THERMO ELECTRONIC LASER ENERGY CONVERSION*

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INTRODUCTION

At the first symposium on laser energy conversion it was suggested (ref. 1) that an energy converter introduced more than a decade ago by Waymouth (ref. 2) might be used for the conversion of laser energy to electrical power. The present paper reports a preliminary study undertaken to determine the expected performance of such a device, and to better define inherent problems.

The Waymouth converter is closely related to the cesium vapor thermionic converter. For the laser converter, it is helpful to keep both devices in mind for comparison. The basic operation of the thermionic converter is described first. The potential distribution and essential geometry of the conventional thermionic converter are shown in figure 1a. The electrodes have about equal areas. Heat supplied to one electrode is absorbed by thermionic emission of a high current of electrons at the emitter temperature. The electron gas in the interelectrode plasma is then heated to a higher temperature through bombardment by the electrons from the emitter which have been accelerated across the plasma sheath V_E at the emitter.

Part of this investment of energy in the plasma is then extracted as the electron gas is cooled when it surmounts the sheath barrier V_C and reaches the collector. The remaining thermionic energy is dissipated in the arc drop V_d required to produce the positive ions which sustain the plasma. The asymmetry required to obtain a net electron flow through the plasma arises because of the thermionic emission at the emitter and because the higher sheath barrier at the emitter blocks the electron gas from returning to the emitter. The total output current is limited primarily by the saturation emission current from the emitter. Output voltage is limited by the arc voltage drop V_d needed to sustain the plasma and by the contact potential difference ($\phi_E - \phi_C$) between the converter electrodes.

Cesium vapor is used in the conventional thermionic converter since its low ionization potential minimizes the arc drop V_d, and its adsorption on the electrode surfaces gives sufficiently low values of the electrode work functions ϕ_E and ϕ_C. About 25 percent of the original energy delivered to the electrons is delivered as electrical power to the external circuit. The remainder is dissipated in the arc drop (~15 percent) and in the collector (~60 percent).

Figure 1b shows the essential geometry and potential distribution for the originally-described Waymouth converter. This device is similar to the thermionic converter except that the primary energy input is directly into the plasma instead of through the emitter. As in the thermionic converter, the hot electron gas in the plasma (heated by rf in Waymouth's demonstration) is cooled

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by collection across a large collector sheath V_C. The asymmetric flow of the electron gas into the collector is obtained by having the emitter area much smaller than the collector area. The collected electrons are replaced by thermionic emission from the emitter. Waymouth experimentally demonstrated an overall energy conversion efficiency of 36 percent with a plasma electron temperature T_e corresponding to an average electron energy $kT_e \simeq 2$ eV. He estimated this would approach 55 percent at higher electron temperatures.

The thermo electronic laser energy converter (TELEC) considered here is essentially a Waymouth converter with the input energy supplied by a high energy laser beam. It is shown that the constraints of this application cause the operating conditions for the TELEC to be substantially different from those envisioned by Waymouth and, in fact, that these conditions more closely approach those for the thermionic converter. The geometry for this initial examination is concentric cylindrical electrodes with the laser energy introduced axially as shown in figure 2.

The calculations and results of this study are only outlined here. Further details are described in a technical summary report (ref. 3).

RADIATION BALANCE

The description of a TELEC device requires a detailed examination of the processes of laser absorption in the interelectrode plasma and of the processes of subsequent re-radiation of this energy. The only radiation considered here is the 10.6-μ line of the CO_2 laser. The dominant laser absorption processes are electron-ion and electron-neutral inverse bremsstrahlung. The latter process dominates when there is a significant presence of neutrals. Radiation from the plasma is a very complicated process involving line radiation from specific transitions, continuum radiation from radiative recombination, and finally bremsstrahlung radiation. Both hydrogen and cesium are considered as candidate gases to determine the dependence of the results on ionization potential.

The calculation of laser absorption in hydrogen is based on the extensive work of Stallcop (ref. 4). The analytical results for hydrogen plasma excitation and radiation processes obtained by Bates, Kingston and McWhirter (ref. 5) and by McWhirter and Hearn (ref. 6) are also used here.

Approximate formulas of Stallcop (ref. 7) are used to calculate laser absorption in cesium. The results of Norcross and Stone (ref. 8) are used for the radiation properties of the cesium plasma.

Some results for the absorption and radiation characteristics for hydrogen plasmas (without electron cooling or heating) are shown in tables 1 and 2, and corresponding results for cesium plasmas are shown in tables 3 and 4. In the tables, the following quantities are shown as functions of plasma density n_e (cm^{-3}) and electron temperature $\hat{T}_e$ (°K):

f $\sim$ degree of ionization

P $\sim$ total pressure (torr)

R_A $\sim$ atomic (line, recombination) radiation intensity, W/cm^3

B_B ~ bremsstrahlung radiation intensity, W/cm^3

R_t ~ total radiation intensity, W/cm^3

K_{en} ~ absorption coefficient due to neutral atoms, cm^{-1}

K_{ei} ~ absorption coefficien due to ions, cm^{-1}

K_t ~ total absorption coefficient, cm^{-1}

Q_m ~ input radiation intensity required to maintain an isolated plasma, W/cm^2

From the calculations of radiation balance it is evident that high plasma densities ($n_e > 10^{15}$ cm^{-3}) are required to obtain reasonable stopping lengths ($1/K_t < 10$ m). It is also evident that the laser flux required to achieve this plasma density is very high for cesium ($\gtrsim 10^4$ W/cm^2) and is generally one to two orders of magnitude higher for hydrogen. For this reason, a detailed TELEC performance analysis is made only for cesium. These results show that for a significant presence of neutrals, electron-neutral inverse bremsstrahlung is the dominant absorption process, and line radiation is the dominant radiation from the plasma. For essentially fully ionized plasmas, electron-ion inverse bremsstralung is the dominant absorption process and recombination is the dominant plasma radiation process.

An important consequence of the high plasma density needed for stopping the laser beam in the TELEC is the possibility of significant effects arising from loss of ions to the electrodes. The energy required to produce these ions is potentially a serious energy loss in the TELEC. The maximum currents possible (twice the random ion current) are shown in figure 3. Actually, the ion losses will be substantially less than indicated in figure 3. The ion-atom scattering cross section is very large in cesium due to resonance charge exchange. The diffusion of ions to the electrodes therefore will be greatly impeded in the presence of neutral atoms. This is true even for fully ionized plasmas since ions which leave the plasma return as atoms, causing large ion density gradients and reduced ion currents near the electrodes. If necessary, ion currents can be reduced still further by the use of a background gas, such as argon, that has a large ion scattering cross section but a low electron scattering cross section. Since a detailed calculation of ion losses is quite complex, and since it is estimated that the resulting effects can be neglected for a first approximation, these effects are not included in the following TELEC performance estimates.

DESCRIPTION OF TELEC OPERATION

In order to calculate the performance characteristics of the TELEC it is necessary to develop analytical expressions for the various converter phenomena. These expressions, given in detail in reference 3, involve the following processes:

1. Plasma particle transport phenomena involving both electron-neutral and electron-ion interactions.

2. Sheath phenomena at the plasma boundary based on particle flux conservation.

3. Emission and work function effects for surfaces with absorbed cesium.

4. Emitter thermal balance involving black-body radiation, plasma radiation and electron cooling.

5. Plasma ionization and multiple component ideal gas behavior.

6. Overall energy balance

To these must be coupled the plasma radiation and absorption effects discussed above. This large system of simultaneous, nonlinear, analytical expressions is solved simultaneously to obtain solutions for all descriptive parameters of the device at various operating points.

Figures 4 through 8 show the electrical output characteristics and efficiency η of TELEC operation calculated for a variety of design variables. because of the very large number of variables, the complexity of the calculations, and the absence as yet of clearly-defined engineering and system constraints, it has not been possible to establish an optimum region of operation. The set of operating conditions for figure 4 are therefore chosen somewhat arbitrarily as a specific reference case for illustration of approximate magnitude of the variables, and for illustration of the effect of changing each design variable in figures 5 through 8.

DISCUSSION OF RESULTS

Laser-Maintained Plasmas

Figure 9 shows that the laser power required to maintain a constant-pressure plasma at first increases with increasing electron temperature and then decreases as complete ionization is approached. This occurs because the plasma density and atomic radiation increase rapidly as the laser radiation initially heats and progressively ionizes the plasma; but as full ionization approaches, the plasma density becomes constant and the atom-electron inverse bremsstrahlung absorption and atomic radiation rapidly disappear with the disappearance of the atoms. This region near full ionization is the typical plasma condition for practical TELEC operation since it results in minimum converter length and radiation losses for a given energy conversion power density requirement.

Another potentially important aspect of laser-maintained plasmas is that above the maximum in figure 9 the dissipation of laser energy in a constant-pressure, isolated plasma tends to increase faster than the plasma can re-radiate this energy; that is, a fluctuation of the electron temperature upward tends to increase the absorption and thus further increase the electron temperature, and vice versa. This suggests that the absorption process may be unstable and that ionization waves may occur.

Although investigation of this complex phenomenon is beyond the scope of this study, it deserves further attention for the following reasons. First, it could profoundly increase or decrease the absorption length, and therefore could critically affect the feasibility of the TELEC. Second, if laser radiation can directly drive strong, coherent density waves in a plasma, this could lead to a plasma-laser rf generator which might be superior to the TELEC.

Feasibility of TELEC

Efficiency – Inspection of figures 4 through 8 shows that maximum efficiencies in the region of 30 to 45 percent are computed for a TELEC operating in the vicinity of the arbitrary and therefore probably off-optimum, reference case (fig. 4). In general, it is likely that the operating point of a practical device would be chosen to be at a voltage somewhat less than that for maximum efficiency (~ 2.0 V in fig. 4) since absorption length $L = K_T^{-1}$ (and also device length) is significantly smaller at lower voltages. In fact, if system weight is more important than efficiency, optimum operation would tend toward the point of maximum output power density (12 W/cm^2 at 1.0 V in figure 4, where efficiency is 26 percent).

It is likely that the optimum operating condition occurs at a higher cesium pressure than the 2 torr reference value. As shown in figure 5, doubling the pressure significantly increases the efficiency and power density and about halves the absorption length. Higher efficiencies also are obtained at larger device diameter D_C and higher laser power density Q but, as seen in figures 6 and 7, these changes alone cause a significant increase in absorption length. The shorter abosprtion length can be mostly recovered by increasing the cesium pressure, however.

Electrode materials – The materials parameters used in the analysis represent the present state of practical electrode development in thermionic converters. The value, $\phi_o = 5.0$ eV for the vacuum work function of the emitter, can be readily achieved by available materials (e.g. oriented rhenium, and oxygenated tungsten). Preliminary exploration indicates that this value is near optimum for the reference case. The required emitter temperatures indicated in figures 4 through 8 (that is, 1600 – 1900° K) coincide with the temperature range of thermionic converter operation where similar electrodes have been operated in a substantial number of devices continuously for several years without degradation.

The value $\phi_C = 1.5$ eV is the collector work function which is obtained spontaneously when most structural metals (e.g. nickel, stainless steel, copper, molybdenum, niobium, etc.) are operated in cesium vapor under typical collector conditions. The effect of collector back-emission in the TELEC is not known. However, if the criterion for thermionic converter collector operation applies in this case, the optimum collector operating temperature for $\phi_C = 1.5$ eV would be near 900°K. This is an important consideration for space-power applications because this is near the optimum temperature for small, lightweight radiators constructed of ordinary structural metals.

A substantial program is presently under way to develop lower work function surfaces for thermionic converter collectors. Values of $\phi_C \simeq 1.3$ eV have been observed for several potentially useful materials, and it is hoped that surfaces similar to the 1.0 eV, S-1 commercial photocathode can be developed also for this application. As can be seen in figure 8, the use of a 1.0 eV collector would significantly increase the efficiency of TELEC operation. It should be recognized, however, that this would probably require a significantly low collector (heat rejection) temperature, probably near 650°K.

Absorption length – The absorption lengths occuring in the reference case, that is, of the order of 10 m for 10.6-μ laser radiation, at first seem to be excessive for a practical device. Specifically, this would mean that only about 60 percent of the laser radiation energy would be absorbed in a 10-m long TELEC, with a corresponding reduction in efficiency. Furthermore, a 10-m long TELEC array may be undesirable from structural and weight considerations. However, a reflector at the exit end of the TELEC cylinder (fig. 2), which allowed a second pass through the device, would permit capture of up to about 85 percent of the incident beam energy, or would allow the length of the TELEC to be halved. Further increases in capture efficiency or decreases in length, or both, could be obtained by constructing the TELEC collector as a cavity with mirrors at both ends; the mirrors result in multiple passes of the laser beam through the device.

Laser beam intensities – The incident radiation intensities required for typical TELEC operation at 10.6 μ that is, 10^4 to 10^6 W/cm^2, also may be excessive by present standards. The ability to achieve such intensities is crucially dependent on collector optics, and on the ability to achieve multiple passes of the beam through the device.

It should be recognized that the absorption length and required laser beam intensity are essentially inversely proportional to the square of the wavelength of the incident radiation. Therefore efficient TELEC operation probably is not feasible at wavelengths much shorter than 10.6 μ, and it becomes much more attractive at longer wavelengths.

Alternate sets of design parameters to those in the reference case can be chosen that result in absorption lengths and laser beam intensities an order of magnitude less than those for the reference case, but with significant reductions in conversion efficiency and output power density. It is clear that a system design study is required to evaluate these trade-offs.

Comparison with the Waymouth and Thermionic Converters

It is instructive at this point to examine briefly how operation under TELEC conditions differs from the operation of the Waymouth converter, since the TELEC is more of an "electron superheat" version of a thermionic converter than a Waymouth converter. Figure 10 is a potential diagram illustrating the operating conditions at Point A of figure 4. It can be seen that most of the energy of the hot electrons from the plasma is first delivered to the emitter, rather than to the collector as in the Waymouth converter. The electron energy flow therefore is as follows.

The energy abosrbed from the laser beam by the plasma is mostly transferred to the emitter. The electrons in the emitter absorb $\phi_E + 2\,kT_E$ as they are emitted (evaporate) at temperature T_E. They are then "superheated" to an electron temperature T_e in the plasma by the laser radiation, and absorb an energy $V_C + 2\,kT_e$ from the plasma as they reach the collector. The electrons dissipate $\phi_C + 2\,kT_e$ as reject heat in the collector, and deliver their remaining energy V_o to the external circuit as they are returned to the emitter.

The primary effect of the superheat portion of the cycle is to allow the plasma electrons to surmount a much larger barrier at the collector, and thereby to deliver a correspondingly larger output energy for each unit of heat rejected; that is, at a higher efficiency. From a thermodynamic viewpoint, this extends the Carnot temperature interval from the emitter temperature T_E to the much higher plasma electron temperature T_e. Since the efficiency of the thermionic energy conversion process is ideally about 60 to 70 percent of Carnot efficiency, the efficiency of such a "superheated" thermionic converter is inherently much greater than that obtainable in the conventional thermionic converter at feasible emitter temperatures.

A design variable which may have a profound effect on TELEC performance is the fraction of incident laser radiation that is captured directly by the emitter, that is, without first being absorbed by the plasma. For the reference case, allowing 15 percent of the laser beam to be directly captured by the emitter causes the overall maximum efficiency to increase from 35 percent to over 42 percent. The basic and engineering implications of operation with the laser energy input divided between the emitter and plasma have not been adequately explored as yet. However, it may be advantageous to supply only the heat to the plasma necessary for the superheat energy and for sustaining the required plasma density to intercept this energy, and to deliver the remainder directly to the emitter.

SUMMARY

Preliminary evaluation suggests that the TELEC concept can potentially convert 25 to 50 percent of incident laser radiation into electric power at high power densities and high waste heat rejection temperatures. Relatively high laser beam intensities (10^4 to 10^6 W/cm^2) and long absorption lengths (1 – 100 m) appear to characterize typical operation with 10.6 μ incident radiation. Detailed system studies, including consideration of collector optics for concentration and multiple passes of the laser beam through the device, and the possibility of longer wavelength laser radiation, are required for assessment of feasibility.

Two important basic aspects of device operation deserve further analysis and experimental evaluation. The possible instability of laser radiation absorption in plasmas under TELEC conditions would profoundly affect the feasibility of the concept, and could possibly lead to direct rf generation by laser radiation in such plasmas. Also, it is possible that interception of most of the laser beam by the emitter, and use of only a small portion to maintain and "superheat" the plasma, may be preferred mode of operation that could result in a substantially higher efficiency than for the reference case studied. Operation in this mode also may significantly relieve some of the design constraints imposed by full beam absorption in the plasma.

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TABLE 1. – HYDROGEN LOG $N_E = 15$[a]

Quantity	T_e, °K					
	4000	8000	16000	32000	64000	128000
f	6.04×10^{-13}	4.1×10^{-4}	.938	.9997	1.00	1.00
P	6.86×10^{11}	2.0×10^{3}	3.42	6.63	13.25	26.5
R_A	7.75×10^{4}	2.40×10^{2}	9.28	1.35	.460	2.31×10^{-1}
R_B	8.98×10^{-3}	1.27×10^{-2}	1.80×10^{-2}	2.54×10^{-2}	3.59×10^{-2}	5.08×10^{-2}
R_T	7.75×10^{4}	2.40×10^{2}	9.30	1.38	4.96×10^{-1}	.282
R_A/R_B	8.63×10^{6}	1.89×10^{4}	517	53.3	12.8	4.55
K_{en}	7.70×10^{5}	1.18×10^{-3}	3.05×10^{-8}	9.54×10^{-11}	2.96×10^{-12}	2.74×10^{-13}
K_{ei}	1.2×10^{-4}	4.50×10^{-5}	1.79×10^{-5}	7.34×10^{-6}	3.04×10^{-6}	1.26×10^{-6}
K_T	7.70×10^{5}	1.23×10^{-3}	1.80×10^{-5}	7.34×10^{-6}	3.04×10^{-6}	1.26×10^{-6}
Q_m	1.01×10^{-1}	1.96×10^{5}	5.16×10^{5}	1.84×10^{5}	1.51×10^{5}	1.84×10^{5}

[a]Plasma density

TABLE 2. – HYDROGEN LOG $N_E = 16$[a]

Quantity	T_e, °K					
	4000	8000	16000	32000	64000	128000
f	3.29×10^{-13}	2.44×10^{-4}	.91	.9997	1.00	1.00
P	1.26×10^{13}	3.39×10^{4}	34.7	66.25	132.5	265
R_A	7.28×10^{6}	2.50×10^{4}	8.83×10^{2}	1.25×10^{2}	4.08 x 10'	2.04 x 10'
R_B	8.98×10^{-1}	1.27	1.80	2.54	3.59	5.08
R_T	7.28×10^{6}	2.50×10^{4}	8.86×10^{2}	1.27×10^{2}	4.44 x 10'	25.49
R_A/R_B	8.11×10^{6}	1.97×10^{4}	4.92×10^{2}	4.91 x 10	1.14 x 10'	4.02
K_{en}	1.41×10^{8}	2.0×10^{-1}	4.40×10^{-6}	1.17×10^{-8}	3.27×10^{-10}	2.69×10^{-11}
K_{ei}	1.20×10^{-2}	4.51×10^{-3}	1.79×10^{-3}	7.34×10^{-4}	3.04×10^{-4}	1.26×10^{-4}
K_T	1.41×10^{8}	2.05×10^{-1}	1.80×10^{-3}	7.34×10^{-4}	3.04×10^{-4}	1.26×10^{-4}
Q_m	5.15×10^{-2}	1.22×10^{5}	4.91×10^{5}	1.70×10^{5}	1.34×10^{5}	1.62×10^{5}

[a]Plasma density

TABLE 3. – CESIUM LOG $N_E = 15$[a]

Quantity	T_e, °K				
	2000	4000	6000	8000	10000
f	3.2×10^{-5}	.89	.9986	.9999	1.000
P	6.4×10^{-3}	.88	1.24	1.66	2.07
R_A	4.34×10^{2}	2.626	.572	.244	.138
R_B	6.35×10^{-3}	8.98×10^{-3}	1.10×10^{-2}	1.27×10^{-2}	1.42×10^{-2}
R_T	4.34×10^{2}	2.64	.583	.257	.152
R_A/R_B	6.8×10^{4}	2.92×10^{2}	52.0	19.2	9.72
K_{en}	.120	6.67×10^{-7}	8.92×10^{-9}	9.32×10^{-10}	2.29×10^{-10}
K_{ei}	3.61×10^{-4}	1.20×10^{-4}	6.70×10^{-5}	4.51×10^{-5}	3.34×10^{-5}
K_T	.120	1.21×10^{-4}	6.70×10^{-5}	4.51×10^{-5}	3.34×10^{-5}
Q_m	3.61×10^{3}	2.18×10^{4}	8.71×10^{3}	5.70×10^{3}	4.56×10^{3}

[a]Plasma density

TABLE 4. – CESIUM LOG $N_E = 16$[a]

Quantity	T_e, °K				
	2000	4000	6000	8000	10000
f	3.39×10^{-6}	.43	.98	.998	.9996
P	6.1×10^{5}	13.7	12.5	16.6	20.7
R_A	4.34×10^{4}	2.49×10^{2}	52.0	21.6	12.0
R_B	6.35×10^{-1}	8.98×10^{-1}	1.10	1.27	1.42
R_T	4.34×10^{4}	2.50×10^{2}	53.1	22.9	13.4
R_A/R_B	6.8×10^{4}	2.77×10^{2}	47.3	17.0	8.46
K_{en}	1.135×10^{2}	7.01×10^{-4}	1.08×10^{-5}	1.24×10^{-6}	3.20×10^{-7}
K_{ei}	3.61×10^{-2}	1.20×10^{-2}	6.70×10^{-3}	4.51×10^{-3}	3.34×10^{-3}
K_T	1.136×10^{2}	1.27×10^{-2}	6.71×10^{-3}	4.51×10^{-3}	3.34×10^{-3}
Q_m	3.82×10^{2}	1.97×10^{4}	7.91×10^{3}	5.08×10^{3}	4.03×10^{3}

[a]Plasma density

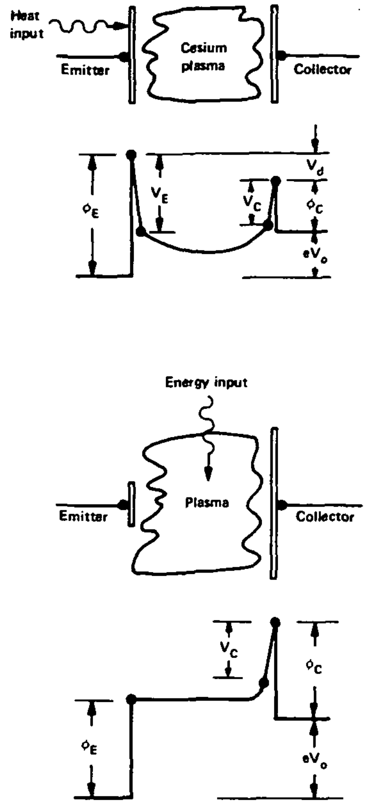

Figure 1.– Geometry and potential distribution.

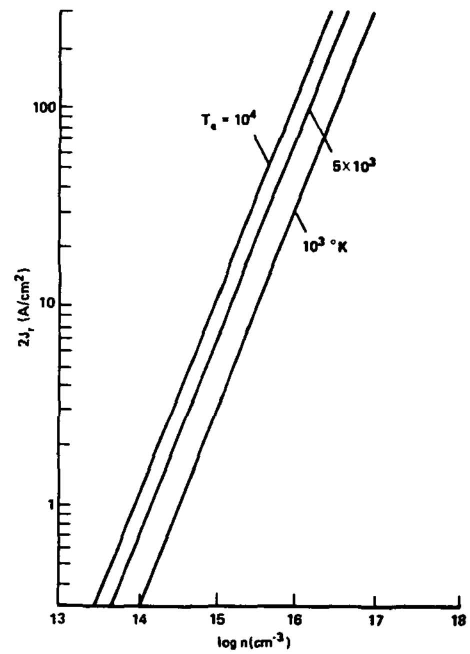

Figure 3.– Twice random ion current.

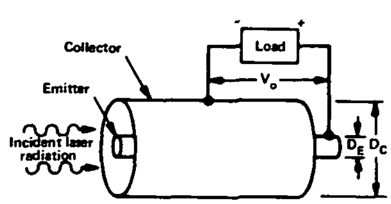

Figure 2.– Elementary TELEC configuration.

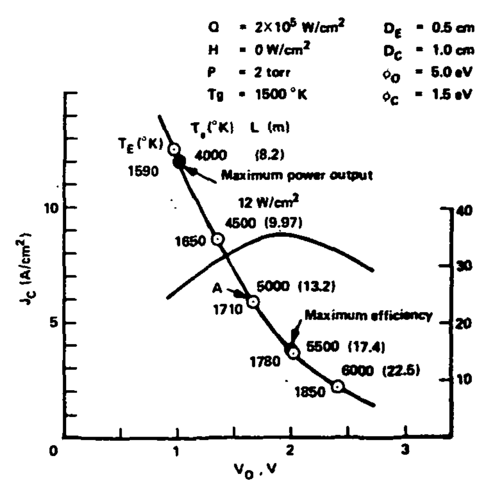

Figure 4.– Electrical output characteristics and efficiency η of TELEC.

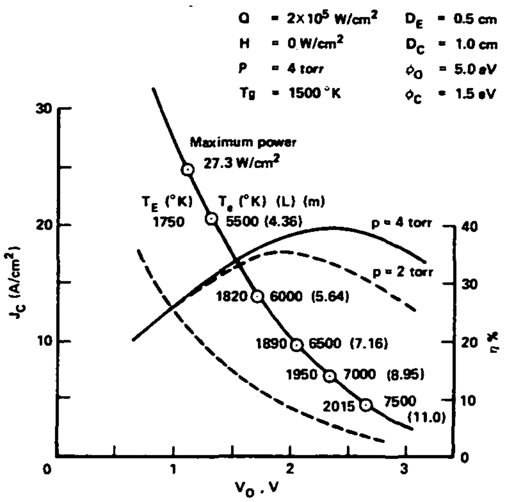

Figure 5.– Electrical output characteristics and efficiency η of TELEC; p = 2 torr.

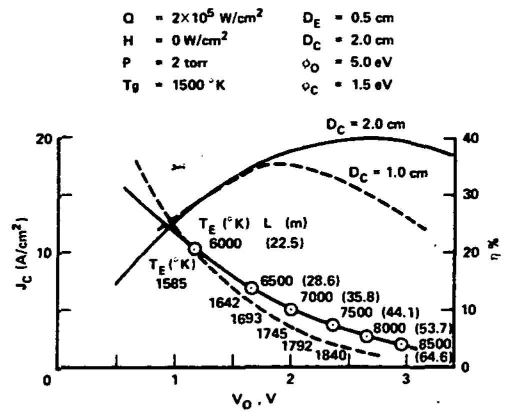

Figure 6.– Electrical output characteristics and efficiency η of TELEC; D_C = 2 cm.

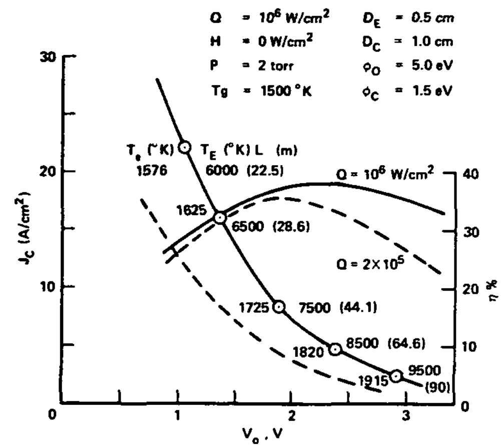

Figure 7.– Electrical output characteristics and efficiency η of TELEC; Q = 10^6 W/cm^2.

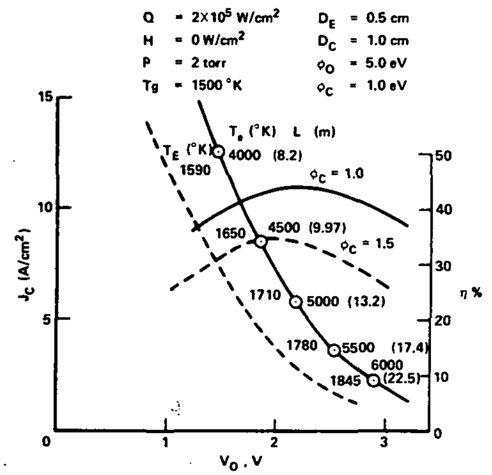

Figure 8.– Electrical output characteristics and efficiency η of TELEC; Q_c = 1.5 eV.

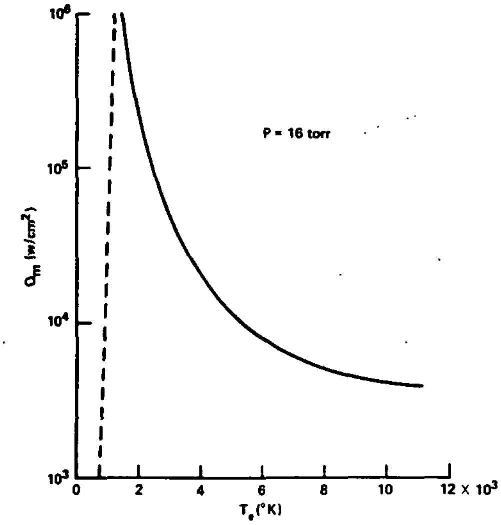

Figure 9.– Laser maintenance flux for cesium.

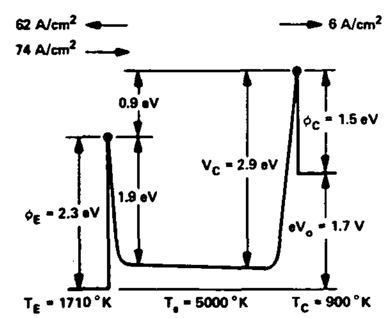

Figure 10.– Conditions at point A in figure 5.

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DISCUSSION

Dick Stirn, J. P. L. – Could you go over again how you calculate your efficiencies?

Answer: Yes. First of all we take a unit length of the device. The laser radiation is decreasing with length. It's the ratio of the electrical power out to the total input laser power absorbed in that unit length. So, for example, if you have a 10-cm-diameter device, that's about 30 cm around so you would have 10 W/cm^2 times 30 cm or 300 W per centimeter of device length.

Tom Karras, General Electric – I'm a little confused on the effects of increasing the pressure. At one point you mentioned that you would increase the efficiency, but later on you said the reverse.

Answer: That was the one exception to that statement and I didn't want to go back and correct it! The pressure, in the couple of cases we have done – Lorin, why didn't you run another case? – was increasing the efficiency as we raised it. But we did not run high enough to see where it is optimum – it must turn over somewhere, however. Our results, 30 percent, are not, therefore, optimum. We don't know how high it will go. When you increase the pressure two good things happen – the efficiency goes up and you shorten the device.

Abe Hertzberg, University of Washington – I thought this was a very interesting paper, but I don't know why you are worrying so much about the intensity problem. Is it because you do not want to add a collector?

Answer: No. For one thing, the emitter is sitting there in the middle of the device. If it's a long device, you are going to have to aim the beam along this long path.

Abe Hertzberg, University of Washington – I think that, compared with some of the other problems, is not a big concern.

Don Nored, NASA Lewis Research Center – Just one comment on your stability work. This is very similar to some work we have been sponsoring at Physical Sciences, Inc. We should intercompare the studies.