NASA TM-81555

DOE/NASA/1062-6
NASA TM-81555

NASA-TM-81555 19800024713

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NOTICE

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Work performed for
U.S. DEPARTMENT OF ENERGY
Fossil Energy
Office of Coal Utilization
Washington, D.C. 20545
Under Interagency Agreement EC-77-A-31-1062

N80-33221#

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SUMMARY

Advantages of thermionic energy conversion (TEC) have been counted and are recounted with emphasis on high-temperature service in coal-combustion products. Efficient, economical, nonpolluting utilization of coal here and now is a critically important national goal. And TEC can augment this capability not only by the often-proposed topping of steam power plants but also by higher-temperature topping and process heating. For these applications, applied-research-and-technology (ART) work reveals that optimal TEC with ~1000-to ~1100 K collectors is possible using well-established tungsten electrodes. Such TEC with 1800 K emitters could approach 26.6% efficiency at 27.4 W/cm^2 with ~1000 K collectors and 21.7% at 22.6 W/cm^2 with ~1100 K collectors. These performances require 1.5- and 1.7-eV collector work functions (not the 1-eV ultimate) with nearly negligible interelectrode losses. Such collectors correspond to tungsten electrode systems in ~0.9-to-~6-torr cesium pressures with 1600-to-1900 K emitters. Because higher heat-rejection temperatures for TEC allow greater collector work functions, interelectrode-loss reduction becomes an increasingly important target for applications aimed at elevated temperatures. Studies of intragap modifications and new electrodes that will allow better electron emission and collection with lower cesium pressures are among the TEC-ART approaches to reduced interelectrode losses. These solutions will provide very effective TEC to serve directly in coal-combustion products for high-temperature topping and process heating. In turn this will help to use coal-and to use it well.

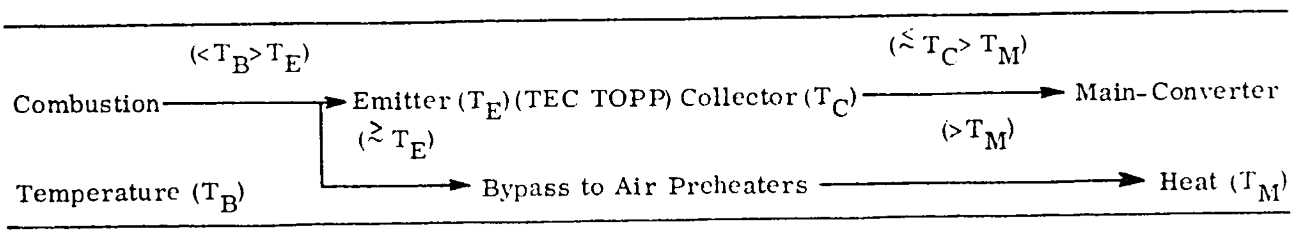
INCREASING IMPORTANCE OF THERMIONIC ENERGY CONVERSION

One of the major near-term energy-policy goals of the United States is the increased use of coal.

But effective coal utilization is difficult: Burning coal produces corrosive products at very high temperatures. So usual power-generation methods degrade coal-combustion temperatures, with dilution or secondary heat-transfer fluids, to levels safe for conventional conversion systems. This approach is inherently inefficient and is rapidly becoming uneconomical as fuel costs soar. Topping with high-temperature power generators is increasing in importance.

Capability to operate directly in coal-combustion products at high temperatures is one of the major advantages of thermionic energy conversion (TEC: refs. 1 to 13). Other desirable TEC features appear in tables 1 and 2. Direct TEC operation in high-temperature coal-combustion products obviates the previously discussed degradation of thermal potential as a sacrifice to power-system safety. It also precludes transforming coal to fluid fuels. This latter extra step imposes additional inefficiency and expense to render a more tractable fuel from coal. Then subsequent reaction of the resulting fluid fuels experiences the further inefficiency and expense of the primary conversion process. And if the coal utilized yields intolerable pollutants, removal of such substances, desulfurization for example, is generally necessary whether producing fluid fuels first or coal-combustion products directly. But direct coal heating of TEC eliminates the cost, loss, and complication of an additional process or operation stage.

Initially, however, analytic results for coal-fired TEC topping of power plants (TOPP) suffered comparatively: Designs incorporating relatively low-temperature, low-power-density TEC indicated worthwhile improvements in overall plant efficiency (OPE) accompanied by uninspiring cost-of-electricity (COE) levels (fig. 1: "unopt '78 TEC, stream," refs. 12 and 13). But recent analyses based on high-temperature, high-power-density TEC (refs. 14 and 15) have begun to imply the much greater possibilities for fully matured TEC TOPP (fig. 1 "part. opt. '78 TEC, steam," refs. 9, 12 and 13). Simplified TEC TOPP appears in the following diagram.



Now TEC-cooled combustor concepts capitalize on existing technology and incre- mental improvements along the way to advanced performance (refs. 16 to 18): burner effluents and components as well as preheating combustion air with high temperature TEC generates electricity - in addition to lower-temperature fluid streams for other conversion systems. This is another example of skimming Carnot thermal efficiency off the top of combustion with TEC. But compared with previous TEC-TOPP proposals TEC combustors offer substantial adaptability, hence smaller economic and system perturbations. Preliminary unoptimized analyses of combined cycles indicate interesting output-power gains with impressive marginal efficiencies and competitive costs for combustors cooled with current TEC capability.

Again direct operation in fossil-fuel combustion products at high temperatures is the big TEC-application advantage. And this of course requires a very effective heat-receiver coating. Silicon-carbide (SiC) clads for TEC TOPP (refs. 1 and 16 to 23) surfaced as one solution to this problem in pre-1970 Office of Coal Research Studies: Reference 1 published on the thermal-shock stability, hot-corrosion protection, molten-slag resistance, and thermal-expansion compatibility of SiC-clad TEC. EPRI-supported work on coal-fired recuperators and regenerators further verifies the value of SiC as a high-temperature heat receiver. And Thermo Electron Corporation recently completed 5000-hour tests of a SiC-clad converter with a 1630 K emitter. They also revealed that TEC fabrication based on chemical vapor deposition (CVD) with suitable SiC cladding is more economical than with lower-temperature superalloy protection. So directly fired TEC appears cost-effective as well as feasible.

For TEC TOPP in general, high-temperature cogeneration, and TEC combustors performance goals remain the same: Reduce TEC internal losses to about one volt. And this is a good target for TEC applied research and technology (ART). But for some high-temperature topping and process-heating applications, optimal TEC is possible with well-established electrodes: New ones are not essential. To amplify this point the present paper examines theoretic results for TEC with 1600-to-1900 K emitters, 900-to-1400 K collectors, 10% back emission, and negligible interelectrode losses.

OPTIMAL FULLY MATURED TEC

For years widely accepted standards of TEC performance have been the power density and efficieny computed for 10% back emission and negligible interelectrode losses. Such results are generally presented for the output at terminals of optimum leads, with ohmic and thermal-conduction losses included. Calculations based on these theoretic performances produced TEC-TOPP values indicated by figure 1 (refs. 12 and and 13).

Similar analyses yielded the COAL MHD, TEC, STEAM point on figure 2. This lowest-COE, highest-OPE system results from a minor operational perturbation of the COAL OPEN-CYCLE MHD, STEAM design: Fully matured TEC now thermally connects the post-MHD "radiant furnace" with its cooling water (ref. 24). The heat transferred to the TEC is less than 24.6% of the total thermal power supplied to the MHD, STEAM plant. Inverted (a.c.) TEC power is about 8% of that overall plant input and approximately 15.3% of the overall electric output. The 53% OPE and 32.7-mills/kW·hr COE shown for COAL MHD, TEC, STEAM on figure 2 derived from 35% TEC effeiciency for ~1800 K emitters with 800-to-850 K collectors. Upgrading to 1900 K, 750 K TEC (~40% efficiency) in the same configuration yields ~54% OPE and less-than-32-mills/kW·hr COE. Again, such numbers represent fully matured technology (figs. 1 and 2).

These and other figure-2 TEC-TOPP values correspond in general to theoretic TEC performance for 700-to-850 K collectors. Figures 3 to 10 from reference 12 present such results calculated by methods described in references 12 to 14. The 700-to-850 K collectors adapt well to topping steam power plants in particular. But scanning tables 3 and 4 (ref. 25) reveals several conversion systems that could be much more efficient with TEC topping interposed between combustion products at 2000 to 2200 K and converter-inlet temperatures considerably lower than those - yet considerably higher than the ~800 K for steam turbines. And like steam turbines, closed-cycle gas turbines as well as Stirling engines require separation of their working fluids from the combustion products. TEC could provide this separation while transporting the necessary heat and generating additional electric power by topping these converters. Furthermore the TEC, STEAM and MHD, TEC, STEAM values of figure 2 imply that the added power would increase OPE and could reduce COE for such TEC-TOPP systems.

Whenever high-temperature combustion supplies energy hundreds of degrees cooler to some power generator, TEC TOPP should be considered to decrease fuel consumption, pollution, and COE as well as to increase output power and OPE.

But considering TEC TOPP with some of the advanced energy converters listed in table 3 means providing inlet temperatures like 839, 1028, 1061 K and higher. This in turn implies TEC collectors hotter than the 700-to-850 K range - and lower efficiencies. How much lower? Figures 11 to 18 answer this question for fully matured TEC (10% back emission, negligible interelectrode losses, optimum-lead ohmic and thermal losses). Figures 17 and 18 in particular show effects of rising collector temperatures on efficiency and power density at 30 A/cm^2 for various emitter temperatures. Advanced-conversion-inlet and air-preheater temperatures also appear on figures 17 and 18. Air (fluid) preheaters are useful for topping as in the TEC, steam system; for providing clean, high-temperature process fluids; and for recuperating energy from "ultra-high temperature flue gases" required in some industries (ref. 26, table 5). And of course combustors cooled by TEC, which in turn heats combustion air and/or injection fluids, can supply the high-temperature flue gases for any of the previously mentioned applications.

After this digression prompted by figures 17 and 18, it should be observed that the efficiencies and power densities for those figures come from figures 11 to 16. In addition to such results as functions of current density and emitter temperature for a given collector temperature, each of figures 11 to 16 presents internal-loss values. This aspect will receive further attention in the next section.

HIGH-TEMPERATURE COLLECTORS FOR OPTIMAL TEC

With negligible interelectrode losses the total internal losses for TEC are effectively the collector work functions. And corresponding to the previously mentioned conversion-system inlet temperatures (tables 3 and 4) the work functions would probably be those for 1000, 1100 K and hotter collectors.

Figures 12 and 13 indicate optimal work functions (internal losses) of about 1.5 and 1.7 eV for 1000 and 1100 K collectors in TEC with 20 to 30 A/cm^2. In turn a Rasor plot (figure 19, refs. 27 to 29) reveals that the old TEC-electrode standards, molybdenum (No) and ⟨110⟩ tungsten (⟨110⟩ W: 1-xtal or CVD'd from WCl_6), provide work functions near 1.5 eV for collector-to-cesium-reservoir temperature ratios (T_C/T_R's) from 1.6 to 2.35. For this range with a 1000 K collector figure 20 shows cesium vapor pressures (P_{Cs}'s) from 0.01 to 7 torr. And 1600-to-1900 K ⟨110⟩W emitters represented on figure 21 for 30 A/cm^2 require P_{Cs}'s from 0.9 to 2.5 torr - well within the limits for 1000 K Mo and ⟨110⟩W collectors.

Therefore ultimate TEC performance corresponds to operation with well-established ⟨110⟩ W electrodes, as 1000 K collectors and as 1600-to-1900 K emitters. No exotic electrode materials are necessary. But now the assumption of negligible interelectrode losses looms large. Of course this goal currently commands primary attention in TEC ART.

For the previously mentioned 1.7 eV optimal work function (internal losses) of 1100 K collectors (fig. 13), the figure-19 Rasor plot indicates that the oldest TEC-electrode standby, polycrystalline tungsten (pxtal W), qualifies: Pxtal W affords near-1.7 eV work functions for T_C/T_R's from 1.6 to 2.0. This gamut on figure 20 covers P_{Cs}'s from 0.9 to 23 torr. And the 1600-to-1900 K pxtal-W emitters for 30 A/cm^2 TEC require 3.3-to-5.7-torr P_{Cs}'s (figure 21) - well within the range for optimal 1100 K pxtal-W collectors.

Again ultimate TEC performance corresponds to operation with well-established electrodes: pxtal W as 1100 K collectors and as 1600-to-1900 K emitters. And again attainment of optimal TEC depends on approaching negligible interelectrode losses through effective ART.

Incidentally the figure-21 collector work functions for 15-to-30 A/cm^2 TEC require at 1200 K 0.20-to-0.36-torr P_{Cs}'s for pxtal W and 0.013-to-0.022-torr P_{Cs}'s for

⟨110⟩W, at 1300 K 0.23-to-0.35-torr P_{Cs}'s for pxtal W and 0.034-to-0.052-torr P_{Cs}'s for ⟨110⟩W, and at 1400 K 0.30-to-0.47-torr P_{Cs}'s for pxtal W and 0.072-to-0.094-torr P_{Cs}'s for ⟨110⟩W. These cesium pressures are considerably removed from those for 1600-to-1900 K emitters of the same materials. So other electrode materials are apparently necessary for optimal TEC with collectors hotter or cooler than this approximate 1000-to-1100 K range.

The preceding reference to emitters and collectors of "the same materials" implies perhaps the simplest solution to the problem of TEC-performance shifts caused by vapor deposition on collectors. An excerpt from reference 30 provides background and context for this problem:

The following quotations describe this problem and indicate a solution.

"A slow deposition of emitter material occurs on the collector surface. . . assemble 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, titanium 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 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 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 eqiulibrium 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.

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 thermophysicochemcial 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.

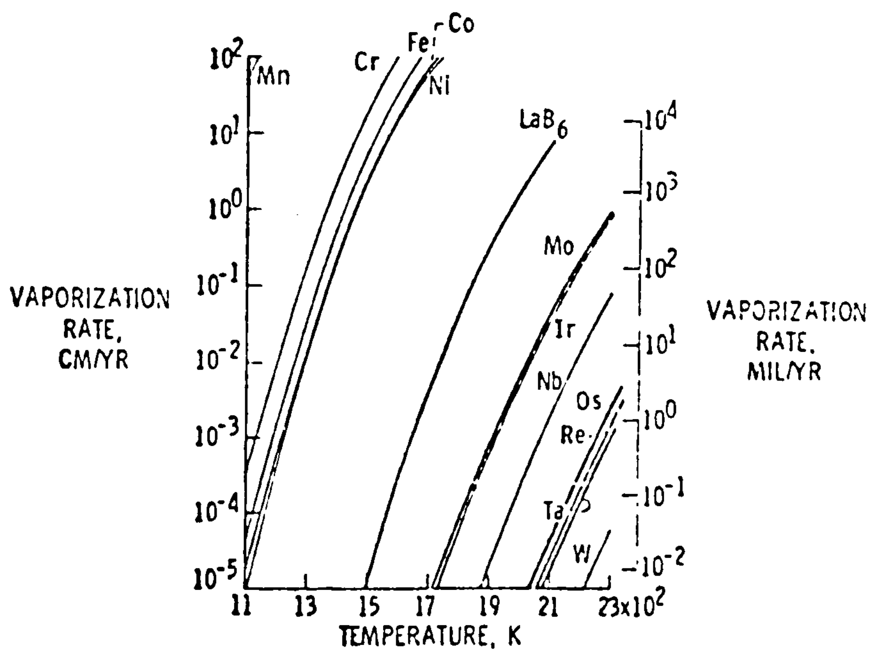


Figure 5. Vaporization of pure metals and lanthanum hexaboride

And although compatible well-established electrode systems might lead to ultimate TEC performance with ~1000-to-~1100 K collectors, other more effective electrodes are necessary for TEC with cooler or hotter collectors. These very important requirements and the critical need for substantially reduced interelectrode losses in any event translate to a mandate for intensive TEC-ART activity.

OPTIMAL TEC: CONVERTER ART

Feasibility and design studies for TEC applications have advanced significantly in recent years, as described in preceding sections. Many other specific TEC-ART accomplishments have also occurred in the interim. Yet broad aspects of converter-ART work, directed toward better electrodes and reduced interelectrode losses, continue to follow a general outline extracted from reference 30:

Approach (Converter ART)
- Substantial interelectrode-loss reductions
  - 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
  - Detailed Approach
    - Lower cesium pressures
    - Inert-gas, cesium plasmas
    - Unignited triodes: ionizer electrode
    - Ignited triodes: auxiliary emitter (plasmatron) or secondary collector (Gabor-type)
    - Pulsed diodes
    - Pulsed triodes
    - Hybrid operating modes: distributed miniature shorted diodes

Effective emitters even in greately reduced cesium pressures
- Gains
  - Greater output current densities--and voltages
  - Increased emission current densities
  - Effective operation at reduced temperatues
  - Lower required cesium pressures
  - Higher voltages at intermediate current densities
  - Longer lifetimes
- Detailed 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

Improved electron collection capability
- Gains
  - Greater output voltages--and current densities
  - Lower electron-collection voltage losses
  - Increased electron-collection current densities
  - Performance maintenance or improvement
  - Long lifetimes
- Detailed 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
    - Additivies 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-depositied on it by emitter
      - Regenerating collector surfaces
      - Asymptotically improving collector performance
      - Negligible accommodation of emitter vapors on collector

Although the outline fails to mention very closely spaced electrodes as an approach to interelectrode-loss reduction, that is where TEC began. And this option, like several others, may evolve subject to clever innovations in detailed converter design and fabrication.

In this vein a theoretic analysis of "plasma resistance effects in thermionic converters" (ref. 31), commenting on and departing from another such study (ref. 32), offers one solution: "Reduction of arc drops to tolerable values may require minimum spacings between emitter and collector, i. e., less than 0.05 cm, which would limit practical thermionic devices to diode configurations." However, "distributed miniature shorted diodes" (outline), like 1-xtal whiskers CVD'd on the emitter to approach the collector thermally but not electrically, might maintain tight spacings and increase ionization between electrodes simultaneously. Or the distributed emitter-lead concept, proposed by Rasor Associates to minimize cumulative effects of high current densities, might also provide shorted-diode ionization and close-spacing maintenance. The "particle thermionic converter," being studied by Thermo Electron Corporation, is another approach to very closely spaced electrodes, which were deemed insurmountable fabrication and operation problems several years ago.

In the same innovative flow, economical mass microfabrication methods will eventuate to allow electrical intervention between TEC electrodes without forcing them apart. This will expand triode capabilities. And techniques for microdistribution will overcome some triode current-density limitations. Electronics and computer technologies testify to the probable feasibility and economics of such relatively simple miniaturized mass production.

Comparatively new TEC technologies "limit practical thermionic devices to diode configurations." But the national TEC-ART program is making worthwhile gains: An "executive summary "of many of these advances comprises the "Thermionics and Plasma Diodes" sections of the Conference Record-Abstracts of the 1980 IEEE International Conference on Plasma Science (University of Wisconsin, May 1980). This TEC-ART work currently projects much better electrodes and reduced interelectrode losses.

SIGNIFICANCE OF OPTIMAL TEC WITH ESTABLISHED ELECTRODES

The TEC-cooled combustor based on current technology is an excellent innovation. Probably even better is TEC TOPP derived from available TEC capabilities (ref. 13): It offers OPE and COE advantages with significant relative COE decreases as fuel cost increases. And OPE as well as COE improve rapidly as TEC performance rises. Also the fact that well-established electrodes can serve optimal TEC with ~1000-to-~1100 K collectors is very worthwhile.

Of course nearly negligible interelectrode losses are necessary for optimal TEC. But that would be one relatively straightforward goal for this limited range: Reduction of interelectrode losses would not be complected with permutations of new-electrode-material emission, electron collection, plasma interaction, fabrication, attachment, thermal-expansion compatibility, reaction, diffusion, vaporization. . . . And for optimal 30 A/cm^2 TEC with 1800 K emitters, performances reach 26.6% efficiency at 27.4 W/cm^2 with 1000 K collectors and 21.7% at 22.6 W/cm^2 with 1100 K collectors. Such converters could effectively top other lower-temperature conversion systems (figs. 17 and 18), preheat air or other fluids for high-temperature process industries (figs. 17 and 18, table 5), and even serve in TEC combustors.

For example initial estimates indicate that topping with optimal TEC having 1100 K collectors could raise the system efficiency for an "advanced technology" Stirling engine (refs. 31 and 32) from ~43% to ~47%. This result derives analytically from putting ~25% of the heat from hydrocarbon combustion through 1800, 1100 K TEC and ~12% through 1600, 1100 K TEC. TEC throughputs, hence OPE, would increase with air preheating by combustion products between ~1600 K and ~1100 K - prior to Stirling-engine heat-pipe inputs. Of course higher efficiencies would also evolve from cascaded topping with optimal TEC having 1900 K emitters and 1100 K collectors ($\eta_{TEC} \approx 24\%$); then 1800 K and 1100 K ($\eta_{TEC} \approx 22\%$); 1700, 1100 (~19%); 1600, 1100 (~15%); and 1500, 1100 (~11%). Such optimal TEC could utilize well-established polycrystalline-tungsten emitters and collectors if negligible interelectrode losses were attained. And TEC heat pipes could supply high thermal power densities required by Stirling engines.

First approximations also predict that TEC cooling can raise to over 51% the 43.4% OPE of the MHD, steam "reference plant 3" with oxidizer enhancement replacing high-temperature air preheating (ref. 33): This improvement results from an 1800, 900 K TEC-cooled MHD combustor, diffuser, and radiant furnace as well as 15% cooling of the seed-recovery furnace with 1600, 900 K TEC. Of course the inverted TEC-power yield reduces the steam-turbine output. But overall power production and OPE gain significantly for the given total thermal input. And these improvements would grow if TEC collector temperatures were cascaded downward from 850 K, just meeting heat-transfer requirements at each stage, rather than being fixed conservatively at 900 K. Again these are estimations based on fully matured conversion technologies. And again the discussion drifts toward lower- rather than high-temperature collectors.

As the section before last implies, optimal TEC with collectors hotter than ~1100 K apparently requires electrode materials that emit more electrons in lower P_{Cs}'s than W does. And as the outline in the preceding section states, reducing P_{Cs}'s is definitely a major approach to decreasing interelectrode losses. That outline also reveals that TEC-ART studies recognize better emitter materials in at least several categories: metals; metal, oxide combinations; metallides; and structured or additive modifications. Work in these areas continues to yield interesting results accompanied by fabrication and maintenance questions requiring new answers.

Of further significance is the viewpoint of many thermionickers that saturated electron emission from collectors should be lower than 10 % of the output current density even in nonoptimal TEC. They observe that high electron emission from the collector at least causes double-valued collector sheaths. These conditions in turn lead to higher virtual-collector work functions and performance reductions. Under such groundrules the W collectors for ~1000-to-~1100 K collectors could be optimal regardless. But this hypothesis deserves testing for each particular converter situation to determine the actual performance optimum.

In any event a 1-eV collector work function is not necessary for optimal TEC with collectors hotter than 700 K. And as figure 21 shows, collector work functions "for high-temperature topping and process heating" are quite far removed from the 1-eV criterion. In fact as previously asserted, W emitters could serve 30 A/cm^2 optimal TEC with ~1000 K-to-~1100 K W collectors if nearly negligible interelectrode losses could be attained for the requisite ~0.9-to-~6-torr P_{Cs}'s. Of course more effective electrode systems that excel at lower P_{Cs}'s are desirable. But for the suggested higher-temperature applications, interelectrode-loss reduction becomes an increasingly important goal.

Meeting this ART challenge will provide very effective TEC to serve directly in coal-combustion products for high-temperature topping and process heating. This will help to use coal - and to use it well.

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TABLE 1. - THERMIONIC-ENERGY-CONVERSION (TEC) ADVANTAGES

Electricity directly from heat
No moving parts or inherent mechanical stresses
High temperatures: high Carnot efficiencies
Great power densities - with
Broad near-maximum-efficiency plateaus
Rapid responses to load or heat variations (const. temp.)
Low weights
Small volumes
Modularity

TABLE 2. - MODULARITY IN TEC APPLIED RESEARCH AND TECHNOLOGY (ART)

TEC ART is essentially independent of other system components
Development and testing on the lab bench are effective
Converters are scalable
Module building blocks adapt to system size and shape
Repetitious rotational fabrication modes apply
Nearest-neighbor load sharing minimizes unit-failure effects
Modular designs allow TEC-UNIT replacements

Economy: research, development, fabrication, application
Adaptability
Reliability
Maintainability

TABLE 3. - MAJOR PARAMETERS STUDIED FOR ADVANCED ENERGY CONVERSION SYSTEMS

System	Parameter	General Electric Co.	United Technologies Corp.
Steam turbine	Turbine configuration	Noncondensing with back pressure at process required pressure	Condensing with single extraction at 50 or 600 psig
	Throttle pressure/temperature, psig/°F	1450/1000 850/825	1200/950 1800/1050
	Boiler type	AFB, PFB	AFB
Open-cycle gas turbine: Liquid fueled	Turbine inlet temperature, °F	2200, 2600	2500
	Pressure ratio	8 to 16	10 to 18
	Recuperator effectiveness:		
	With residual fuel	0	0
	With distillate fuel	0, 0.6, 0.85	----------------
	Ratio of steam injection rate to airflow	0, 0.1, 0.15	0, 0.05, 0.1
	Bottoming cycle	None, steam	None, steam
Coal fired	Turbine inlet temperature, °F:		
	With coal - gasifier	2200	2400, 2500
	With coal - PFB	----------------	1600
	With coal - AFB	----------------	1500
	Pressure ratio:		
	With gasifier	10	17, 18
	With coal - PFB	----------------	6 to 10
	With coal - AFB	----------------	10
	Gasifier type	Entrained bed	Entrained bed
	Bottoming cycle	Steam	None, steam
Diesel: Low speed (2 cycle)	Speed, rpm	----------------	120
	Jacket coolant temperature, °F	----------------	266
	Unit size, MWe	----------------	8 to 29
Medium speed (4 cycle)	Speed, rpm	450	----------------
	Jacket coolant temperature, °F	250	----------------
	Unit size, MWe	0.3 to 15	----------------
High speed (4 cycle)	Speed, rpm	----------------	1800
	Jacket coolant temperature, °F	----------------	Adiabatic
	Unit size, MWe	----------------	0.2 to 15
Closed-cycle gas turbine	Working fluid	Helium	Air, helium
	Turbine inlet temperature, °F:		
	With AFB	1500	1500
	With liquid fuel	----------------	2200

Temperature conversions

°F	K
2000	1367
2200	1477
2400	1588
2600	1700
2800	1811
3000	1922

TABLE 3. - Concluded.

System	Parameter	General Electric Co.	United Technologies Corp.
Closed-cycle gas turbine (concluded)	Pressure ratio:		
	With helium	2.5	3 to 6
	With air	----------------	3 to 14
	Recuperator effectiveness	0, 0.6, 0.85	0, 0.85
	Compressor inlet temperature, °F	80	190, 300
Stirling engine	Fluid	Helium	Helium
	Maximum fluid temperature, °F:		
	With coal - flue gas desulfurization	1390	----------------
	With coal - AFB	----------------	1450
	With liquid fuel	----------------	1600
	Heat input configuration:		
	With coal fuel	Intermediate heat-transfer gas loop	Intermediate heat-transfer gas loop
	With liquid fuel	Heater head in combustion zone	Intermediate heat-transfer gas loop
	Engine coolant temperature, °F	As required by process up to 500	150
	Unit size, MWe	0.5 to 2	0.5 to 30
Fuel cell:			
Phosphoric acid	Stack temperature/pressure, °F psia	375/15	400/120
	Fuel processing:		
	With petroleum-derived fuel	Steam reformer	Steam reformer
	With coal-derived fuel	Steam reformer	Adiabatic reformer
Molten carbonate	Cell stack temperature, °F	1000 to 1300	1100 to 1300
	Cell stack pressure, psia	147	120
	Cell stack temperature control configuration:		
	With distillate-grade fuel	Cathode recycle	Anode recycle
	With gasifier	Excess cathode air	Anode recycle
	Gasifier type (coal-fired case)	Entrained bed	Entrained bed
	Bottoming cycle	None, steam with gasifier	None
Thermionics	Emitter collector temperature, °F	2420/710 1880/900	2400/763 2400/1113
	Configuration	Modular array	Thermionic heat exchanger (THX)
	Air preheat temperature, °F	1000	2200, 1000
	Bottoming cycle	None, steam	None, steam

Temperature conversions

°F	K
2000	1367
2200	1477
2400	1588
2600	1700
2800	1811
3000	1922

TABLE 4. - MAJOR PARAMETERS OF STATE-OF-THE-ART ENERGY CONVERSION SYSTEMS

System	Parameter	General Electric Co.	United Technologies Corp.
Steam turbine	Configuration	Noncondensing with back pressure at process required pressure	Condensing with single extraction at 50 or 600 psig
	Throttle pressure/temperature, psig/°F	1450/1000 850/825	1200/950 ----------------
	Fuel	Pulverized coal with flue gas desulfurization, petroleum residual	Pulverized coal with flue gas sulfurization, petroleum residual
Gas turbine:			
Petroleum distillate fired	Turbine inlet temperature, °F	2000	2000
	Pressure ratio	10	10 to 14
Petroleum residual fired	Turbine inlet temperature, °F	1750	----------------
	Pressure ratio	10	----------------
Diesel			
Petroleum distillate fired	Type	Medium speed, 4 cycle	High speed, 4 cycle
	Speed, rpm	450	1800
	Jacket coolant temperature, °F	180	200
	Unit size, MWe	0.3	0.4 to 1.5
Petroleum residual fired	Type	Medium speed, 4 cycle	Low speed, 2 cycle
	Speed, rpm	450	120
	Jacket coolant temperature, °F	155	158
	Unit size, MWe	1 to 10	8 to 29

Temperature conversions

°F	K
2000	1367
2200	1477
2400	1588
2600	1700
2800	1811
3000	1922

TABLE 5. - PROCESS CHARACTERISTICS PERTINENT TO HTR

(REF. 25)

Process	Flue gas temp. (^{o}F)	Annual energy consumption (10^9 Btu)	Efficiency of present system (%)
Aluminum casting	2000-2800	21.2	30
Brass melting	2000-2200		45
Refractory clay	2300-2500	21.9	
Copper melting	2100-2500	25.5	43
Copper refining	2300-2600	10.1	46
Steel normalizing	1700-1800		
Steel forging	2000-2100	34	15-25
Steel ingots heating	2100-2400	132,000	20-40
Reheating steel	2000-2200	281,000	25-30
Sintering (metal powder)	2000-2100		
Structural clay	2800-3000	150,000	
Continuous casting	2000-2200	4,200	
Glass melting	2600-3000		25-33

Temperature conversions

^{o}F	K
2000	1367
2200	1477
2400	1588
2600	1700
2800	1811
3000	1922

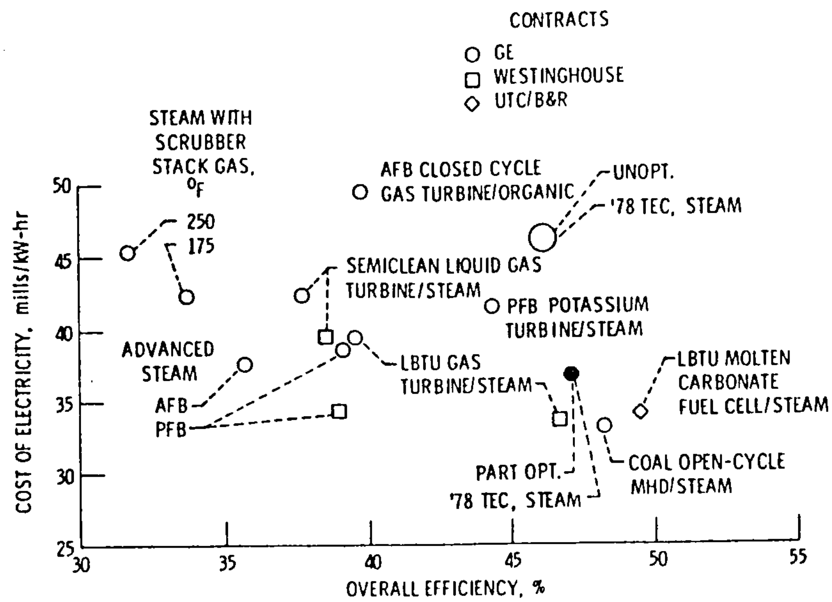

Figure 1. - ECAS Phase 2 results using 30-year levelized cost in mid-1975 dollars. Fuel cost assumed constant in fixed dollars.

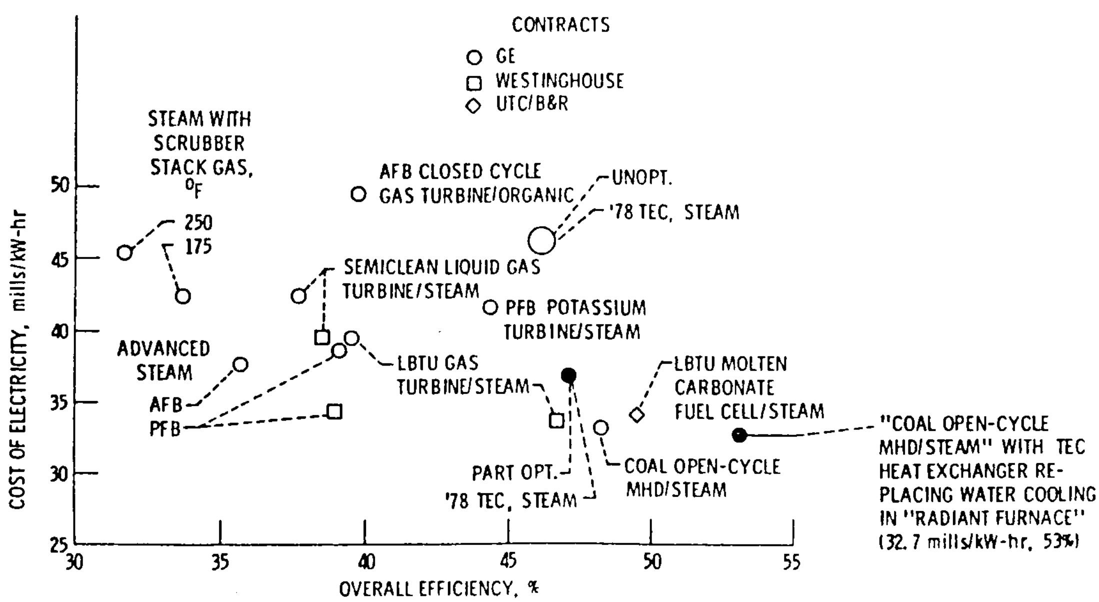

Figure 2. - ECAS Phase 2 results using 30-year levelized cost in mid-1975 dollars. Fuel cost assumed constant in fixed dollars.

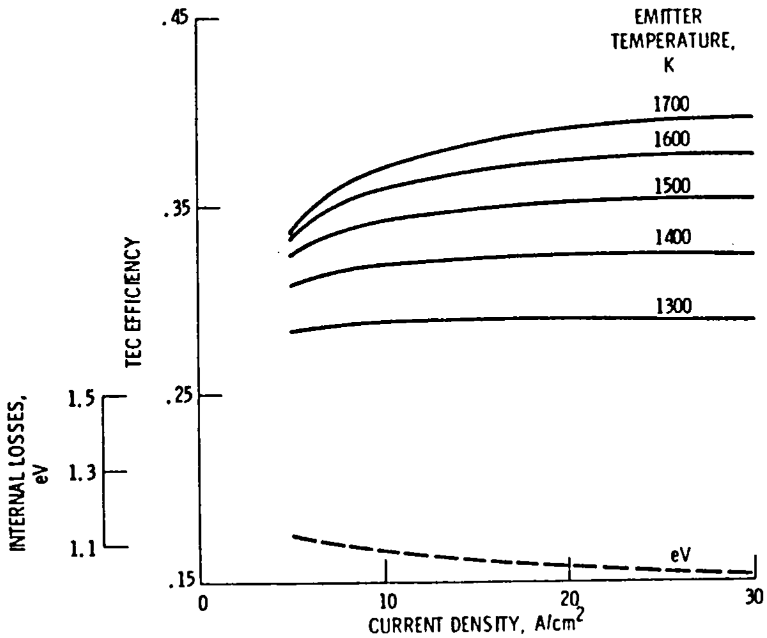

Figure 3. - Calculated thermionic-energy-conversion efficiency (10% back emission, optimum leads) as a function of output current density for 700 K collectors with 1300-to-1700 K emitters.

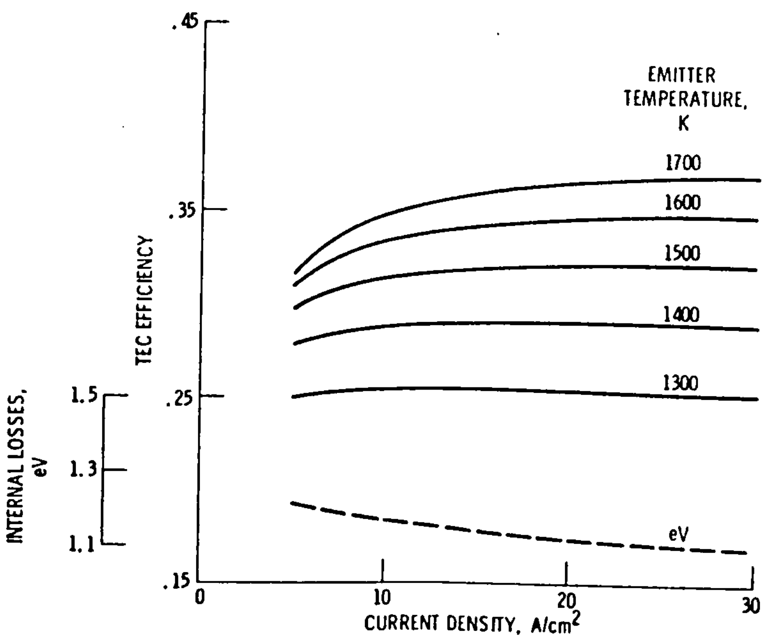

Figure 4. - Calculated thermionic-energy-conversion efficiency (10% back emission, optimum leads) as a function of output current density for 750 K collectors with 1300-to-1700 K emitters.

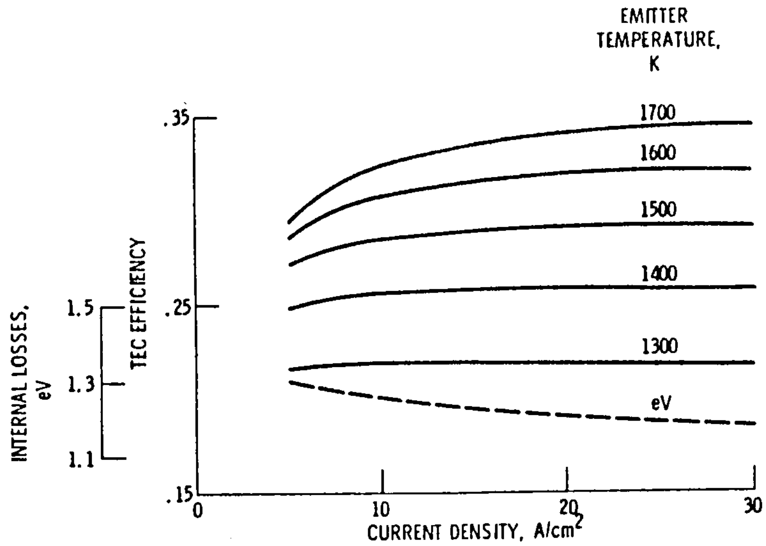

Figure 5. - Calculated thermionic-energy-conversion efficiency (10% back emission, optimum leads) as a function of output current density for 800 K collectors with 1300-to-1700 K emitters.

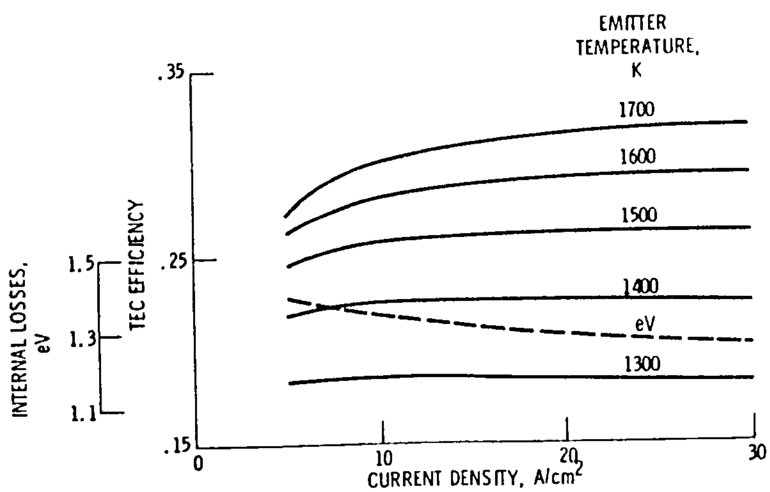

Figure 6. - Calculated thermionic-energy-conversion efficiency (10% back emission, optimum leads) as a function of output current density for 850 K collectors with 1300-to-1700 K emitters.

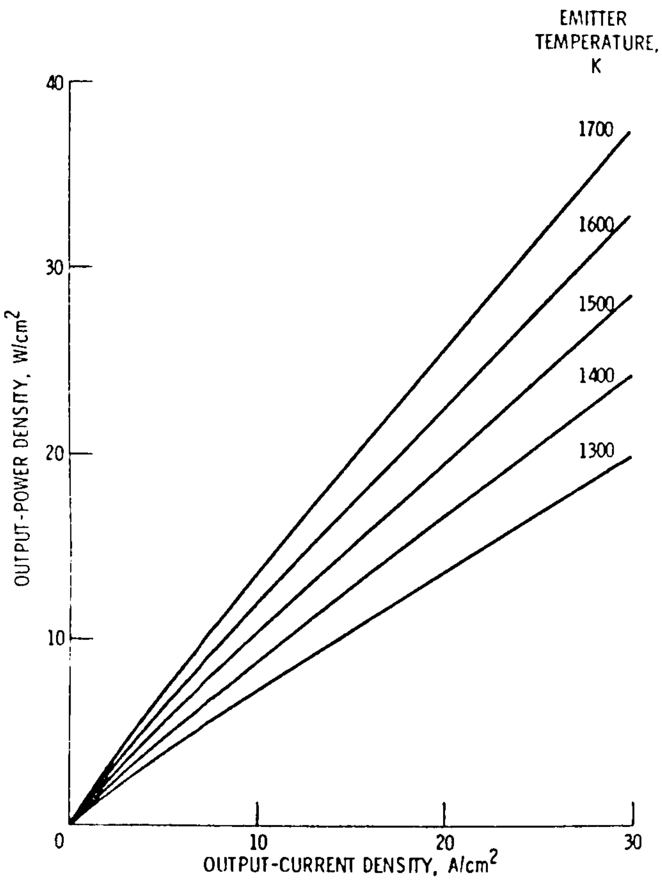

Figure 7. - Calculated thermionic-energy-conversion output-power density (10% back emission, optimum leads) as a function of output current density for 700 K collectors with 1300-to-1700 K emitters.

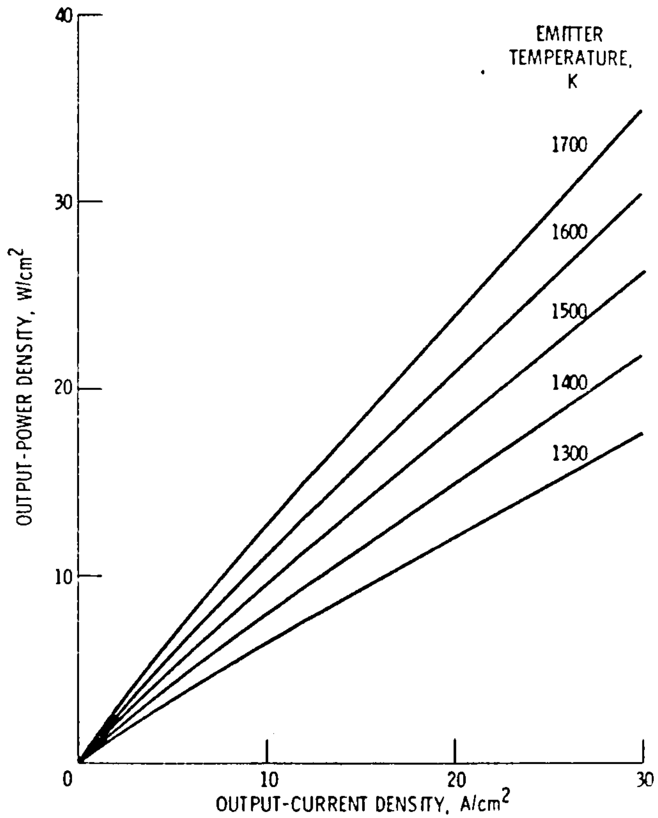

Figure 8. - Calculated thermionic-energy-conversion output-power density (10% back emission, optimum leads) as a function of ouput output-current density for 750 K collectors with 1300-to-1700 K emitters.

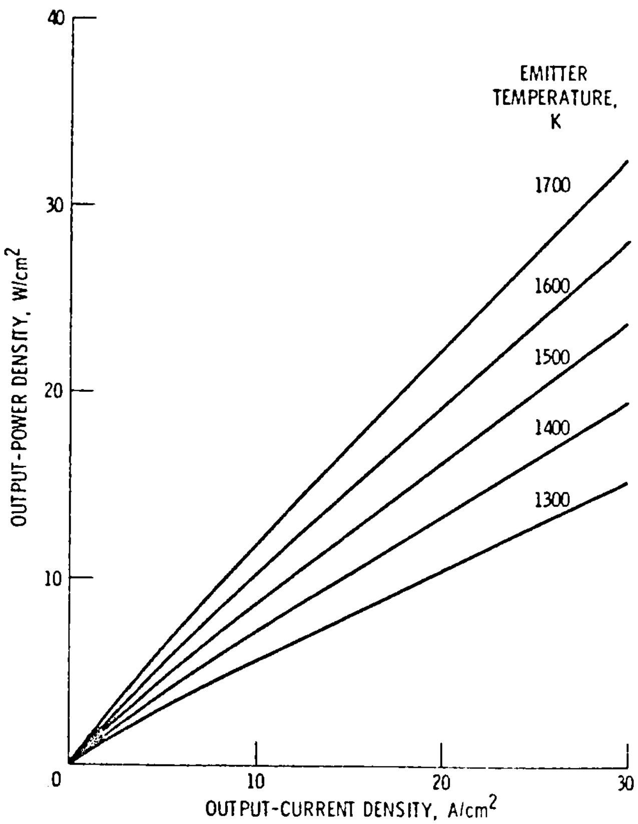

Figure 9. - Calculated thermionic-energy-conversion output-power density (10% back emission, optimum leads) as a function of output-current density for 800 K collectors with 1300-to-1700 K emitters.

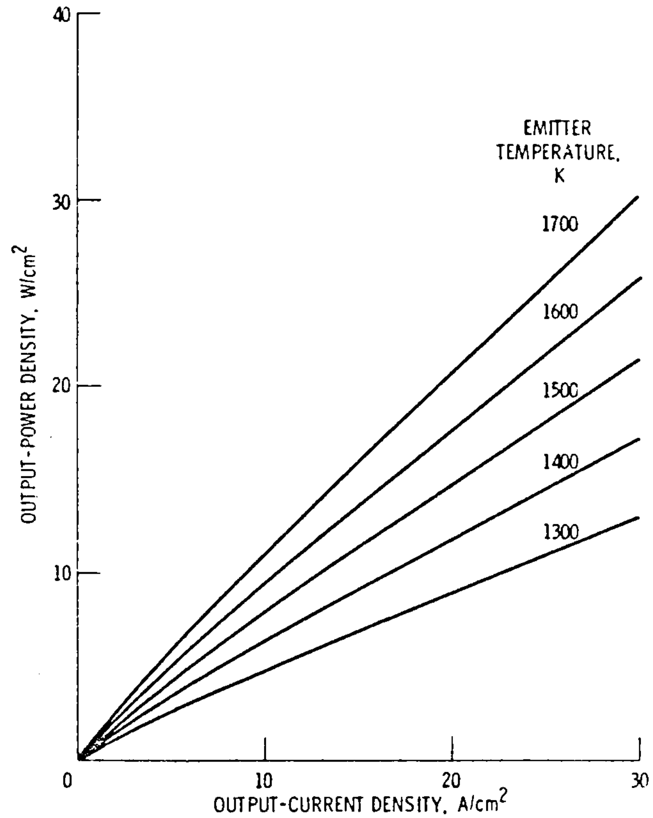

Figure 10. - Calculated thermionic-energy-conversion output-power density (10% back emission, optimum leads) as a function of output current density for 850 K collectors with 1300-to-1700 K emitters.

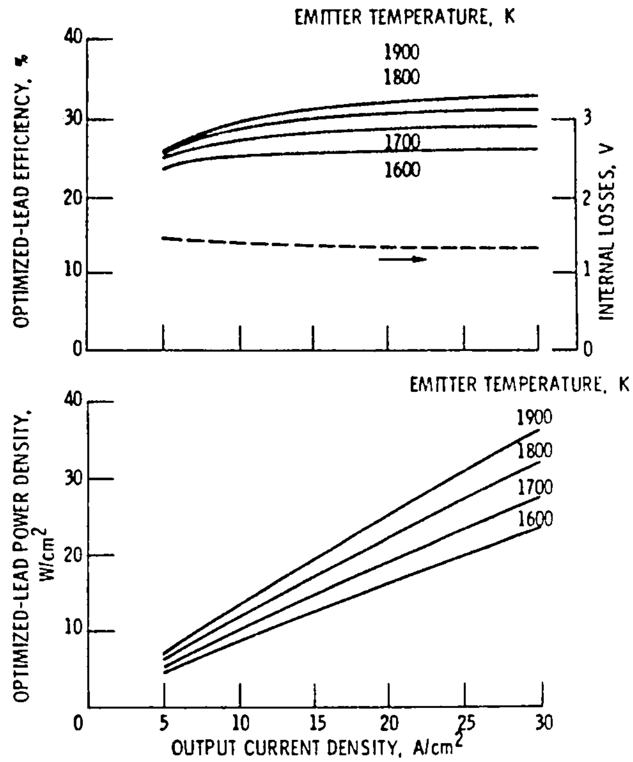

Figure 11. - Thermionic-energy-conversion performance for 900 K collectors with 10% back emission and negligible interelectrode losses.

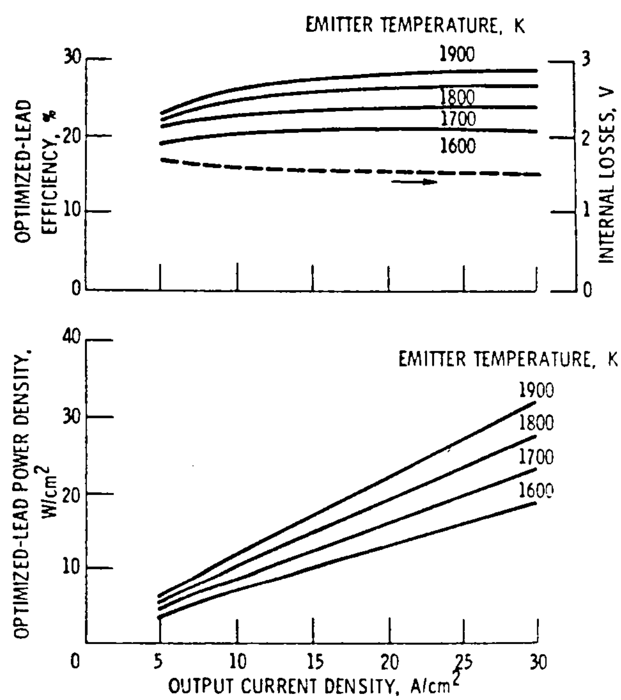

Figure 12. - Thermionic-energy-conversion preformance for 1000 K collectors with 10% back emission and negligible interelectrode losses.

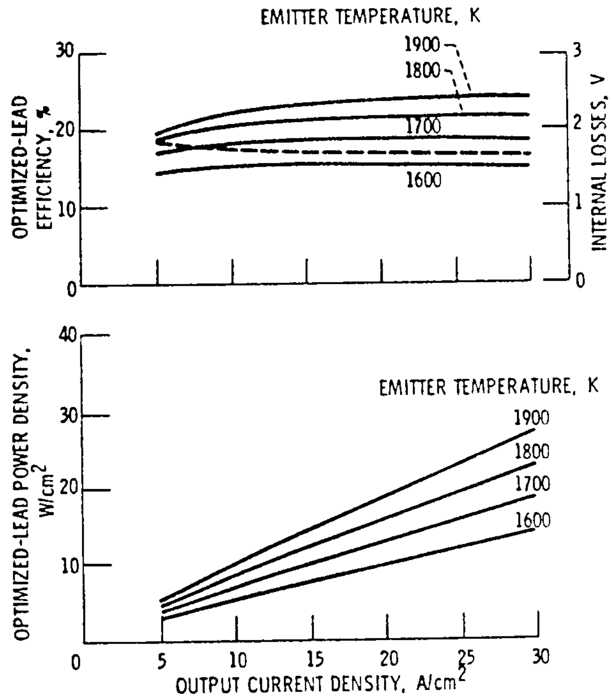

Figure 13. - Therionic-energy-conversion performance for 1100 K collectors with 10% back emission and negligible interelectrode losses.

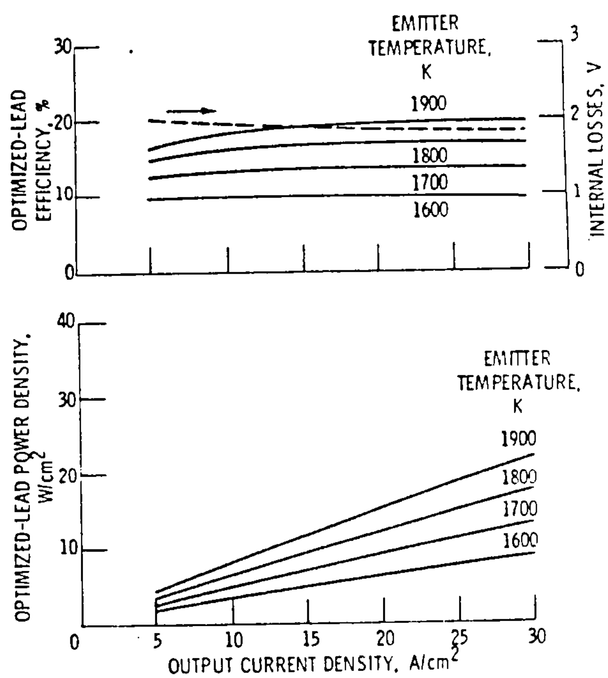

Figure 14. - Thermionic-energy-conversion performance for 1200 K collectors with 10% back emission and negligible interelectrode losses.

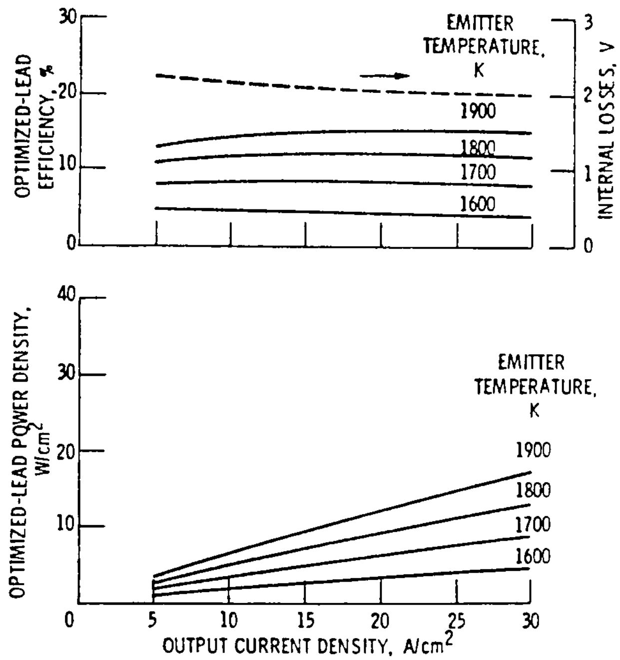

Figure 15. - Thermionic-energy-conversion performance for 1300 K collectors with 10% back emission and negligible interelectrode losses.

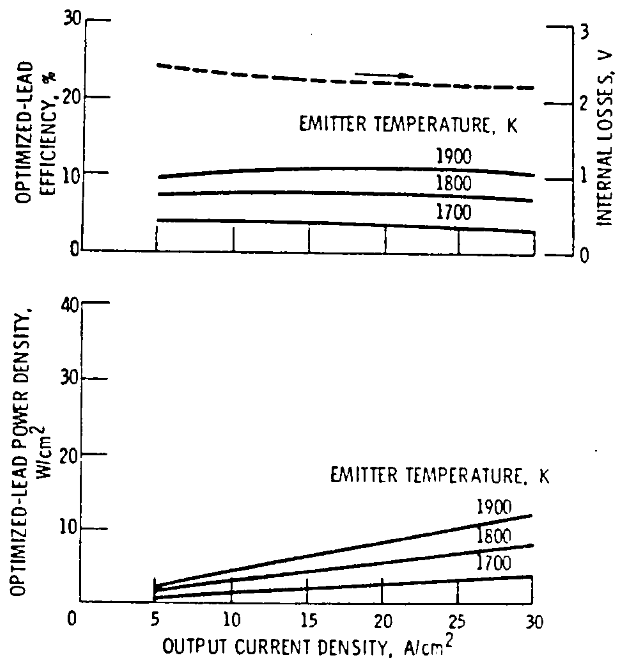

Figure 16. - Thermionic-energy-conversion performance for 1400 K collectors with 10% back emission and negligible interelectrode losses.

STEAM TURBINE	(ST)
CURRENT	(CST)
ADVANCED	(AST)
GAS TURBINE	(GT)
DISTILLATE-FIRED	(DGT)
RESIDUAL-FIRED	(RGT)
COAL-FIRED	(CGT)
CLOSED-CYCLE	(CCGT)
OPEN-CYCLE	(COGT)
FLUIDIZED BED	(FB)
ATMOPHERIC	(AFB)
PRESSURIZED	(PFB)
STIRLING ENGINE	(SE)
AIR PREHEATER	(APH)

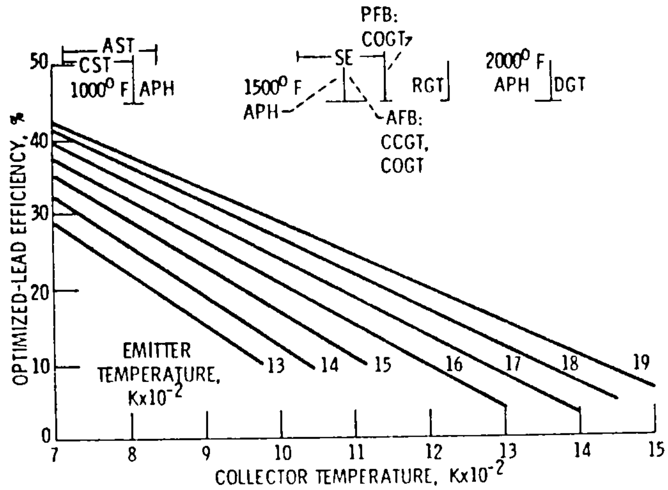

Figure 17. - Thermionic-energy-conversion efficiency at 30 A/cm^2 with 10% back emission and negligible interelectrode losses.

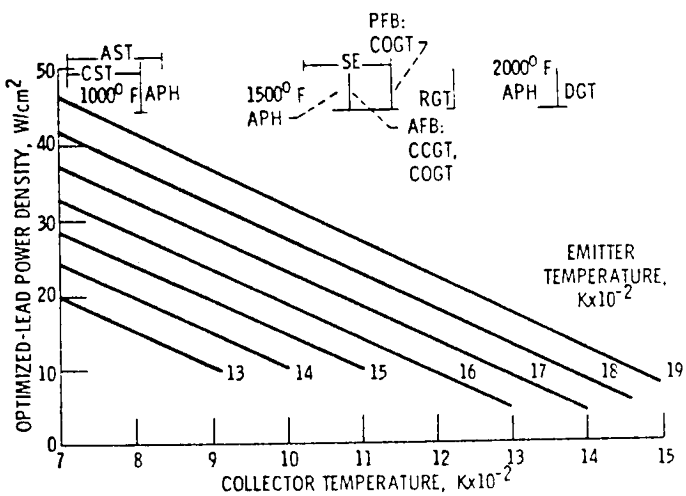

Figure 18. - Thermionic-energy-conversion power density at 30 A/cm^2 with 10% back emission and negligible interelectrode losses.

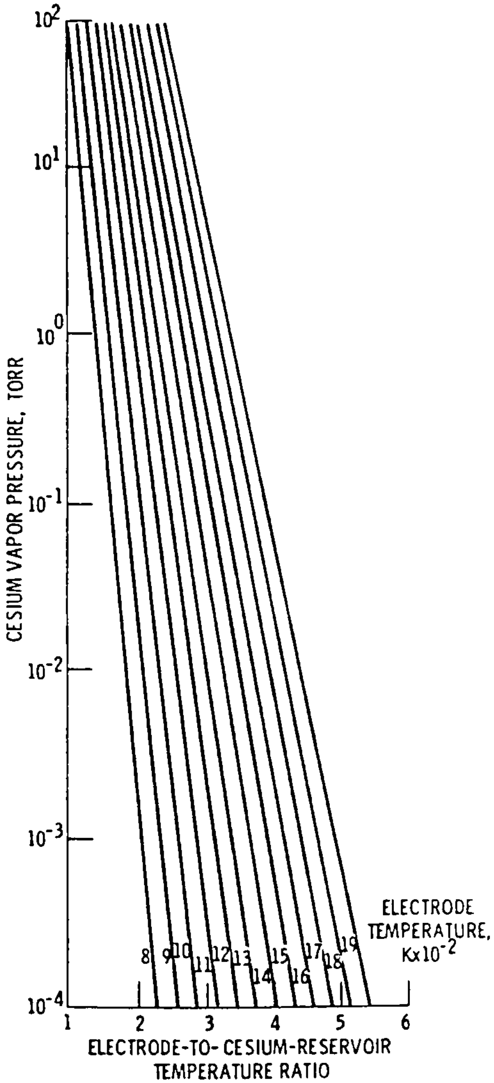

Figure 20. - TEC cesium-pressure, electrode-temperature relationships.

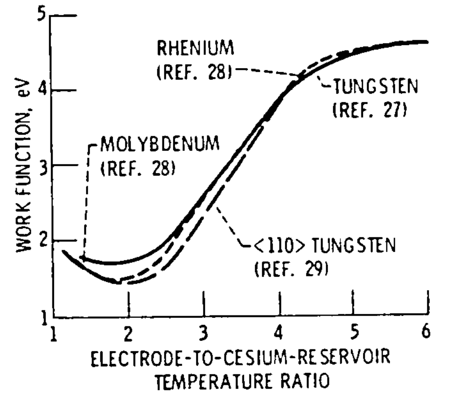

Figure 19. - Work functions of metal electrodes with adsorbed cesium (Rasor plot).

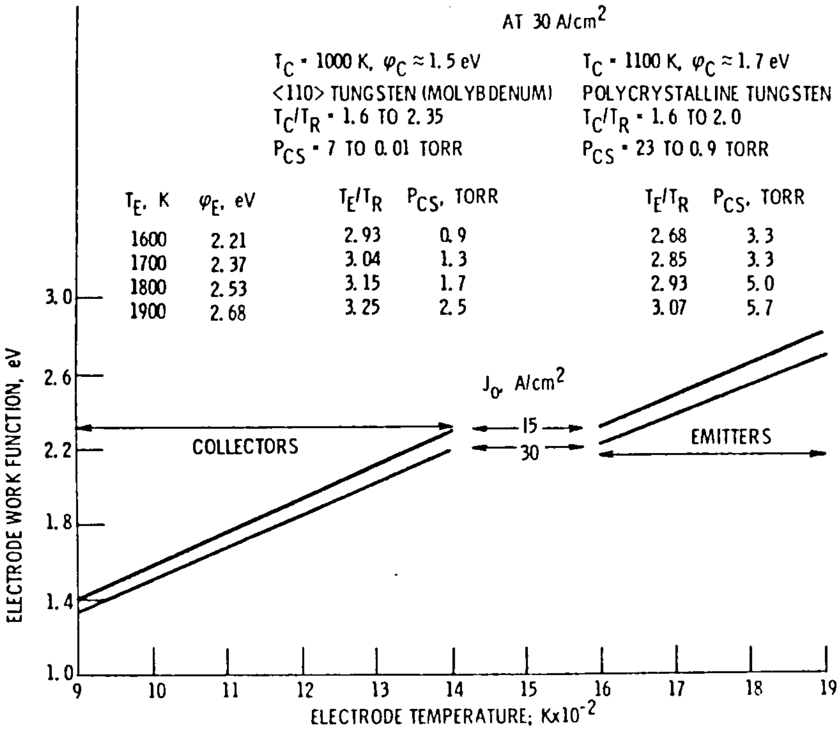

Figure 21. - Electrode work functions for thermionic energy conversion with 10% back emission and negligible interelectrode losses.

1. Report No. NASA TM-81555	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle OPTIMAL THERMIONIC ENERGY CONVERSION WITH ESTABLISHED ELECTRODES FOR HIGH-TEMPERATURE TOPPING AND PROCESS HEATING		5. Report Date July 1980
		6. Performing Organization Code
7. Author(s) James F. Morris		8. Performing Organization Report No. E-514
		10. Work Unit No.
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address U.S. Department of Energy Office of Coal Utilization Washington, D.C. 20545		14. Sponsoring Agency ~~Code~~ Report No. DOE/NASA/1062-6
15. Supplementary Notes Final report. Prepared under Interagency Agreement EC-77-A-31-1062.		

16. Abstract

Advantages of thermionic energy conversion (TEC) have been counted and are recounted with emphasis on high-temperature service in coal-combustion products. Efficient, economical, nonpolluting utilization of coal here and now is a critically important national goal. And TEC can augment this capability not only by the often-proposed topping of steam power plants but also by higher-temperature topping and process heating. For these applications, applied-research-and-technology (ART) work reveals that optimal TEC with ~1000-to ~1100 K collectors is possible using well-established tungsten electrodes. Such TEC with 1800 K emitters could approach 26.6% efficiency at 27.4 W/cm^2 with ~1000 K collectors and 21.7% at 22.6 W/cm^2 with ~1100 K collectors. These performances requires 1.5-and 1.7-eV collector work functions (not the 1-eV ultimate) with nearly negligible interelectrode losses. Such collectors correspond to tungsten electrode systems in ~0.9-to-~6-torr cesium pressures with 1600-to-1900 K emitters. Because higher heat-rejection temperatures for TEC allow greater collector work functions, interelectrode-loss reduction becomes an increasingly important target for applications aimed at elevated temperatures. Studies of intragap modifications and new electrodes that will allow better electron emission and collection with lower cesium pressures are among the TEC-ART approaches to reduced interelectrode losses. These solutions will provide very effective TEC to serve directly in coal-combustion products for high-temperature topping and process heating. In turn this will help to use coal-and to use it well.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Thermionic energy conversion (TEC); High power densities; High temperatures; Terrestrial applications; Topping (TEC, STEAM; MHD, TEC, STEAM; TEC, Stirling...); Process heating; Cost of electricity; Overall plant efficiency	Unclassified - unlimited STAR Category 75 DOE Category UC-90f

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