

General Disclaimer

One or more of the Following Statements may affect this Document

- This document has been reproduced from the best copy furnished by the organizational source. It is being released in the interest of making available as much information as possible.
- This document may contain data, which exceeds the sheet parameters. It was furnished in this condition by the organizational source and is the best copy available.
- This document may contain tone-on-tone or color graphs, charts and/or pictures, which have been reproduced in black and white.
- This document is paginated as submitted by the original source.
- Portions of this document are not fully legible due to the historical nature of some of the material. However, it is the best reproduction available from the original submission.

**NASA TECHNICAL
MEMORANDUM**

NASA TM-73844

(NASA-TM-73844) HIGH-TEMPERATURE,
HIGH-POWER-DENSITY THERMIONIC ENERGY
CONVERSION FOR SPACE (NASA) 17 p HC A02/MF
A01 CSCI 201

N78-13890

Unclas

G3/75 55212

NASA TM-73844

HIGH-TEMPERATURE, HIGH-POWER-DENSITY
THERMIONIC ENERGY CONVERSION FOR SPACE

by James F. Morris
Lewis Research Center
Cleveland, Ohio 44135
November 23, 1977



1. Report No. NASA TM-73844	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle HIGH-TEMPERATURE, HIGH-POWER-DENSITY THERMIONIC ENERGY CONVERSION FOR SPACE		5. Report Date November 23, 1977	
		6. Performing Organization Code	
7. Author(s) James F. Morris		8. Performing Organization Report No. E-9431	
		10. Work Unit No.	
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135		11. Contract or Grant No.	
		13. Type of Report and Period Covered Technical Memorandum	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code	
		15. Supplementary Notes	
16. Abstract <p>Theoretic converter outputs and efficiencies indicate the need to consider thermionic energy conversion (TEC) with greater power densities and higher temperatures within reasonable limits for space missions. This parametric presentation of converter-output power density, voltage, and efficiency as functions of current density covers 1400-to-2000 K emitters with 725-to-1000 K collectors. The results encourage utilization of TEC with hotter-than-1650 K emitters and greater-than-6W/cm² outputs to attain better efficiencies, greater voltages, and higher waste-heat-rejection temperatures for multihundred-kilowatt space-power applications. For example 1800 K, 30 A/cm² TEC operation for NEP compared with the 1650 K, 5 A/cm² case should allow much lower radiator weights, substantially fewer and/or smaller emitter heat pipes, significantly reduced reactor and shield-related weights, many fewer converters and associated current-collecting bus bars, less power conditioning, and lower transmission losses. Integration of these effects should yield considerably reduced NEP specific weights. So true overall system optimization with parametric TEC inputs is desirable.</p>			
17. Key Words (Suggested by Author(s)) Thermionic energy conversion Nuclear electric propulsion		18. Distribution Statement Unclassified - unlimited STAR Category 75	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages	22. Price*

HIGH-TEMPERATURE, HIGH-POWER-DENSITY
THERMIONIC ENERGY CONVERSION FOR SPACE

by James F. Morris
Lewis Research Center

SUMMARY

Theoretic converter outputs and efficiencies indicate the need to consider thermionic energy conversion (TEC) with greater power densities and higher temperatures within reasonable limits for space missions. This parametric presentation of converter-output power density, voltage, and efficiency as functions of current density covers 1400-to-2000K emitters with 725-to-1000K collectors. The results encourage utilization of TEC with hotter-than-1650K emitters and greater-than-6W/cm² outputs to attain better efficiencies, greater voltages, and higher waste-heat-rejection temperatures for multihundred-kilowatt space-power applications. For example 1800K, 30 A/cm² TEC operation for NEP compared with the 1650K, 5 A/cm² case should allow much lower radiator weights, substantially fewer and/or smaller emitter heat pipes, significantly reduced reactor and shield-related weights, many fewer converters and associated current-collecting bus bars, less power conditioning, and lower transmission losses. Integration of these effects should yield considerably reduced NEP specific weights. So true overall system optimization with parametric TEC inputs is desirable.

THERMIONIC ENERGY CONVERSION (TEC) FOR SPACE

Reliable, efficient, durable electric-generation systems with high power-to-weight ratios are essential for future space missions-- particularly those with near-megawatt requirements. Such power-system qualities characterize thermionic converters. In addition TEC embodies simplicity, light weights, small volumes, negligible mechanical stresses, no moving parts, modularity for space safety, great power densities, and high temperatures which allow low-mass radiators. Thermionic converters are also adaptable: They generate electricity directly from thermal energy of nuclear, solar, or chemical origin.

At present the major space TEC application appears to be nuclear electric propulsion (NEP) (refs. 1 to 3). But analyses that properly recognize the high-temperature, high-power-density advantages of TEC may prove it valuable for solar, radioisotope, and topping utilization in space also. Unfortunately, though, some design-feasibility

ORIGINAL PAGE IS
OF POOR QUALITY

studies assume without optimization that low or intermediate temperatures and small power densities are required for space TEC (refs. 1 to 3).

The present report offers some theoretic results that emphasize the need to consider greater power densities and higher temperatures within reasonable limits for TEC in space: Converter outputs and efficiencies for 1400-to-2000K emitters with 725-to-1000K collectors make this point.

SOME TEC BACKGROUND AND THEORY

George Hatsopoulos and Elias Gyftopoulos, long-term international TEC experts, as well as B. Ya. Moyzhes and G. Ye. Pikus, two other world-renowned TEC contributors, elaborate on the thermionic-converter heat engine in their reference works (refs. 4 and 5): For such a device the heat supplied isothermally at absolute temperature T_h is $\int dQ_h = \int T_h dS_h = T_h \int dS_h$, where $\int dS_h$ is the entropy decrease of the source. Similarly the heat rejected isothermally at absolute temperature T_c is $\int dQ_c = \int T_c dS_c = T_c \int dS_c$, where $\int dS_c$ is the entropy increase of the sink. Then according to Carnot the ideal heat-engine efficiency is

$$\lim_{\int dS_c \rightarrow \int dS_h} \left[\eta = \frac{\int dQ_h - \int dQ_c}{\int dQ_h} = \frac{T_h - T_c}{T_h} - \frac{T_c}{T_h} \left(\frac{\int dS_c}{\int dS_h} - 1 \right) \right] = \frac{T_h - T_c}{T_h} = \eta_c$$

From this basic principle comes the expectation that in general raising the emitter temperature or lowering the collector temperature tends to increase TEC efficiency. Local exceptions to this corollary may occur for optimizations of specific converters. But with freedom of selection for electrode types and materials, enhancement modes, and operating conditions this temperature generalization for TEC efficiency prevails.

Occasionally, disseminated information apparently contends with the idea that TEC efficiencies generally rise with increasing emitter temperatures (ref. 3). At such times reaffirmation of the validity of Nicolas Carnot's thermodynamic legacy seems appropriate. But merely pointing to the preceding equation is perhaps somewhat simplistic. So the present report relies on TEC output and efficiency calculations based on the assumptions used to produce pages IV-15 to IV-18 of ref. 3: "Back emission should be limited to 10%" for 1400, 1650, and 1800K emitters (2000K included also) with 725, 925, and 1000K collectors. However the present analysis deletes the ref. 3 assumptions that "converter power density should be set at 5 to 6 W_e/cm^2 " and that the highest emitter temperature should be used only with the highest collector temperature. Also, assumed interelectrode

losses near zero by FY 81 (ref. 6) allow estimates of collector work functions.

The appropriate converter outputs are the current density,

$$J_0 = J_{SE} - J_R, \quad 1)$$

the electrode voltage,

$$V_0 = \phi_E - \phi_C - V_D - V_A = \phi_E - V_B - V_A, \quad 2)$$

the voltage at optimum-lead terminals,

$$V_{OL} = V_0 - 2 V_L, \quad 3)$$

the electrode power density,

$$P_0 = J_0 V_0, \quad 4)$$

and the effective power density with optimum leads attached to the converter,

$$P_{OL} = J_0 V_{OL} \quad 5)$$

Here ϕ_E and ϕ_C are emitter and collector work functions, V_D is the interelectrode voltage drop, $V_B = \phi_C + V_D$ is the barrier index or total internal loss, V_A is the equivalent auxiliary input voltage (not used in the present calculations), and V_L is the voltage loss required for optimum leads.

The current-density components correspond to emitter saturation,

$$J_{ES} = A (1-R_E) T_E^2 \exp(-\phi_E/kT_E), \quad 6)$$

which has a collector-saturation counterpart,

$$J_{CS} = A (1-R_C) T_C^2 \exp(-\phi_C/kT_C), \quad 7)$$

and to the reverse flow J_R , which includes reflections, backscattering, back emission, and other effects that diminish the output current density. In equations 6) and 7) A and k are Richardson and Boltzmann constants, T_E and T_C are emitter and collector temperatures, and R_E and R_C are emitter and collector reflection coefficients.

An important theoretic detail relates to a common inconsistency in the treatment of back emission (refs. 7 and 8): In generalized TEC terminology back emission subtracts from the emitter current in obtaining the net output current. This usual definition of back emission requires it to be only that part of the collector emission

ORIGINAL PAGE IS
OF POOR QUALITY

that reaches the emitter and thereby diminishes the output current according to a net-flow balance at the converter boundaries. Thus back emission is not the saturated collector emission given by equation 7), regardless of R_C modification, because the emission barrier is incorrect: This observation derives from the fact that, in the generally cited TEC power-producing mode, the emitter electron barrier (motive maximum) is a few tenths of a volt (the interelectrode voltage drop) above its collector counterpart. So during steady-state operation the preponderance of collector saturated emission cannot clear the emitter sheath, even in the absence of other deflecting encounters. Therefore most of the collector saturated emission must return to its source nullifying to a large extent its effect on the diminution of the net output current.

Unless the interelectrode loss is much closer to zero than to its currently common value of about a half volt, only a small fraction of the collector emission, the true back emission J_{BE} , will reach the emitter:

$$J_{BE} = A(1-R_{BE}) T_C^2 \exp(-V_B/kT_C) \quad 8)$$

In this equation the effective back-emission reflection coefficient R_{BE} comprises R_C and similar coefficients for all interelectrode mechanisms that return collector-emitted electrons to their source--except those for noncollisional repulsion by the emitter sheath. Thus, using equation 8) without R_{BE} produces a conservative estimate of the converter output current. Such an approximation seems reasonable for low cesium concentrations, reduced enhanced-mode pressures, and small interelectrode gaps. Of course, with zero interelectrode losses assumed (ref. 6 for FY 81) as well as negligible interelectrode-reflection effects, equations 7) and 8) become identical.

A simplified, yet reasonable estimate of TEC efficiency with optimum-lead losses (η_{OL}) embodies the previously discussed inputs (refs. 4 and 9):

$$\eta_{OL} = \frac{(J_{ES}-J_{BE}) \{ \phi_E - \phi_C - V_D - V_A - 2 \left[2.45 \times 10^{-8} \eta_{EC} (T_E^2 - T_C^2) / (2 - \eta_{EC}) \right]^{1/2} \}}{J_{ES}(\phi_E + 2kT_E) - J_{BE}(\phi_E + 2kT_C) + 5.7 \times 10^{-12} \left[0.05 + 7.5 \times 10^{-5} (T_E - 1000) \right] (T_E^4 - T_C^4)} \quad 9)$$

Here the last term of the denominator approximates nonelectronic thermal transport while the factor following the first 2 in the numerator represents the optimum-lead loss V_L . Deleting $2V_L$ from equation 9) transforms that expression into one for the TEC electrode efficiency η_{EC} used here to compute the optimum-lead loss. Of course, the electrode

efficiency is the true converter evaluation analogous to other power-generator performance ratings. But because of relatively high TEC current densities and low voltages the optimum-lead efficiency seems more pragmatic.

TEC-PERFORMANCE TRENDS

Theoretic TEC outputs and efficiencies for converters with 10-percent back emission and optimum leads appear parametrically in figures 1, 2, and 3 for 725, 925, and 1000K collectors. Each figure comprises plots of efficiency, voltage, and power density as functions of current density for 1400, 1650, 1800, and 2000K emitters.

Without exception, for a given collector temperature, all performance curves for higher emitter temperatures rise above those for the lower emitter temperatures. This observation would have gratified Nicolas Carnot.

The efficiency curves reach values very close to their maxima above 5 A/cm^2 for the 1400K emitters; 20 A/cm^2 for 1650K emitters; 30 A/cm^2 , 1800K; and 40 A/cm^2 , 2000K.

The two preceding paragraphs imply that studies of any TEC system should evaluate parametrically the effects of converters with emitters hotter than 1650K and current densities greater than 5 A/cm^2 (refs. 1 to 3). Table 1 for 925K collectors (refs. 2 and 3) further emphasizes this observation. The underlined Table 1 entries indicate output and efficiency improvements (for converters with optimum leads) resulting from raising the emitter temperature from 1650K to 1800K at 5 A/cm^2 and at 30 A/cm^2 .

These underlined values also reveal the significant output and efficiency gains for TEC operation at 1800K and 30 A/cm^2 as compared with 1650K and 5 A/cm^2 (refs. 1 to 3): The 28.5% increase in optimum-lead efficiency means lighter radiators and either more output power or smaller nuclear reactors and lighter shield-dependent weights for NEP. The 10.8% higher optimum-lead voltage requires less power conditioning capability and results in lower transmission-line losses for a given quantity of output power. The 560% gain in effective output power density allows many fewer converters and associated current-collecting bus bars for a given output-power level. And of course the higher emitter temperature (coupled with greater efficiency) enables the use of substantially fewer and/or smaller emitter heat pipes. This reduction in turn should produce significant decreases

ORIGINAL PAGE IS
OF POOR QUALITY

in shielding-related as well as reactor weights. The higher emitter temperature can also make possible considerably increased collector temperatures if parametric studies indicate the need for lower radiator weights (the T^4 influence).

The previously enumerated advantages of 1800K, 30 A/cm² TEC operation over the 1650K, 5 A/cm² case have obviously strong effects on NEP specific-weight reductions. So the importance of true overall system optimization with parametric TEC inputs should not be underestimated.

Omitted tabulations similar to those of Table 1 are also available for collector temperatures of 725K and 1000K. And as figures 1 to 3 attest, the order of performance remains unchanged: For a given collector temperature the highest emitter temperature produces the best TEC performance; the lowest emitter temperature gives the poorest TEC performance.

If the only emitter, collector combinations considered were 1400K with 725K, 1650K with 925K, and 1800K with 1000K all at 5.5 W/cm² as in reference 3, the TEC-output relationships would appear quite different from those in figures 1 to 3. But a parametric TEC-optimization study should evaluate each collector temperature with each emitter temperature. When existing converter-component capabilities preclude such pairings, appropriately directed technology advancements may render them possible in the near future.

Reference 3 states that "the higher temperature converters are limited to higher work function materials, and thus eventually extrapolate to lower operating efficiencies." But the 1800K emitter work functions in the table are obtainable with cesiated tungsten, for example, without invoking oxygenation. Such work functions are even more readily accessible with rhenium and still more easily attainable with iridium.

As for the collector work functions in the preceding table, they are well within reach of cesiated, oxygenated tungsten: This collector has a work-function minimum of 1.21 eV according to recent measurements (ref. 9). Unoxygenated minimum cesiated work functions run 1.45 eV for rhenium (ref. 4) and probably 1.4 or lower for 111 iridium (refs. 7, 8, and 10 to 14). And tungsten, rhenium, and iridium are all satisfactory for 1800K-emitter service.

Incidentally the calculations for figures 1 to 3 give results rather centrally located among those from other TEC efficiency models for 10% back emission and zero arc drop (Private communication with G. D. Fitzpatrick of Rasor Associates, Inc.). The variation occurs because of differences in loss approximations. A comparison of TEC efficiencies appear in Table 2.

Table 2 lists extremes of conditions primarily to compare TEC-efficiency models over wide ranges. But these values also strongly imply the desirability of high-temperature, high-power-density thermionic energy conversion for space.

ORIGINAL PAGE IS
OF POOR QUALITY

REFERENCES

1. Stearns, J. W., Jr.: Status Report on Nuclear Electric Propulsion Systems. AAS paper 75-164, Aug. 1975.
2. Pawlik, Eugene V.; and Phillips, Wayne M.: A Nuclear Electric Propulsion Vehicle for Planetary Exploration. J. Spacecr. Rockets, vol. 14, no. 9, Sep. 1977, pp. 518-525.
3. JPL/LASL Heat Pipe/Thermionic Reactor Technology Development Program. Progr. Rep. for Feb., Mar., Apr., May 1977, Jet Propulsion Lab., 1977.
4. Hatsopoulos, G. N.; and Gyftopoulos, E. P.. Thermionic Energy Conversion. Volume I: Processes and Devices. MIT Press, 1973.
5. Moyzhes, B. Y.; and Pikus, G. Y.: Termoemissionnyye Preobrazovateli i Nizkotemperaturnaya Plazma. Leningrad Inst. Semiconductors, Ioffe Polytech. Inst., USSR, Acad. Sci., 1973.
6. Shimada, K.: Chart Handouts for NASA, ERDA TEC Program Review. Advanced Thermionic Technical Program, Following IEEE Plasma Science Conference, Troy, New York, May 26, 1977.
7. Morris, James F.: NASA Thermionic-Conversion Program. NASA TM X-73644, 1977.
8. Morris, James F.: The NASA Thermionic-Conversion (TEC-ART) Program. Transactions on Plasma Science (to be published).
9. Huffman, F. N.; et al.: High Efficiency Thermionic Converter Studies. (TE 4202-12-77, Thermo Electron Corp.; NASA Contract NAS3-19866.) NASA CR-135125, 1976.
10. Swanson, L. W.: Fabrication and Surface Characterization of Composite Refractory Compounds Suitable for Thermionic Converters. Presented at the NASA ERDA TEC-ART (Thermionic-Energy Conversion Applied-Research-and-Technology) Program Review, Naval Research Laboratory, (Washington, D.C.), Jan. 1975.
11. Swanson, L. W.; and Strayer, R. W.: Field Electron-Microscopy Studies of Cesium Layers on Various Refractory Metals: Work Function Change. J. Chem. Phys. vol. 48, no. 6, 15 Mar. 1968, pp. 2421-2442.
12. Bell, A. E.; et al.: Single Crystal Work Functions and Behavior of Various Adsorbates on Metal Surfaces. (Field Emission Corp.; NASA Contract NAS3-11820.) NASA CR-72657, 1970.

13. Kroeger, Erich W.; Bair, Virginia L.; and Morris, James F.:
Diminiode Thermionic Conversion with 111-Iridium Electrodes.
NASA TM X-73492, 1976.
14. Morris, J. F.: The NASA Thermionic-Conversion (TEC-ART) Program.
NASA TM X-73610, 1977.

TABLE I: EFFECTS OF EMITTER TEMPERATURE AND CURRENT DENSITY ON THERMIONIC CONVERSION PERFORMANCE

Emitter Temp., K	1400	1650	1800	2000	1400	1650	1800	2000	1400	1650	1800	2000	1400	1650	1800	2000
Collector Temp., K	925	925	925	925	925	925	925	925	925	925	925	925	925	925	925	925
Current Density, A/cm ²	5	5	5	5	10	10	10	10	20	20	20	20	30	30	30	30
Output Voltage, V																
V _G	0.59	1.02	1.29	1.63	0.57	0.98	1.23	1.56	0.54	0.93	1.17	1.50	0.52	0.91	1.14	1.46
V _{OL}	0.53	0.93	1.18	1.52	0.50	0.88	1.12	1.44	0.47	0.84	1.07	1.37	0.45	0.81	1.03	1.33
Power Density, W/cm ²																
P ₀	3.0	5.1	6.4	8.1	5.7	9.8	12.3	15.6	10.7	18.7	23.5	29.9	15.6	27.2	34.3	43.8
P _{OL}	2.6	4.7	5.9	7.6	5.0	8.8	11.2	14.4	9.4	16.8	21.3	27.4	13.6	24.4	31.0	40.0
Efficiency, %																
η ₀	22.4	28.4	29.4	28.6	23.3	31.3	33.8	34.9	23.7	32.9	36.5	39.2	23.5	33.5	37.4	40.9
η _{OL}	17.4	23.5	24.9	24.5	17.7	25.4	28.0	29.6	17.7	26.3	29.7	32.7	17.5	26.4	30.2	33.8
Emitter Work Function, eV	2.12	2.55	2.80	3.15	2.04	2.45	2.70	3.03	1.95	2.35	2.59	2.91	1.90	2.29	2.53	2.48
Collector Work Function, eV	1.53	1.53	1.53	1.53	1.47	1.47	1.47	1.47	1.42	1.42	1.42	1.42	1.38	1.38	1.38	1.38

ORIGINAL PAGE IS
OF POOR QUALITY

TABLE 2: TEC EFFICIENCIES

Emitter Temp, K	60 A/cm ²		10 A/cm ²	
	Collector Temp = 725K	Collector Work Function \approx 1.0 eV	Collector Temp. = 1000K	Collector Work Function \approx 1.6 eV
2000	~ 40%	R. Breitwieser	~ 19%	
1400	~ 32%	"	~ 12%	
2000	~ 41%	Razor Associates, Inc.	~ 24%	
1400	~ 29.5%	"	~ 14%	
2000	~ 50%	Thermo Electron Corp.	~ 28%	
1400	~ 35.5%	"	~ 13%	
2000	~ 43.4%	J. Morris	~ 27%	
1400	~ 30.3%	"	~ 13%	

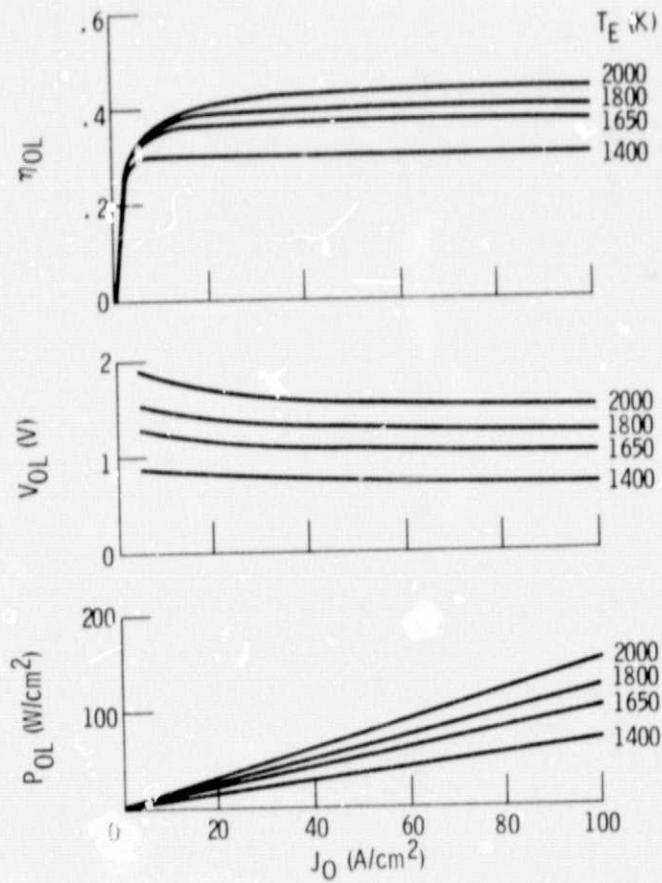


Figure 1. - Optimum-lead TEC efficiency (η_{OL}), voltage (V_{OL}), and power (P_{OL}) versus current (J_0) for four emitter temperatures (T_E) at a collector temperature of 725 K with 10 percent back emission.

ORIGINAL PAGE IS
OF POOR QUALITY

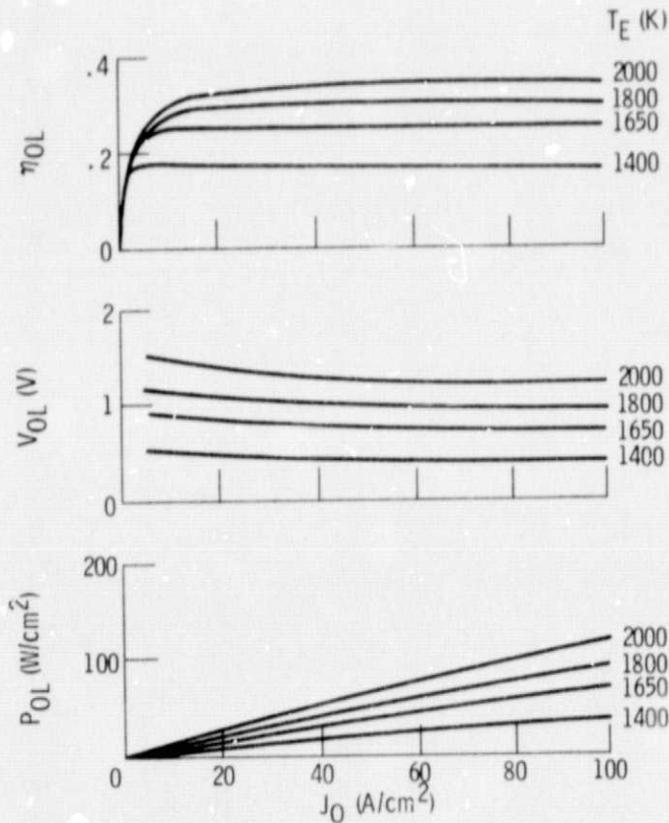


Figure 2 - Optimum-lead TEC efficiency (η_{OL}), voltage (V_{OL}), and power (P_{OL}) versus current (J_0) for four emitter temperatures (T_E) at a collector temperature of 925 K with 10 percent back emission.

ORIGINAL PAGE IS
OF POOR QUALITY

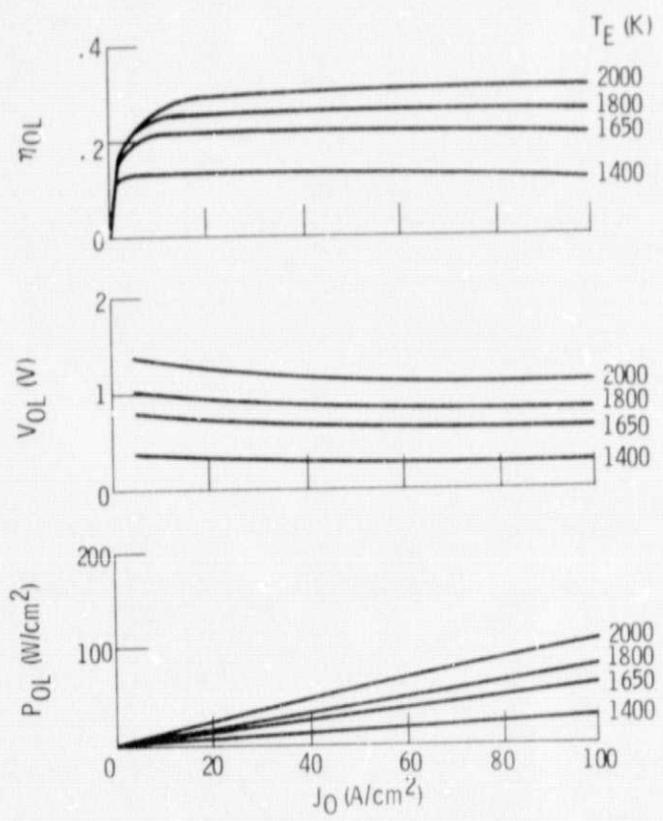


Figure 3. - Optimum-lead TEC efficiency (η_{OL}), voltage (V_{OL}), and power (P_{OL}) versus current (J_0) for four emitter temperatures (T_E) at a collector temperature of 1000 K with 10 percent back emission.