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CONSTRUCTION OF A LABORATORY TYPE, CONVERTABLE
EXCITATION ARGON LASER

BY

ARTHUR P. RECKINGER, JR.

A

THESIS

submitted to the faculty of the

UNIVERSITY OF MISSOURI AT ROLLA

in partial fulfillment of the requirements for the

Degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

Rolla, Missouri

1967

Approved by

Ralph D. Carson (advisor)

Robert Gerson

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ABSTRACT

The purpose of this thesis is to describe the construction of a general purpose, convertible excitation, laboratory type, argon laser. Quartz tubing was used in the final model while attempts to use alumina were made during earlier work.

The final model has a total optical power output of 230 mw at a discharge current of 29 amperes in the dc excitation mode. Provision was also made to utilize RF or pulsed excitation. The device is built so that several values of optical transmittance are available with a wide range of mirror placement.

ACKNOWLEDGEMENT

The author wishes to acknowledge the University of Missouri at Rolla for the use of its laboratory facilities and equipment and for providing the necessary funds for the purchase of the necessary items required for the construction of the laser. Special thanks must go to my advisor, Dr. Ralph St. C. Carson for his advice and encouragement during the long period of experimentation. Thanks must go to Bell Telephone Laboratories and to Mr. E. F. Labuda for contributing the mirrors used during the experiments. The author would like to thank Mr. Leroy Tipton of the UMR Mechanical Engineering Department for his many hours spent constructing the various items of special glassware used during this project. The author wishes to thank Mr. Don Watke for his help during the final phases of the work. Special thanks must also go to my wife, Nanette, for her work in completing this thesis.

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I. INTRODUCTION

This thesis is concerned with the construction of a convertable-excitation cw argon laser. During the past seven years the visible gas laser has been in the research and development stage with low cost helium-neon lasers being available commercially for approximately three years. Many other types of gas lasers are available but at advanced costs (1). Some types of gas lasers, particularly the He-Ne laser, are very simple to construct utilizing materials commonly available in most advanced laboratories. However, the optics are not normally available except as custom items.

The argon laser presently has the highest cw power output available in the visible light range, but this high power output requires excitation power inputs approximately an order of magnitude higher than that required by He-Ne lasers. The increased power requirement subsequently requires better materials for the amplifier portion of the laser than would be required for the largest He-Ne laser.

The major components of the laser are the amplifier and resonator. Supporting equipment consists of a vacuum source, gas supply, power source, a rigid support for the amplifier and resonator, a source of coolant, and various items of instrumentation, the most necessary of which is a vacuum indicator.

Lasers in general have shown great promise in many areas, e.g., distance and motion measurement, illumination, communications, medicine, and microminiature welding, cutting, and shaping. The full potential of all these areas has not at this time been realized and the expected potential will not apparently be realized in any

of these areas in the near future.

If one desired to explore any of the known application areas or perhaps branch into new areas, the first requirement would be a suitable laser. The purpose then in building a laser, when they are commercially available, is to provide a higher power laser at a lower cost, while at the same time uncovering some of the problem areas in construction of lasers.

The literature contains much information on the physics or quantum aspects of lasers such as excitation mechanisms or frequencies available for a given laser material. The information that is lacking lies in the area of engineering such as bore and cathode materials, and gas purity requirements. Within the past year and a half papers have begun appearing that are concerned with the engineering problems of argon lasers (10) (12). As is normal in an economic system of supply and demand, the engineering effort which is starting to be applied to solving the practical problems of building a long-lived argon laser is due to the fact that argon is presently the best source of cw, high power, visible, coherent light.

II. LASER THEORY

Some of the theory concerning lasers is relatively old having as its basis the theory of interferometers. The possibilities of lasers (originally called masers) were predicted in the early 1950's by C. H. Townes with the first laser being discovered in 1959. Then in late 1960, Javen, Bennett and Herriott (2) discovered the helium-neon laser. Since then, advances in lasers have occurred at ever increasing rates. There are several good review papers (3) (4) (5) available on the operation of gas lasers in general and at least one book (6).

The argon laser came into being in 1964, (7) (8) (9), and since then many advances have taken place. The initial laser, operating in the visible range (8), was pulsed and had a bore length of 107 cm and an average power output of 0.5 mw. Currently, on a steady state basis, 1 to 5 watts of output from a 23 cm long laser (10) is the upper long-term limit, with higher powers available in a short term or pulsed mode of operation.

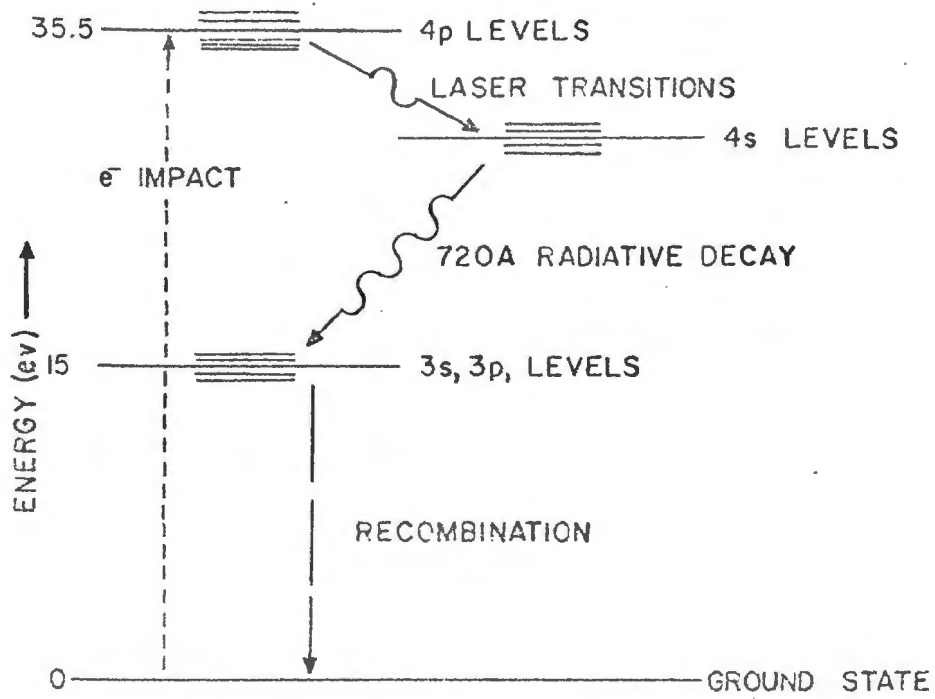
In order that the basic mechanisms of the laser can be better understood, a simplified description will be given. For more detailed descriptions the reader is referred to references (2) (3) (4) (5) (6) (11).

The entire laser can be likened to the electrical oscillator in that the gain of the amplifier (i.e. the bore containing the discharge) must be greater than one. The amplifier is then provided with feedback in the form of mirrors at each end of the amplifier.

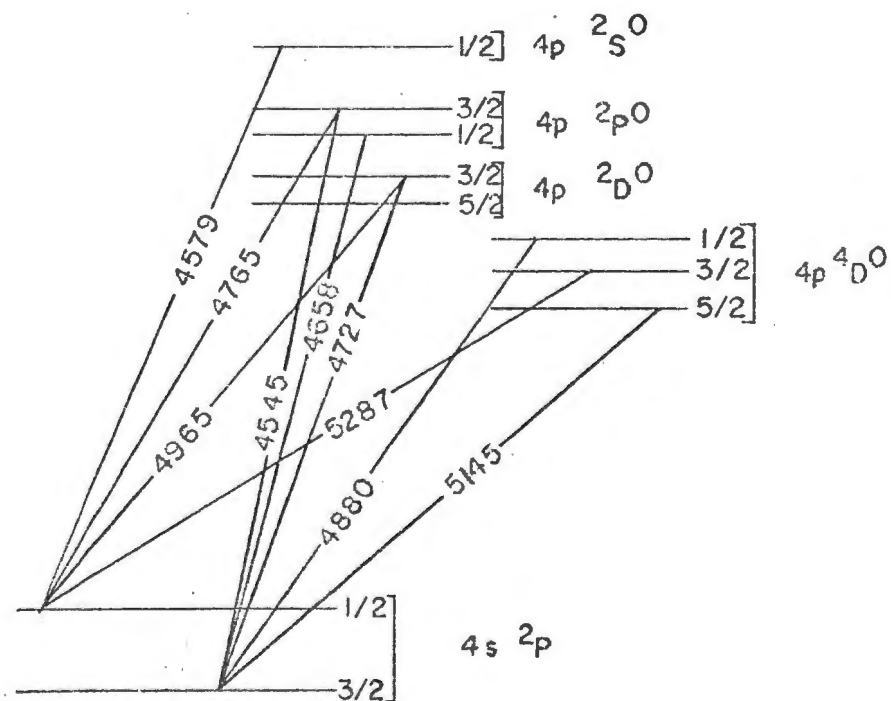
The amplifier consists of a tube containing the appropriate gas and terminating in optically transparent windows. The gas is then excited by an electrical discharge. In argon the discharge must be energetic enough to singly ionize the gas. The discharge excites the argon atoms by electron impact, creating ions with energy levels in excess of 35 eV, (Figure 1). This level of excitation is the upper laser level or 4p level for argon. The ions then lose energy, in a laser transition, to the lower laser level by emitting photons. The lower laser level for argon is the 4s level. From the lower laser level the ions lose energy by radiative decay to the ion ground state. Bennett, et al. (9) indicates that the radiation in this process is approximately 20A. The ions then decay by recombination to the system ground state. The various individual laser transitions, given in Figure 2, were extracted from the paper by Edges (8).

Even though a system produces the transitions noted previously, this is not the only requisite for laser action. A necessary requirement is that the excitation be efficient to produce a so-called population inversion between the upper and lower laser levels. Once the population inversion has been created, stimulated emission can take place. One photon, emitted spontaneously, can stimulate other ions to emit photons of the same frequency and phase.

The fact that stimulated emission can take place is still not a guarantee that laser action will take place. A necessary circumstance is that the gain of the amplifier per pass exceed the losses of the entire system per pass. Thus the diffraction losses in the bore, the window losses, and the mirror losses must be kept low to



1. General excitation level diagram for argon



2. Laser level diagram for argon (not inclusive)

insure laser action. Bridges (8) states that the gains for the 4880A and 5145A lines are approximately 15% and 10% respectively. The use of perpendicular windows rather than Brewster angle windows would increase the losses by approximately 11% per pass.

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III. EXPERIMENTAL PROCEDURES

The construction of the argon laser was undertaken with economy very much in the forefront of the design considerations. This, many times, required the use of items already available in the laboratory, rather than the use of a more refined, commercially available item.

Attempts to use commercial alumina (Al_2O_3) for the bore material resulted in failure. The failures in this area were not the result of alumina failures but due to poor joining or bonding techniques. Further discussion of alumina as a bore material is contained in Section III C. With better construction techniques alumina may still be a good material for argon lasers.

Several construction problems were surmounted during the effort and a strong attempt was made to keep costs low with final costs amounting to \$730.00. The lowest priced commercial laser is quoted at \$3,700 for 30 mw output (1). The laser that was constructed has a great amount of flexibility with changable mirrors, excitation, and gas type.

A. CONSTRUCTION

1. Design of Support for Amplifier and Optics.

Gas lasers, in general, require a rigid relationship to be maintained between the resonator and amplifier and between the mirrors forming the resonator. Even though the confocal configuration, used in the present design, has the largest

alignment tolerance it is still necessary to be able to maintain very tight control over mirror alignment as alignment tolerance is roughly of the order of 1.3 minutes of arc.

The bench or support utilized three pieces of channel, the two smaller pieces bolted to the back of the third. A cross section is shown in Figure 3. The resonator was supported by two mounts attached to the amplifier tube at points A and B of Figure 4. The tube was clamped to the mount with Teflon "C" blocks. The Teflon was used because it was easily machinable, heat resistant, slightly deformable, and a dielectric. The mount provided horizontal and vertical adjustment of each end of the tube. This X-Y adjustment allows the amplifier tube to be centered on the mirrors, although the amount of adjustment was very limited, in the dc excitation mode by the anode, cathode, and gas supply structures. The tube mounts were used to preposition the amplifier in the approximate center of the mirrors, and then the mirrors were carefully shimmed vertically and positioned horizontally to center the mirrors on the optical center of the amplifier prior to clamping the mount. Positioning the mirrors is a very important part of the alignment procedure and must be done with care.

The base of the mirror mount is two pieces of 0.5 inch aluminum flat stock fastened together at right angles. The mirrors are fastened to a separate plate by a cup and cap arrangement with the mirror cushioned at the edges by small O-rings. This plate, with attached mirror, is then held by three, spring-loaded, adjusting screws to the base. The screws are 3.5 inches apart and each screw is at one corner

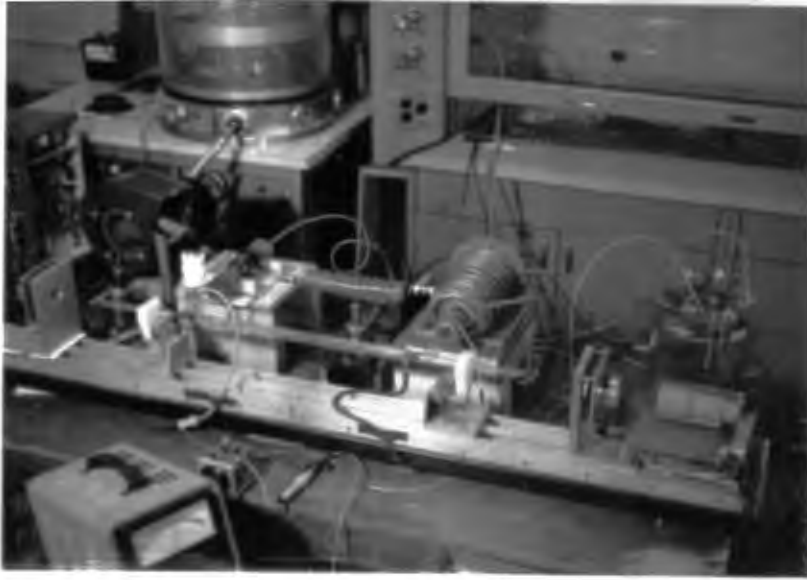


Figure 3a. General argon laser setup showing plate, cathode, gas return, gas supply, optical amplifier, mirror mountings and support structure

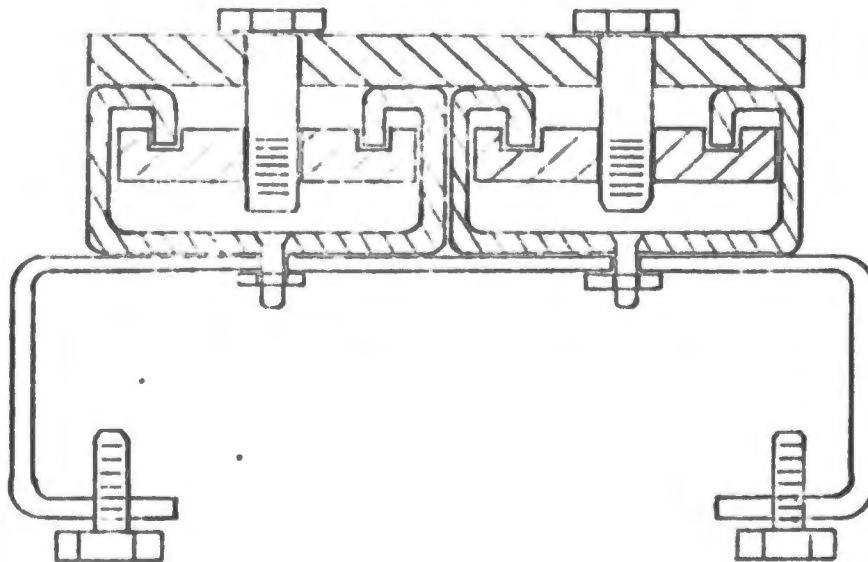


Figure 3b. Cross section of support structure

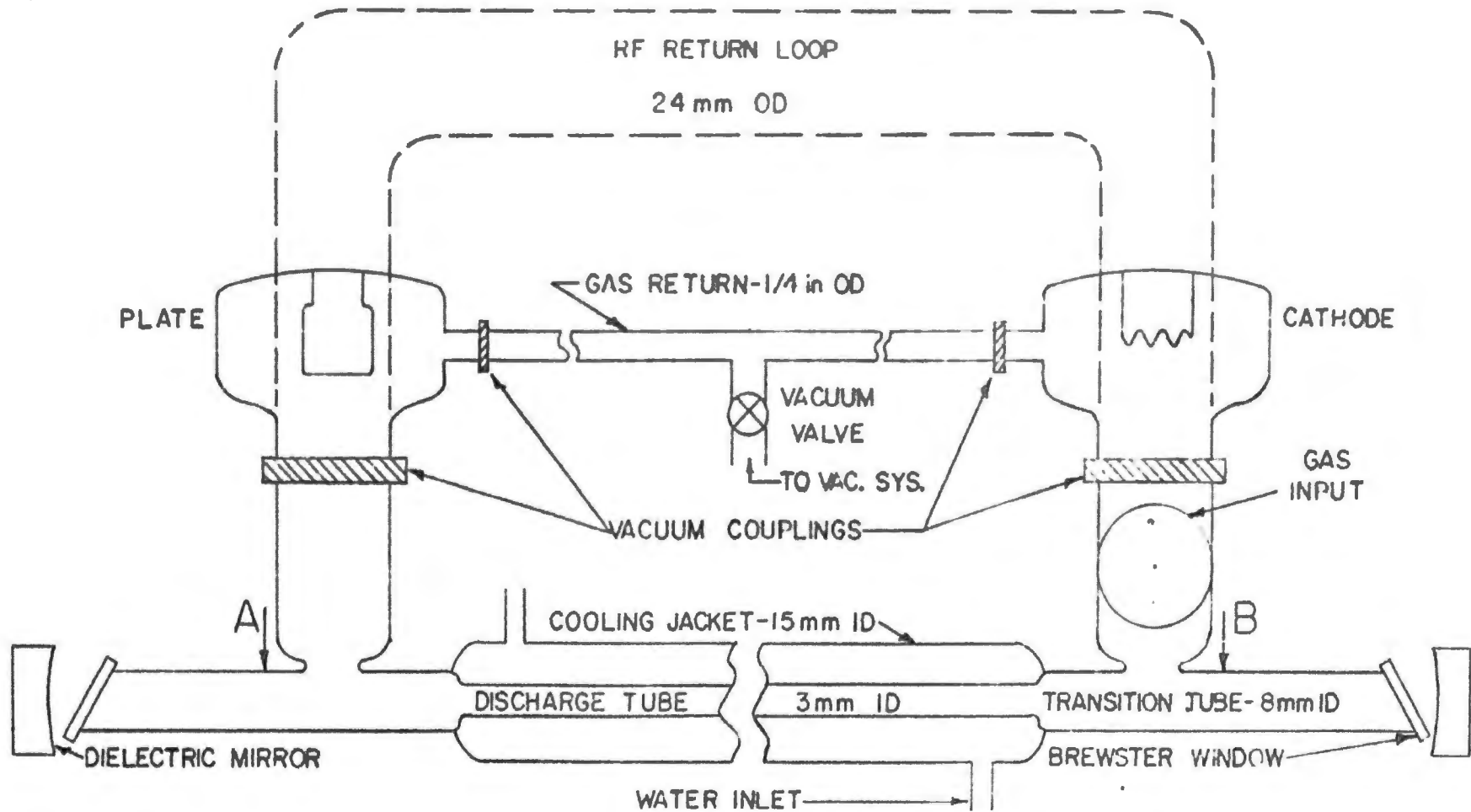


Figure 4. Schematic drawing of basic laser showing basic components of the laser

of the mounting plate. Thus, each pair of screws forms an axis of rotation with the third. Size 10 x 32 screws were used in the final design, although these are not the optimum with respect to thread. One full turn of the screw will cause a 30 minute of arc change in the plate or will move the end of a one meter normal to the plate by approximately 9 mm. This angular change is much larger than the alignment tolerance of 1.3 minutes of arc. Taps and dies were available to make finer threads but at the same time the diameter of the screw was smaller. The smaller diameter screws were not strong enough to give stable support to the mirror-mounting plate; in fact an improvement in the stability of the mirror adjustments could be made by machining a finer precision thread on a larger diameter screw than was used.

2. Resonator Theory and Mirror Selection.

The selection of the mirrors is a fairly simple task, provided one is not trying to operate the laser in a single mode and/or at a single frequency. The spherical mirror is a convenient choice because it allows a large range of mirror placement and ease of alignment in the majority of mirror placements. If the confocal arrangement is used, maximum use of the excited volume of the amplifier tube is used, as opposed to any other configuration utilizing a pair of spherical mirrors. The exception is the large-radius configuration where the mirror radius is very difficult to align, having alignment problems similar to the plane parallel resonator.

After selecting the shape of the mirrors one needs then to select the radius of curvature. It was decided that 80 cm would be a reasonable value as this would

allow the mirrors to be used in either the confocal or spherical mode as desired. Mirror blanks of 80 cm radius of curvature and 3 cm in diameter were ordered from Cal-Astro Optical Laboratories, with a maximum predicted lead time of 75 days. The mirror blanks were finally received after 150 plus days.

During this waiting period Western Electric Company and Bell Telephone Laboratories granted a request for a pair of suitable mirrors. One mirror is almost totally reflective, better than 99.6% at 4880A and 5145A, while the other mirror is 2.2% transmittive at 4880A and 2.7% transmittive at 5145A. The mirrors have a one meter radius of curvature and are approximately one inch in diameter. This particular radius of curvature will not allow the use of a spherical resonator on the present optical bench.

After receipt of the mirror blanks from Cal-Astro Optical Laboratories they were sent to Infrared Industries, Inc. to be dielectric coated. Due to cost, only one frequency was specified to have high reflectance, this being 4880A. One mirror has a 99.6% reflectance while the other mirror has a 2.8% transmittance at 4880A. The calibration chart (Appendix 5) which was supplied by Infrared Industries, Inc. indicates that the coatings have very high reflectances at 5145A. The high reflectance mirror is 98.6% reflective while the partial mirror is 3.2% transmittive. The exact amount of absorption is not known but is estimated to be approximately 0.2 to 0.3%.

Boyd and Kogelnik (14) have developed a relationship which shows the

regions for which a given pair of mirrors will form a stable resonator. Mathematically it is given by

$$0 < \left(1 - \frac{d}{R_1}\right) \left(1 - \frac{d}{R_2}\right) < 1 \quad (1)$$

where d is the mirror separation and R_1 and R_2 are the mirror radius of curvatures. This inequality can also be represented graphically. Probably the best representation is given by Kogelnik and Li (15). Their graph shows that the confocal resonator borders two unstable regions. It is therefore general practice to avoid spacing a pair of supposedly identical mirrors at exactly the confocal spacing as one mirror may be slightly different in radius of curvature from the other due to manufacturing tolerances. Thus one could inadvertently form an unstable resonator.

It was decided to space the mirrors several centimeters in excess of the one meter radius of curvature to insure that an unstable resonator was not accidentally formed.

Another topic which arises in relation to the choice of mirrors is the spot size of the beam expected at the mirrors. Boyd and Gordon (16) developed the theory for the confocal resonator and later Boyd and Kogelnik (14) generalized the theory. Boyd and Kogelnik give, for circular mirrors of equal radius, the spot size w_s of the fundamental mode at the reflectors, as

$$w_s = \sqrt{\frac{R \lambda}{\pi}} \left(\frac{d}{2R^2 - d}\right)^{1/4} \quad (2)$$

where R is mirror radius of curvature and λ is wavelength. For the confocal

system this reduces to

$$w_s = \sqrt{\frac{R \lambda}{\pi}} \quad (3)$$

and is the same for both square or circular mirrors. Knowing the spot size or the mode diameter is important for two reasons; choice of minimum mirror diameter for low diffraction losses, and choice of amplifier bore diameter. In the choice of minimum mirror diameter, it should be noted that w_s is not the maximum radius of the beam, but is the point at which the amplitude of the beam falls to $1/e$ the value at the center of the beam. Thus if one were to use a mirror with a diameter of $2w_s$, the effect on the resonator would be to cause high diffraction losses. This would usually cause elimination of laser action or, at best, cause the resonator to have low gain per pass.

Boyd and Kogelnik (2) have shown that the spot sizes at the mirrors are the same for either square or circular mirrors, therefore one can assume the same diffraction losses for either type of mirror provided that the diameter of the round mirror is the same as the width of the square mirror. Utilizing the results of Boyd and Gordon (4), the fractional diffraction loss per reflection can be found. Thus if the factor $a^2/R\lambda$, where a is the mirror diameter, R is the radius of curvature, and λ is the highest expected operating wavelength, is greater than three then for engineering purposes the mirror diffraction losses are negligible. For example if

$$\frac{a^2}{R \lambda} \geq 3 \quad (4)$$

then the fractional diffraction loss per reflection, α_0 is less than 1×10^{-6} for the TEM_{22} mode. This value is very much lower than the absorption and transmission

losses of the best dielectric mirror available. The almost totally reflective mirror supplied by Bell Telephone Laboratories has losses of approximately .4%, three orders of magnitude larger than the diffraction losses. The factor

$$\frac{\sigma^2}{R \lambda} = \frac{18^2}{1000 (5145 \times 10^{-7})} = 630 \quad (5)$$

for the above mirror.

The spot size, w_s is calculated for the confocal configuration where $R = 1000$ mm, λ is 5145A, to be

$$w_s = \left[\frac{1000 (5145 \times 10^{-7})}{\pi} \right]^{1/2} = 0.405 \quad (6)$$

Boyd and Gordon (16) provide the necessary information to calculate the distance from mirror center at which 99% of the fundamental mode is enclosed. This is the equation

$$F_o = e^{-\frac{x^2 \pi}{R \lambda}} \quad (7)$$

where x is the radius from mirror (or beam) center. Thus when $x = 0.941$ mm in the present case, a circle of that radius encloses 99% of the fundamental mode. A mirror 1.88 mm in diameter would probably enable laser action provided the amplifier had sufficient gain to overcome the residual mirror losses. In practice the mirrors on a gas laser are manufactured with a minimum diameter of $8w_s$.

The mirrors used in the present design were considerably larger than $8w_s$ to provide economy of manufacture, as very small and very large optical lenses (and the mirrors can be considered as lenses (15)) are more costly to manufacture. The approximate 1" diameter also makes the design and construction of mirror mounts

easier. The 1" diameter thus insures that the only losses of the mirrors are those associated with transmittance and absorption of the coatings and substrate. The substrate of the 3 cm mirrors is Pyrex, while the 1" mirrors are believed to be Homosil quartz, as this is the usual substrate for optics produced at Bell Telephone Laboratories.

3. Amplifier Theory and Construction.

The amplifier consists of the bore tube, where the actual optical amplification takes place, the windows, through which the optical power passes, and the other necessary tubulations required for gas entry, instrumentation, window mounting, and the plate, cathode, or RF return loop. (Figure 4). Of major concern in argon lasers is the material of which the bore is constructed. The cause of this concern is the excitation power levels required for even small amounts of output power. The literature (4) (12) (13) (17) (18) shows efficiencies ranging from less than 0.01 to 0.3% with 0.1% being most frequently mentioned. Therefore, 100 milliwatts of output power requires 1000 watts input at 0.1% efficiency or a dissipation of approximately 25 watts/cm of bore for a 40 cm bore length.

The literature (12) (17) (18) indicates that the bore walls are also subject to ion bombardment damage, the severity of the damage being proportional to the current density. Labuda, et al. (12) reports decomposition and darkening of quartz bores at "modest" currents. Present materials are therefore not entirely suitable for long-life lasers. Quartz was finally used for the construction because of the problems attendant with the use of alumina.

In choosing a bore diameter one is faced with opposing choices, gain or power output. As the bore is made smaller the gain of the system is increased but the power gain per unit length is decreased. Since the quality of the optics was not particularly good and the losses of the window optics were relatively unknown, it was decided to keep the gain of the system relatively high. The bore was thus chosen to have minimum diffraction losses for the fundamental mode. Boyd (14) shows that the mode volume at the center of the resonator is reduced by the factor $1/\sqrt{2}$. Therefore to enclose 99% of the fundamental mode the bore diameter required is $2(1.88)/\sqrt{2} = 2.66$ mm. Thus, a convenient diameter tube is 3 mm, which will allow several of the lower order modes to have small diffraction losses.

The choice in bore length is dependent on the power supply available, cavity lengths, and desired output power. Goldsborough, et al. (17) indicates that the voltage drop for argon is inversely related to the tube diameter.

$$\frac{\text{Volts}}{\text{cm}} = \frac{14}{D \text{ (mm)}} \quad (8)$$

For the 3 cm tube this is 4.67 V/cm or 187 volts across the capillary tube. The voltage drop for the remaining tube (approximately 40 cm of 22 mm tube) is approximately 25 volts. Thus the total tube drop should be in the neighborhood of 212 volts, which compares favorably with a measured total voltage across the discharge in the area of 202 to 212 volts. Goldsborough indicates that at RF frequencies the voltage drop is not a function of pressure in the pressure range of an argon laser. This is not true for dc where there is variance in the voltage gradient. Therefore the calculated value of 212 volts is truly an estimate. The 212 volts allows the use of normally available 230 volt power lines provided one can strike the arc initially.

Labuda, et al. (12) indicate that for a 3 mm bore size the output power should be 0.6 mw/cm or 2.4 mw for a 40 cm bore length at 10 amperes discharge current. Since there was not a particular need for a set power level in the output beam, it was not used as a criterion for length.

The remaining consideration was physical restriction set by the 1 meter cavity and requirements of the mounting clamps and tubulations. The mounts require approximately 2 cm and the sidewall tubulations require approximately 5 cm. It was also desired to leave extra tube length for repeated cutting or grinding and for positioning of the machinists blocks used during the grinding of the 8 mm tube (Figure 4) to which the windows are mounted. A good length appeared to be 20 cm for each end. This would give a total length of 80 cm thus allowing 10 cm between the amplifier and mirrors, at each end of the amplifier, for insertion of filters, cavity spoilers, beam splitters, etc., in the cavity if desired.

During earlier trials with alumina, bore warpage with long bores was a problem. Therefore it was also desired to keep the bore reasonably short while still providing sufficient gain to overcome losses in the cavity.

The amplifier was constructed of General Electric Type 204 fused quartz by the glassblowing service at the University of Missouri at Columbia. After the glassblowing was completed, the only work remaining was mounting the windows.

The windows were Pyrex glass flats originally ground to a flatness of 1/10

visible wavelength with a diameter of 3.5 cm and a thickness of 3 mm. The windows, when illuminated by a He-Ne laser, showed considerable scattering of the beam when they were new and an even larger amount after they had been used on several different amplifiers. During one of the initial trials using alumina bore material and pulsed operation, the windows were heavily sputtered with metal from the cathode. After removal of the metal by etching, the flats were examined under a measuring microscope for damage. Pits were found that measured up to 12 microns in diameter. This was expected to considerably increase the losses of the cavity. These losses were later measured at the optimum pressure and 10 amperes of discharge current as 0.03 mw per face with the output beam measuring approximately 2.3 mw. The losses due to window scattering and reflection are approximately 5% or more of the output beam. The losses could easily be higher since the above measurement assumes that the scattering points scatter the beam in the same direction as the beam which is reflected from the window face, thus the losses are undoubtedly higher.

The Brewster angles of the windows are physically measured as 53° and 54.5° with the values being marked on the edges of the windows. A He-Ne laser, photomultiplier, and a calibrated rotating table were used to determine the angle of maximum transmission. The peak of the Brewster angle is quite broad so that accuracy of the window angle need only be held to less than one degree.

Two methods were tested for cutting the terminal tubing at the Brewster angle. In the first, a diamond saw with an 11 thousandths thick wafering blade was used. This method was not as acceptable as grinding, as the blade tended to leave cutting marks

and to wander, leaving an uneven surface. In the second method a watercooled lapidary grinding wheel was used. In this method the amplifier tube was mounted onto small machinists "V" blocks which had Teflon pads under the holding screws. Once the amplifier tube is mounted in the machinists "V" blocks, they must not be moved in relation to the tube because the windows must not be rotated more than 1° with respect to each other. The use of Brewster angle windows polarizes the beam and rotating the windows more than 1° with respect to each other will cause increased cavity losses due to the cross polarization.

A special rotating table (Figure 5) having a long supporting platform was constructed. The platform is approximately set to the Brewster angle. The amplifier tube was then fed slowly into the edge of the grinding wheel until a smooth surface was obtained.

After the initial grinding the angle must be checked for correctness. A simple method is used to do this (Figure 6). A triangle MNO is layed out on a flat surface. Side NO is approximately one meter long and the angle MNO is the Brewster angle. A piece of optical flat glass (reflection plate), is marked as shown in Figure 6, a beam splitter from a bombsight was used in this instance. Another plate, the alignment plate, is made from poster board or metal and has a 2 mm hole drilled as shown. This plate should not be highly reflective for safety reasons. The hole and the intersection of the lines on the reflection plate must be the same height from the flat surface upon which they are positioned. The amplifier is positioned parallel to and approximately centered on side MN with the ground end vertically



Figure 5. Window grinding method showing platform and Pyrex tube in mounting blocks

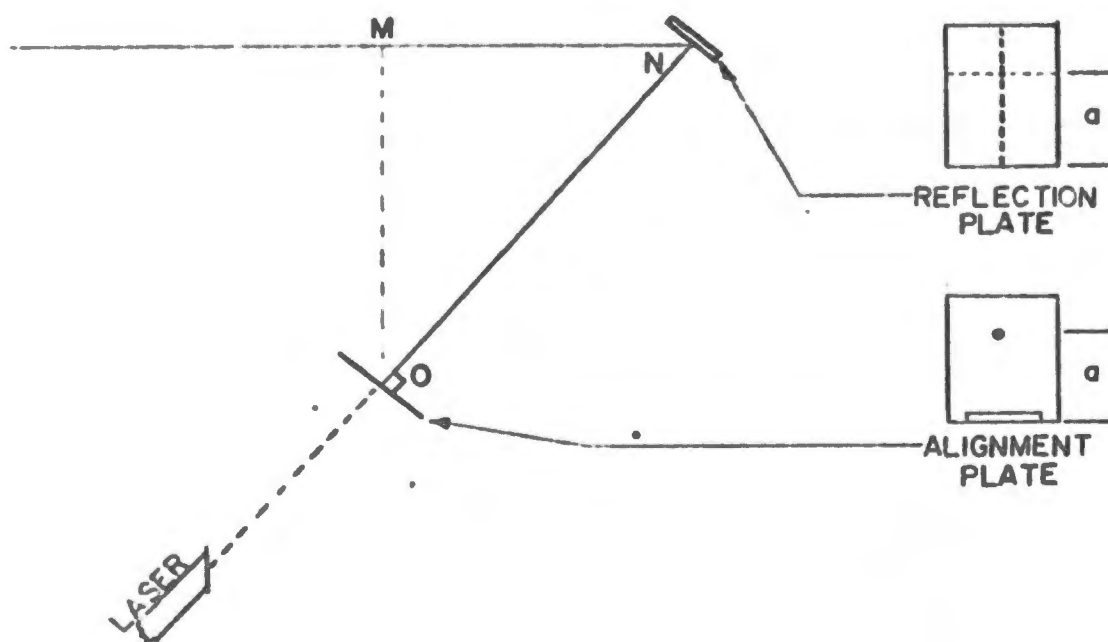


Figure 6. Layout of triangle used to check Brewster angle

above the triangle apex MNO. The reflection plate is then positioned against the ground end of the tube with the vertical line over the apex of the triangle. The alignment plate is positioned with the hole vertically above the line NO as shown in Figure 6. The He-Ne laser is placed about the line NO as shown in Figure 6. The He-Ne laser is placed about two meters from the alignment plate so that the beam passes cleanly through the hole and is centered on the intersecting lines of the reflection plate. The beam will be reflected on the back of the alignment card the distance of the reflection from the hole can be related to the error in the angle of the tube. With reasonable care the angle can be obtained to within 15 minutes of the correct angle. If two different angles must be measured, it will simplify procedures to construct two different lines MN. This will also reduce the chance of error in measuring the rotation. This error could be introduced by movement of both the HE-Ne laser and the alignment plate.

After the ends of the tube are cut to the proper angle the tube should be carefully cleaned, first with detergent and water, then with acetone or trichloroethylene, and then with two changes of methanol. The tube is then placed in the mounts. Next the windows are very carefully washed.

The following washing steps were found to work very well.

1. Wash in warm water and detergent; scrubbing lightly with a clean cotton swab if necessary
2. Two rinses in distilled water
3. Wash in reagent grade acetone

4. Immediately wash in ethyl alcohol
5. Blow dry with dry air or nitrogen

After washing, the windows can be checked for cleanliness by illuminating the surface with glancing white light and inspecting the surface from a low angle.

After cleaning, the windows are mounted on the tube using a good grade of epoxy. The "2 ton" epoxy manufactured by Devcon Corporation was used with good results. The windows can be held in place by the device shown in Figure 7. The pad which rests against the window is made from Teflon and has a flat surface to reduce local pressure against the window. A minimum amount of pressure should be used to hold the window in place. The epoxy is then carefully placed to cover the joint between the window and tube being careful to obtain a good seal. If it becomes necessary to remove the window, the epoxy can be softened and removed by immersing the joint in warm chloroform. Adequate ventilation should be secured when using chloroform. After the epoxy is hard the joint should be covered with two coats of Glyptal. The windows should be wiped off prior to operation of the laser with Silicone treated lens tissues.

Before connecting the required terminations to the amplifier the bore should be roughly centered on the mirrors using the X-Y controls on the mounts.

4. Excitation Methods.

There are several methods available for excitation on an ionized argon laser.

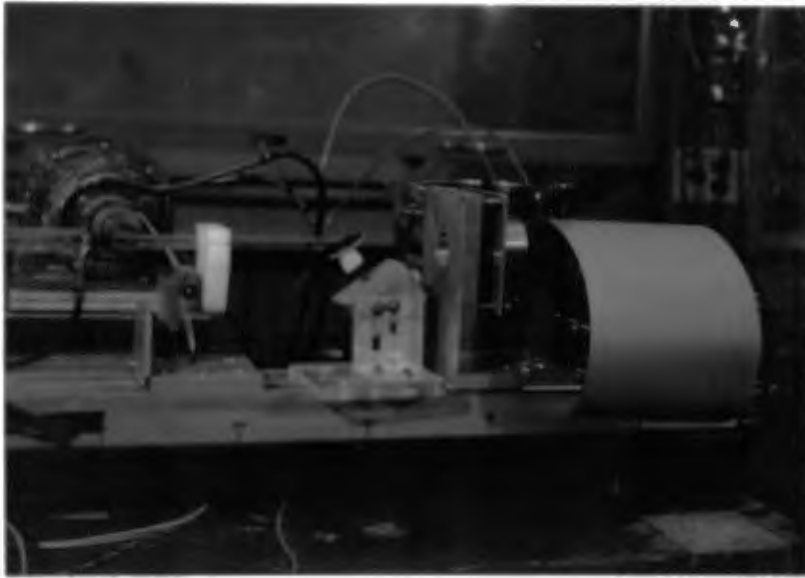


Figure 7. Photograph of device used to hold windows in place during mounting

The two basic categories are RF and dc. The RF method has two variations. In both methods the plate and cathode would be replaced by the RF return loop (Figure 4). The first method (18) then requires a ferrite toroid to be placed concentrically on the back loop. The toroid is then wound with a primary winding. Bell refers to this as E-field coupling. The second method (17) uses a coil, having very few turns, and with its axis parallel to the axis of the loop formed by the back loop and laser bore to couple the RF energy into the gas. These systems have distinct advantages in that corrosive gases can be used in the laser if all internal metallic parts are eliminated. The authors (17) (18) also state that the use of RF energy reduces bore erosion.

The present system has been designed to take advantage in future experiments of the RF excitation methods since the system utilizes vacuum couplings at the point where the plate and cathode join to the bore tube. This will allow the plate and cathode to be replaced by a large bore gas return loop (Figure 4). The present system utilizes metallic couplings thereby limiting the present system to non-corrosive gases.

The dc method requires a heavy duty plate and cathode in place of the RF back loop (Figure 4). The cathode must be capable of withstanding the effects of ion bombardment. The dc method can also be used in a pulsed mode of operation. This allows high power pulses to be obtained from the present laser configuration.

5. Plate & Cathode Construction.

In the course of construction of the laser several cathodes were tried. The earliest model consisted of large brass electrodes 1/4 inch in diameter. The ends were finished to a spherical shape and then polished. The system at this time was operating in a pulsed mode with currents in excess of 80 amperes over a maximum of 300 microseconds. Severe degeneration of the cathode occurred with the subsequent result that hot metallic particles were deposited on the windows causing some pitting.

The next attempt was with large, 2 cm diameter, nickel electrodes, salvaged from high-power commercial tubes. These electrodes held up reasonably well under the same pulsed conditions, showing no visible signs of sputtering. At this point the pulsed system with alumina bores had not yielded any meaningful results mainly due to alignment problems and failure of the alumina to Pyrex joints, and a conversion to quartz was accomplished. With the construction of the quartz system it was decided to convert to a hot cathode system.

The first hot cathode was a pure tungsten cathode mounted in a 70 mm diameter envelope. The cathode consisted of tungsten wire mesh having 0.003 inch diameter wire with 50 wires to the inch. The mesh was in the shape of a rectangle 2 cm by 8 cm with a final area of 15 cm^2 after mounting. This provided a tungsten surface area of 71 cm^2 and when heated to 2500°K had the capability of delivering 21.4 amperes of emission current.

The envelope was constructed with four 1/8 inch tungsten feedthroughs

spaced in a rectangular pattern approximately 2 cm by 4 cm. The interior ends of the feedthroughs were slotted to a depth of 1/4 inch utilizing the diamond saw. A piece of molybdenum, 1 cm by 2 cm and 0.005 inches thick, was folded and crimped over each of the 2 cm dimensions of the mesh to form a header for the cathode. The headers were spot welded to the mesh after crimping using a small spot welder. Tungsten electrodes were used in this procedure when the copper electrodes provided were found unsuitable. Maximum closure pressure and maximum heat, 100 watt-sec were used to make good welds. Any shaping of the headers should be accomplished prior to spot welding to avoid breaking the spotwelds.

After spot welding the headers were forced into the slots cut in the tungsten feedthroughs and again spot welded, this time using an industrial spot welder. The closure pressure was regulated by air pressure which was set at 10 psi and the heat used was 14 amp-seconds. Both settings are minimum settings for the machine. The envelope was then closed by the glassblower. It should be noted that Pyrex envelopes may be repeatedly opened by using hot wire techniques, known to most technical glassblowers, and then reclosed after the work inside the envelopes has been accomplished.

This cathode was unsuccessful for long-term operation due to the heat required by the cathode. The envelope was cooled by a 300 cfm blower with a formed shield to direct the air. After several hours of use the envelope failed.

A new cathode was built utilizing the base of a 10,000 watt transmitting tube.

The feedthroughs are 1/2 inch in diameter, adequate for approximately 150 amperes of current when forced air cooled. Each large feedthrough connects to eight 1/16 inch diameter nickel supports inside the envelope. The cathode, built in 8 sections was mounted on the nickel supports.

An emission coating manufactured by Kulite Tungsten Company was used in this cathode with good results. Each section consists of a piece of Tungsten wire mesh 9.5 cm long and 0.4 cm wide (8 wires) having an effective emitting area after mounting and coating of 7.2 cm^2 . The total effective area is 57.6 cm^2 which will support an estimated emission current of 43 amperes at 900°K . The exact composition of the coating was unknown. Wagener (20) gives an emission estimate of 1 to 17 amperes per cm^2 in the temperature range of 900 to 1200°K , for Barium-Strontium Oxide coatings. In order to have a very conservative estimate of the emission, a value of 0.75 amperes per cm^2 was used. Detailed information for building the cathode is given in Appendix I. The envelope for the cathode was made from a copper pipe having a wall thickness of 1/4 inch. A spiral copper tube was also affixed to the outside of the envelope for water cooling. The cathode requires 40 amperes at 9 volts to heat the filaments to approximately 1000°K . This cathode has proved to be entirely suitable for the present operating conditions.

The plate used with the present system is one of the nickel electrodes described earlier in this section. This electrode has survived several hours of cw operation with currents up to 40 amperes. The only visible damage has been a slight dulling of the finish and the deposition of a very light, semi-transparent film on the envelope.

6. Supply Systems.

The argon gas used in the laser is commercial grade gas. The gas analysis is given in Appendix 2. The gas flow pattern used in the final laser is different from the pattern used in earlier attempts and is the pattern recommended by See, et al. (21). The gas is supplied at the anode portion of the laser and the vacuum is applied at the center of the gas return loop. Even using See's recommendations gas pumping remains a sizeable problem as will be indicated in the measurement section.

The power required to supply the various cathodes was obtained from the ac filament supply of the vacuum system. This supply has three ranges: 100 A. at 20 V., 200 A. at 10V., and 400 A. at 5 V. All the cathodes were designed to be supplied on the 100 ampere range. The filament supply is designed such that the secondary is isolated from the primary.

The remaining supply is the system which must supply the discharge power. The first system used was a single-phase, full-wave, rectified dc supply. Due to the large ripple of the rectified output the arc was not self-sustaining. Because of this the system was changed to a three-phase, full-wave rectified supply.

The supply consisted of a 3 phase variable transformer (Figure 8) having a 3 phase-230 v primary and a 0 to 270 volt secondary. The variable transformer was then connected to a 3 phase step-up isolation transformer bank. The primary of this bank was Delta connected and nominally rated at 240 v. The secondary was wye connected and rated at 480 v. This was then full-wave rectified utilizing Silicon

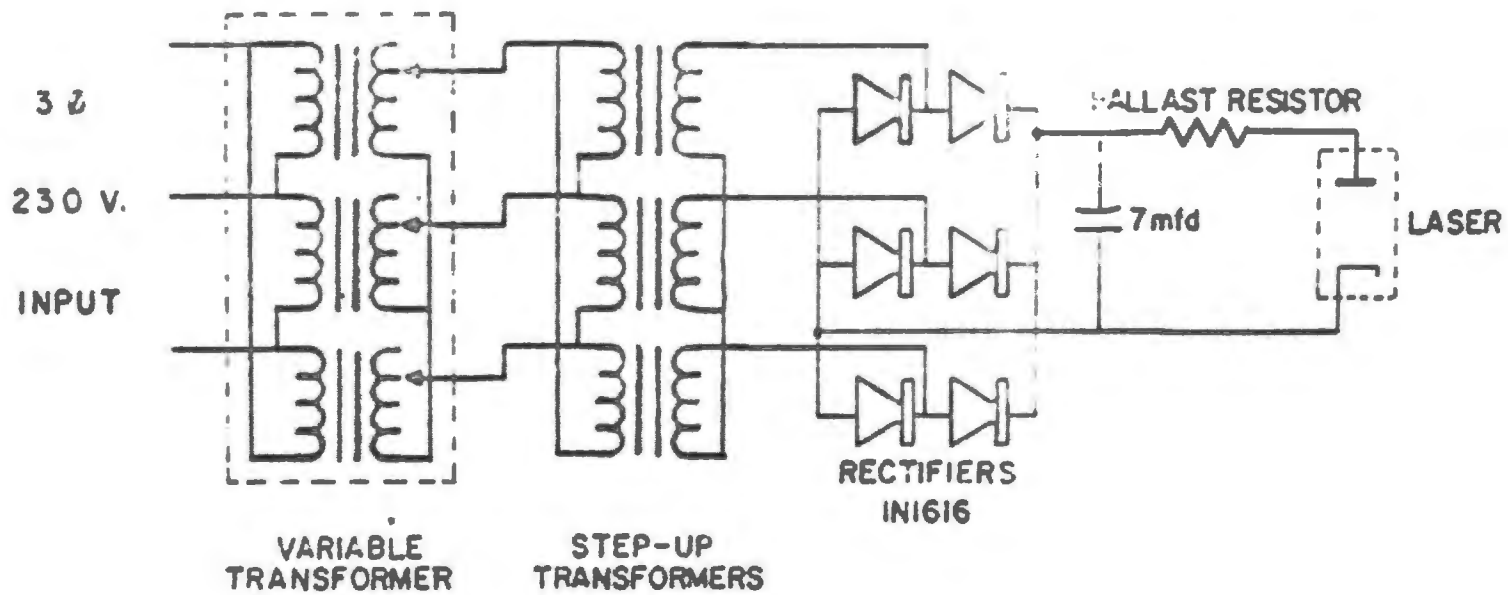


Figure 8. Schematic of discharge power supply

diodes, type 1N1616, rated at 600 volts, 5 amperes. Since the duty cycle is low for each rectifier, and since each diode is heavily heat sinked it was determined that it would be possible to operate the diodes at current levels considerably in excess of their rating. This rectifier set has withstood short-term loads of 40 amperes for periods of up to 20 seconds, and loads of 20 amperes for periods up to 1.5 minutes. The output of the rectifier has a parallel capacitor of 7 μ F for transient spike protection. Large transients occur when the discharge ignites and extinguishes, and have destroyed several diodes, of a different type, in an earlier attempt. After the capacitor was added there were no further failures.

Since the arc exhibits a negative resistance characteristic it was found necessary to use a ballast resistor to control the current during ignition of the arc. The first resistor was approximately 18 ohms and consisted of three 200-watt resistors in parallel. The resistors were then placed in a water bath and successfully withstood 10,000 watt dissipation levels. This ballast resistor was found very suitable during the initial trials but as higher discharge currents were used it was necessary to replace the resistor with a lower value due to voltage limitations of the supply.

The second resistor is rated at 10 ohms and consists of three 100-watt units in parallel and placed in a water bath. This resistance value was not as successful as the 18 ohm unit in the control of the current during ignition.

B. ALIGNMENT OF THE OPTICAL CAVITY

Aligning the optical cavity has proven to be a major problem in the

construction of the laser. Bloom (19) gives the necessary equations to determine the tolerance on alignment accuracy. The resulting equation for confocal resonators is

$$\theta = \frac{w_s}{R} \quad (9)$$

where w_s is the spot size and R is the mirror radius of curvature. This indicates that the normal of the mirror, in the confocal case, can be shifted by the radius of the spot size. For the one-meter radius-of-curvature mirrors spaced one meter and a spot size, w_s , of 0.394 mm at 4880Å,

$$\theta = \frac{0.394}{1000} = 1.35 \text{ minutes} \quad (10)$$

Bloom (19) indicates that the confocal configuration is least sensitive to alignment of all the configurations.

Several methods were attempted but did not result in successful operation of the laser. A very simple method was developed which requires the simplest of materials, and is described here. This method must be done carefully if it is to work properly.

The room in which the laser is located should be fairly dark, a high light level makes the procedure very difficult to perform. It is necessary to construct two cards, 3 to 4 inches on a side which are white on one side and non-reflecting black on the other. Flat white optical paint and black flock paper were found to be good materials for the respective sides. Thin metal sheet, 1/32 inch thick, works very well for base material.

On the white side of the cards two black intersecting lines are drawn so that the intersection is approximately centered on the card. The lines should be about $1/64$ inch wide. At the intersection of the lines a $1/32$ inch diameter hole is drilled. The cards should then be mounted in suitable holders such as a block of wood or metal that is slotted to accept the card. The blocks should be heavy enough that they will stay in position under light pressures.

After the cards have been constructed it is necessary to position the cards on the optical center of the bore with the mirrors removed. Place the cards outside the mirror location so that the mirrors can be placed in position without disturbing the cards. The cards may be coarsely positioned by sighting down the bore tube through the hole in the card. The cards are then closely positioned by sighting down the bore from the opposite end and carefully adjusting the cards so that the intersection of the lines appears to be centered in the circle formed by the bore.

The vertical height can be very carefully controlled by using slips of paper as shims. The paper used in this project was 0.004 inches thick and was found very useful as shim stock. It was found helpful during the fine positioning of the cards to sight down the unobstructed bore, by using a common flat mirror positioned between the card and Brewster windows. The use of small lights to illuminate the side of the bore and the card being sighted is necessary. As a final check on the centering of the cards on the bore, one looks through the hole in the card at one end of the amplifier and sights the intersecting lines of the opposite card. One will find it slightly more difficult to see the lines when sighting through the hole. After the

cards are positioned, one must be very careful to avoid moving them. The holes in the cards physically identify the optical center of the bore.

The next step is to mount one of the mirrors in position. The first mirror must be aligned prior to placing the second mirror. The position must be correct horizontally, vertically, and laterally. In this step the card at the opposite end of the amplifier must be brightly illuminated. With the mirror approximately positioned, one looks through the hole and sights the opposite card. Then holding a finely divided scale on the near side of the mirror, accurately position the mirror vertically and laterally. The centering of the mirrors is important and must be done accurately. Carefully clamp the base of the mirror and recheck accuracy. Again paper shims can be used for adjusting the vertical height.

The last step is to illuminate the white side of the near card, but not too brightly. The level of illumination should not be so bright that one cannot see the lines on the opposite card. Looking at the back of the near mirror one will see the image of the lines of the near card. One should also be able to see the lines on the far card, and by adjusting the screws on the mirror mount, the image of the lines on the near card can be brought into coincidence with the lines on the far card, and should be done accurately. This procedure is then repeated for the second mirror.

After aligning the mirrors the laser should be ready for operation. All work such as attachment of the plate structure to the amplifier should be done prior to aligning the mirrors to avoid changing the alignment.

It may be necessary to excite the laser somewhat above the expected threshold, initially, in order to cause laser action. Once laser action has occurred the mirrors may be closely adjusted to obtain the maximum output.

C. PRELIMINARY DESIGNS

It has already been mentioned in this thesis that the input power levels required for an argon laser are relatively high, necessitating the use of high temperature materials. Thus, when this endeavor was started it was desired to try a material other than quartz, which had already been shown to be a less than optimum material. A review of several easily obtainable, high temperature materials showed that alumina (Al_2O_3), which is gas tight and has a working temperature of 1900°C , might be a suitable material.

The shape or design of the initial model is very similar to that of Figure 4, except that the 3 mm bore is alumina rather than quartz, and the ends are Pyrex. The construction problem here was how to join the alumina to the Pyrex. It was decided to try to use high temperature epoxies to form the joints. Several different style joints were tried, all of which resulted in failure, not of the bonding materials, but of the Pyrex. The joints were all of the sleeve type with the Pyrex as the outer layer. The failures generally resulted because the alumina, which has a coefficient of expansion similar to Pyrex, was being heated to a higher temperature than the Pyrex, which resulted in the alumina expanding into the Pyrex and finally breaking it. The joints had been tested for temperature stability in a furnace where the joints were evenly heated and found to be very stable.

The next model that was attempted was entirely alumina. Discussions with people in the ceramics field and with McDanel Refractory Porcelain Company had led to the idea that joints of alumina to alumina could be made. Thus, additional alumina tubing and pure alumina cement was ordered from McDanel Refractory Porcelain Company for construction purposes.

The joints in this case consisted of a small diameter tube being inserted into the sidewall of a larger diameter tube and cemented in place. After the cement was set the structure was sintered, the process taking approximately 36 hours. Initially it was found necessary to overcoat, and refire the joint at least two times in addition to the initial coat, before the joint appeared to be gas tight. Subsequent vacuum testing showed that the joints formed were very porous. Additional overcoating did not eliminate the problem. It was finally determined that the original tubing was formed by an extrusion process which very closely packs the granules and upon sintering forms a vacuum tight material.

It is felt that alumina may still be a successful bore material provided that the structure formed may be made vacuum tight. It is probable that by having the refractory company build the structure in one piece, possibly in slightly different form, that a vacuum tight structure may be formed. This may be a possible area for future effort.

During the course of the initial trials with the alumina and Pyrex models, both RF and pulsed operation were attempted. Laser action was never achieved in

those efforts for two probable reasons.

The first was the use of a vacuum line that was too small and of a material, polyethylene, which outgased rather badly. Thus the proper pressure was not obtained within the laser structure even though the pressure indicators on the vacuum system showed very low pressures being attained. Therefore one should be warned to use vacuum supply lines of a fairly large diameter especially if one is coupling over distances more than a foot or two. In the final design a 3/4 inch diameter, flexible tube, approximately 3 feet long was used with reasonable results. The use of a larger pipe will definitely enhance the pumping rate possibly improving the gas flow pattern in the laser.

The second reason is alignment. There is a good possibility that the mirrors, during the early trials, were never accurately enough aligned to allow laser action even under otherwise ideal conditions.

D. SAFETY CONSIDERATIONS

When working with or around lasers one should be very careful to protect the eyes from the laser beam. Each time there is an interface between the laser beam and a reflecting surface or optical surface e.g. at the Brewster windows, mirrors, or at additional optic interfaces, there is the opportunity of a stray beam of sufficient power to damage the eyes. There is no absolute power level below which one is safe. The range of 1 to 4 mw is generally accepted as the danger point. There are several papers on safety in the use of lasers, two of which are listed in the bibliography

(25) (26). Regardless of the power of the laser it is recommended that the eyes not be allowed to directly observe the beam or a reflection of the beam from a bright surface at any time.

IV. CONCLUSIONS

The goal of the work covered by this thesis was to build a working argon laser as economically as possible, while at the same time finding problem areas for future work. This goal has been achieved. The laser that was constructed is easily alterable so that different plate and cathode structures, different gas mixtures, different types of excitation can be used, and other mirror systems can be easily mounted. By using the present set of four mirrors several combinations of transmittances and a large range of cavity configurations are available. The output of the laser compares favorably with those reported previously in the literature. The magnitude of the output for long-term operation is limited by heating considerations.

A. EXPERIMENTAL MEASUREMENTS

Experimental measurements were performed on the laser to obtain data necessary to indicate the proper operating point, the available optical power output for various discharge currents, and the available output frequencies under dc discharge conditions.

The optimum operating point was determined by measuring the optical output for various pressures with a constant discharge current. The results of two different measurement periods are shown in Figure 9. Data runs B and C were made after the system was flushed several times with argon. The difference in amplitude between curves B and C was caused by readjustment of the mirrors.

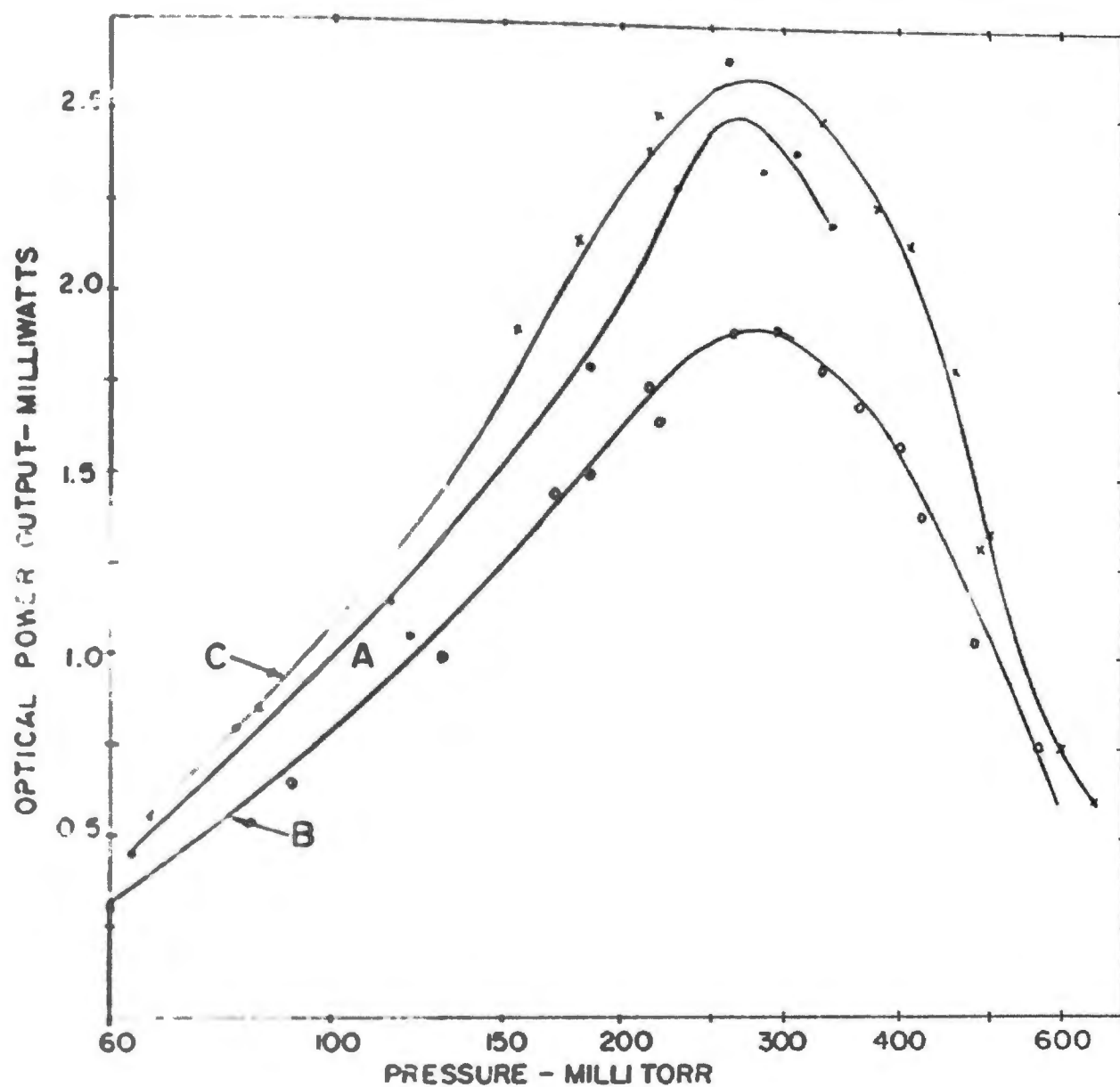


Figure 9. Curves of optical power output versus pressure at a constant discharge current of 10 amperes. The curves are for three separate runs where the argon gas or mirror alignment was changed.

The third curve labeled A, which is incomplete, is also shown. This curve was made without flushing the laser with argon after the laser had been inactive for a period of 15 hours. The curve was not completed because of severe heating of sections of the amplifier. The areas that were visibly heated were the sections of 8 mm tubing between the 3 mm bore and the junctions with the 22 mm tubing (Figure 4). The cause of the heating is believed to be impurities which leaked into the system during the inactive period. It is interesting to note that the data for curve A was obtained prior to readjustment of the mirrors. After taking the data for curve A, the laser was flushed with argon several times, and then the data for curve B was obtained. The data indicates that the optimum pressure for this laser is approximately 280 m Torr. This value is in the range stated in the literature (5) (13) (17).

The laser has been operated at the optimum point over a wide current range. Three representative curves, are shown, Figure 10, from the many for which data was obtained. All the curves obtained had the same general shape and differed mainly in the power output for a given discharge current.

Gas pumping (21) (22) was found to be a major factor affecting the output of the laser and every effort should be made to minimize the effects of gas pumping. The effects of gas pumping were observed during the taking of data. After a change in the current level the output would either decrease or increase from the initial new output depending on whether the current was increased or decreased. The change was small, 10%, at low current levels but increased to approximately 25% at a

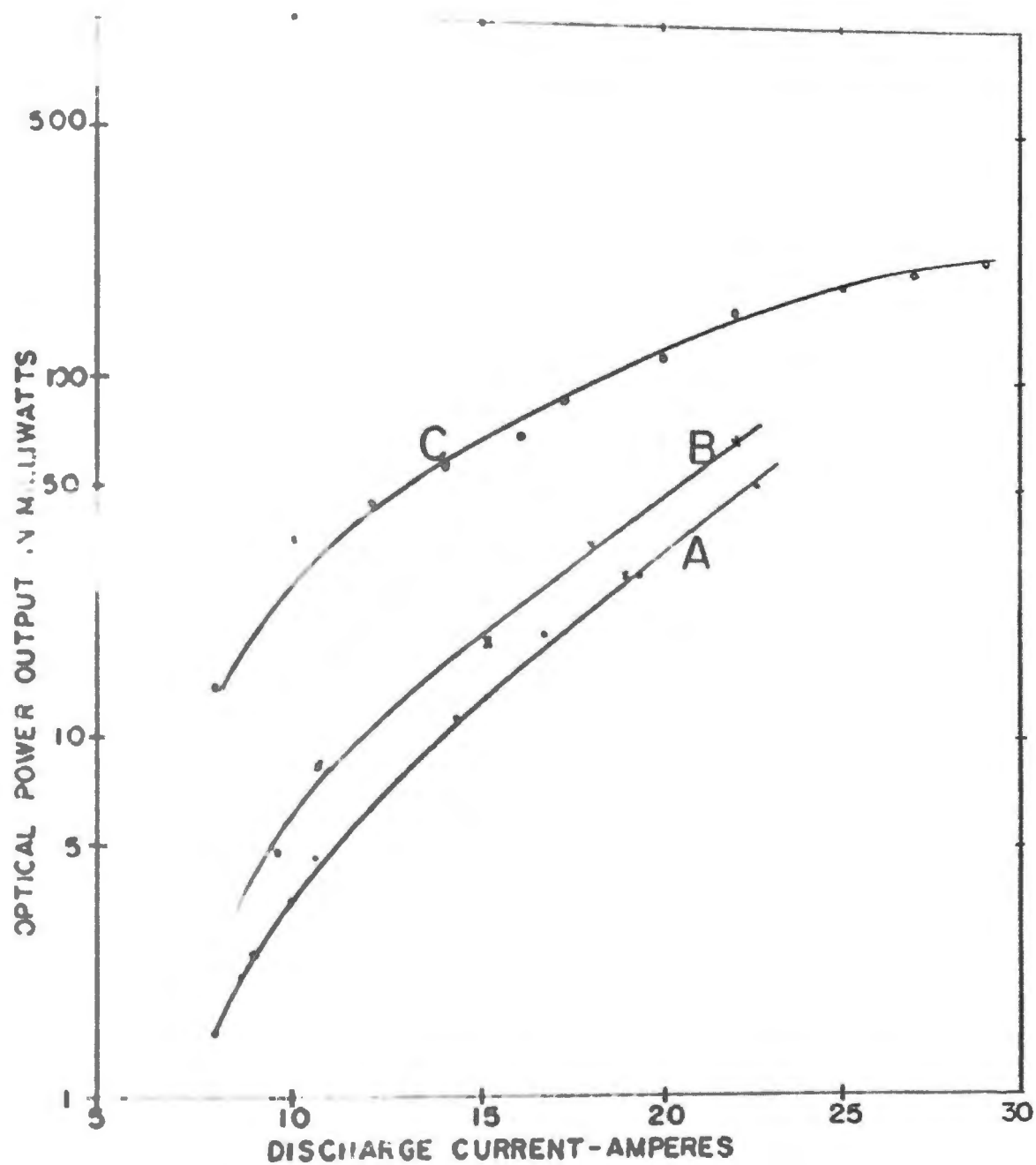


Figure 10. Curves of optical power output versus discharge current at optimum pressure of 280 m Torr. The curves are for three different data runs. The method used to acquire the data for curves A and B differs from the method used for curve C.

current of 20 amperes.

The data for curves A and B of Figure 10 were taken after the optical output reached steady state. The data for curve C was produced as the current was steadily increased. The higher output for a given discharge current is most likely due to a more optimum gas pressure for a given discharge current and indicates that the optimum pressure point may be different for different values of current. Even though the gas return system incorporates the recommendations given by See, et al. (21) it is obviously not optimum and additional investigation is needed in this area. The power output at several different current levels compared very favorably to the values given by Labuda (12).

True thresholds were not determined for the various frequencies present in the laser beam. A diffraction grating system from a monochromator was used to identify the frequencies in the beam. Tables of known frequencies given by Gordon, et al. (13) and Bridges, (8) were used to help identify the frequencies. The thresholds given are simply the current levels at which some output could be visually detected. The gas pressure used when determining the threshold values was the optimum pressure determined for 4880A. The four frequencies, other than 4880A, that were identified and their respective thresholds are:

4727 A at 24.0 amperes
4765 A at 12.0 amperes
5017 A at 14.4 amperes
5145 A at 13.2 amperes

The threshold for 4880A for this laser is the same as the minimum current required to maintain ionization or approximately 5 amperes.

The voltage drop across the discharge was approximately 210 volts at the optimum gas pressure, although this varied by ± 5 volts from curve to curve. During the period which the optimum pressure was being sought it was found that the discharge voltage was at a minimum when the optimum pressure was reached. The voltage necessary to start the discharge in conjunction with the Tesla coil was approximately 420 volts.

During the early stages of operation of the laser there was some concern that the O-rings in the vacuum couplings would overheat. Because of this the temperature of the couplings was monitored using Chromel-Alumel thermocouples. At current levels of 10 amperes, it required approximately 5 minutes for the couplings to reach 100°C , the maximum temperature which was allowed. The maximum working temperature of the O-rings, which are Viton, is listed as 200°C , but in order to maintain a margin of safety 100°C was set as the upper temperature limit. The O-rings are presently the limiting factor for long-term operation.

B. PROBLEMS FOR FUTURE INVESTIGATION

Several recommendations have been made for future improvement of the laser and for future investigations. The present work was hampered by the lack of required information in the area of materials, and of suitable materials, and facilities. The work would have been aided by having a large flat surface upon which to work. One facility, visited by this writer, had obtained a large slab of granite approximately 4 by 8 feet that was ground flat within 0.01 inches for less than \$100.00. Additional items of equipment which would have aided the construction work are a "clean bench"

and a mass spectrometer type leak detector. If impurity studies are to be undertaken in the future, a mass spectrometer is a necessity. A spectrum analyzer would also be a highly desirable item.

The first recommendation for future effort has been mentioned earlier and is a continuation of efforts to utilize alumina. It is entirely possible that other even more suitable materials are available. A likely source of new "super" materials is this country's space program and this area should be investigated for materials. Carbon has shown some promise as reported by Hernquist (10). A suitable material must possess a high service temperature, 2000 to 3000°C and have a low sputtering yield. It is desirable that it be a dielectric but this is not entirely necessary (10) (12).

A modification of the present laser that should be undertaken as soon as possible is to raise the present temperature limit of the structure. An easy step in doing this would be to replace the present O-rings with ones of a higher temperature limit such as silicone O-rings, or possibly replacing the present couplings with a flange type, metal O-ring, joint system. It would be possible to considerably extend the service temperature by utilizing the flange system rather than the couplings.

It is very likely that the present gas flow system can be much improved. The present gas return loop is of rather small, 8 mm, inside diameter, and is terminated in 1/4 inch OD tube so that vacuum couplings already on hand could be used. It would most likely improve the system to use as large a diameter and as short a section

as possible, keeping in mind that the electrical impedance of the gas return must be greater than that of the bore section. Under RF excitation, the conditions are complementary in that both the electrical impedance and the gas flow impedance should be very low. It may be possible to devise a multiple return system using a number of smaller tubes that individually have a high electrical impedance and a relatively low gas flow impedance, so that in combination, they would still exhibit the high electrical impedance required, but a very low gas flow impedance.

The entire area of maintaining an optimum gas pressure in the bore appears to be an almost untouched area of endeavor at the present time. It is felt that effort spent in this area is very much warranted from the conversion efficiency standpoint.

In the same area as gas flow is the subject of impurities in the gas. In this work commercial grade gas was used for economy reasons. It was fairly certain that this gas would be of sufficient quality before work commenced on the system since it had been reported (8) that the argon line, 4880A, had been very difficult to eliminate even with repeated flushings with a buffer gas.

During the data runs it was noted that severe heating occurred under conditions that indicated that large amounts of impurities were present in the system. It would seem, therefore, that a study of the effect of impurities, such as common atmospheric constituents, on the system is very desirable. Some changes, e.g. elimination of the Viton O-ring seals, in the system would be required to insure that the laser was leak free.

An additional modification of the system, that would be very advantageous, would be the addition of a magnetic coil to the bore, sufficient to provide an axial field of 1200 gauss. Labuda, et al. (12) indicate that this would enhance the output power by a factor of 5 for a 3 mm bore and this is a sizable increase. This coil should probably be hand formed on the bore rather than attempting machine winding.

The use of magnetic enhancement is also possible under RF or pulsed excitation modes. The RF generator presently available is capable of continuous power output at 10 MHz, of 800 watts and short-term output to 1000 watts. This would provide power outputs in the area of 20 to 50 mw without enhancement and RF excitation appears desirable from the standpoint of extending the life of the bore.

One item which would improve the efficiency of the amplifier would be the replacement of the Brewster windows with high quality quartz flats. The present windows, as noted earlier, have very high scattering losses. There presently appears to be little method to specifying polish quality of the windows. It would appear, that many times very fine tolerances, i.e. 1/50 or 1/100 of a visible wave length flatness, are specified in lieu of specifying the grade of polish. It is suggested here, that one method might be to specify the allowable percentage of reflected or scattered light from an optical surface when a laser beam such as a He-Ne laser is impinging at the Brewster angle on that surface. When the present windows were ordered, Cal-Astro Optical Laboratories gave assurances that the polish would be the best obtainable. When the windows arrived and were illuminated with a laser beam, they appeared to have a fairly high level of scattering in comparison to some that