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

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SUMMARY

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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

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

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

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,

$$J_O = J_{SE} - J_R, \qquad 1)$$

the electrode voltage,

$$V_O = \phi_E - \phi_C - V_D - V_A = \phi_E - V_B - V_A, \qquad 2)$$

the voltage at optimum-lead terminals,

$$V_{OL} = V_O - 2\,V_L, \qquad 3)$$

the electrode power density,

$$P_O = J_O\,V_O, \qquad 4)$$

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

$$P_{OL} = J_O\,V_{OL} \qquad 5)$$

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,

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

which has a collector-saturation counterpart,

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

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

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:

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

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):

$$\eta_{OL} = \frac{(J_{ES}-J_{BE})\left\{\phi_E-\phi_C-V_D-V_A-2\left[2.45\times10^{-8}\,\eta_{EC}(T_E^{\,2}-T_C^{\,2})/(2-\eta_{EC})\right]^{1/2}\right\}}{J_{ES}(\phi_E+2kT_E)-J_{BE}(\phi_E+2kT_C)+5.7\times10^{-12}\left[0.05+7.5\times10^{-5}(T_E-1000)\right](T_E^{\,4}-T_C^{\,4})} \qquad 9)$$

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

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/cm^2 TEC operation over the 1650K, 5 A/cm^2 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/cm^2 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.

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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_O	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_O	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_O	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	24.9	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

TABLE 2: TEC EFFICIENCIES

Emitter Temp, K	60 A/cm^2 Collector Temp = 725K Collector Work Function ≃ 1.0 eV		10 A/cm^2 Collector Temp. = 1000K Collector Work Function ≃ 1.6 eV
2000	~ 40%	R. Breitwieser	~ 19%
1400	~ 32%	"	~ 12%
2000	~ 41%	Rasor 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%

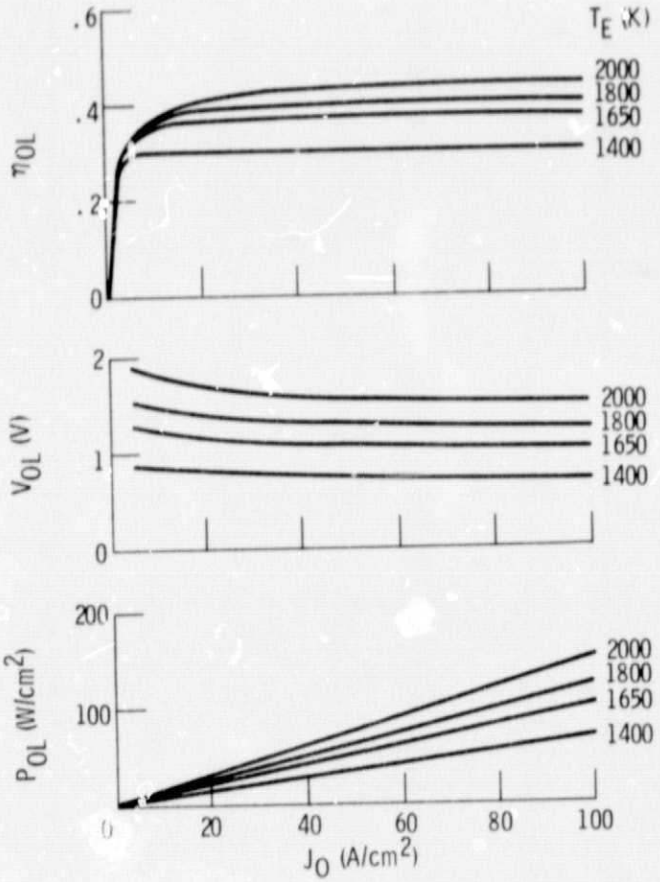

Figure 1. - Optimum-lead TEC efficiency (η_{OL}), voltage (V_{OL}), and power (P_{OL}) versus current (J_O) for four emitter temperatures (T_E) at a collector temperature of 725 K with 10 percent back emission.

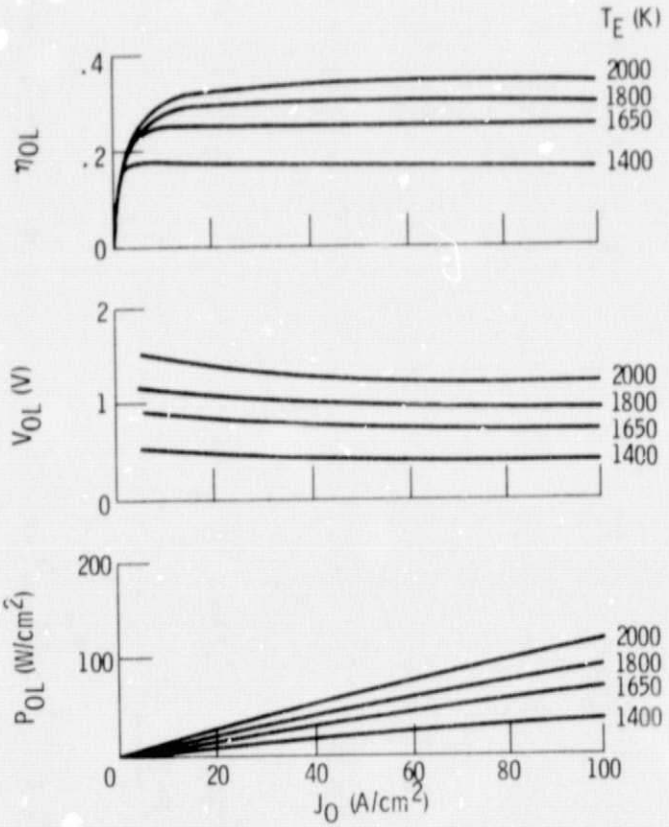

Figure 2. - Optimum-lead TEC efficiency (η_{OL}), voltage (V_{OL}), and power (P_{OL}) versus current (J_O) for four emitter temperatures (T_E) at a collector temperature of 925 K with 10 percent back emission.

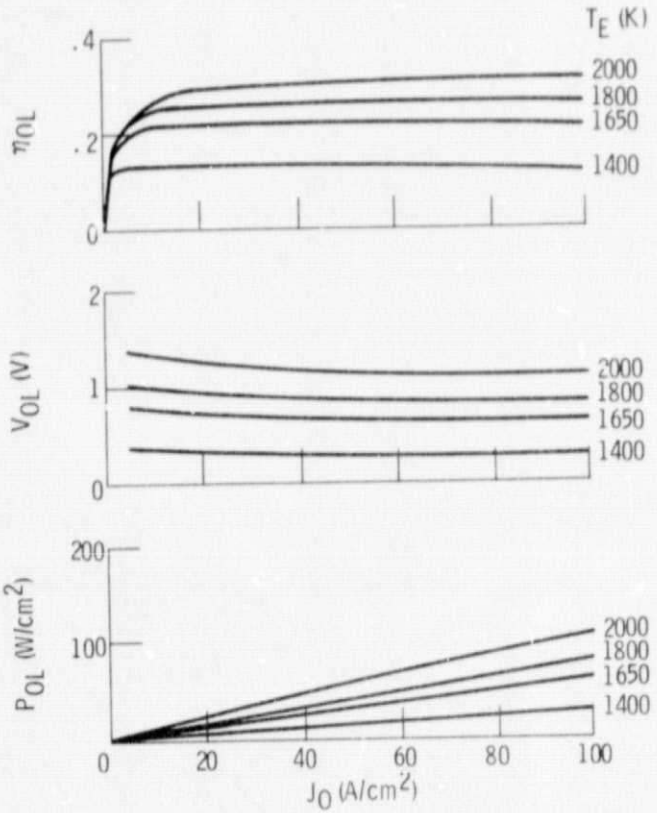

Figure 3. - Optimum-lead TEC efficiency (η_{OL}), voltage (V_{OL}), and power (P_{OL}) versus current (J_O) for four emitter temperatures (T_E) at a collector temperature of 1000 K with 10 percent back emission.