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A Preliminary Assessment

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COMMERCIAL APPLICATION OF THERMIONIC CONVERSION USING A FUSION REACTOR ENERGY SOURCE
- A PRELIMINARY ASSESSMENT -

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ABSTRACT

A preliminary assessment of using thermionic conversion as a topping cycle for fusion reactors is presented. Because of the absence of restrictive temperature limitations for fusion-reactor blankets, fusion reactors may offer significant advantages, compared to fission reactors and fossil-fuel energy sources, for utilizing thermionic topping cycles.

A system with a thermionic topping cycle and a conventional steam-turbine generator that utilizes the heat rejected by the thermionic converters is presented for illustration. This system consists of conceptual laser-fusion reactors with high-temperature radiating reactor blankets serving as heat sources for the thermionic topping cycle. The design concept appears to be equally adaptable to magnetically confined fusion reactors.

For the example analyzed, net conversion efficiencies of combined thermionic and steam-turbine cycles are high, exceeding 50% for some values of the operating parameters, and the cost of producing low-voltage direct current for electrochemical processing is low.

INTRODUCTION

Thermionic emission was discovered by Edison; however, commercial applications have been restricted mainly to electronics, e.g., hot-cathode electron tubes. Considerable research, directed at the use of thermionic emission to produce electric power in significant quantities, has been done over the past two decades as part of the space program. This research led to the development of devices for converting heat to electricity generally referred to as thermionic converters.

Thermionic-conversion research in the U.S. has been redirected since the curtailment of the ambitious space program in 1973. Current emphasis by ERDA contractors is on the design of systems to be used as topping cycles for electric generating stations. Thermionic conversion for this application is attractive because the heat-rejection temperatures are high enough to permit normal operation of conventional conversion cycles with the heat rejected from thermionic converters.

Conceptual fusion reactors may offer significant advantages over fission reactors for utilizing thermionic-conversion topping cycles. These advantages stem from the performance characteristics of thermionic converters with increasing efficiency and output resulting from high-temperature operation and from the absence in fusion reactions, of high-temperature limitations due to fuel-element distortion (or melting) and fission-product release. Temperatures in fusion reactors are limited, in principle, only by the properties of refractory materials.

The normal electric output of thermionic converters is low-voltage direct current (pulsed output suitable for transforming has also been demonstrated. An attractive fusion-reactor concept "the subject of this study," would produce (1) low-voltage direct current from a thermionic topping cycle for electrochemical processing and (2) conventional commercial electric power with the reject heat from the topping cycle.

STATUS OF THERMIONIC CONVERTER DEVELOPMENT

Current thermionic-conversion research is directed toward overcoming the limitations of small size, high cost, close electrode spacings, and loss of performance at low cathode temperatures associated with the first generation of thermionic converter design. Converters are now capable of efficient operation at substantially lower cathode temperatures and much larger interelectrode spacings than was the case for designs of a few years ago. Thermionic converters are categorized into:

(1) systems that have been demonstrated in power-plant (including reactor) environments,

(2) near-term converters that have been demonstrated in the laboratory and are expected to be demonstrated for power-plant application in the near future, and

(3) converters with improved performance, anticipated to be available in a few years.

The status of this research is surveyed in Refs. 1-8.

Preliminary designs of thermionic topping cycles for use with either coal-fired or fission-reactor electric generating stations have been evaluated by Rasor Associates[3] in partial fulfillment of a contract with ERDA. Systems were designed with heat-rejection temperatures compatible with the steam cycle for the Bull Run coal-fired electric generating station, which has a turbine inlet temperature of 810 K.

Thermionic-converter performance typified by units that have been tested in the laboratory and are being developed and adapted for power-plant application is appropriate for use in conjunction with a developing technology such as fusion. Performance data, representative of so-called second-generation, near-term converters used in this study were taken from Refs. 3, 4, and 7.

THERMIONIC-CONVERTER DESIGN FOR FUSION REACTORS

Thermionic diodes are basically very simple. A diode consists of an emitter (cathode) and a collector (anode) separated by an inter-electrode gap containing cesium at low pressure ($\sim$1 torr). For most designs, both the emitter and the collector are made of a refractory metal. The inter-electrode space is maintained by a suitable insulator, and electric leads complete the diode. The output is direct current at $\sim$1 V. Combination series-parallel networks permit efficient recovery of the electric output at voltages as high as 100 V. The simplest diode geometry consists of parallel flat plates for both the emitter and the collector.

The high-temperature capabilities of fusion reactors invite investigation of two categories of converter design for use as topping cycles. For the first case, a high emitter temperature is utilized and, together with this, a high heat-rejection temperature. The emitters could be heated by radiation and heat could be rejected to a flowing coolant. Designs in the second category are based on the use of a circulating liquid metal for heating the thermionic emitters.

The thermionic topping cycle proposed by Rasor Associates for the Bull Run electric generating station utilizes a circulating liquid metal to heat the thermionic emitters to the operating temperature of 1370 K. This topping cycle increases net plant efficiency from 41.3 to 47% and increases the generating capacity by 27.6%. Higher temperatures than 1400 K are potentially available from fusion reactors; thus, the potential improvement in overall generating station performance from the use of a thermionic topping cycle is greater for fusion reactors than for the Bull Run generating station. To illustrate this point, preliminary analyses have been made of a conceptual laser-fusion reactor (LFR) generating station with high-temperature radiating reactor blankets serving as heat sources for thermionic topping cycles. The design concept appears to be equally adaptable to magnetically confined fusion reactors.

SYSTEM DESIGN

A detailed reactor design will evolve, in part, from a concurrent study of high-temperature laser-fusion radiators for generating process heat. The reactor will probably be cylindrical or spherical, with the cavity walls protected from pellet-debris plasma by magnetic fields. Calculations for this study were done in spherical geometry, for convenience. A cross section of the spherical reactor model is shown in Fig. 1. The cavity has a radius of 4 m. Photon and neutron energy is deposited in a 0.5-m-thick graphite region surrounding the cavity. The graphite, in turn, is enclosed by a 0.05-m-thick region consisting of boron carbide and graphite in which neutrons thermalized in the intervening graphite region are captured. The thermionic diodes, in parallel flat-plate geometry, are supported on the surface of the boron carbide-graphite region and are heated by radiation. It was assumed that the thermionic-diode structures completely enclose the radiating graphite surface and that 90% of the surface of these structures consists of thermionic emitters. Heat rejection from the thermionic-diode collectors is by conduction to an intermediate heat-transfer loop containing circulating sodium. The entire system is enclosed by a stainless steel structure.

Energy deposition in the graphite regions consists of deposition by x and gamma radiation and by neutron scattering and exoergic neutron

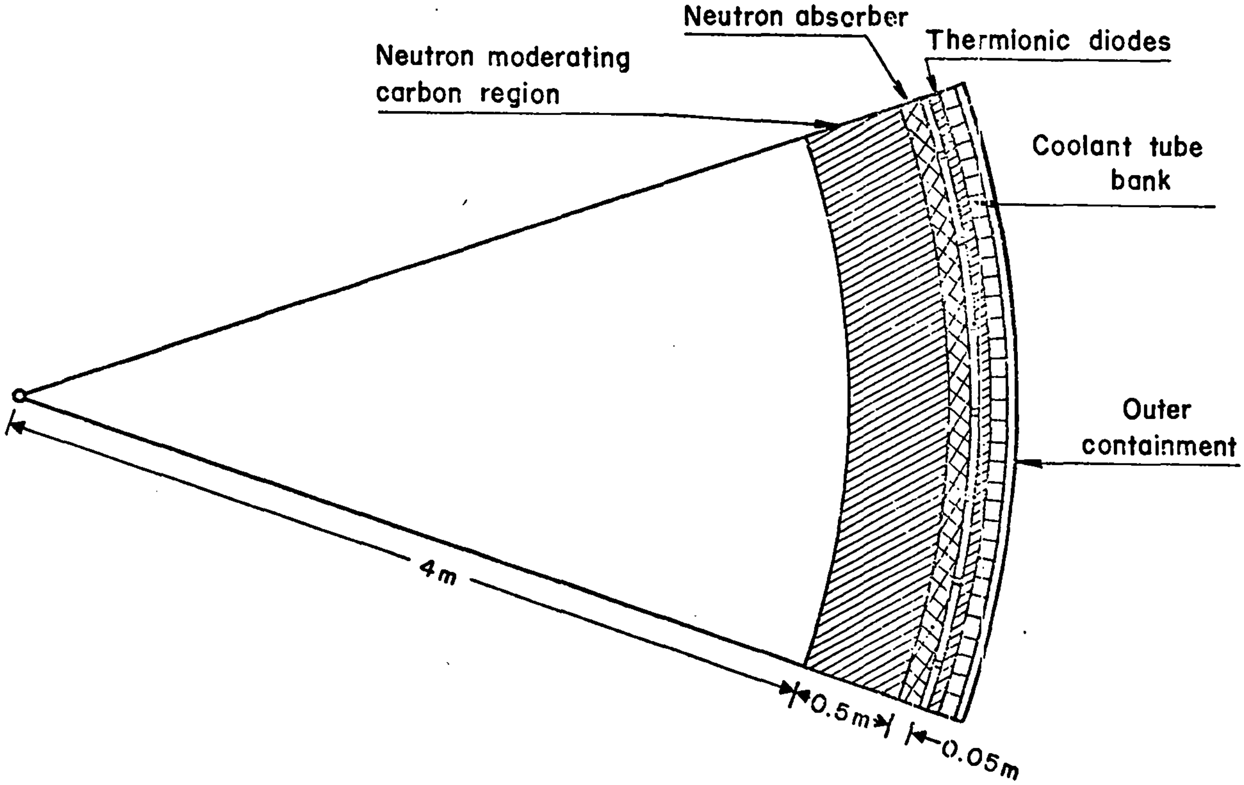

Fig. 1
Cross section of spherical laser-fusion reactor model.

reactions. It was assumed that the energy of the pellet debris is recovered as heat directly from the cavity and is combined with the heat rejected by the thermionic diodes for conversion to electricity in a conventional steam-turbine generating plant.

RESULTS OF PARAMETRIC STUDIES

The thermionic emitter and collector temperatures in the study ranged from 1400 to 1800 K and from 700 to 920 K, respectively. The diode power output per unit of emitter area was based on data given in Ref. 3 and is shown in Fig. 2. Diode efficiency was estimated, based on data given in Refs. 3, 4, and 7, to be 53.5% of Carnot efficiency. This estimate does not include ohmic losses in the electrodes and losses in the conductors from the diodes to the load, which were taken to be 8 and 15%, respectively. Thus, the net thermionic conversion efficiency assumed is 42% of Carnot efficiency.

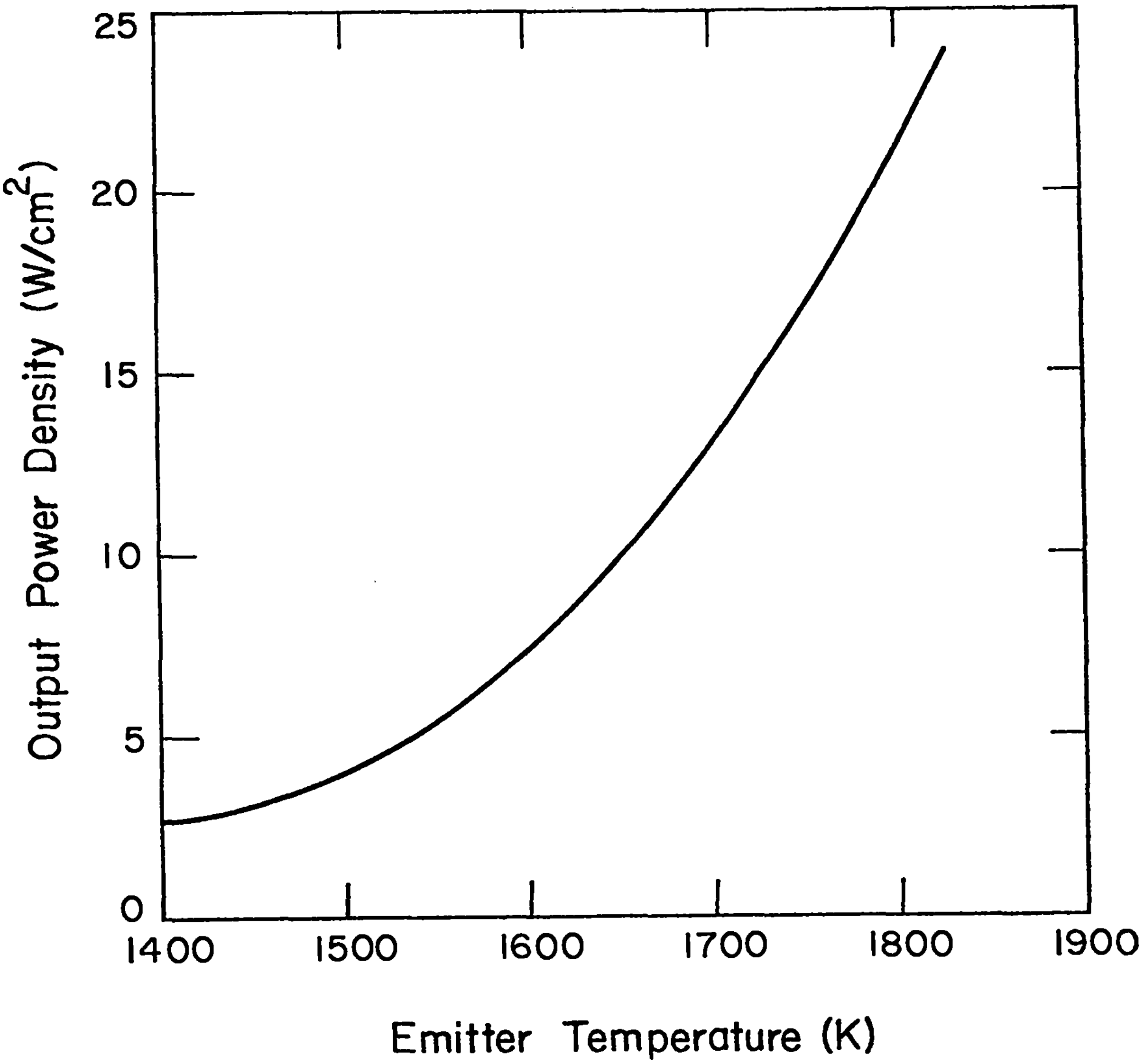

Fig. 2
Temperature dependence of thermionic diode output power density.

The diodes were assumed constructed from 0.127-cm-thick refractory-metal plates with the properties of molybdenum. Diode output was determined from Fig. 2 as a function of emitter temperature, and diode efficiency was calculated as functions of emitter and collector temperatures. The necessary radiator surface temperature and radiating power level were determined from the thermionic diode output and efficiency. Energy deposition distributions in the reactor blanket were calculated with neutronics codes, and temperature distributions through the radiating blanket were calculated from these distributions and total power levels. The maximum temperature in the carbon blanket was well below the sublimination temperature ($\sim$4000 K) of carbon in all cases.

Conversion of the heat rejected by the thermionic diodes, ohmic losses in the conductors, and the energy of the pellet debris in a steam-turbine generating plant was evaluated with a temperature-dependent model used in LFR parametric studies.

Capital costs of the reactors, of heat-transfer and steam generating equipment, and of the steam-turbine generating equipment were estimated in terms of 1973 dollars from data used in LFR systems studies. Capital costs of the thermionic systems were taken from estimates given in Refs. 3 and 5, which ranged from \$144/kWe to \$160/kWe, based on 1972 dollars. A value of \$160/kWe was assumed for this study.

Energy deposition in the graphite blanket from 100-MJ fusion pellet microexplosions was calculated to be 90 MJ per microexplosion. In addition, 23 MJ is recovered directly from the cavity from each microexplosion. Thus, exoergic nuclear reactions in the blanket result in an enhancement of the fusion yield by 13%.

Performance evaluations were based on a conceptual power plant containing 14 reactor cavities. The total thermionic power generated is, according to the model assumed, dependent only on the emitter temperature and area and is given for the 14-reactor plant in Fig. 3.

The electric power generated by the steam cycle depends on the total reactor power level, on the efficiency of the topping cycle, and on the steam-turbine inlet temperature. These quantities are, in turn, dependent on the emitter and collector temperatures of the thermionic topping cycle. The net electric power produced by the steam cycle (after providing for recirculating power requirements) is shown in Fig. 4 as a function of diode collector temperature with emitter temperature as a parameter. The thermal-to-electric conversion efficiency for the combined cycles is shown in Fig. 5 as a function of diode collector temperature for the extremes of emitter temperature considered.

Economic analyses were made with a modified version of the laser-fusion systems analysis computer program. It was assumed that the direct-current output of the thermionic diodes would be used in an electrochemical process rather than being conditioned for distribution in a power grid

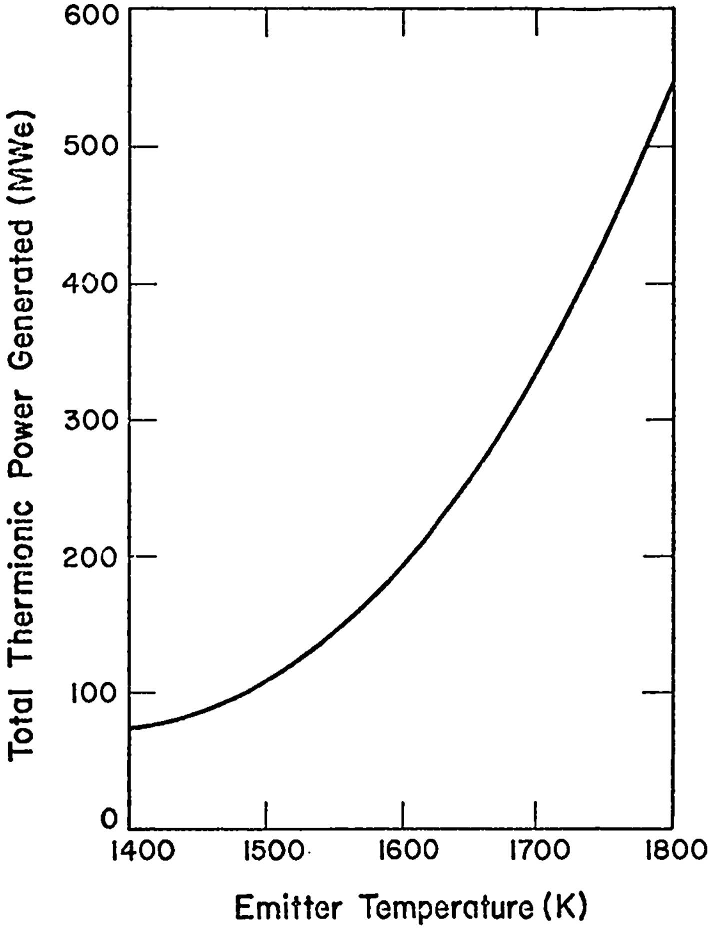

Fig. 3
Dependence on thermionic-emitter temperature of power generated by topping cycle.

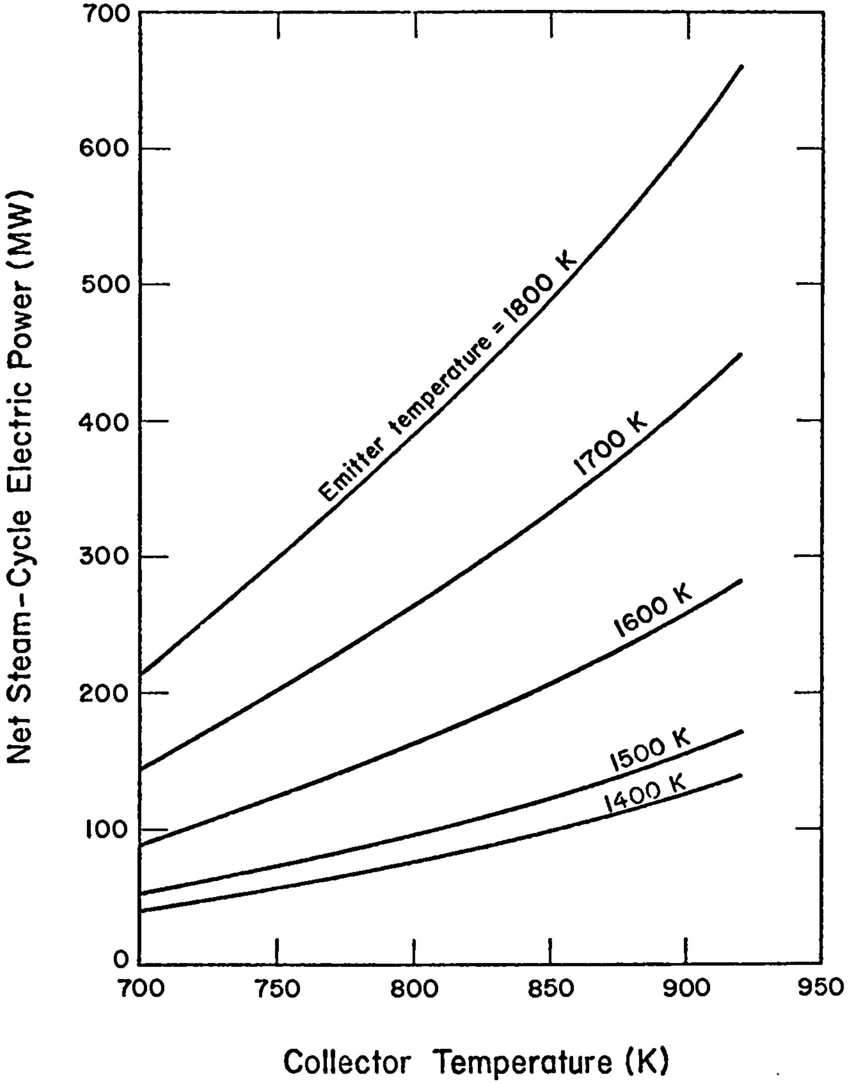

Fig. 4
Electric power generated by the steam cycle as functions of thermionic diode operating conditions.

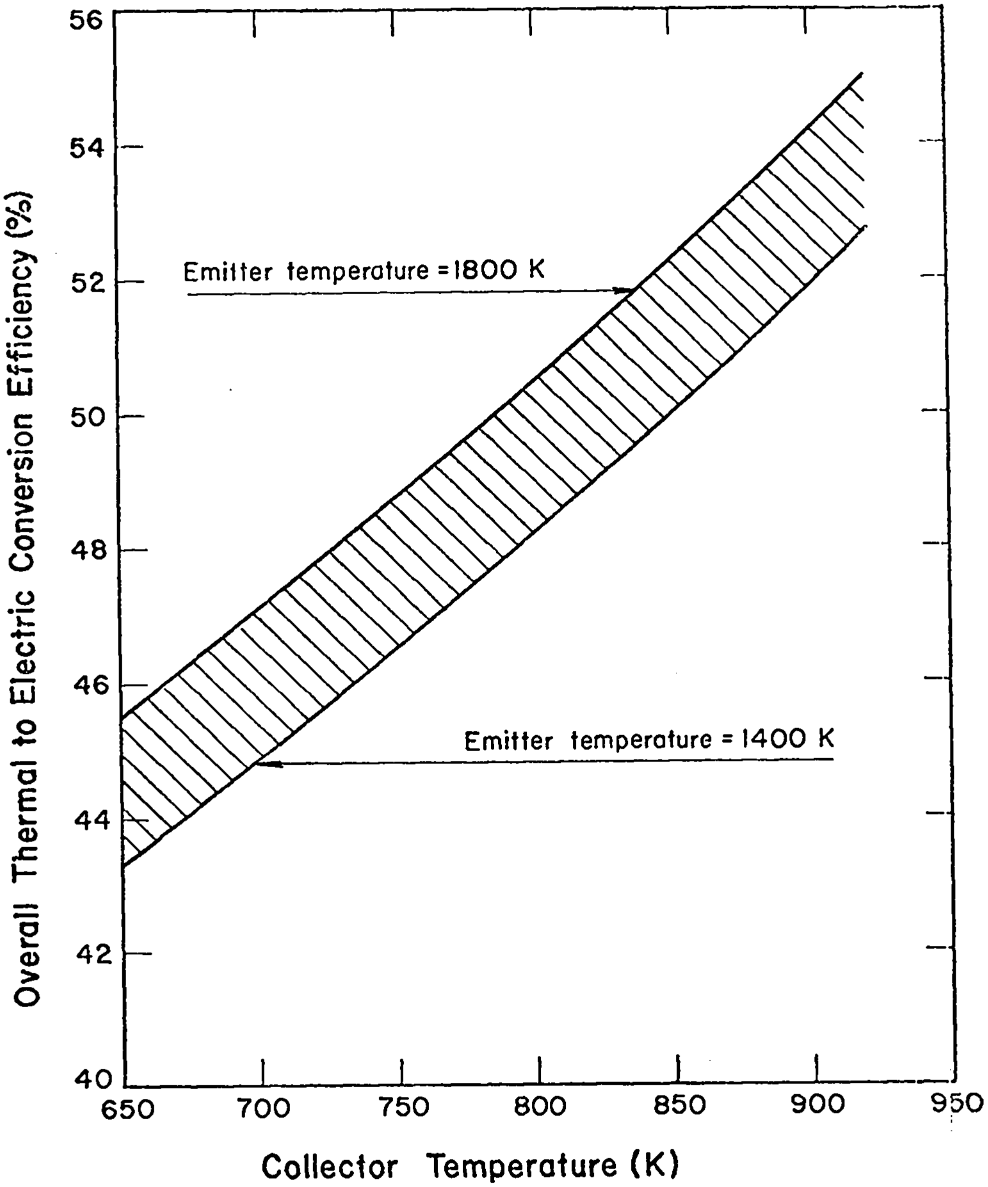

Fig. 5
Thermal-to-electric conversion efficiency of combined cycles as functions of thermionic diode operating conditions.

(although this is certainly also possible); thus, the thermionic output was evaluated separately from the steam-turbine output. Since the reactor concept considered does not include a provision for tritium breeding, the fuel cost was increased to account for the purchase of tritium from another source.

No attempts were made to estimate component lifetimes or replacement schedules so that calculated power-production costs are too low by the amount of maintenance costs. The radiating blanket as well as the simplified thermionic diodes should be very rugged structures. Also, the total thermal power per reactor is limited by the performance of the topping cycle to much lower values than are usually assumed for the magnetically protected LFR concept, resulting in low fusion-microexplosion repetition rates, and thus contributing to long lifetimes of components. A duty factor of 85% was assumed.

Typical results of the economic analysis (in 1973 dollars) are given in Fig. 6, which consists of plots of production costs of thermionic power as functions of diode collector temperature, with the value of the power

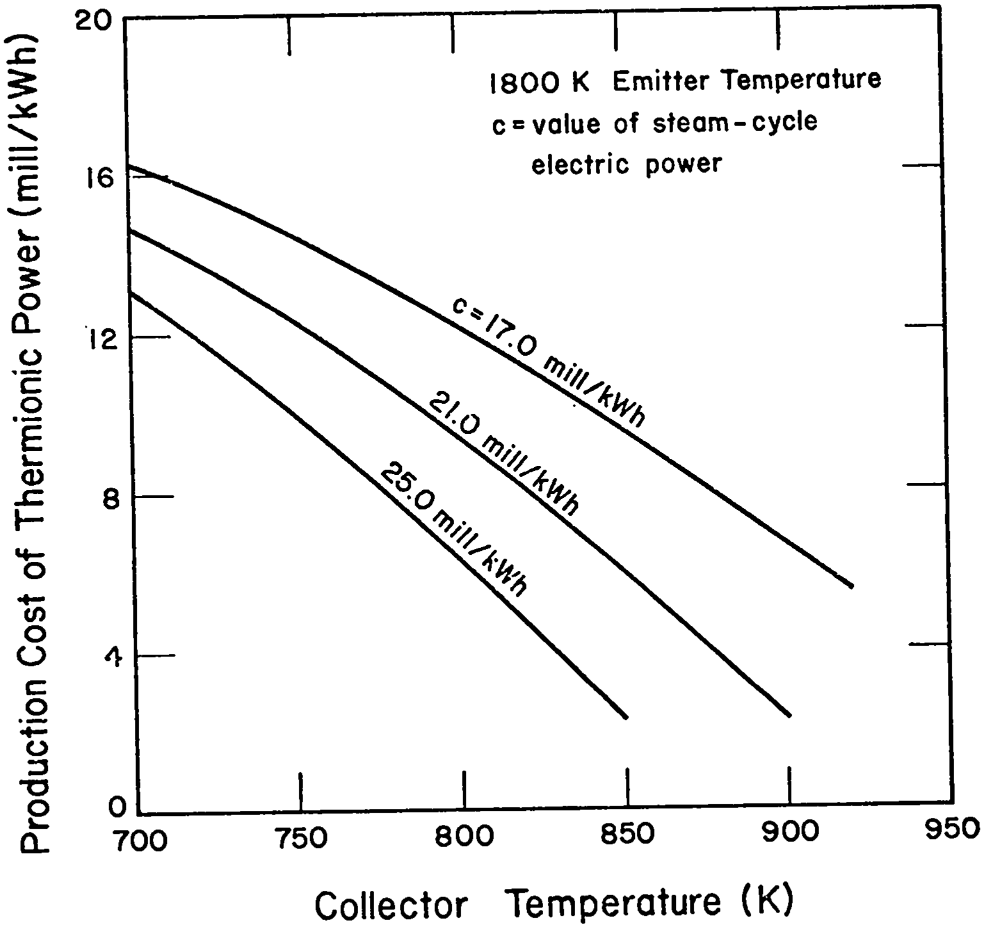

Fig. 6
Production costs of by-product thermionic power with the value of conventional electric power as a parameter.

produced by the steam turbines as a parameter. The range of costs for power produced by the steam turbines (17 to 25 mill/kWh) corresponds to the estimated range of power-production costs from magnetically protected LFRs in standard electric generating stations. The diode emitter temperature for these calculations was 1800 K. This method of evaluating production costs associated with the topping cycle is based on treating the topping-cycle output as a by-product which, in reality, it is not since major changes in reactor design were incorporated to permit inclusion of the topping cycle. An alternative approach to evaluating the combined cycle would be to determine an average production cost for the total electrical output. Such an average production cost of total electrical output is given in Fig. 7 for diode emitter temperatures of 1600 and 1800 K as a function of diode collector temperature.

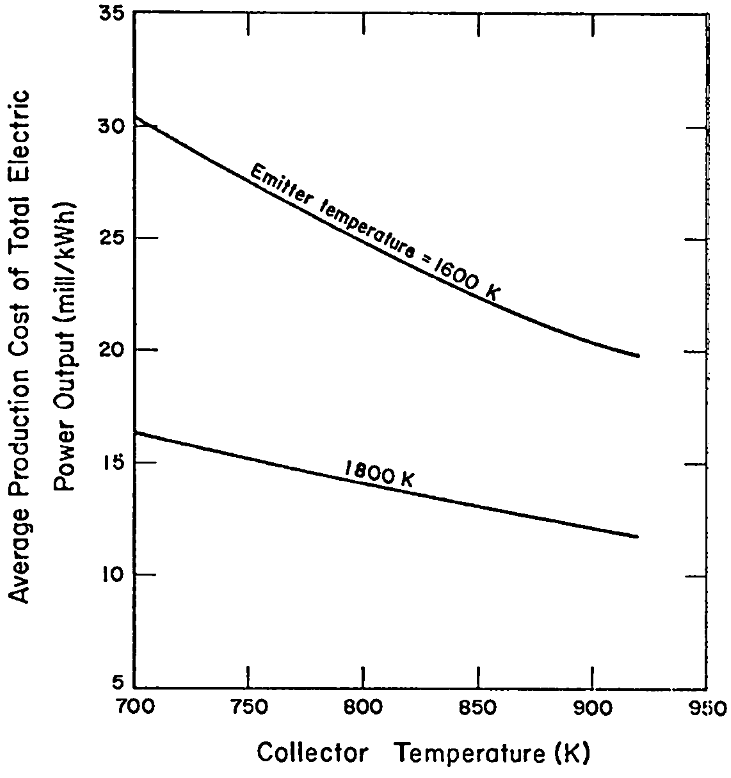

Fig. 7
Average production costs of electric power from combined cycles as functions of thermionic diode operating conditions.

CONCLUSIONS

The results of this preliminary scoping study of using thermionic conversion to create low-voltage direct current from fusion reactors for electrochemical processing are encouraging. Fusion reactors appear better suited to take advantage of thermionic topping cycles than fission or fossil-fuel generating stations although optimization of thermionic topping cycles can only be achieved with major redesign of fusion-reactor blankets.

For the LFR example analyzed, net conversion efficiencies of combined thermionic and steam-turbine cycles in an electric generating station are very high, and the costs of producing direct current as a by-product are low. For example, if conventional electric power is sold at 21 mill/kWh and the thermionic-diode emitter and collector temperatures are 1800 and 875 K, respectively, the production cost of direct current is 4 mill/kWh. If this direct current were used to electrolyze water to produce hydrogen at 75% efficiency, the hydrogen production costs (neglecting additional capital amortization due to electrolysis equipment) would be 1.5$/$10^6$ Btu energy content of the product.

The economic benefit of thermionic topping cycles can also be expressed in terms of average power-production costs that are significantly lower for combined thermionic and steam cycles than for steam cycles only. These reductions may be as large as 30% depending on the topping-cycle operating temperature.

The reactor designs used in this study are quite inadequate, and additional capital costs may result from analyses of more detailed systems. Plant maintenance cost should also be estimated and included in production costs. The thermionic performance data were taken from the open literature and should be verified by investigators actively involved in thermionic research. On the other hand, no attempt was made to optimize the system.

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