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Investigation of RF Plasma
Light Sources for Dye
Laser Excitation

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TABLE OF CONTENTS

	<u>Page</u>
SUMMARY.	1
RESULTS AND RECOMMENDATIONS.	3
INTRODUCTION	5
PLASMA LIGHT SOURCE TESTS.	9
Test Configurations	10
Test Procedures	14
Measurement of Plasma Radiation Characteristics	16
Results of Tests With Unseeded Plasma	25
Results of Seeded Plasma Tests.	40
SUPPORTING ANALYTICAL STUDIES.	47
Method of Pulsing Light Source.	47
Method of Mirror Integration.	48
Development Plan for High Power Pump Source	55
REFERENCES	60
LIST OF SYMBOLS.	62
APPENDIX I: DESCRIPTION OF UTRC 1.2-MW RF HEATER.	64
APPENDIX II: ENDWALL AND SEED INJECTOR DESIGN HEAT TRANSFER CONSIDERATIONS	68

Investigation of RF Plasma Light Sources
for Dye Laser Excitation

SUMMARY

Analytical and experimental studies were performed to assess the applicability of radio frequency (rf) induction heated plasma light sources for potential excitation of continuous dye lasers. Experimental efforts were directed toward development of a continuous light source having spectral flux and emission characteristics approaching that required for pumping organic dye lasers. Analytical studies were performed to investigate (1) methods of pulsing the light source to obtain higher radiant intensity and (2) methods of integrating the source with a reflective cavity for pumping a dye cell.

The test program was conducted using the UTRC 1.2-MW rf induction heater operating at a frequency of approximately 5.5 MHz. Initial tests were conducted following modification of an existing 5.7-cm-ID source chamber configuration. Based on the results obtained, a new smaller 2.8-cm-ID source chamber configuration was fabricated. A series of tests directed toward attainment of a source power-per-unit-volume of 100 kW/cm^3 were conducted with this configuration. For each source chamber configuration, the endwalls were made of copper, water-cooled, and polished to provide surface reflectivity. Argon gas, injected at the periphery of each end-wall, was used to drive a vortex used to stabilize the location of the light source within the test chamber.

Source chamber pressures up to 10 atm, total plasma power levels up to 130 kW, and total plasma power-per-unit-volume levels exceeding 83 kW/cm^3 were attained with the 2.8-cm-ID chamber configuration. The source power-per-unit-volume levels attained were approximately 2.5 times greater than has been obtained previously from rf vortex stabilized light sources. Further increases in radiant power will be required for such sources to be used efficiently as dye laser pumps. Results of spectral measurements of the radiant emission in wavelength bands which are typical of laser dye absorption bands indicate radiant powers ranging from 304 W in a band between 354 nm and 381 nm to 912 W in a band between 556 nm and 629 nm. A portion of the tests were also conducted with injection of tungsten hexafluoride seed gas into the plasma source to increase the radiant emission in the 300 nm to 600 nm wavelength band. The maximum operating pressure and power levels in the tests were limited by failure of the transparent wall surrounding the source chamber. Possible changes in the test configuration and operating procedures were identified which could result in attainment of higher levels of power-per-unit-volume and pump-band radiant emission in future tests.

Based on the experimental results and on supporting analytical studies, two integrated light-source/pump-cavity configurations were identified which potentially could provide a capability for pumping a high power dye laser. For each configuration attempts were made to identify those areas where improvements in existing technology could lead to performance improvements.

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RESULTS AND RECOMMENDATIONS

1. Experiments performed using rf induction heated plasma light sources resulted in the following performance levels.

(a) Total source power-per-unit-volume levels in excess of 83 kW/cm^3 were attained in a steady-state vortex stabilized argon plasma light source operating within a 2.8-cm-ID by 5-cm-long source test chamber. This level is approximately 2.5 times that previously attained and represents progress toward demonstration of minimum levels required for continuous dye laser pumping.

(b) Measurements of spectral emission in wavelength regions typical of laser dye absorption bands resulted in radiant powers ranging from 304 W in a band between 354 nm and 381 nm to 912 W in a band between 556 nm and 629 nm.

(c) Injection of heavy-atom seed material in the form of tungsten hexafluoride resulted in significant increases in radiant emission in wavelengths between approximately 300 nm and 450 nm. Use of this technique was limited to plasmas having power-per-unit-volume levels of approximately 5.5 kW/cm^3 or less due to heat transfer limitations of the probe used to inject the tungsten hexafluoride seed material into the source.

2. The performance levels achieved could be increased with further effort in the following areas.

(a) Improvement of the vortex flow injection geometry to provide a flow pattern with reduced mixing and turbulence in the region between the plasma source boundary and the inner wall of the source configuration.

(b) Improvement of the endwall geometry and cooling method to allow higher total power level operation without contamination of the source configuration inner transparent wall by vaporized solid materials.

(c) Development of a high-pressure closed-cycle argon/xenon gas flow system for operation of the vortex stabilized plasma light source. Such a system could provide both an increase in source radiant emission in the wavelength bands of interest and a means of controlling the buildup of foreign material in the gases used to stabilize the light source. The presence of such materials can lead to deposits on the source transparent wall.

3. Supporting analytical studies of light source pulsing and mirror integration yielded the following results.

(a) Intermittent operation of an rf system appears to be an attractive means of producing source power-per-unit-volume levels in the MW/cm^3 range for periods up to $100 \mu\text{s}$ long and at repetition frequencies of approximately 1000 Hz. By operating such a system at a continuous power-per-unit-volume level of 50 to $100 \text{ kW}/\text{cm}^3$ between pulses, shock wave interactions produced during the high power pulses could be made small.

(b) Conventional elliptical cavities fabricated using segmented dielectric mirror components are an attractive integrated source cavity configuration. Cavity configurations utilizing both focal and exfocal pumping were considered.

(c) Development of multiple-source cavity configurations with rf induction heaters: light sources is not recommended due to the rf heater system complexity required to operate multiple sources simultaneously.

INTRODUCTION

Photochemical isotope separation promises high separation factors, high efficiencies, and greatly reduced cost. Laboratory scale investigations are now being conducted at Lawrence Livermore Laboratories and elsewhere to establish the feasibility of dye laser induced selective excitation for application to separation of uranium isotopes. These investigations are being carried out using dye laser systems with an average output power of approximately 2 W or less. For commercial process applications, dye laser systems with average powers of approximately 10 kW to 100 kW may be required. Development of high repetition rate pulsed dye lasers or continuous (cw) dye lasers is necessary to efficiently meet these laser power requirements.

Optical distortion produced in the dye laser active volume by heating due to excitation must be carefully controlled for the laser to operate continuously. The potential ability to control and compensate for optical inhomogeneities is an attractive feature favoring cw lasers in high power systems. Inhomogeneities produced in pulsed lasers are very difficult to control because they occur in a time span of 100 μ s or less. These optical inhomogeneities could ultimately limit the maximum repetition frequency for which pulsed lasers may be operated.

Numerous different types of excitation sources for single pulse lasers are available. Operating characteristics of some typical excitation sources are described in Refs. 1 and 2. However, excitation sources for cw lasers are at present limited in availability. Almost all visible wavelength cw dye lasers operated to date have been excited using argon ion lasers. Commercial cw pumping lasers with single or multiple line output powers of several watts are now available. However, for large-scale process applications such as uranium isotope separation much larger systems will be required. For these larger systems utilization of excitation from high intensity plasma light sources may be desirable.

The minimum excitation power density required to reach laser threshold is a function of a number of excited state molecules present in the S_1 singlet state, the dimensions of the active medium, and the decay time of the induced fluorescence. Threshold excitation for typical systems is in the range of approximately 5 to 100 kW/cm² of beam cross-sectional area. With low excitation power the laser operates close to the threshold and the overall efficiency is low. Values of excitation equal to several times the threshold value lead to more efficient systems. High threshold excitation is also required for pumping shorter wavelength lasers. Absorption in typical laser dyes occurs within an approximately 50 nm wide band. Production of the excitation fluxes required to reach laser threshold for the typical dye requires a source having a black-body radiating temperature of 10,000 K or greater over the 50 nm wide dye absorption band.

Figure 1 shows the fractional distribution of black-body radiation for several radiating temperatures. It can be seen that for a 10,000 K black-body 50 percent of the energy occurs at wavelengths less than 405 nm and the total radiant flux is 56.7 kW/cm^2 . Figure 2 shows the variation of spectral radiance from black bodies for several radiating temperatures. The spectral radiance is equal to the radiant flux emitted per unit solid angle per unit of the projection of the emitter surface on a plane perpendicular to the direction of observation (i.e., a 1-cm-dia spherical source emitting 100 W would have a spectral radiance of $10.13 \text{ W/cm}^2/\text{ster}/\text{nm}$). The spectral radiance as shown in Fig. 2 is numerically equal to $1/\pi$ times the Planck black-body spectral intensity. For the 50 nm wide wavelength band centered at 530 nm the spectral radiance of a 10,000 K black-body would be approximately $1.0 \text{ kW/cm}^2/\text{ster}$. Radiation fluxes of this order of magnitude are the minimum required for excitation of a cw laser. For excitation of lasers at shorter wavelengths sources having radiating temperatures of 15,000 K to 20,000 K within the optical pump band are desirable. Attainment of fluxes in the range of 10 to 100 kW/cm^2 of source surface area from cw plasma sources is beyond the present state-of-the-art.

The objective of the work conducted during this investigation was to assess the applicability of radio-frequency (rf) induction heated plasma light sources for potential excitation of large dye lasers. Efforts were made toward development of light sources having spectral flux and emission characteristics suitable for pumping cw organic dye lasers. The program was divided into two areas: (1) Plasma light source tests utilizing the United Technologies Research Center (UTRC) 1.2-MW rf induction heater were conducted with the objective to develop a plasma source with radiant emission characteristics and spectral intensity distribution approaching that required for pumping cw dye lasers. Tests were conducted with both argon plasmas and argon plasmas seeded with small amounts of tungsten hexafluoride to increase the radiation in visible wavelength portions of the spectrums. (2) Supporting analytical studies were performed to investigate methods of pulsing the light source and methods of integrating the source with a mirror cavity for pumping a dye cell. The results of the program were used to determine characteristics of new light source configurations. A complete description of the tests performed and the results obtained under the program is presented in the following sections of this report.

**VARIATION OF SPECTRAL RADIANCE WITH WAVELENGTH OF A BLACK-BODY SOURCE
FOR SEVERAL RADIATING TEMPERATURES**

PLASMA LIGHT SOURCE TESTS

Induction heated plasmas are an attractive means of producing high intensity cw light sources. Considerable previous research has been performed in efforts to develop high intensity rf induction heated plasma light sources. The research performed under these programs is described in Refs. 3 through 10. Steady-state plasma light sources having source power-per-unit-volume up to 34.8 kW/cm^3 were developed. This power-per-unit-volume level, though less by approximately a factor of 3 to 5 than that required for threshold operation of a cw dye laser, is the highest reported flux for any cw induction heated plasma. Based on results of previous research, a test program was undertaken with the objective of increasing the source power-per-unit-volume to a level of 100 kW/cm^3 , or higher if possible.

During the test program, a total of approximately one-hundred seventy-five (175) test runs were completed. The tests were conducted over a range of source pressures and vortex and seed flow rates to identify the test conditions which result in the highest source power-per-unit-volume and the highest spectral intensity in the 300 to 600 nm wavelength range. The spectral irradiance of the source was measured in approximately 50 nm wide wavelength bands between approximately 300 and 600 nm wavelengths for approximately one-hundred-twenty (120) of the test conditions. Secondary seed gas consisting of pure argon or a mixture of argon and WF_6 was injected along the centerline of the test configuration to determine the effect of seed gas injection on the source irradiance characteristics. Quantitative data were obtained for approximately sixty (60) test conditions.

Unseeded plasma tests were performed at source total power levels up to 130 kW and source pressure levels up to 10 atm. Values of average source power-per-unit-volume exceeding 83 kW/cm^3 were determined from the results of these unseeded plasma tests. This power-per-unit-volume level is approximately 2.5 times greater than the highest reported level of 34.8 kW/cm^3 obtained with the configuration described in Ref. 9. The number of seeded plasma tests conducted were limited by the inability to adequately cool the seed injector tip during prolonged exposure to the high heat fluxes present in the region where the injector tip was located and thermal stress induced failure of the source fused-silica envelope.

Consideration was given to performing some tests with WF_6 seed injection; however, due to the problems encountered with the seed injector tips melting and the problems involved with cleaning up the test area should a WF_6 release occur, no tests employing WF_6 seed gas were attempted.

The shape of the plasma discharge was, in general, ellipsoidal and axisymmetric about the vortex chamber centerline. The ellipsoidal shape results from the combined effects of the vortex flow pattern which results from the endwall argon injection geometry and the axial variation in the azimuthal electric field due to the finite length of the rf work coil.

The size and shape of the plasma discharge varied with changes in the rf heater and vortex flow parameters: namely; discharge total power, rf operating frequency, chamber pressure, and argon mass flow rate. In general, the discharge diameter changed substantially with variations in argon mass flow rate and discharge total power but only slightly with variations in chamber pressure and rf operating frequency. The discharge diameter increased with increasing total power but decreased with increasing argon mass flow rate, chamber pressure, and rf operating frequency. Substantial increases in argon mass flow rate tended to make the discharge shape more cylindrical possibly due to the reduction of axial variation of the radial pressure gradient. These operating parameters were inter-related in that increasing the argon mass flow rate increased the rf heater resonator voltage which then necessitated an increase in discharge total power to maintain the discharge. An increase in chamber pressure was also required for the 5.7-cm-ID configuration to prevent unconfined breakdown of the argon and arc-over of the plasma into a recirculation flow region behind the endwalls.

The variations in the discharge with changes in operating conditions have been observed in previous tests (see Refs. 6 and 7) and were similar for the two configurations tested in the present report. In the tests with the smaller 2.8-cm-ID configuration, the discharge was observed to be more cylindrically shaped than in tests with the larger 5.7-cm-ID configuration. This effect was probably due to reduced axial variations in the vortex radial pressure gradient and in the azimuthal electric field for the 2.8-cm-ID configuration as compared with the 5.7-cm-ID configuration.

Test Configurations

The test configurations employed are shown in Figs. 3 and 4. The cylindrical test chamber shown in Fig. 3 is approximately 10-cm-long and 5.7-cm-ID. Argon to provide a vortex flow was introduced into the chamber through sixteen (16) tangential injectors located near the periphery of the test chamber endwalls. The flow pattern allows operation of a vortex-stabilized plasma within the 5-cm-long region near the test chamber centerline. The argon flow was removed through ports located at the center of each 2-cm-OD copper endwall. Energy was added to the plasma region through inductive coupling from the rf work coils. The coils are part of the output tank circuit of the UTRC 1.2-MW rf heater which was operated at a frequency of approximately 5.5 MHz. A complete description of the rf heater system is presented in Appendix I.

All components of the plasma source configuration are highly water-cooled to allow continuous operation. Radiant energy from the plasma was transmitted through an inner 5.7-cm-ID fused-silica tube to the surroundings. A portion of the radiant energy was absorbed in water flowing through the annular coolant passage. The remainder of the radiant energy passed through an outer 6.5-cm-ID fused-silica tube

SKETCH OF 5.7-CM-ID PLASMA SOURCE CONFIGURATION

R75-91915-10

FIG. 3

DETAILS OF 2.8-CM-ID PLASMA SOURCE CONFIGURATION

(a) PHOTOGRAPH OF 2.8-CM-ID PLASMA SOURCE CONFIGURATION

(b) SOURCE CONFIGURATION END-WALL DETAILS

which formed the pressure vessel for the test chamber to the surroundings. The copper endwalls for the test configuration were identical to those used in previous studies. The copper end flanges shown in Fig. 3 were incorporated into the test configuration for the current tests. These flanges allow much shorter fused-silica tubes to be used and reduced the effort required to make changes in the test chamber configuration. The distance between the copper vortex injectors was reduced from the 16.5 cm used in previous tests (see Ref. 7) to 10 cm for the tests described herein.

The endwall surfaces and the surfaces near the injectors were polished to provide capability for reflection of plasma radiation incident on these surfaces out of the test chamber through the fused-silica tubes. Operation at high plasma source power levels necessitates reflection of as much radiation as possible in order to minimize the coolant requirements for the source configuration components. The test configuration shown in Fig. 3 was originally designed for operation at plasma pressure levels up to 20 atm. However, for the tests described herein, the maximum pressure employed was 10 atm.

The plasma source configuration shown in Fig. 4 was designed for tests with smaller plasma discharges than could be obtained in tests with the 5.7-cm-ID test configuration shown in Fig. 3. The tests with this configuration were directed toward operation with source power per unit volume levels of approximately 100 kW/cm^3 . The flow configuration used is similar to that for the 5.7-cm-ID configuration. Argon gas to provide a vortex flow was introduced through the fourteen (14) injection ports (seven (7) ports in each endwall) located near the outer periphery of the endwalls. The swirling argon flow was removed on the centerline of the test chamber through the thru-flow exhaust ports in the endwall assemblies. Figure 4(a) is a photograph of the assembled configuration showing the 2.8-cm-ID inner and 3.6-cm-ID outer fused-silica tubes, the plasma region, and the location of the endwall assemblies. The configuration was designed such that the distance between the endwalls could be changed from 5 cm to a maximum length of 10 cm. For most of the tests described herein the distance between the endwalls was 5 cm. Source configuration endwall details are shown in Fig. 4(b). The endwall assemblies were water-cooled. The coolant path was such that coolant entered one endwall and flowed along the thru-flow duct wall to the endwall face, radially outward cooling the endwall face, and then flowed into the annular coolant passage between the 2.8-cm-ID fused-silica tube and the 3.6-cm-ID fused-silica tube. Upon leaving the annular coolant passage, coolant entered the opposite endwall flowing radially inward to cool the endwall face and turned and flowed along the thru-flow duct before exiting the endwall assembly. Thermocouples were located at the inlet and outlet of the endwall assemblies as well as the inlet and outlet of the annular coolant passage.

Also shown in Fig. 4(b) is a probe for seed gas injection. During some tests employing seed gas this water-cooled probe was positioned on the centerline of the test chamber. The distance which the probe tip protruded into the plasma was varied from the location flush with the endwall face to a location approximately 1.5 cm into the test chamber region.

Additional details of the endwall assemblies are shown in the photographs of Fig. 5. These assemblies shown in Fig. 5(a) were attached to the 1.5-m-dia aluminum test tank which is part of the UTRC 1.2-MW induction heater. The coolant water inlet and thru-flow exhaust lines are denoted in Fig. 5. Detail of the endwall face region is shown in Fig. 5(b). The endwall was designed to provide vortex injection through 0.18-cm-ID vortex injectors drilled at a 15 deg angle into the endwall face. A discussion of endwall design heat transfer characteristics is presented in Appendix II. The endwall face also contains a seed gas injection port located a distance of approximately 0.3 cm from the centerline of the configuration. For some tests, attempts were made to inject seed gas through this injection port into the plasma region. The endwall also included a static pressure tap for measuring pressure within the chamber during tests.

During endwall shakedown tests an internal water leak was noted in one of the injectors. To maintain symmetry in the vortex injection flow, one injector in each of the endwalls was plugged with solder prior to conducting the high power plasma light source tests.

Test Procedures

Once the test configuration was installed within the heater tank circuit and the heater system activated to produce rf power, the following test procedures were used. The test chamber was evacuated to a pressure of approximately 10^{-2} atm. The voltage across the rf work coils was then increased to approximately 3 kV to provide the magnetic and electric field strength sufficient to cause a low pressure breakdown to occur in the plasma region. Following the low pressure breakdown, argon gas was introduced into the test chamber through the vortex injectors. The argon flow rate was increased until confinement of the discharge occurred. Generally, confinement of the discharge away from the peripheral walls of the test chamber occurred at a pressure of approximately 0.5 atm. Simultaneous with the increasing of argon flow, the saturable reactor control was used to provide additional dc power to the power amplifier stages. Once the plasma flow and pressure were increased such that the plasma pressure was approximately 1.0 atm the system was allowed to stabilize. Typically, this was done at a power level of approximately 50 kW dc power into the heater system. Increases in the dc power and argon flow were then made until the desired test conditions were reached.

PHOTOGRAPHS OF 2.8-CM-ID PLASMA SOURCE CONFIGURATION END WALLS

(a) END-WALL ASSEMBLIES

(b) DETAIL OF END-WALL FACE REGION

For tests employing gaseous seed injection a similar plasma starting procedure was used. In addition, the seed flow system shown in Fig. 6 was also used for these tests. This seed flow system was designed to provide a controlled flow of either argon or mixtures of argon and WF_6 to the test chamber. The flow diagram of the system shown in Fig. 6(a) indicates the method by which argon or an argon seed gas mixture could be preheated and flowed to the test chamber. Because WF_6 has a vapor pressure of 1 atm at approximately room temperature, it was necessary to heat the WF_6 to provide sufficient vapor pressure for injection into the test chamber at pressures greater than 1 atm. Provision was made in the seed system to provide heat to the WF_6 supply canister using either warm air circulated through an air heater or direct electrical heating through the outer wall of the supply canister. In addition, argon flowing through the seed system was preheated to prevent condensation of WF_6 in the ducting between the seed supply canister and the test chamber. A photograph of the seed system assembly is shown in Fig. 6(b). The seed system was designed to be operated at pressures up to approximately 40 atm. During the tests conducted the maximum pressure used in the seed supply canister was approximately 8 atm.

Measurement of Plasma Radiation Characteristics

Measurement of the plasma radiation emission was accomplished using the equipment shown in Fig. 7.

Determination of Plasma Diameter

Figure 7(a) is a sketch of the system used for determination of the source diameter. The major components of this system are a 0.33-mm-ID collimating tube, and a motor-driven traversing mechanism mounted on the aluminum test tank cover. Light emitted from the plasma passed between the work coils and out through the viewing window on the test tank cover into the collimating tube. At the output of the collimating tube the light passed into a fiber optic bundle and was propagated to a photomultiplier. The system was activated manually and the collimating tube traversed such that a trace of the chordal intensity of the plasma as a function of time was produced and displayed on a strip chart recorder. Calculations indicated that for the 68.6 cm distance at which the collimating tube was located from the plasma that the spot size at the plasma viewed through the collimating tube was 0.74 cm. This aperture was used in all tests. During many tests with the 5.7-cm-ID test configuration both diameter scans and photographs of the plasma were obtained. Analysis of these data indicated good agreement between the plasma diameters obtained by both measurement techniques. The results indicated the diameter of the highly luminous portion of the plasma on the photographs was consistently equal, within a few percent, to the width, measured at 50 percent of the peak intensity, of the output trace obtained using the scanning collimating tube system.

SEED GAS HANDLING SYSTEM USED IN PLASMA SOURCE TESTS WITH WF_6 SEED

(a) SCHEMATIC FLOW DIAGRAM

(b) PHOTOGRAPH OF SEEDER ASSEMBLY

FIG. 6

SYSTEMS USED FOR SOURCE DIAMETER AND BROADBAND SPECTRAL RADIATION MEASUREMENTS

(a) SYSTEM FOR PLASMA SOURCE DIAMETER SCANNING MEASUREMENTS

(b) SYSTEM FOR BROADBAND SPECTRAL RADIATION MEASUREMENTS

In addition, continuous observation of the discharge was accomplished using a projection screen system. A 45.7 cm focal length convex relay lens and neutral density filter system was used to project an image of the plasma discharge onto an overhead screen. Horizontal and vertical grid lines were ruled on the screen which permitted on-line visual monitoring of the changes in the discharge shape as the test parameters changed.

Broadband Spectral Radiation Measurement

A block diagram of the radiometer optical system used for broadband spectral radiation measurements is shown in Fig. 7(b). A Ruedeer RBL 500 thermopile detector with a fused-silica window was used as the radiation sensing element. The detector output was connected through an operational amplifier having a gain of 1000 and displayed on a strip chart recorder. Spectral interference filters were mounted in a chopper wheel assembly located ahead of the radiometer window. The bandwidth of the filters was such as to allow radiation measurements to be made in approximately 50 nm wide wavelength bands in the region between 300 nm and 630 nm. The measured transmission characteristics of the filters used in the radiometer are shown in Fig. 8. The detector and amplifier assembly was calibrated several times during the program using an Eppey Laboratory calibrated Standard of Spectral Irradiance. Following each calibration of the radiometer a calibration constant was determined relating the detector output to the power reaching the detector. The total power radiated from the plasma between wavelengths of 250 nm to 1300 nm was determined from measurements through an open aperture in the chopper wheel. A neutral density filter of optical density 2.5 was used in this aperture to attenuate the radiant energy from the plasma prior to entering the radiometer. For most tests the radiometer assembly was located approximately 1.0 m from the centerline of the plasma source. An iris nominally set at F5.6 was positioned in the optical path. This iris was present during all calibrations. The solid angle viewed by the radiometer with the filters present was such as to include the entire plasma length.

The transmission characteristics of the filters are listed in Table I. The filters essentially covered the spectral range between approximately 300 nm out to 630 nm. The effect of different filter transmission levels on the detector output was accounted for by radiometer calibration. In some tests, particularly those at high power levels, Nigrosine α_e was mixed in the cooling water passed through the annular coolant passage. This dye was used to reduce the amount of radiation from the rf plasma to the surroundings and to serve as a heat sink for measurement of total radiation emitted from the plasma. Nigrosine was selected for use in these tests based on results of previous tests in which several different dyes were investigated (see Ref. 10). In addition, Nigrosine has a fairly broadband absorption spectrum and is readily soluble in water. The absorption spectrum of Nigrosine due in water was measured using a Cary spectrometer to allow for the effect of dye absorption on the attenuation of radiation entering the radiometer optical system. The results of

TRANSMISSION CHARACTERISTICS OF FILTERS USED FOR
BROADBAND SPECTRAL RADIATION MEASUREMENTS

SEE FIG. 7 (b) FOR OPTICAL SYSTEM DETAILS

TABLE I

OPTICAL CHARACTERISTICS OF FILTERS USED IN RADIOMETER

Filter	Short Wavelength Cutoff-nm	Long Wavelength Cutoff-nm	Peak Transmission	Wavelength of Peak Transmission
1	296.0	353.6	0.155	324.8
2	353.8	381.4	0.245	367.0
3	377.7	403.9	0.380	390.8
4	401.6	449.0	0.600	425.3
5	451.7	495.1	0.600	473.4
6	498.0	541.6	0.608	519.8
7	556.0	629.0	0.668	603.0
8	220.0	1300.0	-	OPEN APERTURE

these measurements are shown in Fig. 9 for a dye concentration of 16 ppm in a path length of 1 cm. The spectral absorption coefficients for the dye water mixture is highest at a wavelength of 300 nm with an additional peak at a wavelength of approximately 600 nm. The absorption peaks at approximately 1000 nm and 1200 nm are water absorption peaks. In tests with dye present, the radiometer output levels were adjusted to account for effects of the Nigrosine dye attenuation on the measured radiation in each wavelength band. This was accomplished by sampling of the dye concentration after test data were taken. The total dye concentration present on that particular test day was determined from spectral absorption measurements using a Cary spectrometer. No evidence of optical bleaching effects, indication of photochemical degradation, or decomposition of the dye were observed during the course of the tests conducted in the program.

A series of dye calibration tests were conducted at constant source flow and power conditions in which the variation of emitted radiation reaching the radiometer with changing dye solution concentration was determined. The source test conditions correspond to those for test point No. 1 in Table IV. The results of these tests are shown in Fig. 10 for each of the seven filters used in the radiometer. The results in Fig. 10 are presented in the form of the average spectral dye attenuation factor which is equal to I/I_0 , the fraction of light transmitted through the dye as a function of the dye solution concentration. The symbols in Fig. 10 correspond to dye concentrations used in the calibration tests. The dye attenuation factor was assumed to vary in accordance with the Lambert Law for other concentrations. The upper and lower cutoff wavelengths for each of the seven filters in the radiometer optical system are also indicated in Fig. 10. The values shown are for 2 mm thickness of dye water solution which is equal to that which was used in the plasma source configuration annular coolant channel.

A check on calibration test data was performed by graphically integrating the spectral absorption coefficient data for the dye in Fig. 9 over the filter bandwidth to determine the average attenuation of the dye solution in each wavelength band. The results were in agreement with those obtained from the source calibration tests.

Determination of Total Power Deposited in the Plasma

The total power deposited in the plasma was determined from an overall energy balance in the following manner. The water coolant flow rates were measured using rotometers. Thermocouples were used to determine coolant temperature rises in the source configuration endwalls and heater components. The power deposited in the coolant was determined from thermocouple measurements at the inlet and outlet of the annular coolant passage. The total power radiated from the plasma through the fused-silica tubes is less than the total power radiated from the plasma by an amount equal to the radiated power absorbed in the endwalls. Examination of the geometries of the 5.7-cm-ID source configuration and the 2.8-cm-ID source configuration indicates that a greater fraction of the total radiation emitted from the plasma would be intercepted by the endwalls in the 2.8-cm-ID configuration. This results in higher

MEASURED SPECTRAL ABSORPTION CHARACTERISTICS OF NIGROSINE DYE AND WATER

PATH LENGTH = 1 CM
DYE CONCENTRATION = 16 PPM
TEMPERATURE $\approx 20^{\circ}\text{C}$

VARIATION OF AVERAGE SPECTRAL DYE ATTENUATION FACTOR WITH DYE SOLUTION CONCENTRATION

NIGROSINE DYE - 0.2 CM THICKNESS

AO: -148-2

endwall heat loading and indicates the importance of polishing the endwall surfaces to produce high reflectivity and thereby reflect a large fraction of this radiation out through the fused-silica tubes. For all tests sufficient time was allowed for coolant temperatures to reach a steady-state level. The total power deposited in the plasma is equal to the sum of the power deposited in the endwall coolant, the annular coolant, and the power determined from the radiometer output voltage.

Determination of Plasma Volume

The plasma volume was determined in the following manner. A representative diameter for the plasma was determined from the scanner system output trace based on the diameter as measured at 50 percent of the peak intensity. The plasma was assumed to be ellipsoidal and the volume was calculated from the standard ellipsoid volume formula, $V = \pi d^2 / 6$, where d is the plasma diameter at the axial midplane and l the distance between endwall faces.

Results of Tests With Unseeded Plasma

Tests With 5.7-cm-ID Test Configuration

Using the test configuration shown in Fig. 3, a series of plasma light source tests was conducted in an attempt to increase the power-per-unit-volume of the argon plasma light source beyond the level of 34.8 kW/cm^3 obtained previously (Ref. 7). The tests were conducted over a range of source power levels, argon flow rates, and source chamber pressures. A summary of the test results including all pertinent data obtained is presented in Table II. In addition, selected data from ten test conditions are presented in Figs. 11 through 13. The data shown in Figs. 11 through 13 are representative of the test conditions over the complete range of total source power, argon flow rate, and test chamber pressure used in the test series. Results shown in Fig. 11 depict the variation of source power-per-unit-volume with the total source power determined calorimetrically. The results show an increase in source power-per-unit-volume as the total source power was increased from 21.6 kW to approximately 50 kW. Over this range of total source power level the source power-per-unit-volume varied from approximately 1.8 kW/cm^3 to a high of 18.8 kW/cm^3 . During this test series, it was not possible to obtain a steady-state plasma with power-per-unit-volume greater than 19 kW/cm^3 . Operation at total source power levels between 50 kW and 105 kW resulted in increased plasma volume and decreased plasma power-per-unit-volume within the ranges of argon flow rate and source chamber pressures used in the tests.

Results shown in Fig. 12 depict the variation of source power-per-unit-volume with source pressure. The source power-per-unit-volume increased from 1.8 kW/cm^3 to 18.8 kW/cm^3 as source chamber pressure was increased from 2 to 9.5 atm. This

result was expected since the power-per-unit-volume for a given plasma geometry should increase as the fraction of total power radiated from the plasma increases. The amount of radiation from argon is approximately in direct proportion to pressure at a given gas temperature (see Ref. 11). The highest power-per-unit-volume level achieved in the tests was approximately 19 kW/cm^3 . This level is below the 34.8 kW/cm^3 level previously reported in Ref. 7. The 34.8 kW/cm^3 level was obtained at a pressure of approximately 19 atm, whereas the highest source pressure in the present tests was 10 atm. The source pressure for the present tests was limited to 10 atm due to the occurrence of unstable plasma conditions within the test chamber. At these conditions, the discharge extinguished in the confinement region between the test chamber endwalls and reignited in the region of the test chamber near the argon vortex injectors. The underlying causes which lead to the onset of this plasma condition were not fully identified. However, as noted in Ref. 7, under some test conditions a similar phenomenon also was observed. Attempts were made to adjust the argon flow rate and several vortex injection parameters to suppress the onset of this condition. However, within the program time available for these tests, the attempts were not successful. Thus, it appears that the modifications made to the 5.7-cm-ID light source configuration for the tests were in some way responsible for the onset of unstable plasma conditions at source pressures above approximately 10 atm.

Results shown in Fig. 13 illustrate the variation of source power-per-unit-volume with argon weight flow rate. Values of source pressure for each of the test conditions are shown in parentheses. The results show the effect of changes in source pressure on source power-per-unit-volume are significantly greater than the argon flow rate effects on power-per-unit volume. For the tests described in Ref. 7 argon flow rates up to 18.2 g/s were used. In the present tests, the maximum argon flow rate for which a stable plasma could be obtained was 6.4 g/s.

During the test series, measurements were made, using the radiometer system shown in Fig. 7(b), of the source spectral emission in approximately 50 nm wide wavelength bands between approximately 300 and 630 nm. A compilation of the measured irradiance 1 m from the source which was obtained in the tests is presented in Table III. For all test points except points 8 and 9, Nigrosine dye present in the annular coolant channel attenuated the source radiation prior to its reaching the radiometer. Results shown for the cases without dye (8 and 9) indicate approximately uniform irradiance in the 402 nm to 609 nm wavelength band and reduced levels at shorter wavelengths. These data were obtained at approximately 15 kW source total power and a source chamber pressure of 3.3 atm. Results of tests at higher power and pressure levels are discussed in the following subsection.

TABLE II

FLOW AND POWER CONDITIONS FOR UNSEEDED PLASMA TESTS WITH 5.7-CM-ID SOURCE CONFIGURATION

Data for Test Points 1 through 10 also Shown on Figs. 11 through 14

Test Point No.	Source Power Per Unit Volume, KW/CM ³	DC Plate Voltage, KV	DC Input Power, KW	Source Chamber Pressure, ATM	Total Source Power, KW	Power Radiated- Annular, Coolant, KW	Argon Flow Rate, G/Sec	Source Diameter, CM
1	1.8	6.0	140	2	21.6	6	3.6	2.2
2	2.3	14.4	200	5	23	12.8	4.5	2.0
3	3.7	8.0	270	5	33	17.9	3.6	1.8
4	4.1	9.4	250	5	49	29	5.0	2.2
5	5.8	10	350	5	70	41	5.4	2.2
6	6.9	8.8	300	7.7	48	31	3.6	1.6
7	7.2	10.9	305	5	72.3	42.1	5.5	2.0
8	8.8	13.3	340	7	79.1	50.6	5.5	1.9
9	11.7	14.4	540	8	105.6	63.9	6.4	1.9
10	18.8	9.5	320	9.5	49	33.6	4.1	1.0
11	0.34	4.3	100	2	7.8	4.2	1.8	3.0
12	0.39	3.4	40	2	6.2	4.2	1.8	2.5
13	0.70	5.1	120	2	11.2	4.2	2.7	2.5
14	0.9	10.8	100	5	8.8	4.3	4.5	2.0
15	1.7	7.0	150	2	16.7	4.0	4.5	2.0
16	1.8	6.5	150	5	21.6	12.5	3.6	2.2
17	1.8	7.0	175	5	20.4	8.3	3.6	2.1
18	2.9	6.1	130	5	22	12.5	3.6	1.8
19	3.4	6.0	120	5	54	25	3.6	2.5
20	4.5	13.8	220	10	45.4	29.8	5.5	2.0
21	6.6	10.0	160	9	78.7	52	4.5	2.2
22	9.0	12.0	325	6	72.3	42.1	5.5	1.7
23	--	8.0	280	10	48	33.6	3.6	--

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VARIATION OF SOURCE POWER PER UNIT VOLUME WITH
TOTAL SOURCE POWER FOR UNSEEDED PLASMA TESTS

SYMBOL	TEST CONFIGURATION	RANGE OF SOURCE PRESSURE - ATM	RANGE OF ARGON FLOW RATE - G/SEC
O	SEE FIG. 4	2.7 TO 9.5	3.6 TO 7.7
Δ	SEE FIG. 3	2.0 TO 10	3.5 TO 6.4

SEE TABLES III AND IV FOR OTHER TEST CONDITIONS
NUMBERS IN PARENTHESES DENOTE SOURCE PRESSURE IN ATM

VARIATION OF SOURCE POWER PER UNIT VOLUME WITH SOURCE PRESSURE FOR UNSEEDED PLASMA TESTS

SYMBOL	TEST CONFIGURATION	RANGE OF TOTAL SOURCE POWER - KW	RANGE OF ARGON FLOW RATE - G/SEC
O	FIG. 4	37 TO 130	3,6 TO 7,7
Δ	FIG. 3	21,8 TO 105	3,6 TO 6,4

SEE TABLES III AND IV FOR OTHER TEST CONDITIONS
NUMBERS IN PARENTHESES DENOTE TOTAL SOURCE POWER IN KW

**VARIATION OF SOURCE POWER PER UNIT VOLUME WITH
SOURCE ARGON FLOW RATE FOR UNSEEDS PLASMA TESTS**

SYMBOL	TEST CONFIGURATION	RANGE OF TOTAL SOURCE POWER - KW	RANGE OF SOURCE PRESSURE - ATM
○	FIG. 4	37 TO 130	2.7 TO 9.5
△	FIG. 3	21.6 TO 105	2 TO 10

SEE TABLES III AND IV FOR OTHER TEST CONDITIONS
NUMBERS IN PARENTHESES DENOTE SOURCE PRESSURE IN ATM

TABLE III

SUMMARY OF SOURCE INVESTIGATED, MAINTENANCE PERIOD

UNDESIGNED PLASMA TESTS WITH 4.7-ohm SOURCE COMPENSATION

Test Point No.	DC Plate Voltage, KV	DC Input Power, KW	Source "Inherent Pressure", ATM	Total Source Power, KW	Power Radiated- Annular Gradient, OF	Axial Flow by Compensation, ft ³ /sec	Nominal Velocity, ft/sec	Source Temperature at 1.0-M, 1.0-M, 1.0-M, 1.0-M, 1.0-M, 1.0-M, 1.0-M, 1.0-M, 1.0-M, 1.0-M									
								354 to 354	354 to 354	354 to 354	354 to 354	354 to 354	354 to 354	354 to 354	354 to 354	354 to 354	354 to 354
1	2.0	20	1	4.5	--	3.9	900	--	--	--	2.5	2.5	--	--	--	--	36
2	3.0	60	1	4.5	--	4.5	900	--	1.6	3.2	7.7	3.6	1.9	4.1	1,017	--	1,017
3	5.0	80	2.3	6.8	2.1	4.5	900	29	1.8	81	153	90	36.4	27.25	8,568	--	8,568
4	4.0	90	5.0	6.8	4.3	3.6	500	12	2.6	39	8.9	17.9	6.3	6.4	8,032	--	8,032
5	4.2	100	5.0	7.5	4.3	4.5	500	24	2.4	1.6	125	64	28	26	10,424	--	10,424
6	4.3	100	5.0	8.8	4.3	4.5	500	24	32	60	144	83	38	29	8,985	--	8,985
7	5.6	110	5.0	7.3	4.3	4.5	500	48	6.4	120	256	164	61	50	14,637	--	14,637
8	5.8	120	3.3	15	--	4.5	0	--	2,664	2,502	4,966	4,224	4,224	5,373	67,473	--	67,473
9	5.8	120	3.3	15	--	4.5	0	--	2,439	2,659	4,569	4,198	3,891	5,194	63,946	--	63,946
10	5.8	120	3.3	15	--	4.5	100	347	546	710	1,139	717	435	466	26,775	--	26,775
11	5.8	120	3.3	15	--	4.5	200	72	128	203	320	141	57.6	68	15,768	--	15,768
12	6.6	190	5.0	19.8	6.7	3.0	500	63	90	156	333	224	112	103	9,996	--	9,996
13	6.9	190	5.0	19.6	8.7	3.1	500	46	80	140	294	198	96	88	8,568	--	8,568
14	7.2	190	5.0	23.0	13	3.1	500	60	96	180	371	250	122	111	11,761	--	11,761
15	7.0	190	5.0	31.0	15	5.4	500	14	32	60	154	102	45	41	12,852	--	12,852
16	7.2	200	5.0	23.0	13	3.1	500	36	64	100	205	139	64	63	6,426	--	6,426
17	5.7	200	10.0	23.0	13	5.8	500	24	64	128	282	177	74	64	15,329	--	15,329
18	7.3	220	5.0	35.0	19	5.4	500	36	48	120	269	173	67	59	15,768	--	15,768
19	5.7	220	10.0	45.4	30	5.4	500	43	80	148	339	208	72	74	16,422	--	16,422

Results of Tests With 2.8-cm-ID Test Configuration

The results of the tests with the 5.7-cm-ID test configuration were used in the design of the 2.8-cm-ID source configuration shown in Fig. 4. The endwall geometry used for the 2.8-cm-ID source configuration was designed to eliminate the flow recirculation region near the vortex injectors believed to be one cause of unstable plasma conditions discussed previously. This is the region where rf breakdown occurred prior to or simultaneous with the onset of unstable plasma conditions in tests with the 5.7-cm-ID source configuration. The results of the 5.7-cm-ID source tests were used to determine the diameter of the new rf work coils used in the tests. The 2.8-cm-ID source configuration was designed to operate with a ratio of plasma diameter to coil diameter of approximately 0.2. This was done in order that approximately the same range of coil voltages could be used at similar plasma total power levels in the 2.8-cm-ID configuration. Thus the results of tests with the 5.7-cm-ID test configuration provided important information for selecting the size of the source configuration for high source power-per-unit-volume tests.

A series of unseeded plasma light source tests were conducted to demonstrate steady-state operation of the source at total source power-per-unit-volume levels of up to 100 kW/cm^3 . Based on information from radiation levels of argon plasmas reported in the literature, it was estimated that operation of steady-state source at a total power-per-unit-volume level of approximately 100 kW/cm^3 would be a significant step toward achieving the required intensity level for cw dye laser operation. It is recognized that power-per-unit-volume levels higher than 100 kW/cm^3 would be required for practical systems.

Results of tests conducted over a range of total source power from 37 kW to 130 kW, source chamber pressure from 2.7 atm to 9.5 atm, and argon flow rate from 3.6 g/s to 7.7 g/s are shown in Figs. 11 through 14. Additional information on flow and power conditions used in the tests is presented in Table IV. Results in Fig. 11 depict the variation obtained of the source power-per-unit-volume with the total source power. The highest value of source power-per-unit-volume for which complete data were obtained was 83.2 kW/cm^3 . This level of source power-per-unit-volume is a factor of 4.4 times the highest level obtained in the 5.7-cm-ID source configuration tests over the same range of source chamber pressure and a factor of 2.4 times the highest level reported in Ref. 7. Partial data were obtained at higher values of source power-per-unit-volume. The highest level achieved is estimated to be 91 kW/cm^3 . The highest total source power level in the tests was 130 kW. The plasma diameter was 0.74 cm based on measurements using the diameter scanning system. The source power-per-unit-volume increased as the total source power increased.

The same test data are presented in Fig. 12 to show the variation of source power-per-unit-volume with source chamber pressure. As expected, the source power-per-unit-volume increased with increased source pressure. The maximum pressure utilized in the tests was 9.5 atm. Results shown in Fig. 13 illustrate the variation of source power-per-unit-volume with argon weight flow rate. For a given source pressure level, the effect of the increasing argon flow rate on the source power-per-unit-volume is small relative to the effect of increasing the source chamber pressure. This would be the expected result for radiation dominated light sources.

The spectral irradiance at a distance 1 m from the source was determined from radiometer measurements made during the test series. The results of irradiance measurements for the source operating at a power-per-unit-volume of 83.2 kW/cm^3 are presented in Fig. 14 and Table V. Data are shown for eight wavelength bands over the wavelength range from 220 nm to 1300 nm. In Fig. 14, data are presented showing the as-measured irradiance (lowest lines for each of the wavelength bands) as well as the adjustment applied in each wavelength band to account for the effect of filter transmission (intermediate lines) and dye attenuation (top lines). Quantitative data on the radiant energy distribution are shown in Table V. From Table V, the radiation from the plasma in the various filter bands was highest ($1350 \mu\text{W/cm}^2$) in the 556 nm to 629 nm band. Second highest ($1154 \mu\text{W/cm}^2$) was the 402 nm to 449 nm band. The irradiance per unit of wavelength is also shown in Table V together with the calculated percent of the total radiation for each wavelength band. The total watts radiated in each wavelength interval were also calculated and are given in Table V. The results range from a high of 912 W radiated in the 556 nm to 629 nm wavelength band to 304 W in the 354 nm to 381 nm wavelength band.

The spectral intensities in Table V are somewhat below those required to reach threshold for operation of a dye laser. According to Ref. 12, approximately 5 kW of total pump-band power would be required to operate a Rhodamine 6G dye laser with dye cell dimensions the same as those of the source used in the present tests. Therefore, although significant increases in source intensity were obtained in the present tests, additional increases in source power-per-unit-volume are necessary to meet the requirements for a high power cw dye laser pump.

No evidence of the unstable plasma conditions was noted in tests with the 2.8-cm-ID source configuration. The power and pressure levels achieved were limited primarily by cracking of the inner 2.8-cm-ID fused-silica tube surrounding the source test chamber due to thermal stress. During several tests at high total source power levels, the inner 2.8-cm-ID fused-silica tube either developed cracks or failed. The thermal stress characteristics of fused-silica are shown in Fig. 15. The data indicate that for a wall temperature difference of 1000 K, a thermal stress of 3000 psi tension would be produced in the tube outer wall. This level of stress is within the range where tube cracking commonly occurs. The maximum allowable

tensile stress for fused-silica tubes is 7000 lb/in.^2 . The total stress produced is independent of the thickness of the tube wall and depends only upon the temperature difference across the tube wall. Calculations were made to estimate the total power which could be conducted through the 2.8-cm-ID fused-silica tube. The results indicate that about 2.7 kW could be conducted through the tube with a temperature gradient of 1000 K per mm. This power level is only 2 percent of the total plasma power for a 130 kW power level. Thus, if higher powers are to be obtained, it will be important that the tube walls be maintained clean and free of radiation absorption and that fluid mixing in the regions between the source boundary and test chamber wall be minimized to ensure the heat transfer to the tube inner wall be as low as possible.

Figure 16 illustrates the condition of two typical tubes which were removed after tests. A thermal stress crack can be seen in the tube at the left. Significant deposits of copper vapor and other foreign materials were accumulated on the tube during operation. A clean tube is shown at the right for reference. For tests at the highest power level, a 1.5 mm wall thickness tube was used instead of the 2 mm wall thickness tube used for most tests. This approach was successful and allowed the power-per-unit-volume level of 83.2 kW/cm^3 to be achieved. Further reductions in tube wall thickness are probably not practical in tubes of this large diameter. Future efforts should be directed toward reducing the tube heat load by improvements in the gas flow system, component cooling capability, and reduction of mixing in the region between the plasma on the tube inner wall. Major emphasis should be directed toward removal or elimination of contamination of the tube wall by particulate matter, metal vapors, etc. which are generated in high power source tests.

In summary, the results of the unseeded plasma tests indicate that progress toward operation at minimum threshold power levels was achieved with the 2.8-cm-ID source configuration. Attainment of higher power levels would require modification of the configuration injection geometry, cooling method, and gas flow system. Results also indicate that order of magnitude increases in power-per-unit-volume are not likely to be obtained with a configuration of this type unless significant changes in the flow and geometric configurations are made to eliminate the degradation of the optical transmission characteristics of the fused-silica tube. Such optical degradation very quickly leads to buildup of thermal stress within the tube and results in failure. The failure point is directly related to the average power transmitted through the fused-silica tube. One method of increasing the peak intensity of the source without significantly increasing the average power is described in the following section entitled SUPPORTING ANALYTICAL STUDIES.

TABLE IV

FLOW AND POWER CONDITIONS FOR UNSEEDED PLASMA
TESTS WITH 2.8-CM-I.D. SOURCE CONFIGURATION

Data Shown on Figs. 11 through 14

Test Point No.	Source Power-Per-Unit-Volume, kW/cm ³	DC Plate Voltage, kV	DC Input Power, kW	Source Chamber Pressure, atm	Total Source Power, kW	Power Radiated-Annular Coolant, kW	Argon Flow Rate, g/sec	Source Diameter, cm
1	10.3	6	110	2.7	37	4.2	3.6	1.17
2	17.8	7	150	3.0	57	6.5	3.9	1.11
3	24.0	8	200	3.0	68	10.9	4.5	1.04
4	35.5	9.2	218	4.4	82	33.0	5.4	0.94
5	36.0	9.2	250	4.4	94	26.3	5.9	1.00
6	45.3	10	250	5.2	96	30.7	5.9	0.90
7	45.8	10	300	5.2	97	28.0	6.4	0.90
8	65.6	10.5	310	7.0	99	30.0	6.4	0.76
9	83.2	12.1	400	8.3	119	38.0	7.3	0.74
10	86.0*	--	--	9.0	123	37.0	7.5	--
11	90.9*	13	480	9.5	130	45.0	7.7	--

*Calculated assuming no change in diameter from Test Point No. 9.

MEASURED IRRADIANCE CHARACTERISTICS OF UNSEEDED PLASMA LIGHT SOURCE

SOURCE TOTAL POWER/VOLUME = 83 kW/cm³

SOURCE TOTAL POWER = 119 kW

SOURCE CHAMBER PRESSURE = 8.5 ATM

SEE FIG. 4 FOR TEST CONFIGURATION DETAILS

RADIOMETER LOCATED 1-M FROM SOURCE

COIL BLOCKAGE EFFECTS NOT INCLUDED

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TABLE V

RADIANT ENERGY DISTRIBUTION FOR TEST
POINT AT 83.2 KW/CM³ PER UNIT VOLUME

Total Source Power = 119 kW

Wavelength Band, nm	Adjusted Irradiance, W/cm ²	Irradiance Per nm, W/cm ² /nm	Percent Of Total	Power Radiated To Surroundings, W
296-354	515	8.9	0.9	342
354-381	431	16	0.8	304
378-404	593	23	1.1	418
402-449	1154	25	2.1	798
452-495	713	13	1.3	494
542-608	626	9.5	1.1	418
556-629	1350	34	2.4	912
220-1300	55,170	51	100	38,000

THERMAL STRESS IN FUSED SILICA TUBES

$$\sigma_T = \frac{E \alpha \Delta T}{2(1 - \nu)}$$

PHOTOGRAPHS SHOWING TYPICAL POST-TEST CONDITION
OF 2.8-CM-ID FUSED SILICA TUBES
FOLLOWING HIGH POWER OPERATION

SEE FIG. 4 FOR TEST CONFIGURATION DETAILS

Results of Seeded Plasma Tests

Seeded plasma tests were conducted with both the 5.7-cm-ID test configuration and the 2.8-cm-ID test configuration. The purpose of these tests was to investigate the effect of addition of small amounts of heavy-atom hexafluoride materials to the argon plasma region with the purpose of increasing a radiation emission in the 300 nm to 600 nm wavelength region, without significantly increasing the total radiation from the source. The approach would take advantage of the complicated line structure of atoms such as tungsten and uranium to increase the source radiation. Previous research reported in Refs. 8 through 11 has shown that this technique is feasible and was demonstrated in sources with low power-per-unit-volume.

Tests with seeded plasmas were conducted in which the seed gas was injected by four different methods. Initially some tests were conducted with the 5.8-cm-ID configuration (see Fig. 3) for which a small amount of WF_6 seed material was premixed with the incoming argon vortex injection. Three other methods were also used which involved direct injection of the seed gas into the plasma region. These injection configurations are shown schematically in Fig. 17. Figure 17 shows a geometry used in tests with the 5.7-cm-ID source configuration. For this configuration a seed gas injection port was located 0.5 cm from the centerline of the test chamber in one endwall. In Fig. 17(b) a similar endwall injection configuration utilized in tests with the 2.8-cm-ID source configuration is shown. The configuration shown in Fig. 17(c) utilized an injection probe positioned on the centerline of the source configuration for direct injection of the seed gas into the plasma region. Results and test conditions obtained in the seeded plasma tests are given in Table VI for the premixed seed injection cases. During these tests, measurements were made of the change in the spectral distribution of radiation due to the presence of the heavy-atom hexafluoride seed materials. Flow and power conditions for the tests are also presented in Table VI. Cases I through V correspond to low power and low pressure test conditions. Changes in total source power and total radiated power deposited in the source coolant water due to the addition of seed gas were too small to be determined accurately and thus no change is indicated in the Table. Examination of the radiometer output, however, indicates the spectral content of the emitted radiation increased when WF_6 was added in the filter wavelength bands between 296 and 450 nm for all cases. Results of a test with the injection probe configuration (see Fig. 17(c)) presented in Fig. 18 show that the presence of tungsten atoms in the plasma region significantly alters the spectral distribution of emitted radiation. The plasma power-per-unit-volume for the data shown in Fig. 18 was only 5.5 kW/cm³.

Throughout the course of the seeded plasma test series difficulties were encountered with injection of seed material into the high power-per-unit-volume sources which are desired for dye laser pumping.

One source of the difficulties was due to the large effect of the seed material in the plasma on the plasma electrical characteristics. In many tests the plasma extinguished when attempts were made to inject seed material. In addition, because the WF_6 decomposes in the plasma and forms condensible products which at ordinary temperatures and pressures resulted in coating of portions of the tube walls after a relatively short time with seed being injected. This coating resulted in a degradation of the optical characteristics of the source. Finally, difficulties were encountered in injecting heavy-hexafluoride seed materials into the plasma source due to chemical reaction in the seed injection ports which often lead to plugged injectors.

The most effective method found of the four attempted for injecting seed material into the plasma region was through the probe located on the centerline of the configuration (Fig. 17(c)). However, this location presents an extremely hostile environment for any solid material. Heat transfer from the plasma to the probe is extreme because of the high plasma power-per-unit-volume.

Figure 19 shows details of the seed injector used on the centerline of the 2.8-cm-ID test configuration. Figure 19(b) indicates the condition of some of the injector tips following testing in the high density plasma environment. During the course of this program it was not possible to obtain a injector design survivable in power-per-unit-volume plasmas much above 5.5 kW/cm^3 . It can be seen from Fig. 19(b) that the injector degradation which occurred resulted from melting and subsequent vaporization of metal in the region of the injector tip, indicative of insufficient cooling of the injector. The injectors were cooled with 45 atm pressure water flowing at the inlet and atmospheric water on the outlet. Although they were highly-cooled, the hostile environment in which they were placed caused tip failure in a short time. It was not possible to develop an injector tip design in the time available in the program which would withstand long-term operation in high heat transfer environments present in the 2.8-cm-ID source configuration. Discussion of injector design heat transfer procedures used is presented in Appendix II.

Although seeding of low power density plasmas has been accomplished previously (see, for example, Refs. 9 and 10) with probes similar in design, the high source power-per-unit-volume requirements for cw dye laser pumps will preclude the use of injectors of this type in the source region. This together with the potential which exists for optical degradation on the outer fused-silica tube flow due to contamination from the seed material indicates that use of heavy hexafluoride seed materials in the present source configurations is not likely to provide the order of magnitude type increases in pump band radiation desired for cw dye laser pumping.

Because the radiation from the plasma was enhanced by the presence of the heavy atom materials, an alternative approach which should be investigated is a closed-cycle flow system in which small amounts of xenon or krypton are added to the argon

used to drive the vortex to increase the radiation. Use of xenon or krypton would eliminate the possibility of degradation and chemical reaction with components in the plasma source configuration. Premixing eliminates the need for a seed injector and could lead to reliable and long-term source operation.

In summary, the results of the seeded plasma tests indicate that experimental difficulties associated with seeding the high density plasmas must be overcome before a reliable high intensity seeded plasma source is developed. It is likely that considerable improvement could be obtained with the addition of heavy atom inert gas such as xenon or krypton through use of a closed-cycle flow system for the vortex gas used to drive the source.

TABLE VI

RESULTS OF SEEDED PLASMA SOURCE TESTS

5.7-cm-1.4. Source Configuration

WF₆ Premixed with Argon Vortex Gas

	CASE NUMBER											
	I		II		III		IV		V		VI*	
Composition	A	A/WF ₆	A	A/WF ₆	A	A/WF ₆	A	A/WF ₆	A	A/WF ₆	A	A/WF ₆
Wavelength Interval-nm	RADIOMETER DETECTOR OUTPUT VOLTAGE, mv											
296-354	3.5	8.5	5	24	5	35	16	18	5.0	20	0.3	0.75
354-381	3.3	5.8	6.5	15	8	19	13.4	15	4.8	11.5	1.0	1.5
373-404	6	10.8	13	20	16	27	26	29	9.0	16.8	3.0	6.0
402-449	18	31	38	40	49	50	78	86	27.5	33.5	12.0	21.0
452-495	17	27	36	27	48	30	76	88	27.5	28.5	8.0	13.5
498-542	16	25	35	19	45	20	74.6	68	26	18.5	3.5	5.5
556-625	24	36	53	20	65	21	120	138	40	22.5	3.5	5.0
250-1300	13	20	26	14	32	13	58	68	20.5	15	36	44
Source Pressure-atm	1		2		2		2		2		9	
Total Source Power-KW	8 est		12 est		15 est		20 est		15 est		32.3	36.8
Source Radiated Power-KW	2 est		4 est		5 est		6 est		4 est		16.2	20.8
Argon Weight Flow Rate g/s	2.3		3.6		3.6		4.5		3.6		5.5	

*Nigrosine Dye Spectral Absorption Effects Not Included in Data For Case VI.
For Case I-V Dye Spectral Absorption Effects Not Significant.

SKETCHES SHOWING INJECTION CONFIGURATIONS USED IN SEEDED PLASMA SOURCE TESTS

SEE FIGS. 3 AND 4 FOR OTHER TEST CHAMBER DETAILS

(a) ENDWALL SEED INJECTION CONFIGURATION I

(b) ENDWALL SEED INJECTION CONFIGURATION II

(c) CENTERLINE SEED INJECTION CONFIGURATION

MEASURED IRRADIANCE FROM 5-CM LENGTH OF SEEDED AND UNSEEDED PLASMA LIGHT SOURCE

SOURCE TOTAL POWER/UNIT VOLUME = 5.5 KW/CM³ (w/o WF₆)

SOURCE TOTAL POWER = 23 KW (w/o WF₆)

SOURCE CHAMBER PRESSURE = 4.0 ATM

TEST CONFIGURATION - 2.8-CM-ID x 7.5-CM LONG

RADIOMETER LOCATED 1-M FROM SOURCE

DETAILS OF SEED INJECTOR USED IN TESTS WITH 2.8-CM-ID
PLASMA SOURCE CONFIGURATION

(a) GEOMETRY OF SEED INJECTOR

(b) TYPICAL POST-TEST CONDITION OF SEED INJECTOR TIP REGION

SUPPORTING ANALYTICAL STUDIES

Supporting analytical studies were performed to assess the test results obtained in terms of requirements for cw sources for pumping dye lasers and to provide direction for future source development efforts. The studies were directed toward preliminary examination of methods of pulsing the light source, methods of integrating the light source into a mirror configuration to provide efficient transfer of radiant energy from the source to the dye cell, and to identify the design characteristics of new light source configurations building upon the test results described in the section entitled PLASMA LIGHT SOURCE TESTS.

Method of Pulsing Light Source

Pulsed light sources with $1 \mu\text{s}$ or less rise time have been used for pumping dye lasers since 1966. However, difficulties with such pulsed light sources have generally been encountered when attempts are made to operate at high pulse repetition frequency. Limitations result from shock interactions produced by the high instantaneous power levels in such light sources. One of the most powerful, in terms of average power, light sources used for pumping dye lasers is described in Ref. 13. This 50 kW average power dc arc source is a vortex stabilized light source similar in some respects to that which was utilized in the tests described herein. The combined effects of shock wave interactions with the outer fused-silica envelope and increased thermal stress in the envelope produced during high average power operation could eventually limit the pulse repetition frequency for pulsed source operation. One method of reducing the strength of shock waves produced from repeated application of high energy pulses to an rf light source was identified in the present studies. In this concept, the source would be operated at a steady-state condition such that the radiant emission was at or near the minimum threshold power level required for pumping a dye. Intermittently the rf system could be pulsed to produce approximately $100 \mu\text{s}$ wide high power pulses. It is estimated that the intensity from the source might be increased by a factor of 5 to 10. This approach would significantly reduce the strength of shock waves produced compared with pulsing the source in the usual manner because it would only increase the gas temperature by a factor of 2 over the steady-state value. Further, the average power from the source would only be increased 10 to 20 percent, depending on the value of the duty cycle used. Figure 20 depicts the effect of rf frequency on the pulse repetition rate for 10 and 20 percent duty cycles. The rf plasma operates in a high "Q" tank circuit. (The "Q" of the circuit is equal to the ratio of the energy stored per cycle to the energy dissipated per cycle.) Typically, rf plasma source systems operate with output "Q's" of approximately 100 to 200. The results shown in Fig. 20 are for a high power pulse width which is equal to 2000 separate rf cycles. The calculated pulse width in μs is shown in the right abscissa. The high power pulse so produced would be relatively flat with rise time and fall time characterized

approximately by $"Q"/f_0$ s. It would be desirable to use the highest rf operating frequency possible to obtain a fast rise time pulse. From Fig. 20, operation at a pulse repetition frequency of 1000 Hz with a total high power pulse width of 100μ s and a duty cycle of 10 percent could be obtained with an rf operating frequency of 20 MHz. The net increase in average power of the source would be equal to the duty cycle (10 percent), whereas the source intensity would be increased significantly, possibly a factor of 5 to 10.

The rf tubes and associated equipment for producing such pulses are available commercially. Table VII contains the typical characteristics of high power tubes which are commercially available which could be utilized in a system. A block diagram of a system for intermittent operation is shown in Fig. 21. The system shown would utilize 2 ML-7560 tubes connected in parallel and could be capable of producing 6 MW of total power. The system is driven by several stages of driver amplifiers. Pulse control is produced by modulation of the grid of the final amplifier tubes. Modulation of the grid serves to turn the tube on or off.

Use of an intermittent rf system such as that shown schematically in Fig. 21 appears to be an attractive means to produce plasma power-per-unit-volume levels in the MW/cm^3 range on an intermittent basis with only moderate increases in average power level. Development of a high power rf system similar to that of Fig. 21 would be a considerable engineering task. However, the development could be pursued in stages. This would allow needed information on plasma load characteristics to be obtained prior to construction of the final high power stage. The total estimated cost for a high power system such as that outlined in Fig. 21 using all new components including power supply, controls, etc., would be approximately $3\frac{1}{2}$ to 5 million dollars including engineering. The total cost of a system would be reduced by utilization of existing power supplies, and components assembled from existing systems. It is recommended that the initial step in developing a system would be a demonstration of the source operation in a grid modulated amplifier stage at approximately a 100 kW output power level with a plasma load.

Method of Mirror Integration

Demonstration of laser operation using an rf induction heated high intensity light source requires integration of the source into a reflective cavity geometry such that radiation from the rf light source can be reimaged into a dye cell. Two concepts for mirror integration resulted from the studies performed under the program. The first concept, illustrated in Fig. 22, employs a transverse flow dye configuration with exfocal pumping of the laser system. Exfocal pumping has been used at UTRC (Ref. 13) and other laboratories (Ref. 14) for pumping of dye laser systems for a number of years. This pumping method involves location of the pump light source along a major diameter of a sphere or ellipse in a region between the

TABLE VII

ELECTRICAL CHARACTERISTICS OF AVAILABLE HIGH POWER VACUUM TUBES

Power Amplifier Tubes

Tube Type	Typical CW Rating	Maximum Frequency	Voltage	Current	Plate		Approximate Cost
					Input	Dissipation	
Machlett ML-7482	330-440 kW	30 MHz	20 kV	30 A	600 kW	200 kW	\$5,000
Eimac X-2159	2090 kW	30 MHz	20 kV	125 A	2500 kW	1250 kW	\$25,000

Pulse Modulator Tubes

Tube Type	Pulse Ratings	Pulse Duration	Duty Factor	Voltage	Plate		Approximate Cost
					Current	Dissipation	
Machlett ML-8041	5 MW	1000 μ sec	0.01	60 kV	175 A	60 kW	\$2,700
Machlett ML-7560	15 MW	1000 μ sec	0.01	55 kV	550 A	175 kW	\$5,000
Eimac X-2159	43 MW	500 μ sec	0.01	55 kV	780 A	1250 kW	\$25,000

EFFECT OF RF FREQUENCY ON PULSE REPETITION RATE
FOR INTERMITTENT SOURCE OPERATION

BLOCK DIAGRAM OF RF SYSTEM FOR INTERMITTENT OPERATION

FIG. 21

peripheral wall and the cavity focus. Using this pumping scheme, the radiant emission from the source is imaged into the dye cell located in a symmetric position at the opposite end of the cavity. A major advantage of exfocal pumping of this type is that the dye cell is irradiated symmetrically. This is desirable since it reduces the effect of index of refraction changes on the laser operation. Transverse flow in the dye cell is desirable because the pressure loss is lower than that of a longitudinal flow geometry for the same dye residence time and active volume dimensions. Considerable attention should be given to the fluid dynamic design of the dye cell region to avoid occurrence of cavitation and recirculating flow which adversely affects laser operation.

The rf light source geometry would be similar to that illustrated in Fig. 22. Coolant and gas flow enter the source configuration external to the cavity and flow through the cavity peripheral wall down to the opposite endwall. Both coolant and gas exit from the same endwall out through the cavity. The rf work coils would be located within the cavity region. It may be desirable to fabricate the reflector cavity using discrete segments. This would allow adjustment of individual segments to be made at the time the source is fabricated to optimize the radiation transport within the cavity. This would provide more flexibility in imaging the source radiation into the active volume of the laser. Consideration should be given to use of a dielectric reflector for the cavity segments. Dielectric reflectors might be developed to reflect only that radiation which is desired for pumping the dye, thereby reducing the heat load due to unwanted radiation. Such reflectors also offer the added advantage that they are nonconducting and compatible with rf fields. Arc-over problems from the cavity to the rf coils could be eliminated through use of dielectric reflectors. The effect of high temperature operation on dielectric reflectors is not well known at present and additional research is required to demonstrate the capability of such reflectors in the high power rf environment.

Additional detail of the plasma light source configuration is shown in Fig. 23. A plasma light source approximately 0.5 cm in diameter would be located in a 2.8-cm-ID configuration made-up of two concentric fused-silica tubes. The tubes would provide for annular coolant. It is possible that coolant could be used wherein the injection geometry of the vortex chamber could be optimized through the use of peripheral wall injection techniques similar to those described in Ref. 15. This method of injection would be used to provide essentially laminar flow in the region between the plasma source and the inner fused-silica tube. For operation at a pressure of approximately 20 atm, the coolant capability provided by high pressure argon could be made sufficient to allow operation of the light source without water cooling the annular channel. Further research is required to develop a light source using this cooling concept; however, it appears that significant improvements could be obtained in the radiation output and operating characteristics of the light source by providing improved fluid dynamic injection for the vortex flow.

SKETCH OF TRANSVERSE FLOW CONFIGURATION WITH EXFOCAL PUMPING

DIMENSIONS OF DYE ACTIVE VOLUME
APPROXIMATELY 0.7 CM x 0.7 CM x 5.0 CM

R03-148-4

LIGHT SOURCE CONFIGURATION FOR EXFOCAL PUMPING

UPPER HALF OF REFLECTOR NOT SHOWN

R75-911915-10

FIG. 23

Improved source operating performance might also be obtained by replacement of the fused-silica tube surrounding the source with a tube fabricated from a different material. A summary of the important properties of candidate transparent materials is contained in Table VIII. The desired properties are good UV transmission and high thermal conductivity. Of the materials listed, the most attractive is single-crystal beryllium oxide. To date this material is not available in tube forms. However, if the fabrication technology were developed, the gains in heat transfer capability afforded by beryllium oxide compared to fused-silica would be significant.

A longitudinal flow configuration for a cw dye laser with focal pumping in an elliptical cylinder was also investigated. The configuration is shown in Fig. 24. Coolant for the light source enters and exits through the plane reflective ends of the cylinder. The reflector segments could be dielectric coated to reflect only that portion of the light which is desired for pumping the dye. The reflector could be fabricated using an array of flat-faced mirror segments arranged to form an approximate ellipse. This approach has been utilized previously in the high power laser technology field with some success to correct for phase distortion effects in high power beams. The rf work coils which surround the plasma source would enter through the reflective cavity through an insulated feedthrough. For this configuration it is likely that a source length greater than 5 cm could be utilized to advantage to provide increased total radiation output and higher flux per unit dye cell cross-sectional area. A cylindrical dye cell similar to that which has been utilized previously for many flashlamp pumped lasers could be used. For this configuration it is necessary that very high pressure, high velocity fluids be used in the dye cell. The technology for high pressure, high velocity fluid flow is developed well beyond that which has been used to date in conventional dye lasers. High velocity water jets have been reported for which velocities as high as 1000 m/s were achieved in a 0.005-cm-dia jet. Further investigation of possible application of this technology to the dye laser field is recommended.

Multiple cavity configurations were also investigated as possible methods of integration of the light source with the dye cell. As described in Refs. 18 and 19, multiple cavity configurations do offer certain advantages in terms of uniform pumping and pumping symmetry. However, development of an rf system to operate multiple source configurations would be difficult. As a result, these configurations are not well-suited for operation with rf excited systems.

Development Plan for High Power Pump Source

Development of a light source suitable for pumping cw multi-kilowatt average power dye lasers will require considerable additional effort. A possible plan leading to development of such a high power laser pump is outlined in Fig. 25. The plan consists of three phases. Phase I corresponds closely to the activities

completed under the present program. Under Phase II it is recommended the approach toward low power intermittent operation of the plasma source to achieve MW/cm³ type power-per-unit-volume at peak intensity with average powers to 150 to 200 kW be explored further. Additional plasma tests are recommended for Phase II to investigate the effects of xenon and krypton gas seeds on radiation and to optimize the gas flow and source radiation requirements for high power operation. Under Phase III development of the high power rf equipment and high power demonstration tests would be accomplished. Phase III would also require integration of the source with equipment being developed for mode locking and production of narrow bandwidth in the output beam as required for use in isotope separation processes. Obviously the total time required for completion of Phases II and III is a function of the level of effort applied; however, it is estimated that a minimum of 2½ to 4 years to complete Phases II and III would be required.

TABLE VIII

IMPORTANT PROPERTIES OF CANDIDATE TRANSPARENT MATERIALS

Data from Refs. 16 and 17

Material	Transmission Window $\lambda_{UV} \rightarrow \lambda_{IR}$, NM	Melting Point, $^{\circ}\text{C}$	Thermal Conductivity @ 300°K $\text{W/cm}^{\circ}\text{K}$
SiO_2	160 $\rightarrow$ 4000	1450	0.016
Al_2O_3	140 $\rightarrow$ 6000	2050	0.026
BaF_2	130 $\rightarrow$ 12,000	1320	0.11
MgF_2	120 $\rightarrow$ 7500	1310	0.12
LiF	110 $\rightarrow$ 6200	870	0.11
BeO^*	125 $\rightarrow$ 4000	2800	2.0

* - Single Crystal Form

SKETCH OF LONGITUDINAL FLOW CONFIGURATION WITH FOCAL PUMPING IN ELLIPTICAL CYLINDER

LIGHT SOURCE GAS AND COOLANT ENTERS AND
EXITS THROUGH CYLINDER ENDS

FIG. 24

DEVELOPMENT PLAN FOR HIGH AVERAGE POWER DYE LASER PUMP

FIG. 25

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LIST OF SYMBOLS

A	Area, cm^2
B	Spectral radiance, $\text{W}/\text{cm}^2\text{-ster-nm}$
d_H	Hydraulic diameter, cm
E	Elastic modulus, $\text{lb}/\text{in.}^2$
f_o	RF frequency, MHz
h_f	Film coefficient, $\text{W}/\text{cm}^2/^\circ\text{C}$
I	Source irradiance, W/cm^2
I/I_o	Ratio of transmitted intensity to incident intensity, dimensionless
k	Thermal conductivity, $\text{W}/\text{cm}/^\circ\text{C}$
P_c	Source pressure, atm
Pr	Prandtl number, dimensionless
q	Quantity of heat transferred, J
Q_T	Source total power, kW
Re	Reynolds number, dimensionless
t_p	Total rf pulse width, s
t_R	Time between rf pulses, s
t_w	Wall thickness, cm
T	Temperature, $^\circ\text{K}$ or $^\circ\text{C}$
V_S	Source volume, cm^3
W_A	Argon weight flow rate, g/s
α	Coefficient of thermal expansion, $^\circ\text{K}^{-1}$

LIST OF SYMBOLS (Concluded)

T	Temperature difference, $^{\circ}\text{K}$
λ	Wavelength, nm
T	Thermal stress, lb/in.^2
ν	Poisson's ratio, dimensionless

APPENDIX I: DESCRIPTION OF UTRC 1.2-MW RF HEATER

The plasma light source tests conducted during this program utilized the UTRC 1.2-MW rf induction heater. This heater facility was originally constructed during 1966 and 1967 as part of a Corporate-sponsored program. The heater was designed to deposit approximately 600 kW of rf power into an approximately 4 cm³ volume discharge. The overall system efficiency of the heater when matched to a plasma load is approximately 30 to 45 percent. This efficiency is based on the total rf power deposited in the load divided by the total dc power supplied to the heater.

A block diagram showing the primary components of the heater is presented in Fig. 26. The heater is driven by a variable-frequency oscillator whose approximately $\frac{1}{2}$ W power output is amplified to 2 kW using a neonron amplifier stage. The rf operating frequency is determined by the values of inductance and capacitance in the output tank circuit. The rf operating frequency for the tests varied between approximately 5.4 MHz and 5.6 MHz depending on the test configuration. The 2 kW output of the neonron is used to drive a 40 kW power output amplifier stage. The 40 kW stage in turn drives an 80 kW buffer amplifier. The 80 kW buffer amplifier is the final driving stage for the two final stage power amplifiers.

A saturable reactor type dc supply powers the 40, 80, and 440 kW output stages. All intermediate stages have controls for tuning and impedance matching at the output in order to provide efficient coupling to the final amplifier input stages. Adjustments may be made to the various amplifier stages to accommodate a wide range of plasma load conditions. The final amplifier stages are powered by ML7482 triode tubes connected in a push-pull configuration to drive a resonant tank circuit. Each power tube is designed to operate with up to 600 kW dc input power and produce up to 440 kW output power. Power and voltage levels noted in Fig. 26 corresponds to the maximum rated rf output power and dc voltage for the various amplifier stages. The maximum total dc input power to the power amplifiers utilized in the tests during this program was 540 kW.

Figure 27(a) is a photograph of the resonator tank circuit section of the heater. It is located within a 1.5-m-dia aluminum test tank. The resonator section is made-up of two arrays of ten vacuum capacitors each connected to a work coil to form a parallel resonant circuit used to couple rf power into the plasma discharge. The ends of the capacitors are water-cooled to remove the small amounts of energy dissipated in the capacitor structure during operation at high power. Two types of work coils were used in the tests conducted during this program. For the 5.7-cm-ID configuration the work coils consisted of two single-turn coils, each madeup from five water-cooled 0.475-cm-ID copper tubes silver-soldered together to form a single structure (see Fig. 3). The ID of the work coils was 7.8 cm. The coils are silver-plated to reduce resistive heating due to high coil currents, as well as to enhance their reflectivity to radiation emitted from the plasma.

Installation of the 2.8-cm-ID test configuration in the 1.2 MW heater required design and fabrication of new rf work coils. These approximately 4-cm-ID coils consisted of single-turn silver-plated copper tubing connected to the capacitor section of the 1.2 MW rf heater. The coil geometry was designed to produce minimal blockage of the plasma radiation from the test chamber. The rf coils utilized with the 5.7-cm-ID configuration shown in Fig. 3 blocked approximately 60 percent of the total peripheral wall area. For the new coils only approximately 12 percent of the peripheral wall area was covered by the coils. The coils were designed to have the same inductance as the coils used with the 5.7-cm-ID configuration to allow the rf operating frequency for the heater tank circuit to be maintained at approximately 5.5 MHz.

For tests conducted in which the dc plate voltage was in excess of about 7 kV the test tank was pressurized with sulfur hexafluoride. The maximum sulfur hexafluoride pressure utilized during this program was 2.5 atm. Access to the test tank is provided by removing the aluminum dome cover thereby exposing the capacitor portion of the resonator section for maintenance or servicing. A photograph of the control console for the rf heater is shown in Fig. 27(b). All components of the heater are water-cooled except the filaments of the amplifier tubes which are air-cooled. The total amount of water required is approximately 200 l/min for cooling the heater components. Provision is also made for metering of the water-coolant flow rates, gas flow rates, and temperature rises in order that a complete energy balance on the system may be made for a given test run.

BLOCK DIAGRAM OF UTRC 1.2-MW RF INDUCTION HEATER

OPERATING FREQUENCY = 5.5 MHz

POWER LEVELS SHOWN ARE MAXIMUM DESIGN VALUES

FIG. 26

R75-911915-10

PHOTOGRAPHS OF 1.2-MW RF INDUCTION HEATER

SEE FIG. 26 FOR BLOCK DIAGRAM

(a) RESONATOR SECTION DETAILS

(b) HEATER CONTROL AREA DETAILS

APPENDIX II: ENDWALL AND SEED INJECTOR
DESIGN HEAT TRANSFER CONSIDERATIONS

The endwalls and seed injectors used in the tests with the 2.8-cm-ID configuration were designed to withstand the highest possible heat fluxes compatible with available cooling and geometry constraints of test region. Quantitative thermal heat transfer data on the thermal environments that the endwalls and seed injectors must withstand is unavailable. The approach taken was to analyze the maximum thermal capability of the coolant flows and apply empirical information on the thermal loading to estimate the limitations of the design. In the case of the endwalls it is known from previous tests with similar configurations (Ref. 8, Figs. 13 and 20; Ref. 9, Figs. 13 and 23) that a maximum of approximately 8 percent of the total power in a confined plasma is deposited in the endwall coolant.

In the case of the seed injectors virtually no applicable empirical data from previous tests were available due to design and size variations used in previous tests. The approach taken with the seed injection probe was to design for the maximum possible cooling capability within the given size constraints, operate at the highest possible water flow rate (maximum inlet pressure available), and determine experimentally the heat flux (maximum water temperature rise) at which successful operation could be maintained.

Analysis of the thermal loading on the seed injector and endwalls was complicated by the presence of small arcs that formed from the plasma and attached to the probe and endwalls. These arcs are probably caused by the high electric fields present in the plasma region. Each arc results in continual erosion and vaporization of a minute amount of copper from the surface. After a period of time the wall thickness is measurably reduced, thereby further limiting the maximum allowable tensile stress on the component wall. It is also noteworthy that the injector tips were silver-brazed to concentric tubes and any erosion of the braze material would seriously weaken the integrity of the injector tip. Failures of the probes was therefore probably due to high wall temperatures and reduced tensile strength combined with a high internal water coolant pressure.

The endwalls are not subject to the same size constraints as the seed injection probes and were designed to operate much greater total discharge powers. Also, since the faces of the endwalls are a factor of 2 thicker than the seed injector probe tips, the small arcs that occurred caused relatively minor damage to the endwalls. It should be noted, however, that the copper vaporized from the endwalls and injectors by these arcs may have plated out on the cool inner surface of the 2.8-cm-ID fused-silica tube causing increased radiant heating and contributing to the failure of the fused-silica tube due to thermal stress.

Endwall Heat Transfer

The endwall heat transfer is characterized by the following computations in which actual data from the highest power test are used. The original design calculations were based on assumed operating conditions and were different from the actual parameters obtained in the tests. The endwall cooling water flow rate was 59 l/min giving an average water velocity through the endwalls of 18 m/s. The bulk water temperatures at a total power into the discharge of 130 kW were as follows: $T_1 = 15.6^\circ\text{C}$, $T_2 = 23.3^\circ\text{C}$, $T_3 = 40^\circ\text{C}$, and $T_4 = 47.8^\circ\text{C}$, where the subscript 1 indicates the upstream endwall inlet water station, 2 the upstream endwall outlet water station (annular water inlet station), 3 the downstream endwall inlet water station (annular water outlet station), and 4 the downstream endwall outlet water station. Because of the design of the endwall assemblies it is not possible to separate the power absorbed by the endwall assemblies and the power absorbed in the integral thru-flow heat exchangers. Assuming, pessimistically, that 10 percent of the total power of 130 kW was deposited in each endwall, the resulting average heat flux, $(Q/A)_{\text{EW}} = 840 \text{ W/cm}^2$. The film coefficient, h_f , for the upstream endwall (this represents the worst case since the higher temperature water in the downstream endwall cools more effectively) is: $h_f = 8.4 \text{ W/cm}^2\text{-}^\circ\text{C}$. The convective film coefficient was calculated using the standard relation:

$$h_f = 0.023 \frac{k}{d_e} \text{Re}^{0.8} \text{Pr}^{0.33}$$

where k = thermal conductivity, d_H = the equivalent diameter of the flow passage, Re = Reynolds number, and Pr = Prandtl number. Because of the relatively large film temperature drop, it was necessary to iterate on the film coefficient calculation in order to obtain the correct corresponding average of the bulk water and wall surface temperatures. Then using the familiar relation:

$$q/A = h_f \Delta T$$

we obtain the film temperature drop $\Delta T_f = 98.4^\circ\text{C}$. The maximum wall temperature drop occurs where the wall is thickest. In the present design $t_{\text{max}} = 0.33 \text{ cm}$. The wall temperature drop was calculated using the equation: $T = (t/k)(q/A)$ and for the present case: $\Delta T_w = 55.2^\circ\text{C}$. Summing the temperature drops for the endwall gives a plasma region wall surface temperature $T_w = 194^\circ\text{C}$ and an average wall temperature $T_{w \text{ avg}} = 158^\circ\text{C}$, which are well below the usual limiting design wall temperature for OFHC copper of 260°C . Thus it is expected the source could have been operated at higher total powers without exceeding the cooling limit on the endwall design.

Seed Injection Probe Heat Transfer

Similar heat transfer calculations were performed for the seed injection probes. The following data apply for one of the probes at the time of failure:

Water coolant flow rate = 2.1 l/min
 Water coolant flow velocity = 9.3 m/s
 Water coolant inlet temperature = 23.3 C
 Water coolant outlet temperature = 80.6 C
 Total power absorbed = 8.5 kW
 Approximate water pressure at tip = 20 atm

Assuming (conservatively, since the tip region is surrounded by the plasma source) that 50 percent of the total power absorbed by the probe is absorbed in the first 2.5 cm from the tip (only the first 18 cm from the tip is subjected to heating by the plasma), then the average heat flux at the tip is, $q/A = 0.061 \text{ W/cm}^2/\text{C}$. Again, by iterating on the calculation for the film coefficient such that the correct average of the bulk water temperature and the wall surface temperature is obtained, we have: $h_F = 10.4 \text{ W/cm}^2\text{-C}$. The resulting film temperature drop is: $\Delta T_F = 102 \text{ C}$. The maximum wall temperature drop occurs at the tip of the probe where the wall thickness is: $t_{\max} = 0.16 \text{ cm}$.

Summing the temperature drops for the seed injector gives a plasma region wall surface temperature $T_w = 227 \text{ C}$ and an average wall temperature $T_{\text{avg}} = 205 \text{ C}$. If all of the total power absorbed by the injector is transferred in the first 2.5 cm length from the tip, then the injector wall surface temperature in the source region is: $T = 374 \text{ C}$ and the average wall temperature is: $T_{w\text{avg}} = 330 \text{ C}$. Because of the relatively high tensile stress on the injector, the aforementioned arcing at the injector tip and the high wall temperatures it is probable that failure occurred at a condition for which slightly more than 50 percent of the total power absorbed was transferred to the injector in the tip region.