment must be determined experimentally. These parameters were determined for tube "B" and are given in Figure III-1 along with the approximate possible time curve.

Once these parameters x and τ are known we can determine, for the same cathode geometry, gas volume and current density, a new lifetime τ_2 for any initial pressure P_2. Doing this for an initial pressure of 2.0 torr, which is about optimum for the SQL, results in a pressure of 1.58 torr after 10,000 hours operation. Thus it would appear that the new cathode geometry will be capable of lifetimes in excess of the 10,000 hour requirement.

This extrapolation is substantiated by the life test results thus far obtained for the metal ceramic prototype discharge tube number 1 which has operated over 5500 hours and is still operating. This cathode design is basically the same as tube "A" except it is 1.8 inches in diameter

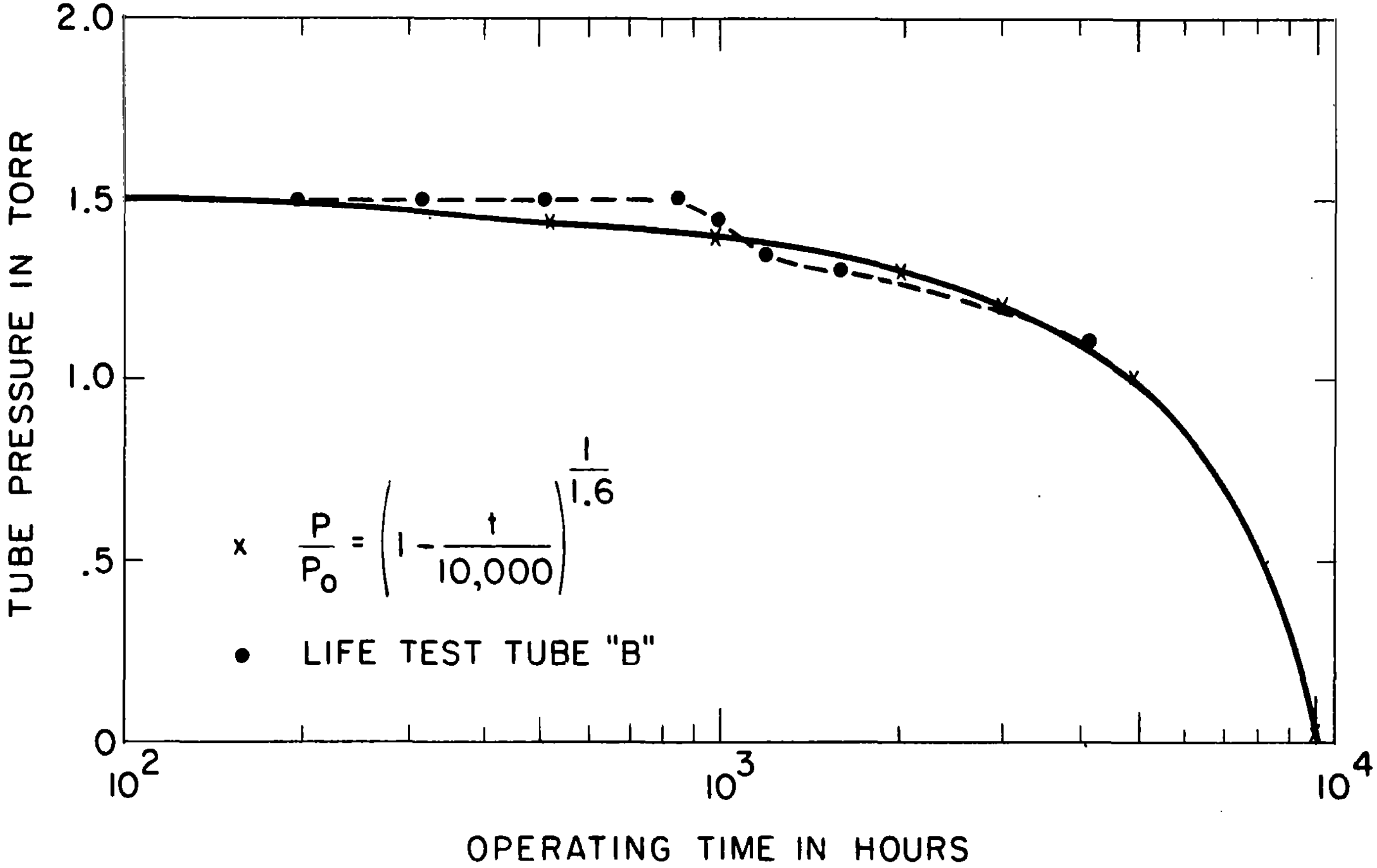

Figure III-1 Cathode geometry evaluation lifetest data.

whereas tube "A" was only 1.4 inches. The higher cathode current density results in a lower expected lifetime τ. The new cathode geometry for the SQL should therefore be much superior to that used in prototype discharge tube number 1 since the cathode diameters are the same.

Lifetests are continuing on Hughes Model 3082H tubes which are being manufactured for Keuffel and Esser Company for use in an alignment laser, see Table III-2, page 49 of Reference 1. Tube numbers 5, 25, and 27 are still operating of 14,740, 7,827 and 8,853 hours respectively. Number 43 failed after only 950 hours due to a vacuum leak. These results again demonstrate the long life capability of this cold cathode design.

B. MIRROR STUDIES

An extensive mirror evaluation program was conducted during Phase I of this contract. The results of this program are presented in Section III-G of Reference 1. In so far as this evaluation was conducted on an external mirror laser, additional tests were required to determine if any problems existed when these same mirror coatings were used internally.

During Phase I a discharge tube, shown in Figure III-2, was constructed with a split bore, common cathode and two anodes. Bellows were attached to the anodes and mirrors were then epoxied to the bellows. The results of these tests are shown in Figure III-3. The results from an identical tube which had Brewster windows and external mirrors is shown in Figure III-4. Thus it was determined that both Optical Coating Labs and Spectra-Physics mirror coatings yielded equivalent results when used internally and substantially more power than was obtained externally.

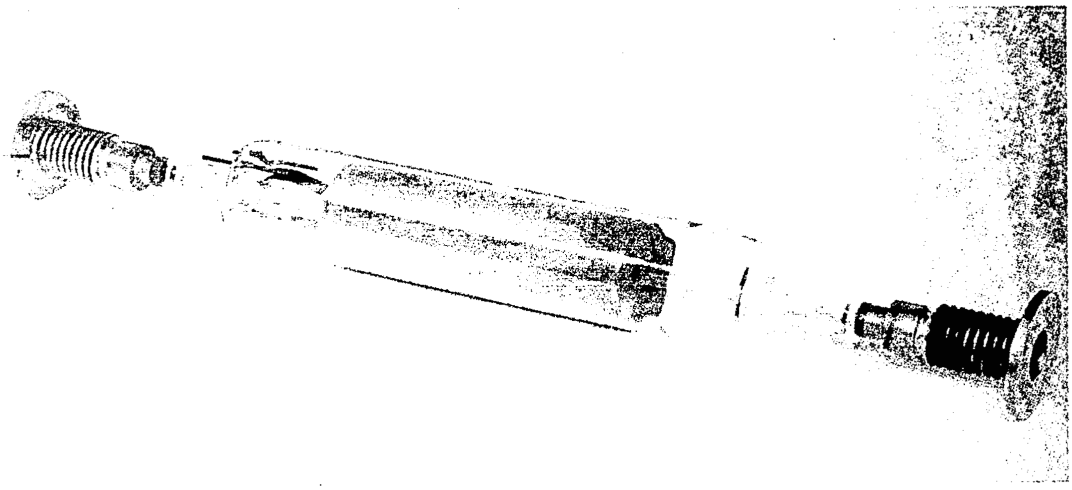

Figure III-2 Glass tube used for internal mirror tests.

Internal mirror lifetests were started to investigate the possibility of long term mirror coating deterioriation. Two glass laser discharge tubes were constructed with a pre-aligned flat high reflecting mirror epoxied on one end and a Brewster angle window on the other end. This design makes possible the use of various external output mirrors which can be readily adjusted. The high reflecting flats were obtained from Optical Coating Labs and Spectra Physics to compare the two different coatings. Both lasers have been running for over 5300 hours with no signs of deterioration and both have essentially the same output power as a comparable external mirror laser. These mirrors are epoxied near the anode of the tube at approximately the same distance as in the SQL design. This is to insure the detection of any mirror degradation due to the deposition of sputtered anode material or particle bombardment that could occur in the SQL design.

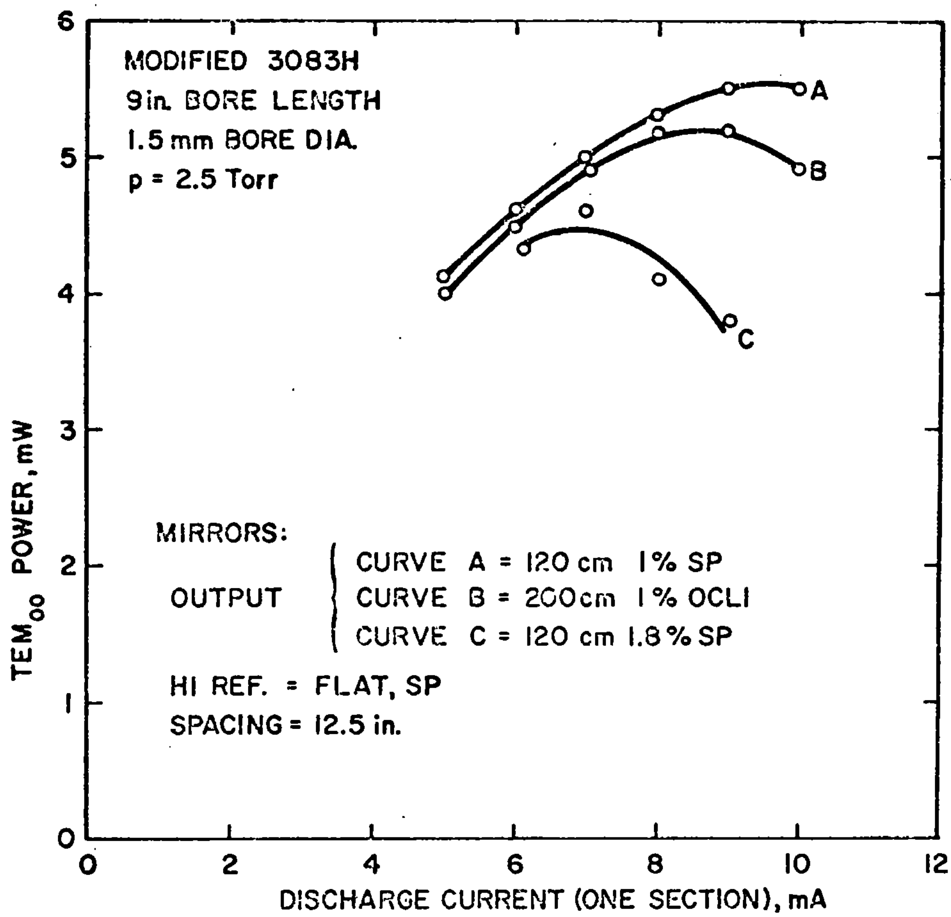

Figure III-3 Measured TEM_{00} power output for a short (9 in.) bore 3083H with different radius internal mirrors.

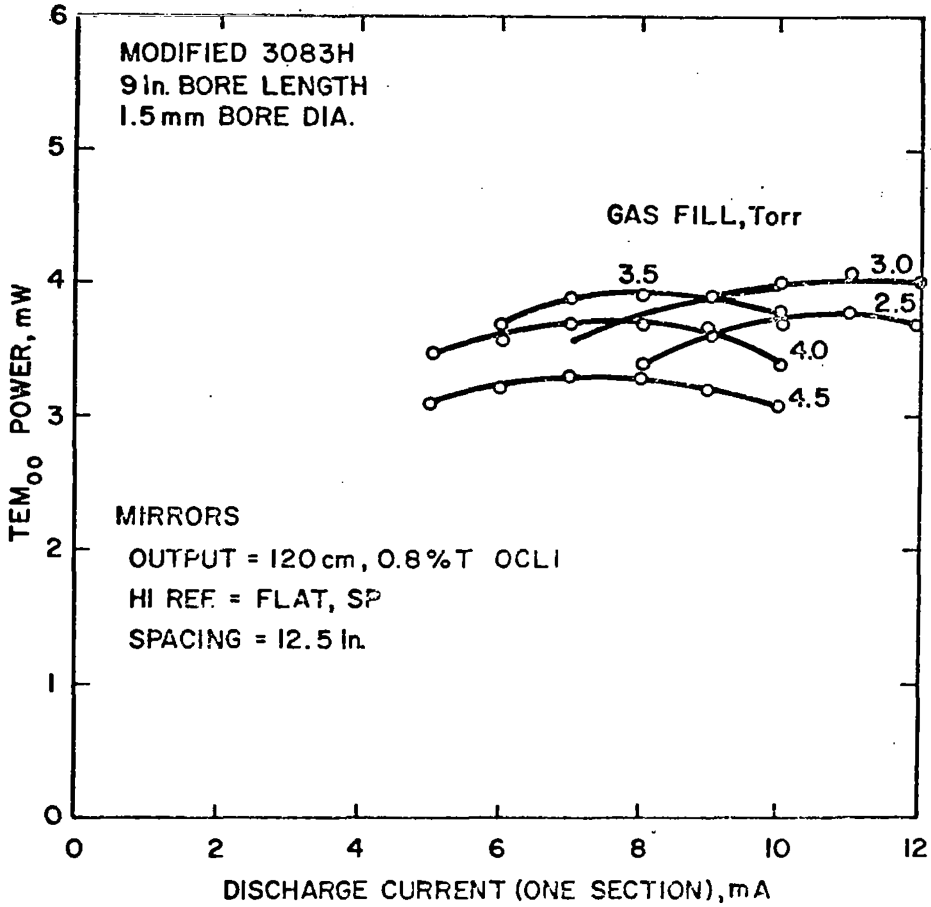

Figure III-4 Measured TEM_{00} power output for a short (9 in.) bore 3083H with external mirrors.

C. MIRROR AND WINDOW SEALS

During Phase I a method was worked out for sealing the output mirror onto the laser without the need for epoxy or other cement. This technique is described in Section III-4 of Reference 1. Upon careful inspection of these glass to metal mirrors fabricated and coated during the initial phase of the program, small vacuum leaks were found in the glass to metal interface. Since the leaks were not discovered until after the mirrors were heliarced to the discharge tube they were initially thought to be caused by thermal stresses set up during heliarcing. However, careful helium leak checking revealed leaks in all the glass to metal mirrors fabricated. These glass to metal mirrors apparently did not leak before grinding, polishing, and coating. Therefore it is believed that these operations may have been the cause of the problem. The reliability of any part of the SQL design should be proven wherever possible. Thus the glass to metal mirrors were dropped in favor of a somewhat space consuming but much more reliable design.

This alternate design, shown in Figure III-5, employs an internal output mirror coated on a fused quartz substrate which will be mechanically mounted. The output beam passes from this mirror through a more conventional optical flat output window. The output window is sealed to a short section of glass tubing which is sealed to a Kovar heliarc flange. This technique is quite straight forward and these seals have proven to be very reliable and are widely used in vacuum viewing ports. Several of the output window assemblies have been fabricated with no problems. The central 3/8 inch aperture remains free of distortion after sealing. A heliarc weld test has been performed on one assembly. This unit shown in Figure III-6 was then subjected to a typical bakeout temperature cycle (ambient to 450°C for 24 hours and back to ambient). The assembly was still leak tight after these tests.

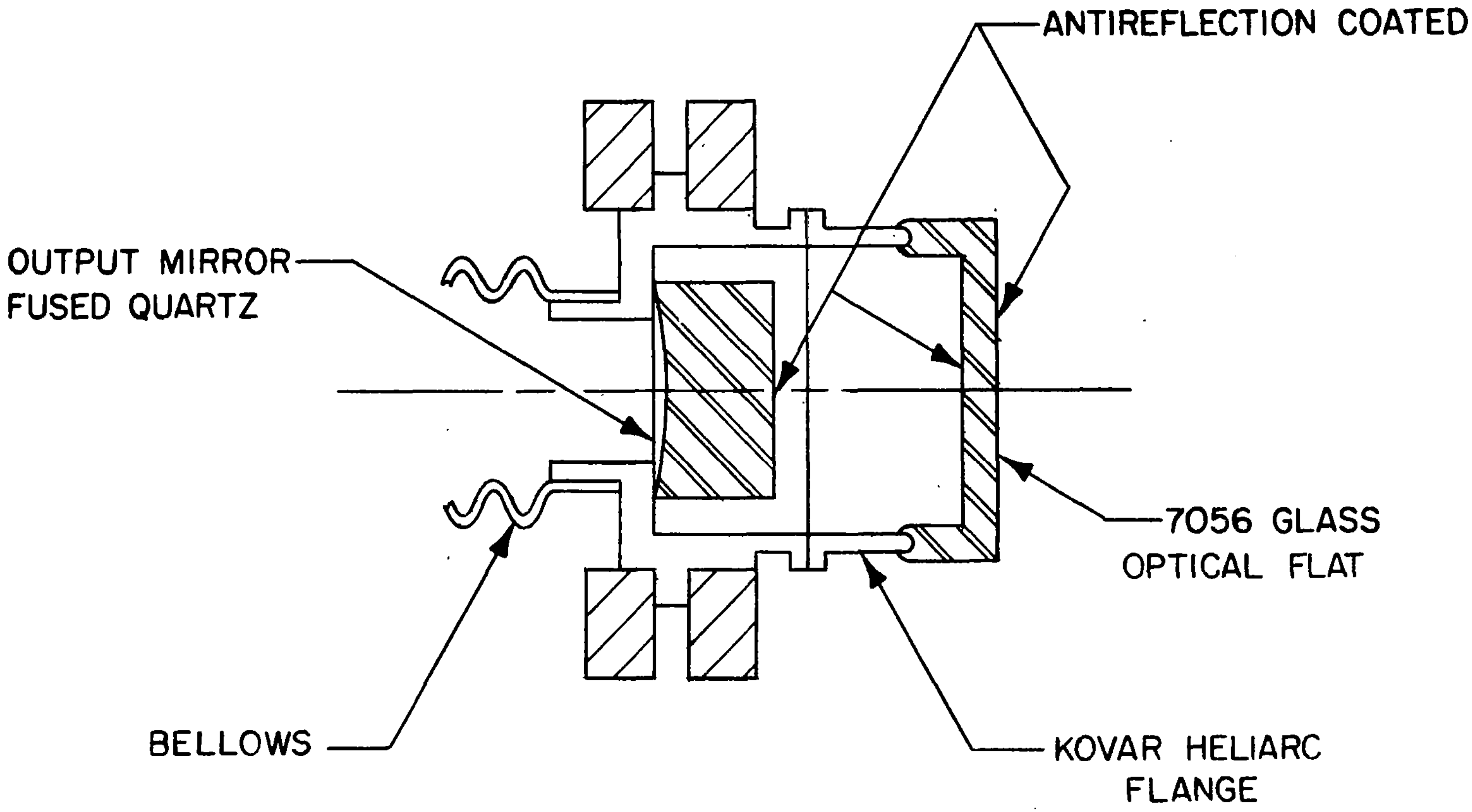

Figure III-5 Output mirror and window design.

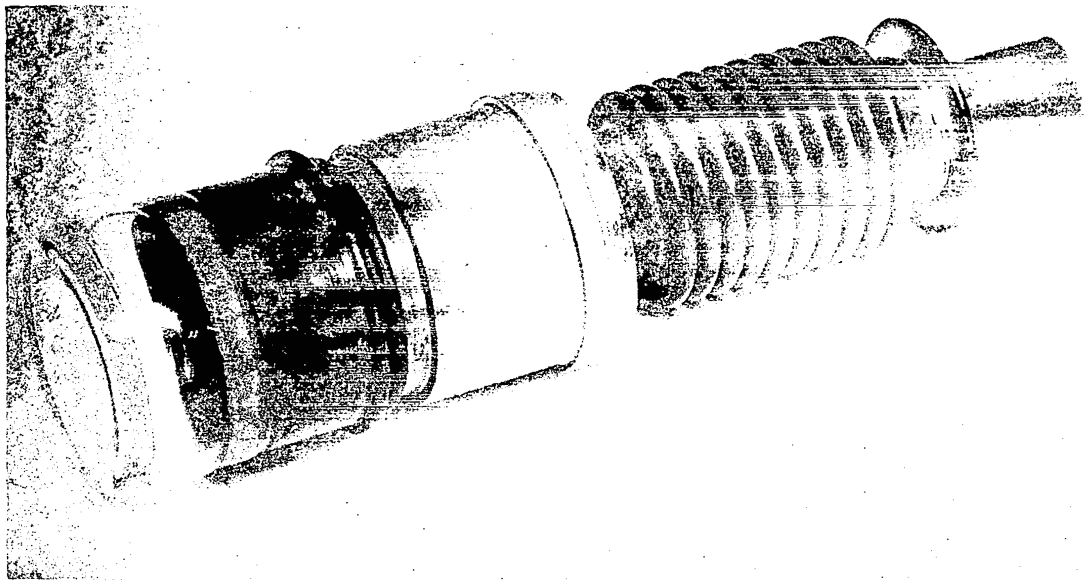

Figure III-6   Output window test assembly.

There are no problems associated with putting an antireflection coating on the outside surface of this window assembly. Since the inside surface is somewhat masked by the kovar flange this may present a problem. However, a maximum reflection of 1.0% total for both surfaces (over a 3/8 inch aperture) seems achievable. These AR coatings have been tested by the manufacturer and are not degraded by the bakeout temperature.

D. ENVIRONMENTAL TESTING

Two prototype metal ceramic laser discharge tubes of the design shown in Figure II-2 of Reference 1 were constructed during Phase I of this program. The second of these units, prototype discharge tube number 2, was processed and packaged. This laser was then subjected to the required sinusoidal vibration test. A resonance was noted at 1100 Hz and the forces measured on the ends of the mirror support cylinder reached 120 g's. Although the unit did not suffer permanent failure, the mirrors did misalign. This was determined to be due to movement of the mirror support which was held by four screws to the mirror support cylinder. In the modified design shown in Figure II-1 the mirror support is held in place by a threaded retainer ring which should prevent any movement. It is also instructive to note that the resonant frequency of the mirror support frequency of the mirror support cylinder, which is proportional to $(E/\rho)^{1/2}$ where E is the modulus of elasticity and ρ the density, would have been approximately 2800 Hz had it been made of beryllium rather than aluminum. Thus the resonance noted would have been above the 5 to 2000 Hz frequency range of the test and since the modified design is shorter the resonance will be well above this range.

This unit was also subjected to part of the required shock test. It was shocked three times in each of the two axes mutually perpendicular to the long axes. Again the only problem was misaligned mirrors due to movement of the mirror support. Since an expensive fixture would have been required for shock testing this unit along the long axis it would have been required for shock testing this unit along the long axis it did not seem feasible to conduct the test but rather to wait and test the modified design later in the program.

E. DISCHARGE TUBE NUMBER ONE

The first discharge tube of the modified design (Figure II-1) has been constructed and tested. No problems were encountered in the fabrication of the various subassemblies. The time required during final assembly to align the two ceramic bores was greater than anticipated. This can be rectified in future construction with proper fixturing.

The tube was then placed in a vacuum bakeout station. It was baked out at 350^{o}C maximum for approximately 20 hours. The tube was pumped with a vac-ion pump system during bakeout.

After bakeout the tube was valved off under vacuum and placed in a test cavity support structure. It was then connected to an oil diffusion pump vacuum station for back filling and testing.

The discharge was extremely clean and free of contamination but all efforts to get lasing action failed. The prism was then removed by grinding down the heliarc weld flanges and replaced with a high reflectance flat mirror which was epoxied in place. Lasing action was obtained but the output power was low; the best obtained was only 1.7 mW. Both mirrors were then removed and upon careful inspection the output mirror was found to be crazed, apprarently from the temperature cycling during bakeout. The prism coating which had also gone through the bakeout appeared to be unaltered. Both the mirror and prism were checked in an external mirror laser, the prism was unchanged (both were tested in this manner before the tube was assembled) but the output mirror appeared lossy, apparently due to the crazed coating. The output mirror had been coated by Optical Coating Labs and the prism by Spectra-Physics. It is interesting to note that OCLI coats with a substrate temperature of 300^{o}C while SP uses 350^{o}C. As we reported previously, except for this crazing problem, both of these manufacturers' mirrors have been evaluated and determined to be of equal quality. Although the lossy output mirror, which was crazed, explains the low power it does not explain the non-lasing seen when the prism was used. This problem was apparently due to difficulties experienced in mirror alignment when a prism is used.

Spectra-Physics mirrors were then epoxied on discharge tube number 1. An output power of 4.8 mW was obtained. This was in the TEM_{01} trans-mode due to the use of a 120 cm radius output mirror selected because it was a stock item and readily available from SP. Although slightly less power would be expected in the TEM_{00} mode, the above data was taken with He^4 rather than He^3 and between 10% and 20% more power can be expected with the He^3 isotope.

The flat high reflectance mirror was then removed and replaced by a Brewster's angle prism. This was epoxied to an extension that increased the mirror spacing by 1.0 cm. Data taken with He^3 isotope is shown in Figure III-7. This appears to be almost all TEM_{00} as shown in Figure III-8, which is a sketch of the laser output modes observed with a Spectra-Physics Model 420 optical spectrum analyzer.

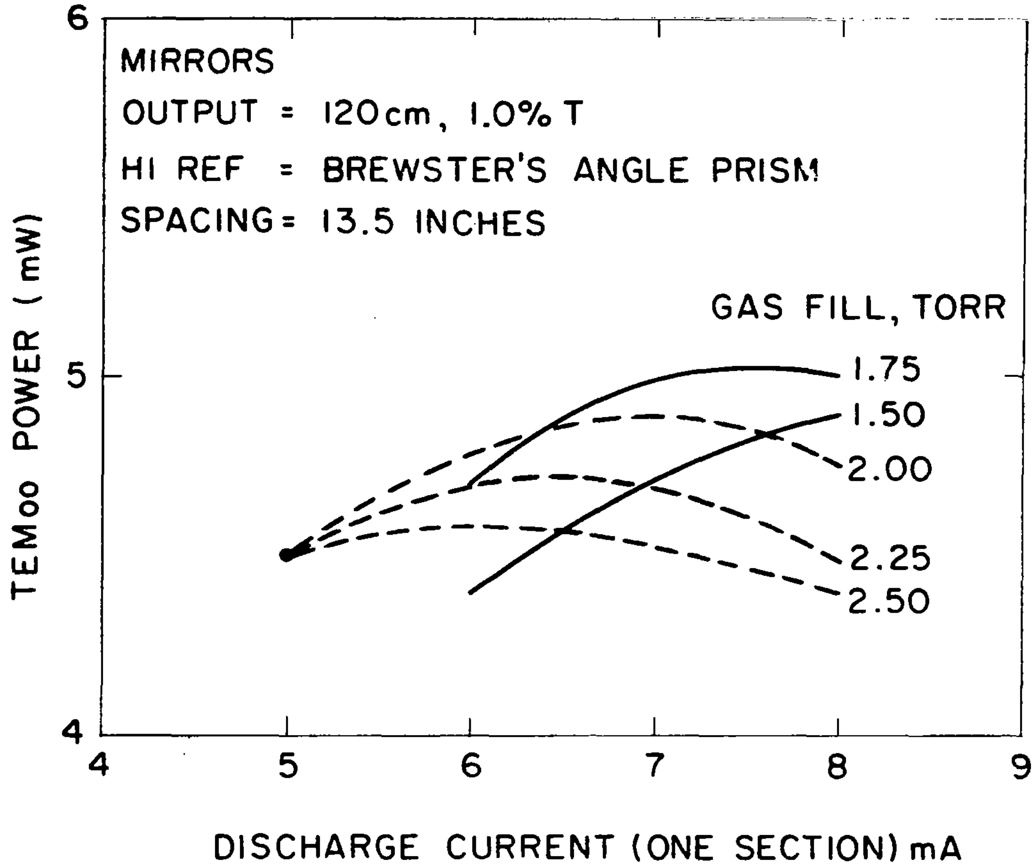

Figure III-7 Measured TEM_{00} power output for discharge tube number one.

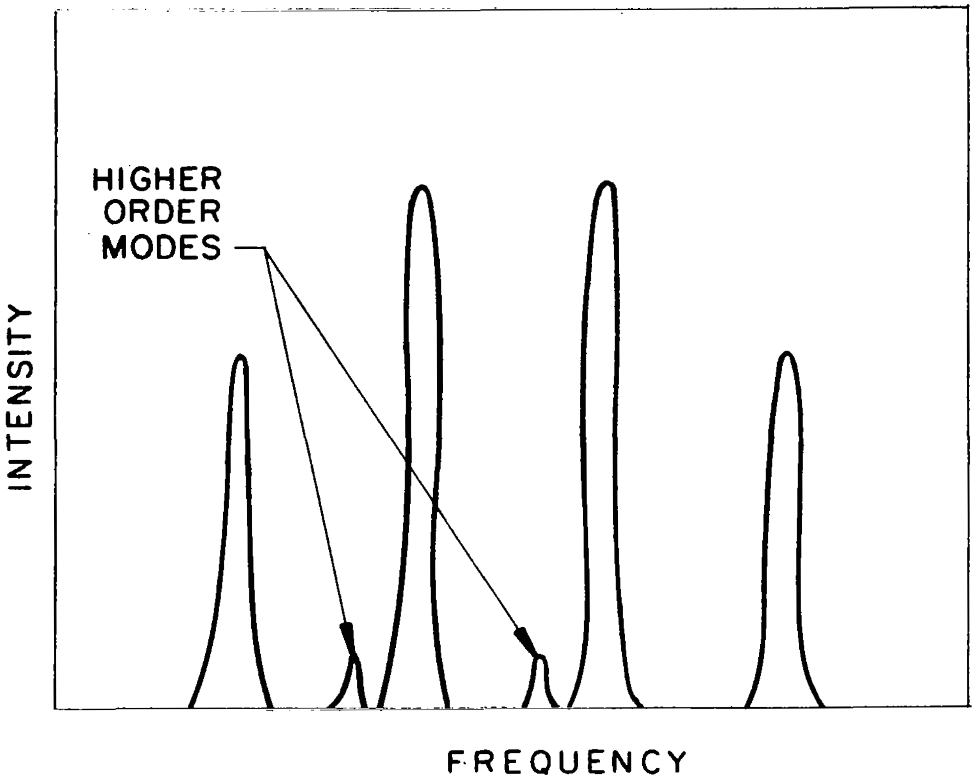

Figure III-8 Sketch of output modes observed with optical spectrum analyzer.

Discharge tube number 1 was then subjected to part of the required environmental shock test. It was mounted in the test cavity fixture as shown in Figure III-9. The laser performance was not changed by this test which consisted of 3 shocks perpendicular to the long axis. Shock tests along other axes were not performed due to special fixturing requirements.

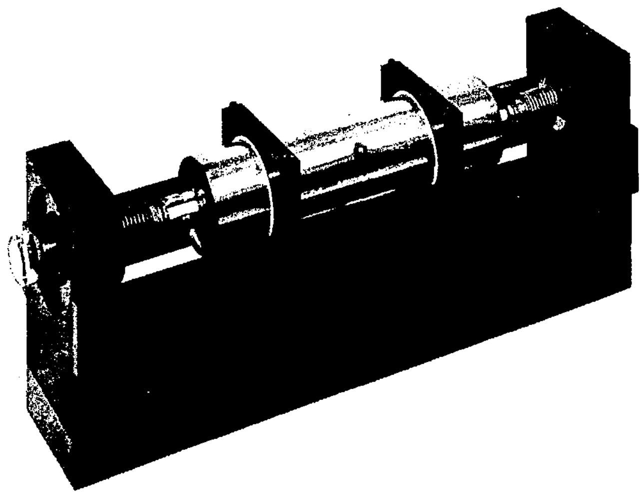

Figure III-9 Laser mounted in special test cavity.

The same laser configuration was then subjected to the required sinusoidal vibration test. The laser output power was measured before and after vibration testing in each of three mutually perpendicular axes and again remained constant.

Although these tests were not performed in the SQL cavity support structure they give great confidence as to the ruggedness of the entire design. Forces of 30-40 G's were measured on the mirror supports during vibration yet the mirrors stayed in alignment. The actual SQL cavity support structure using the beryllium cylinder should have not resonances below 2000 Hz, the upper end of the required vibration testing spectrum, and therefore the forces on the mirror supports should not reach these high G levels.

The epoxied-on mirrors were then removed from discharge tube No. 1 and replaced with Spectra-Physics mirrors of the required design, i.e., a 200 cm output mirror and a cylindrical Brewster's angle prism. The mirror and prism with respective holder parts and the output window are shown in Figure III-10. The prism holder and the anti-reflection coated output window were then heliarc welded to the discharge tube. The discharge tube was then baked out as before at 325°C for 24 hours.

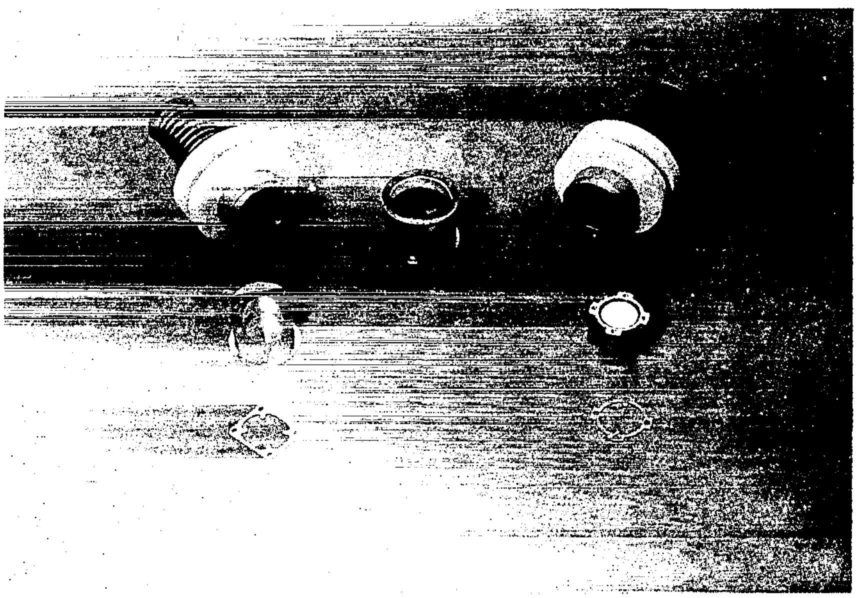

Figure III-10 Laser mirror and prism with their respective holder and bellow assemblies and the output window.

Discharge tube No. 1 was then mounted in the test cavity and backfilled with He-Ne. The maximum power output obtained was between 4.0 and 4.4 milliwatts. This is all in the TEM_{00} transverse mode as verified with the Spectra-Physics Model 420 Optical Spectrum Analyzer. The reason for the low power was never determined. The getter was activated and the tube pinched off. It is shown in Figure III-11 just before packaging. This laser was packaged in an aluminum cavity support cylinder and used for power supply tests.

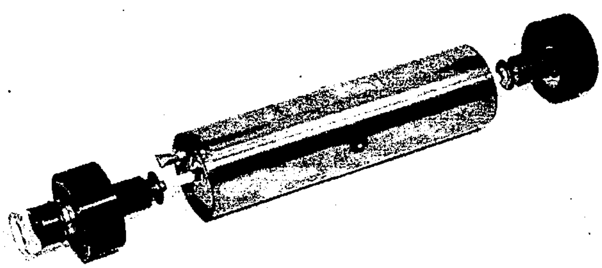

Figure III-11. Discharge tube ready for packaging.

SECTION IV

FUNDAMENTAL DESIGN PROBLEMS

A. DISCHARGE TUBE NUMBER TWO AND THE BREWSTER'S ANGLE PRISM TEMPERATURE INSTABILITY

A second discharge tube was constructed identical to discharge tube number one (DT No. 1). The construction of the vacuum assembly was again performed with no difficulties. The discharge tube subassemblies are shown in Figure IV-1. This tube was baked out at a maximum temperature of 200^{o}C for 72 hours.

After bakeout the tube was placed in the test cavity as shown in Figure III-9 and connected to an oil diffusion pump vacuum station for cathode activation and testing. The tantalum cold cathodes were activated by operating an oxygen discharge in each half of the discharge tube one side at the time. The 0_2 pressure used was 2.0 Torr and the discharge current was 45 miliiamps.

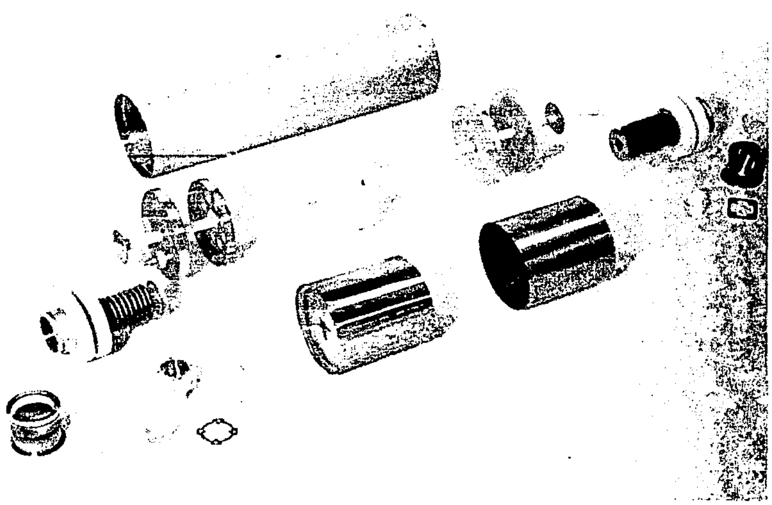

Figure IV-1 Discharge tube subassemblies. Cathode cylinder, bore assemblies, ceramic septum, bellows assemblies tantalum cathodes, and optical parts.

The mirrors were then aligned and a maximum power of 4.3 milliwatts was obtained at pressure of 2.0 Torr and a discharge current of 7.5 milliamps per side. The output power with either side of the discharge running separately was 1.5 milliwatts. The tube was then pinched off and the mirrors realigned. The maximum power obtained was 5.7 milliwatts which proved to be all in the TEM_{00} mode as verified with the optical spectrum analyzer. The spectrum consisted of 4 but sometimes 5 lines. Two of the lines were extremely weak when the mirror spacing was such that 5 lines were present.

DT No. 2 was then removed from the test cavity and placed in the beryllium mirror support cylinder. It was held in place inside the cylinder with set screws rather than being actually potted. The mirrors were aligned and a power output of 5.5 milliwatts was obtained.

In this configuration the laser was found to be very temperature sensitive. Operating on an insulated stand allowing only convection cooling the laser package would stabilize at approximately 45°C. If the mirrors were aligned under this condition and the laser turned off and allowed to cool and then turned back on it would not start lasing with reasonable power, $\approx$5 mW, until the temperature of the cylinder was back up to 42 - 45°C. By running each side of the discharge independently it was determined that the problem was associated with the prism end of the laser. The initial thought was the stainless steel mount, to which the prism is clamped at an angle, was causing a rotation of the prism with temperature. A calculation showed this to be a problem but did not explain the magnitude of the misalignment that was measured. Next, the change in index of refraction of the fused quartz (from which the prism is made) with temperature was investigated. This turned out to be the problem and calculations (see Appendix C) and measurements have definitely pinned this down. The misalignment due to the prism was calculated to be over 10 microradians per degree centigrade and 80 - 100 microradians misalignment is sufficient to completely stop lasing.

The temperature stability problem never showed up in all of the testing that was done in the test cavity fixture, Figure III-9. This was apparent because the prism and mount are so well thermally isolated from the discharge tube, where the heat is generated. The laser was never thermally cycled in this configuration.

B. STARTING INSTABILITY AND CATHODE SPUTTERING

During the testing of the packaged power supplies with DT No. 1 and No. 2 a starting instability problem began to appear which became more pronounced the longer the discharge tube was operated. Either side of the split discharge column would start and operate normally but keeping both sides on simultaneously became impossible unless the operating current was increased from the design value of 7.5 milliamps to approximately 10 milliamps per side. In addition, this instability could be brought on by a slight increase in the anode to cathode stray capacitance and this problem also became increasingly worse as a function the operating time logged.

Discharge tube number one was autopsied and evidence of severe cathode sputtering was found. However, this sputtering occurred on only one of the two tantalum dual cathodes. The photograph of the two bore assemblies with the unsputtered cathode still attached is shown in Figure IV-2. The black deposit on the one bore is sputtered material which is probably tantalum. However, there is evidence that brazing

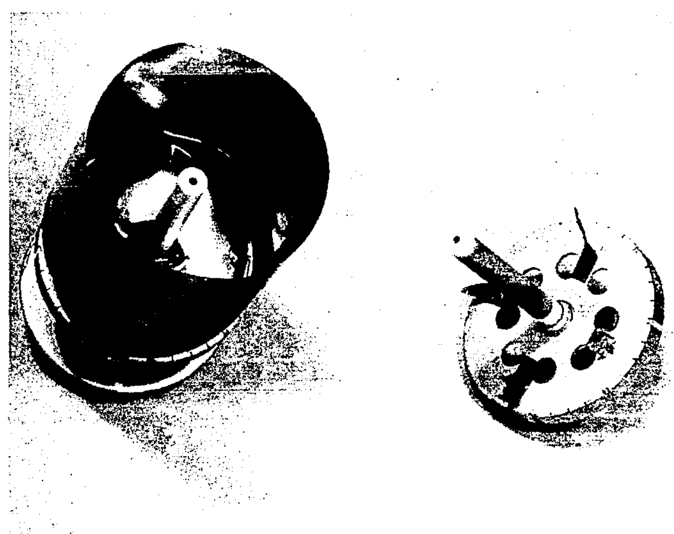

Figure IV-2 Bore assemblies from DT No. 1 showing the results of severe cathode sputtering.

material has also been sputtered. The discharge appears to have been getting outside of the cathode can through the gap between the cathode end cap and the ceramic bore. The back end of the cathode end cap, which was removed from this bore, showed evidence of sputtering. There is no evidence of sputtering of the other cathode bore assembly. The cathode sputtering appeared to be the cause of the starting instability. However, the reason for the cathode sputtering in view of the previous lifetests as discussed in Section III-A was not known. A glass discharge tube with an identical dual cathode design was constructed and lifetested to investigate the sputtering problem. The glass tube showed operating characteristics similar to DT No. 1 and No. 2 and failed due to gas cleanup caused by sputtering in less than 1000 hours of operation. The sputtering again occurred on only one cathode.

SECTION V

DESIGN INVESTIGATIONS AND PROBLEM SOLUTIONS

A. SOLUTION TO THE BREWSTER'S ANGLE PRISM TEMPERATURE INSTABILITY AND 3.39 MICRON COMPETITION

A possible solution to the laser cavity misalignment problem discussed in Section III-F was investigated. The Brewster's angle half prism was replaced by a subassembly which consists of an internally mounted Brewster window and a flat high reflecting mirror. This subassembly, shown in cross section in Figure V-1, was designed to replace the Brewster's angle prism assembly which is shown in Figure II-1. An analysis of the internal Brewster window-flat mirror configuration shows that the first order effect of a change in the index of refraction of the material from which the window is fabricated results in a lateral displacement of the beam on the flat mirror but does not result in any angular misalignment. This lateral displacement would, however, result in an angular misalignment if the mirror was curved rather than flat.

A single bore metal-ceramic laser was built on an internally funded program. The optical cavity used in this laser design was essentially the same as that employed in the SQL design. However, the Brewster's angle prism was replaced with the internal Brewster window-flat mirror design as shown in Figure V-1. The window was made of fused quartz and was 2 mm thick. The optical parts which were used along with their respective holders and clamps are shown in Figure V-2.

Tests performed on the single bore laser have proven the internal Brewster window-flat mirror design to be a solution to the temperature misalignment problem. However, 3.39 micron competition can now become a serious problem and was one reason for the Brewster's angle half prism

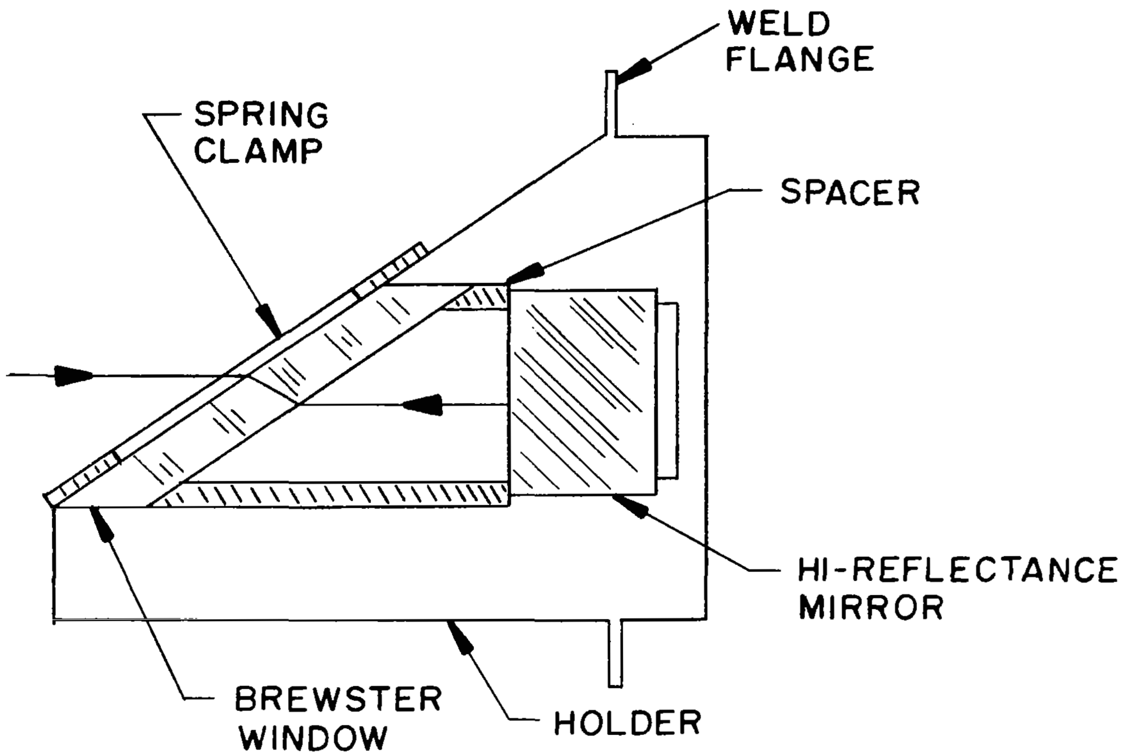

Figure V-1 Mirror/window holder assembly

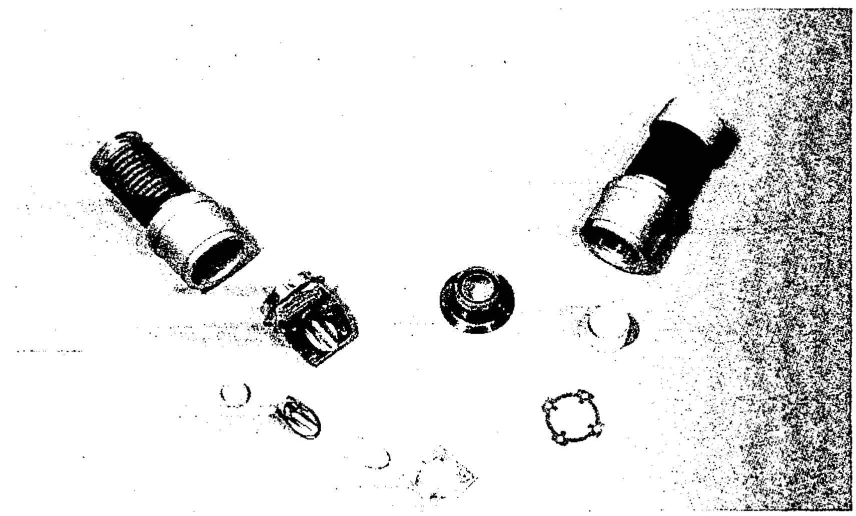

Figure V-2 Parts for internal Brewster window-flat mirror assembly, output mirror and output window.

being employed in the SQL design. A discussion of this competition problem can be found in a recently published book by Bloom[4].

The single bore metal-ceramic laser suffered from severe 3.39 competition effects. The recording of the laser output power as function of time during warm-up shown in Figure V-3 clearly illustrates the competition effect. As the laser cavity increases in length due to thermal expansion the laser lines corresponding to the various longitudinal modes at both 632.8 nanometers and 3.39 microns are sweeping across their respective Doppler broadened gain curves. Two periodic variations appear in the power output recording in Figure V-3. The small amplitude variation is due to the 632.8 nm lines sweeping the gain curve and even the effect of the Lamb dip can be seen. The large amplitude variation is due to the 3.39 micron competition which causes a maximum decrease in the visible power output when the single line which can oscillate is centered on the 3.39 micron gain curve. The width of the half-maximum points on the Doppler curve is given by Bloom[4] to be 310 megahertz and the longitudinal mode spacing for this cavity is approximately 455 megahertz, hence only a single line at 3.39 micron. The periods or fluctuation rates of these variations are related by the ratio of the two different wavelengths, approximately 5:1. If the intensity of the spontaneous radiation at 359.3 nanometers, the lower laser level of the 3.39 micron line, is also recorded during warm-up complete correlation with the previously described visible output data is observed.

The 3.39 micron reflectivity of a mirror coated during the same run as the output mirror used in the laser just described was measured to be 12%. A similar measurement on the flat high reflectance mirror used in this laser gave $\approx$ 5%. Although the 3.39 micron reflectivity of laser mirror designed for optimum performance at 632.8 nanometer can be controlled to below 5% per mirror, another

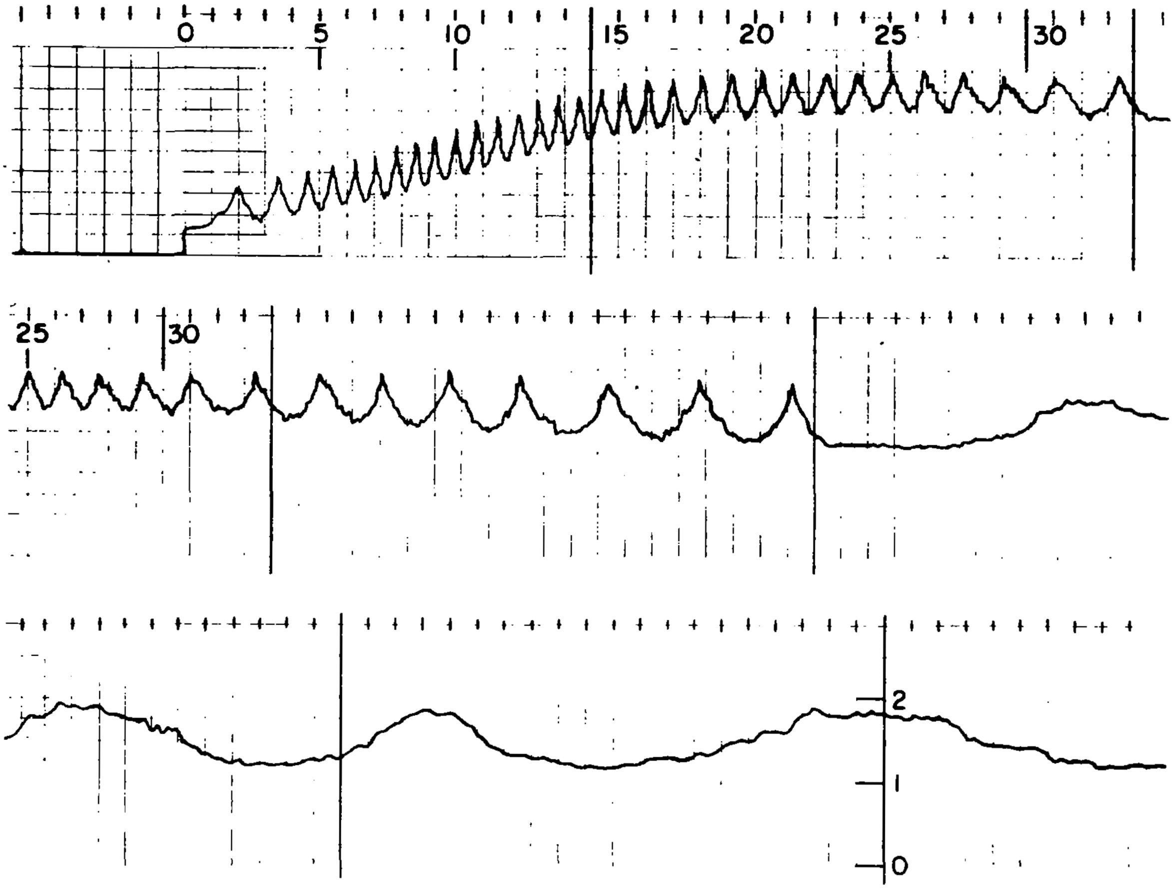

Figure V-3 A recording of laser output power vs time during warm-up which shows the effect of 3.39 micron competition.

solution has been quite successful. This solution is the use of a glass Brewster angle window, either BK-7 or BSC-2, which both have very high absorption at 3.39 microns, see Figure V-4. However, a combination of the glass Brewster window and low 3.39 micron reflectivity would obviously be the most desirable solution.

B. FABRICATION AND TESTING OF A MODIFIED LASER DESIGN EMPLOYING ALUMINUM COLD CATHODES

The SQL laser design was modified in an attempt to solve the two problems discussed in Section IV: 1. The temperature stability, 2. The cathode sputtering.

The Brewster's angle prism was replaced with an internal Brewster window-flat mirror assembly as described in Section V-A. However, the Brewster window which was used was made of BK-7 optical glass rather than fused quartz in an effort to suppress 3.39 micron competition effects. Due to the time required to obtain new mirrors with lower 3.39 micron reflectivity we were forced to use those which were available, i.e. 12% and 5% 3.39 micron reflectivity for the output and high reflector respectively.

From an analysis of discharge tube No. 1 it was determined that the starting instability problem is brought on by cathode sputtering. This sputtering occurs on only one of the two identical cathodes. A glass discharge tube with an identical dual cathode design was constructed and lifetested. It showed similar operating characteristics and failed due to gas cleanup caused by sputtering. This sputtering again occurred on only one cathode. The reason why one cathode sputters is not known. It could be the cathode geometry, the dual cathode design, the cathode processing (oxidation), or possibly it is associated only with Ta_2O_5 on Ta cold cathodes. However, the fact that we have run successful lifetests on single Ta cathode tubes would certainly indicate the latter was not the cause.

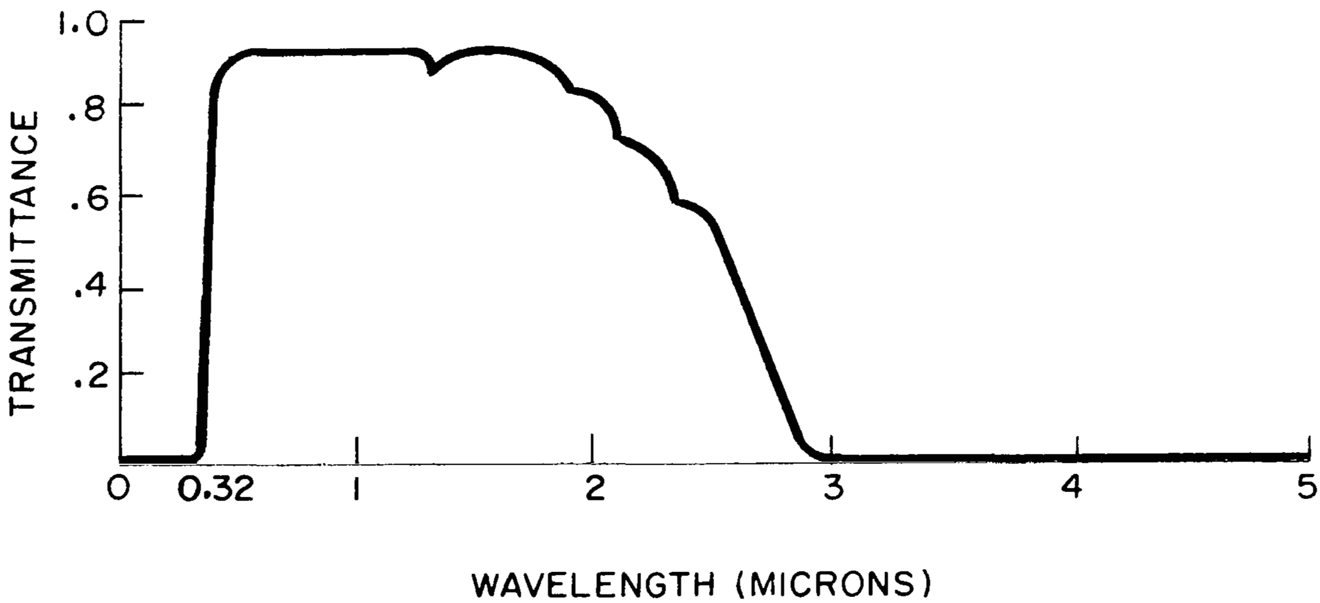

Figure V-4 Transmission of BK7 Borosilicate Glass (thickness 1/2 inch, reflection losses included, taken from manufacturers catalog).

We have run extensive evaluation on tantalum and aluminum cathodes in glass tubes. We have found that both kinds can demonstrate equally good life (>5000 hours) but that tantalum cathodes have shown more irregular results, and aluminum is preferred in our present designs. The only difference between Al and Ta that we have seen is the greater cathode fall ($\approx$ 130V) associated with the Ta-Ta_2O_5 cathode. However, we have not tested Al in the double cathode configuration. We have tested Al in a single-bore, metal-ceramic laser and it appears to be performing satisfactorily after 3500 hours. Thus, a possible solution to the sputtering problem encountered in the dual cathode discharge tube could be the use of Al_2O_3 on Al cathode.

The cold cathodes for the modified design were made from 2024 aluminum alloy. One of the cathode cylinders along with the aluminum cathode end cap and the alumina dielectric separator is shown in Figure V-5. In

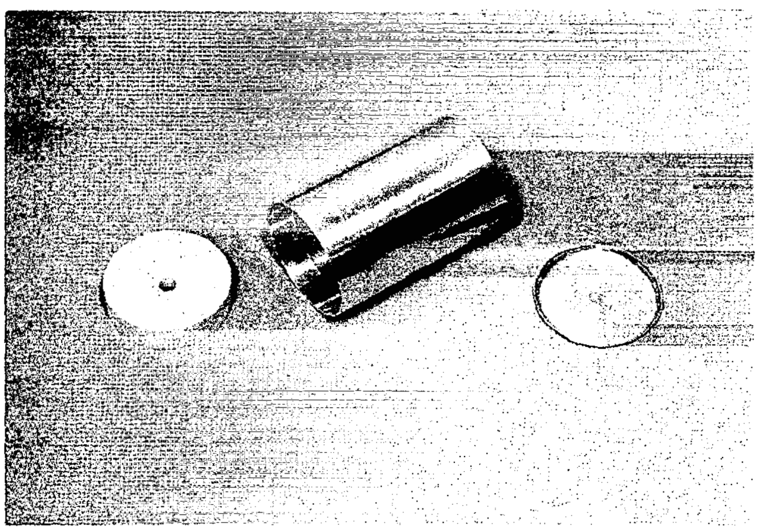

Figure V-5 Aluminum cold cathode cylinder, end cap and dielectric septum.

addition to changing the cold cathode material small aluminum cylinders were placed over the bores between the cathode end caps and the internal bore supports, see Figure II-1, to shield the brazing material at this joint from the discharge. As discussed in Section IV-B there was evidence that this area had been sputtered in discharge tube number 1.

The modified SQL discharge tube was baked out at 300°C for 16 hours and then the temperature reduced to 200°C and the bakeout continued for another 24 hours. The tube was then valved off and placed in the test cavity, see Figure III-9. It was connected to an oil diffusion pump vacuum station for cathode processing(oxidation) and testing. The aluminum cathodes were oxidized in the same manner as the Ta cathodes (see Section IV-A) had been oxidized previously.

The tube was then filled to 2.0 Torr with He-Ne gas. After the mirrors were aligned a laser output power of 2.6 milliwatts was obtained at approximately 7.5 milliampere per side. The tube was run overnite and the power increased slightly to 2.85 milliwatts at 7.5 milliamps per side which was the optimum current for this gas pressure. There were no signs of any 3.39 micron competition effects.

The tube was then pumped out and refilled to 2.0 Torr and the power output increased to 3.0 milliwatts. After two more days of continuous operation a maximum power of 3.4 milliwatts was obtained at an optimum current of 8.0 milliamps per side. There were still no signs of power fluctuations to indicate the presence of 3.39 micron competition.

The tube was again evacuated, the getter activated and then it was refilled to 2.0 Torr. After 2 more days of operation the output power was holding constant at 3.5 milliwatts. The tube was then pinched off and the laser output was observed to be all in the TEM_{00} mode. The noise in the laser output was measured to be less than 1% peak-to-peak from <30 Hz to 0.3 MHz. The input to the SQL current regulated power supply, see Sections II-c and V-c, was 0.76 amps at 30 VDC. This compares to an input of 0.90 amps at 30 VDC required for the tantalum cathode discharge tubes which have a higher cathode fall.

The discharge tube was then potted inside the beryllium mirror support cylinder and the mirrors realigned. An output power of 3.9 milliwatts was obtained. Approximately one hour was required for warm-up from an ambient temperature turn on. There was absolutely no signs of 3.39 micron competition. A maximum power of 4.1 milliwatts was obtained when the mirrors were in perfect alignment.

After 1000 hours of continuous operation there has been no indication of performance change. The laser output power as well as the discharge tube voltages and currents are being monitored. During part of the time the laser has been operating in the package with the top closed. The power output is 3.7 milliwatts with the beam splitter in place.

From the test results obtained to date it appears that the modification of the design has solved the two major problems. The only remaining major problem is associated with the extremely sensitive mirror alignment requirements imposed by the long radius cavity design. This problem is discussed in the summary, Section VI.

C. LASER POWER SUPPLY AND PACKAGE FABRICATION AND TESTING

Two laser power supplies and packages of the design discussed in Sections II-C and II-D were fabricated and tested. Photographs of the package with and without the laser in place are shown in Figures V-6 and V-7. The outline and mounting drawing of the laser package is shown in Figure V-8. One of the power supply/package units was tested with discharge tube number one. The results of these tests along with a discription of a new starting circuit is discussed below.

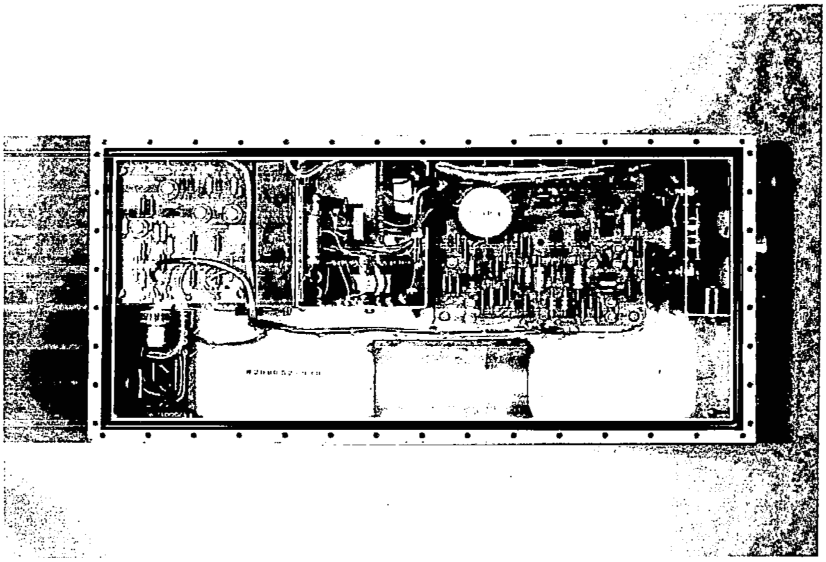

Figure V-6   SQL package with laser removed.

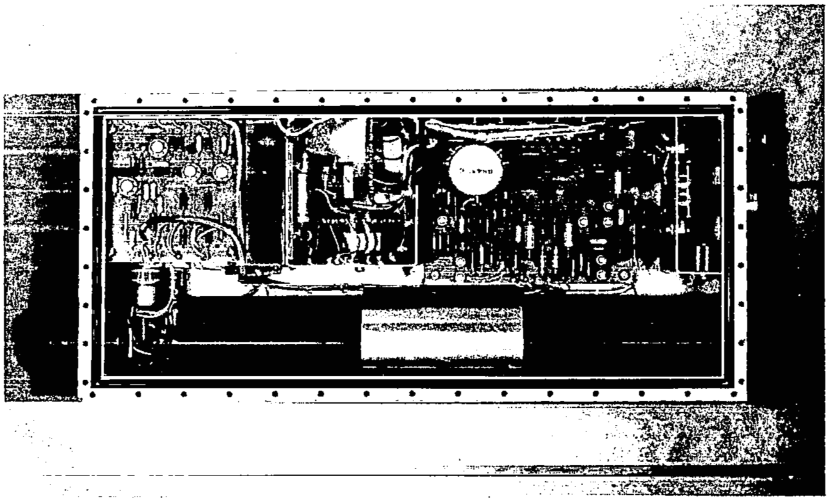

Figure V-7   SQL package with top removed showing laser in mounting.

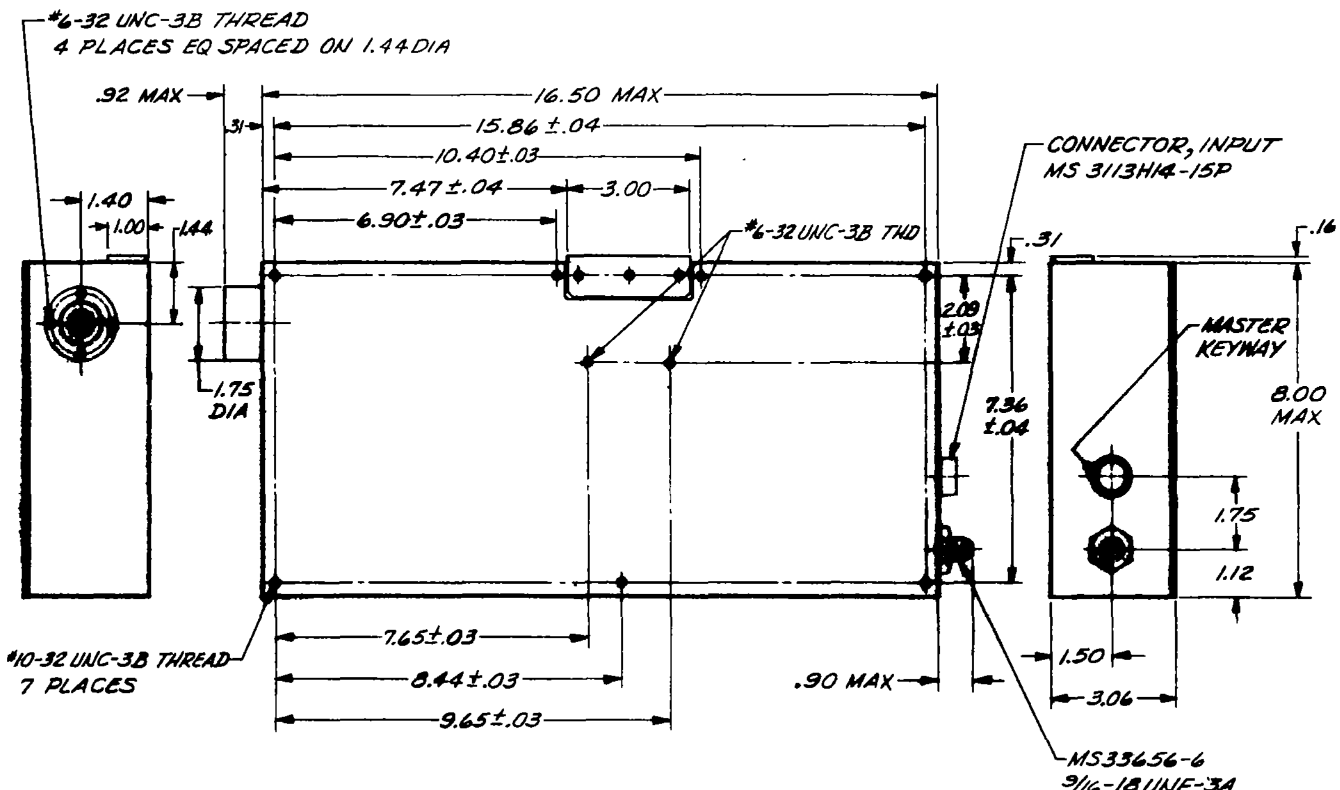

FIGURE V-8

REDUCED SIZE

A new laser discharge tube starting scheme, which replaces the SCR high voltage transformer approach, was designed and tested. This design, shown in the block diagram Figure V-9, employs a voltage multiplier stage to provide a DC voltage to initially exceed the required ionizing voltage. Once the discharge tube draws current this starting voltage will appear across the large 100 mega-ohm dropping resistor and the current regulated lower voltage supply will sustain the discharge. Schematic drawings of the SOL power supply are shown in Figure number V-10. (See sheets 1 through 5.) The power supply design was modified to incorporate this new approach and tested in the breadboard model from -40°C to +75°C. Although this outside the required operating range (-10°C to +50°C), the starting circuit performed exceedingly well: the discharge tube was outside the chamber during these tests.

Laser power supply package, (Serial Number 1) and a laser discharge tube in an aluminum mirror support cylinder (Serial Number 1) was subjected to the required thermal cycling test. In addition, cold starts of the discharge tube at both -20°C and -40°C were conducted with no problems. The unit was actually operated from -40°C to +74°C but the laser thermally detuned apparently due to the problem with the prism. The total current regulated between 14.9 ma and 15.15 ma over the required -10°C to +50°C range.

The optical power output telemetry transducer and circuitry was tested and found to meet all design requirements. It was tested from -10°C to +50°C and the output is essentially constant for a constant laser light input. (The temperature coefficient of the solar cell is approximately 0.1% current charge per degree C.) The remaining telemetry circuits were all calibrated and subjected to similar temperature cycling test.

The second unit weighed 14.0 pounds; the package and power supply weigh 11.0 pounds and the laser dischrage tube/beryllium mirror suppor weigh only 3.0 pounds. The laser power supply package design from the tests and evaluations which were performed would appear to be ready for qualification testing.

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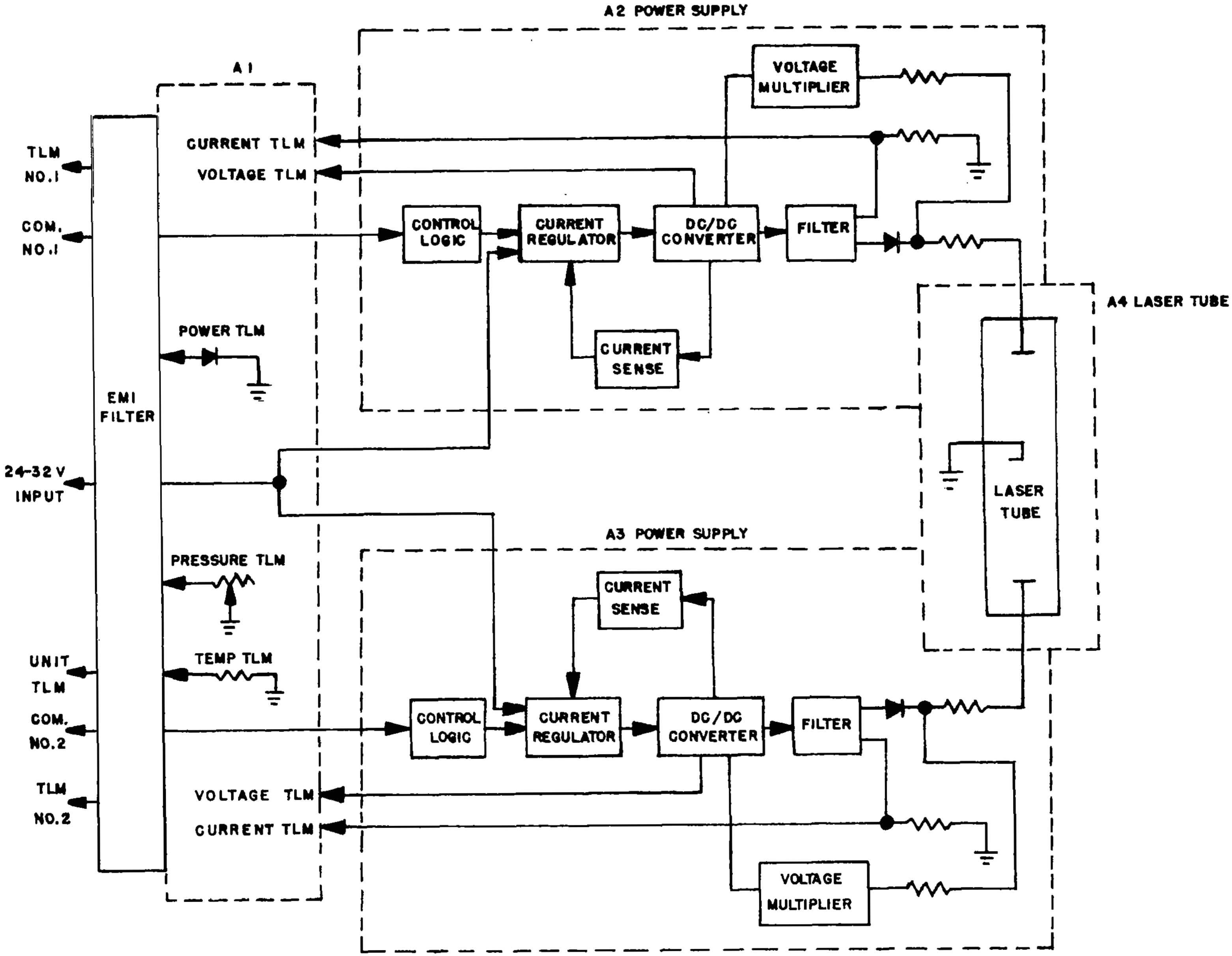


Figure V-9. Block diagram of SQL power supply modified to incorporate the new starting scheme.

REFERANCE DESIGNATION		
ASSY	LAST NO. USED	NO. NOT USED
THIS	A6	
	C4	
	FL4	
	J1	
	L2	
	MT1	
	Q10	
	R2	
	RT1	
	T4	
	V1	
A1	C11	
	CR23	
	Q8	
	R35	
	T1	
	VR5	
A2	C2	
	CR5	
	L1	
	R1	
A3	C2	
	R5	R3
	V1	
	Z1	
A4	C6	
	R24	R2, R8, R14, R17, R19
	Z4	
A5	C8	
	CR8	
	R2	
A6	C6	

FIGURE V-10 (Sheet 1).

4. Z1, Z2, Z3, & Z4 - PIN 7 ARE CONNECTED TO +10 V

3. Z1, Z2, Z3, & Z4 - PIN 4 ARE CONNECTED TO -10 V

2. ALL CAPACITANCE VALUES ARE IN UF, ±10%, 200 V

1. ALL RESISTOR VALUES ARE IN OHMS, ±1%, 1/8 W

NOTES - UNLESS OTHERWISE SPECIFIED

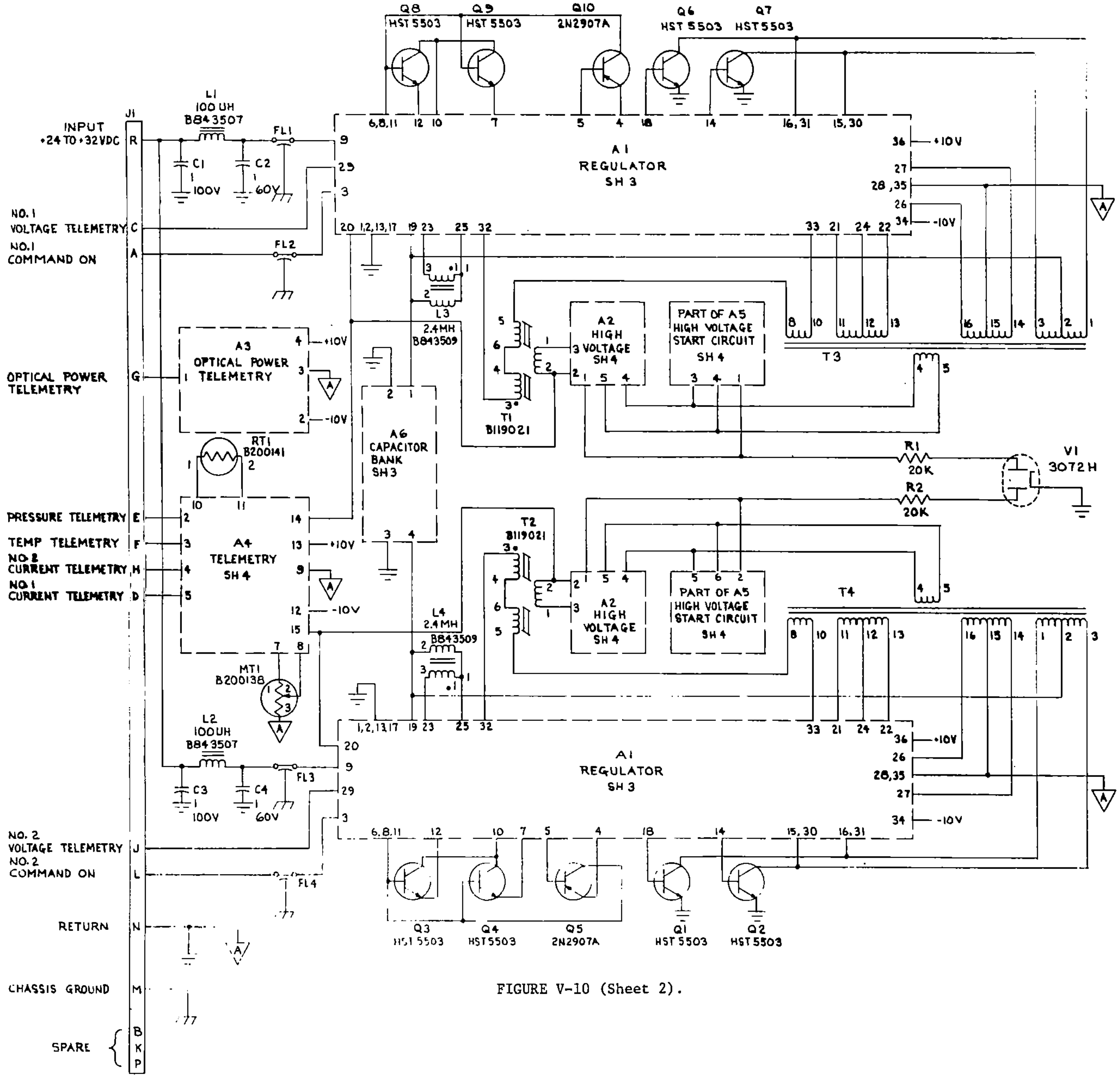


FIGURE V-10 (Sheet 2).

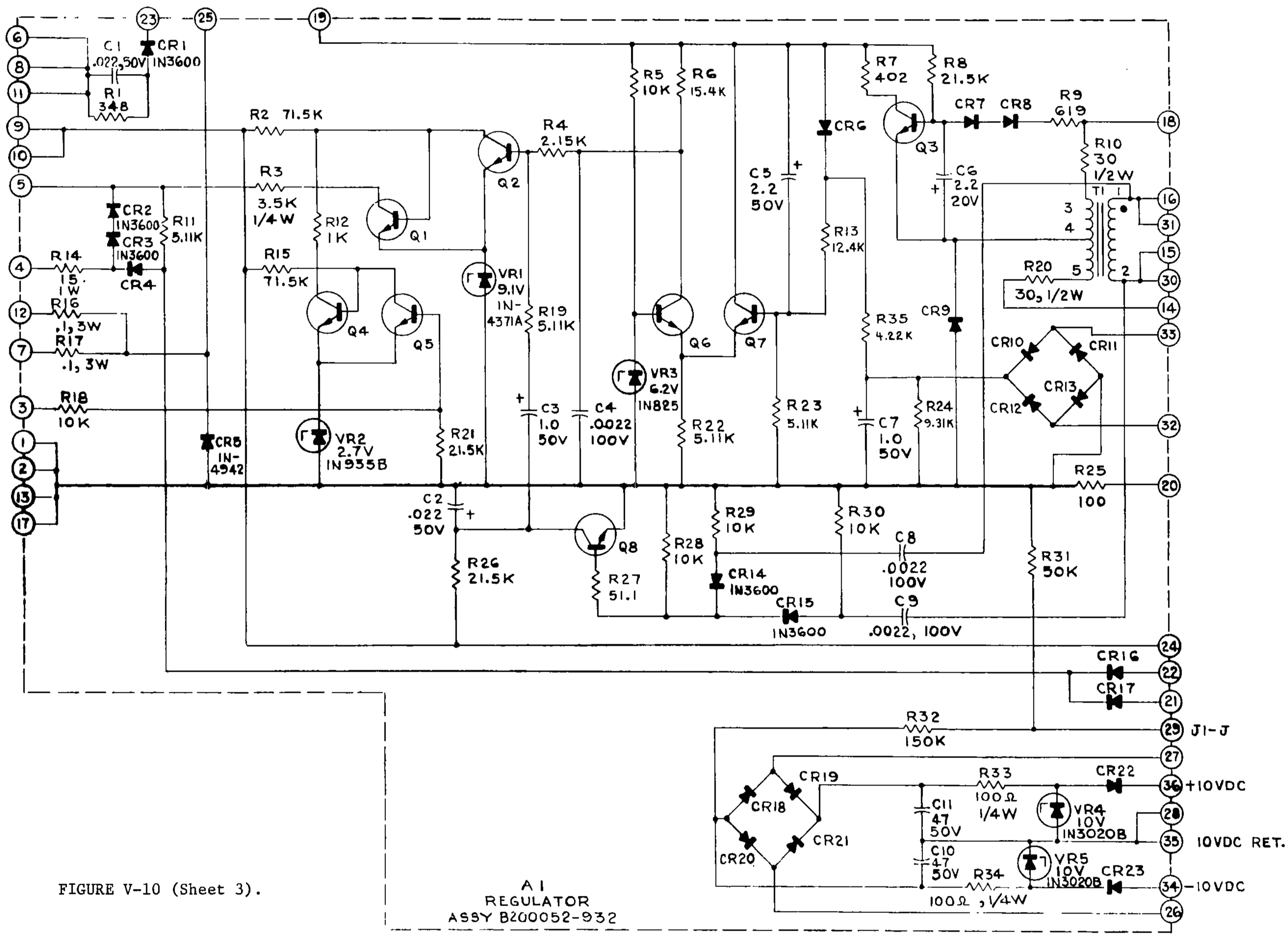
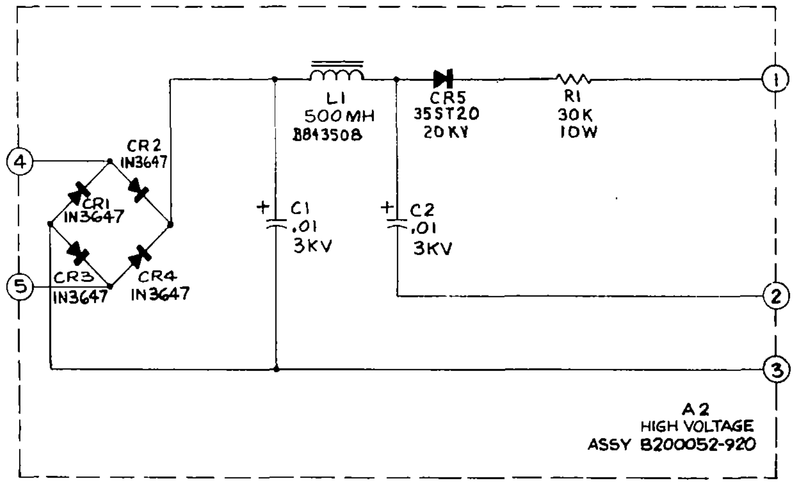
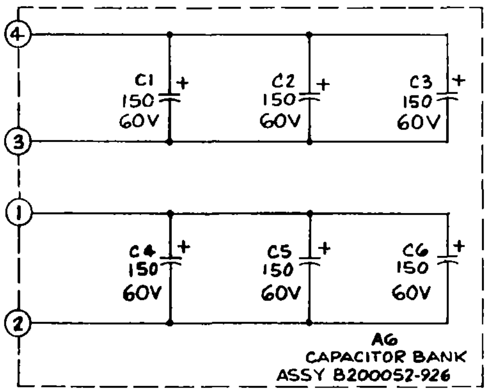
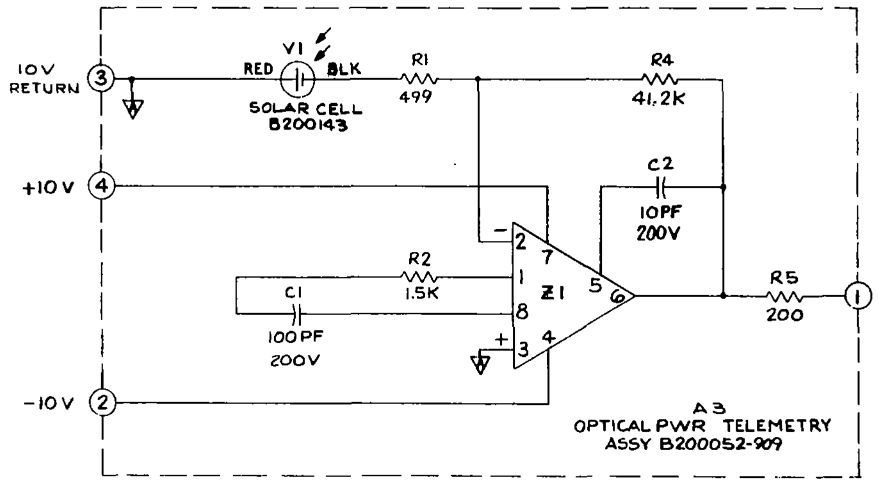


FIGURE V-10 (Sheet 3).







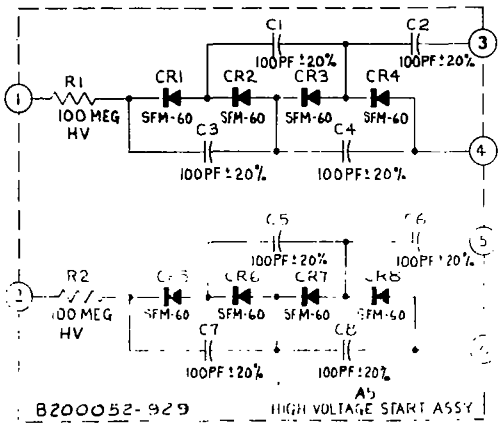


FIGURE V-10 (Sheet 4).

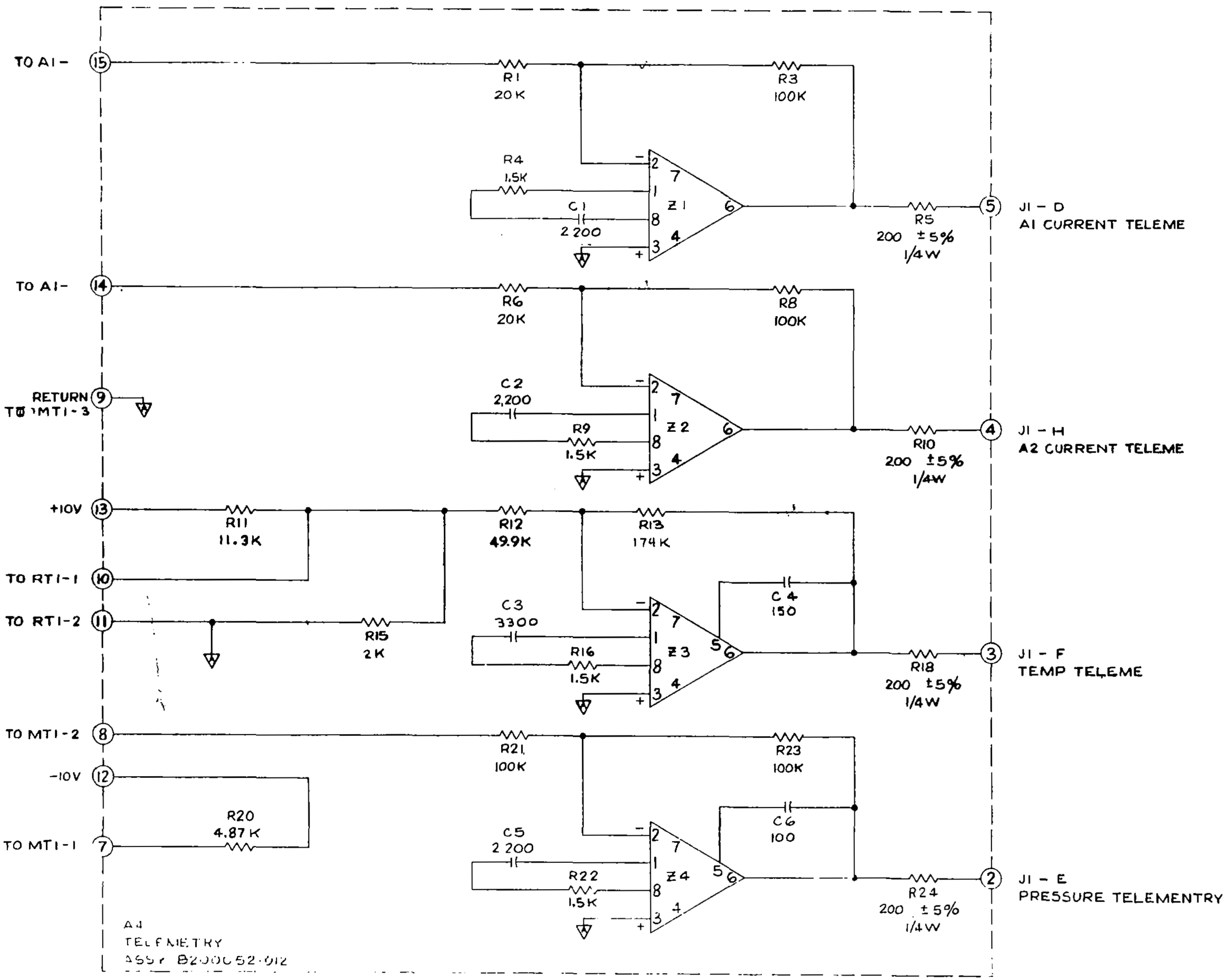


FIGURE V-10 (Sheet 5).

SECTION VI

SUMMARY AND RECOMMENDATIONS FOR FUTURE INVESTIGATIONS

This section contains a historical summary of the Space Qualified He-Ne Laser Program, a discussion of recent advances in He-Ne laser design and recommendations for a program to update the SQL design.

A. Summary

Phase I - (June 1967 - February 1968)

Early in 1968 Hughes Aircraft completed an initial design phase and presented a laser design to NASA-Electronic Research Center. During this phase experiments were conducted to verify this design. These experiments were:

1. Mirror evaluation
2. External mirror laser tests
3. Internal mirror laser tests
4. Bakeable mirror tests
5. Cathode life tests
6. Prototype metal ceramic discharge tube construction
7. Prototype power supply fabrication and test
8. Protytype laser/power supply integrated package fabrication and test.

This work is all documented in the Space-Qualified Laser Oral Presentation Data[1] presented in February 1968. At the end of this first phase there were several areas which required additional investigation, namely:

1. Cathode processing and geometry
2. Mirror sealing techniques
3. Long-term mirror coating degradation

4. Effect of high temperature bakeout
5. Environmental testing
6. Long-term operation of metal-ceramic laser discharge tubes.

Interim Period - (February 1968 - July 1968)

Hughes continued to investigate some of the above mentioned areas under a company-funded effort after the completion of Phase I. Lifetests were conducted to determine if there was any long-term degradation of internal mirrors and to evaluate new cathode processing techniques and geometry. The metal-ceramic Space-Qualified Laser prototype was reworked and lifetested. The results of these tests are reported in Section III of this report.

Phase II - (July 1968 - January 1970)

The period from July to December 1968 was spent modifying the original design and investigating various problem areas. To briefly summarize the original design described in Reference 1, it consisted of a metal-ceramic discharge tube with internal mirrors. A long radius output mirror and Brewster's angle prism were employed to achieve maximum TEM_{00} output in a minimum length discharge. The output mirror substrate was made of Kovar sealing glass and sealed to a Kovar flange which was heliarced to the discharge tube. A prism made of fused quartz and held internally was used to achieve a polarized output and also suppress the 3.39 micron line. The design utilized a split discharge column employing two anodes and a cold cathode common to both discharge columns. This feature reduced the required operation voltage by one-half and also allowed independent operation of either discharge section since two separate power supplies were employed.

The major modifications to this original design were:

1. The addition of a glass output window with both the output mirror and prism mounted internally.
2. The addition of a dielectric septum in the common cold cathode.

During December 1968 and January 1969 the first discharge tube, DT No. 1, was constructed and tested. Initial problems were encountered with mirror coatings which crazed apparently due to the 350°C bakeout. The mirrors were replaced and the laser was subjected to both shock and vibration tests with no problems. DT No. 1 was then reworked and baked out at 325°C. It was tested and found to perform satisfactorily. DT No. 1 was then packaged in an aluminum cylinder and tested with the complete dual power supply.

The second discharge tube, DT No. 2, which yielded over 5 milliwatts was packaged during March and April 1969. During evaluation of DT No. 2 a temperature instability of the laser cavity caused by the change of index of refraction of the quartz Brewster's angle prism was discovered. During this same period unstable laser starting characteristics were noted consisting of alternate firing of the two sections of the discharge. This problem became more pronounced the longer the discharge tube was operated.

It was at this point that Hughes reported the program status to NASA - Electronics Research Center and requested a change in scope of the program and an unfunded continuation to investigate these problems.

There were several questions which had remained unanswered at the end of Phase I which could be answered at this time.

1. The laser design, including mirror coatings, can withstand at least a 325°C bakeout and perform satisfactorily.

2. The mirror coatings were not degraded by long exposure (>5000 hours) to the vacuum-discharge environment.

3. The long-term (>5000 hours) operation of an alumina ceramic bore laser discharge tube had produced no bore erosion or thermal fracturing.

4. The design had been subjected to some environmental testing and could withstand shock, vibration and temperature cycling and still perform as required.

5. The laser power supply, telemetry and package was essentially completely designed and tested and could be space-qualified.

The areas which had not been investigated or which posed problems were mainly associated with the laser. They were:

1. Detuning of the laser cavity with temperature.

2. Cause of the laser starting instability.

3. Sputtering of the tantalum cathodes in the dual cathode design.

4. Discharge tube life in view of the above problem.

5. Operation of the laser in a vacuum.

6. Output amplitude modulation caused by noise.

7. Laser beam drift.

8. Alignment of the laser beam with the package reference.

Since the end of May 1969, the effort has mainly consisted of investigations in these areas. The following questions have been answered.

1. The temperature instability problem caused by the prism can be solved by replacing the prism with a combination of an internal Brewster window to select polarization and a flat high reflectance mirror. This design change solved the original problem but can introduce a 3.39 micron competition effect. The competition effect can be solved, however, by replacing the quartz Brewster window with one made of glass (BK-7 or BSC-2) or by careful control of mirror reflectivity at 3.39 microns.

2. From an analysis of DT No. 1 it was determined that the starting instability problem is brought on by cathode sputtering. This sputtering occurs on only one of the two identical cathodes. A glass discharge tube with an identical dual cathode design was constructed and lifetested. It showed similar operating characteristics and failed due to gas cleanup caused by sputtering. This sputtering again occurred on only one cathode. The reason why only one cathode sputters is not known. It could be the cathode geometry, the dual cathode design, the cathode processing (oxidation), or possibly it is associated only with Ta_2O_5 on Ta cold cathodes. However, the fact that we have run successful lifetests on single Ta cathode tubes would certainly indicate the latter was not the cause.

3. During the past year Hughes has accumulated a great deal of experience and lifetest data on aluminum - aluminum oxide cold cathodes. The only difference between Al and Ta that has been seen is the greater cathode fall ($\approx$ 130V) associated with the Ta-Ta_2O_5 cathode. However, aluminum had not been tested in the double cathode configuration. It had been tested in a single-bore, metal-ceramic laser and appears to be performing satisfactorily after 3500 hours. Thus, a possible solution to the sputtering problem encountered in the dual cathode discharge tube could be the use of Al_2O_3 on Al cathode.

The laser design, that was used for DT No. 1 and No. 2, was modified to incorporate an aluminum dual cathode and a glass internal Brewster window-flat mirror. A laser of this modified design was fabricated and tested. The results obtained after over 1000 hours of continuous operation indicate the following:

a. The temperature instability and 3.39 micron competition problems have been solved,

b. The cathode sputtering problem appears to have been solved; however, several thousand hours of additional operation are required for absolute proof.

To briefly conclude this summary, it appears that all of the fundamental problems associated with the dual discharge SQL design have been solved. The possible exception is the cavity stability requirement imposed by the use of the long radius mirror configuration. However, during this program it has been established that certain design changes should be undertaken not only to update the design but also to overcome some basic design deficiencies. These topics are discussed in the following recommendations.

B. Recent Pertinent Advances in He-Ne Laser Design

During the past year, Hughes Electron Dynamics Division has been engaged in a program to develop a 5 mW, 15 in. long He-Ne laser for use in laser recorders and scanners in high performance aircraft. This laser must be compact and lightweight and operate satisfactorily under environmental conditions as specified in MIL-E-5400. Under this program several significant design changes were proven out which have improved laser performance and simplified laser construction.

A key problem area recognized at the start of this program was the problem of temperature detuning of the laser. The Space-Qualified Laser cavity which employs a 2m mirror and a flat is completely misaligned by a mirror tilt of 80 microradians. A near-hemispherical cavity of the same length can withstand an order of magnitude greater misalignment with only a 50% decrease in output power and lasing does not cease until the mirror tilt exceeds 2 milliradians. The disadvantages of going to a hemispherical cavity, as contrasted to a long radius cavity, is the smaller resulting mode volume which typically produces only one half the output power of the latter in a uniform-bore tube.

The important design change which has been adapted is to use a tapered bore discharge tube such that the bore is tailored to match closely the mode shape. This greatly increases the gain-mode volume product (the output power is a function of this product) over that which can be achieved with a conventional straight bore-hemispherical cavity design. To illustrate this point, the results of comparative tests of four different 12-inch long glass tubes, each with the bore size optimized to give maximum TEM_{00} laser output for the particular mirror combination, is given below:

Tube	Design	TEM_{00} Output Power
A	Uniform bore, long radius cavity	4.0 mW
B	Uniform bore, hemispherical cavity	2.0 mW
C	3-Step tapered bore, hemispherical cavity	3.0 mW
D	Continuous tapered bore, hemispherical cavity	4.0 mW

As may be seen the output power obtained in Case D is equal to that obtained in Case A. Similar data has been recorded in a 15-inch long tube, and under as yet unoptimized conditions have achieved 4.5 mW from a 3-step bore using a hemispheric cavity.

As well as decreasing mirror detuning problems, the use of a hemispheric cavity greatly simplifies mirror adjustment problems. A simple, extremely rugged aluminum mirror support structure has been developed which does not require differential screw adjustments and cost less than one-tenth that of the present space-qualified laser beryllium support structure. The mirror support structure also provides a hermetic seal for the laser head.

This tapered-bore tube design has been tested while operating to most of the environmental requirements imposed by MIL-E-5400 for airborne equipment. The tube operates over the range of $-54^{\circ}C$ to $74^{\circ}C$ and 0 to 70,000 ft. altitude with less than 30% power variation. Under 15 g shocks and 2.5 g peak-to-peak vibration from 70 to 2000 Hz, no mirror misalignment occurs. A photograph showing the external appearance of the complete 12-inch long by 2 1/4 inch diameter laser head and a laboratory power supply is shown in Figure VI-1.

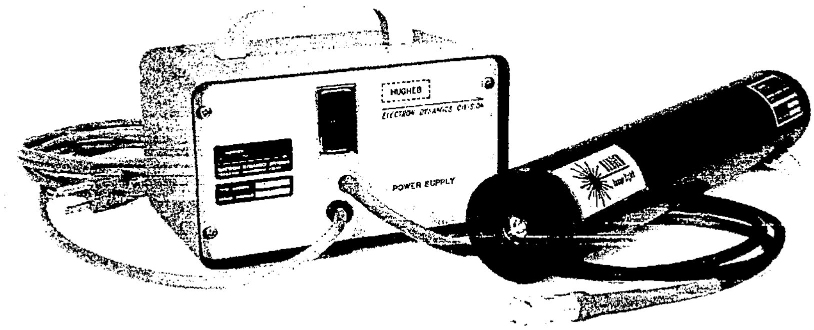


Figure VI-1 Airborne recorder laser prototype with laboratory power supply.

A single cathode, single bore, metal ceramic He-Ne laser with approximately equivalent output performance characteristics to the dual discharge SQL has also been designed, fabricated and tested by Hughes EDD during the past year. This was part company funded program aimed at developing a rugged metal-ceramic laser for military-airborne applications. The laser tube parts are shown in Figure VI-2 and the finished laser assembly in Figure VI-3.

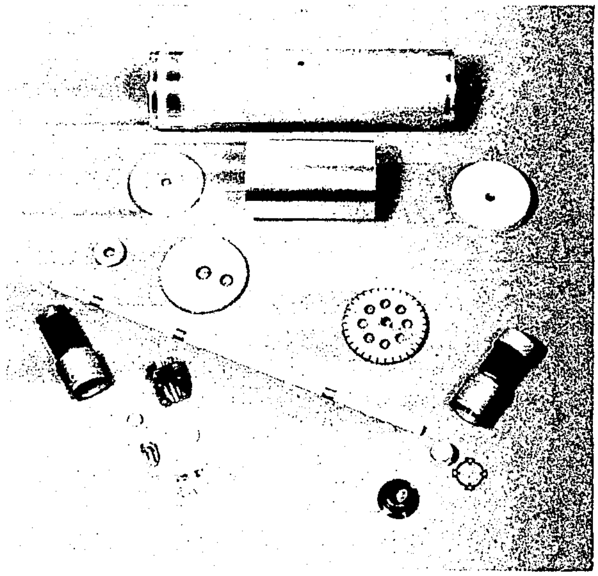


Figure VI-2 Tube parts for single bore, single cathode metal-ceramic laser.

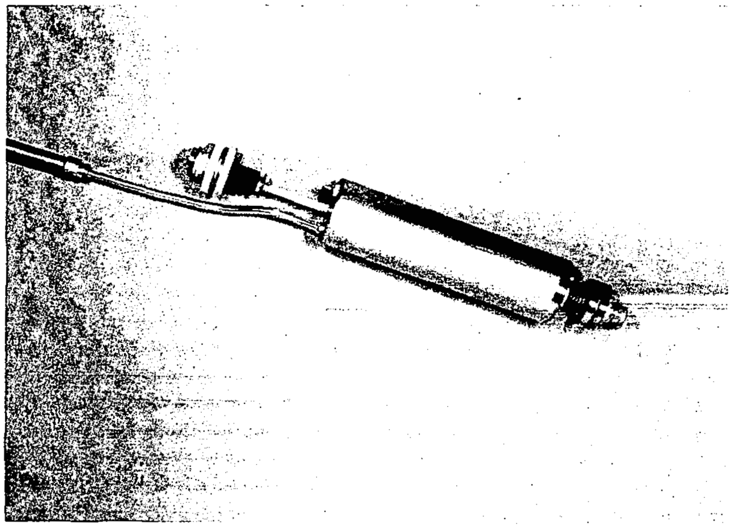


Figure VI-3 Assembled single bore, single metal-ceramic laser.

This laser design employed the fused quartz internal Brewster window-flat mirror configuration previously described in Section V-A and suffered from severe 3.39 micron competition effects. However, it also employed an aluminum cold cathode and has been in life test for over 3500 hours without showing any signs of performance degradation. This design, although different in basic concept, is, as can been seen quite similar mechanically to the SQL design.

C. Proposed Development Program

Based on our experience gained from the Space-Qualified Laser Program and other tube development programs as discussed above, we propose a laser development program which would result in a simplified metal-ceramic laser design that can be successfully space-qualified. This program would involve design modifications to update the present Space-Qualified Laser. The major changes would be: (1) adoption of a single cathode design, (2) use of a tapered or multiple stepped bore, (3) use of a hemispherical cavity, (4) incorporation of a simpler cavity design. Although this approach does not have the dual bore advantages of the present Space-Qualified Laser design it does have the following:

1. Smaller, lighter, simpler, cheaper power supply with the power losses of only one cathode fall, ballast resistor and converter.

2. Considerably longer operating life (see Appendix D).

3. Simpler discharge tube construction.

4. Increased cavity stability.

5. Simpler mirror support structure.

6. In conjunction with Item 4 it should be possible to use an unpressurized package, thereby reducing package complexity and weight.

The scope of the proposed program would be to design, build and test several such metal-ceramic discharge tubes with mirror support systems. The technology required for power supplies, telemetry and packaging is considered to be advanced enough from the present program that additional work is not required at this time. This program would bring the basic laser to a fully designed status. Only after this first program, that is, after it has been demonstrated that the cylindrical laser head performs satisfactorily, would a program to fully qualify the entire laser system be warranted.

Specific tasks which we feel would be appropriate to this program would be:

1. Modify laser to a single cathode metal-ceramic design.
2. Construct four metal-ceramic laser discharge tubes.
3. Process, test and burn-in lasers.
4. Lifetest two Al cathode metal-ceramic discharge tubes.
5. Thoroughly measure and document optical performance of the laser.
6. Perform environmental tests (shock, vibration, temperature cycling and vacuum operation).
7. Define power supply, telemetry, and package design, and provide manufacturing cost data.

After successful demonstration to NASA of a practical laserhead assembly which satisfied performance and environmental requirements, a second phase would logically follow to implement the simplified power supply and telemetry design and reconfigure the housing. (It is anticipated that the housing need not be sealed, and that the total laser weight can be reduced to less than 10 lbs.) Several complete lasers could be fabricated and these units delivered for test by NASA or provided to prospective system users. The exact scope of this phase should logically be guided by the anticipated use of the laser.

REFERENCES

1. W. B. Bridges, "Design for a Space Qualified Laser - Phase I," NASA CR-1663, 1970

2. U. Hochuli and P. Haldemann, "Cold Cathodes for Possible use in 6328 Å Single Mode He-Ne Gas Lasers," Rev. Sci Instr. 36, 1493 (1965).

3. U. Hochuli, P. Haldemann, and D. Hardwich, "Cold Cathodes for He-Ne Gas Lasers," presented at 1967 IEEE Conference on Laser Engineering and Applications, Washington, D. C., June 1967.

4. A. L. Bloom, "Gas Lasers," John Wiley & Sons, Inc. 1968.

APPENDIX A

NEW TECHNOLOGY

After a diligent review of the work performed under this contract, no new innovation, discovery, improvement or invention was made.

APPENDIX B

SPECIFICATIONS FOR SPACE QUALIFIED LASER (He-Ne), PHASE II

GENERAL

The work under Space Qualified Laser (He-Ne), Phase II is intended to initiate and carry to completion development work on a laser design reported in Hughes "Design for a Space Qualified Laser - Oral Presentation Data" (SQLOP) of February 1968.

The laser designation shall be Model 3072H He-Ne Laser.

The Model 3072H He-Ne Laser is to be of metal-ceramic construction mounted integrally with the solid state power supply. Cooling is to be accomplished by conduction to a heat sink through one surface of the package. The optical output is to be accurately referenced to one edge of the package to provide alignment during installation. The laser is to use a cold cathode and internal mirrors. Two separate power supplies and laser discharge structures are to be provided for redundancy and to allow operation at approximately one-third power output upon command. Seven active telemetry outputs and their associated tranducers are to be provided.

The development work will conform to the SQLOP design unless otherwise noted herein. No changes or deviations of any significance are to be made without prior approval of the contract technical monitor. It is the desire of NASA/ERC that problem areas be promptly brought to its attention in order to fully utilize the combined resources of the two organizations in problem solutions.

MIL Spec Electronic or equivalent parts are to be used in this phase with the exception of magnetics.

The funds provided for documentation purposes are intended mainly to support direct laser and power supply exigencies. The major portion certainly should go for Process Specification, Process Instruction, and Assembly Instruction documentation.

The laser plasma tubes built in this phase shall be assembled in a Class 100,000 clean room as defined in NASA and MIL Specs.

The parts and materials used will conform to the list below unless during the development phase other components are found to be more reliable or to provide a simpler, better overall laser package. NASA concurrence of such changes must be obtained from the contract technical monitor.

High Alumina Ceramic Bore
Stainless Steel 327, 302, and 304
Kovar
Vacuum Melted Iron
OFHC Copper
Tantalum
Beryllium
Nickel Grade A
Tantalloy
Fused Quartz
Gold-Copper Braze Alloy
Corning 7052 Glass
Aluminum
Dow Chemical Sylgard 185 (Potting Material)
Barium Getter
Helium Gas
Neon Gas
Space Qualified Black Paint
Electrical Components

The desired reliability for the specified three year laser life shall be 85% or greater, although recognizing that MIL Spec. parts are used in this phase for reasons of economy. The 85% figure is a projected one for a later phase when the combination of a fully proven laser head is integrated with a power supply incorporating high reliability parts. The design and selection of components shall be governed by this requirement. A recalculation of the expected reliability shall be made for the Interim Scientific Report and again for the final Design Revew.

The provisions of NASA Contract NAS 12-579 modification document of February 19, 1968, submitted by L. J. Smith of Hughes shall apply to this phase except as noted herein.

The contractor shall exercise adequate Quality Assurance requirements and maintain Quality Control to the degree required for this development program. Parts, materials and assemblies shall receive adequate inspection and test. For the follow-on contract qualification phase the contractor's selected procurement sources should be able to comply with applicable requirements on NPC-200-2-3 and the contractor and his suppliers are subject to evaluation, review, and inspection by NASA/ERC or its designated representatives to determine that:

a. The Quality Assurance and Control continuously meets contractual requirements.

b. Articles, materials, and related services satisfy contractual requirements and are of satisfactory quality to meet the intended design.

A system shall be incorporated to ensure control of documents affecting the design, reliability, and overall quality and for the incorporation of changes in such documents. These documents include engineering drawings, specifications and procedures, QA and test control, and similar documents.

OPTO-ELECTRICAL SPECIFICATIONS

1. To operate at 6328 Å with He-Ne.

2. To operate in a single transverse mode, TEM_{00q} $TEM_{00q + j}$.

3. To operate at an initial output power level not less than five (5) milliwatts, CW. Measurement point to be outside of laser package.

4. The operating/shelf life shall be three (3) years as a design objective, the operating portion of which shall be not less than 10,000 hours. The output power shall not drop below 3 mW at 7000 hours operating time and 2 mW at 10,000 hours operating time. These values shall be attained for any combination of operating/shelf times.

5. To operate a polarized output, linear to one part in 1000. The plane of polarization shall be specified to within one (1) degree.

6. To operate with a beam diameter not greater than two (2) millimeters as measured to the $1/e^2$ points, at a location 2" from the output aperture. The beam shall be essentially parallel at this location.

7. To operate with a beam divergence consistent with the diffraction limit for gaussian or modified gaussian beams of the selected beam diameter. The beam is to be round.

8. To operate with no detectable lasing at the 3.39 μ and 1.15 μ wavelengths.

9. To operate without liquid cooling.

10. To operate within a light-tight enclosure except for an exit window. Spontaneous radiation from laser to be minimized (by apertures, window coating, etc.).

11. To operate normally in space vacuum environments after rocket launch.

12. To operate with a minimum angular deviation of the beam axis as a function of temperature, time, vehicle spin, laser age, magnetic fields, etc. A single mission deviation of less than two (2) arc-seconds is desired.

13. To operate with a minimum of discharge and mode noise in the output radiation. An rms noise level of 1% peak-to-peak and 5 mW as measured in a 0 - 3 MHz frequency range with a 1 KC bandwidth is provisionally acceptable.

PHYSICAL SPECIFICATIONS

1. The laser, its power supply, the power monitor, the telemetry transducer, etc., will all be integrated into a single metal-body case or package. This package shall be approximately 16" X 5" X 5" in dimensions, exclusive of any necessary protuberation for input/output connections. The case shall be pressurized at approximately one (1) atmosphere with dry He gas. The center of gravity (C of G) shall be as low as possible, and its location shall be approximately specified on a suitable drawing. The total target weight will be ten (10) pounds.

2. The laser output beam will be parallel to within ten (10) seconds of the nearest long edge of the case and will be some predetermined distance from it to within 0.002" in both X and Y axes.

3. The case is intended to mount to a flat heat sink on one 16" X 5" surface, and means for accomplishing this will be provided. This surface must allow for metal-to-metal contact. All other major surfaces should be made black by painting or anodizing.

4. A set of three (3) or four (4) tapered holes is to be provided and disposed symmetrically about the laser beam axis on the 5" X 5" end plate, for mounting auxiliary optical equipment as needed. A standard diameter and tap size shall be used if a standard exists; otherwise the base circle diameter can be 2.5".

5. The case cover shall be sealed by "O" rings or other semi-permanent means. The sealing method must be compatible with the lifetime requirements.

6. The materials used must be compatible with NASA requirements for Manned and Unmanned space flights.

INPUT-OUTPUT SPECIFICATIONS

1. The laser will operate normally for supply voltages in the range of 24 - 32 VDC and over a base plate temperature range of -10^{o}C + 50^{o}C in any combination.

2. The power drain will not exceed 33 W for any condition of temperature, laser age, etc.

3. The laser turn-on period will be shorter than ten (10) seconds. Both "semi-lasers" are to be simultaneously or sequential startable.

4. The current drain in the laser "OFF" situation is to be less than 5 mA, exclusive of the telemetry drain.

5. The power supply design, insofar as possible, must provide against catastrophic bus drain due to failure of any component.

6. A total of nine telemetry outputs shall be provided for; these are the seven (7) listed on page 95 of SQLOP and two (2) spare positions. The interface connectors to the case exterior will conform to NASA telemetry usage.

APPLICABLE DOCUMENTS

The following documents of the revision in effect on the date of issue of this exhibit are applicalbe to the extent specified herein. Should conflicting requirements exist, the requirements listed in other paragraphs in Exhibit A and Exhibit B shall govern. Documents listed here but not specified elsewhere shall be used for information only in program planning and documentation.

1. MIL-STD-810 - Environmental Test Methods for Aerospace and Ground Equipment.

2. MIL-I-6181 - Electromagnetic Interference Requirements and Test Levels.

3. NPC-200-4 - NASA Requirements for Soldering of Electrical Connections.

4. MIL-STD-785 - Requirements for Reliability Programs.

5. NPC-200-3 - Inspection System Provisions.

6. MIL-W-5008 - Wiring.

7. MIL-STD-202 - Test Methods for Electronic and Electrical Components.

8. MIL-STD-781 - Reliability Test and Exponeutral Distribution.

9. MIL Handbook-217A - Reliability Stress and Failure Rate Data for Electronic Equipment.

10. NASA-RA-006-013-1A - Procedure for Failure Mode, Effect, and Criticality Analysis.

ENVIRONMENTAL SPECIFICATIONS

For the purposes of testing any assembly, part, substructure or complete package the following environmental conditions shall prevail. When a sequence of tests is to be performed, the ordering of page 94 of SQLOP shall be used. The Group I tests will be performed as developmental tests. All tests will not necessarily be performed on the same unit.

Group 1

1. Sinusoidal Vibration: As on page 96 of SQLOP except that, whenever possible the laser shall be energized to aid in determination of any failure point as evidenced by loss of radiation.

2. Random Vibration: As on page 96 of SQLOP with same qualification as above.

3. Shock: As on page 96 of SQLOP.

4. Temperature Cycling: As on page 96 of SQLOP.

5. Acceleration: As on page 96 of SQLOP.

6. Thermal-Vacuum: As on page 97, item 6.2 of SQLOP except that lower temperature shall be $-10^{o}C$.

It is expected that the laser package will have been exposed to and can fully meet these (Group 1) environmental specifications at the end of Phase II work.

Group 2

1. Acoustical Noise: Per the profile outlined below 1/3 octave band acoustical specification Pc 2×10^{-4} Dynes/cm^2. Test duration - three minutes minimum.

1/3 Octave Band Geom. Mean Freq. (cps)	dB Level
5.0	138.5
6.3	140.0
10.0	142.5
25.0	146.0
40 - 60	146.0
100	143.0
160	136.0
200	132.5
250	130
500	121
1000	112
1600	105.5

2000	102.5
3150	95.5
4000	92.0
5000	89.0
6300	85.0
8000	81.0
10000	78.0

Overall 156.5 + 4 dB
- 0 dB

1/3 octave band sound pressure levels + 4 dB
- 0 dB

2. Humidity: Ten days of accelerated humidity.

3. Oxygen Atmosphere: The equipment shall be capable of operating in a pure oxygen atmosphere at 5 psia pressure.

4. Explosive Atmosphere Test: Per MIL-STD-810A.

5. Electromagnetic Compatibility: In accordance with MIL-I-6181.

These Group 2 tests shall be regarded as design objectives, to the end that the laser package may ultimately be subjected to any or all of these. The contractor is required to become familiar with these tests and provide at the contract oral reivew his best estimate of the laser package performance thereunder.

APPENDIX C

THE TEMPERATURE MISALIGNMENT PROBLEM OF A BREWSTER'S ANGLE PRISM

The following is a derivation of the total angular misalignment an incoming ray would suffer due to a change in the index of refraction of the fused quartz prism with temperature. The change in the angle, θ, see Figure C-1, due to a change in the index, n, is given by

$$\frac{d\theta}{dn} = \frac{\partial\theta}{\partial n} - \frac{\partial\theta}{\partial\phi}\frac{\partial\phi}{\partial n} \qquad (1)$$

The minus sign is introduced because the incoming ray is reflected by the mirrored back surface. When a similar expression is written for a ray traveling through a Brewster's angle window, both partial derivatives would have the same sign. Using Snell's Law we have

$$\phi = \sin^{-1} \frac{\sin\theta}{n} \qquad (2)$$

and

$$\frac{\partial\phi}{\partial n} = \frac{-\sin\theta}{n^2} \frac{1}{\sqrt{1 - \frac{\sin^2\theta}{n^2}}} \qquad (3)$$

Again for Snell's Law

$$\theta = \sin^{-1} n \sin\phi \qquad (4)$$

$$\frac{\partial\theta}{\partial\phi} = \frac{n\cos\phi}{\sqrt{1 - n^2\sin^2\phi}} \qquad (5)$$

and

$$\frac{\partial\theta}{\partial n} = \frac{\sin\phi}{\sqrt{1 - n^2\sin^2\phi}} \qquad (6)$$

Combining

$$\frac{d\theta}{dn} = \frac{\sin \phi}{\sqrt{1 - n^2 \sin^2 \phi}} + \frac{\sin \theta \quad \cos \phi}{n \sqrt{1 - \frac{\sin^2 \theta}{n^2}} \sqrt{1 - n^2 \sin^2 \phi}} \qquad (7)$$

Simplifying using Snell's Equation

$$\frac{d\theta}{dn} = \frac{2 \tan \theta}{n} \qquad (8)$$

Now to include the change in n due to a change in temperature, we have

$$\frac{d\theta}{dT} = \frac{\partial\theta}{\partial n}\frac{\partial n}{\partial T} \qquad (9)$$

From Corning's published optical properties for 7940 fused quartz, (attached) from which the prism is made, we have

$$\frac{\partial n}{\partial T} = + 1.38 \times 10^{-5}/^{o}C \qquad (10)$$

and

$$n = 1.4567 \qquad (11)$$

so

$$\Delta\theta = \frac{2 \tan \theta}{1.4567} \quad (1.38 \times 10^{-5}) \, \Delta T \qquad (12)$$

Thus, $\Delta\theta$ is 27 microradians per degree centigrade using 55^{o} for θ. It should be noted that an angular change of the prism of only half this value is required for realignment.

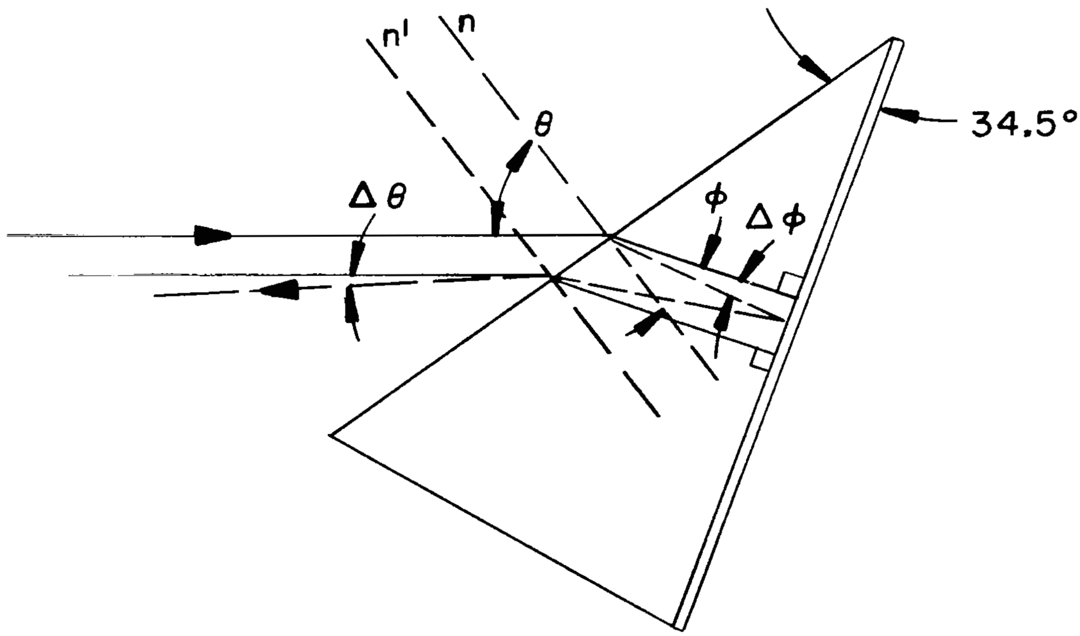


Figure C-1 Brewster's Angle Prism

APPENDIX D

A COMPARISON OF THE PREDICTED LIFETIME FOR A SINGLE VERSUS A DUAL COLD CATHODE LASER

Consider the following argument; laser discharge tube A and laser discharge tube B are idnetical, i.e. they had the same initial gas pressure, the same cold cathode material, the same volume and therefore should have the same lifetime (say $\approx$ 5,000 hours) is they were both operated under the same conditions. Now if laser discharge tube A and laser discharge tube B had been connected together by a small capillary of negligible volume and operated under the identical conditions the lifetime of each would be unaffected. Assuming this argument to be valid we can then make the following statement: the present SQL dual cathode split discharge tube would have the same lifetime as either of its two sides if separated at the dielectric septum see Figure II-1 and operated under identical conditions.

However, if the volume of discharge tube B were added to discharge tube A and this configuration operated under conditions identical to those previously described the predicted lifetime would be considerably longer. Such would be the case for single cathode laser with equivalent output characteristics as the dual cathode SQL.

Why does the discharge tube with the single cold cathode operating under identical conditions in twice the volume have considerably longer lifetime than the same cathode operating in the smaller volume? Starting with the basic fact that the major cause of failure in cold cathode He-Ne lasers is gas cleanup caused by sputtering of the cathode material, (little if any sputtering occurrs in the bore), the following reasons are given:

1. The sputtering yield for identical cathode would be independent of gas volume.

2. However, the sputtering rate is a strong function of gas pressure; the lower the pressure the greater the sputtering rate.

3. Therefore the gas pressure would remain higher much longer for the cathode operating in twice the volume and the sputtering yield as a function of time would be less.

Although, it is not possible to predict the increase in lifetime for a single cathode laser with equivalent performance to the dual cathode SQL, it is sufficient to say that it could possibly be better by at least a factor of two.