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THE CESIUM TELEC EXPERIMENT AT LEWIS RESEARCH CENTER

FINAL REPORT

BY

E. J. BRITT

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16. Abstract

A novel concept known as a Thermo-Electronic Laser Energy Converter (TELEC), has been studied as a method of converting a 10.6 μm CO_2 laser beam into electric power. The calculated characteristics of a TELEC seem to be well matched to the requirements of a spacecraft laser energy conversion system.

The TELEC is a high power density plasma device which absorbs an intense laser beam by inverse bremsstrahlung with the plasma electrons. In the TELEC process, electromagnetic radiation is absorbed directly in the plasma electrons producing a high electron temperature. The energetic electrons diffuse out of the plasma striking two electrodes which are in contact with the plasma at the boundaries. These two electrodes have different areas: the larger one is designated as the collector, the smaller one is designated as the emitter. The smaller electrode functions as an electron emitter to provide continuity of the current. Waste heat is rejected from the collector electrode.

An experiment was carried out with a high power laser at Lewis Research Center using a cesium vapor TELEC cell with 30 cm active length. Laser supported plasma were produced in the TELEC device during a number of laser runs over a period of several days. Electric power from the TELEC was observed with currents in the range of several amperes and output potentials of less than 1 volt. The magnitudes of these electric outputs were smaller than anticipated but consistent with the power levels of the laser during this experiment.

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This report describes a joint experiment to demonstrate a Thermo-Electronic Laser Energy Converter (TELEC) performed by Rasor Associates and the NASA Lewis Research Center. The author would like to gratefully acknowledge the substantial contributions to this effort made by LeRC personnel and NASA sponsorship of the project. The TELEC device was tested with the high power laser facility at LeRC. Mr. Don Alger was the NASA Project Monitor. He was also responsible for the design and construction of the closed chamber optical system used in the experiment. In addition to Mr. Alger, the efforts by Mr. E. J. Manista to setup the data acquisition system are noted. Dr. J. W. Dunning, Mr. R. B. Lancashire are acknowledged for operation of the laser system. Necessary facility modifications and setup of the experiment were handled by Mr. Gene Pleban and Mr. Bob Gott. Advice and support for the project by Mr. Jack Slaby and Dr. R. M. Stubbs are also acknowledged. Gratitude is expressed to all of the individuals mentioned, and to the Lewis Research Center for providing the laser facility to perform the tests.

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Nomenclature

A_E	Active area of the TELEC emitters	(cm^2)
D_C	Diameter of the beam hole in the collector	(cm)
I_C	Collector current (total current) of the TELEC cell	(A)
I_{E1}	Current flowing through the TELEC emitter #1	(A)
I_{E2}	Current flowing through the TELEC emitter #2	(A)
Laser H	Direct heating of the emitter surfaces by laser beam impingement	($watts/cm^2$)
P_{laser}	Total power in the incident laser beam	(kw)
Q	Incident laser beam power density	(kw/cm^2)
P_{Cs}	Pressure of cesium vapor in the TELEC cell	(torr)
R_p	Ion loss parameter for TELEC calculations (R_p = 0% implies total reflection of ions at plasma boundaries)	(%)
T_E	Temperature of the TELEC emitters	(°K)
T_C	Temperature of the TELEC collector	(°K)
V_{E1}	Voltage of emitter #1 relative to the collector	(volts)
V_{E2}	Voltage of emitter #2 relative to the collector	(volts)
ΔV	Resistive voltage drop occurring in the TELEC electrodes between the electrode surfaces and the output terminals	(volts)
ϕ_C	Collector work function	(eV)

1.0 INTRODUCTION AND SUMMARY

1.1 Laser Power Transmission

The NASA high-power laser technology program has been conducting investigations of the generation and transmission of power over long distances by means of laser beams. Preliminary analyses of power conversion systems show laser systems could be competitive with conventional systems if the conversion system is capable of high efficiency, low mass, low cost, and operation at high power density.

The payload mass of a spacecraft can be more effectively utilized if none of the mass is consumed by electric power generating equipment. The alternative to on-board power generation, is power transmission from another source. Various options exist for transmitting the required power, but for long distance transmission, a laser beam system has distinct advantages. The coherent nature of the laser permits the beam divergence to be maintained near the diffraction limit. Furthermore the shorter wavelength of an optical beam also reduces the beam divergence, and thus a correspondingly smaller antenna will be required at the receiver than for similar systems which use microwave transmission.

A laser power transmission system requires an efficient, reliable, lightweight method of converting the received laser beam into useful electric power. It is also desirable if the waste energy which is not converted into electric output can be radiated at high temperatures. This reduces size and mass of the waste heat radiator.

A novel concept that may satisfy these requirements is a plasma-type device known as a Thermo-Electronic Laser Energy Converter (TELEC), which has been studied as a method of converting a 10.6 μm CO_2 laser beam into electric power. The calculated characteristics of a TELEC seem to be well matched to the requirements of a spacecraft laser energy conversion system.

1.2 The TELEC Concept

The TELEC is a high power density plasma device which absorbs an intense laser beam by inverse bremsstrahlung with the plasma electrons. A high beam intensity ($\geq 10^4$ watts/cm^2) is required to maintain a high electron temperature and sustain the plasma while producing output power. The favored configuration of a TELEC requires a narrowly focused collimated beam with a long optical path in the plasma to absorb nearly all of the beam energy. Suitable optics (mirrors and/or lenses) to concentrate and collimate the beam will be required on the receiver spacecraft. The system must also include a chamber with windows that are transparent to the laser radiation to contain the plasma gas.

In the TELEC process, electromagnetic radiation is absorbed directly in the plasma electrons producing a high electron temperature. The energetic electrons diffuse out of the plasma striking two electrodes which are in contact with the plasma at the boundaries. These two electrodes have different areas: the larger one is designated as the collector, the smaller one is designated as the emitter. The smaller electrode functions as an electron emitter to provide continuity of the current. Waste heat is rejected from the collector electrode.

Electrons and ions, produced and maintained by the inverse bremsstrahlung absorption process, are transported by ambipolar diffusion to the plasma boundaries, and hence strike the larger-area collector preferentially; thus, a net electron current to the collector results in subsequent flow through the external load. Ion current to the collector reduces the net output current, and the associated energy transport could result in a major loss of efficiency. However, the ion-loss rates are expected to be substantially smaller than predicted by ambipolar diffusion. A large flux of neutral cesium atoms continually enters the plasma after deionization at the cooler electrode surfaces. These suppress the escape of plamsa ions by charge-exchange collisions which have a very large cross section. Also, it is likely that there is a transition region between the plasma and electrodes where the laser-beam illumination will not support a high degree of ionization. This transition region would act as a reflector, also helping to return outgoing ions into the plasma. Some modeling of these two effects has confirmed the expected reduction of the undesirable ion currents.

1.3 Previous Calculations and Experiments

The TELEC concept was first introduced by N. S. Rasor[1] in 1973 as a variation of an earlier RF heated plasma converter developed by Waymouth.[2] To couple the wavelengths of existing high power/efficient lasers into the device, Billman suggested that inverse bremsstrahlung could be used. In this process, the energy of a plasma electron is increased by absorption of a photon with the momemtum imbalance being taken up by an ion or neutral species.[3-5] Subsequent detailed modeling and analytical assessment by Hansen and Rasor[6] and Britt and Yuen[7] established the viability of the TELEC concept and the preferred operational parameters. Although gases, such as hydrogen, could be used, it was shown that cesium vapor was an ideal medium because of its low ionization potential, large atomic mass (and, therefore, low ionic mobility), and favorable reduction of electrode work functions, to provide the plasma in the device. A laser intensity in excess of 10^4 W/cm^2 was shown to be sufficient to maintain the requisite high electron temperature and to sustain the plasma against losses, while producing output electrical power. The studies indicated that single-pass absorption in a sufficiently long TELEC, or in a shorter multipass device (absorption depth = 10-100 m, depending upon operating pressure), could result in conversion of 10.6-μm CO_2 laser radiation to electric power with efficiencies in excess of 42%.

An experimental TELEC apparatus was constructed and tested at the Ames Research Center using a 40 kW combustion laser.[8-10] The experiments with the Ames laser showed that stable plasma formation in a 1 in long TELEC cell can be obtained by absorption of a 10.6 μm laser beam. Based on the observed results, inverse bremsstrahlung absorption in cesium would evidently be able to deposit enough energy to sustain a long plasma column in a collimated laser beam. While the possibility of serious laser-supported absorption waves had been suggested, no evidence of such waves was observed.

It was found in the Ames TELEC experiment that an ionizing pulse is helpful to initiate beam absorption in the plasma, but such a pulse is not essential. A blade type geometry for the emitter was proven suitable for the TELEC operation. The tungsten blade can maintain electrical contact with the plasma and survive the heating by laser beam at ≥ 40 kW/cm^2 without damage.

However, the data obtained with the Ames TELEC experiment was inconclusive because of a chemical reaction between the cesium vapor and the sodium chloride windows used in the test chamber. The chemical reaction caused the windows to become nearly opaque or "severely frosted." Fortunately, it was found that the 10.6 μm laser beam could be transmitted through the frosted windows despite their opaque appearance to visible light. However the beam intensity in the TELEC chamber was considerably reduced after passing through the windows. This prevented the experiment from being carried out in a controlled manner with adequate beam intensity. Electric power generated in this test corresponded to calculations for very low laser intensity and was not completely distinguishable from thermionic converter behavior.

Another experiment was performed at NASA Lewis Research Center using argon gas as the plasma medium and different geometric configuration of the electrodes.[11-13] This experiment also produced a stable laser maintained plasma in the focal region of a converging beam (~f/3 optics) of a ~6 kW CO_2 laser beam. Small amounts of electric power were delivered to an external circuit via a pointed-rod electrode opposite a concave-shaped electrode.

1.4 The Cesium TELEC Experiment at Lewis Research Center

The most recent experiment was carried out with a high power laser at LeRC using a cesium vapor TELEC cell with 30 cm active length which is long enough to absorb a sizeable fraction of the incident beam energy. This most recent experiment is the subject of this report.

The electrode configuration of the TELEC device in the present work is shown schematically in Fig. 1. The collector consists of a split nickel block with a 1 cm diameter hole drilled through its length. Two tungsten blades which function as emitters are inserted in the sides of the nickel block. The tips of the emitter blades protrude a small distance ($\lesssim$ 1 mm) into plasma produced by the laser beam. An approximately collimated beam passes down the central hole and is absorbed in a cesium vapor (~5-10 torr) plasma.

The end regions of the TELEC chamber (not shown in Fig. 1) contain an inert gas. The cesium vapor is maintained separate from the inert gas and confined to the central region by operating the chamber as a heat pipe oven[14] where recirculating cesium vapor diffusion-pumps the inert gas toward the ends and produces a sharply defined transition interface between the cesium vapor and the inert gas. In this way, cesium does not come in contact with the chamber windows; thereby eliminating the problem encountered in the previous experiment at NASA Ames.

The TELEC device was constructed at Rasor Associates and shipped to LeRC for testing in the beam of a high power CO_2 laser. This laser has a design capability of ~20 kW from single channel optics. Use of folded path optics and electron beam excitation have been projected to extend the maximum power limit to ~70 kW.[15] These power levels agree with theoretically predicted beam requirements for TELEC operation (i.e. $\gtrsim$10 kW/cm^2) if the beam can be suitably collimated in a ~1 cm diameter path.

The TELEC test chamber was mounted in the optical path of the laser at LeRC. A system of high power mirrors was used to form a beam of the desired size and direct it into the electrode space. An ionizing pulse was applied between the emitter blades at the beginning of each run to initiate a plasma and start the beam absorption. Once initated by this technique, the plasma was maintained in the central hole of the TELEC by the beam heating. Electric output from the device was measured with a circuit containing a sweeping power supply to vary the current and voltages of the electrodes.

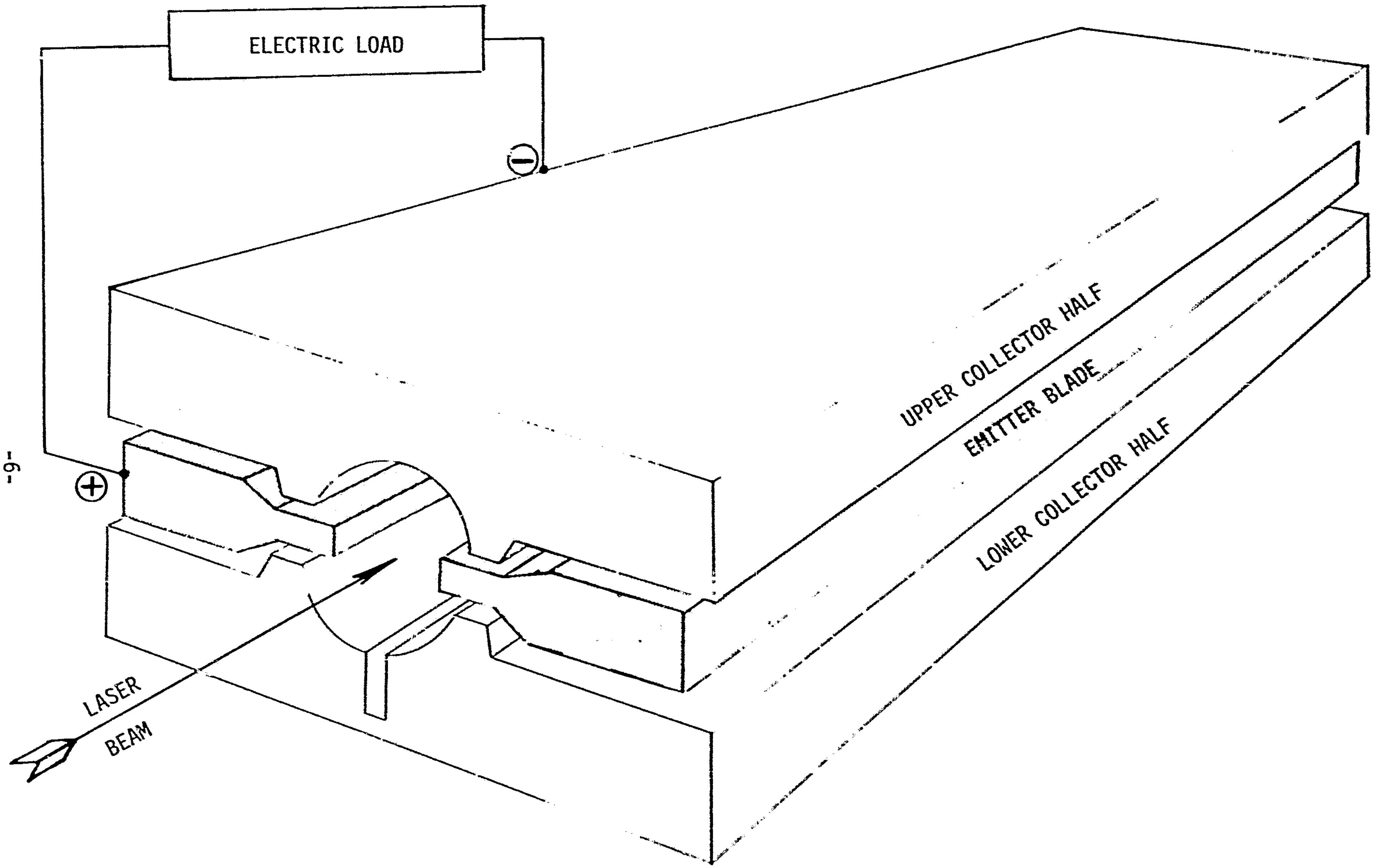

Fig. 1 Schematic Representation of the Electrodes in the LeRC TELEC Experiment.

1.5 Summary of the Results

After some difficulties with the optical setup and the laser operation, laser supported plasmas were produced in the TELEC device for approximately 8 out of 55 runs over a period of several days. (A number of runs were made to calibrate meters and characterize the laser beam.) Electric power from the TELEC was observed with currents in the range of several amperes and output potentials of less than 1 volt. The magnitudes of these electric outputs were smaller than anticipated but consistent with the low power levels of the laser during this experiment. Equipment problems limited the laser output to a maximum of ~11 of 12 kWe and the electric power producing runs occurred at laser power levels less than 10 kW. Since the power required to just sustain a cesium plasma has been calculated to be ~10 kW/cm^2, very little output power is expected at these low levels.

The TELEC chamber, consisting of a cesium-xenon gas heat pipe oven, was successful in keeping the cesium confined and away from the optical components. The cesium-xenon interface apparently tolerated heating by the concentrated laser beam and was not disrupted. This system maintained a cesium pressure of ~10 torr, with the TELEC collector section at temperatures of 750°K to 800°K for two days until an air leak terminated the testing by contaminating the cesium.

A crucial question in interpretation of the experimental results is to distinguish between small, low voltage TELEC output power and possible thermionic converter effects. If the beam impinges on the emitters and heats them to a very high temperature, some thermionic power could be produced. Although at high beam intensities the TELEC output voltages are expected to be substantially higher than thermionic voltages, the observed output voltages of less than 1 volt are comparable to thermionic outputs. However the possibility can be ruled out because thermocouples mounted in the emitter blades showed that the temperature of the emitters did not rise above 1000°K, even for laser runs as long as ~60 seconds. Emitter temperatures of ~1000°K are too low for any sizeable thermionic converter outputs. Even the possibility of a localized emitter hot spot can be discounted as most unlikely, since thermocouples were located less than 6 mm from the point of the highest heat loading (front corners of the blade tips) and these temperatures rose only ~30°K (780°K to 810°K) during operation. Thus the small electric outputs which were observed appear to truly represent the TELEC operation.

2.0 TEST VEHICLE

2.1 Electrode Design Based on Theoretical Calculations

As part of a previous contract with NASA LeRc, a theoretical study was undertaken to predict the performance of a megawatt level TELEC spacecraft system. During part of this study, the operating characteristics of a TELEC experiment at a 20 kW power level was examined by computer calculations of its performance. The purpose of these calculations was to establish the feasibility of conducting an experiment with a high power laser at LeRC. The ground rules for the TELEC experiment were that the experiment must absorb a sufficient amount of beam power to allow absorption measurements, the output should be able to unambiguously demonstrate TELEC operation, and these data should provide a measurement of the TELEC efficiency so the performance could be projected to higher power levels.

Performance calculations for a TELEC device operating with laser input power of 20 kW are shown in Fig. 2. Two lines are shown in this figure, which represent the power absorbed from the beam, and the output power generated by the TELEC device as a function of the device length. The predicted beam absorption is near 2300 watts for a 30 cm length, while the output power calculated for this device is about 300 watts. Thus, a 30 cm long TELEC experiment should be capable of absorbing approximately 10 percent of the beam power and yielding an efficiency measurement which can be scaled up.

The calculated current-voltage characteristic of the proposed TELEC device is shown in Fig. 3. Both the current density and the efficiency are plotted versus the output voltage in Fig. 3. Collector current densities of several amps/cm^2 at ~2 to 3 volts should be available as output. Calculated efficiencies of greater than 30 percent (output power divided by power absorbed from the beam) are predicted for this device, if the laser beam power can be maintained at 20 kW and concentrated into a 1 cm diameter beam path.

Based on the results of the calculations and the previous experience with the Ames experiment, it was decided to construct the electrodes for LeRC TELEC in the form of 2 horizontrally opposed tungsten blades

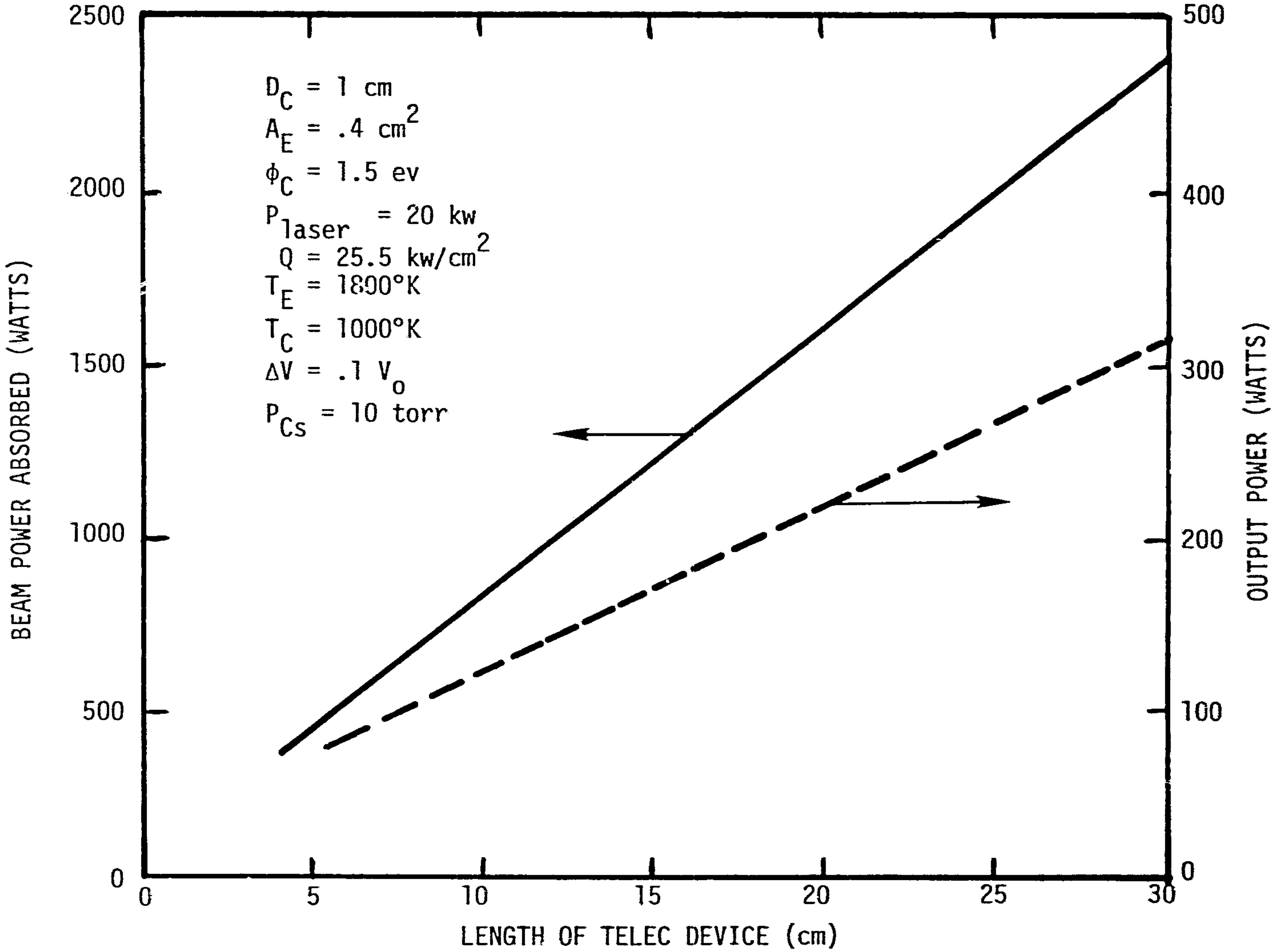

Fig. 2 Calculated Variation with Length of the Absorbed Power and Output of a Proposed Cesium TELEC Device with Eccentric Emitters. Laser input power = 20 kW.

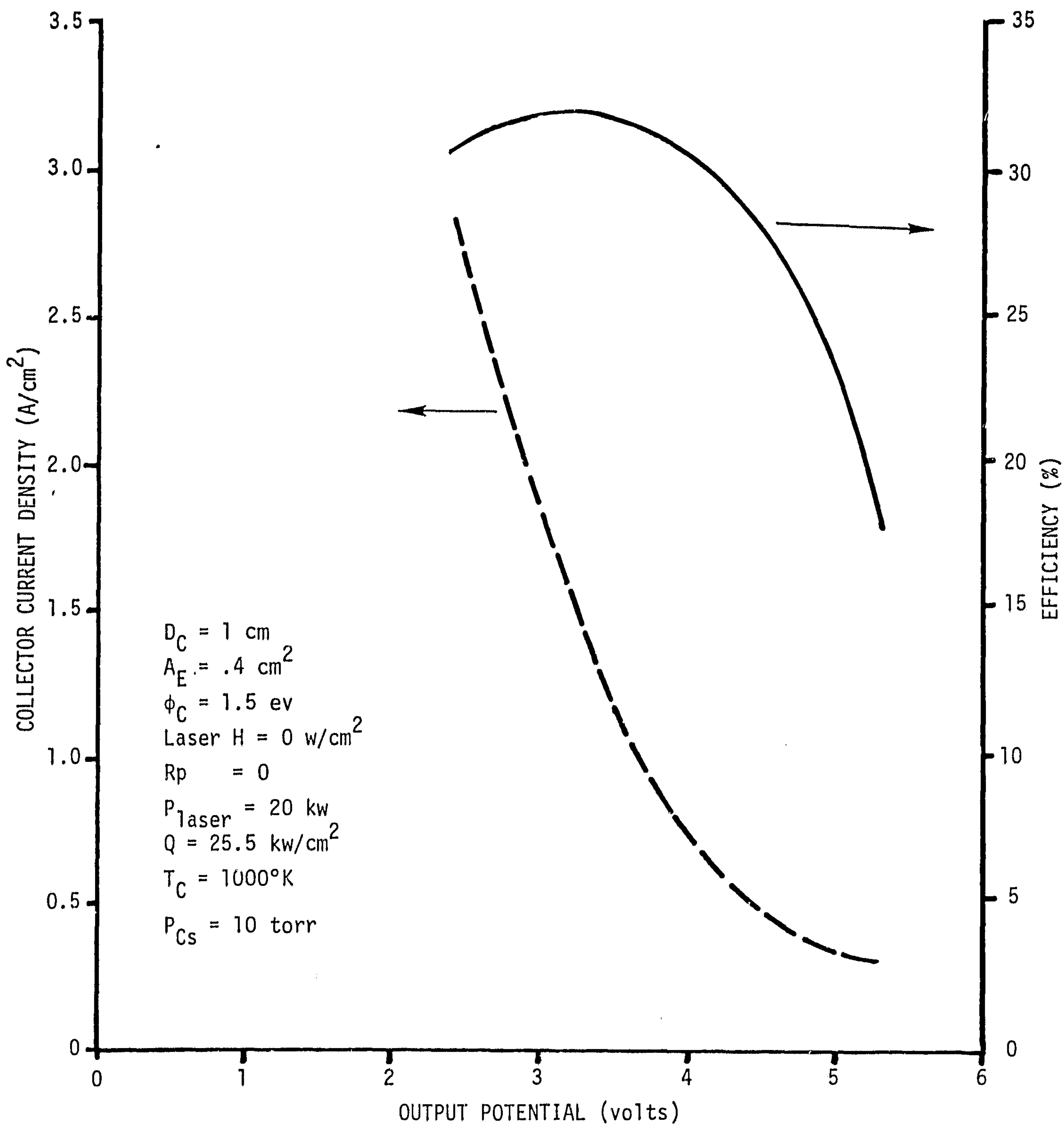

Fig. 3 Calculated Volt Ampere Curves an Efficiency of a Proposed Experimental Cesium TELEC Device with Eccentric Emitters. Laser input power = 20 kW.

(emitters) protruding into a cylindrical hole in a nickel collector. Dimensioned drawings of electrode design are shown in Figs. 4, 5, and 6. The emitter blades are 1 mm thick at their tips. The distance which the blade tips protrude into the plasma can be varied from 0 to ~1.5 mm by 4 bellows-sealed positioning mechanisms

The total exposed area of the two emitter blades (emitter area per cm of axial length) can be varied from 0.2 cm^2 at the fully retracted position to 0.8 cm^2 at full insertion of 1.5 mm. The experiments were carried out with the blades protruding a depth of 1 mm into the plasma, and under these conditions the emitter area per unit length is 0.6 cm^2. The area of the collector surface per unit length is 2.2 cm^2. This leads to a area ratio of about 3.7. The total collector area for the 30 cm long electrodes is 67 cm^2. Thus the total currents are expected to be 67 times the values of the current density shown in Fig. 3.

Detailed heat transfer calculations were carried out to verify that the emitter blades could withstand the heat loading due to beam impingement and contact with the plasma at the 20 kW level. These calculations indicated that conduction away from the beam tip into the larger section of the flat blade cross section can adequately dissipate the heat and protect the tip from melting. Further verification for this prediction came from the Ames TELEC device which also had a 1 mm thick blade electrode exposed to the plasma and the beam.

2.2 Exterior TELEC Chamber

The chamber for this experiment was arranged to act as a cesium heat pipe with two regions of inert gas at each end. A refluxing action of the cesium vapor is accomplished by evaporating the cesium in the central region of the device and condensing the vapor into a liquid in two wicks located at each end. This liquid cesium then returns via capillary action through the wick back to the center region to be evaporated once again. This refluxing motion diffusion pumps the inert gas out of the central region toward the ends. A sharp transition interface is (~1 cm thick) established between the cesium vapor and the inert gas. The cesium is adequately confined by this technique and does not escape into the end

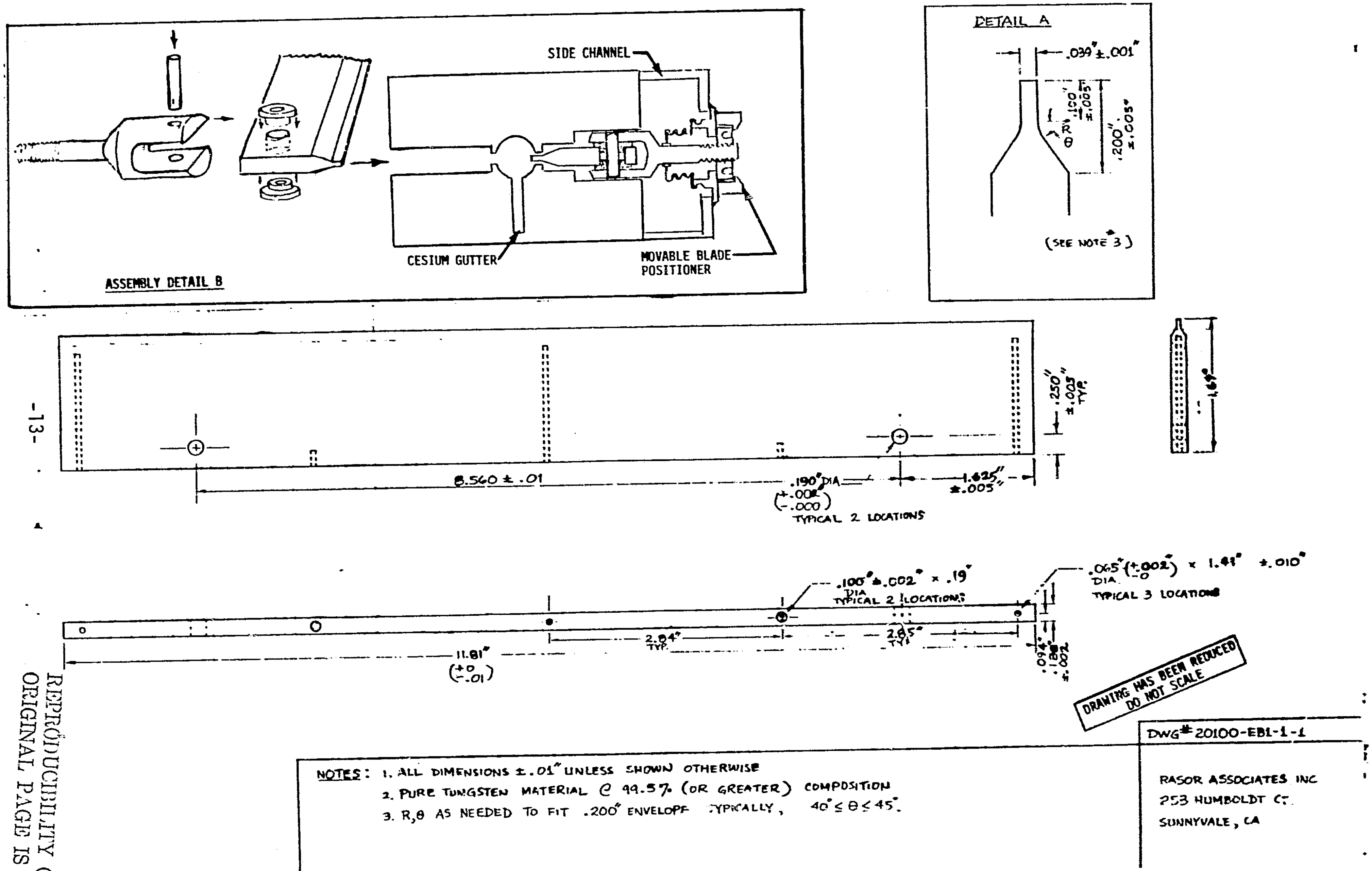

Fig. 4 Dimensioned Drawing of TELEC Tungsten Emitter Blade. Assembly detail is also shown.

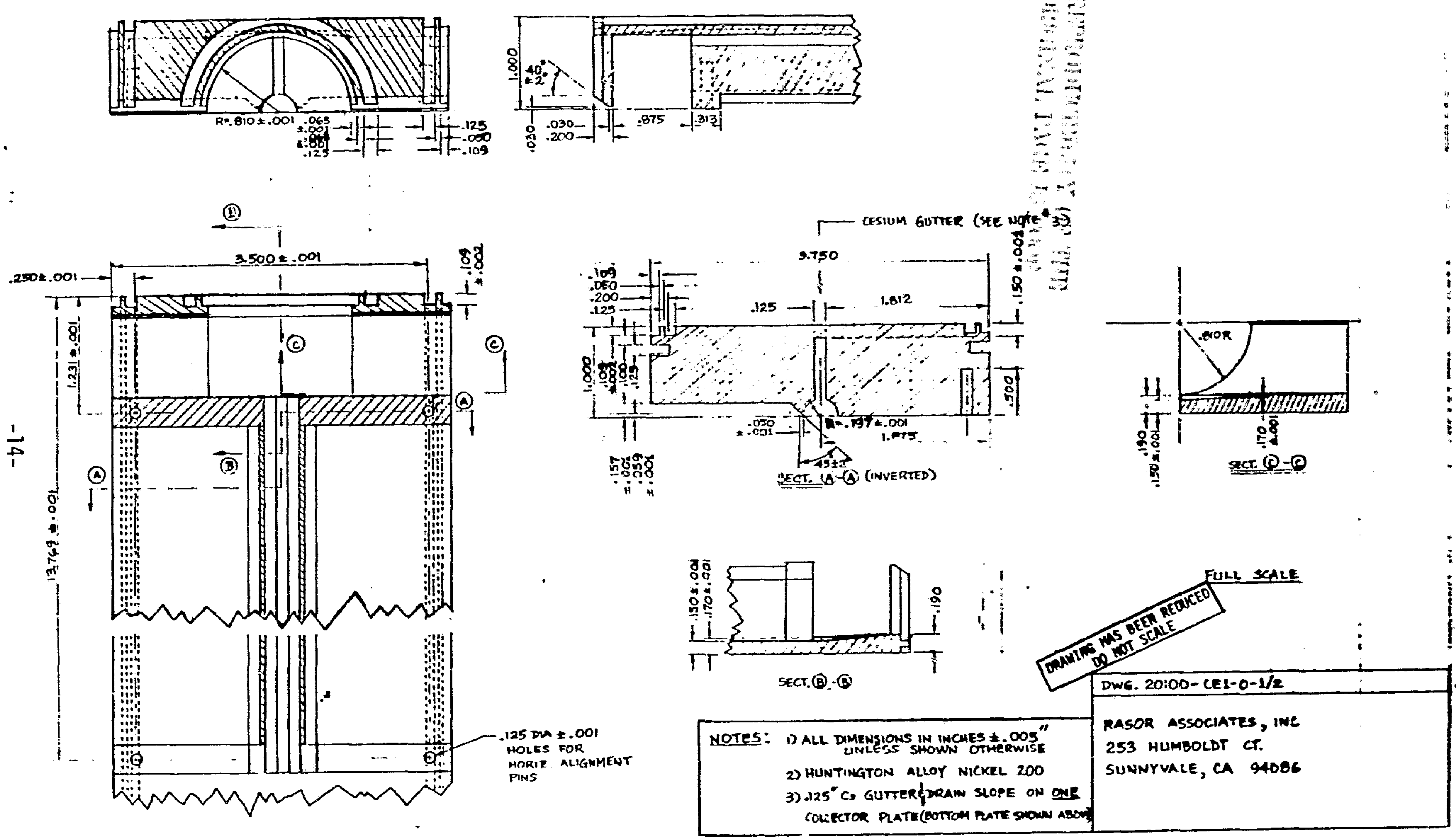

Fig. 5 Dimensioned Drawings of the Lower Half of the Split Block Nickel Collector.

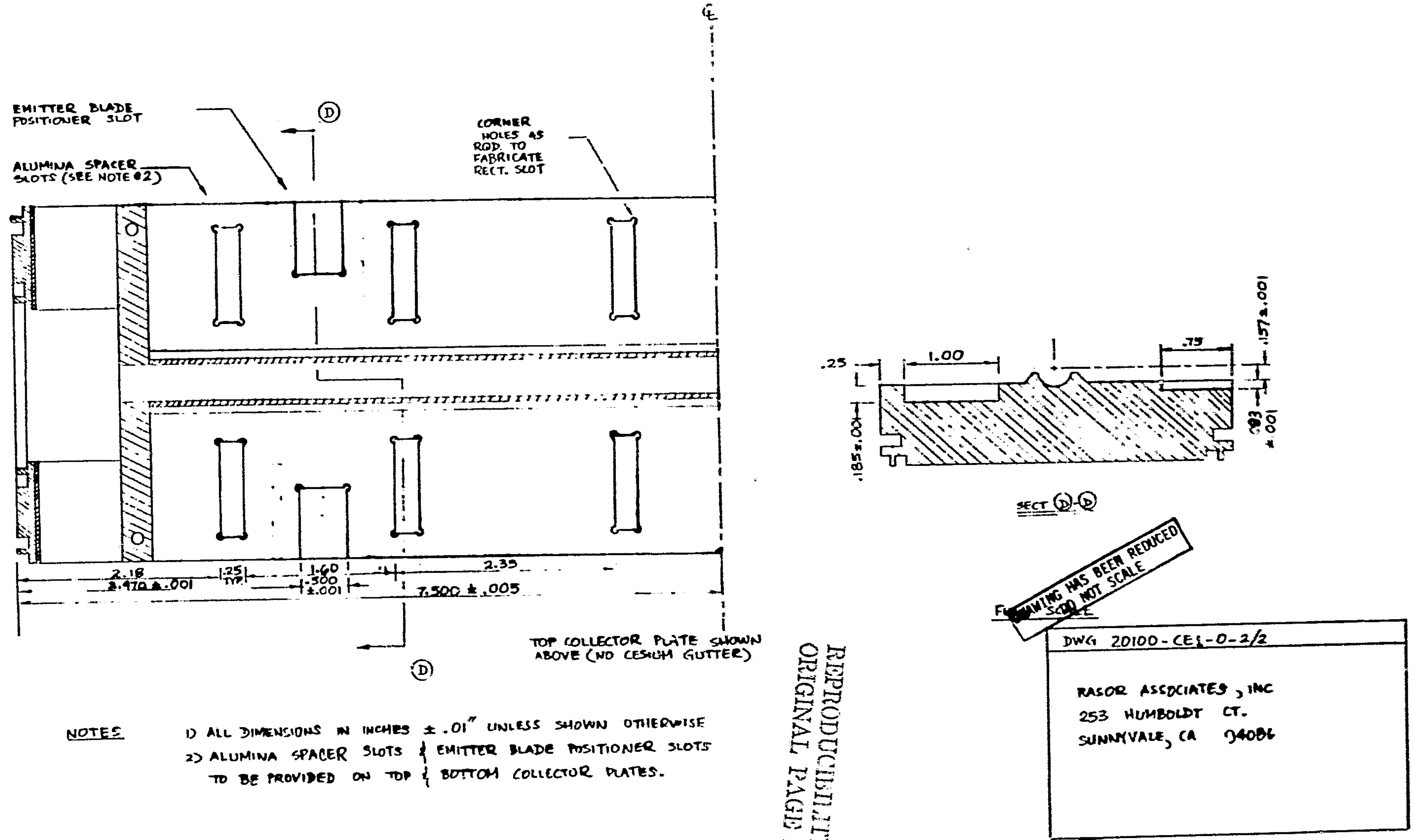

Fig. 6 Dimensioned Drawing of the Top Half of the Split Block Nickel Collector.

regions; so that windows, mirrors and other optical components can be placed in the ends without contacting any cesium vapor.

A simplified section drawing of the TELEC chamber is shown in Fig. 7; the view is from the top. Two side channels are welded onto the rectangular central section formed out of the two halves of the collector. Attached to each end of the active section in the center are short lengths of 1.5 in diameter stainless steel tubing, in which the cesium heat pipe wick is installed. This tubing section is joined via bellows to a flanged coupling which has ports for feedthroughs. The wick regions and the approximate locations of the cesium xenon interfaces are indicated in Fig. 7. Also shown in the figure are the positioning mechanisms which penetrate through the side channels to allow motion of the emitter blades. Six thermocouples (indicated by small numbered circles) are installed in the emitter blades to monitor their temperature. In addition to these thermocouples, four hot filament cesium detectors (indicated by numbered squares) are also shown. The cesium detectors measure the emission from a directly heated filament, and from this, the local cesium vapor pressure can be inferred.

All electrical connections are made in the side channel regions and then brought around the end of the collector block and down the periphery of the circular wick regions and out to feedthroughs at the ends. Two-fold redundancy of all voltage measurements and temperatures along with their electrical connections was provided in the TELEC chamber, in order to ensure reliability.

A photograph of the completed device prior to installation in the optical path is shown in Fig. 8. The central region seen in this photograph wrapped with thermal insulation is both heated and cooled in order to control its temperature and ensure the proper heat pipe action. Water is piped through the copper plumbing at the top and bottom of the collector of the TELEC. This cooling system is used in conjunction with the electric heaters wrapped around the TELEC collector to remove any waste heat dissipated by absorption of the laser beam and maintain the collector temperature at the proper level during operation. The device is mounted on a double base plate. The upper plate is movable and can be adjusted with

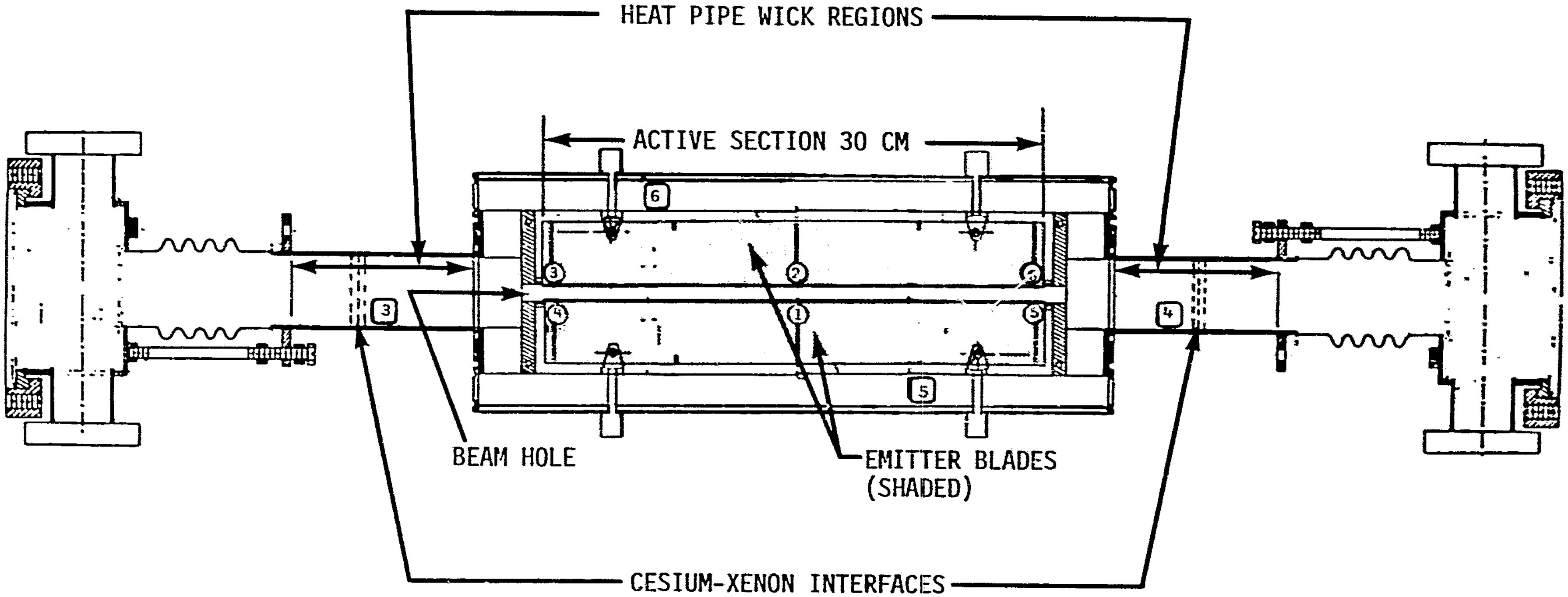

Fig. 7 Simplified Section Drawing (Top View) of TELEC Apparatus.

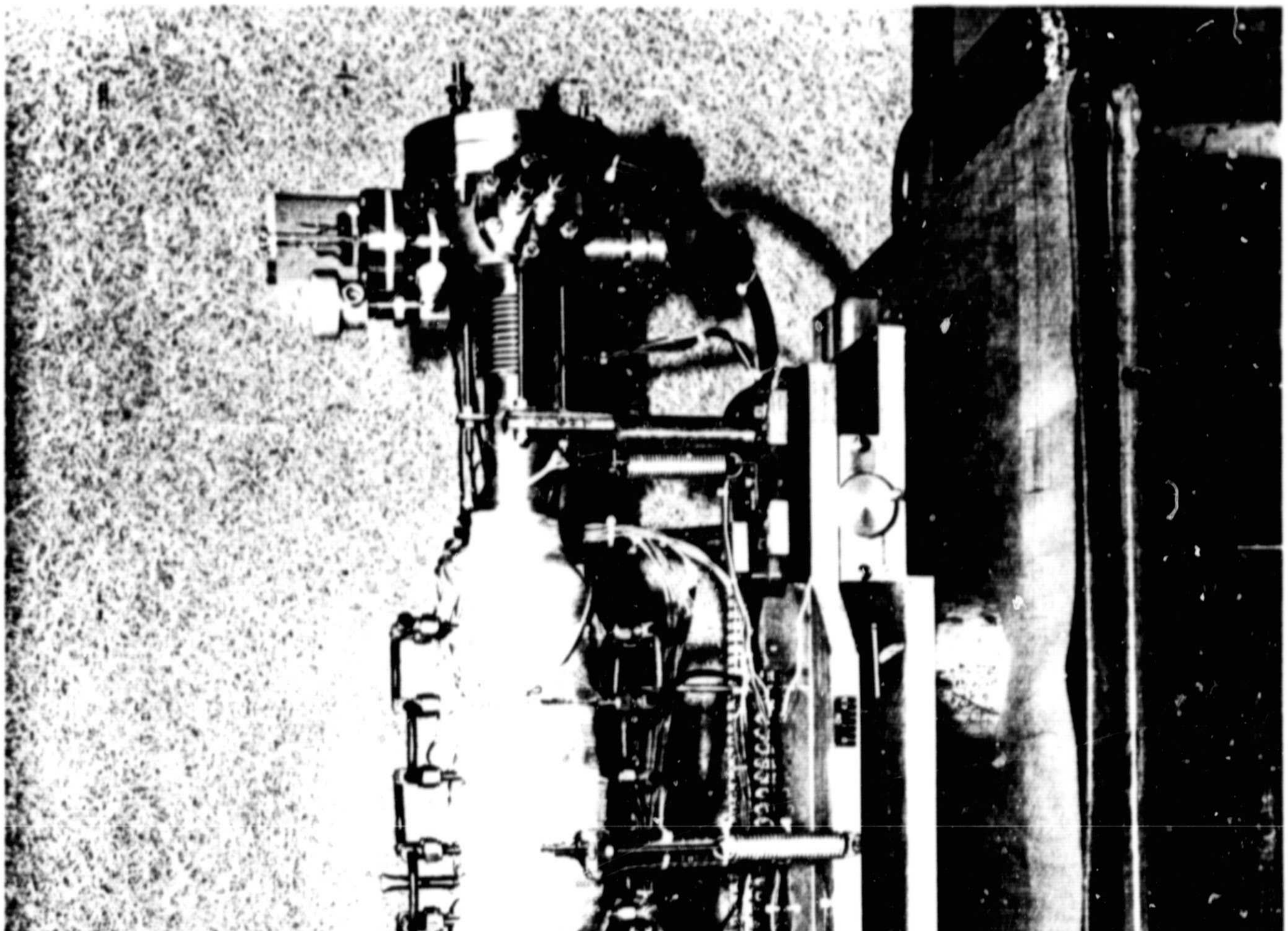

Fig. 8 Photograph of Completed TELEC Device Prior to Installation at the Laser Facility.

precision slides. In addition, the vertical height can be adjusted at each end independently. A special type of sliding suspension (ball and V-grooves with outrigger) was designed to allow thermal expansion while keeping the central portion of the TELEC device aligned with the optic axis. The two end regions seen in the figure are coupled through flexible bellows in order to allow positioning of the central region independent of the rest of the test apparatus. Approximately 40 thermocouples were also mounted on the exterior of the device to provide multiple temperature measurements and adequately determine the temperature profile during operation.

A end view of the TELEC system is shown in Fig. 9. Electric connections are brought out through conflat flange feedthroughs located at right angles to the beam. Two large high current leads, which carry the output current of the device are visible on the left of the photo. The emitter temperature thermocouples are connected to the set of feedthrough pins located at the top. Voltage probes and connections for the cesium detectors are brought out through feedthroughs located on the right side. The small air operated valve at the top left of the figure is used to control the xenon filling pressure in the inert gas region of the device. The bottom flange port has a window in it in order to view light emitted from the plasma in the active area of the electrodes. The active area of the electrodes and the beam hole are located in the central portion of the figure; but are not visible in this photograph.

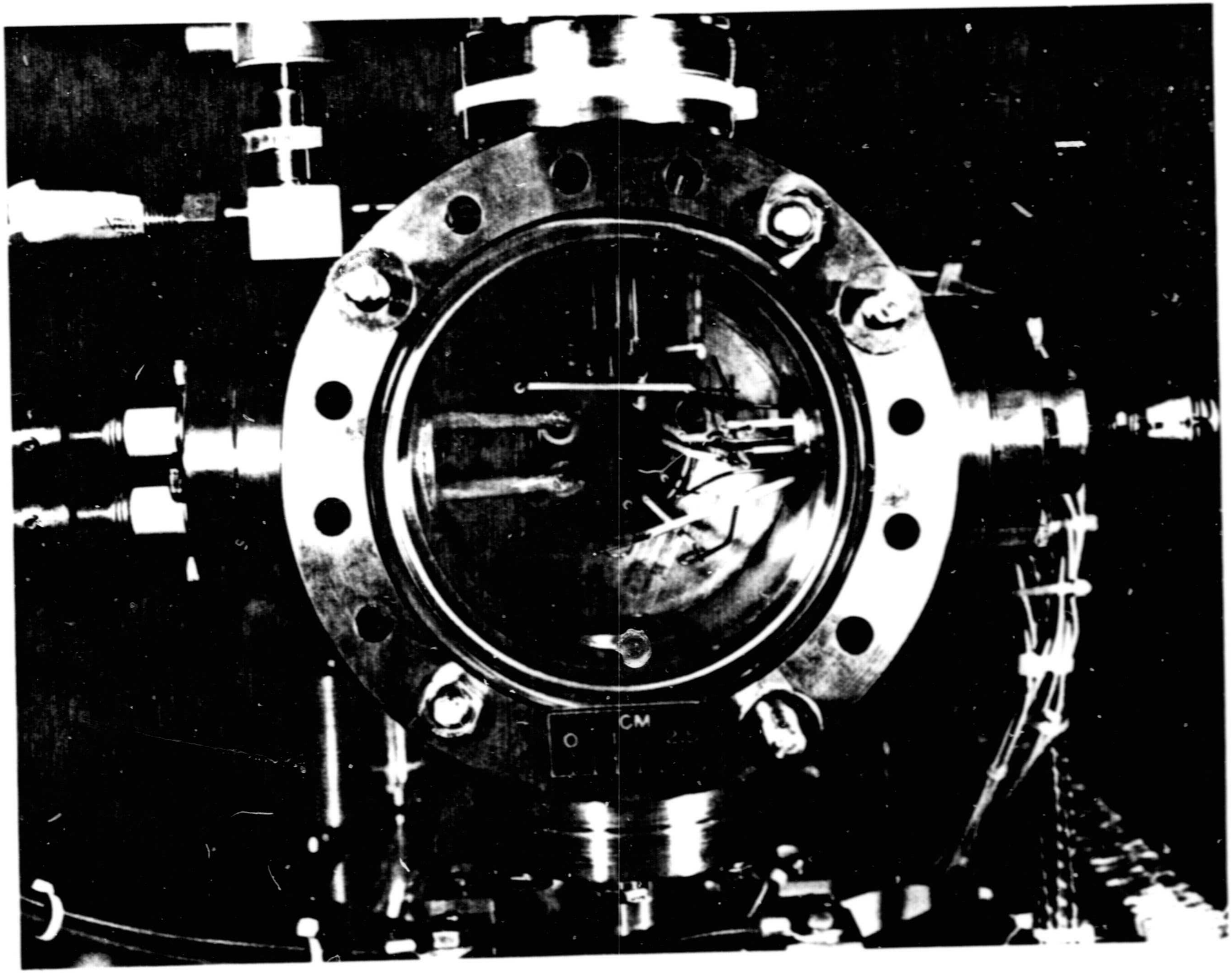

Fig. 9 Beam Entrance End View of the TELEC Device Showing Electrical Connections to Thermocouples Voltage Probes and Output Power Leads.

3.0 NASA LeRC LASER FACILITY

3.1 The High Power Laser

The laser used for this set of TELEC experiments was a high power carbon dioxide laser located at the Lewis Research Center in Cleveland. This laser has a closed cycle recirculating loop of the lasing gas mixture. Either an electric discharge from either a set of pins or an electron beam system can be used for excitation. The laser system is shown schematically in Fig. 10 (reprinted from Ref. 15). As shown in the figure, the laser gases are recirculated by a large blower through a rectangular channel, which is the active beam cavity, and then through a heat exchange system to cool the gas. The electric discharge which excites the lasing is produced by a set of pins located above the cavity as shown in Fig. 11 (reprinted from Ref. 15). Lasing at 10.6 μm is obtained with a single-pass unstable resonator cavity with mirrors located at right angles to the gas flow direction. As shown in this figure, the laser beam is extracted with a "periscope" type optical system and the beam output can be remotely steered. Either single channel optics as shown in Fig. 11 or a multi-path folded optical arrangement can be used.

With single channel optics, a laser beam output of 20 kW or less is the maximum power expected.[15] Using a multi-pass laser cavity and electron-beam excitation, the maximum power for this laser has been projected in the range of 50-70 kW. It was planned to use electron-beam excitation and a folded path cavity to produce the maximum possible power for this experiment. However there were difficulties with stability in the electron beam apparatus and the beam, which eventually required that the system be run with single channel optics and pin discharge excitation for the TELEC experiment. This limited the maximum output power to ~10 kW.

3.2 Beam Collimation

The ideal type of beam for TELEC operation is a highly concentrated parallel beam with a uniform intensity which completely fills the cross section of the central beam hole. Some preliminary consideration was given to making the central hole in the TELEC device 0.6 cm diameter or smaller in order to obtain higher concentration. However, design was

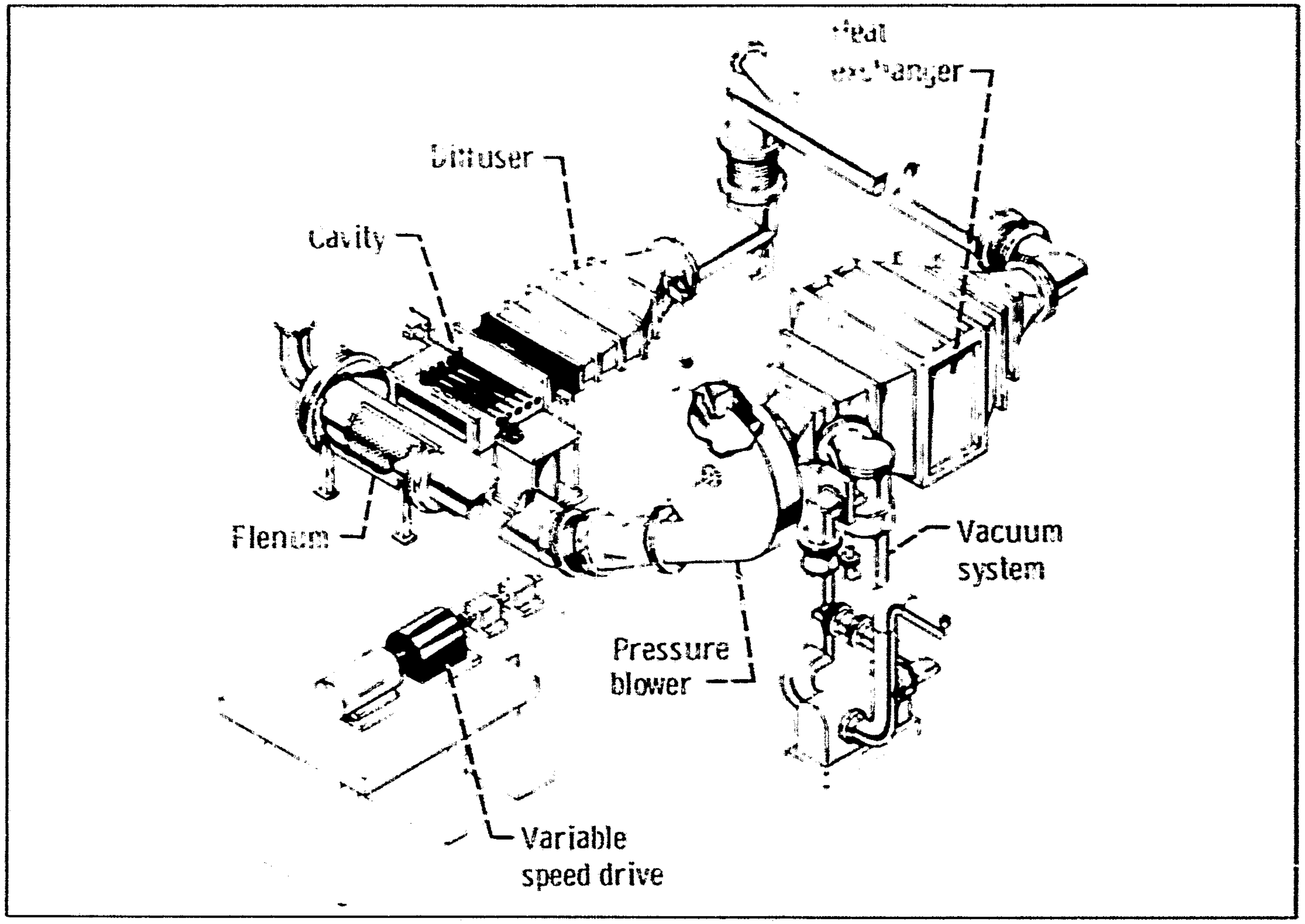

Fig. 10 Schematic Drawing of the NASA High Power Laser.

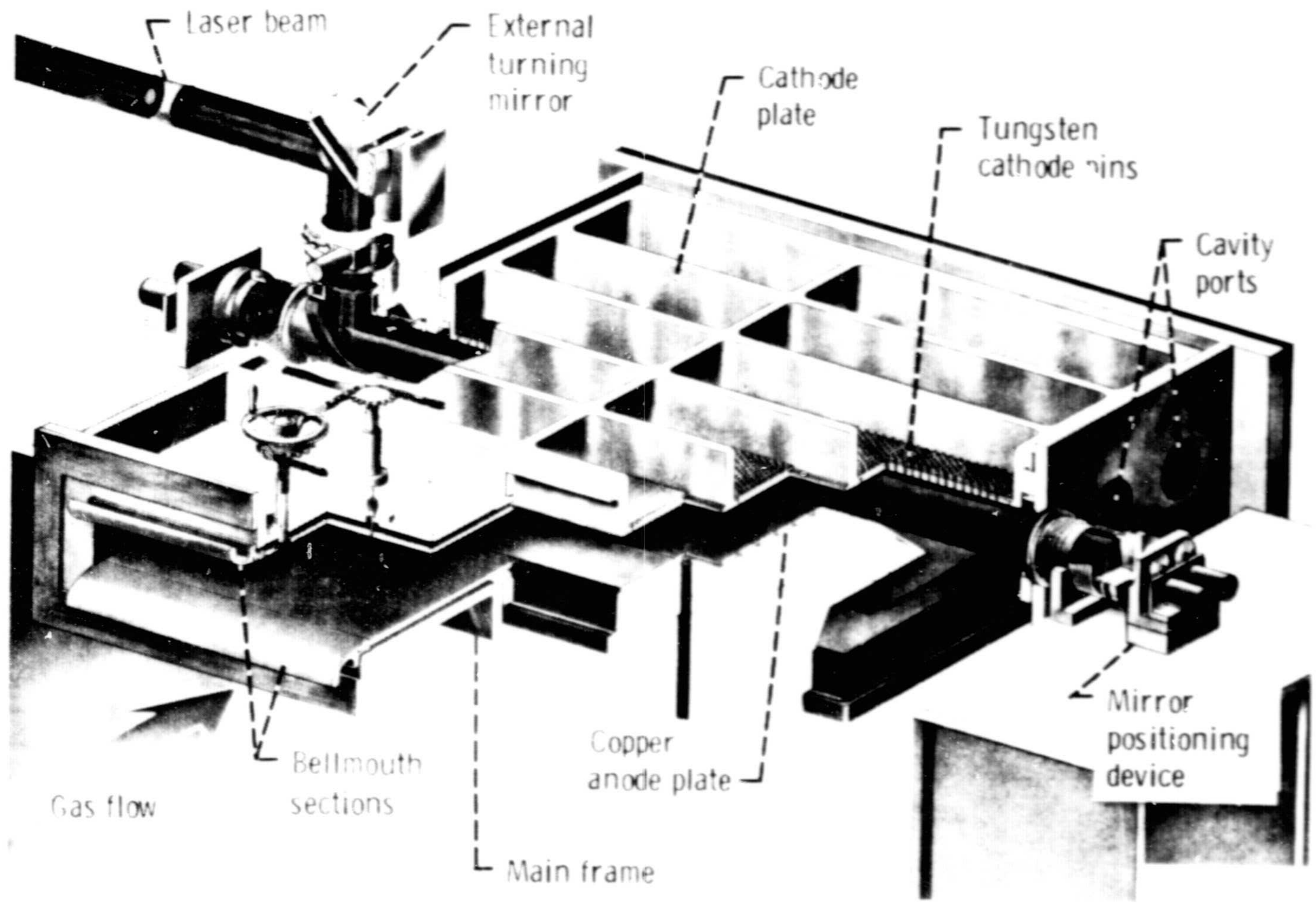

Fig. 11 NASA High Power Laser Test Cavity with Pin-to-Plane Self Sustaining Discharge.

chosen with a 1 cm diameter beam hole as a compromise between the desire for high intensity and the problems of device fabrication and precise location of the laser beam. Thus a parallel beam 1 cm in diameter is desired for this experiment.

Originally the optical system was designed with both converging and diverging mirrors to first focus the beam into a small cross section with the converging mirror, and then, using the diverging mirror, to convert the narrow beam into a parallel one. Preliminary tests using visible light (He-Ne laser) indicated that this type of optical system could produce a beam of desired shape and size. However tests with the actual 10.6 μm CO_2 laser resulted in scattering of the beam by defraction and poor beam quality. Consequently a different type of optical system using two converging mirrors replaced the converging-diverging system. The second system used two converging long focal length mirrors to produce a nearly parallel small cross section beam with a very slight angle of convergence. A polished copper plate with a 3/4" aperture hole drilled in the center was used to intercept any stray portions of the beam which might enter the device off axis and strike something other than the desired beam hole.

Burn patterns in plastic blocks were made at various positions in the TELEC section of the beam path. Photographs of these burn patterns can be seen in Figs. 12, 13, and 14. These patterns respectively represent the beam cross section at the entrance, center, and exit end of the active portion of the TELEC electrodes. As can be seen from these figures the power density is concentrated in the center of the beam, in a region ~6-8 mm in diameter. The intensity tapors off toward the edges of the beam. Almost all of the power contained in a circular cross section of 1 cm or less. Slight convergence and divergence of the beam is evident from Figs. 12 and 14 whose cross sections are slightly larger than Fig. 13 which was located near the focal point.

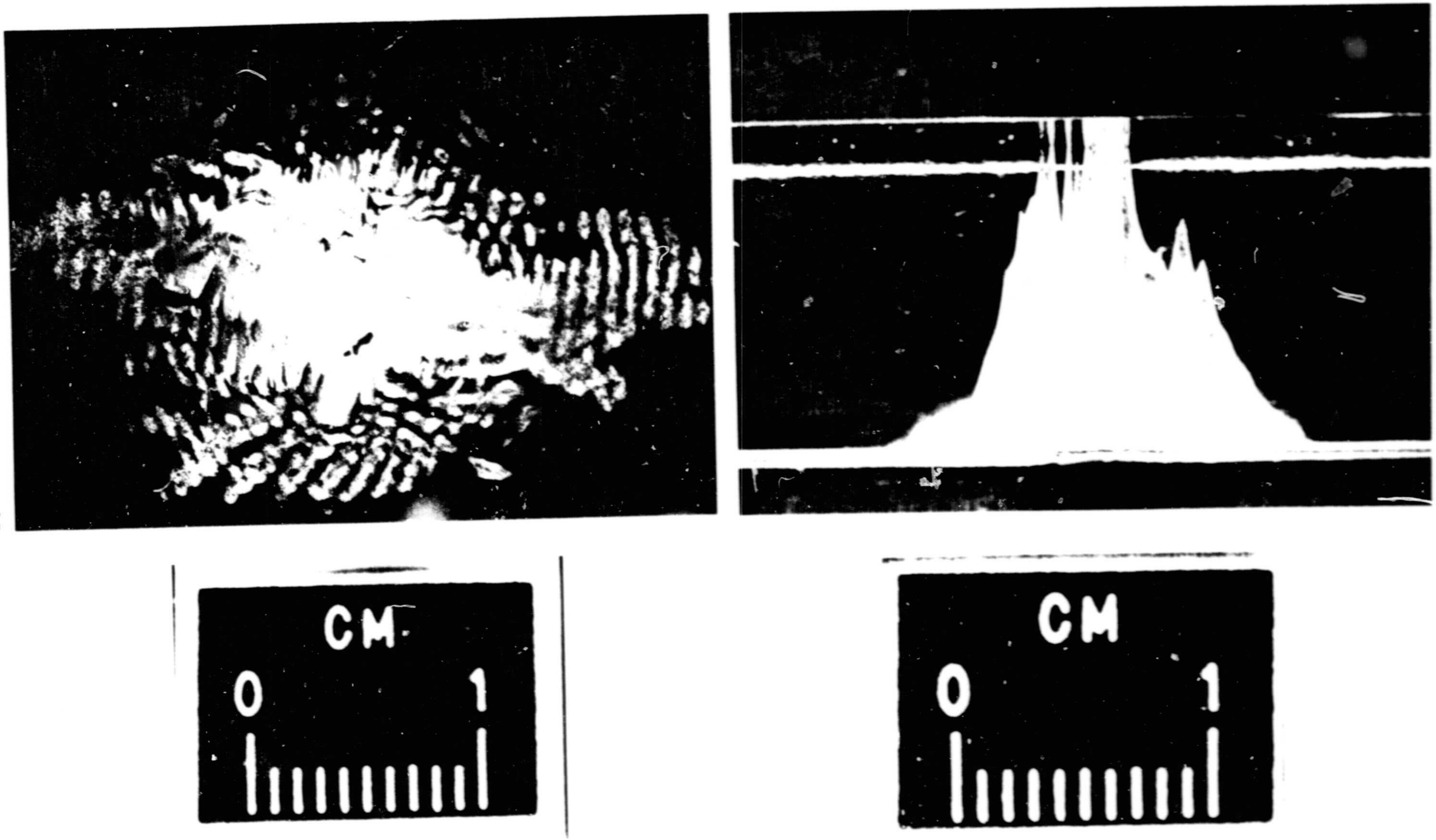

Fig. 12 Axial and Profile Views of Burn Patterns Produced by the Laser Beam Striking a Plastic Block Located Approximately in Place of the Entrance End of the TELEC Active Section.

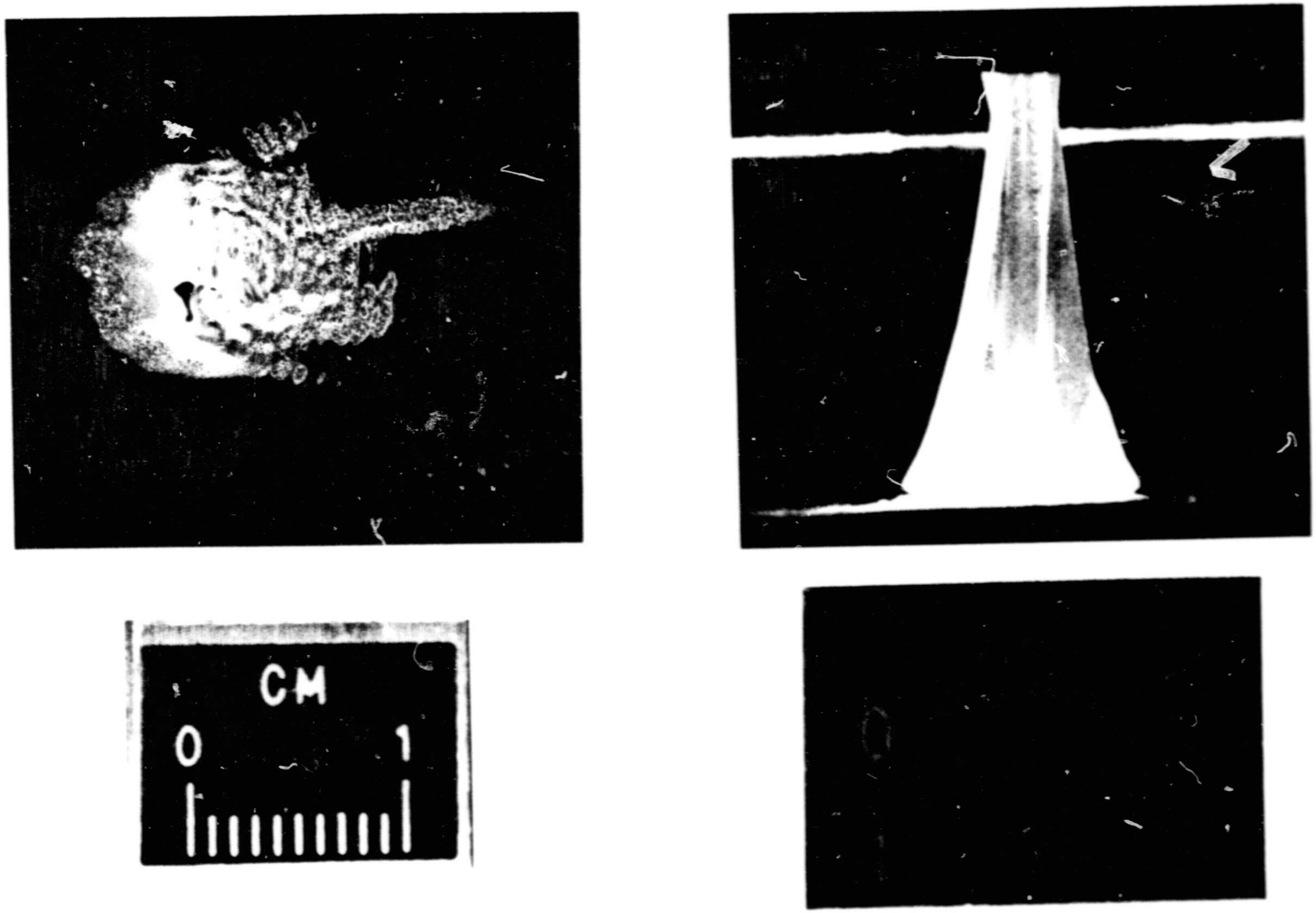

Fig. 13 Axial and Profile Views of Burn Patterns Produced by the Laser Beam Striking a Plastic Block Located Approximately in Place of the Center of the TELEC Active Section.

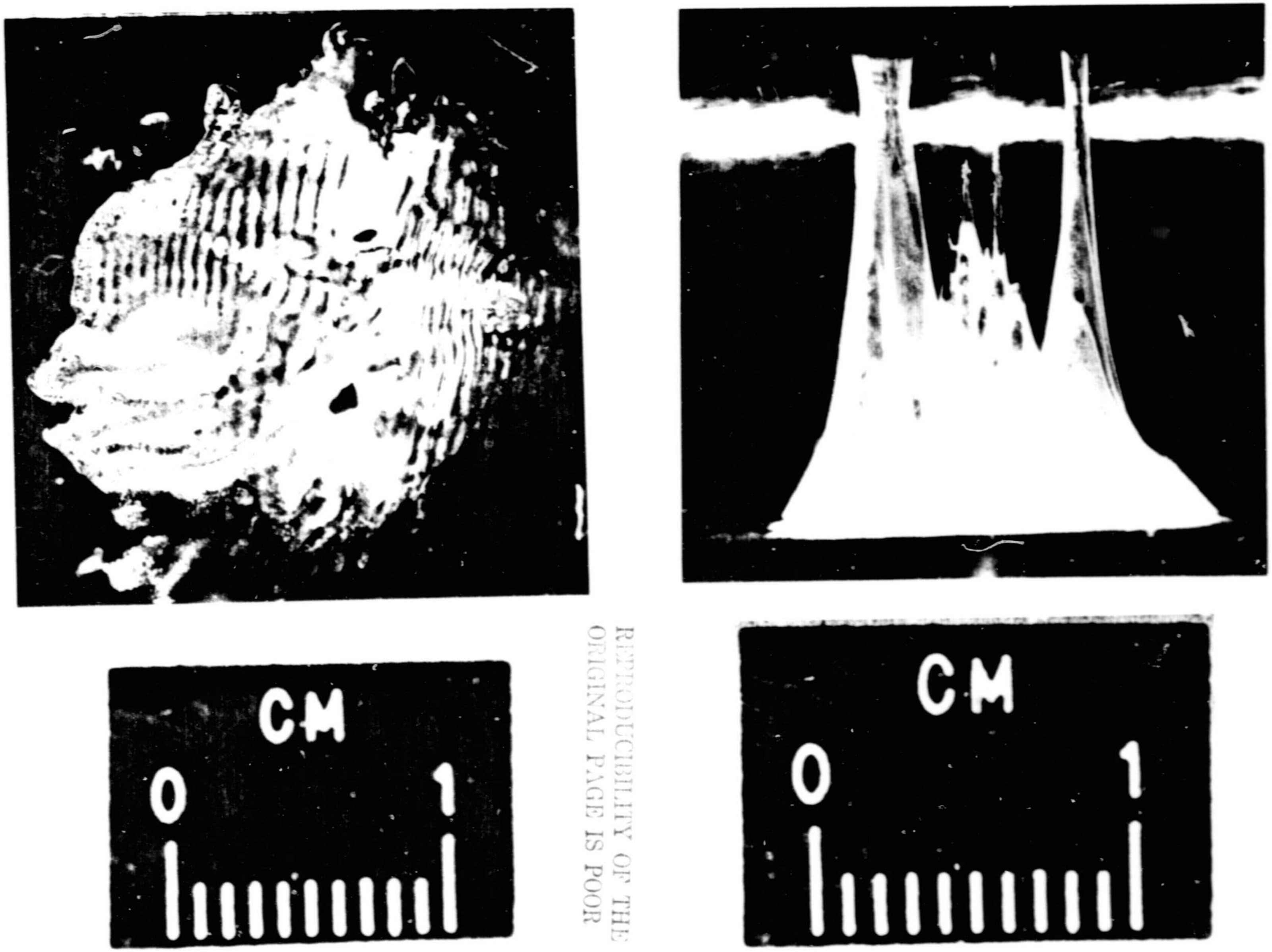

Fig. 14 Axial and Profile Views of Burn Patterns Produced by the Laser Beam Striking a Plastic Block Located Approximately in Place of the Exit End of the TELEC Active Section.

4.0 EXPERIMENTAL TESTS

4.1 Experimental Setup

4.1.1 Beam Alignment

The TELEC device was installed in the optical path of the NASA laser with an apparatus setup as shown in Fig. 15. As shown in the figure, the incident laser beam is reflected from an externally mounted mirror into a closed chamber through a zinc-selenide window. Following this, the beam strikes a second mirror and is directed off axis through the TELEC device along its length. After passing through the TELEC unit, the beam is reflected a third time from an internally mounted mirror and exits through the zinc-selenide window at the end of the closed chamber. The space in the two end chambers, which contain the mirrors, is filled with xenon gas. This is kept separate from the cesium vapor in the central TELEC section by the heat pipe interface as described earlier. All three of the mirrors can be adjusted by slight angular tilting to direct beam into a desired path.

Alignment of the device was accomplished by first setting up a small helium-neon laser on the same optical path as the large CO_2 laser. Then this small laser was used to align the device by propagating a beam through the entire apparatus and setting up reticle targets at the entrance and exit windows. The cross hairs in the surveyor's transit were aligned with the axis of the optical path. Next, white light was used to illuminate the apparatus through the target on the entrance window. The location of the TELEC electrodes was then viewed by surveyor's transit through the exit window and compared with the location to the reticle target. This could be used as a reference to adjust the position of the TELEC center section until the beam hole was properly aligned with the optic axis.

A photograph of the TELEC unit installed with the laser apparatus is shown in Fig. 16. One of the entrance windows for the laser beam is visible at the right hand side of Fig. 16. The lower base plate of the TELEC unit was bolted solidly to an optical table. The upper base plate, which is moveable with precision positioners, was then adjusted to locate the electrodes along the beam axis.

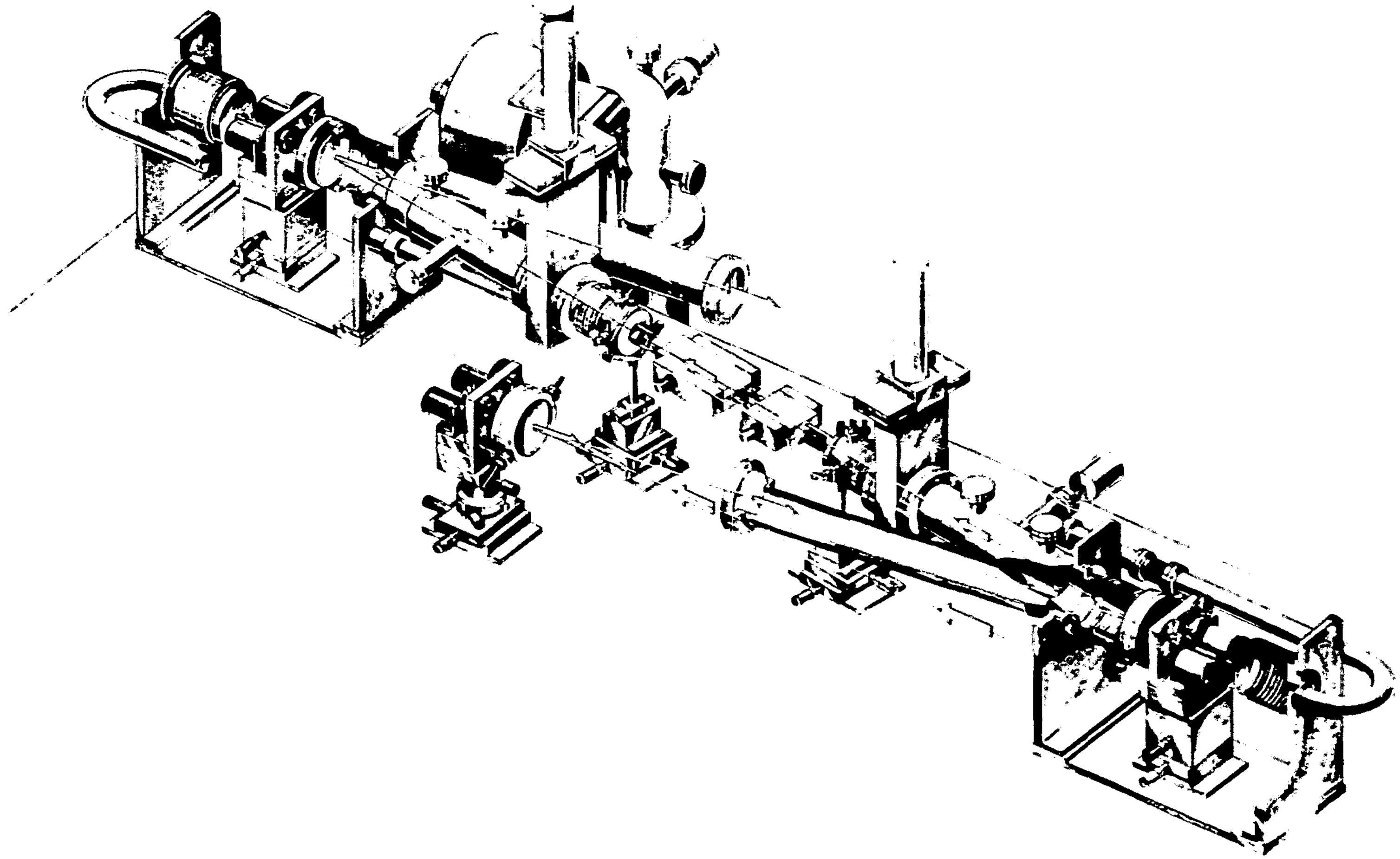

Fig. 15 Drawing of the Optical Setup used to Produce a Narrow Laser Beam and Direct it through the TELEC Apparatus. The TELEC active section is coupled between two inert gas filled end chambers which have high power laser mirrors at each end. There are zinc selenide windows on the ends of oblique mounted tubes which permit the laser beam to enter and exit the test apparatus.

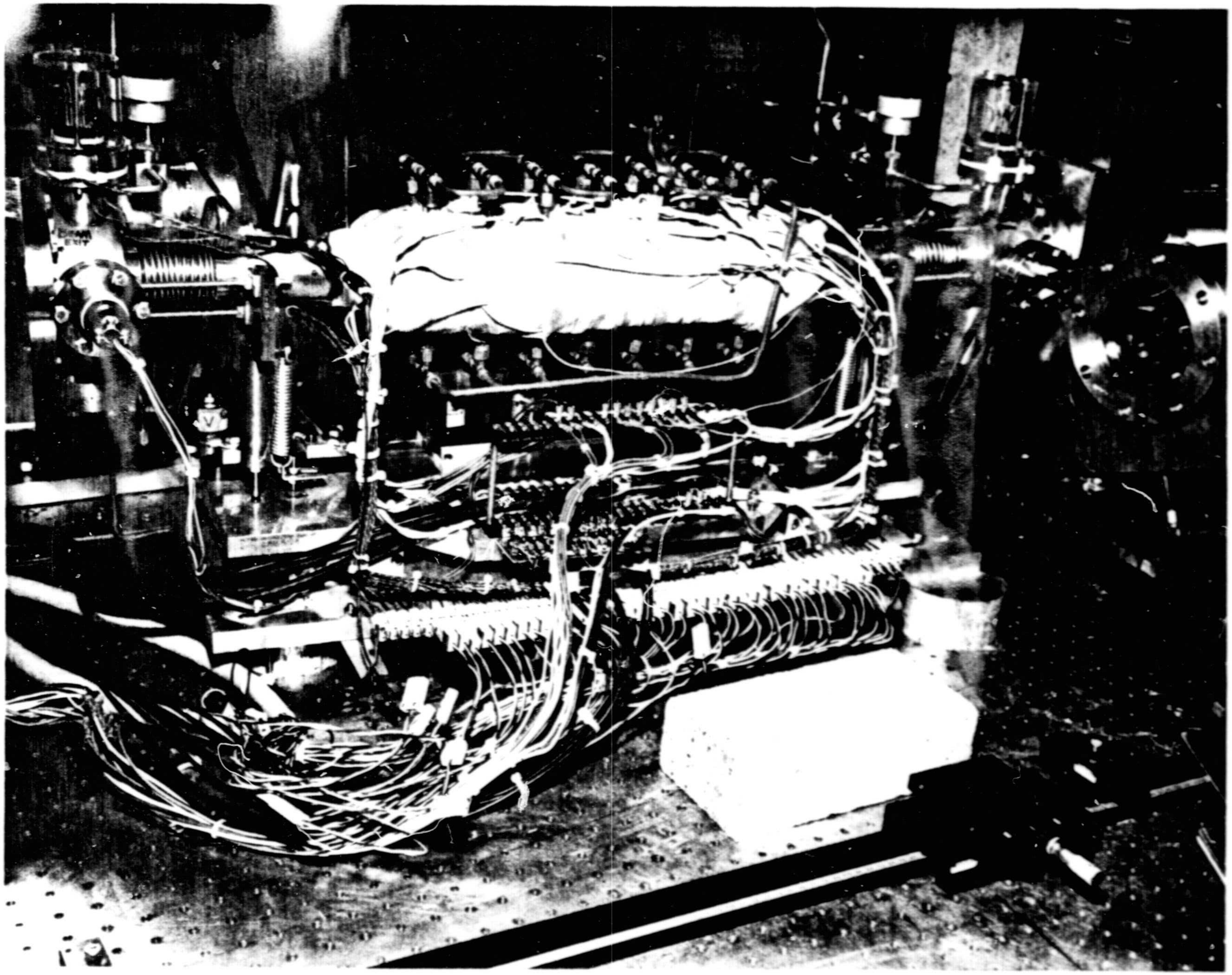

Fig. 16 Photograph of the TELEC Unit Installed with the Optical Setup at the Laser Facility. The beam entrance window is visible at the right hand side of the picture.

4.1.2 Cesium Filling

The TELEC unit was not filled with cesium prior to its shipment. The necessary cesium metal was shipped separately and the TELEC device was filled after it had been installed at the laser site. Special procedures were necessary to accomplish the filling, since cesium chemically reacts on contact with air. The filling was accomplished by pressurizing the TELEC apparatus with an inert gas at slightly above atmospheric pressure. Then a syringe filled with liquid cesium was inserted through a small fill tube, located at the top center of the TELEC. A predetermined charge of cesium was injected into the apparatus from the syringe, while maintaining an outflow of argon gas to prevent any air from entering the apparatus. After the cesium had been inserted, the syringe was withdrawn and the small fill tube was then welded closed to seal the unit.

4.1.3 Electrical Circuit

The TELEC electrodes have three separate potentials. The upper and lower collector halves (welded together) comprise one potential, which is at the circuit ground. Each of the two emitter blades is at a separate potential from the collector. The electrical circuit used in the test setup is shown in Fig. 17. Voltage probes and current measuring shunts are provided for each of the emitter blades as well as the collector. A sweep power supply was used to drive the potential of the emitter blades through the volt-ampere curve. The power supplies is coupled to the emitter blades by a center tapped 600 μh inductor. This power supply produces a triangular type of sweep wave-form whose base width is 25 milliseconds. The sweep begins with the two emitter blades biased positive relative to the collector. Then they are driven through 0 into negative voltages as the current is increased.

In addition, a high power pulse generator is connected across the two emitter blades to initiate the plasma by a 100 μs pulse discharge. This pulse necessitates the presence of the inductor in the circuit. The inductor provides high frequency isolation between the two emitter blades so the pulse is not shorted out and thus is forced to strike an arc in the plasma.

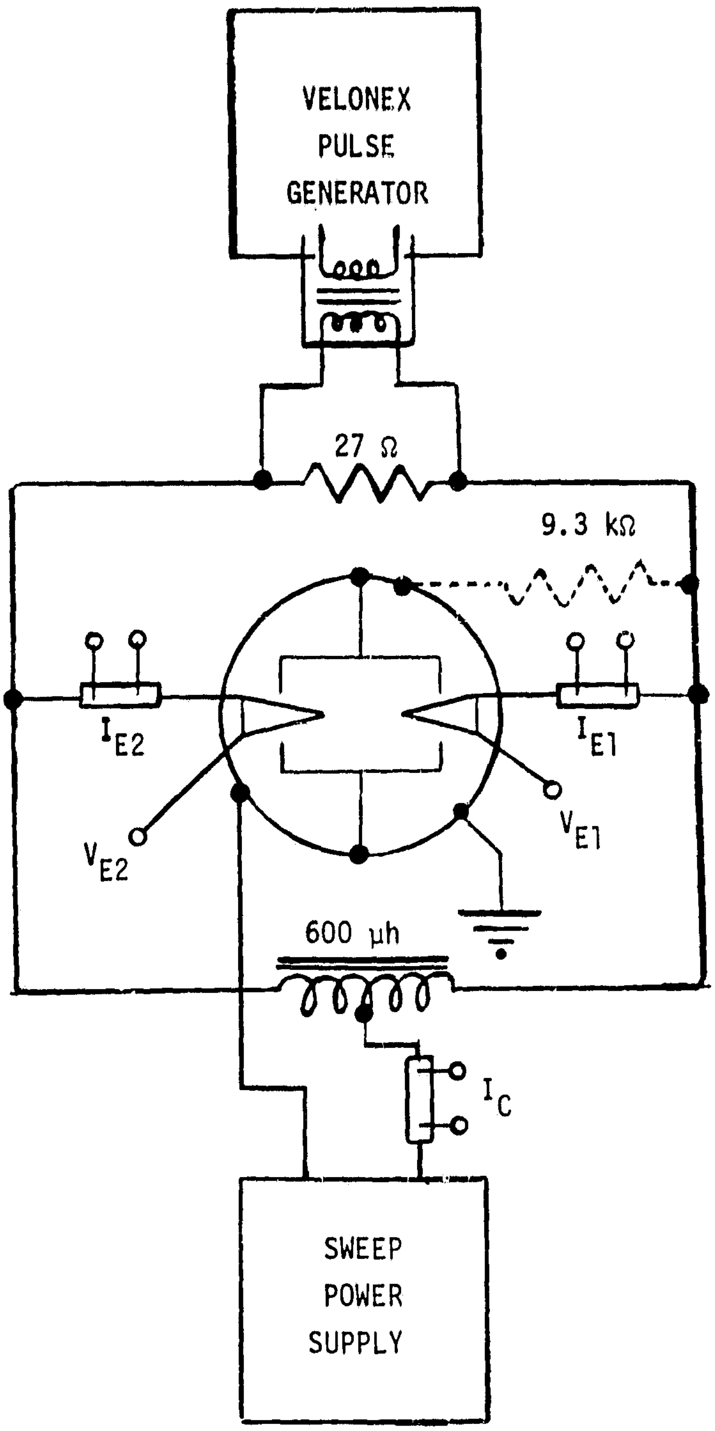

Fig. 17 Electrical Circuit Schematic Used for the TELEC Tests at LeRC.

The 27 Ω resistor shown in Fig. 17 is a dummy load connected across the pulse generator to prevent extreme voltage transients. The 9.3 kΩ resistor (shown as a dotted line in Fig. 17) represents imperfect isolation between emitter No. 1 and the ground.

The center tapped inductor was intended to provide as little interference with the sweep wave-form as possible. If balanced currents flow from the two emitter blades, the magnetic fields generated in the inductor cancel each other and the inductor offers no impedance to sweep power supply. Under these conditions the voltage wave-form remains in phase with the current. Preliminary tests with approximately balanced emitter currents showed it to be very effective in this regard. However in retrospect it did not perform exactly as anticipated. This is because the laser produced plasma caused unbalanced currents from the emitter during operation. In most of the runs, nearly all of the current came from only one emitter blade and this caused phase shifts as well as voltage differences between the two emitter blades.

4.1.4 Instrumentation

During each run, current signals from both of the emitter shunts as well as the collector shunt were monitored. The potentials of each of the blades were also separately recorded. These data were recorded on magnetic tape for later play-back analysis. Play-back of the tape, through a Biomation digital wave-form recorder connected to an X-Y plotter, permitted the wave-form of each individual sweep to be displayed. Cuing marks were recorded on the tape identified each sweep cycle. Other data which indicates the laser power level entering and exiting from the TELEC device was also recorded on the tape. Beam power measurements were obtained by monitoring the signals from small thermal power meters which intercepted portions of the laser output split off from the main beam. A large water cooled calorimeter was used to measure the beam power at the beginning of each run prior to transmitting the beam into the TELEC device.

Besides the magnetic tape system a computerized data acquisition system known as "ESCORT" was available in the laser test facility. The ESCORT system is not a continuous real time system; but rather it is a data logging system for simultaneously recording a large number of parameters at a given instant. ESCORT was used to record all information regarding the laser operating parameters and all of the TELEC temperatures. The readings of all thermocouples on the outside of the TELEC unit and five thermocouples in the emitter blades were monitored and stored in the ESCORT data bank. The gas pressures in the chamber and the signals from cesium detectors were also recorded by the ESCORT system. The information stored by the ESCORT system provides a permanent record of many operating parameters for each run.

4.2 Test Protocol

Testing of the TELEC device with the Lewis high power laser was carried out with the following procedures. At the beginning of each run, the laser was brought up to power slowly over a period of about 20 to 30 seconds. During the start-up sequence, the beam was not directed in the TELEC system. Instead it was reflected from a polished copper shutter plate into the water cooled beam calorimeter. This allowed the laser power at the beginning of each run to be established with some precision. When the desired power level had been achieved, the shutter was dropped admitting the beam into the TELEC electrode system. The pulse generator was manually fired at this point to initiate the plasma and start the beam absorption. The magnetic tape recorder and the sweep power supply were automatically sequenced into operation at the beginning of the run. Repetitive sweeps, spaced about 1 second apart, continued throughout the duration of the entire run. Current and voltage data as well as instantaneous readings from the beam spliter power meters were recorded during all of this time.

Three days of testing with the NASA high power laser were carried out with the TELEC device. Thirteen runs were made on the first day 26 July, 1978. On the second day, July 27, eight more runs were conducted. The last five runs, were made on July 28, making a total of 25 runs in all. A laser supported plasma was obtained during seven of these runs. The first five runs or so, were used to establish the conditions of the laser beam. During these first runs, burn patterns were made in the front of the first laser mirror and/or at the end of the laser of the TELEC exit section in order to establish that the beam propagated completely through the device.

4.3 Test Results

Volt ampere curves were obtained on the seventh, eigth, tenth, twelth, and sixteenth runs. Although current was conducted through the plasma in each of the aforementioned runs, electric power output was observed only during the seventh run. Some data taken during the seventh run will be presented to show an example of the type of information obtained. Current and voltage signals on the sweep cycle just before the laser beam was admitted to the TELEC cell are shown in Figs. 18 and 19. The designation of Cue = 2 for these figures means that it is the second I-V sweep which was recorded on the magnetic tape for that run. Since the laser has not yet entered the TELEC active section no current is observed, even though the voltage is varied through its full amplitude sweep. This data is presented just to provide a zero reference, and verify that no current is conducted without laser input.

One second later at Cue = 3 the laser beam had entered the TELEC active section, when the beam shutter was dropped. The beam power for that run was ~8 kW. The data taken on this I-V sweep are shown in Figs. 20, 21, and 22. Three signal traces versus time are plotted in Fig. 20. The upper trace in the Fig. 20 represents the current signal for emitter No. 1; the center trace is the current signal from the collector shunt, and the lower trace is the emitter No. 1 voltage signal. A similiar set of curves is shown in Fig. 21, with the only difference being, that the upper trace in this figure represents the current from the emitter No. 2. Comparison of Figs. 20 and 21 shows

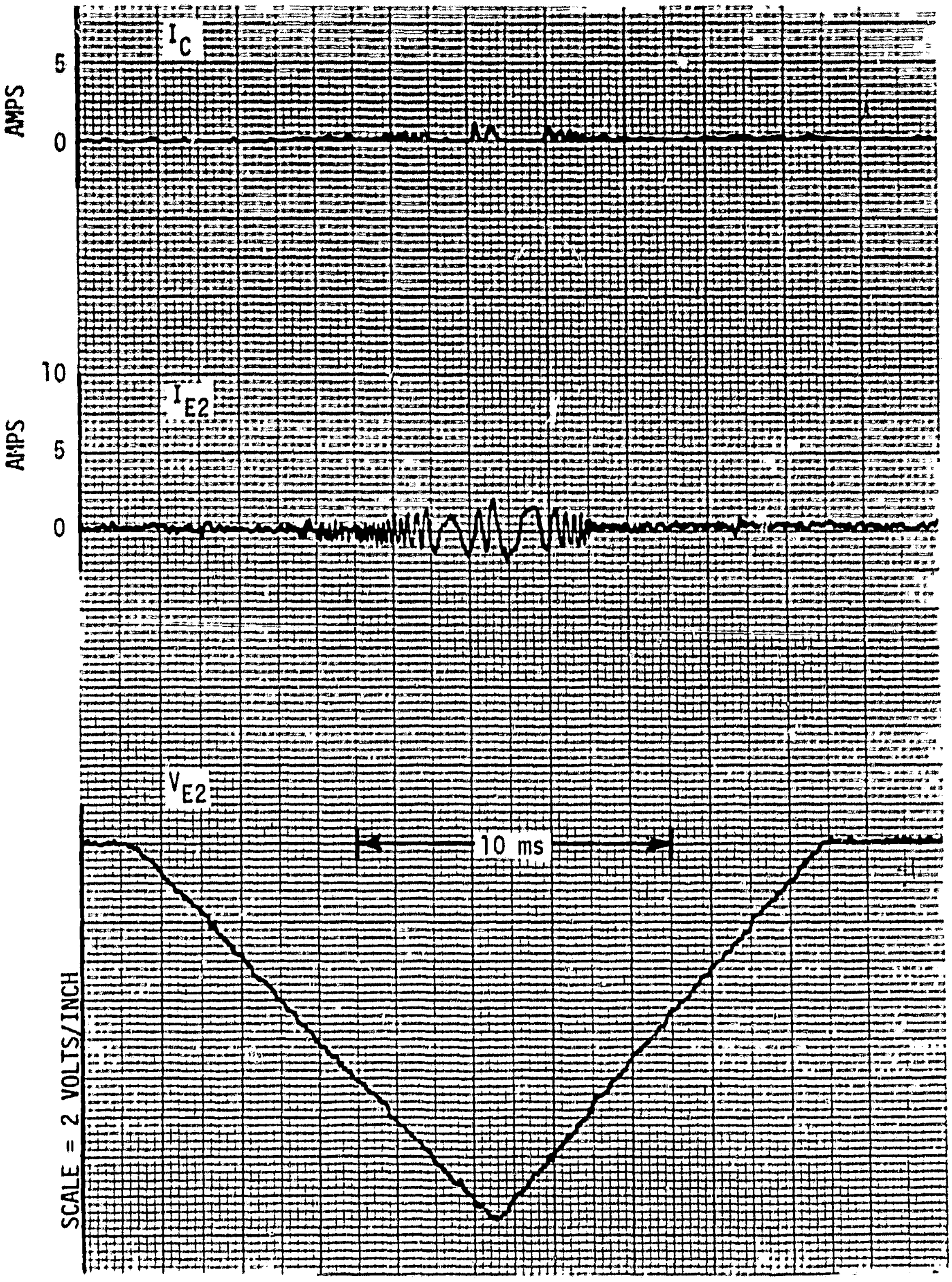

Fig. 18 Time Variation of the Currents from the TELEC Emitter Blades (Upper Two Traces) and their Voltage (Lowest Trace). Data was obtained at Cue = 2 on the 7th un. No laser input. Cs pressure = 10.5 torr.

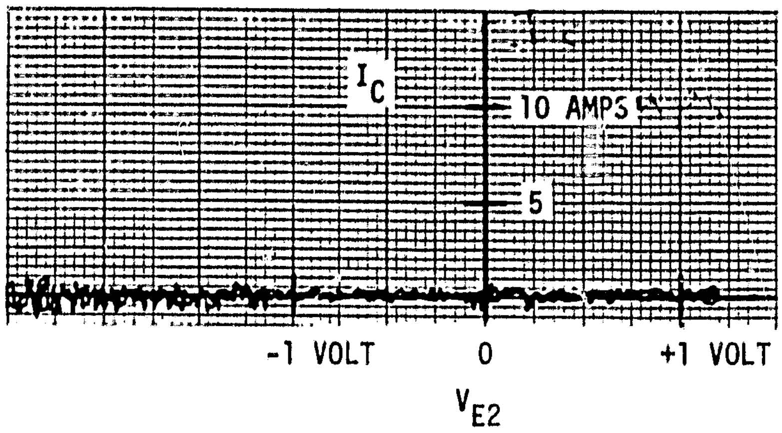

Fig. 19a Current vs Voltage Plot for TELEC Emitter No. 1.

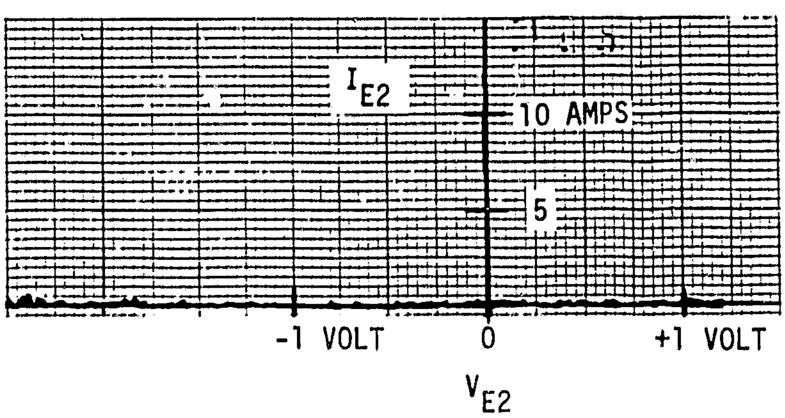

Fig. 19b Current vs Voltage Plot for TELEC Emitter No. 2

Data was Obtained at Cue = 2 on the 7th run. No laser input. Cs pressure = 10.5 torr.

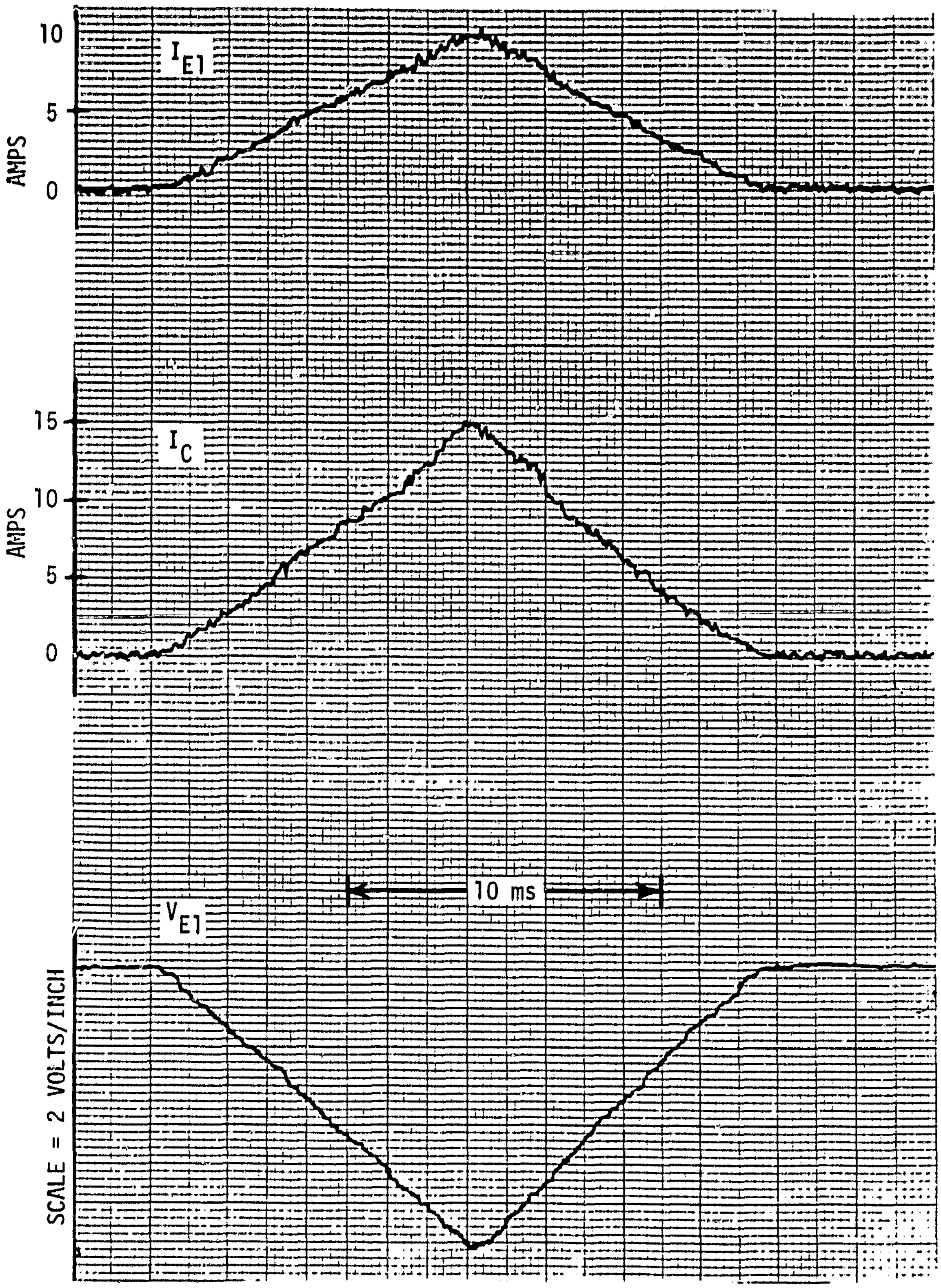

Fig. 20 Time Variation of the Currents from Emitter Blade No. 1, and the Collector (Upper Two Traces) and the Voltage of Emitter No. 1 (Lowest Trace). Data was obtained at Cue = 3 on the 7th run. Laser beam plower ~8 kW. Cs pressure = 10.5 torr.

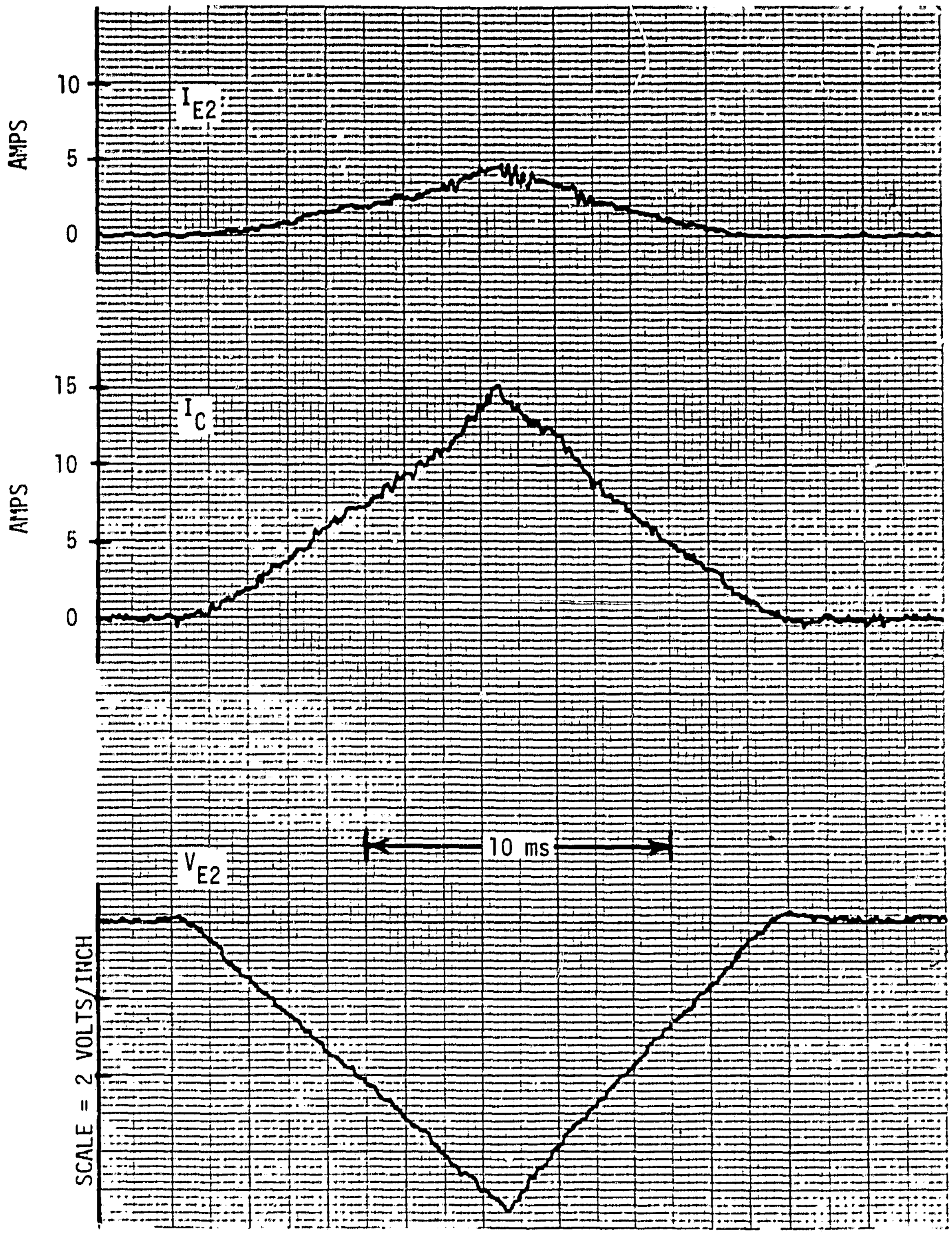

Fig. 21 Time Variation of the Currents from Emitter Blade No. 2, and the Collector (Upper Two Traces) and the Voltage of Emitter No. 2 (Lowest Trace). Data was obtained at Cue = 3 on the 7th run. Laser beam power ~8 kW. Cs pressure = 10.5 torr.

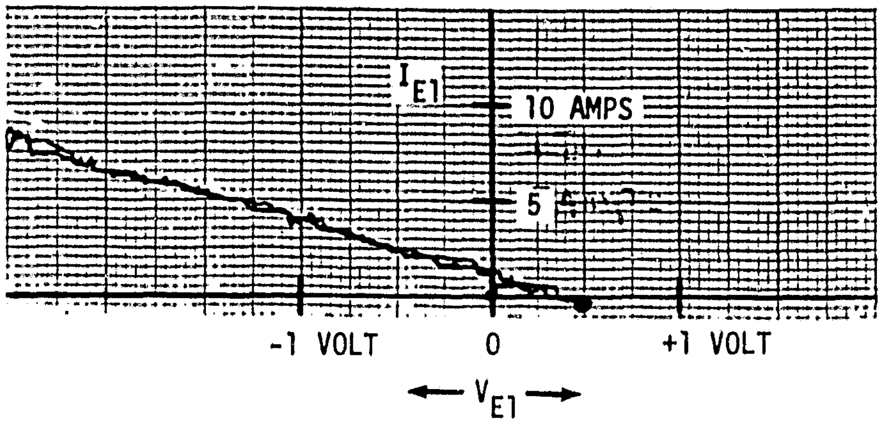

Fig. 22a Current vs Voltage Plot for TELEC Emitter No. 1.

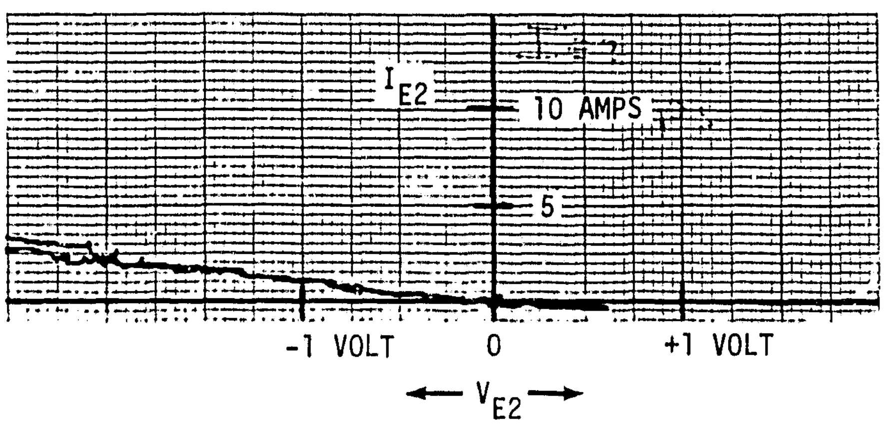

Fig. 22b Current vs Voltage Plot for TELEC Emitter No. 2.

Data was obtained at Cue = 3 on the 7th run. laser beam power ~8 kW. Cs pressure = 10.5 torr.

that nearly all of the current was coming from emitter No. 1. Note that the horizontal portion of the voltage trace does not represent 0 volts. At the onset of the I-V sweep, the power supply biases the TELEC cell so the emitters are positive with respect to the collector. Thus the horizontal portion of the voltage trace represents a voltage level on the emitters of ~0.5 to 0.7 volts. In Fig. 22 the currents from each of the two emitter blades are plotted versus their respective voltage. These I-V curves show that a small amount of output power was obtained from emitter No. 1, but no current in the power quadrant was obtained from emitter No. 2.

Another set of data corresponding to Cue = 10, where the I-V sweep occurred 7 seconds later, is shown in Figs. 23, 24, and 25. As in the previous data, Fig. 23 shows the time behavior of the signal from emitter No. 1 as well as the total current. Fig. 24 shows the data for emitter No. 2. Fig. 25 shows the I-V curves for the two emitters. This time a relatively large amount of current is obtained from emitter No. 1 and again nothing is obtained from the emitter No. 2. This amount of output power obtained on this sweep cycle is about as much as was obtained on any of the runs. Comparison of data for Cue = 3 (just after the laser was admitted) with the data for Cue = 10 (7 seconds later) shows that the plasma and current were formed immediately and changed very little for a period of at least 7 seconds. This is an indication of the degree of stability in the laser beam and the conditions in the TELEC cell.

Some 3 seconds later during run No. 7, the output power of the laser apparently was slightly reduced. This was manifested by a change in the current signals obtained in the TELEC cell. Data from the I-V sweep taken at Cue = 13 are shown in Figs. 26, 27, and 28. The format of these figures is the same as previous ones. The main noteable feature is that in this case even though the current amplitudes are still large, Fig. 28 shows that no current is produced in the power quadrant. Thus although a conducting plasma continues to exist, there is no output power produced. The actual change in the laser power between Cue = 10 and Cue = 13 is not large; but the disappearance of any electric output verifies that these tests were conducted very close to the threshold value of laser intensity for plasma maintenance.

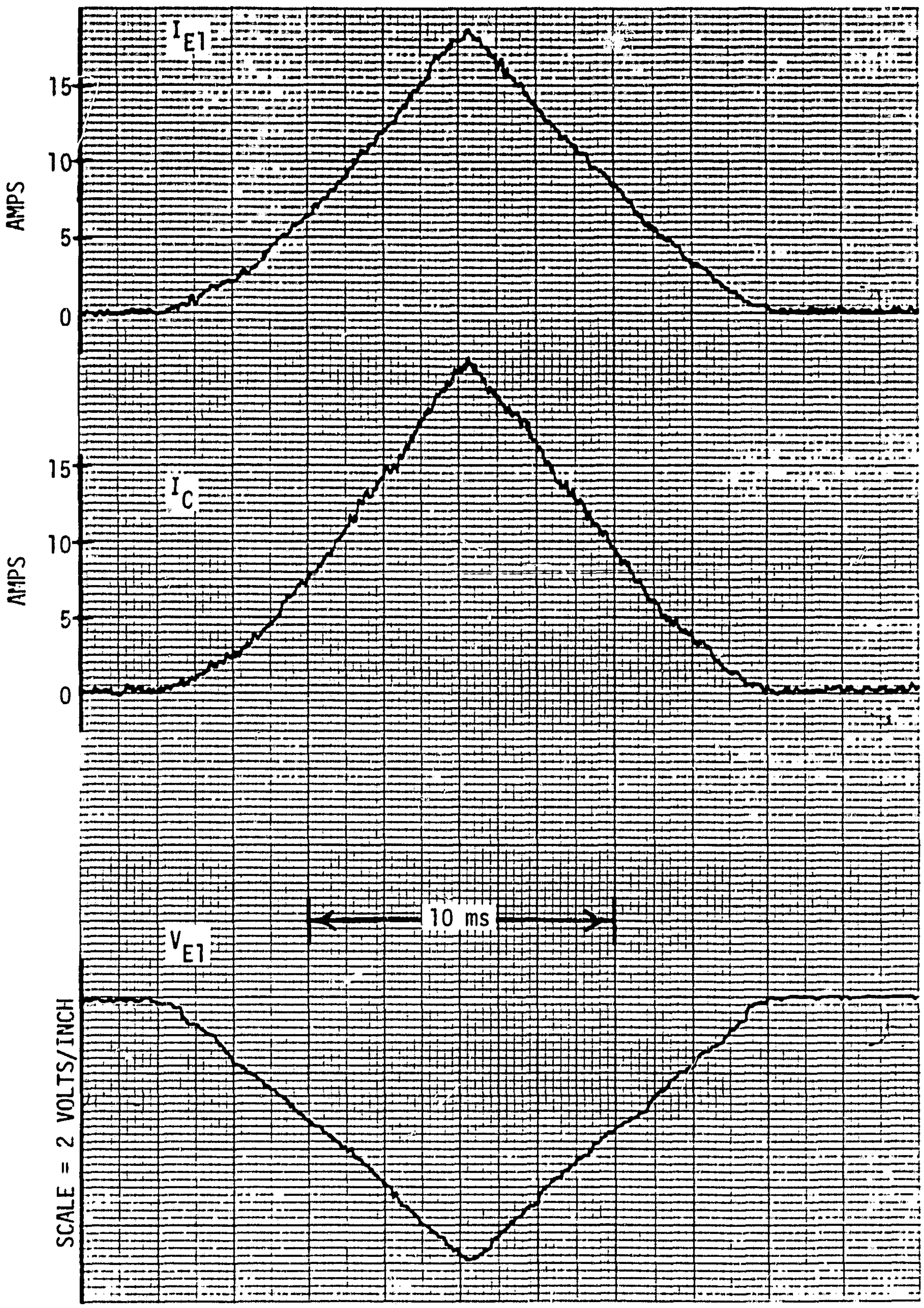

Fig. 23 Time Variation of the Currents from Emitter Blade No. 1, and the Collector (Upper Two Traces) and the Voltage of Emitter No. 1 (Lowest Trace). Data was obtained at Cue = 10 on the 7th Run. Laser beam power ~8 kW. Cs Pressure = 10.5 torr.

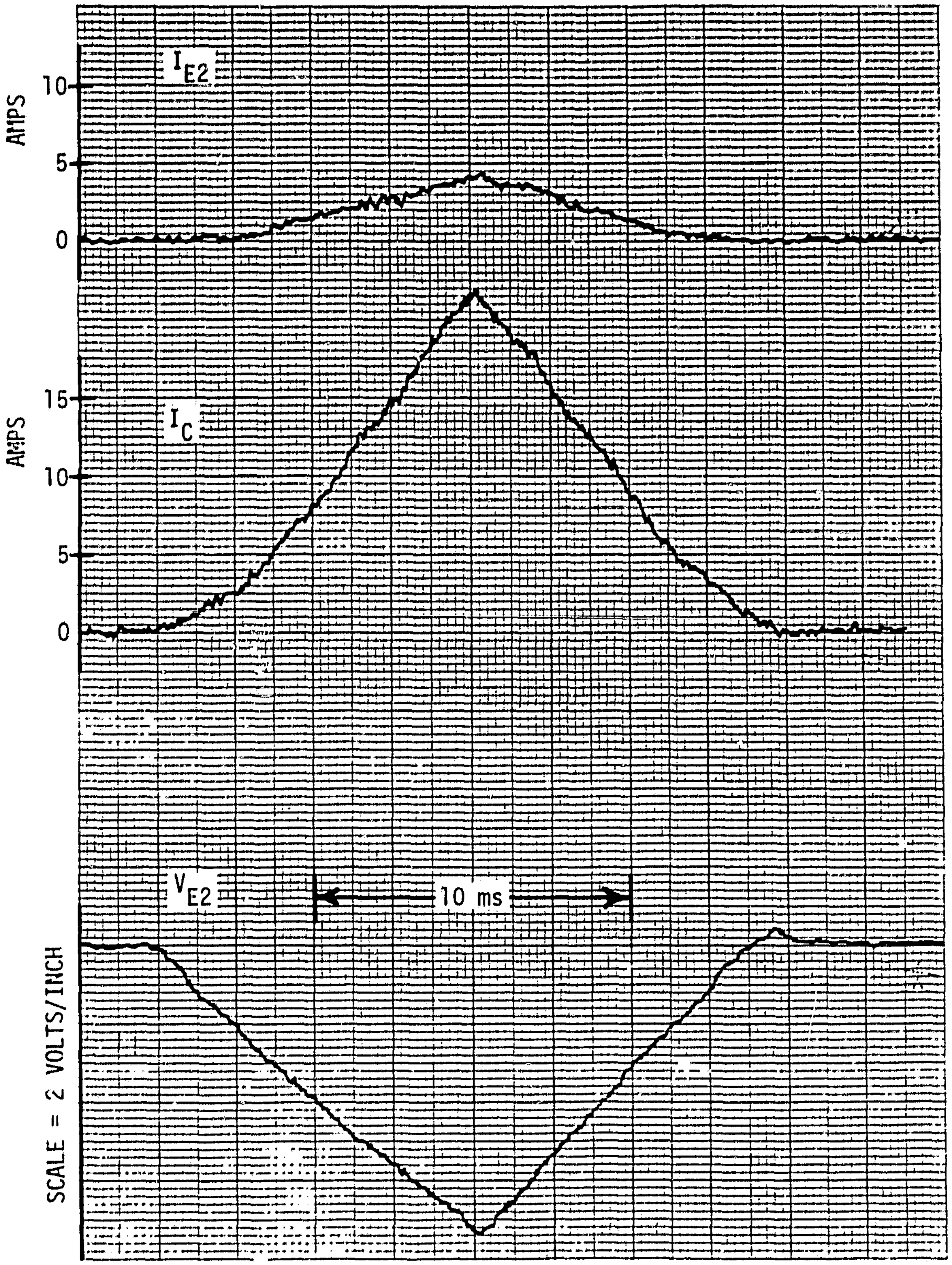

Fig. 24 Time Variation of the Currents from Emitter Blade No. 2, and the Collector (Upper Two Traces) and the Voltage of Emitter No. 2 (Lowest Trace). Data was obtained at Cue = 10 on the 7th run. Laser beam power ~8 kW. Cs pressure = 10.5 torr.

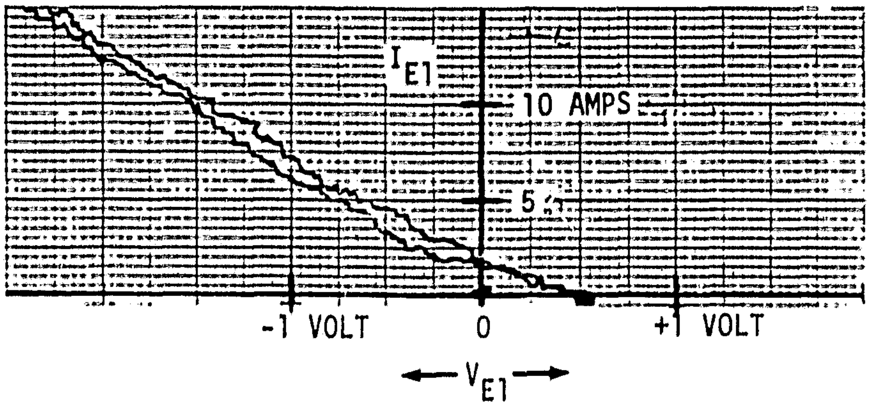

Fig. 25a Current vs Voltage Plot for TELEC Emitter No. 1

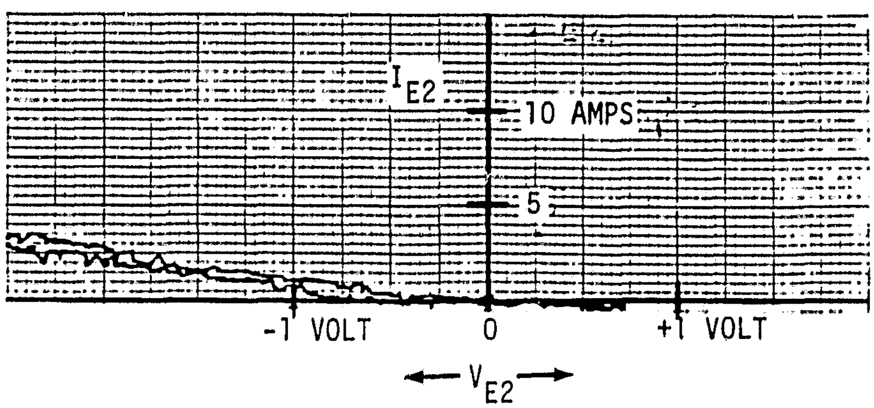

Fig. 25b Current vs Voltage Plot for TELEC Emitter No. 2.

Data was obtained at Cue = 10 on the 7th run. Laser beam power ~8 kW. Cs pressure = 10.5 torr.

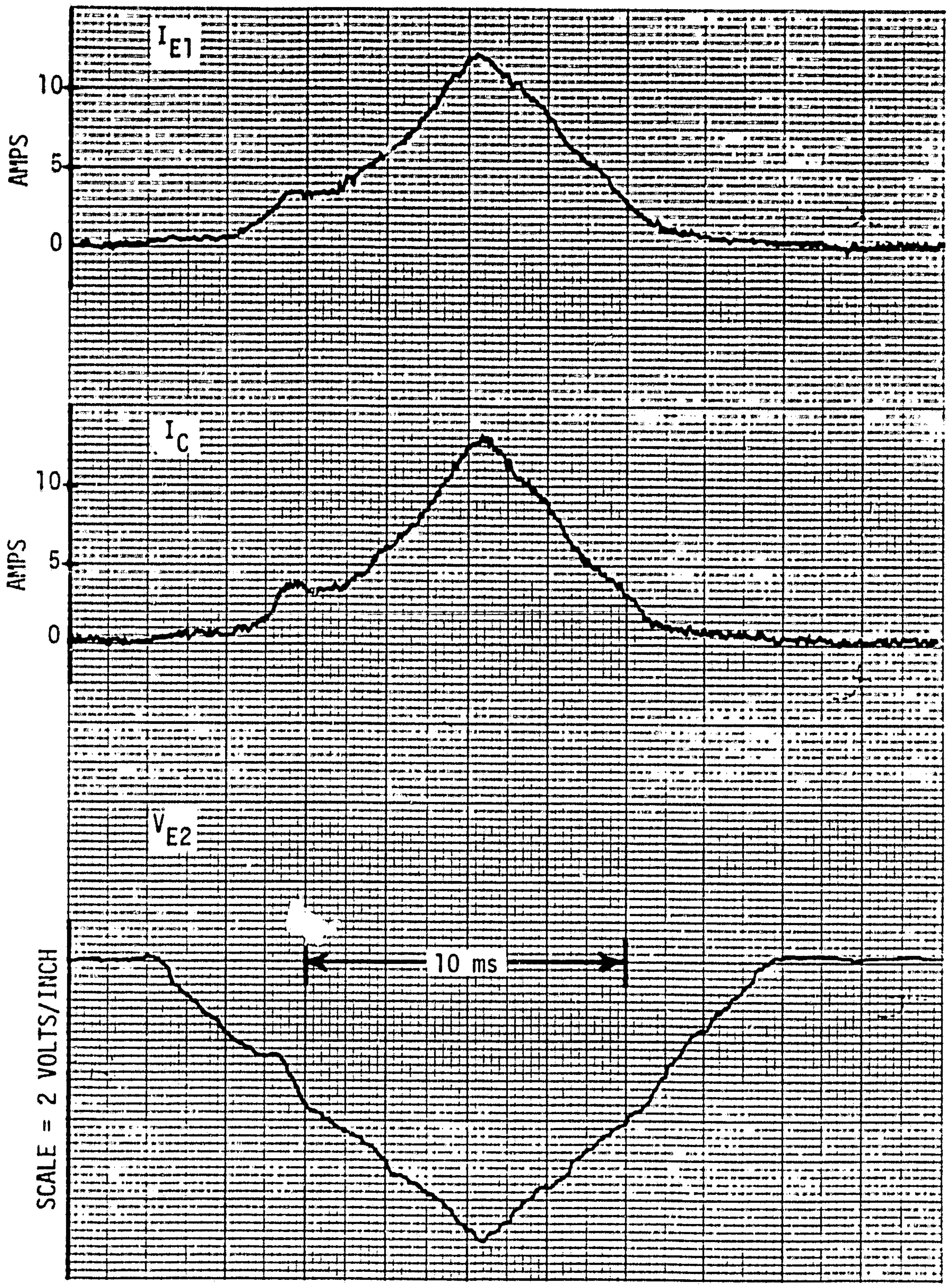

Fig. 26 Time Variation of the Currents fron Emitter Blade No. 1, and the Collector (Upper Two Traces) and the Voltage of Emitter No. 1 (Lowest Trace). Data was obtained at Cue = 13 on the 7th run. Laser beam power ≲8 kW. Cs pressure = 10.5 torr.

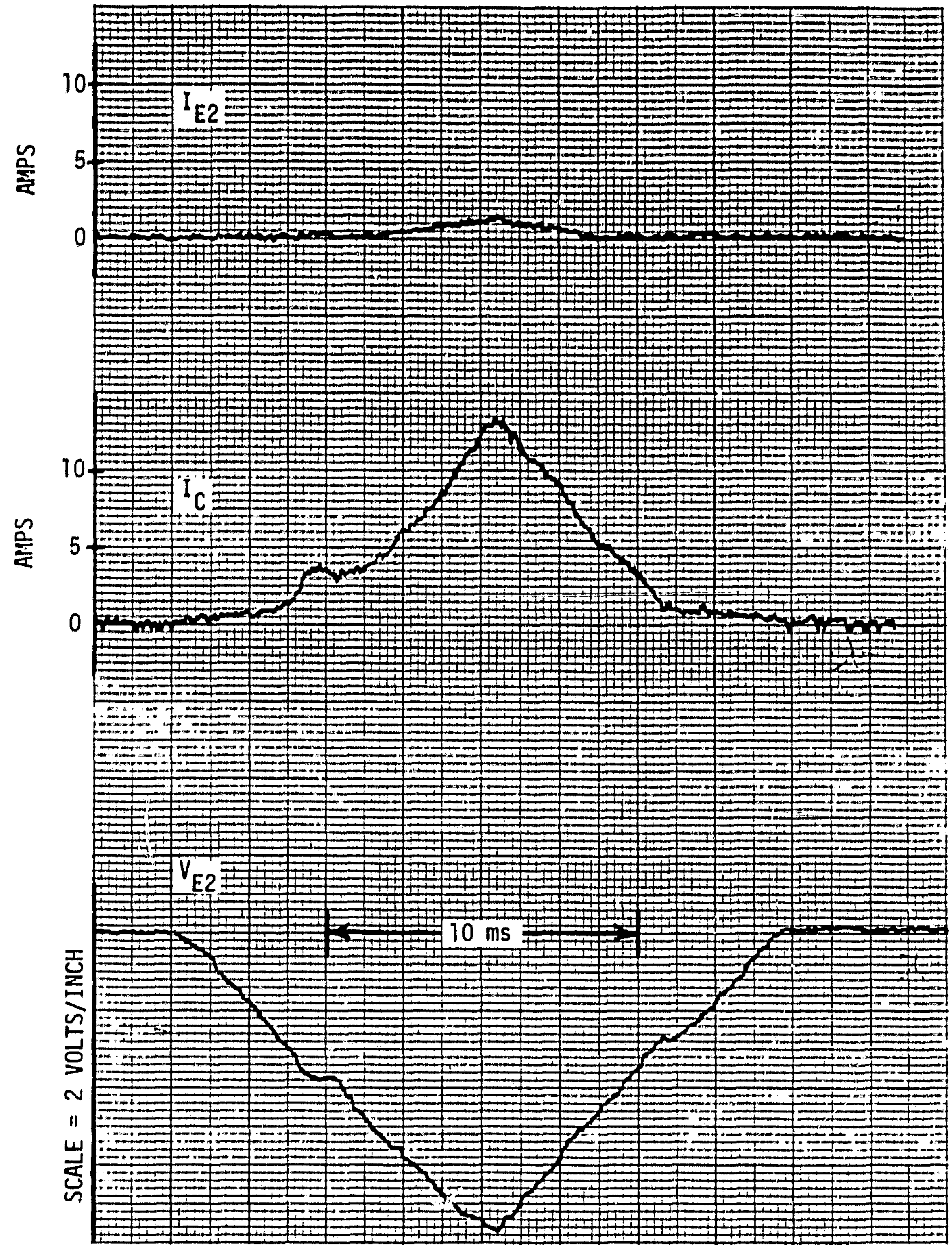

Fig. 27 Time Variation of the Currents from Emitter Blade No. 2, and the Collector (Upper Two Traces) and the Voltage of Emitter No. 2 (Lowest Trace). Data was obtained at Cue = 13 on the 7th run. Laser beam power $\lesssim$8 kW. Cs pressure = 10.5 torr.

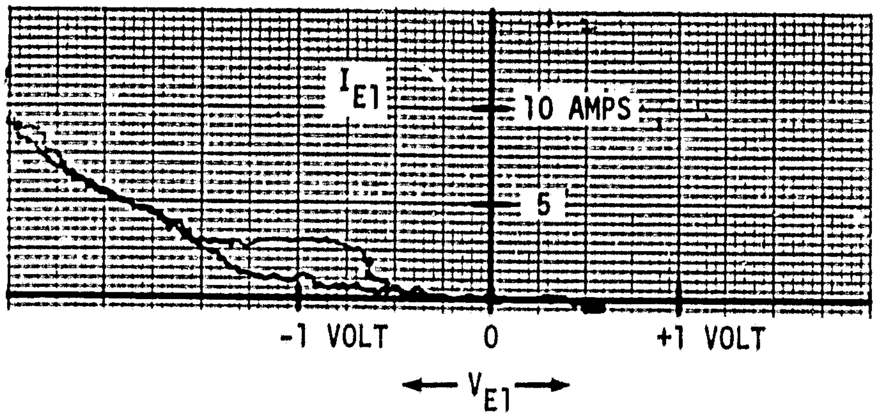

Fig. 28a Current vs Voltage Plot for TELEC Emitter No. 1.

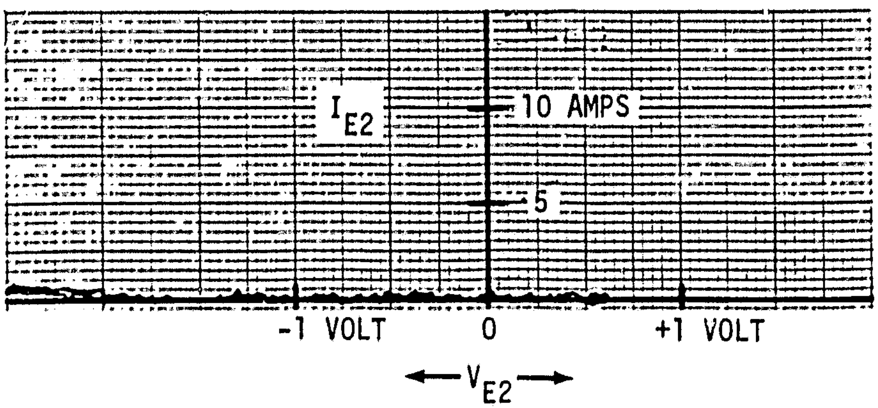

Fig. 28b Current vs Voltage Plot for TELEC Emitter No. 2.

Data was obtained at Cue = 2 on the 7th run. Laser beam power $\leq$8 kW. Cs pressure = 10.5 torr.

The current during nearly all of the runs was observed to come from emitter No. 1. However during run 12, a counter example of this occurred. On the 16th I-V sweep of run 12, a large current was observed from emitter No. 2 (over 35 amperes, not in the power quadrant), and at the same time only ~3 amperes flowed through emitter No. 1. Yet on the very next I-V sweep the current in emitter No. 2 was reduced to ~0 while the current in emitter No. 1 increased to about 8 amperes. Subsequent I-V sweeps showed a small current from emitter No. 1 and nothing from emitter No. 2 until the laser was shut down during that run.

Data obtained during run No. 16, which occurred on the second day, is also interesting. During this run approximately equal currents were produced from each of the emitter blades simultaneously. However none of the current was observed in the power quadrant. This was also the last run in which any current carrying plasma was obtained.

After run No. 16 in order to obtain more equally distributed current from the two emitter blades, the TELEC active section was shifted laterally as much as 2 mm in a direction such as to bring emitter No. 2 closer to the center of the beam and emitter No. 1 further away from the center. However this offsetting was not successful in equalizing the currents, since on the subsequent runs no current conducting plasma was observed.

The test was terminated on the last day, when a leak developed in one of the bellows-sealed blade positioners. Air leaking in through the bellows failure eventually oxidized all of the cesium, and the plasma could no longer be produced. However it's significant to note that until this time, control of the cesium vapor by the heat pipe/inert gas interface was completely successful. There was no indication that sudden heating of the vapor by the beam disrupted this interface or caused fluctuations in the vapor pressure.

5.0 DISCUSSION OF THE RESULTS

5.1 Comparison with Theoretical Calculations

The electric power obtained with these TELEC tests is substantially lower than that predicted from theoretical calculations. However the theoretical calculations are based on the assumption of 20 kW or more laser power for the tests (see Figs. 2 and 3). Analytical modeling indicates that approximately 10 kW is necessary as a "front end investment" of energy to sustain the plasma before output can be obtained. Computer calculations of the TELEC system predicted that it would be necessary to reduce the size of the beam hole to 6 mm if the laser power level were reduced to 10 kW.[16] This would be necessary to maintain an adequate beam intensity for plasma maintenance. A design for the electrodes with a 6 mm diameter beam hole was considered in the planning phase of the TELEC experiment. However a decision was made to construct a 1 cm hole, considering fabrication and alignment difficulties; along with the belief that large laser power levels would be available at the time of the test.

Because the device was built and operated with a 1 cm diameter beam hole, the laser powers obtained at the time of the test were marginal for TELEC output. During the runs in which the TELEC plasma was well behaved and output currents were observed, the beam powers were about 6 to 8 kW. With a 1 cm diameter beam hole, this means the average beam intensity was about 8 to 10 kW/cm^2. In view of these low values of beam intensity, the small electric output powers observed in this test are consistent with the predicted behavior.

A further consideration regarding the laser beam intensity is that the power density profile through the beam cross section is considerably anisotropic (see Sec. 3.2). This means that the beam intensity in many parts of the beam hole was substantially less than necessary intensity to maintain the plasma. Its likely therefore, that only a portion of the beam hole in the TELEC cell was filled with plasma during most of the runs. Most likely this fact is the cause of the unbalanced emitter currents which were observed.

The very small TELEC output powers observed on run No. 7 consist of currents at voltages which are small enough to be comparible with thermionic converter behavior. A crucial question of interpretation is to distinguish between the low level TELEC output power and possible thermionic effects which may have occurred if the emitter blades are heated to a high temperature by the plasma or beam impingement. Under these conditions it might be possible that the emitter blade could act as one electrode of the thermionic converter and produce some output power. However this possibility can be ruled out, because thermocouples mounted in the emitter blades showed that the blade temperature did not rise above ~900°K to ~1000°K, even for the longest laser runs. These emitter temperatures are too low for any sizeable thermionic converter output.

The possibility exists that a localized hot spot might have occurred in a portion of the emitter blades which was too far away from any of the thermocouples to be detected; but the evidence is against this. The reasons are: first of all, that the thermal conductivity of tungsten is quite large and the blade was specially designed to distribute the heat and prevent localized heating. More important, however, is that the most likely place for hot spots to occur are at the front (beam entrance end) corners of the blade tips and the temperature is known at these locations. This front corner of the blade tip is oriented directly in line with the edge of the laser beam at this point. Any plasma formation is most likely to occur at this location. If plasma were to form further down inside the beam hole it would propagate up the beam toward the laser end of the 1 cm diameter hole in the collector. Thus, the front corner location on the tip of the emitter blades is the point with the highest heat loading, and would probably be the hottest point anywhere. Thermocouples were located in both blades within 6 mm of the point on the blades, and these thermocouples showed temperatures of approximately 800°K, although there was about 30° temperature rise in the thermocouples during the duration of the laser runs. Thus it appears that whatever small electric output was observed during these tests could not have been due to contributions from thermionic converter behavior caused by the hot emitter blades.

5.2 Conclusions

In addition to the performance observations, several ancilary facts regarding TELEC construction and operation with lasers may be concluded from the results of this set of tests. The heat pipe-oven design appears to be a feasible approach for producing a confined vapor of cesium as a plasma gas. Vapor pressures of ~10 torr and chamber temperatures of ≳750°K were maintained in the TELEC cell without difficulties, once the cesium was loaded. No instabilities were detected in the cesium-xenon interface, when the laser beam was admitted to the chamber.

Other conclusions can be drawn about the optics required to produce high power laser beam with a narrow cross section. A multi-kilowatt beam with 10.6 μm wavelength was successfully concentrated to a diameter of ~1 cm for distance of about 1/2 meter. The difficulties which were encountered with the converging-diverging optical setup (intended to produce a parallel beam) can probably be overcome, if the primary output beam from the laser is very uniform in cross section. (The beam from the Lewis laser has a "doughnut" cross section and considerable azimuthal variation.) Based on the experience of these tests, it likely would be difficult to produce a parallel high power beam at 10.6 μm with a cross section much smaller than 1 cm. Thus TELEC electrodes should be probably designed to accept a beam with about 1 cm diameter, if a CO_2 laser is to be used.

The TELEC electrical output power observed in these tests is very small compared to anticipated power levels based on theoretical calculations. However, the small output power is not inconsistent with the analytical predictions for the laser intensities of $\lesssim 10$ kW/cm^2 available at the time of the test. The small output which was observed does appear to truly represent TELEC operation as opposed to thermionic effects; since the emitter blades were too cold to act as power producing thermionic converters.

The amount of TELEC power produced by these tests was insufficient to provide measures of efficiency and power density that could be scaled up to verify the analytical predictions of a megawatt level TELEC spacecraft system. This was an objective of the experiment that cannot be met with the results obtained. Further testing at higher laser power levels will be needed to get an unambiguous assessment of TELEC performance cabablities.

REFERENCES

1. Rasor, Ned S., "Thermionic, Plasma, and Photoemission Energy Conversion," Laser Energy Conversion Symposium, NASA TM X-62, edited by K. W. Billman, Sept. 1973, pp. 51-62.

2. Waymouth, J. F., "Electrical Energy from High-Temperature Plasma," J. Inst. of Electrical Engrs., Vol. 8, Aug. 1962, pp. 380-383.

3. Stallcop, J. R. and Billman, K. W., Plasma Phys. 16, 1974, p. 1189.

4. Stallcop, J. R., Astrophys. J. 187, 1974, p. 179.

5. Billman, K. W. and Stallcop, J. R., Appl. Phys. Lett. 28, 1976, p. 704.

6. Hansen, L. K. and Rasor, N. S., "Thermo-Electronic Laser Energy Conversion," Second NASA Conference on Laser Energy Conversion, NASA SP-395, edited by K. W. Billman, Jan. 1975, pp. 133-146.

7. Britt, E. J. and Yuen, C., "Thermo-Electronic Laser Energy Conversion for Power Transmission in Space," No. 779242, 12th Intersociety Energy Conversion Engineering Conference, Aug. 1977, pp. 1453-1460.

8. Britt, E. J., "TELEC Laser Experiment," NASA CR-152-077, Oct. 1977.

9. Britt, E. J., "The TELEC - A Plasma Type of Direct Energy Converter," Radiation Energy Conversion in Space, edited by K. W. Billman, Vol. 61 of Progress in Astronautics and Aeronautics, March 1978, pp. 421-436.

10. Britt, E. J., Rasor, N. S., Lee, G, and Billman, K. W., "A Cesium Plasma TELEC Device for Conversion of Laser Radiation to Electric Power," Appl. Phys. Lett. 33, Sept. 1, 1978, p. 5.

11. Laser Focus 13. 20-21 (1977).

12. Thompson, R. W. and Alger, D. L., Appl. Phys. Lett. 32, 1978, p. 610.

13. Alger, D. L., Manista, E. J., and Thompson, R. W., "A Review of the Thermoelectronic Laser Energy Converter (TELEC) Program at Lewis Research Center," Radiation Energy Conversion in Space, edited by K. W. Billman, Vol. 61 of Progress in Astonautics and Aeronautics, March 1978, pp. 437-449.

14. Vidal, C. R. and Cooper, J., "Heat-Pipe Oven: A New, Well-Defined Metal Vapor Device for Spectroscopic Measurements," J. Appl. Physics, Vol. 40, July 1969, pp. 3370-3374.

15. Lancashire, R. B., Alger, D. L., Manista, E. J., Slaby, J. G., Dunning, J. W., and Stubbs, R. M., "The NASA High-Power Carbon Dioxide Laser A Versatile Tool for Laser Applications," Optical Engineering, Vol. 16 No. 5, Sept./Oct. 1977, pp. 505-512.

16. Britt, E. J. and Yuen, C., "Thermoelectronic Laser Energy Conversion," Monthly Progress Report No. 7, Rasor Associates, Inc., Sunnyvale, Calif., NASA Contract NAS3-200089, Nov. 1976.