NASA TECHNICAL MEMORANDUM

NASA TM X-73610

NASA TM X-73610

THE NASA THERMIONIC-CONVERSION (TEC-ART) PROGRAM

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

TECHNICAL PAPER to be presented at the
Plasma Science Conference sponsored by the
Institute of Electrical and Electronics Engineers
Troy, New York, May 23-25, 1977

(NASA-TM-X-73610) THE NASA THERMIONIC-CONVERSION (TEC-ART) PROGRAM (NASA) 19 p HC A02/MF A01 CSCL 10A

N77-23604

Unclas
G3/44 29068

THE NASA THERMIONIC-CONVERSION (TEC-ART) PROGRAM

James F. Morris, Technical Manager
Head, Thermionics and Heat-Pipe Section
NASA Lewis Research Center
Cleveland, Ohio 44135

E-9093

ABSTRACT

The NASA program for applied research and technology (ART) in thermionic energy conversion (TEC) comprises in-house, university-grant, and industrial-contract studies. In a few years this TEC-ART program has produced important results. Although many of these accomplishments are incremental, their integration has yielded performance gains and the knowledge necessary to direct future work. The current emphasis on out-of-core thermionics allows materials and designs previously prohibited by in-core nucleonics and geometrics. The additional degrees of freedom offer new potentialities. But as always high-temperature material effects will determine the level and lifetime of TEC performance: New electrodes must not only raise power outputs but also maintain them regardless of emitter-vapor deposition on collectors. In addition effective electrodes must serve compatibly with hot-shell alloys. Then, of course, space TEC must withstand external and internal high-temperature vaporization problems. And terrestrial TEC must tolerate hot corrosive atmospheres outside and near-vacuum inside. Finally reduction of losses between converter electrodes is essential even though rather demanding geometries appear to be required for some modes of enhanced operation. In these and other areas from basic material characterizations to possible system definitions, significant progress is being made in the NASA TEC-ART Program.

EVOLUTION OF THE NASA TEC-ART PROGRAM

The present NASA program for applied research and technology (ART) in thermionic energy conversion (TEC) has evolved since 1973. This work began as an antithesis following termination of the in-core-nuclear-thermionics development. Because of its obvious advantages for multi-hundred-kilowatt space power, thermionic conversion had received its complete support from the in-core-nuclear program. So when space-nuclear-power funding ceased in early 1973, cesium-diode r&d also stopped--even though thermionic converters transform heat from various sources to electricity for various applications.

STAR Cat

The in-core nuclear program had generated a wealth of information on tungsten service with uranium-carbide fuels and had demonstrated the feasibility of thermionic conversion: High temperature cesium diodes had run continually for years in life tests funded by NASA contracts. One example was a cylindric converter with a 16-cm^2 1975K tungsten emitter 0.23 mm from a 1073K niobium collector. That cesium diode had produced 8 W/cm^2 at 0.76V with a 14% electrode efficiency for well over 5 years by 1973. Contract termination, not diode failures, stopped such demonstrations.

When its remaining adherents brought thermionic conversion back from oblivion, most of them worked conscientiously to project a new image, if not a different identity: terrestrial, not space applications; fossil, not nuclear fuels; gaseous, not vacuum environments; low, not high temperatures; and corrosion-resistant, not refractory materials. But these other categories are also legitimate areas of thermionic-conversion technology. Thus, the new program initially emphasized thermionic topping of coal-fired central power stations. And the proposed thermionic-converter had a 1400K-or-cooler emitter, a very-low-work-function collector, requisite plasma enhancement, and predominantly stainless-steel or superalloy materials. In less than a year the relevant thermionic-converter prototype had shifted from the ultra- to the infra-thermal end of the TEC spectrum.

This change permeated NASA- and ERDA-supported TEC-ART presentations made at the 1975 IEEE International Conference on Plasma Science and echoed at the Intersociety Energy Conversion Engineering Conference and the Thermionic Specialists Conference that same year.

Because of its high-temperature capability, however, the thermionic converter still offers obvious advantages for multihundred-kilowatt space power: Increased waste-heat-rejection temperatures mean decreased radiator weights, which are large fractions of near-megawatt space-power systems. The effective area of the radiator varies approximately inversely with the fourth power of its temperature. And high-temperature thermionic converters can readily allow 1000K radiators, as the previously mentioned 1073K collector indicates. Also, even for new improved thermionic converters, efficiencies and power outputs in the practical operating range should rise with increasing emitter temperatures similar to the general trends for cesium diodes indicated in figure 1 (ref. 1). Of course an increment in TEC efficiency is equivalent to a direct decrement in waste heat the radiator must reject. For these reasons NASA continues to recognize the value of TEC ART for eventual space applications such as those in the upper, right corner of figure 2 (ref. 2).

FIGURE 1
RELATION OF MAXIMUM POWER OUTPUT
AND EFFICIENCY TO EMITTER TEMPERATURE
HATSOPOULOS & GYFTOPOULOS, 1973

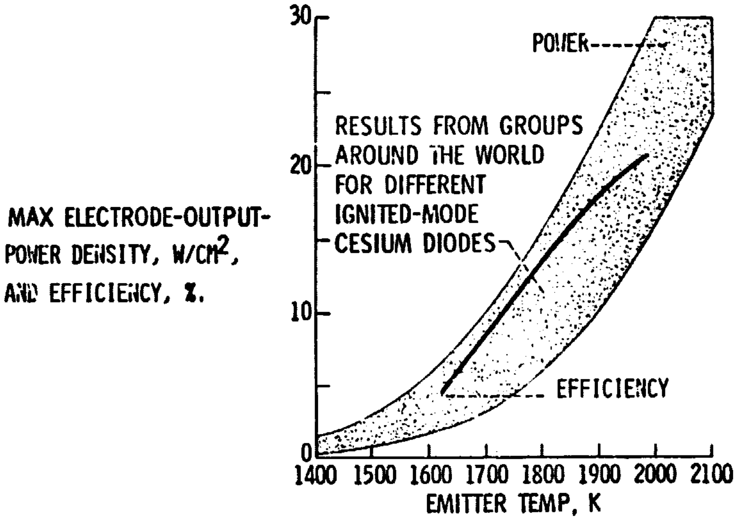
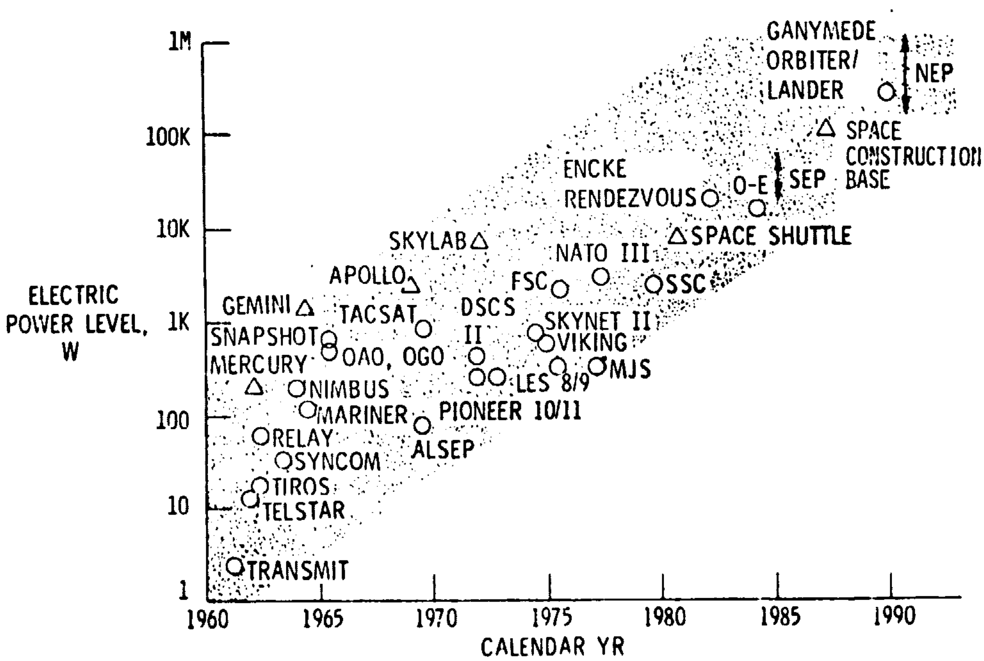


FIGURE 2
SPACE-POWER REQUIREMENTS FROM 1960 THROUGH 1990



Anticipating nuclear electric propulsion (NEP) JPL proposed a compromise: out-of-core, not in-core thermionic space power fueled with uranium dioxide (UO_2), not uranium carbide (UC) and fabricated with molybdenum (Mo), not tungsten (W) (ref. 3). "Unfortunately, tungsten is expensive and difficult to fabricate. It is also brittle at low temperatures, which can cause reliability problems in a launch environment." Therefore, that design (ref. 3) prescribed thermal-power transport out of the reactor to 1650K converter emitters via lithium, molybdenum heat pipes. And by August 1975 TEC ART had resurged to include higher temperatures and nuclear considerations because of eventual space applications.

But for more than a year prior to that date the Lewis Research Center (LeRC), which now manages the NASA TEC-ART Program, had advocated covering the full range of practical TEC operating temperatures. Then a November 1975 report by JPL and its contractors (ref. 4) presented "a comparative assessment of out-of-core nuclear thermionic power systems." That report contained recommendations for TEC with 1800K emitters and uranium carbide (UC) as a high-temperature alternative to UO_2.

Such counsel coupled with the current technology for the W, 25%-Re (rhenium) alloy, summarized in Table 1, firmly supports ART work on high-temperature out-of-core nuclear thermionic power systems for space. Therefore the present NASA TEC-ART Program encompasses high, intermediate, and low operating temperatures using nuclear, solar, and chemical heat sources for the appropriate practical applications. And the step-by-step recovery of TEC ART from an antithesis of the pre-1973 in-core development to a productive full-range program is complete.

TABLE 1

TUNGSTEN, 25%-RHENIUM (W, 25 RE) TECHNOLOGY

WOULD ALLOW HIGHER EMITTER TEMPERATURES, HENCE GREATER THERMIONIC CONVERSION EFFICIENCIES AND LOWER RADIATOR WEIGHTS FOR MULTIHUNDRED-KILOWATT SPACE-POWER SYSTEMS.

RESISTS IMPACT AND VIBRATION BREAKAGE BETTER THAN PURE W OR MOLYBDENUM (MO) (LeRC MATERIALS EXPERTS).

FABRICATES AND WELDS BETTER THAN PURE W, MO, AND EVEN TZM (LeRC MATERIALS EXPERTS).

WITHSTANDS CREEP ABOVE 1200°C BETTER THAN OTHER REFRACTORY ALLOYS (AND EVEN PURE W TO 1700°C) (LeRC MATERIALS EXPERTS).

IS ACCEPTABLE NUCLEONICALLY FOR FAST-REACTOR HEAT PIPES (LeRC AND EURATOM NUCLEAR MATERIALS EXPERTS).

OFFERS MANY YEARS OF SERVICE FOR LITHIUM (LI) HEAT PIPES AT 1600°C (EURATOM NUCLEAR MATERIALS EXPERTS).

WOULD CAUSE MINOR MONEY PERTURBATIONS FOR MULTIHUNDRED-KILOWATT SPACE-POWER SYSTEMS BECAUSE COSTS OF DEVELOPMENT OVERWHELM THOSE OF MATERIALS.

SUPPORTS THE FULL RANGE TEC-ART PROGRAM:
- 1800K EMITTERS FOR ULTIMATE SPACE-POWER APPLICATIONS.
- 1650K EMITTERS FOR INTERMEDIATE SYSTEMS.
- 1400K EMITTERS FOR TERRESTRIAL DEVELOPMENT.

CURRENT STATUS OF THE NASA TEC-ART PROGRAM

The NASA TEC-ART Program has evolved, as Table 2 demonstrates, to cover durable, high-efficiency thermionic converters for the full range of operating conditions, energy sources, and applications. Current emphasis on out-of-core thermionics allows materials and designs previously prohibited by in-core nucleonics and geometrics. These additional degrees of freedom offer important new TEC potentialities. However, moving in productive directions, rather than diffusing into a maze of interesting but impractical possibilities, requires continual re-evaluation. NASA's current approach to these overall TEC-ART goals is the subject of Table 2 and its subsequent elaborations throughout this section.

TABLE 2

NASA TEC-ART PROGRAM

INTENDED ACCOMPLISHMENTS

SIGNIFICANTLY INCREASED EFFICIENCIES.
DEMONSTRATED MULTIYEAR DURABILITIES.
IMPROVED ECONOMIES.
UTILIZATION OF NUCLEAR, SOLAR, AND CHEMICAL HEAT SOURCES.
ANTICIPATED APPLICATIONS FOR SPACE POWER, NEP, ...
TERRESTRIAL TOPPING CYCLES AND SPINOFFS.

CURRENT SCOPE

FULL-RANGE, HIGH-EFFICIENCY TEC
HIGH-EMITTER, HIGH-COLLECTOR TEMPERATURES (ULTIMATE HIGH-POWER SPACE APPLICATIONS: LOW RADIATOR WEIGHTS).
HIGH- OR -INTERMEDIATE-EMITTER, LOW-COLLECTOR TEMPERATURES (LOW POWER APPLICATIONS LIKE RADIOISOTOPES: NONCRITICAL RADIATOR WEIGHTS).
LOW-EMITTER, LOW-COLLECTOR TEMPERATURES (TERRESTRIAL APPLICATIONS IN HOT, CORROSIVE ATMOSPHERES).
PROBABLE OPERATING TEMPERATURE RANGES, K:
EMITTERS: 1300 TO 1800 (EXP. DATA: 1100 TO 2000).
COLLECTORS: 500 TO 1100 (EXP. DATA: 400 TO 1200).
RESERVOIRS: DEPENDENT ON ELECTRODE AND PLASMA-LOSS-REDUCTION REQUIREMENTS.

APPROACH (CONVERTER ART)

SUBSTANTIAL INTERELECTRODE-LOSS REDUCTIONS.
EFFECTIVE EMITTERS EVEN IN GREATLY REDUCED CESIUM PRESSURES.
IMPROVED ELECTRON COLLECTION CAPABILITY.
DURABLE EMITTER, COLLECTOR COMBINATIONS THAT MAINTAIN PERFORMANCE AGAINST TEC VAPORIZATION, DEPOSITION EFFECTS.

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 BASIC RESEARCH ON ELECTRON EMISSION AND COLLECTION AND THERMOPHYSICOCHEMICAL STABILITY OF PROMISING ELECTRODE MATERIALS.
PRECEDING IN-CORE NUCLEAR THERMIONIC TECHNOLOGY.

The "approach" section of Table 2 lists broad work areas in the NASA TEC-ART Program. Tables 3 through 5 expand on studies to reduce interelectrode losses, to obtain more effective emitters, and to produce improved collectors.

TABLE 3

NASA TEC-ART APPROACH

REDUCED INTERELECTRODE LOSSES

GAINS

GREATER OUTPUT VOLTAGES--AND CURRENT DENSITIES.
LOWER PLASMA MAINTENANCE VOLTAGES.
MORE EFFECTIVE IONIZATION.
BETTER ION DISTRIBUTION AND UTILIZATION.
SMALLER PLASMA RESISTIVE DROPS.
LESS CURRENT LOSSES BY ELECTRONIC SCATTERING.

APPROACH

LOWER CESIUM PRESSURES.
INERT-GAS, CESIUM PLASMAS.
UNIGNITED TRIODES: IONIZER ELECTRODE.
IGNITED TRIODES: AUXILIARY EMITTER (PLASMATRON) OR SECONDARY COLLECTOR.
PULSED DIODES.
PULSED TRIODES.
HYBRID OPERATING MODES: DISTRIBUTED MINIATURE SHORTED DIODES.

TABLE 4
NASA TEC-ART APPROACH
IMPROVED EMITTERS

GAINS

- GREATER OUTPUT CURRENT DENSITIES--AND VOLTAGES.
- INCREASED EMISSION CURRENT DENSITIES.
- EFFECTIVE OPERATION AT REDUCED TEMPERATURES.
- LOWER REQUIRED CESIUM PRESSURES.
- HIGHER VOLTAGES AT INTERMEDIATE CURRENT DENSITIES.
- LONGER LIFETIMES.

APPROACH

- NEW METALLIDE EMITTERS.
  - MUCH LOWER BARE WORK FUNCTIONS (SOME METALLIC HEXABORIDES).
  - POSSIBLE TEC EMITTERS WITHOUT CESIUM ADSORPTION.
  - WORK-FUNCTION REDUCTIONS WITH CESIUM ADSORPTION.
  - GOOD THERMOPHYSICOCHEMICAL CAPABILITIES.
    - HIGH MELTING POINTS.
    - LOW VAPOR PRESSURES.
    - ELECTRICAL AND THERMAL CONDUCTIVITIES NEAR THOSE OF METALS.
    - CHEMICAL RESISTANCE.
- BETTER METAL, OXIDE EMITTERS.
  - DEVELOPED AND DEMONSTRATED TUNGSTEN, OXYGEN, CESIUM ELECTRODES.
  - PROMISING NEW METAL, OXIDE COMBINATIONS.
- BEST METALLIC-EMITTER PROSPECTS.
  - 111 IRIDIUM.
  - 0001 OSMIUM.
  - 0001 RHENIUM.
- STRUCTURED OR ADDITIVE-MODIFIED EMITTERS.
  - INCREASED EFFECTIVE EMISSION AREAS.
  - REDUCED INTERNAL ELECTRON REFLECTIVITIES.
  - INCREASED EXTERNAL ELECTRON REFLECTIVITIES.

TABLE 5
NASA TEC-ART APPROACH
IMPROVED COLLECTORS

GAINS

- GREATER OUTPUT VOLTAGES--AND CURRENT DENSITIES.
- LOWER ELECTRON-COLLECTION VOLTAGE LOSSES.
- INCREASED ELECTRON-COLLECTION CURRENT DENSITIES.
- PERFORMANCE MAINTENANCE OR IMPROVEMENT.
- LONG LIFETIMES.

APPROACH

- REDUCED COLLECTOR WORK FUNCTIONS (UNLESS BACK EMISSION IS PROHIBITIVE).
  - NEW MATERIALS (METALLIDES AND METAL, OXIDE COMBINATIONS).
  - EFFECTIVE CESIATION.
  - ADDITIVE ENHANCEMENT OF CESIATION EFFECTS.
- LOWER ELECTRON REFLECTIVITIES BY COLLECTOR SURFACES.
  - NEW MATERIALS.
  - ADDITIVES TO INCREASE ELECTRON ACCEPTANCE.
  - STRUCTURED COLLECTOR SURFACES (ELECTRON TRAPS GREATER AREAS).
- GOOD THERMOPHYSICOCHEMICAL CAPABILITIES (LOWER TEMPERATURES THAN EMITTERS).
- SUITABLE ELECTRON-COLLECTION CHARACTERISTICS UNDER VAPORIZATION, DEPOSITION EFFECTS.
  - COLLECTOR MADE OF MATERIAL VAPOR-DEPOSITED ON IT BY EMITTER.
  - REGENERATING COLLECTOR SURFACES.
  - ASYMPTOTICALLY IMPROVING COLLECTOR PERFORMANCE.
  - NEGLIGIBLE ACCOMMODATION OF EMITTER VAPORS ON COLLECTOR (IMPROBABLE).

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_O), which equals the product of the current-density (J_O) and voltage (V_O) outputs:

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

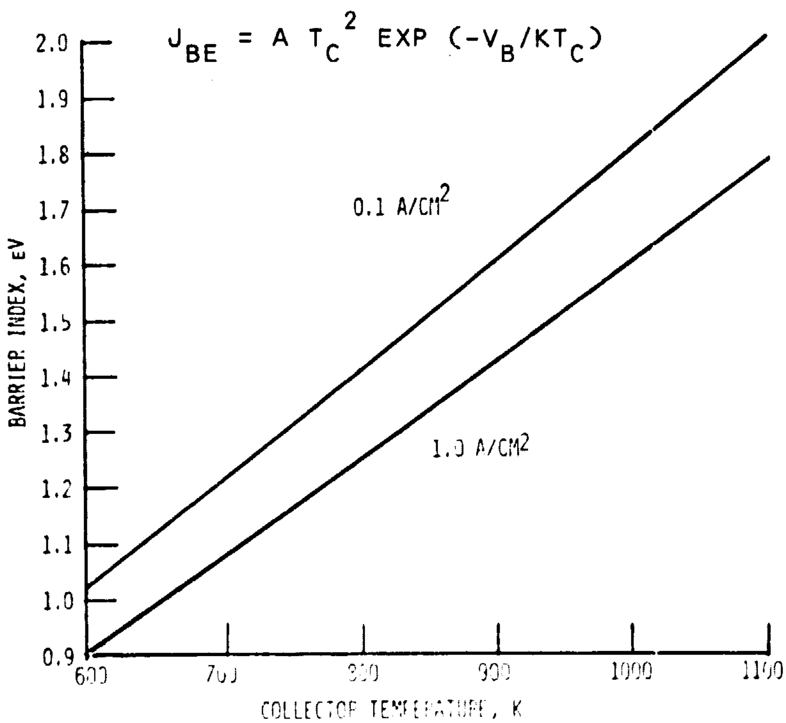
Here J_{SE} is the saturated emitter current density; J_R, total reverse current density including back emission (J_{BE}), surface reflection, and back scatter; ϕ_E, emitter work function; ϕ_C, collector work function; V_D, interelectrode voltage drop comprising resistive, scattering, ionization, and 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.

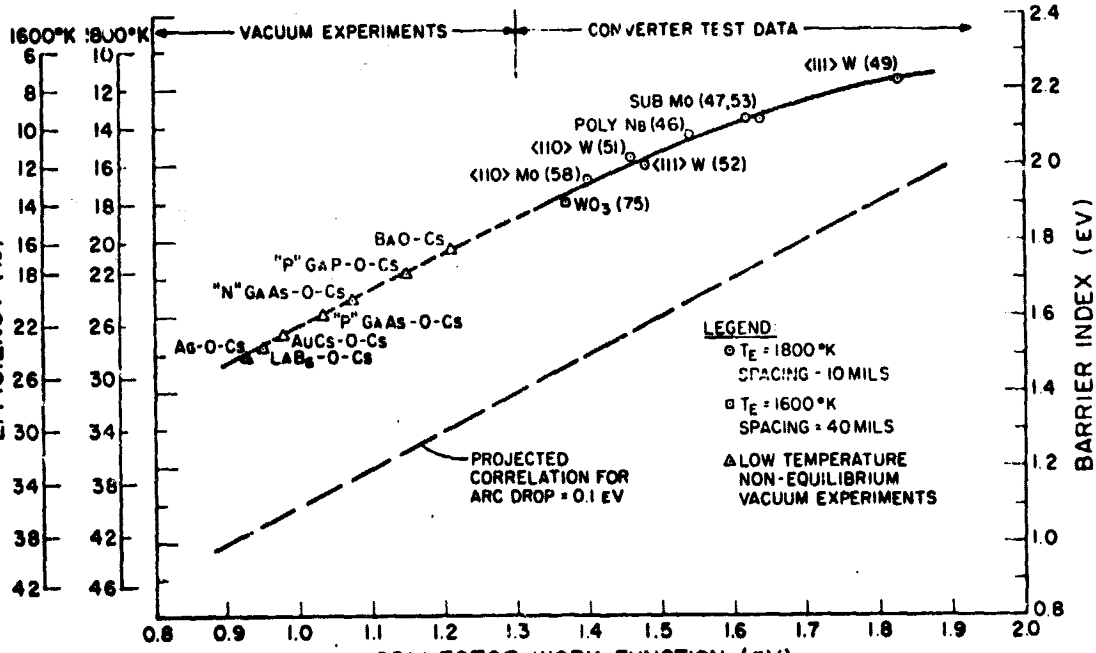
The barrier index provides a good example of different relative effects at high and low temperatures: Decreasing the barrier index raises the output voltage directly, but reduces the output current density through its exponential influence on back emission. The extent of this detraction depends strongly on the collector temperature as figure 3 reveals. 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 3 implies barrier indices greater than 1.6 eV.

FIGURE 3
TEC BACK EMISSION



Some effects of barrier indices, collector work functions, and interelectrode losses (arc drops) on TEC efficiency appear parametrically in figure 4. 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.

FIGURE 4
EFFECTS OF COLLECTOR WORK FUNCTION AND ARC DROP ON THERMIONIC CONVERSION EFFICIENCY
(THERMO ELECTRON CORP.)



CS-74587

In essence figure 4 presents a correlation showing that increased TEC efficiencies derive from higher emitter temperatures, lower collector work functions, and reduced interelectrode losses. But all figure-4 data points do not represent practical collectors. In fact, only the solid curve in the upper, right quadrant of figure 4 indicates experience with actual converters. And among those, just the cesium diodes with tungsten emitters and niobium or molybdenum collectors underwent extended lifetesting.

The figure-4 data for "vacuum experiments" reveal that low-work-function collectors are obtainable: In turn this observation allows a high-probability extrapolation of the solid-curve correlation into the lower, left quadrant of figure 4. However practical utilization of such collectors depends not only on their low work functions but also on their thermophysicochemical capabilities, emitter compatibilities, and application requirements. Some discussions of these additional qualifications arise in the preceding and subsequent sections. As a result of overall considerations, though, the collectors of barium oxide (BaO, Cs) and of oxygenated lanthanum hexaboride (LaB6, O, Cs) are the most promising new ones listed in figure 4.

In any event equations 1) and 2) as well as figure 4 emphasize the significance of the TEC-ART work covered by Tables 3 through 5 on interelectrode losses, emitters, and collectors.

Transporting thermal power to emitters and from collectors in practical thermionic converters is often best accomplished through heat pipes. So TEC-ART organizations frequently find it convenient to work with metallic-fluid heat pipes also. Accordingly, Table 6 mentions an appropriate part of the program in the Thermionics and Heat-Pipe Section at LeRC.

TABLE 6
NASA TEC-ART APPROACH
IMPROVED METALLIC-FLUID HEAT PIPES

GAINS

- SIMPLE, LIGHTWEIGHT, SELF-CONTAINED, SELF-PUMPED HEAT-TRANSPORT SYSTEMS.
- HIGH-THERMAL-POWER DENSITIES LIKE THOSE OF THERMIONIC CONVERTERS.
- NEARLY ISOTHERMAL CONVERTER-ELECTRODE SURFACES.
- HEATING OR COOLING WITH VERY SMALL TEMPERATURE DROPS.
- EXCELLENT PROSPECTS FOR COOLING NUCLEAR REACTORS.
- EFFECTIVE ELEMENTS FOR SPACE RADIATORS.

APPROACH

- MATERIALS AND DESIGNS FOR APPROPRIATE HEAT-PIPE PERFORMANCE.
- FLUID, WICK, ENVELOPE COMPATIBILITIES.
- ENVELOPE COMPATIBILITIES WITH CONVERTER INSULATORS AND REACTOR FUELS.
- ENVELOPES RESISTANT TO CREEP, THERMAL CYCLING, VIBRATION...
- LOW ENVELOPE-VAPORIZATION RATES (HIGH TEMPERATURES, HARD VACUUM).

While the last line of Table 6 refers to external vaporization, the last line of the "approach" section of Table 2 refers to crucial internal vaporization in TEC. Table 7 presents some quotations on this subject. And figure 5 graphically illustrates the emitter-vaporization, collector-deposition problem of TEC. Of course escape rates from alloys differ from those of the pure materials because of dilution, association, and diffusion effects. But figure 5 should enable order-of-magnitude estimates of high-temperature vaporization for dilute, near-ideal solid solutions in equilibrium with their vapors--or of high-temperature vaporization into vacuum for nonassociated surface components. Such approximations of emitter-vaporization and collector-deposition rates are important because thermionic converters must perform stably for years in many applications. And adsorption of only a fraction of an atomic monolayer, 10^{-8} to 10^{-7} cm, can drastically change work functions and electron reflectivities of a collector substrate.

TABLE 7

EMITTER-VAPORIZATION, COLLECTOR-DEPOSITION EFFECTS
TEC-ART OBSERVATIONS

"A SLOW DEPOSITION OF EMITTER MATERIAL OCCURS ON THE COLLECTOR SURFACE...ASSEMBI CONVERTERS USING IDENTICAL MATERIALS FOR THE EMITTER AND COLLECTOR." ROUKOLOVE (JPL): IEEE TRANSACTIONS ON ELECTRON DEVICES, AUGUST 1969.

"FOR THE ANODE BaO ON W GIVES A VERY LOW WORK FUNCTION, BUT IS LIABLE TO BE POISONED BY ATOMS EVAPORATED FROM THE CATHODE. THE USE OF THE SAME MATERIAL AS FOR THE CATHODE, RELYING ON THE Cs LAYER, IS THEREFORE PREFERRED IN THE INTEREST OF LONG LIFE." THRING (QUEEN MARY COLLEGE): CHARTERED MECHANICAL ENGINEER, JULY 1975.

"THAT CONVERTER SHOWED SIGNIFICANT IMPROVEMENT WITH TIME, PERHAPS DUE TO PLATINUM (EMITTER) DEPOSITION ON THE COLLECTOR." RASOR ASSOCIATES: NASA, ERDA TEC-ART STATUS REPORT, APRIL 1976.

"AT THE COMPLETION OF A SERIES OF EXPERIMENTS, T[illegible]ANIUM WAS FOUND TO HAVE TRANSFERRED FROM THE EMITTER GROOVES (1200K TO 1280K) TO THE COLLECTOR FACING THE GROOVES." SHIMADA (JPL): ERDA PROGRESS REPORT, MAY 1976.

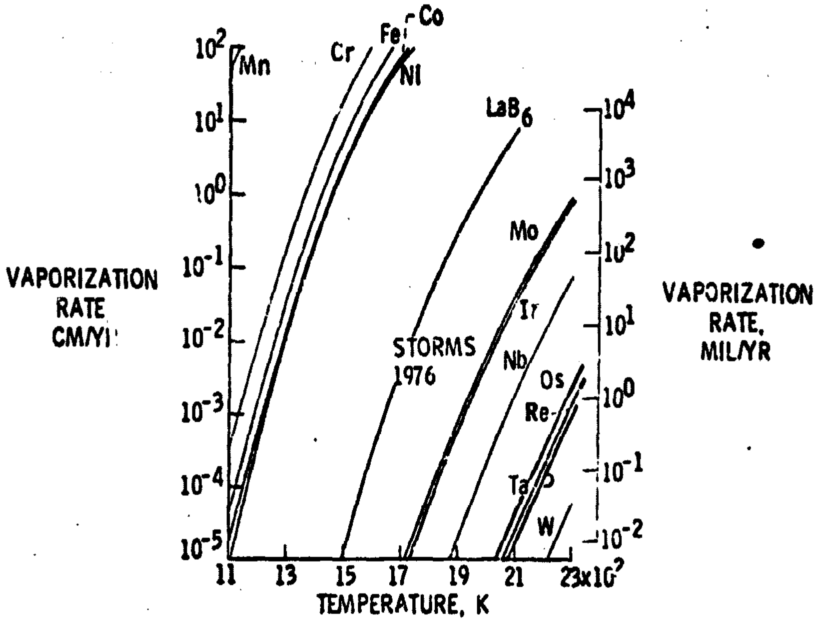
"PROBLEMS... HAVE ARISEN IN ATTEMPTS TO MEASURE ACCURATELY THE EMISSION FROM SUPERALLOYS... THE EXPERIENCE IN THIS LABORATORY IS THAT ABOVE 1200°K VERY HEAVY DEPOSITS OF EVAPORATED MATERIAL HAVE BEEN FOUND ON THE COLLECTOR AND GUARD RING." JACOBSON (ASU): NASA CR-135063, JULY 1976.

"THE HOT, CLOSE-UP EMITTER PRACTICALLY COVERS THE SEVERAL-HUNDRED-DEGREES-COOLER COLLECTOR. AND THE EMITTER VAPOR PRESSURE IS SEVERAL ORDERS OF MAGNITUDE HIGHER THAN THAT OF AN EMITTER-VAPOR DEPOSIT ON THE COLLECTOR...OTHER METHODS FOR COPING WITH THIS VAPORIZATION, DEPOSITION EFFECT ARE POSSIBLE BUT EXCEPTIONAL. 'USING IDENTICAL MATERIALS FOR THE EMITTER AND COLLECTOR' IS SIMPLE AND GENERAL." MORRIS (LERC): IECEC PAPER (NASA TM X-73430), SEPTEMBER 1976.

"ONE UNKNOWN FACTOR IS THE DEGREE TO WHICH THE CESIUM ATMOSPHERE MAY REDUCE THE DEPOSITION ON THE COLLECTOR, BUT THIS REDUCTION IS NOT LIKELY TO BE MORE THAN A FACTOR OF TEN... EVAPORATION OF THE EMITTER MATERIAL ONTO THE COLLECTOR WOULD BE RELATIVELY HARMLESS IF COLLECTOR AND EMITTER MATERIALS WERE IDENTICAL." HUFFMAN ET AL. (TECO): NASA CR-135125, NOVEMBER 1976.

FIGURE 5

VAPORIZATION OF PURE METALS AND LANTHANUM HEXABORIDE



The simple, general solution for this TEC 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.

ACCOMPLISHMENTS OF THE NASA TEC-ART PROGRAM

Coordinated NASA, ERDA TEC-ART Program

During the nearly 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.

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 ARIZONA STATE UNIV. (ASU) ELECTRON EMISSION, THERMAL STABILITY OF ELECTRODE MATERIALS	PRINCETON UNIVERSITY (PU) PLASMA THEORY LOS ALAMOS SCIENTIFIC LAB (LASL) MATERIALS, VAPOR PRESSURES HEAT-PIPE-COOLED REACTOR NAVAL RESEARCH LAB (NRL) DISPENSER-ELECTRODE STUDIES	ERDA TEC-ART MANAGEMENT
JET PROPULSION LAB (JPL) MISSIONS VEHICLES CONVERTERS	UNIV. OF MINNESOTA (UM) PLASMA-DIODE ION 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	

Demonstrated TEC Technology

Table 9 highlights some of the NASA TEC-ART contributions. The first entry 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. 4). 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.

TABLE 9

NASA TEC-ART ACCOMPLISHMENTS

18% EFFICIENCY WITH 1800K EMITTERS IN TUNGSTEN, CESIUM, OXYGEN DIODES (TECO, FIG. 4).

DEMONSTRATED INTERELECTRODE-LOSS REDUCTIONS FOR CURRENT DENSITIES LESS THAN 2 A/CM^2 (RA, TECO).

ENHANCEMENT AT PRACTICAL CONVERTER OUTPUTS POSSIBLE WITH EITHER PRIMARY (TECO) OR AUXILIARY (RA) ELECTRODES CLOSELY SPACED.

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

CONFIRMED ENERGY STORAGE IN VIBRATIONALLY EXCITED MOLECULAR NITROGEN TO USE FOR IONIZING CESIUM IN CONVERTERS (SUNY).

THEORETIC INTERELECTRODE-LOSS DIMINUTIONS AT ALL OUTPUT LEVELS WITH STRUCTURED ELECTRODES (RA).

HIGHER TEC EFFICIENCIES IN GENERAL FROM COLLECTORS WITH LOWER WORK FUNCTIONS AND OPTIMIZED TEMPERATURES (TECO, FIG. 4).

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

ABOUT-1.3 EV COLLECTOR WORK FUNCTIONS WITH CESIATION. WITHOUT OXYGENATION (TECO: BAO, ZNO; OGC: LaB_6).

METALLIC-HEXABORIDE (MB_6) EMITTER PROSPECTS
- LOW BARE WORK FUNCTIONS (CeB_6: 2.25 EV (THERMIONIC); LaB_6: 2.47 EV (THERMIONIC), 2.28 EV (RETARDING POTENTIAL))(OGC).
- REDUCTION OF (LaB_6) ELECTRON REFLECTIVITIES AS WELL AS WORK FUNCTIONS (1.3 EV) WITH CESIUM ADSORPTION (OGC).
- CONGRUENT VAPORIZATION WITH VAPOR PRESSURES CONSIDERABLY BELOW PREVIOUSLY PUBLISHED LEVELS (LaB_6) (LASL, FIG. 5).

PROPOSED EMITTER, COLLECTOR COMBINATIONS WITH VAPORIZATION, DEPOSITION COMPATIBILITY IN CESIUM CONVERTERS (TECO: W,O; LERC: MB_6).

OUT-OF-CORE-NUCLEAR TEC SYSTEM DESIGNS FOR MULTIHUNDRED-KILOWATT SPACE-POWER APPLICATIONS (JPL, LASL).

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

Enhanced-Mode Results

The next five items of Table 9 are findings related to enhanced-mode TEC: Recent work (refs. 6 and 7) reveals that plasma losses lower than 0.1 eV are attainable in rather normal converter geometries only at relatively low power densities. But augmentation at practical output levels is possible with emitters very near to their collectors (ref. 6) or with closely spaced auxiliary electrodes (ref. 7). Argon or xenon plasmatrons are more effective than the cesium version because of their favorable ratios of atomic cross sections for ionization to those for electron scattering. Improved enhancement may result from energized particles like vibrationally excited nitrogen molecules spreading auxiliary-power inputs more widely before effecting cesium ionization (ref. 8). And structured electrodes or additives that increase the effectiveness of collector acceptance and emitter rejection and emission of electrons should reduce plasma losses for all TEC power densities.

Findings on Low-Work-Function Collectors

Following the enhancement-mode section of Table 9 are three entries on low-work-function collectors: As figure 4 shows, collectors with lower work functions operating at optimum temperatures yield higher TEC efficiencies in general. But overall-system considerations like radiator weights strongly influence optimizations for multihundred-kilowatt space power. Thus, as stated earlier, a 1.0-eV-work-function collector and a 0.1-eV arc drop look good for waste-heat rejection at 700K. But because of back emission, barrier indices greater than 1.6 eV appear more practical for collectors hotter than 1000K in near-megawatt space applications.

So critical NASA requirements tolerate smaller reductions in both interelectrode losses and collector work functions than those needed for terrestrial topping cycles. For example, at collector-to-cesium-reservoir temperature ratios of 1.8 to 2.0, cesiated rhenium has work functions below 1.5 eV (ref. 1). For 1000-to-1100K collectors, this ratio range means 500-to-610K reservoirs, which yield cesium pressures suitable for effective diode operation. For 1800K, corresponding 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. And as reference 9 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. 1).

The preceding discussion involves a converter with no additives and with its emitter and collector made of the same materials: The proposed electrodes of metals with high bare work functions can operate effectively at elevated temperatures appropriate to efficient, long-life TEC in space. The indicated interelectrode losses are 0.2 to 0.3 eV, 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 and reduced collector work functions apparently attainable only with cesiated exotic materials and oxygenation.

But such collectors seem obtainable: Table 9 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 4: 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, at least the supply, control, and lifetime aspects of oxygenation complicate its use in TEC. Reference 6 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 9 indicates that progress is also being made in this TEC-ART area.

Emitter Progress

Two entries on TEC emitter prospects follow the section on collectors in Table 9. Already mentioned are refractory-metal emitters with high bare work functions and low vaporization rates (fig. 5) exemplified by 110 tungsten, 0001 rhenium, and 111 iridium. These materials allow 1800K operation with its advantage of 4 efficiency points over 1600K converters (fig. 4). 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.

With oxygenated-tungsten electrodes in a cesium diode (ref. 6) "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." This 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 be promising emitter, collector combinations with vaporization, deposition compatibility. Bare-work-function determinations for 100 faces (Table 9, ref. 10) 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 would perform well without additives. On the figure-4 curve for unenhanced TEC a 1.3-eV collector corresponds to 15% efficiency at 1600K and 19% at 1800K. For a 0.1-eV arc drop figure 4 indicates 27% 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 figure 5 shows, LaB_6 vaporization rates (ref. 11) may preclude 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. So these metallic hexaborides should adapt most effectively to intermediate- and low-temperature TEC.

The thermionic work functions for hexaborides given in Table 9 correspond to experimentally determined emission-equation coefficients (A) lower than 120 $A/cm^2/K^2$. In a very recent communication, however, OGC indicated that congruently vaporizing 100 LaB_6 exhibits an effective work function of 2.52 eV to be used in the Richardson, Dushman equation 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. 10). And "field emission patterns continue to show that the (100) direction of LaB_6 is not the lowest work function direction."

New electrode possibilities are an interesting and fertile field in the NASA TEC-ART Program.

Mission Analysis and Vehicle Design

Within NASA, JPL is responsible for studies of missions and vehicles. References to some of this work appear in a preceding section. Of course, circumspect analyses produce information of major importance to the NASA TEC-ART Program. Such analytic efforts require continual updates and enlightened extrapolations of the various contributing technologies. But judicious analyses can point parametrically to critical needs for ultimate space applications like those in the upper, right corner of figure 2. In the best form these studies can asymptotically predict and thereby bring together the most effective current contributions of the participating technologies at the crucial time.

Theoretic Descriptions of TEC Processes

Also essential in maintaining productive directions for NASA TEC-ART studies are theories and empirical correlations that predict and describe research and development requirements and results. 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

The preceding discussions detail primary accomplishments of the NASA TEC-ART Program. However, each of these results required significant contributions in secondary technologies. Unfortunately much of the supporting work, which made the present paper possible, is beyond the scope of this presentation.

Yet in a short time the NASA TEC-ART Program has produced important results ranging from basic material characterizations to possible overall-system definitions. And these accomplishments have yielded not only TEC performance gains, but also the knowledge necessary to direct future ART studies.

REFERENCES

1. G. N. Hatsopoulos and E. P. Gyftopoulos: Thermionic Energy Conversion, Volume I, Processes and Devices. Cambridge: Mass. Inst. Tech., 1973.

2. J. F. Morris and J. G. Lundholm "NASA Thermionic-Conversion Program," Proceedings of the Eleventh Intersociety Energy Conversion Engineering Conference, vol. 2, Am. Inst. Chem. Eng., 1976, pp. 1625-1655.

3. J. W. Stearns, "Status Report on Nuclear Electric Propulsion," presented at the Twenty-First Annual Meeting, American Astronautical Society, Denver, Colorado; August 1975.

4. W. C. Estabrook, D. R. Koenig, and W. Z. Prickett, "Comparative Assessment of Out-of-Core Nuclear Thermionic Power Systems, "Jet Propulsion Lab. Tech. Memo 33-749, Nov. 1975; also NASA CR-145972.

5. R. E. Gluyas and G. K. Watson; "Materials Technology for an Advanced Space Power Nuclear Reactor Concept-Program Summary," NASA TN C-7909, March 1975.

6. F. N. Huffman et al., "High-Efficiency Thermionic-Converter Studies," Thermo Electron Corp. Report TE4202-12-77, Nov. 1976; also NASA CR-135125.

7. L. K. Hansen, G. L. Hatch, and N. S. Rasor, The Plasmatron: Advanced-Mode Thermionic Energy Conversion, NASA CR-135139, November 1976.

8. D. T. Shaw, C. H. Lee, and C. N. Manikopoulos, "N_2-Cs Thermionic Converter Development," Proceedings of the Eleventh Inersociety Energy Conversion Engineering Conference, vol. 2, Am. Inst. Chem. Eng., 1976, pp. 1625-1629.

9. E. W. Kroeger, V. L. Bair, and J. F. Morris, "Diminiode Thermionic Conversion with III-Iridium Electrodes," NASA TM X-73492, Sept. 1976.

10. L. W. Swanson, J. T. Dickinson, and D. R. McNeely, "Fabrication and Characterization of Composite Refractory Compounds Suitable for Thermionic Converters," NASA CR-1668, March, 1976.

11. E. K. Storms, "Work Function Determination of Promising Electrode Materials for Thermionic Energy Converters," Arizona State Univ., July 1976; also NASA CR-135063.