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A REVIEW OF THE THERMOELECTRONIC LASER ENERGY CONVERTER (TELEC) PROGRAM AT LEWIS RESEARCH CENTER

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A REVIEW OF THE THERMOELECTRONIC LASER ENERGY CONVERTER (TELEC)

PROGRAM AT LEWIS RESEARCH CENTER

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SUMMARY

The investigation of the Thermoelectronic Laser Energy Converter (TELEC) concept at the Lewis Research Center (LeRC) began with a feasibility study of a 1 megawatt sized TELEC system. The TELEC was to use either cesium vapor or hydrogen as the plasma medium. The cesium vapor TELEC appears to be the more practical device studied with an overall calculated conversion efficiency of greater than 48%. Following this study, a small TELEC cell was fabricated which demonstrated the conversion of a small amount of laser power to electrical power. The cell developed a short circuit current of 0.7 amperes and an open circuit voltage, as extrapolated from volt-ampere curves, of about 1.5 volts. Work is now in progress to construct and test a cesium vapor TELEC capable of absorbing 20% of an incident 10 kW, 10.6 micrometer beam, and converting 35% of this power to electrical power.

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INTRODUCTION

The purpose of the NASA high-power laser research program is to define and evaluate the potential of such lasers for NASA applications. One possible application is the generation and transmission of power in space over long distances by means of a laser beam. To be a competitive space power system, though, laser power transmission requires an efficient, reliable, lightweight method of converting the laser power into electrical power. One conversion method, Thermoelectronic Laser Energy Conversion (TELEC), was first proposed in reference 1. The calculated overall efficiency of greater than 48% (for a 1 megawatt system)(ref. 2) and the high waste heat rejection temperature (about 1000 K) of the relatively small radiator system make the TELEC a potential candidate for a spacecraft energy converter system.

In the TELEC process, a plasma is sustained by the inverse bremsstrahlung absorption of electromagnetic radiation of the laser. A cooled, large area collector electrode surrounds the plasma, while a smaller, uncooled, emitter electrode is in contact with the plasma. The largest fraction of the high energy electrons that diffuse out of the plasma are intercepted by the collector leaving it with a negative charge relative to the plasma. The small emitter is heated by radiation from the plasma to a thermionic emission temperature (1900 to 2500 K) where it is capable of emitting large currents (on the order of 100 amps/cm^2) of low energy electrons into the plasma leaving the emitter positively charged relative to the plasma. When the collector and emitter are connected through an external load circuit, an electrical

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current will flow. The magnitude of the developed output voltage is proportional to the plasma electron temperature.

Once the plasma is ignited, the function of the laser is not only to sustain the plasma but to increase the energy of the thermionically emitted electrons. The TELEC may be thought of as a heat engine whose peak cycle temperature is the plasma electron temperature. Since the temperature is generally very high ($<10^4$ K), the ideal Carnot thermodynamic cycle efficiency approaches 100%.

The TELEC concept was first introduced by Rasor at the Laser Energy Conversion Conference in 1973 (ref. 1). A preliminary investigation of the converter was conducted during 1974-75 by Hansen and Rasor (ref. 3). During 1976, the theoretical investigation and conceptual design of a 1 megawatt TELEC was performed by Britt and Yuen (refs. 2 and 4).

In this paper, some results of the parametric analysis and conceptual TELEC design study of Britt and Yuen will be given. The testing of a small TELEC that was constructed during 1977 by LeRC personnel will be discussed. This TELEC demonstrated the conversion of a small fraction of 10.6 micrometer laser radiation to electrical power. Finally, the cooperative contracted program that is now underway between LeRC and Rasor Associates, Inc. for the fabrication of a 10 kW TELEC will be described. This TELEC design concept has the unique capability of isolating the window and optical components from the TELEC cesium vapor filled electrode region by using a xenon-cesium vapor barrier.

A CONCEPT FOR A ONE MEGAWATT TELEC

The study performed by Britt and Yuen (refs. 2 and 4) was conducted to determine the feasibility of a 1 megawatt sized TELEC system. The inherent design problems associated with coupling laser radiation into a multi-megawatt TELEC were not considered in this study. It was desired to first evaluate the performance capability of a large TELEC device. That is, what would be the most desirable electrode configuration for the TELEC? What gaseous medium should be chosen and how would the size, output power, and efficiency of the TELEC vary with pressure of the gaseous medium?

The resulting conceptual system was a three-unit, series-connected TELEC that was designed to absorb 95% of the incident, CW, 1 megawatt beam. An artist's conception of how a TELEC system might appear as a power receiver of a spacecraft is shown in Fig. 1 (ref. 2).

Initially a TELEC unit was conceived as a concentric, cylindrical emitter-collector configuration (ref. 3), Fig. 2. Such a shape simplifies theoretical analysis but was soon abandoned due to impracticality. Replacing this concept is an eccentric emitter design, shown in Fig. 3, which consisted of four longitudinal blades placed symetrically in slots of the collector (ref. 4). The laser beam can much more easily be focused through the hollow cylindrical opening of this electrode design without damaging the emitter.

Both cesium vapor and hydrogen gas were considered as a TELEC plasma medium. Hydrogen was considered because hydrogen plasmas have been extensively studied, and although the hydrogen molecule has a high ionization potential (13.53 V), the gas is relatively inert with respect to chemical reactions with potential electrode, optical, and housing materials. On the other hand, cesium vapor is a logical choice as a medium because of the very low ionization potential (3.87 V), and also because of its ability to reduce the work function of the collector and emitter electrodes (ref. 5). Cesium vapor, however, is very reactive with most materials (ref. 6), especially the salt and/or zinc selenide (ref. 7) windows which are necessary to pass the infrared radiation into the TELEC cell. So, in considering both hydrogen and cesium vapor as possible TELEC media, the extremes of ionization potential and gas molecular size upon TELEC performance were evaluated as well as compatibility of materials.

With cesium vapor as the TELEC medium, calculations of the characteristics of a 1 megawatt TELEC were performed at cesium pressures of 40, 100, 400, and 800 torr. For these calculations input power was 1 megawatt, collector temperature was held at 1000 K, collector internal diameter was constant at 2 cm, and the emitter area was held at 0.1 cm^2 per centimeter of emitter length. Total length of the TELEC was allowed to vary as cesium pressure was varied. Summarized in Fig. 4 are values of overall TELEC conversion efficiency and total TELEC length plotted as a function of cesium pressure (refs. 2 and 4). Note that although the TELEC overall conversion efficiency is highest at low cesium pressure, there is only a small decrease in this efficiency with increase in cesium pressure to 800 torr. At low cesium pressure, total TELEC length is a sensitive parameter in relation to slight changes in cesium pressure. For cesium pressure greater than about 400 torr, however, the rate of change of total system length, as well as overall efficiency, is small with respect to large changes in cesium pressure.

Calculations of the characteristics of a 1 megawatt TELEC with hydrogen as a gas medium indicated that a laser beam power density in excess of 10^6 watts/cm^2 is required to maintain a hydrogen plasma. This power density alone is sufficient to downgrade hydrogen from consideration as a TELEC medium. However, if one is able to surmount these problems and operate a hydrogen TELEC, a conversion efficiency between 20 - 25% appears to be possible, but the output power density is quite small at the low pressure where this efficiency occurs (about 2 torr) which means that the hydrogen TELEC would be very long. At higher pressures the output power density is high, but the efficiency decreases.

The results of the design study of the 1 megawatt TELEC system were encouraging for the cesium vapor system. However, the problem of TELEC window materials for the laser intensities of $(3\text{-}20)\times10^4$ watts/cm^2 that are required for this system are severe because the window must be heated above the cesium reservoir temperature to prevent cesium condensation, and because cesium will react with some window materials (ref. 7). One solution to this problem is discussed in a later section of this paper.

An experimental demonstration of the TELEC effect is necessary to ensure that no unforeseen problems have been overlooked in the theoretical TELEC analysis. One such experimental verification of the TELEC effect is described in the following section.

THE TELEC CONCEPT EXPERIMENT

Concurrent with the TELEC investigation was a LeRC study of the feasibility of laser-supported plasmas for rocket propulsion systems. The energy absorption mechanisms and fluid dynamic considerations for efficient conversion of high power laser radiation into a flowing plasma was studied both by contract (ref. 8) and in-house. Laser supported plasmas, ignited by an electrical arc, were formed in air and argon using a zinc-selenide lens focusing system, a quartz chamber, and the Lewis High Power CO_2 Laser (LHPL) as the source of multi-kilowatt, CW, 10.6 micrometer laser radiation. Fig. 5 shows a laser-sustained argon plasma formed at the focus of an 18 cm focal length plano-convex zinc-selenide lens. This test and similar experiments demonstrated that the plasma ball position could be controlled by the movement of the focussing lens.

It was then apparent that with the addition of an appropriate pair of electrodes placed in contact with the laser-sustained plasma, the TELEC effect could be investigated. Therefore, an experimental TELEC cell was fabricated that consisted of a 6 cm diameter by 15 cm long quartz tube with opposing collector and emitter electrodes penetrating the tube wall at 90^o to the optic axis. (Fig. 6) The ends of the tube were closed by aluminum flanges containing zinc-selenide windows. Electrode separation was about 8 mm. The emitter, heated by radiant energy from the plasma, was made from a 9.5 mm diameter rod of thoriated-tungsten that tapered to a 3 mm diameter flat surface at the active tip. The water-cooled thoriated-tungsten collector was 19 mm in diameter with the active end curved to match the approximate contour of the prolate spherical shaped-plasma.

The experimental setup used in this study is shown in Fig. 7. The LHPL was used with a triple pass, unstable resonator configuration. The nominal 5 cm diameter annular 10.6 micrometer beam was focused with an 18 cm focal length plano-convex, zinc selenide lens to a point between the two pointed tungsten spark electrodes. An identical lens recollimated the beam and directed it into an NBS calibrated powermeter. Argon gas at 840 torr flowed axially along the 6 cm diameter quartz tube chamber with a mass flow rate of 0.1 gm/sec. A momentary 30 kV electric arc discharge across the focus initiated argon breakdown (Fig. 8). Once the laser-sustained plasma was formed, the front focusing lens was moved 2 cm toward the laser until the plasma was centered between the emitter and collector electrodes as shown in Fig. 9. A laser irradiation run typically lasted from 2 to 5 minutes.

An enlarged sectional view of the emitter and water-cooled collector electrodes is shown in Fig. 10. Both the emitter and collector electrodes were made of tungsten with 2% thorium. Identical electrode materials minimize the effects of the thermionic energy conversion mechanism which depends upon the difference in emitter and collector work functions (ref. 9). However, small differences in electrode work functions and emission can be expected from electrode temperature differences as well as from the presence of gaseous impurities such as oxygen in the test chamber.

A dynamic load circuit designed for thermionic converter tests was used to obtain the current, voltage characteristics (ref. 10). To sweep out the load characteristic, the collector-emitter voltage was varied linearly from the collector bias voltage (typically -1.5 V) to +8 volts and back to the bias voltage using a manually pulsed sweep generator with a base width of 50 milliseconds. The collector-emitter voltage and the electron current to the collector were displayed on an x-y scope and photographed.

Several checks were performed during the runs. Voltage sweeps made before plasma ignition determined the zero current, x axis. Sweeps made with a resistor connected across the emitter and collector determined the zero current, zero voltage point, and provided a check on the current and voltage scale calibration.

Ten test runs were then conducted with a plasma formed. The first series of laser irradiation runs failed to produce a current-voltage (I-V) curve in the power producing quadrant. This is the I-V quadrant where an electron current is collected at the collector even though a retarding potential exists at the collector. Using a Polaroid camera (stopped down to f/90) it was determined that the emitter and collector were not properly aligned with the plasma. After adjusting the chamber position relative to the laser beam and moving the electrodes closer together, an increase in electron current to the collector was observed.

Two runs were made with the plasma present to verify the current-voltage characteristic obtained using the transient loading technique. One of the runs was made with the dynamic load cell replaced with a 5 ohm load resistor. This run is equivalent to operation at a single load point as shown in Fig. 11. The I-V point obtained is seen to lie on the I-V curve obtained using the dynamic circuit and sweep generator.

A typical current-voltage characteristic that was obtained in run 8 is shown in Fig. 12. The approximate plasma conditions and laser power conditions that existed at the time the I-V scans of runs 8 and 9 were made are presented in TABLE I. Plasma dimensions were obtained by analyzing a 16 mm color movie (7.3 m/sec, f/22). Area and volume approximations assume a prolate spherical geometry. TABLE I also includes data from run 10, the final run, in which the focusing lens and input window fractured. Just prior to the fracture of the focusing lens and window, short duration currents, far in excess of currents measured during previous scans, were observed. Unfortunately these scans were not recorded. The I-V characteristic presented in Fig. 12 shows a short circuit current of about 0.7 amperes, and by extrapolating the I-V characteristic to near zero current, a collector-emitter voltage approaching the bias level of -1.5 volts. The saturation current is greater than 8.0 amperes. Unfortunately, the true open circuit voltage was not measured in this investigation.

It has been reported that the efficiency of thermoelectronic energy conversion depends upon the ratio of collector to emitter surface area in contact with the plasma (ref. 4). According to TELEC theory, for low pressure plasmas, as this area ratio becomes large the short circuit current should approach the saturated emitter current in magnitude. However, predications of the theory may be less accurate at the near atmospheric pressures used in this experiment. It was found in this experiment that although the electrodes were designed to give a maximum area ratio of 40, slight misalignment of the plasma with respect to the electrodes could drastically change this value. (See for example, Fig. 10.) Because of this uncertainty in plasma position, the surface area ratio dependence could not be determined. It was observed however, that small changes in position of the electrodes with respect to the plasma had a noticeable effect on the output current, although changes in both emitter temperature and contact area must be considered. Although emitter temperature was not measured directly, color movies showed that the emitter became white-hot during runs 8, 9, and 10. (See Figs. 9 and 12, and TABLE I.)

Although quantitative agreement with TELEC theory was not possible, the experiment demonstrated CW conversion of a small fraction of laser energy to electrical energy. It should be mentioned that experimental conditions were selected to minimize the effects of the thermionic energy conversion mechanism and therefore do not represent optimum conditions according to TELEC theory.

A TELEC experiment that is designed to provide a more meaningful and quantitative test of the TELEC theory is now in progress and is discussed in the following section.

FABRICATION AND TESTING OF A 10 kW TELEC

A contractual effort is underway to fabricate and test the TELEC system shown in Fig. 13. This TELEC will be capable of intercepting at least 10 kW of input radiation and absorbing 20-25% of this amount within the 30 cm long plasma column that is defined by the length of the TELEC electrodes. The TELEC cell is being designed and built by Rasor Associates, while the remainder of the TELEC system, called the LeRC TELEC test rig (LTTR), is being provided by LeRC. The entire TELEC system has a length of about 300 cm. The TELEC cell is 91.4 cm long and contains the 30 cm long active TELEC electrode section.

TELEC Cell Description

The solid machined nickel body of the TELEC cell is the collector electrode. The collector is joined to the LTTR by insulator and bellows sections. The TELEC cell is held in alignment by adjustable supports that rest upon the optics table.

The emitter electrodes define the 30 cm active cell length. The emitter configuration is a variation of the eccentric type shown in Fig. 3, which will have only two opposing blades 180^{o} apart. Each emitter blade is insulated from the collector and is held in position in a milled slot of the collector by flexible supports. Each support member passes through a bellows feed-through device which is attached to the emitter vacuum housing cover. The device permits movement of the emitter relative to the plasma by external adjusting screws. Each emitter piece is machined to receive tungsten-rhenium thermocouples which are positioned close to the emitting surface to monitor emitter temperature.

The internal diameter of the active portion of the collector block is bored along the center-line to approximately a 6 mm diameter. The exact dimension depends upon the diameter of the collimated beam that will pass through the collector, and the final machining dimension will be based on an actual beam diameter measurement. The end regions of the TELEC cell, bored to a larger diameter, contain the cesium condenser sections of the TELEC cell. Approximately 30 chromel-alumel thermocouples are imbedded into the collector over its length. A milled slot, running parallel to the hole bored along the center line, contains a wick that runs the full length of the TELEC cell. The wicking joins a centrally located cesium reservoir to the cesium condenser regions at each end of the cell.

Xenon-Cesium Vapor Interface

A unique feature of the TELEC system is the use of a heat pipe oven technique within the TELEC cell to provide a separation of cesium vapor from xenon gas in the end regions of the cell. The optical components in the end pieces of the TELEC system are therefore protected from the corrosive affect of the cesium vapor. In order to set up the xenon-cesium vapor interface, the entire TELEC system is evacuated and filled with xenon gas to the desired pressure. Liquid cesium, contained in the centrally located cesium reservoir, is heated to vaporize some of the cesium. As cesium vapor diffuses toward the cooled ends, the cesium molecules collide with xenon molecules causing them to drift toward the end regions. Some cesium condenses on the wicking and returns to the reservoir by capillary action. A cesium pressure gradient is established between the pure cesium region at the center of the TELEC cell and the pure xenon regions at both ends of the cell. This type of metal vapor-inert gas separation has been used previously to protect windows of spectroscopic measurement devices (ref. 11).

LeRC TELEC Test Rig (LTTR)

In addition to physically supporting the TELEC cell, the other functions of the LTTR are to provide vacuum capability of the system to less than 10^{-6} torr, and to house the optical train required to reduce and collimate the LHPL beam to an approximate 0.5 cm diameter. The TELEC system is mounted on a 1.22 by 3.66 meter optics table.

The optical train. - The optical train consists of three high-pressure, water-cooled, copper mirrors. The first mirror, M1, shown in Fig. 13, first intercepts the incident 5 cm diameter beam. It is a concave, spherical mirror having a focal length of 1.65 meters and an aperture of 10 cm. This mirror is supported from the optical table by a free-standing mount that provides adjustment for beam alignment. The mirror is designed to withstand beam intensities to 5 kW/cm^2. The second and third mirrors in the optical chain, M2 and M3, are located on opposite ends of the enclosed TELEC system. They are both convex, spherical mirrors with 5 cm aperatures and 20 cm focal lengths. The two mirrors are designed to reflect a 10.6 micrometer beam having an intensity of 100 kW/cm^2.

Mirrors M1 and M2 form a concave-convex, confocal, off-axis mirror system that reduces the diameter of the laser beam and produces a collimated 0.5 cm diameter beam through the TELEC cell to mirror M3. Mirror M3 then expands the transmitted beam to its approximate initial diameter and directs it into a powermeter. Each mirror requires a 114 liter/min coolant flow of ethylene-glycol that is circulated from a 7500 liter tank by a pitot tube pump through a 10 micrometer diameter particulate filter system.

The laser beam enters and exits the TELEC system through 7.6 mm thick zinc-selenide windows that are positioned in a converging (and diverging on exit) region of the beam where the beam intensively is less than 2 kW/cm^2.

The vacuum system. - A 500 L/s turbo-molecular vacuum pump and a 1600 L/s titanium sublimation pump are used in parallel to evacuate the TELEC system. The sublimation pump was added to ensure an extremely low residual level of oxygen and hydrogen in the system. The presence of trace amounts of oxygen and hydrogen in a cesium vapor thermionic converter can cause degradation of output power as well as failure of the converter components (ref. 6). These gases may therefore be detrimental to TELEC operation as well.

Predicted Analytical Results and Test Procedures

Predicted results. - Britt and Yuen (ref. 12) performed an analysis for a 30 cm long cesium TELEC having a collector internal diameter of 6 mm, a collector temperature of 1000 K, and a laser input power of 10 kW. Emitter temperature and cesium vapor pressure were the parameters. The best emitter temperature appeared to be 1800 K. In the study, the cesium pressure was varied from 10 to 40 torr. Over this cesium-pressure range, conversion efficiencies between 30-35% were indicated at an output voltage of about 3 volts.

Since only about 20% of the laser beam is absorbed over the length of the 30 cm TELEC electrode section, the output power from the TELEC should be about 750 watts.

Test procedure. - An experimental procedure is planned that will allow separation of the TELEC and thermionic energy conversion mechanisms. A typical time sequence of events that will occur during an experiment is shown in Fig. 14. Note that during an emitter heating cycle, both TELEC and thermionic energy conversion mechanisms may be taking place. After the emitter has reached an equilibrium temperature, the laser is shutdown and the cooling cycle begins. During the cooling cycle, the effect of any thermionic energy conversion mechanism can then be measured.

Since it is important that the I-V scans for "laser on" and "laser off" conditions be taken at the approximate same emitter temperature, the timing sequence of the experiment will be automated. Short, repetitive runs with a time duration of approximately 30 seconds, will be used to test the TELEC system over a cesium pressure range from 10 to 100 torr. The same dynamic load circuit described in the TELEC CONCEPT EXPERIMENT section will be used to sweep out the load characteristics of the TELEC cell at a rate of approximately one scan per second. Each experiment will be initiated by removal of a shutter located between the LHPL and TELEC system. The experiment will be terminated by shut-down of the laser which occurs over a few millisecond time span. The power levels of the laser beam incident on the TELEC input window and transmitted through the TELEC system will be monitored by power meters that receive a small fraction of the beam reflected to them by beam splitters. The LHPL, as well as the programmed experimental cycle, will be controlled by a DEC 14/30 Programmable Controller.

CONCLUDING REMARKS

Some results of an analytical conceptual design study of a three unit, cesium vapor TELEC have been described. The resulting system would absorb 95% of the incident, 1 megawatt, 10.6 micrometer laser beam, and convert as much as 48% of this to electrical power. Beam intensities as high as 2×10^5 watts/cm^2 would be required between the TELEC electrodes to maintain the plasma. A hydrogen medium TELEC was studied briefly with calculated conversion efficiencies on the order of 20-25%. However, this gas required a very high beam intensity in excess of 10^6 watts/cm^2 between the TELEC electrodes.

Test results of an experimental TELEC that converted a small fraction of laser power to electrical power were also described. Short circuit currents as high as 0.7 amps were measured and open circuit voltages, extrapolated from volt-ampere curves, of about 1.5 volts were indicated.

A cesium vapor TELEC system is presently being designed to intercept at least 10 kW of 10.6 micrometer laser beam power, absorb 20% of this, and convert 35% of the absorbed power to electrical power. This TELEC should provide the scaling data necessary to estimate the performance of a full length TELEC in which nearly all of the input laser radiation is absorbed.

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TABLE I

Run number	Length, cm	Width, cm	Power, kW in	Power, kW out	Area, cm^2	Volume, cm^3
8	4.5±0.3	1.2±0.1	~6	1.3	13.6	3.4
9	4.4±0.3	1.2±0.1	~5	1.2	13.4	3.3
10	5.3	1.5	~8	1.4	20	6.2

TABLE I. - Approximate laser power and plasma dimensions for runs shown. Variations in dimensions for runs 8 and 9 show instability in plasma possibly due to small variations in laser power. Run 10 (for which I-V curves were not taken) dimensions were taken from a still photograph and thus did not show plasma variations.

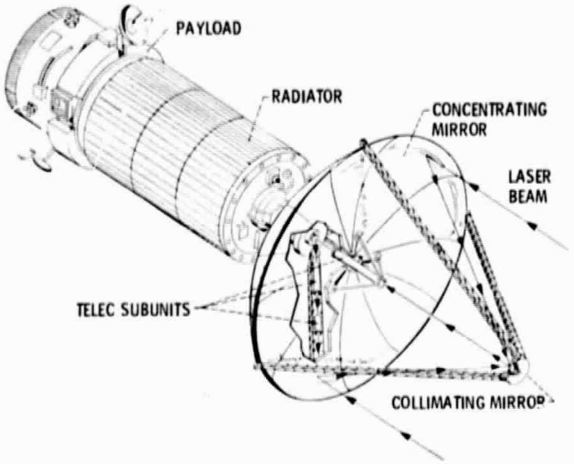

Figure 1. - Artist's concept of a TELEC powered spacecraft.

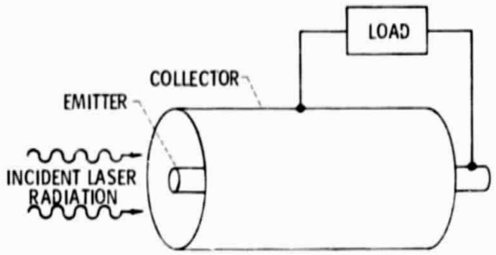

Figure 2. - Elementary TELEC configuration.

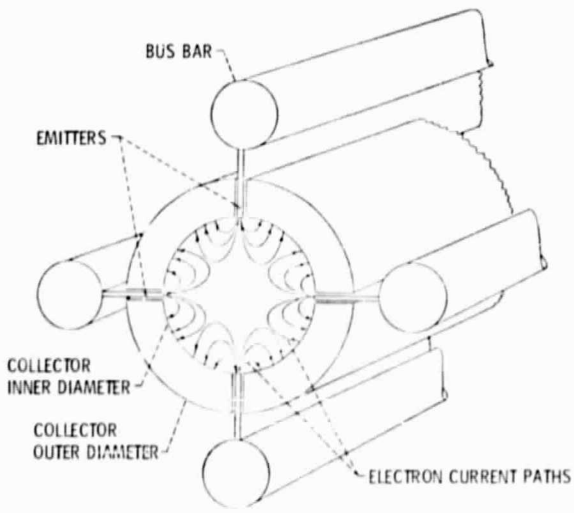

Figure 3. - Conceptual TELEC design with eccentric emitters.

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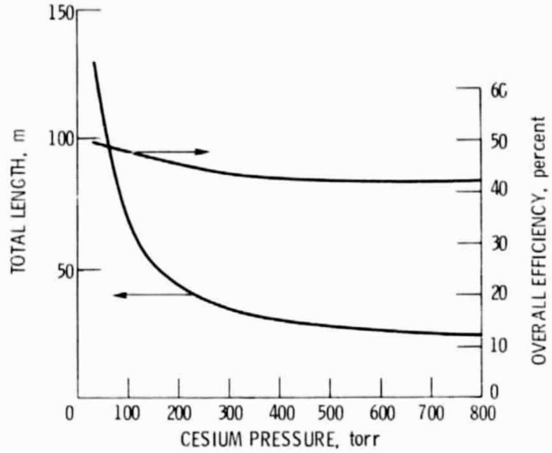

Figure 4. - Variation of total length and overall conversion efficiency as a function of cesium plasma pressure for a conceptual one megawatt TELEC system.

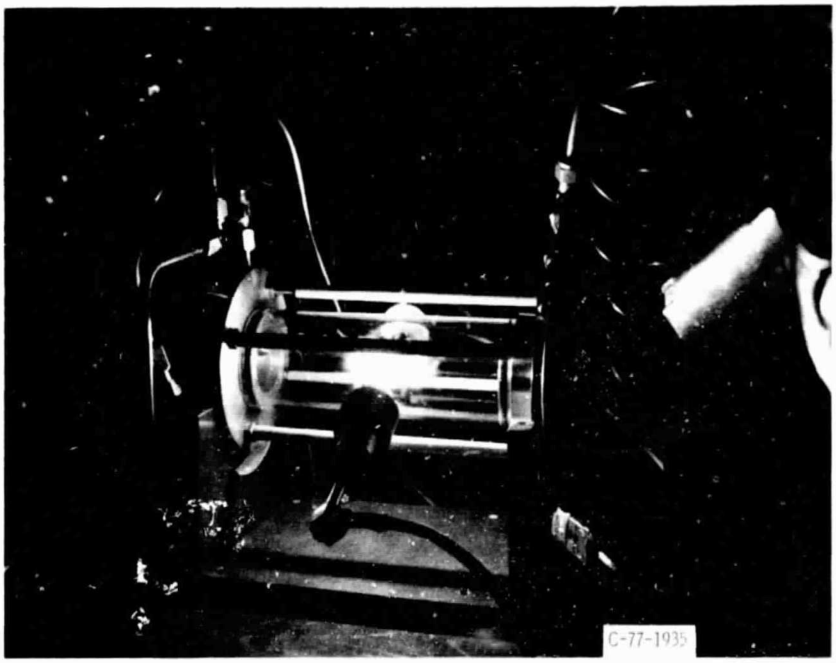

Figure 5. - Argon plasma, sustained by approximately 5 KW of 10.5 micrometer continuous wave radiation from the Lewis High Power CO_2 Laser, at the focus of an 18 cm focal length plano-convex zinc-selenide lens.

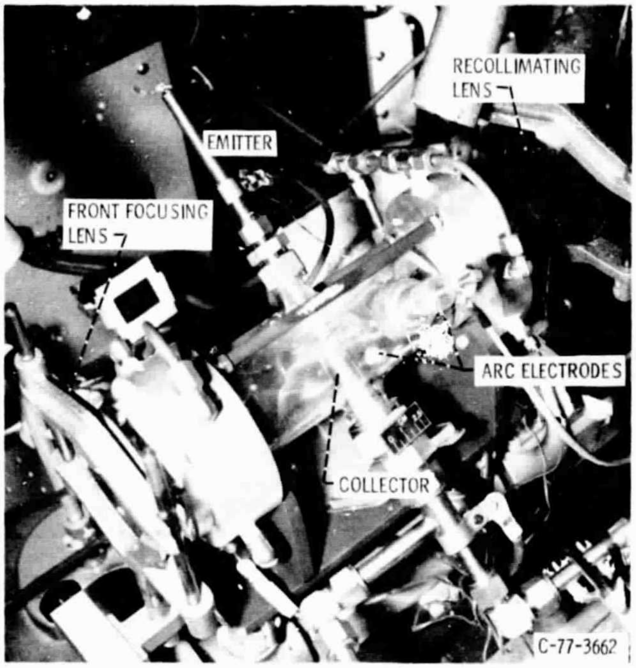

Figure 6. - TELEC demonstration cell.

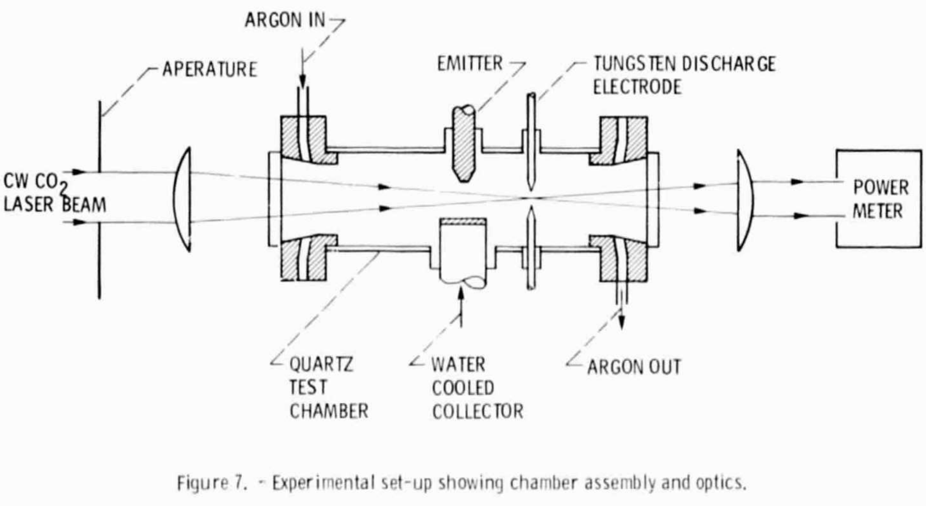

Figure 7. - Experimental set-up showing chamber assembly and optics.

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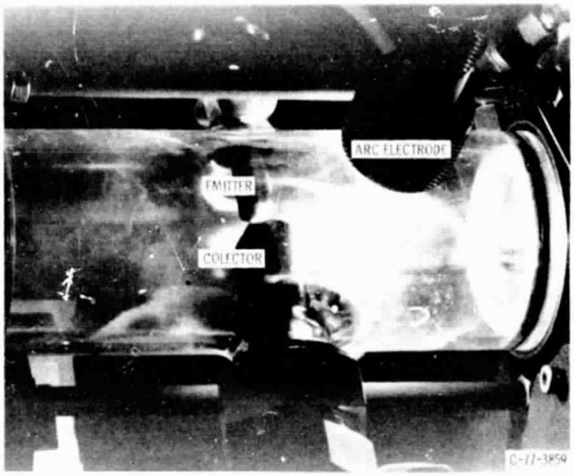

Figure 8. - Laser-sustained argon plasma just after ignition by a momentary 30 KV arc across the pointed electrodes. Laser beam enters chamber from the left.

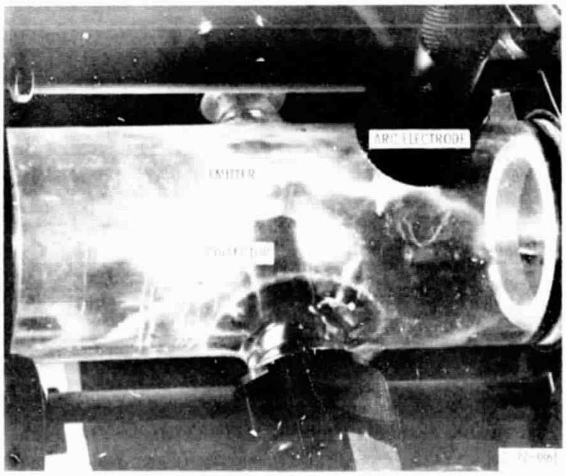

Figure 9. - Laser-sustained plasma between collector (foreground) and emitter electrodes. End of emitter electrode is glowing white-hot.

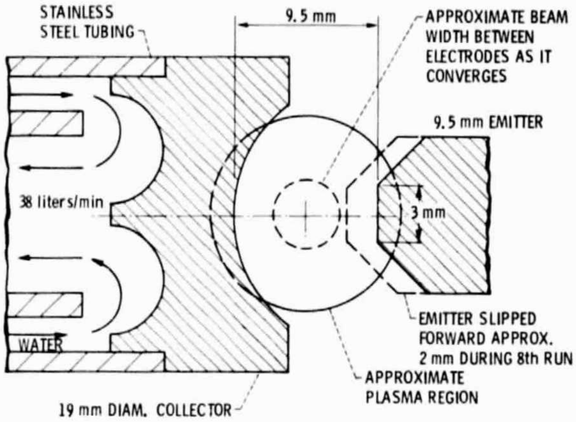

Figure 10. - Enlarged sectional view of emitter and water-cooled collector. Note dependence of contact surface area ratio on plasma position.

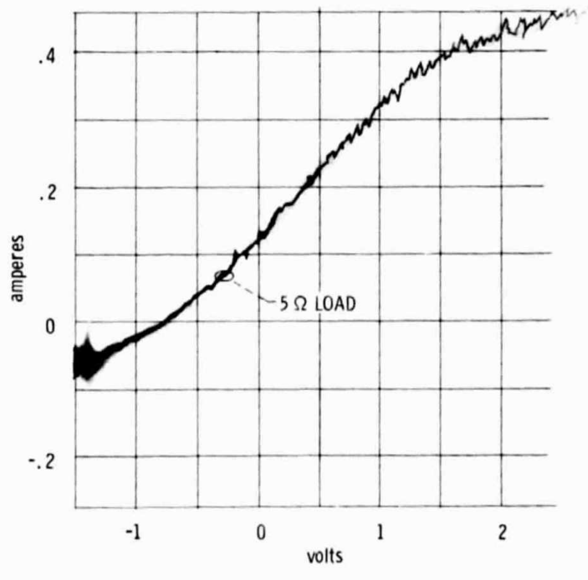

Figure 11. - Collector electron current vs collector-emitter potential difference. Bias at -1.5 volts. Steady-state point with 5 ohm load resistor.

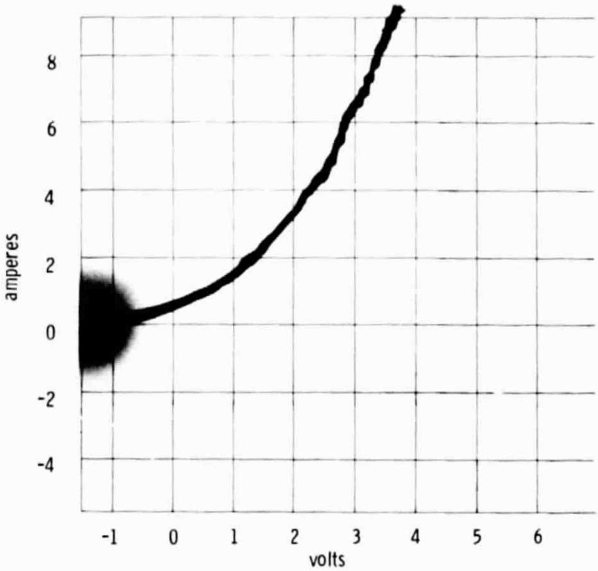

Figure 12. - Collector electron current vs collector-emitter potential difference. Bias at -1.5 volts. Run 8.

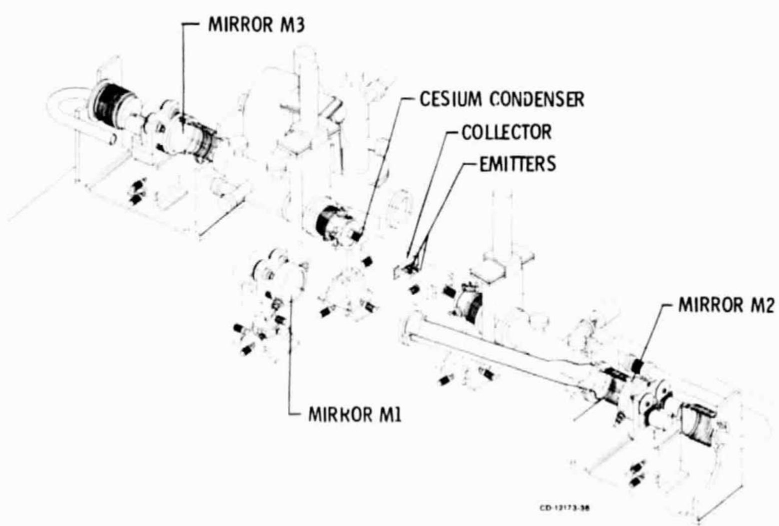

Figure 13. - The 10 kW TELEC system.

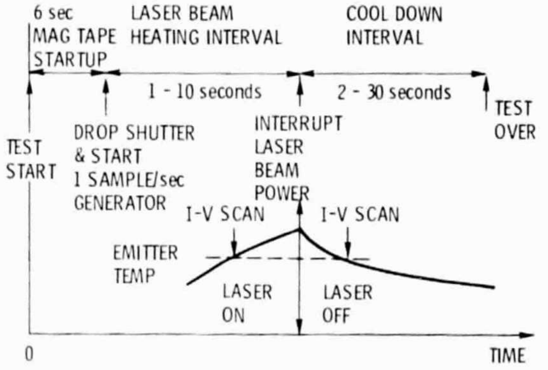

Figure 14. - Typical time sequence of events that will occur during a TELEC experiment. (Current-voltage (I-V) scans taken at approximately the same emitter temperature for both "laser on" and "laser off" conditions.