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OPTIMIZE OUT-OF-CORE THERMIONIC ENERGY CONVERSION FOR NUCLEAR ELECTRIC PROPULSION

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OPTIMIZE OUT-OF-CORE THERMIONIC ENERGY CONVERSION FOR NUCLEAR ELECTRIC PROPULSION

(Presentation for May 1978 IEEE International Conference on Plasma Science; Monterey, California)

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SUMMARY

Current designs for out-of-core thermionic energy conversion (TEC) to power nuclear electric propulsion (NEP) assign 1650K emitters, 5 to 6 W/cm^2 outputs, and 925K radiators (Koenig, Ranken, Salmi: J. Energy 1, 237, July-August 1977; Pawlik, Phillips: J. Spacecraft 14, 518, September 1977; other JPL publications cited in NASA TM-73844). But a UC, ZrC reactor with a Brayton generator can provide comparable specific weights more economically without additional technical risks involving unestablished nuclear and converter concepts (English: Comment on "Heat-Pipe Reactors for Space Power Applications," submitted to J. Energy). This revelation bares the crux: Either TEC offers significant advantages for NEP, or it is unnecessary in its major anticipated space application.

Fortunately impressive TEC gains are available with higher emitter temperatures and greater power densities (Morris: NASA TM-73844). And reactor experts from the old in-core nuclear thermionic program point to good potentialities for accommodating external high-temperature, high-power-density TEC with heat-pipe-cooled reactors.

In that vein this presentation emphasizes approaches to improve out-of-core TEC and indicates probabilities for success. Subsequent design studies should optimize TEC for NEP, increasing performance up to acceptable-risk limits. A comfortably competitive system is neither needed nor wanted: NASA will undoubtedly develop at most one nuclear electric power capability for adaptation to various multi-hundred-kilowatt space missions. And if TEC fails to lead all other NEP-power competitors by substantial margins, that failure will relegate it to the category of interesting long-range space r&t possibilities. To avoid such an end this presentation advocates determination and pursuit of maximum TEC performance for NEP with reasonable potentialities for mission accomplishment.

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CURRENT DESIGNS

Designs for out-of-core thermionic energy conversion (TEC) to power nuclear electric propulsion (NEP) still react to the 1973 termination of the in-core TEC program (ref. 1): "The 1650K thermionic converter operating temperature permits the use of lighter, less brittle, and lower-cost materials than tungsten" (ref. 2 paraphrasing ref. 3). "Converter power density should be set at 5 to 6 We/cm^2 and back emission should be limited to 10%" (ref. 4). Reference 5 describes the reactor predicated on the preceding assumed design limitations: In essence uranium-dioxide, 60-volume-percent-molybdenum fuel (UO_2, 60 v/o Mo) heats molybdenum, lithium (Mo, Li) heat pipes, which in turn heat the TEC emitters. "A molybdenum-sialon cermet sleeve is sandwiched between the pipe and the converters to provide electrical insulation" (ref. 5).

As a result of detailed examination and rational analysis of reference 5, reference 6 makes a rather significant observation:

> An alternate, more economical approach appears practical inasmuch as the UC-ZrC reactor in combination with Brayton appears able to achieve the specific weight required for electric propulsion.... Considerable programmatic economies thus appear possible through broadened use of a single technology. While still achieving the specific weight required for electric propulsion, technical risks can also be avoided, viz.; risks from an additional reactor concept, risks from an additional power conversion concept, and risks from operating at considerably higher temperature.

For NEP, TEC based on the preceding design assumptions offers no significant advantages over Brayton (ref. 6). For NEP, TEC based on the preceding design assumptions is in fact risky compared with Brayton (ref. 6). For NEP, TEC gains based on the preceding design assumptions fail to justify additional r&t risks relative to those of Brayton (ref. 6). And for TEC, NEP is the major anticipated space application.

TEC POTENTIALITIES FOR NEP

The reference-6 revelation cuts through superficial discussions of design preferences to expose one hard fact: TEC either promises substantial NEP advantages or defaults in its most important space-application opportunity. And if the latter alternative eventuates, TEC will again become a possible candidate for undefined future space-power considerations.

These conditions force re-examination of the advocacy for "the 1650K thermionic converter operating" "at 5 to 6 W_e/cm^2" with "a molybdenum-sialon cermet...to provide electrical insulation.' Presumably 1650K "permits the use of lighter,less brittle, and lower-cost materials than tungsten" (W)--the "Mo 40 vol % UO_2" fuel (ref. 5), the "molybdenum/lithium heat pipe" (ref. 4), and "a sialon/molybdenum cermet and molybdenum emitter sleeve." But are such conveniences worth the performance limitations that they inflict on the TEC design for NEP?

This is a critical question because, as reference 7 shows, TEC with higher emitter temperatures and greater output power densities produces characteristics very favorable to lower NEP specific weights (table 1 and figures 1 to 3):

> 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 (2 to 4)). Table 1 for 925K collectors (refs. 2 and 3 (4)) 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 (2 to 4): <u>The 28.5% increase in optimum-lead efficiency</u> means lighter radiators and either more output

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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.

Of course postulating higher TEC temperatures provokes adamant protests: Higher temperatures 1) cause greater fuel swelling, 2) preclude the proposed use of molybdenum, and 3) assure ineffectiveness of the sialon, molybdenum cermet.

1) Reference 8 from the source used by reference 5 shows 0.1-to-0.3 $^v/o$ swelling per 10^{20} fissions/cc for 1900K clad surfaces on 72%-dense-UO_2, 30 $^v/o$-W fuels. Reference 8 also gives 0.8 $^v/o$ swelling per 10^{20} f/cc for dense UO_2 with 1675K clad surfaces. The corresponding fuel samples had 0.5-mm W, 26%-Re clads. For comparison, reference 5 stipulated 1 $^v/o$ swelling per 10^{20} f/cc for UO_2, 60$^v/o$-Mo fuel with 1675K clad surfaces.

Furthermore reference 8 shows that small increases in oxygen content decrease swelling substantially for oxide fuels tested with W, 26%-Re clad surfaces between 1950 and 2000K.

In addition reference 8 points to a "promising configuration for oxide fuels":

> Another geometric configuration that could reduce stresses on the cladding is the so-called "inside-out" configuration which places the coolant in tubes inside the fuel. If the inner coolant tubes are bonded to the

fuel, then they become an integral part of the fuel and must expand with it, as is the case with certain graphite dispersion-type fuel elements. However, if the fuel is bulk oxide and the coolant tube is metallic, then the bond between metal and oxide should be weak, and the fuel could be expected to expand, break the bond between fuel and coolant tube, and leave the coolant tube unstressed by anything except the coolant pressure. This concept remains essentially untested even though the satisfactory behavior of the inner claddings of numerous annular oxide fuel elements suggests that the basic principle is sound.

This "promising configuration for oxide fuels" is, of course, the geometry for the heat-pipe-cooled reactor. Further discussions of this highly important configuration appear in the concluding remarks of this presentation.

The important point to be made here is that quite apparently fuel-swelling technology does not limit TEC for NEP to 1650K emitters.

2) The desire to use molybdenum is admirable. But the rationale may not be as definite as the somewhat simplistic assertion of "lighter, less brittle, and lower-cost materials than tungsten."

First, although Mo has about half the density of tungsten, it has a much lower creep strength: Figure 4 (ref. 9) presents temperature effects on creep strengths for refractory metals including W; W, 25 Re; and TZM (Mo, 0.5 Ti, 0.08 Zr, 0.03 C). The creep strength of pure Mo is substantially lower than that of TZM, which is an order of magnitude lower than the creep strengths of W and W, 25 Re at 1650K and perhaps two orders of magnitude lower at 1800K (ref. 9). Quite probably using W or W, 25 Re rather than Mo for stressed elements would result in a weight saving for the NEP system even with 1650K TEC.

So the allegation of "lighter...materials than tungsten" is highly suspect.

Next, some comments on current W, 25-Re technology by LeRC and Euratom materials experts seem apropos: W,25-Re alloy
a) resists impact and vibration breakage better than pure W or Mo (LeRC materials experts).
b) fabricates and welds better than pure W, Mo, and even TZM (LeRC materials experts),
c) withstands creep above 1200°C better than other refractory alloys (LeRC materials experts),

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d) is acceptable nucleonically for fast-reactor heat pipes (LeRC and Euratom nuclear materials experts),
e) offers many years of service for lithium (Li) heat pipes at 1600°C (Euratom nuclear materials experts), and
f) would cause minor money perturbations for multihundred-kilowatt space-power systems because costs of development overwhelm those of materials.

Now the allusion to "less brittle and lower-cost materials than tungsten" appears quite questionable--particularly if the limitations of such materials cost the future of TEC for NEP.

3) Finally other high-temperature electrical isolators seem necessary because the effectiveness of the sialon, molybdenum cermet insulator is debatable even for 1650K emitters (refs. 10, 11, and LeRC materials experts). Sialons contain silicon nitride (Si_3N_4), alumina (Al_2O_3), and aluminum nitride (AlN). As such these chemical systems are immediately suspect as being subject to high-temperature reaction and decomposition.

In January 1976 reference 12 indicated rapid decomposition of a typical proposed TEC sialon system in vacuum at 1400°C, which was to be expected. This report also stated that "the high aluminum oxide sample...displayed the best vacuum behavior," which is also to be expected: Compositions sufficiently near the extreme Al_2O_3 corner of the SiN_4, AlN, Al_2O_3 phase diagram should, of course, approach the good high-temperature, hard-vacuum behavior of Al_2O_3. But what about sialons as opposed to diluted aluminum oxides?

Reference 10 presents data and analyses of "thermal decomposition of Al_2O_3-Si_3N_4 mixtures" at 1720K, an appropriate temperature for the proposed 1650K TEC emitter. Very high decomposition rates are the rule rather than the exception. In fact reference 10 supports well the probable degradation reaction:

$$Si_3N_4(c) + Al_2O_3(c) = 3\ SiO(g) + 2AlN(c) + N_2(g)$$

This equation indicates that reference 12 need not have added the AlN to the "β materials prepared from equimolar amounts of Si_3N_4, AlN and Al_2O_3." They could have combined equimolar parts of Si_3N_4 and Al_2O_3 and reacted a third of each at 1720K to obtain the desired number of AlN moles and twice as many moles of gas (SiO plus N_2).

Reference 10 qualitatively implies this result in the latter half of the third paragraph: "Heat treatment increased the Al content in all specimens (this result, as will be explained, resulted from evaporation of SiO), and the fraction of β-Si_3N_4 in heat-treated specimens increased with Al content. It should be noted that one specimen (A-48) contained a considerable amount of AlN after decomposition."

Then what high-temperature characteristics do Si_3N_4 and AlN offer?

Reference 11 reveals 1600K vapor pressures of 10^{-3} atm for AlN, similar to that of silver (Ag), and $3x10^{-5}$ atm for Si_3N_4, similar to that of copper (Cu). Pure Cu at 1700K vaporizes at $4x10^4$ g/cm^2/yr or about $4x10^3$ cm/yr; pure Ag at 1610K vaporizes at $5x10^5$g/cm^2/yr or about $5x10^4$ cm/yr (ref. 13). Reference 11 also gives evaporation rates for Si_3N_4 of $2x10^{-4}$ g/cm^2/sec or $6x10^3$ g/cm^2/yr at 1600K and $4x10^{-3}$ g/cm^2/sec or $1x10^5$ g/cm^2/yr at 1800K.

So vaporization rates implied by Si_3N_4 and AlN vapor pressures offer little relief compared with the gasification reported in reference 10 and represented by the preceding degradation reaction. Of course Si_3N_4 and AlN vaporization would be reduced somewhat in solid mixtures if that degradation reaction were not in effect.

In any event the sialon, molybdenum cermet is a dubious TEC emitter insulator for NEP.

Fortunately other methods are available for transferring great thermal power densities at high temperatures with electrical isolation. For example reference 14 proposes transporting heat from the reactor heat pipe through a small helium-filled gap to the emitter heat pipe. The latter heat pipe then transforms thermal power densities, limited by transfer through the helium gap, up to levels acceptable for TEC operation. This method also greatly reduces thermal-expansion-matching problems that are so critical for solid insulators between reactor heat pipes and TEC emitters.

Another possibility for elimination of the sialon, molybdenum cermet is inductive coupling and transforming as part of a pulsed thermionic converter. Other alternatives would undoubtedly arise if a concerted r&t program were initiated in this important TEC area.

In an overall sense the preceding TEC potentialities for NEP open many approaches to significantly improve performance.

TEC FOR NEP?

Considering current designs (refs. 2 to 5), their limitations, and risks (ref. 6) raises critical questions about the use of TEC for NEP. But rational alternatives promise TEC capabilities substantially greater than those of "the 1650K thermionic converter operating" "at 5 to 6 W_e/cm^2" with "a molybdenum-sialon cermet...to provide electrical insulation." Reference 7 indicates extents and implications of such TEC improvements.

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Reference 8 reveals logical potentialities for reactors with heat pipes running significantly hotter than the 1675K of references 2 to 5. Private communication with L. Yang (Gulf General Atomic) (GGA) and G. Fitzpatrick (formerly of GGA, now of Rasor Associates), fuel-swelling experts of the pre-1973 nuclear thermionic program, reinforce this positive outlook. The overall viewpoint heightens expectations for successful operation of out-of-core TEC with a heat-pipe-cooled reactor at much higher temperatures than those tolerable for the in-core counterpart.

Based on geometric considerations alone, fuel swelling should be far less problematic in a heat-pipe-cooled reactor for out-of-core TEC: The in-core thermionic fuel element (TFE) contains a nuclear compound within a tungsten-emitter capsule with a diameter of about 2.5 centimeters and wall thicknesses of the order of a millimeter. The fission gases and swollen fuel cause tension in the thin tungsten container. Tensile and heating effects usually localize, resulting in small regions of severe bulging or cracking. Such local distortions are catastrophic to a converter with a near-0.25-millimeter interelectrode gap subject to electrical shorting as well as to plasma and electrode adulteration.

In contrast the reactor for out-of-core TEC surrounds the heat pipes with fuel. So the heat-pipe envelope supports fuel swelling in compression rather than tension--a distinct advantage. Furthermore, with a weak fuel like UO_2 the full advantages of the "inside-out" configuration of reference 8 obtain. Discussions of these strong configurational gains with both L. Yang and G. Fitzpatrick resulted in their concurrences with the reference-8 postulate. The isothermalizing propensities of heat pipes greatly enhance this advantageous configuration by substantially reducing the prospect of local failures resulting from overheating. And available forgiving wick geometries and relatively large central heat-pipe openings obviate the catastrophic effects of distention suffered by in-core TEC because of the 0.25-millimeter interelectrode gap.

Configuration, isothermalization, and spacing effects in heat-pipe-cooled reactors for out-of-core TEC are so different from those of in-core TEC that capsule-swelling data aimed at TFE's are all but inapplicable in current NEP designs. In fact, after considering these factors and sifting through a wealth of old TFE fuel-swelling results, G. Fitzpatrick indicated that Li; W,25-Re heat pipes should serve well probably at 1900K and almost certainly at 1850K for cooling reactors. And of course, thermally derating a higher-temperature reactor for other applications would be much easier than upgrading a lower-temperature version for ultimate NEP requirements.

Apparently a reactor cooled by hotter-than-1675K heat pipes has good potentialities. TEC with higher temperatures and greater power densities than the currently proposed 1650K, 5-to-6 W_e/cm^2 version offers substantial gains. And some other approaches to high-temperature electrical isolation appear promising--and desirable even as an alternative to the sialon, molybdenum cermet for 1650K TEC. In any event, high-power-density, high-temperature TEC for NEP appears attainable.

Under these conditions and in the light of the precursory reference-6 revelation, a positive recommendation seems apropos: Optimize out-of-core thermionic energy conversion for nuclear electric propulsion. Although current TEC designs for NEP (refs. 2 to 5) seem unnecessary compared with Brayton versions (ref. 6), large gains are apparently possible with increased temperatures and greater power densities. And Brayton systems would require a completely new materials technology to compete with high-temperature TEC for NEP. But rationalizing previous design assumptions and demonstrating prototypic elements derived from those assumptions block technology development required for NEP TEC designs that could overwhelm competition.

Comfortably competitive TEC for NEP is unacceptable: NASA will undoubtedly adapt one nuclear electric power system to serve all multihundred-kilowatt space missions. And failure to substantially lead other NEP-power competitors will again make TEC just an interesting long-range space r&t possibility. To avoid this end, TEC designs for NEP must aim at maximum performance compatible with reasonable success probabilities. And reliable design-study predictions of significantly improved TEC potentialities for NEP should emerge before comments like those of reference 6 become commonplace. Or these new TEC results may also prove unnecessary.

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REF. 7

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_0 (at electrodes)	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} (with opt. leads)	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 (electrode)	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} (effective 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 (electrode)	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} (optimum-lead)	17.4	23.5	24.9	24.9	17.7	25.4	28.0	29.6	17.7	26.3	29.7	30.7	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

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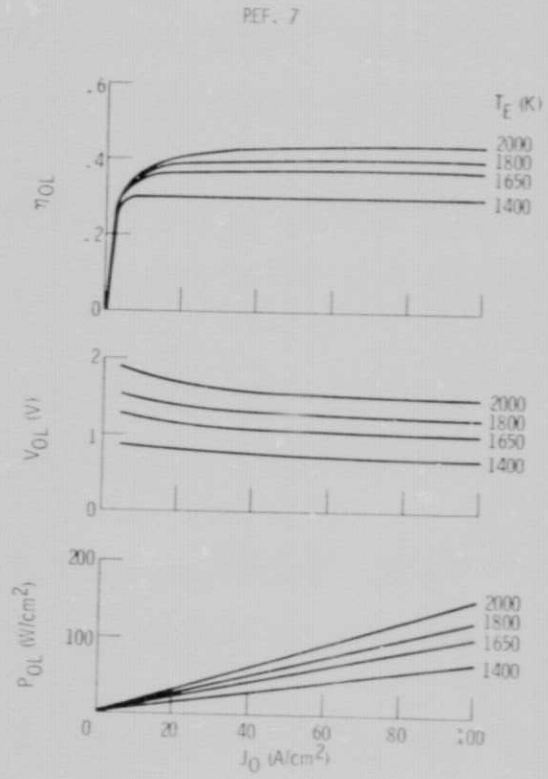

Figure 1. - Optimum-lead TEC efficiency (η_{OL}), voltage (V_{OL}), and power (P_{OL}) versus current (J_O) for four emitter temperatures (T_E) at a collector temperature of 725 K with 10 percent back emission.

REF. 7

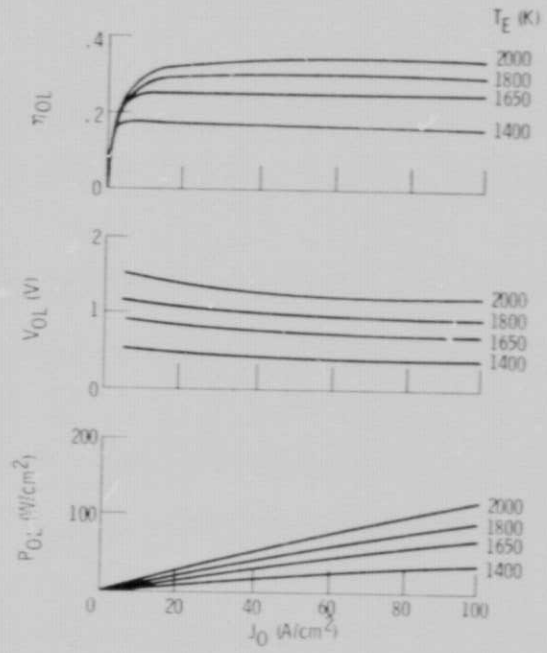

Figure 2. - Optimum-lead TEC efficiency (η_{OL}), voltage (V_{OL}), and power (P_{OL}) versus current (J_O) for four emitter temperatures (T_E) at a collector temperature of 925 K with 10 percent back emission.

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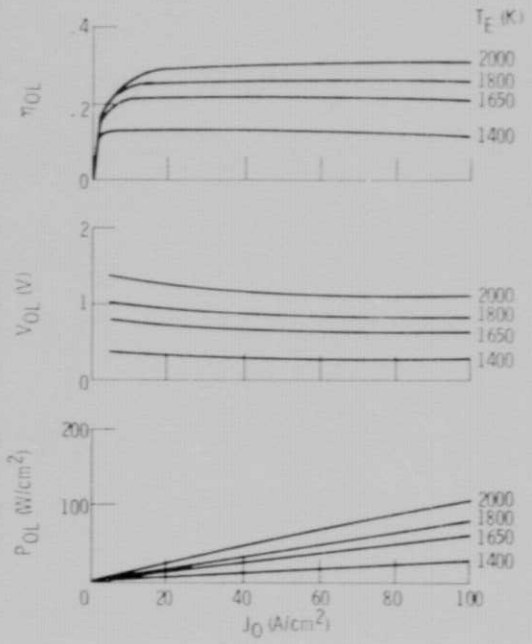


Figure 3. - Optimum-lead TEC efficiency (η_{OL}), voltage (V_{OL}), and power (P_{OL}) versus current (J_0) for four emitter temperatures (T_E) at a collector temperature of 1000 K with 10 percent back emission.

REF. 9

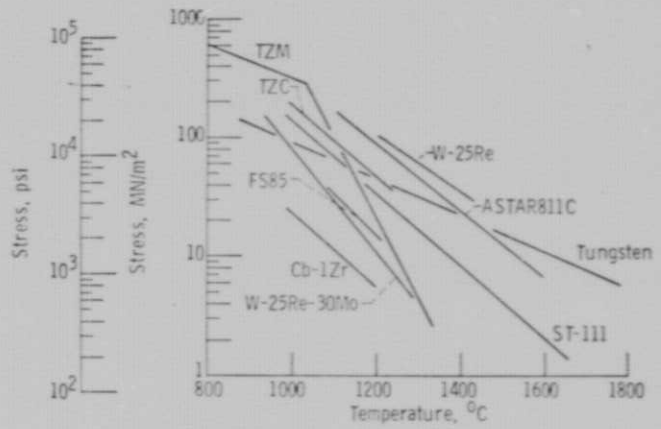


Figure 4. - Creep strength of some refractory metals and alloys for 1 percent creep in 10 000 hours.

REF. 7

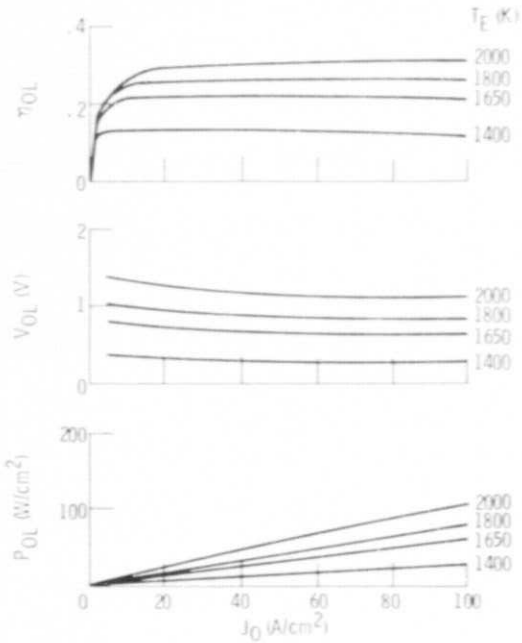
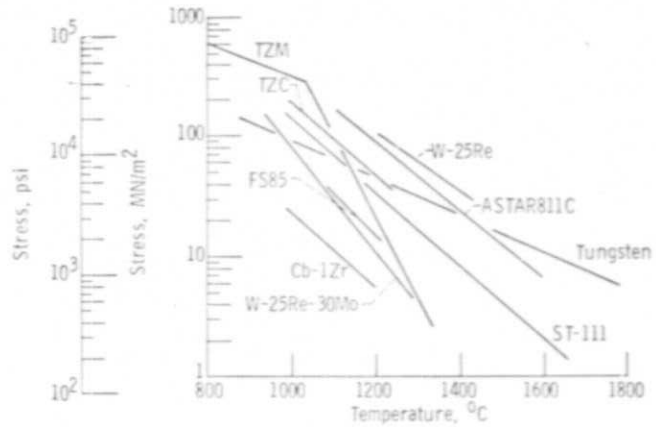


Figure 3. - Optimum-lead TEC efficiency (η_{OL}), voltage (V_{OL}), and power (P_{OL}) versus current (J_O) for four emitter temperatures (T_E) at a collector temperature of 1000 K with 10 percent back emission.

REF. 9



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