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NASA TECHNICAL
MEMORANDUM

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NASA THERMIONIC-CONVERSION PROGRAM

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NASA THERMIONIC-CONVERSION PROGRAM

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Abstract

NASA's program for applied research and technology (ART) in thermionic energy conversion (TEC) has made worthwhile contributions in a relatively short time: Many of these accomplishments are incremental, yet important. And their integration has yielded gains in performance as well as in the knowledge necessary to point productive directions for future work. Both promise and problems derive from the degrees of freedom allowed by the current programmatic emphasis on out-of-core thermionics. Materials and designs previously prohibited by in-core nucleonics and geometries now offer new potentialities. But as a result a major TEC-ART responsibility is the efficient reduction of the glitter of diverse possibilities to the hard glint of reality. As always high-temperature material effects are crucial to the level and duration of TEC performance: New electrodes must increase and maintain power output regardless, of emitter-vapor deposition on collectors. They must also serve compatibly with hot-shell alloys. And while space TEC must face high-temperature vaporization problems externally as well as internally, terrestrial TEC must tolerate hot corrosive atmospheres outside and near-vacuum inside. Furthermore, some modes for decreasing interelectrode losses appear to require rather demanding converter geometries to produce practical power densities. In these areas and others significant progress is being made in the NASA TEC-ART program.

GENERAL DIRECTION OF THE NASA TEC-ART PROGRAM

In recent conferences on thermionic energy conversion (TEC) for space applications, NASA representatives concurred in two major programmatic targets: 1) Demonstrate by 1980 electrically isolated thermionic converters with emitters between 1400 and 2000K and collectors between 650 and 1100K capable of operating at 20% efficiency for 10 years in nuclear- or solar-power service. 2) Provide by 1985 the technology basis for heat-pipe, thermionic-converter modules initiating in the reactor and terminating in the radiator of an out-of-core nuclear power system. Applied research and technology (ART) aimed at these NASA TEC targets are subjects of a series of papers (refs. 1 to 5) that stress 1000K TEC radiators to reduce weights of multihundred-kilowatt space-power systems.

This NASA activity complements without overlapping ERDA's thermionics work (refs. 5 and 6), which emphasizes central-power-station topping cycles. Thus the overall Governmental effort covers high-efficiency, durable, economical thermionic converters for the full range of operating conditions, energy sources, and applications. These general objectives and specific targets, summarized in Table 1, indicate the direction of the NASA TEC-ART Program.

Full-range out-of core thermionics allows electrode materials, converter geometries, and operating modes that were impractical for its in-core counterpart. However, these additional degrees of freedom not only promise gains but also pose problems: A major programmatic difficulty is the efficient reduction of numerous possibilities and permutations to a manageable field of high probabilities. Effective screening results from continuing intensive literature surveys and critical applied-research determinations.

THE NASA TEC-ART APPROACH

Thermionic converter improvement is crucial. But the NASA TEC-ART Program includes other important categories typified in Table 2: Mission and vehicle analyses reveal the best applications, necessary operating conditions, related system requirements and technological weaknesses or gaps. Advantageous utilization of advanced TEC also depends on appropriate developments of heat sources, metallic fluid heat pipes, and electrical isolators for high-temperature converters. And throughout this work contributions from continuing basic materials research and from the preceding in-core thermionics technology are invaluable.

TABLE 1
NASA TEC-ART PROGRAM
OBJECTIVES AND TARGETS

EFFICIENT, DURABLE, ECONOMICAL CONVERTERS FOR--
    ALL APPROPRIATE SPACE APPLICATIONS AND TERRESTRIAL SPINOFFS
    NUCLEAR, SOLAR, CHEMICAL THERMAL-ENERGY SOURCES
    FULL RANGE OF OPERATING CONDITIONS: EXPERIMENTALLY--
        EMITTERS: 1100 TO 2000K
        COLLECTORS: 400 TO 1200K
        RESERVOIRS: DEPENDENT ON ELECTRODE AND INTERELECTRODE REQUIREMENTS

BY 1980 20%-EFFICIENT ELECTRICALLY ISOLATED CONVERTERS WITH PROJECTED 10-YEAR LIVES
    (EMITTERS: 1400 TO 2000K, COLLECTORS: 650 TO 1100K)

BY 1985 TECHNOLOGY FOR HEAT-PIPE, THERMIONIC-CONVERTER MODULES OF AN OUT-OF-CORE
    NUCLEAR POWER SYSTEM

STAR Cat. 75

TABLE 2
NASA TEC-ART PROGRAM
OTHER IMPORTANT ART

MISSION AND VEHICLE ENGINEERING STUDIES

WORK ON METALLIC-FLUID HEAT PIPES

DEVELOPMENT OF ELECTRICAL ISOLATORS FOR CONVERTERS

HEAT-SOURCE STUDIES

FABRICATION RESEARCH

CONTINUING RESEARCH ON ELECTRON EMISSION AND COLLECTION AND
    THERMOPHYSICOCHEMICAL STABILITY OF PROMISING ELECTRODE MATERIALS

PRECEDING IN-CORE NUCLEAR THERMIONIC TECHNOLOGY

While these activities progress, the central TEC-ART thrust moves toward more effective thermionic converters through the general approach outlined in Table 3. The first three entries appear as amplified presentations in Tables 4 to 6 on reduced interelectrode losses and improved electrodes. And the fourth item of Table 3 implies a simple, general solution to the TEC vaporization, deposition problem: Use a collector surface made of the material vapor-deposited on it by the emitter (refs. 2 and 4). Other methods for coping with this vaporization, deposition effect are possible but exceptional.

TABLE 3

NASA TEC-ART PROGRAM

APPROACH (CONVERTER ART)

SUBSTANTIAL INTERELECTRODE-LOSS REDUCTIONS.

EFFECTIVE EMITTERS EVEN IN GREATLY REDUCED CESIUM PRESSURES.

IMPROVED ELECTRON COLLECTION CAPABILITY.

DURABLE EMITTER, COLLECTOR COMBINATIONS (AGAINST TEC VAPORIZATION, DEPOSITION EFFECTS).

TABLE 4

NASA TEC-ART APPROACH

REDUCED INTERELECTRODE LOSSES

GAINS: GREATER VOLTAGES (AND CURRENTS)
         MORE EFFICIENT IONIZATION
         BETTER ION UTILIZATION
         SMALLER RESISTIVE DROPS
         LESS ELECTRONIC SCATTERING

APPROACH
         LOWER CESIUM PRESSURES
         INERT-GAS, CESIUM PLASMAS
         IGNITED TRIODES
           AUXILIARY EMITTER (PLASMATRON)
           SECONDARY COLLECTOR
           PULSED OR STEADY-STATE
         UNIGNITED TRIODES (IONIZER)
         PULSED DIODES
         HYBRID MODES

TABLE 5

NASA TEC-ART APPROACH

IMPROVED EMITTERS

GAINS: GREATER CURRENTS (AND VOLTAGES)
         INCREASED EMISSION
         REDUCED TEMPERATURES
         LOWER CESIUM PRESSURES
         HIGHER VOLTAGES AT 10 A/CM^2
         LONGER LIFETIMES

APPROACH
         NEW METALLIDES
           LOWER BARE WORK FUNCTIONS
           LITTLE OR NO CESIUM
           WORK-FUNCTION REDUCTIONS WITH CESIUM
           GOOD THERMOPHYSICOCHEMICAL CAPABILITIES
         BETTER METAL, OXIDE EMITTERS
         BEST METALLIC CRYSTAL FACES
         STRUCTURED SURFACES
         ADDITIVES

TABLE 6

NASA TEC-ART APPROACH

IMPROVED COLLECTORS

GAINS: GREATER VOLTAGES (AND CURRENTS)
         LOWER ELECTRON-COLLECTION LOSSES
         INCREASED ELECTRON COLLECTION
         MAINTAINED PERFORMANCE
         LONGER LIFETIMES

APPROACH
         REDUCED WORK FUNCTIONS
           NEW MATERIALS
           ADAPTABLE EMITTERS
           ADDITIVES
         LOWER ELECTRON REFLECTIVITIES
           NEW MATERIALS
           ADDITIVES
           STRUCTURED SURFACES
         THERMOPHYSICOCHEMICAL CAPABILITIES
         SUITABLE OPERATION WITH EMITTER-VAPOR DEPOSITION

Additional information on these approaches to thermionic-converter improvements follows in the "accomplishments" section. But prior to that, the following insertion of an excerpt from reference 4 should clarify further discussions of interelectrode, emitter, and collector effects:

For these categories full-range TEC ART applies generally: The same phenomena operate at the high- and low-temperature ends of the TEC scale, although their relative effects may change. The impacts of many of these processes appear in the equation for ignited-mode output power density (P_0), which equals the product of the current-density (J_0) and voltage (V_0) outputs:

$$P_O = J_O V_O = (J_{SE} - J_R)(\phi_E - \phi_C - V_D - V_A)$$
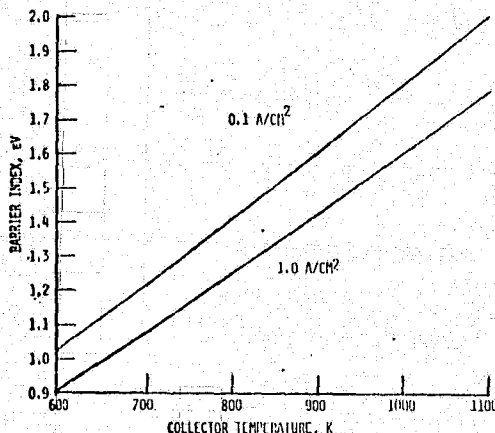
$$= (J_{SE} - J_R)(\phi_E - V_B - V_A) \quad (1)$$

Here J_{SE} is the saturated emitter current density; J_R, total reverse current density including back emission (J_{BE}), surface reflection, and back scatter; ϕ_E, emitter work function; ϕ_C, collector work function; V_D, interelectrode voltage drop comprising resistive, scattering, ionization, and double-sheath losses; V_A, equivalent externally applied auxiliary voltage; and V_B, barrier index ($\phi_C + V_D$). The Richardson, Dushman equation indicates the thermal-emission current densities:

$$J_{SE} = A\, T_E^2 \exp(-\phi_E/kT_E) \text{ and } J_{BE} =$$

$$A\, T_C^2 \exp(-V_B/kT_C) \quad (2)$$

where A is the Richardson coefficient; T_E, emitter temperature; T_C, collector temperature; and k, Boltzmann constant.

The barrier index provides a good example of different relative effects at high and low temperatures: Decreasing the barrier index raises the output voltage directly, but reduces the output current density through its exponential influence on back emission. The extent of this detraction depends strongly on the collector temperature as figure 1 reveals ($A = 120$ A/cm^2/K^2). Because advocated TEC operations often involve current densities near 10 A/cm^2, back emission of 0.1 A/cm^2 is negligible, while 1.0 A/cm^2 is significant. So struggling to attain a 1.0-eV collector work function and a 0.1-eV interelectrode drop is desirable for a 700K collector. But for collector temperatures above 1000K figure 1 implies barrier indices greater than 1.6 eV.

FIGURE 1

TEC BACK EMISSION
$$J_{BE} = A\, T_C^2 \exp(-V_B/kT_C)$$

Some effects of barrier indices, collector work functions (corresponding to near-optimum temperatures), and inter-electrode losses (arc drops) on TEC efficiency appear parametrically in figure 2. Note there also that an 1800K emitter holds an advantage of four efficiency-percentage points over a 1600K emitter. Obviously high emitter
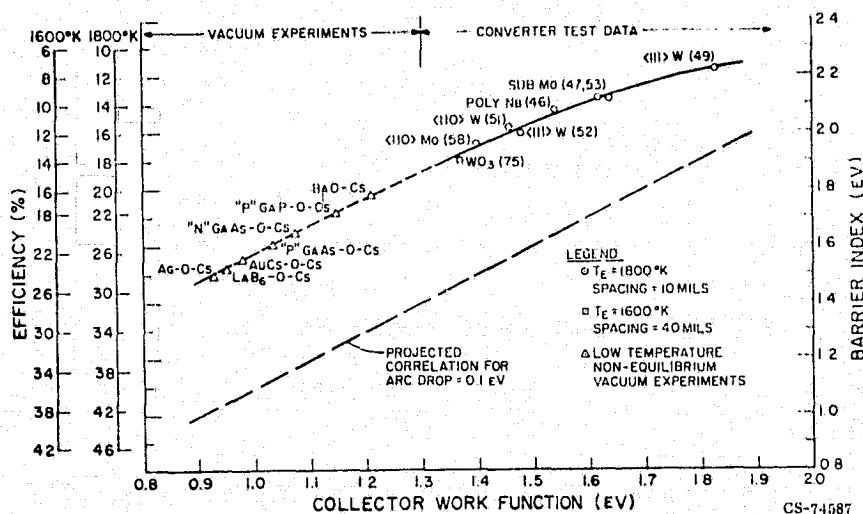
temperatures are more important relatively for the hotter collectors (higher barrier indices) required by multihundred-kilowatt space power than for the cooler collectors (lower barrier indices) needed in terrestrial applications.

In essence figure 2 presents a correlation showing that increased TEC efficiencies derive from higher emitter temperatures, lower collector work functions, and reduced interelectrode losses. But all figure-2 data points do not represent practical collectors. In fact, only the solid curve in the upper, right quadrant of figure 2 indicates experience with actual converters. And among those, just the cesium diodes with tungsten emitters and niobium or molybdenum collectors underwent extended life testing.

A common characteristic of the encircled data points on figure 2 allows some additional observations on effects of collector work functions in thermionic-converter losses: The circles all represent results for 1800K tungsten emitters with near-900K collectors (ref. 7 confirmed by F. N. Huffman of TECO). So the comparison of the extremes of those data presented in Table 7 should be instructive: For the 1800K converters of Table 7 and figure 2, lower collector work functions reduced barrier indices and produced higher TEC efficiencies--even though interelectrode losses increased.

The only factor listed in Table 7 that could have contributed to raising the interelectrode losses of <110> Mo (58) 0.16 eV above those of <111> W (49) was the saturated collector emission. Back emission, which is the fraction of the saturated collector emission received by the emitter, was negligible for both converters. But while the saturated collector emission for <111> W (49) was very small, it was a significant fraction of the converter output current density (~ 10 A/cm^2) for <110> Mo (58) at 2.4 A/cm^2. And nearly all of it returned to the collector because of the previously mentioned negligible back emission that reached the emitter. So at the <110> Mo (58) collector surface the electron concentration corresponded to 2.4 A/cm^2 of saturated collector emission plus its reflected stream of nearly 2.4 A/cm^2 in addition to the net output from the emitter of about 10 A/cm^2. This cumulative effect coupled with electron reflectivity quite probably caused space-charge problems at the collector.

The true virtual-collector work function for <110> Mo (58) was probably lower than the sum of the actual-collector work function (1.40 eV) and the maximum space-charge barrier assumed for Table 7 (V_D with significant collector emission minus V_D with negligible collector emission = 0.56 - 0.40 eV). But the assumption of a 1.56-eV virtual-collector work function for <110> Mo (58) allows another estimate: The electron concentration caused by collector-emission effects between the emitter and collector sheaths corresponded to at least 0.33 A/cm^2 emitted over the collector space-charge barrier and nearly 0.33 A/cm^2 reflected back. Such cumulative electron concentrations are not negligible compared with those related to usual net emitter current densities or converter outputs of about 10 A/cm^2.

FIGURE 2
EFFECTS OF COLLECTOR WORK FUNCTION AND ARC DROP
ON THERMIONIC CONVERSION EFFICIENCY
(THERMO ELECTRON CORP.)

TABLE 7

EXTREMES OF "CONVERTER TEST DATA" FOR 1800K TUNGSTEN EMITTERS FROM TECO:
"EFFECTS OF COLLECTOR WORK FUNCTION AND ARC DROP ON THERMIONIC CONVERSION EFFICIENCY"

	$\langle 11 \rangle$ W(49)	$\langle 110 \rangle$ Mo(58)
CONVERTER DESIGNATION (TECO)		
NEARLY OPTIMUM COLLECTOR TEMPERATURE (T_C), K	875	925
BARRIER INDEX (V_B), EV	2.23	1.96
BACK EMISSION (J_{BE}), A/CM^2	0.00001	0.0022
COLLECTOR WORK FUNCTION (ϕ_C), EV	1.83	1.40
SATURATED COLLECTOR EMISSION (J_C), A/CM^2	0.0025	6.4
INTERELECTRODE ("ARC") LOSSES (V_D), EV	0.40	0.56
TEC EFFICIENCY (η), %	11.6	16.6
VIRTUAL-COLLECTOR WORK FUNCTION (ϕ_{VC}), EV	-1.83	-1.56
(IF THE PRIMARY EFFECT OF COLLECTOR		
EMISSION WAS COLLECTOR SPACE CHARGE)		
VIRTUAL-COLLECTOR EMISSION FOR ϕ_{VC} (J_{VC}), A/CM^2	0.0025	0.33

OBSERVATIONS

BACK EMISSION: NEGLIGIBLE FOR BOTH CONVERTERS.
COLLECTOR EMISSION: NEGLIGIBLE FOR $\langle 11 \rangle$ W(49), BUT FOR $\langle 110 \rangle$ Mo(58)
 6.4 A/CM^2 OUT AND -2.4/CM^2 REFLECTED BACK IN ADDITION TO ~10 A/CM^2 NET FROM THE EMITTER.
$\langle 110 \rangle$ Mo(58) RELATIVE TO $\langle 11 \rangle$ W(49):
ϕ_C 0.43 EV LOWER, V_B 0.27 EV LOWER, AND η 5% HIGHER; BUT V_D 0.16 EV HIGHER.

LOWER COLLECTOR WORK FUNCTIONS PRODUCE HIGHER TEC EFFICIENCIES.
BUT EFFECTS OF INTERELECTRODE ELECTRON CONCENTRATIONS GREATLY INCREASED BY COLLECTOR
 ELECTRON EMISSION AND REFLECTION RAISE INTERELECTRODE LOSSES SIGNIFICANTLY.

Thus figure 2 provides some insight into the nature and extent of interelectrode losses caused by low-work-function collectors in converters with 1800K tungsten emitters: First with both back emission and saturated collector emission at negligible levels (V_B = 2.23, ϕ_c = 1.83 eV) interelectrode losses were 0.4 eV. Second with negligible back emission but significant saturated collector emission compared with converter output current densities (V_B = 1.96, ϕ_c = 1.40 eV) interelectrode losses reached 0.56 eV. If nearly that entire increase in interelectrode losses for the latter converter (0.16 eV) redounded from collector space-charge effects, saturated emission from the resulting virtual collector (ϕ_{VC} = 1.40 + 0.16 = 1.56 eV) still affected the plasma between the emitter and collector sheaths. And third if the sum of the low collector work function and the interelectrode losses had diminished to a barrier index of 1.6 eV

or lower, the back emission of 1.0 A/cm^2 or greater would have posed a problem in addition to the difficulties caused by intense saturated collector emission.

But still figure 2 shows that in general lower collector work functions produce higher TEC efficiencies.

So with reference to the general approaches of Table 3, the preceding discussion dramatizes the need to develop methods yielding "substantial interelectrode-loss reductions." Furthermore, because electron collisions with cesium atoms contribute to interelectrode losses, a desirable class of converter electrodes comprises "effective emitters even in greatly reduced cesium pressures." Also lower collector work functions and decreased electron reflections are nominal TEC requirements

in the category of "improved electron collection capability."

Tables 4 to 6 and the following section elaborate on these approaches and their results. And finally, according to Table 3, assured performance maintenance demands "durable emitter, collector combinations (against TEC vaporization, deposition effects)." As previously stated, the simple, general solution for the vaporization, deposition problem is to fabricate the collector of the material vapor deposited on it by the emitter. In deference to this TEC principle each electrode pair evaluated in the current LeRC diminiode program is an emitter and a collector of the same material.

Additional vaporization, deposition problems involve changes in converter geometry and integrity: Locally extreme deposit buildups can alter or even bridge interelectrode gaps. Conductor deposition on insulator surfaces can also short-circuit emitters to collectors, but line-of-sight shielding usually precludes this defect. Of course, structural and containment members for space TEC must withstand both internal and external high-temperature vaporization effects. And terrestrial TEC devices must tolerate hot corrosive atmospheres outside and near-vacuum inside.

Finally TEC components must serve together in general thermophysicochemical compatibility. This requires acceptable resistance to chemical reactions, appropriate matches of thermal-expansion coefficients, suitable contributions to overall thermal and electrical conductivities or resistivities where necessary, and sufficient capability to withstand thermal cycling, gradients, and creep.

In short, high-temperature material effects will determine the level and lifetime of TEC performance.

NASA TEC-ART ACCOMPLISHMENTS

NASA, ERDA TEC-ART Program

During the two years that LeRC has managed the NASA TEC-ART Program technically and fiscally, careful coordination with ERDA has assured maximum coverage without overlaps in this work area. Table 8 depicts the cooperative NASA, ERDA TEC-ART Program and lists grant, contract, and in-house studies. Such cooperation facilitates more effective approaches to promising TEC applications like central-power-station topping for ERDA and multihundred-kilowatt space systems for NASA.

Current Technology

Tables 9 to 13 highlight some of the NASA TEC-ART contributions. Table 9 represents the most highly developed example of current TEC capability: 18% at 1800K and 14% at 1600K for the cesium diode with a tungsten emitter and an oxygenated-tungsten collector (fig. 2). These performance levels compare with 14% at 1800K and 10% at 1600K for the 1973 standard, a cesium diode with a tungsten emitter and a niobium collector.

Enhanced-Mode Results

Table 10 lists findings related to interelectrode-loss reductions: Recent results (refs. 8 and 9)

indicate that plasma losses lower than 0.1 eV are attainable in rather conventional converter geometries only at relatively low power densities. However, enhancement at practical output levels is possible with the emitter very near to the collector (ref. 8) or with closely spaced auxiliary electrodes (ref. 9). Argon or xenon plasmatrons are more effective than the cesium versions because of favorable ratios of atomic cross sections for ionization to those for electron scattering. Greater augmentation may also result from energized particles like vibrationally excited nitrogen molecules spreading auxiliary-power inputs more widely before affecting cesium ionization (ref. 10). And collector reception as well as emitter reflection and emission of electrons provided by structured electrodes or additives should reduce losses for all TEC power densities.

Collector Findings

Table 11 presents results for low-work-function collectors: As figure 2 shows, collectors with lower work functions operating at optimum temperatures yield higher TEC efficiencies in general. However, as stated earlier, overall system considerations like radiator weights strongly influence optimizations for multihundred-kilowatt space power. So barrier indices greater than 1.6 eV appear more practical for collectors hotter than 1000K in near-megawatt NASA applications.

Critical NASA requirements allow smaller reductions in both interelectrode losses and collector work functions than those needed for terrestrial topping cycles. To illustrate this point the following example demonstrates that current TEC technology is quite close to the NASA 20%-efficiency target. At collector-to-cesium-reservoir temperature ratios of 1.8 to 2.0, cesiated rhenium produces work functions below 1.5 eV (ref. 11, page 163). With 1000-to-1100K collectors, this ratio range corresponds to 500-to-610K reservoirs, which yield cesium pressures suitable for effective diode operation. And for 1800K, emitter-to-reservoir temperature ratios would be 2.95 to 3.6 giving estimated cesiated-rhenium work functions of 2.5 to 3.3 eV with approximate saturated emission of 39 to 0.24 A/cm^2 ($A = 120$ $A/cm^2/K^2$). Then with a 0.2-eV arc drop, perhaps from structured electrodes, 1800K cesiated rhenium having a 2.7-eV work function and emitting 11 A/cm^2 to a 1050K cesiated rhenium collector should generate about 10 W/cm^2 with near-22% efficiency.

As reference 12 explains, 111-iridium electrodes should perform better than rhenium, probably allowing even higher interelectrode losses for comparable TEC outputs: This possibility might combine a 0.3-eV arc drop with a cesiated-111-iridium collector having a 1.4-eV work function, which is not far below the 1.45-eV minimum for cesiated rhenium (ref. 11).

Such a converter involves no additives. And its emitter and collector are made of the same material: The electrode metals with high bare work functions and low vapor pressures can operate effectively at elevated temperatures appropriate to efficient, long-life TEC in space. The required interelectrode losses are only about 0.2 eV lower than the 0.4-to-0.5 eV values common in conventional cesium diodes. In contrast, low-temperature TEC applications often demand negligible arc drops

TABLE 8
NASA, ERDA TEC-ART PROGRAM

NASA HQ PROGRAMS	NASA	ERDA	ERDA HQ
LEWIS RSCH CTR (LeRC) MATERIALS ELECTRODES CONVERTERS HEAT PIPES NASA TEC-ART MANAGEMENT	OREGON GRADUATE CENTER (OGC) SINGLE-CRYSTAL STUDIES OF PROMISING ELECTRODE MATERIALS	PRINCETON UNIVERSITY (PU) PLASMA THEORY	ERDA TEC-ART MANAGEMENT
	ARIZONA STATE UNIV. (ASU) ELECTRON EMISSION, THERMAL STABILITY OF ELECTRODE MATERIALS	LOS ALAMOS SCIENTIFIC LAB (LASL) MATERIALS, VAPOR PRESSURES HEAT-PIPE-COOLED REACTOR	
JET PROPULSION LAB(JPL) MISSIONS VEHICLES CONVERTERS	UNIV. OF MINNESOTA(UM) PLASMA-DIODE ION STUDIES	NAVAL RESEARCH LAB (NRL) DISPENSER-ELECTRODE STUDIES	
AMES RSCH CTR (ARC) SURFACE STUDIES	STATE UNIVERSITY OF NEW YORK (SUNY) ADVANCED-MODE PLASMA STUDIES EQUIPMENT FUNDING ALSO NSF SUPPORT		
	RASOR ASSOCIATES, INC. (RA) ADVANCED-MODE STUDIES CONVERTER EVALUATIONS	ENGINEERING STUDIES LARGE-CONVERTER EFFECTS	
	THERMO ELECTRON CORPORATION (TECO) SURFACE STUDIES ENHANCED-CONVERTER EXPS CONVERTER EVALUATIONS	SURFACE, PLASMA THEORIES ENGINEERING STUDIES MATERIALS DEVELOPMENT	

TABLE 9
NASA TEC-ART ACCOMPLISHMENTS
CURRENT TECHNOLOGY

18% AT 1800K WITH TUNGSTEN, CESIUM, OXYGEN DIODES (TECO)

1973 STANDARD

14% AT 1800K WITH TUNGSTEN, NIOBIUM DIODES

TABLE 10
NASA TEC-ART ACCOMPLISHMENTS
ENHANCED-MODE RESULTS

INTERELECTRODE LOSSES BELOW 0.1 VOLT FOR LESS THAN 2 A/CM^2 (RA, TECO).

PRACTICAL ENHANCEMENT WITH PRIMARY (TECO) OR AUXILIARY (RA) ELECTRODES CLOSELY SPACED.

ARGON PLASMATRONS MORE EFFECTIVE THAN CESIUM COUNTERPARTS (RA, TECO).

CESIUM IONIZATION WITH VIBRATIONALLY EXCITED MOLECULAR NITROGEN (SUNY).

INTERELECTRODE-LOSS REDUCTIONS WITH STRUCTURED ELECTRODES (RA).

1973 STANDARD

INTERELECTRODE LOSSES OVER 0.5 VOLT FOR 10 A/CM^2.

TABLE 11
NASA TEC-ART ACCOMPLISHMENTS
COLLECTOR FINDINGS

HIGHER TEC EFFICIENCIES FROM (OPTIMIZED) COLLECTORS WITH LOWER WORK FUNCTIONS (TECO).

BELOW-1.2 eV WORK FUNCTIONS WITH CESIATED, OXYGENATED COLLECTORS (TECO, JPL).

ABOUT-1.3 eV COLLECTOR WORK FUNCTIONS WITH CESIATION WITHOUT OXYGENATION (TECO, OGC).

1973 STANDARD

ABOVE-1.5 eV WORK FUNCTIONS WITH CESIATED NIOBIUM COLLECTORS.

and reduced collector work functions apparently attainable only with cesiated exotic materials and oxygenation.

But these collectors seem obtainable also: Table 11 reveals that some cesiated, oxygenated collectors produce work functions below 1.2 eV; a few, in fact, near 1.0 eV. The implications of these low-work-function collectors appear in figure 2: There, for example, the LaB$_6$, O, Cs entry with a work function lower than 1.0 eV has projected efficiencies of 24% for service with a 1600K emitter and 28% for 1800K on the extrapolated curve for unenhanced cesium diodes. With an arc-drop reduction to 0.1 eV the LaB$_6$, O, Cs combination corresponds to an estimated 36% for 1600K and 40% for 1800K. However, although 1600K is feasible for LaB$_6$ emitters, 1800K appears unsuitable for long-term TEC because of vaporization (refs. 2 and 4).

In addition, at least the supply, control, and lifetime aspects of oxygenation processes complicate their use in TEC. Reference 8 states that "the most satisfactory solution to supplying oxygen to a thermionic converter would be a cesium oxide reservoir that would supply an equilibrium cesium and oxygen atmosphere of the proper composition." But possible avoidance of such complexities justifies the search for cesiated materials that produce low work functions without oxygenation. And Table 11 indicates that progress is also being made in this TEC-ART area.

Emitter Progress

Table 12 tabulates some TEC-emitter information. Already mentioned are refractory-metal emitters with high bare work functions and low vaporization rates exemplified by 110 tungsten, 0001 rhenium, 0001 osmium, and 111 iridium. These materials allow 1800K operation with its advantage of 4 efficiency points over 1600K converters (fig. 2). This gain coupled with the modest interelectrode-loss reductions and near-optimum cesiated collectors previously discussed for rhenium and iridium shows particular promise for use with the high radiator temperatures of multihundred-kilowatt space power. And vaporization does not preclude the use of tungsten, rhenium, or osmium emitters up to 2000K or above.

TABLE 12
NASA TEC-ART ACCOMPLISHMENTS
EMITTER PROGRESS

METALLIC-HEXABORIDE EMITTER PROSPECTS (1600K)

LOW BARE WORK FUNCTIONS (CeB$_6$:2.25 (TI), LaB$_6$:2.47 (TI), 2.28 eV (FERP)) (OGC).

REDUCED WORK FUNCTIONS (LaB$_6$: 1.3 eV) AND ELECTRON REFLECTIVITIES WITH ADSORBED CESIUM (OGC).

CONGRUENT VAPORIZATION (LaB$_6$) AT MUCH LOWER RATES THAN PREVIOUSLY PUBLISHED (LASL).

111 IRIDIUM BETTER THAN 0001 RHENIUM BETTER THAN 110 TUNGSTEN (1800K) (LeRC).

EMITTER, COLLECTOR COMBINATIONS TO WITHSTAND VAPORIZATION, DEPOSITION EFFECTS (TECO, LeRC).

1973 STANDARD
CVD TUNGSTEN, NEARLY AS GOOD AS 110 TUNGSTEN.

With oxygenated-tungsten electrodes in a cesium diode (ref. 8, pages 67 and 68) "a further improvement of the barrier index to 1.85-1.95 eV can be obtained. This level may be stable for about 100 hours after which the barrier index will return to 2.1 eV... . However, if the oxygen is in the combined state (such as might be the case with a cesium oxygen reservoir) with the oxygen appearing only after contact with the hot emitter surface, external control and supply are feasible." Recent evaluations place the operational stability of this diode at considerably longer than "100 hours." The tungsten, oxygen, cesium converter is the best currently demonstrated example of improved performance with electrodes that could withstand the emitter-vaporization, collector-deposition effect.

Metallic hexaborides also appear to offer promising emitter, collector combinations with inherent vaporization, deposition compatibility. Work-function determinations for clean 100 faces (Table 12, ref. 13) reveal that hexaborides of lanthanum (LaB$_6$) and of cerium (CeB$_6$) could serve as good emitters with little or no adsorbed cesium-- perhaps in the previously mentioned argon or xenon plasmatrons. With cesium adsorption the work function of 100 LaB$_6$ reduces to about 1.3 eV without oxygenation. Apparently cesium diodes with LaB$_6$ emitters and collectors could perform well without additives. On the figure-2 curve for un-enhanced TEC a 1.3-eV collector corresponds to 15% efficiency at 1600K and 31% at 1800K with a 1.3-eV collector. LeRC will evaluate such converters after solving existing problems caused by impurities and high-temperature brazes.

But as previously stated, LaB$_6$ vaporization rates (refs. 2, 4, and 14) may prevent long-term service at temperatures much above 1600K in conventional TEC geometries. And initial tests indicate that CeB$_6$ has a vapor pressure somewhat higher than that of LaB$_6$ (ref. 13). So these metallic hexaborides should adapt most effectively to intermediate- and low-temperature TEC.

The hexaboride thermionic (TI) work functions given in Table 12 correspond to experimental emission-equation coefficients (A) lower than 120 A/cm^2/K^2. In recent communications, however, OGC indicated that congruently vaporizing 100 LaB$_6$ exhibits an effective work function of 2.52 eV to be used with an A of 120 A/cm^2/K^2 for 1700K. This yields 12 A/cm^2 without cesiation, which would reduce both the work function and the electron reflection coefficient (ref. 13). And "field emission

patterns continue to show that the (100) directions of LaB$_6$ is not the lowest work function direction."

New TEC electrode possibilities are an interesting and productive field.

Mission Analysis and Vehicle Design

In the NASA TEC-ART Program, JPL is responsible for studies of missions and vehicles (Table 13). Of course, circumspect analytic and design efforts require continual updates and enlightened extrapolations of the various necessary technologies. But judicious analyses can point parametrically to critical needs for ultimate space applications. And these studies will asymptotically predict and thereby bring together the most-effective technological contributions at the crucial time.

TABLE 13
NASA TEC-ART ACCOMPLISHMENTS
ANALYTIC AND THEORETIC GUIDANCE

MULTIHUNDRED-KILOWATT OUT-OF-CORE SPACE-POWER-SYSTEM DESIGNS (JPL, LASL)

THEORETIC DESCRIPTIONS OF TEC PROCESSES (RA, SUNY, TECO)

1973 STANDARD

MULTIHUNDRED-KILOWATT IN-CORE NUCLEAR POWER SYSTEMS

Theoretic Descriptions of TEC Processes

Theories and empirical correlations that predict and describe research and development requirements and results are also essential in maintaining productive directions for NASA TEC-ART studies (Table 13). In general, program participants generate these theoretic descriptions as they are required in the various projects. At present quite effective theories exist for various TEC operating modes.

Concluding Comments

Although this discussion details only primary NASA TEC-ART accomplishments, each of these results required significant contributions in secondary technologies. Unfortunately much of the supporting work that made the present paper possible is beyond the scope of this presentation.

In a short time the NASA TEC-ART Program has provided important results ranging from basic material characterizations to possible overall-system definitions. These accomplishments have yielded the knowledge necessary to direct future ART studies as well as to produce TEC performance gains.

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