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ADVANCED THERMIONIC TECHNOLOGY PROGRAM

Summary Report

October 1984

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AC21-83MC20352

For
U. S. Department of Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
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Waltham, Massachusetts

and

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Sunnyvale, California

Technical Information Center
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United States Department of Energy

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PREFACE

This report summarizes the progress made by the Advanced Thermionic Technology Program during the past several years. This Program, sponsored by the U.S. Department of Energy, has had as its goal adapting thermionic devices to generate electricity in a terrestrial (i.e., combustion) environment. The technology has previously been developed for astronautical applications.

The report is organized in four volumes, each focused as much as possible on the needs of a particular audience. Volume 1 contains Part A, the Executive Summary. This Executive Summary describes the accomplishments of the Program in brief, but assumes the reader's familiarity with the thermionic process and the technical issues associated with the Program. For this reason, Volume 1 also contains Part B, a minimally technical overview of the Advanced Thermionic Technology Program. It is suggested that readers just being introduced to the Program review both portions of Volume 1 before consulting the more technical volumes which follow.

Volume 2 (Part C) concentrates on the progress made in developing and fabricating the "current generation" of chemical vapor deposited hot shell thermionic converters and is addressed to those primarily concerned with today's capabilities in terrestrial thermionic technology. Volume 3 (Part D) contains the results of systems studies of primary interest to those involved in identifying and evaluating applications for thermionics. Volume 4 (Part E) is a highly technical discussion of the attempts made by the Program to push the state-of-the-art beyond the current generation of converters and is directed toward potential researchers engaged in this same task. These technical discussions are complemented with Appendices where appropriate.

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PART A

EXECUTIVE SUMMARY

1. EXECUTIVE SUMMARY

1.1 Introduction

Thermionic energy converters are remarkably simple and environmentally clean devices for converting heat to electricity. A metal electrode, the emitter, is heated until electrons "boil" from its surface. The emitted electrons cross a narrow interelectrode gap and "condense" on the collector. This flow of electrons constitutes an electric current that delivers power to a load.

Research into this technology conducted over a number of years prior to 1973 had led both to greatly increased understanding of the underlying physics of this phenomenon and to practical electricity-producing devices which proved themselves suitable for astronautical applications. In 1973, national concern over energy supplies and the need for conservation brought attention to the possibility that thermionics might also be suitable for use in increasing the efficiency with which energy could be used through "topping" conventional generation plants or industrial processes. At that time, what is now the U.S. Department of Energy initiated a plan to adapt this proven astronautical technology for terrestrial use with fossil fuels. For the past several years this effort, referred to as the Advanced Thermionic Technology Program, has been chiefly administered through the Department of Energy's Morgantown Energy Technology Center. At this time, anticipated changes in this role make it appropriate to prepare a Summary Report documenting the findings and accomplishments of the Program and indicating directions for further research.

1.2 First Generation Flame-Fired Converter Development

It has become common within the Advanced Thermionic Technology Program to refer to the process of thermionic technology development in terms of distinct generations. First generation devices would achieve high performance in a flame-fired environment with minimum modifications to the basic converter design already proven for astronautical applications. The major modification required for such achievement is the means for protecting the converter from the corrosive and ablative properties of the flame environment. At temperatures above 1200 K the kind of refractory metal emitters envisioned for space use, such as tungsten and molybdenum, cannot survive in a combustion atmosphere. Two general approaches to protection have been considered during the Program. The first, referred to as the Thermionic Heat Exchanger (THX), surrounds multiple converters with a single protective shell and uses heat pipe technology to provide a more homogenous heat flux over each of them. The second approach places each converter in an individual "hot shell" created by chemical vapor deposition. These individual hot shell converters would be series and parallel connected into larger Thermionic Array Modules (TAM's).

It is this second, hot shell approach which has received the greatest attention in connection with the development of first generation flame-fired converters. Throughout the Program steady progress has been achieved in the improvement of these devices. Technical successes have included an increase in operating life to 12,500 hours, and an increase in the operating emitter temperature to 1925 K for at least limited periods. The latter, leading to increased converter performance, has resulted in devices of lower potential cost per unit of electrical output.

Exhibit A-1.1 illustrates the steady progress made during the Program in obtaining longer lived converters as shown by the results of flame-heated testing. In 1978, the then state-of-the-art flame-fired converters with superalloy emitter hot shells were life tested to 2,000 hours at a maximum temperature of 1400 K. By the year 1980 the technology of building thermionic converters with silicon-carbide tungsten emitter hot shells, manufactured by chemical vapor deposition, was sufficiently advanced to result in a life test of 5,000 hours at an emitter temperature of 1650 K. In the same year, another life test began which culminated in 12,500 hours in 1982. This test was run at an emitter temperature of 1730 K. Thus, both the longevity of the converters and the operating temperature of the emitters were increased throughout the Program.

The barrier index achieved by these first generation devices has also been improved, as illustrated in Exhibit A-1.2, to the point where values as low as 2.1 eV are routinely obtained and values even below 2.0 eV are sometimes observed.

These achievements were largely realized because the Program also made a significant advance in chemical vapor deposition (CVD) technology for the fabrication of such flame-fired converters. A technique was developed to make a composite hot shell and emitter structure consisting of a unique combination of a CVD tungsten emitter protected by a CVD silicon carbide envelope, with a graphite interlayer. During the demonstrated operating life of 12,500 hours at an emitter temperature of 1730 K, no life-limiting interactions were revealed (i.e., by post test examination). These CVD structures also have shown excellent thermal shock resistance, surviving quenching from 1800 K by both liquid nitrogen and water.

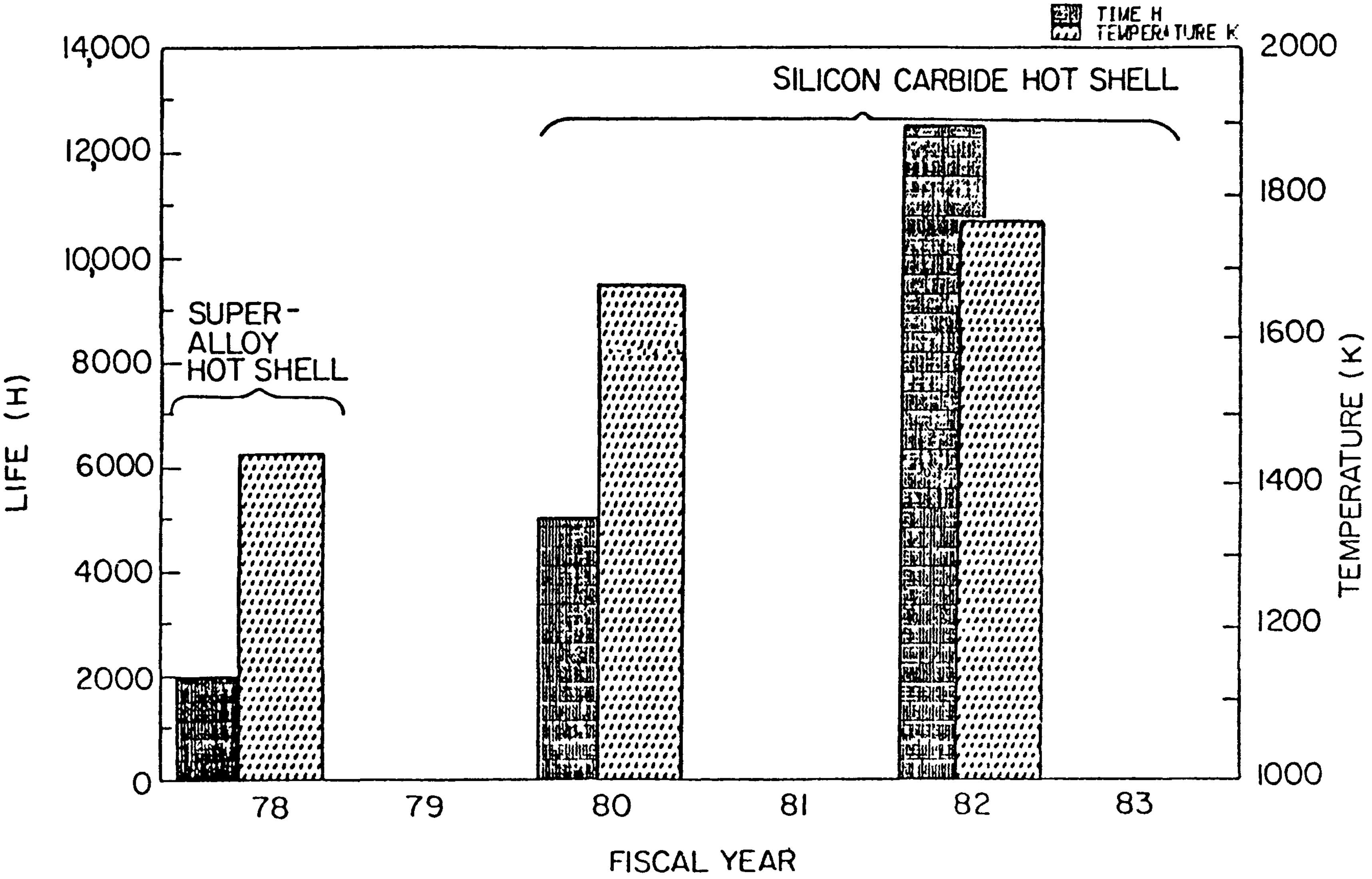

Exhibit A-1.1

Progress in Increasing Lifetime and Operating Temperatures of Flame-Heated Converters

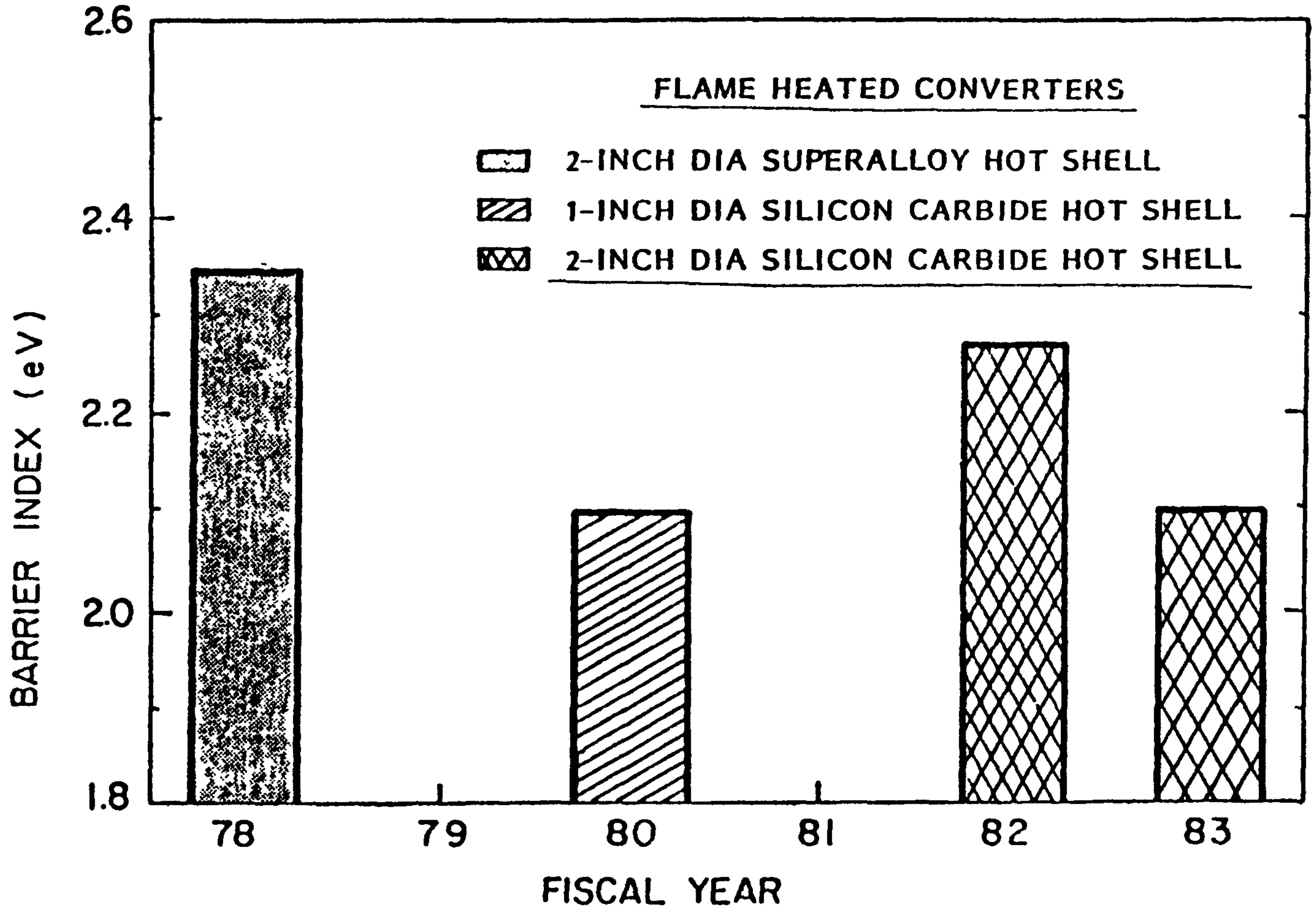

Exhibit A-1.2

Progress in Improving Barrier Index of Flame-Heated Converters

Specific procedures for converter fabrication using the CVD technique have been enumerated and their compatibility with mass production techniques has been established. Preliminary cost estimates have shown that emitter structures made by CVD would be significantly less expensive than those made by more conventional methods, resulting in a thermionic converter cost which makes the use of these converters in flame-fired terrestrial applications much more attractive.

Nearly all of the converters so far tested have been small, producing power at levels on the order of 100 Watts or less. Practical applications will require some combination of larger devices and/or series-parallel connection into larger arrays. Work in this area of thermionic development has not yet been extensive, but has demonstrated that the effects of temperature dependencies between converters in a large array are likely to be important areas for further research. In addition, limited testing of very large converters (i.e., having a short circuit current of 6500 Amperes) has revealed no unexpected phenomena (e.g., plasma-induced magnetic effects) which might preclude the development of such converters.

1.3 System Studies

The Advanced Thermionic Technology Program has been guided by the results of several systems studies conducted during the course of the Program. Thermionic converters were considered for combined gas and steam turbine power plants, in industrial cogeneration, and in central station fossil-fueled electrical generation systems.

One of the combined gas and steam turbine systems selected for study was a nominal 100 MW system. The gas turbine produced 70 MW, the steam turbine 30 MW, and the thermionics 8 MW. The thermionic converters were incorporated in the walls of the gas turbine combustor can and the plant used the output gas from a coal gasifier.

Results of the study are shown in Exhibit A-1.3 and are a summary of work done by Thermo Electron, Brown Boveri Turbomachinery and Stone and Webster Engineering Corporation. In this exhibit the incremental cost of topping a combined cycle power plant with thermionics has been plotted against emitter operating temperature, parametric in barrier index, V_B. The projected cost of the converters was based on a production rate of 200,000 converters per year. The operating regime of first generation hot shell converters has been shown shaded on the exhibit. The study estimated that the incremental cost of thermionic topping would vary from $425 to $650 per kilowatt installed thermionic power, including the cost of all the auxiliaries required to operate the thermionic converter, the direct current to alternating current transformation, and the cost of installing the converters into the gas turbine combustor.

A parallel study by Rasor Associates, Inc. and United Technology Corporation considered thermionic topping of a somewhat larger (i.e., about 400 MW) combined cycle power plant integrated with an on-site coal gasifier. In that case the marginal capital cost of the thermionics was estimated at $494 per kilowatt, and $1058 per kilowatt was required where gasifier and other plant costs were included. The output power improvement derived would be equivalent to that which could be obtained through increasing the temperature of the gas turbine by 100 K to 200 K.

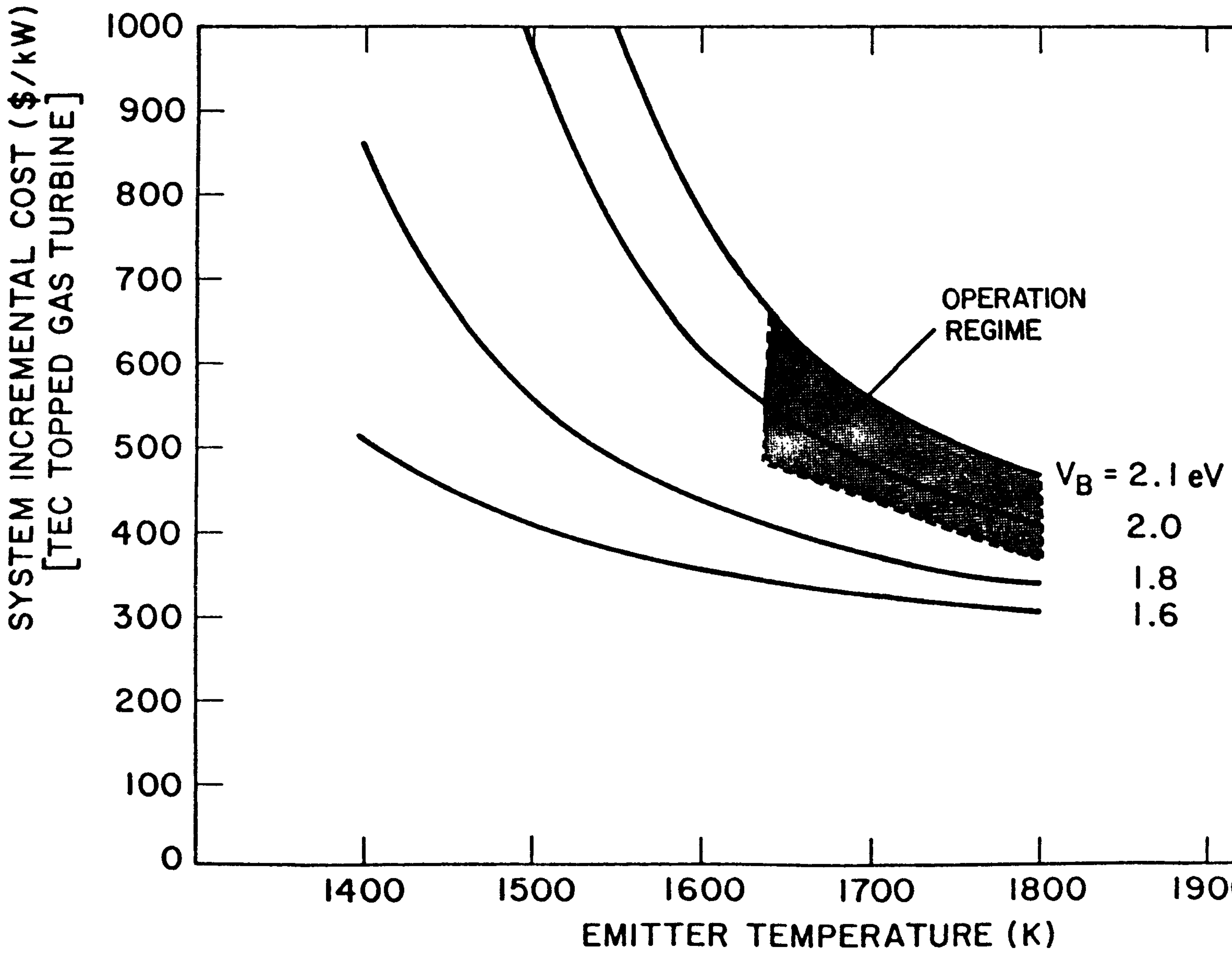

Exhibit A-1.3

Incremental Cost of Thermionic Topping in Combined Gas and Steam Turbine Topping Study

Studies were also carried out for topping steam turbine central (i.e., baseload) electrical generation stations. In these applications, the thermionic converters were incorporated in the firewalls of a coal-fired boiler. The performance of the thermionic converter in these studies was assumed to correspond to fully developed thermionic technology (i.e., assuming a lower barrier index than realized for first generation devices) to be consistent with the assumptions for other advanced systems (e.g., magnetohydrodynamics) treated in an important study not sponsored by the Program. Thermo Electron and Stone and Webster Engineering Corporation studied the use of TAM's in such power plants, while Rasor Associates, Inc., Bechtel National Inc. and Foster Wheeler Development Corporation studied the use of THX modules.

In these studies, thermionic topped systems were found to be substantially more efficient than the conventional steam cycle, and quite comparable to most of the advanced systems now under research and development. Based on 1975 costs, the thermionic system cost was projected in a range, depending on the barrier index assumed, which varies from $450 to $750 per kilowatt. These values bracketed the conventional steam cost at $525 per kilowatt.

Although these studies cannot be taken as representative of actual costs as they would be projected today -- the capital cost of a new conventional coal-fired power station is currently estimated to have risen to $1000 per kilowatt or above -- they do indicate the tremendous progress realized during the Program in reducing the costs of this technology.

Exhibit A-1.4 shows the combined effects of increased operating temperature and decreased barrier index on system cost. The calculations were made for the

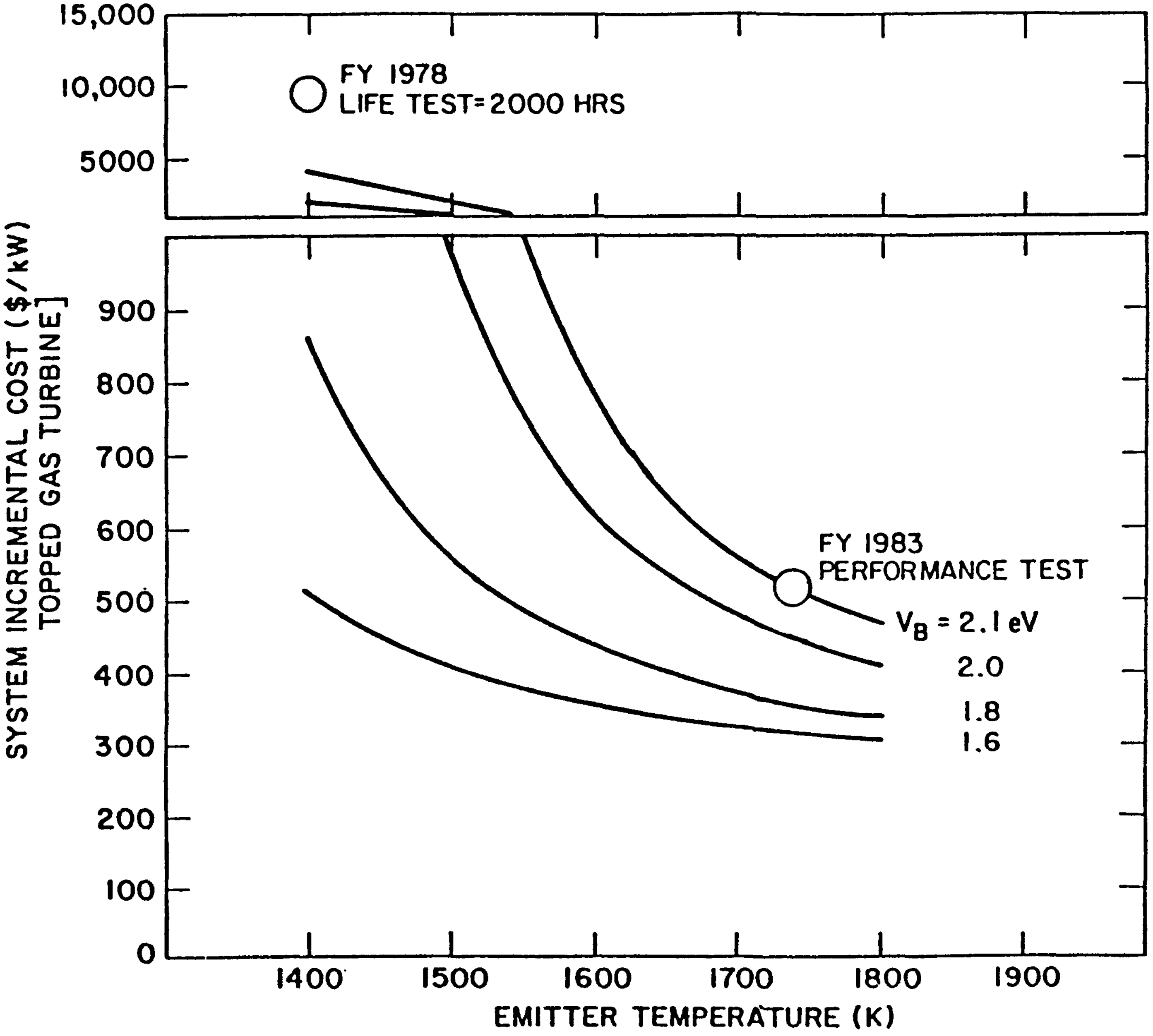

Exhibit A-1.4

Progress in Reducing System Incremental Cost thermionically topped combined cycle plant producing 100 MW electrical output. The costs shown are for the thermionic portions of the plant only (i.e., marginal costs per kilowatt). Based on the 1978 test of superalloy converters, the system cost would have been on the order of $10,000 per kilowatt. In contrast, a flame-fired test in 1983 showed that a $500/kW cost could be obtained. Thus, in relative terms, the Program has succeeded in decreasing capital costs for this technology by a factor of 20. This, in turn, suggests that capital costs are not likely to be a limiting factor in the acceptance of thermionic technology by the utility industry. Far more important will be the necessity of demonstrating converter lifetimes economically compatible with the 30-year useful lives assumed in typical utility financial analyses of generation options, and demonstrating the ability to produce thermionic arrays on the scale assumed in these studies.

Studies were also made to evaluate the performance of a thermionic cogeneration burner. This gas or oil burner, equipped internally with a set of thermionic converters, would generate process gas at high temperatures. It would be designed so that it could replace a conventional burner in a furnace. The design of the cogeneration burner is similar to a conventional high temperature burner, except that the combustion air is preheated internally by the collector of the thermionic converter. The performance of such a burner was shown to peak in electrical output at an output (i.e., process) gas temperature of 1200 K to 1300 K. At this temperature, a power output of 18 kWh per 10^6 Btu of fuel could be produced.

A number of potential cogeneration applications were examined in a preliminary fashion during the Program, and these examinations showed that thermionic cogeneration could reduce energy costs substantially in several of these processes. Although much analysis remains to be done in this area, two points should be noted. Most of the applications so far considered involve electric demands (i.e., when the system is designed to match thermal demand, as is usually the economically optimal course in cogeneration) far smaller than the systems studied for utility applications. Secondly, financial analyses of cogeneration systems are governed by different, and often less stringent, expectations about process lifetimes than is the case with utility analyses. Thus, cogeneration applications may be correspondingly less limited by the problems of scale and lifetime which are of concern for utility applications, and it appears likely that cogeneration systems may see commercial application at an earlier date.

1.4 Advanced Converter Development

The output power density and efficiency of a thermionic converter increases rapidly with increasing emitter temperature. The potential exists for lowering the threshold of economical operation to below 1200 K and doubling performance at higher temperatures. The Program has also made progress in achieving these objectives. Typically research converters were used for studying converter performance in this effort.

The research converter has proven to be a valuable tool for investigating many different electrode materials and observing their performance characteristics under controlled laboratory conditions. Research converter tests resulted in several independent achievements. For example, it was demonstrated that cesiated graphite reservoirs integral to the collector could achieve equivalent performance compared to converters with liquid cesium reservoirs. It was shown that the graphite could be cesiated to obtain maximum performance at the optimum collector temperature. Converters constructed with cesium-graphite reservoirs would not require a separate heater and controller to vary the cesium vapor pressure. This simplifies the most likely system configurations which would require the simultaneous operation of a number of thermionic converters.

Four approaches to improving converter performance were pursued during the Program: improved ignited mode operation (structured electrodes, divergent geometry); close interelectrode spacing; operation with an auxiliary ion source; and low collector work function.

Conventional thermionic converters operate with a low-voltage cesium discharge in the interelectrode space. Approximately .5 Volts are lost across this discharge, cutting converter performance approximately in half. Several techniques for reducing this loss were developed. First, the use of microstructured electrodes was shown analytically to be potentially capable of reducing this loss and increasing output by .1 Volts. Research converter experiments partially confirmed this improvement. Second, analytical models predicted an improvement of about .2 Volts if a "divergent" plasma geometry was used. Tests of the latter concept using a small .02 inch diameter cylindrical emitter in a .06 inch diameter collector confirmed an improvement near .15 Volts.

The use of small interelectrode spaces of about ten microns to improve performance has long been recognized, but practical converters have not been built because of problems with interelectrode shorting. A new approach

(SAVTEC) using small, independent, radiantly heated emitters was developed which promises a solution to this problem. A combustion-heated 19-converter array was built and 16 of the converters in the array generated electricity in preliminary tests, despite problems with collector temperature control.

The most effective performance improvement approach may be the combination of an auxiliary source of ions (i.e., a third electrode or pulsing of the two primary electrodes) with an inert gas plasma in the interelectrode space (i.e., instead of cesium). Experimental results confirmed low voltage losses in the plasam but it was found necessary to keep the partial pressure of cesium in the discharge below about one Pascal. Thus, the bulk of the effort concentrated on development of electrode surfaces capable of working at such low cesium pressures. Extensive testing and analysis indicate that surfaces generated from a very low pressure cesium and cesium oxide mixture may satisfy this need.

The performance of a converter can be substantially improved if low work function (i.e., less than 1.5 eV) collector surfaces are used. Surface physics work identified two such surfaces: 1) a single crystal tungsten (110) special two-dimensional oxide and 2) metals covered with a thick cesium oxide surface. However, both require such low cesium pressures that they may not be compatible with the conventional ignited mode of operation. Tests with inert-gas auxiliary ion source converters should be pursued.

The understanding of the physics of the thermionic converter was improved greatly in the course of the Program. This improvement is reflected in much more accurate analytical models of both the ignited and auxiliary ion source modes of converter operation, models which have already played an important role in guiding the development work described above.

This work has also led to formation of a theory on the role oxides play in a converter. Evidence compiled from mass spectrometry and Auger spectroscopy measurements and results from thermochemical calculations indicate that cesium oxide is formed by the interaction of the cesium vapor with a refractory oxide coating on the collector. Subsequently, the cesium oxide is desorbed from the collector onto the emitter and greatly enhances its electron emission at a given electrode temperature and cesium pressure. Improved understanding of the oxygen mechanism in the future might lead to preparation of better electrode surfaces.

Converters constructed with tungsten or molybdenum oxide collectors with tungsten emitters have achieved the highest output performance to date of any emitter and collector combination. This finding is now supported by many thousands of hours of testing.

Other approaches to improving converter performance have also been investigated, but less extensively than those described above. One such approach involved the use of gas-buffered heat-pipe techniques to introduce an inert gas region within the converter envelope, thereby permitting the use of low-temperature, low-cost rubber and plastic insulator seals. This approach also appeared to fortuitously achieve very favorable surface properties on the electrodes; very high performance was observed during these tests.

Two techniques for stepping up the output voltage from a converter using a transformer were also demonstrated. These techniques eliminate the need for series connection of a number of converters prior to power conditioning, thereby greatly reducing high-temperature electrical insulation difficulties in some designs.

1.5 Heat Transfer Technology

The electrical output of the thermionic converter is a direct function of the thermal energy flux through the converter. Efficent heat transfer to the emitter and from the collector are of primary importance to the proper operation of the converter, and to the development of practical thermionic systems.

The collector cooling air power requirement can be minimized by optimizing the heat exchanger. Methods studied for improving collector cooling heat transfer have included jet impingement techniques, ball matrix heat exchangers, and finned heat exchangers.

The finned collector design was found to be preferable because it reduces both the required air flow and the required pumping pressure to achieve proper cooling at the desired collector temperature. This reduces the total required pumping power for collector cooling by a factor of four, compared to the ball matrix system, to less than one Watt per diode in a full-scale thermionic module.

Heat transfer into the emitter has not generally presented problems in test furnaces. As demonstration units approach more practical designs; however, the benefits of enhancing the heat flux into the emitter will become more evident.

PART B

INTRODUCTION TO THE ADVANCED THERMIONIC TECHNOLOGY PROGRAM

1. INTRODUCTION TO THERMIONIC CONVERSION

Thermionic energy converters (see Exhibit B-1.1) are remarkably simple and environmentally clean devices for converting heat to electricity. A metal electrode, the emitter, is heated until electrons "boil" from its surface. The emitted electrons cross a narrow interelectrode gap and "condense" on the collector. This flow of electrons constitutes an electric current that delivers power to the load.

In order to escape from the emitter, an electron must obtain enough energy to overcome the attraction of the positively charged atomic nuclei in the emitter surface. This energy requirement, referred to as the "emitter surface work function," is strongly dependent upon the material from which the emitter is made, and can also be influenced by the presence on the emitter surface of adsorbed vapors or trace impurities. In order to generate current with available temperature sources, the surface work function can be at most a few Volts per electron (i.e., a few eV).

An additional barrier to escape from the surface arises from the repulsive effects of those electrons which have already escaped but have not entered the collector. This "space-charge" must somehow be neutralized if current is to flow steadily, and the most common way to do this is to introduce a low-pressure cesium vapor into the interelectrode space. The highest-energy electrons leaving the emitter are sufficiently energetic to ionize the cesium, producing a positively charged plasma able to neutralize the space charge of the electrons. This cesium also serves another function: it is one of those

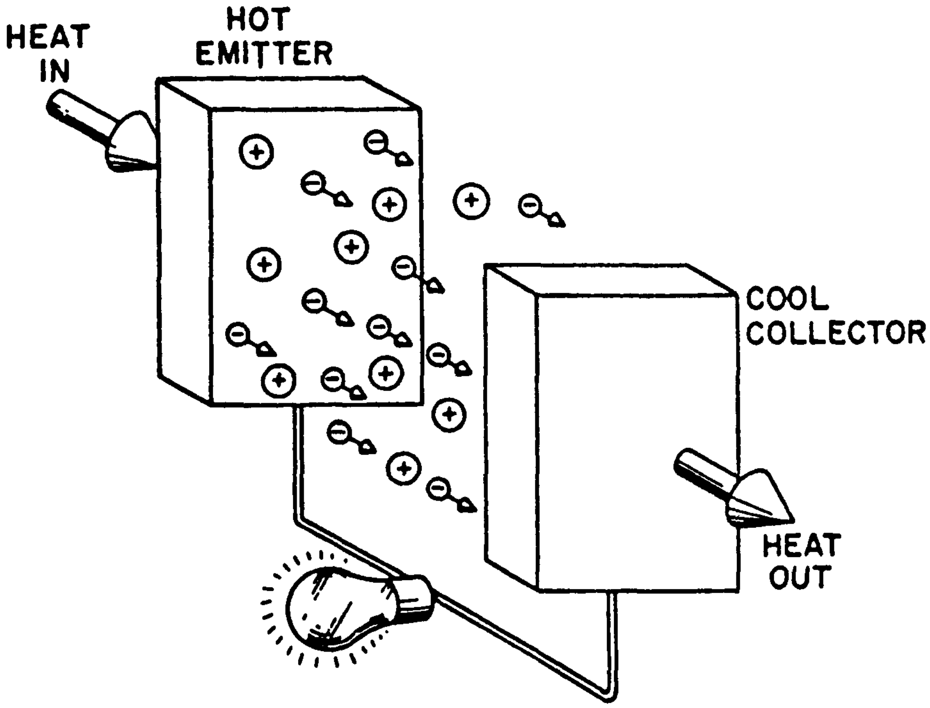

Exhibit B-1.1

A Thermionic Module Converts Heat Directly to Electricity vapors which, when adsorbed onto the surface of an electrode, dramatically lowers the surface work function.

The collector also has a surface work function and produces a back-current. Thus, it must normally be kept at a substantially lower temperature than the emitter in order to produce a reasonable net current. Because of this requirement, much of that energy supplied to the emitter which is not recoverable as electric current, is recoverable as high temperature waste heat from the collector. This high temperature energy is perfectly suited for more conventional industrial process or power generation systems. The actual energy losses of a thermionic converter are primarily those due to electron scattering in the plasma, cesium ionization, and other interelectrode voltage losses -- which, together, are known as the "arc-drop" -- plus thermal losses due to radiation and electric resistance heating. The arc-drop will be a function of the cesium pressure, electrode spacing and the current density. The converter output voltage, V_o, is then the difference in the Fermi levels between the emitter and collector, i.e., in the potential energy of electrons "bound" in the respective surfaces.

Because the energy conversion process is independent of the converter size, converters may be made in modules optimized for given applications. These standard modules can be assembled in arrays to provide the desired output power level and, by virtue of their redundancy, the desired level of reliability.

Thermionic energy converters can produce current with any heat source capable of providing temperatures above approximately 1250 K. Fossil fuel burners, nuclear reactors, isotope capsules, and solar concentrators have all been used successfully as heat sources.

A current density-voltage curve (J-V curve) is the performance characteristic used to judge thermionic converters. In principle, it is generated by varying the electric load between the emitter and collector and measuring the output current density and corresponding voltage. Among other things, the J-V curve produced depends upon the emitter, collector, and cesium reservoir temperatures and electrode spacing. For a converter operating at a given current density, there exist characteristic values of the collector and cesium reservoir temperatures and electrode spacing, dependent on the emitter temperature, that result in maximum output voltage. The characteristic values are termed optimum values since an increase or decrease in their value results in a decrease in output voltage.

The barrier index, V_B, is also a parameter that serves as a figure-of-merit for thermionic converter performance. It is equal to the sum of the arc-drop potential, the collector work function, and other potential loss terms associated with the interelectrode space. The barrier index is formally defined as the difference between the observed voltage and that predicted by the applicable "Boltzman equation" at a current density of six Amperes per square centimeter, with the collector work function and the cesium reservoir temperature both equal to zero. The smaller the value of the barrier index, the better the converter performance. Thus, reduction in the barrier index, with all other parameters held constant, is equivalent to a greater conversion efficiency and output power. Alternatively, for the same efficiency and output power, a lower barrier index is equivalent to using a lower emitter temperature or operating at a less than or greater than optimum collector temperature, electrode spacing or cesium reservoir temperature.

Efforts to improve converter performance are thus aimed at obtaining desired properties from the surfaces of emitter and collector materials while simultaneously reducing interelectrode losses. For example, the converter output depends on the cesium reservoir temperature through the changes in the electrode work functions and the interelectrode losses produced by cesium vapor. The combined effects of cesium on electrode work functions and interelectrode losses determines the optimum cesium reservoir temperature. Preferred electrode materials give rise to low optimum reservoir temperatures and higher power output. A desirable larger optimum interelectrode spacing usually accompanies the lower optimum reservoir temperature.

The modern era of thermionic conversion research and development began in 1958 with the publication of experimental results showing that a practical operating regime existed using the spontaneous processes in the elementary cesium vapor diode. Shortly thereafter, several alternate approaches were demonstrated experimentally that gave superior performances by employing more complex configurations and processes.

By 1963, sufficient progress had been made in the basic and applied technology to permit initiation of its reduction to engineering practice to satisfy the then-projected space-power requirements. Because the performance and configurational constraints of this application were satisfied by the elementary cesium diode converter, it was selected for exclusive emphasis in the development program that followed.

By 1972 the engineering capability to construct a thermionic reactor system had been demonstrated. Thermionic converters with prototype geometries had operated stably outside reactors in life tests exceeding 46,000 hours, and thermionic fuel elements were operated in excess of 8,000 hours in reactor cores. Operation of a complete thermionic reactor system was initiated in the USSR in 1970.

In 1973, however, the United States reactor space-power program was abruptly terminated, including almost all of the thermionic work. In the latter part of 1973, a new effort was initiated as a response to the energy crisis in the United States and based on the possibility of achieving advanced methods of thermionic energy conversion that would make the technology more cost effective for both space and terrestrial applications.

Thermionic power systems have characteristics that make them attractive for a variety of terrestrial applications. Some of these have been discussed -- their ability to use any high-temperature heat source, their compatibility with conventional process and generation systems, and their modular nature.

Thermionic converters also operate at high power densities. Typically, they provide 3,000 to 10,000 Watts of electrical power per square foot of electrode area. As a result, they can be made very compact. Their high power density also permits the use of relatively inexpensive materials and fabrication techniques, making them cost-effective in hostile environments.

Since no moving parts or high pressures are needed, the reliability of the converter can be high, so that maintenance is minimized. The LC-9 converter developed in the space program operated stably for over five years without maintenance until the test was terminated for programmatic reasons.

Since the thermionic converter is an electronic device, it can respond very rapidly to variations in load or heat input. For example, within 1/100 second the converter can respond to as much as a factor of 10 change in input power, depending upon its design operating point. Sudden changes in load requirements can be accommodated with similar speed. Such changes can be made in a manner that maintains constant electrode temperatures, thereby minimizing stresses to the system.

The cost of a thermionic converter in $/kW is less at output power density levels higher than those that provide peak efficiency. The design operating point of practical converter modules will be a compromise between cost and peak efficiency. As a result, the modules will have excellent part-load efficiency characteristics.

The potential terrestrial applications considered by the Advanced Thermionic Technology Program, the technical requirements for such applications to be successfully realized, the concept design approaches considered, and the expected capabilities of the technology are the subject of Part B, Section 2, which follows.

2. TERRESTRIAL APPLICATIONS, REQUIREMENTS, APPROACHES AND ACHIEVEMENTS

2.1 Opportunities for Terrestrial Application

Thermionic converters are not highly efficient electricity generators compared to conventional methods of generation, such as fossil fuel or nuclear power stations. Today's converters have electrical efficiencies a little above ten percent, with efficiencies of approximately twice that amount believed achievable by fully mature technology. By contrast, conventional and other developmental technologies for power generation typically are 30% to 40% efficient. For this reason, thermionic conversion is not attractive as a stand-alone system for power generation.

However, perhaps the key fact about thermionic converters is their ability to reject their waste energy at temperatures high enough to be useful as inputs to other generating technologies (i.e., in so-called "topping" applications) or directly to industrial processes (i.e., in cogeneration applications). Thus, by designing thermionic modules to serve as initial stages in cogeneration or power generation systems, highly efficient and economical systems can potentially be developed.

As long as one can ignore some rather complex physical phenomena which may arise at some scales of operation (e.g., temperature inhomogeneities, magnetic effects in the interelectrode space, etc.), converter output is essentially proportional to total electrode surface area. Thus, the technology can produce power at almost any scale by changing the size of the electrodes and/or by cross-connecting many electrodes in series-parallel arrays. Consequently, the applications for which thermionics is appropriate are most easily classified according to the typical scale of the associated non-thermionic systems.

Processes of interest for cogeneration systems may require power at scales anywhere from a few kilowatts to a few tens of megawatts. Thermionic cogeneration systems could be sized to produce more electricity than needed at the industrial facility -- with the excess being sold to the local utility -- but, as a general rule of thumb, experience with other cogeneration technologies has shown that greatest economies occur when systems are sized to meet thermal demand and the resulting electrical output closely matches facility electrical demand.

The processes of interest for cogeneration may be able to use thermionic waste heat either as direct heat or for steam generation. Although AC power at voltages comparable to those available from utility grids is most often required, certain processes make use of DC power at low voltage. Thermionic technology is uniquely capable of providing this latter form of electricity without rectification inefficiencies.

Peaking stations are used by utilities to supply electricity at times of high seasonal or daily demand. They are typically sized to provide power at scales of a few megawatts to two or three hundred megawatts. In many cases these stations are former baseload units which have been downgraded due to age, cost, or technical obsolescence. They most often use coal or fuel oil to supply their energy. Many other units are of types which are inherently more economical or practical at these scales than at the scales of larger baseload units, such as gas turbines or combined-cycle stations. Any of these technologies are potentially adaptable to thermionic topping.

Baseload stations operate at sizes from those of the largest peaking stations up to 4000 MW (i.e., for the largest multiunit complexes now in planning). Individual units are common in sizes from 600 MW to 1200 MW. On a national basis, most of these stations are coal-fired or nuclear, but oil-fired stations are dominant in particular regions where that fuel is locally available in large quantities or where environmental considerations make coal impractical. The Program has given relatively little attention, particularly in recent years, to nuclear applications. However, larger versions of the topping systems proposed for peaking applications would be appropriate for topping of fossil-fuel baseload generating stations.

2.2 Technical Requirements for Successful Application

Adaptation of thermionic technology from previously successful astronautical systems to these types of terrestrial applications requires the solution of a number of practical scientific and engineering problems. Cogeneration or utility thermionic systems must operate at high heat flux and/or temperature in order to be economical. Almost all terrestrial thermionic systems would use combustion as the source of the thermal energy. Converters must, therefore, be designed to survive in a flame environment which can be both highly corrosive and ablative. In a practical sense, then, adaptation of thermionic technology to terrestrial applications first of all requires that the converter itself be shielded from the flame environment by some material which can survive that environment and which is not itself prohibitively expensive. Once a suitable material has been identified, some way must be found to place this shield around the converter without disrupting the converter's electrical, surface chemistry, or thermal properties, or having the shield itself disrupted by them.

Space-borne thermionic devices have demonstrated successful operating lives of several years. This is more than adequate for use in applications such as satellites. However, a typical utility executive will evaluate an investment in a generating station under the assumption that that station will have a useful life of perhaps 30 years -- a time much longer than an expected life for a satellite. Consequently, a second major technical requirement for a successful terrestrial thermionic system is a major extension in service life, or, alternatively, a capital cost so low that replacement of the thermionic module several times during the service life of the generating station is nevertheless economical. This requirement is less stringent in cogeneration systems, where the investment may be analyzed over a shorter time frame in keeping with the dynamic nature of product markets, but it remains an important consideration even there.

Both the flame protection and lifetime problems would be lessened if the temperatures required for economical operation could be further reduced. This could most logically be achieved by general improvements in the efficiency of thermionic devices at a given temperature, which, of course, would also be desirable in and of themselves. Such efficiency improvements would be especially important in utility peaking and baseload applications where improved efficiency would directly translate into a reduced cost of electricity. The improvements would also sharply increase the number of potential industrial processes for which thermionic cogeneration systems could be designed giving a suitable match with process thermal and electrical demand. Achieving these efficiency improvements dictates the need for both improved theoretical understanding of the thermionic conversion process, and for experimental studies to investigate ways of turning previous theoretical insights into practical converter designs.

At a given level of device efficiency, an alternative method of enhancing thermionic system economics is to operate at higher emitter temperatures (i.e., without causing unacceptably reduced operating lifetimes). Early studies suggested that the emitter must operate at temperatures of 1700 K or more for terrestrial thermionic systems to become practical, and this was at least 300 K higher than was achievable in a flame environment prior to the Program.

In a very real sense, therefore, operating temperature, operating lifetime, and operating efficiency (i.e., as measured by the barrier index) are the three most critical parameters that must be improved for thermionics to be applied to terrestrial applications.

The issue of large-scale electrical output must also be addressed. As indicated above, most of the applications being considered would involve power requirements far in excess of those employed for typical space payloads. This can either be achieved by increasing the effective area (or efficiency) of individual converters, or by connecting increasing numbers of converters into arrays. Either approach is potentially associated with its own set of problems, requiring a separate set of investigations.

During operation, the interelectrode space of a converter is filled with plasma, and the physics of plasma is notoriously complex. As the size of the electrodes is increased, therefore, the possibility exists that unanticipated plasma effects could become important and that the behavior of large converters might differ in measurable ways from that expected on the basis of simple extrapolation from the small converters. Increased electrode size (i.e., especially to the point where an electrode's surface area becomes comparable to the area of the flame source) also opens the issue of temperature uniformity. Since current emission is clearly temperature dependent, consideration must be given to designs which can keep the entire electrode surfaces at close to their optimum temperature while maintaining the proper interelectrode "gap" in the presence of thermal expansion and creep.

A different issue of temperature uniformity must be considered when the approach to large outputs involves series-parallel arrays. The electrical connections in an array create dependencies between the electrical outputs of the various converters. Adjustment to these dependencies in turn influences the temperature of the emitter and collector of each converter. Consequently, variations in the input heat flux "seen" by the various converters might lead to unexpected operating conditions for converters in an array as opposed to converters operating individually. In extreme situations, this could lead to sharp losses in array efficiency, or even to failure of some of the converters. Arrays must also be designed in which lead (i.e., resistance heating) power losses are kept to a minimum.

At least one further requirement exists: the final converter design or designs, including the flame shielding, must be able to be manufactured in quantity both reliably and inexpensively. In many respects, a thermionic converter is no different from a conventional electronic circuit element for which manufacturing problems have long since been solved. However, compatibility with manufacturing could have very important impacts on how the flame protection is to be provided in the design, and through that linkage, on questions of lifetime and operating temperature. Compatibility could also be critical in evaluating the merits of proposed designs for improved efficiency or greater scale of output, especially if such designs should need to be more complex than the conventional thermionic converters. Thus, adaptation of thermionics also requires research into the most appropriate manufacturing techniques.

2.3 Program Organization and Approaches

The Advanced Thermionic Technology Program was designed to address each of the technical requirements outlined above, and bring into being practical new energy supply options. To facilitate this objective in light of the numerous tasks to be accomplished, the Program's effort has been divided among several contractors and subcontractors. The bulk of the effort, however, has been undertaken by Thermo Electron Corporation and by Rasor Associates. Although there has been a certain amount of overlap between the work of these two organizations, Thermo Electron's efforts have focused more specifically on development of a "first-generation" converter which could demonstrate long operating life and high operating temperature at a barrier index at least comparable to astronautical converters, but do so in a flame environment. By comparison, Rasor Associates' work has been directed more toward creating the theoretical and experimental bases for the design of higher-efficiency "second generation" converters. Both companies have been involved in the study of systems applications and obstacles for terrestrial thermionics.

Two major conceptual system approaches have emerged during the Program, and each of the two major Program participants has also tended to focus their efforts on one of these concepts. Thermo Electron Corporation has been evaluating Thermionic Array Modules (TAM's) consisting of arrays of relatively small individual thermionic converters, as shown in Exhibit B-2.1. Such a TAM would have an electrical output of about half of a megawatt. Individual converters in the array would more nearly approximate the size of converters developed previously for the space program. Production economics would be realized by using mass production techniques developed for light structures (such as spinning, stamping, and bulk processing).

The more important characteristic of this technical approach, however, is the method of providing protection from the flame environment. Each individual converter would be completely enclosed in its own individual "hot shell" made by depositing (i.e., through the technique of "chemical vapor deposition") a protective ceramic material on the outside of a suitable inert substrate, and similarly depositing the emitter material on the inside. The collector, cesium reservoir, and power leads would be mechanically installed and the entire structure sealed.

Thermo Electron has carried out extensive studies on chemical vapor deposition techniques as they would be applied to the fabrication of hot shells. Detailed understanding has been acquired of preferred fabrication procedures and of the advantages and disadvantages of a variety of hot shell designs. An

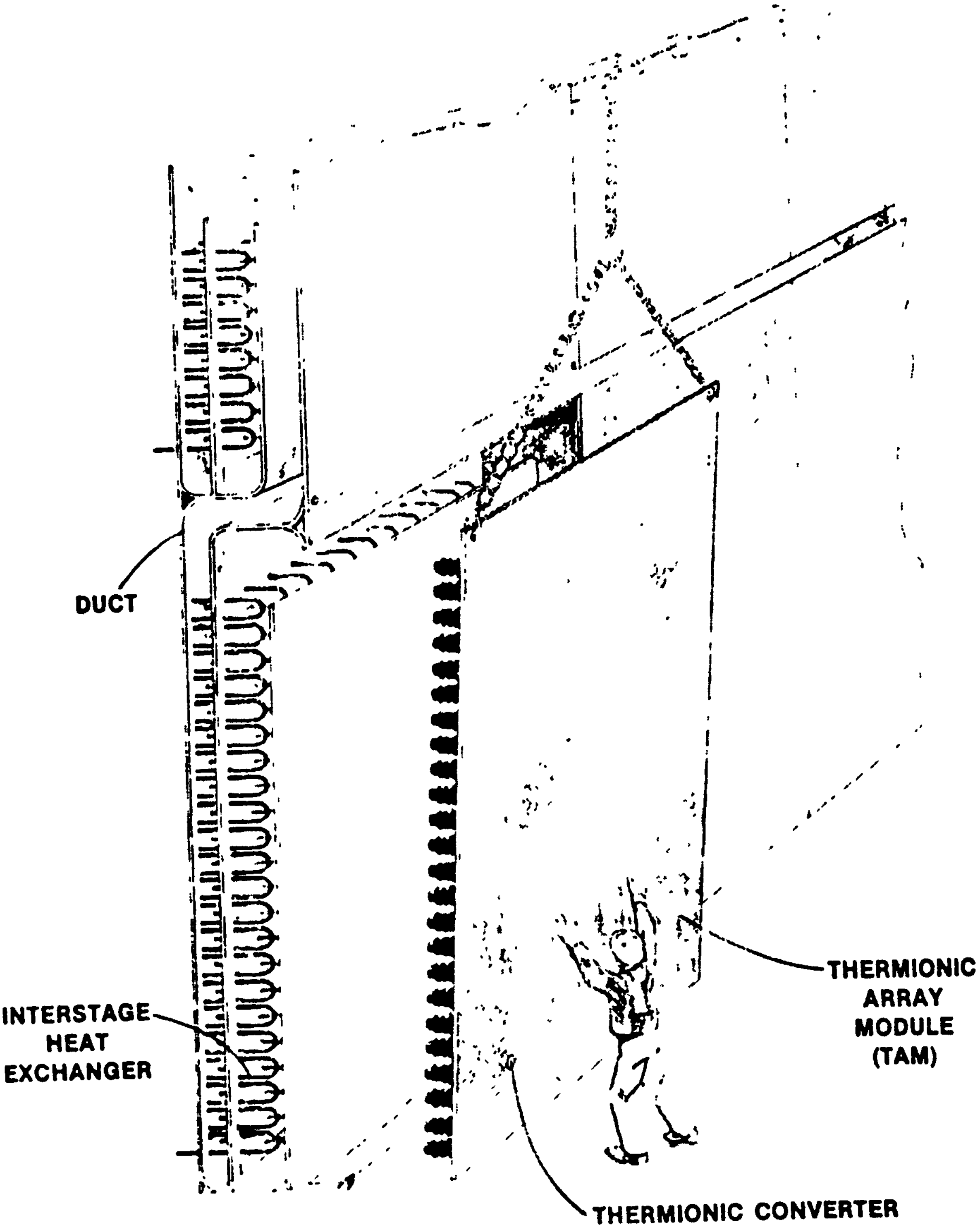

Exhibit B-2.1

Installation of 500-kW(e) Thermionic Array Module extensive test program of small (i.e., on the order of 10 - 100 Watts) converters has also been conducted to guide design efforts. The test program has been further expanded to assist in the effort to develop converter arrays and advanced converters.

Rasor Associates, Inc., has examined the concept of thermionic heat exchangers (THX's). As shown in Exhibit B-2.2, these are large components designed to achieve economies of scale. The THX consists of at least three thermionic cells, with multiple converters thus being protected by a single ceramic (i.e., probably silicon carbide) shield from the flame environment. A heat pipe is used to further isolate the converters from the flame and to produce a more uniform heat flux throughout the THX. Whereas the TAM modules are well adapted for using their reject heat to preheat furnace air, the THX modules are more suitable for direct generation of steam, and they incorporate steam tubes in their design. Because of Rasor Associates' emphasis on advanced converter development, work on the THX has tended to lag behind that of the TAM, but both design concepts appear promising.

Attempts to develop second-generation converters have been based on a variety of both theoretical and experimental studies. One major approach has involved attempts to modify the surface properties of emitters and collectors through the controlled addition of oxides to those surfaces. It has long been known that such materials can strongly influence converter properties, but understanding and control of the mechanisms involved has proven elusive. Another major line of attack has involved modifications of converter geometry. Among the most promising concepts of this types is "SAVTEC," based on the notion of creating a composite emitter from a number of extremely small, electrically

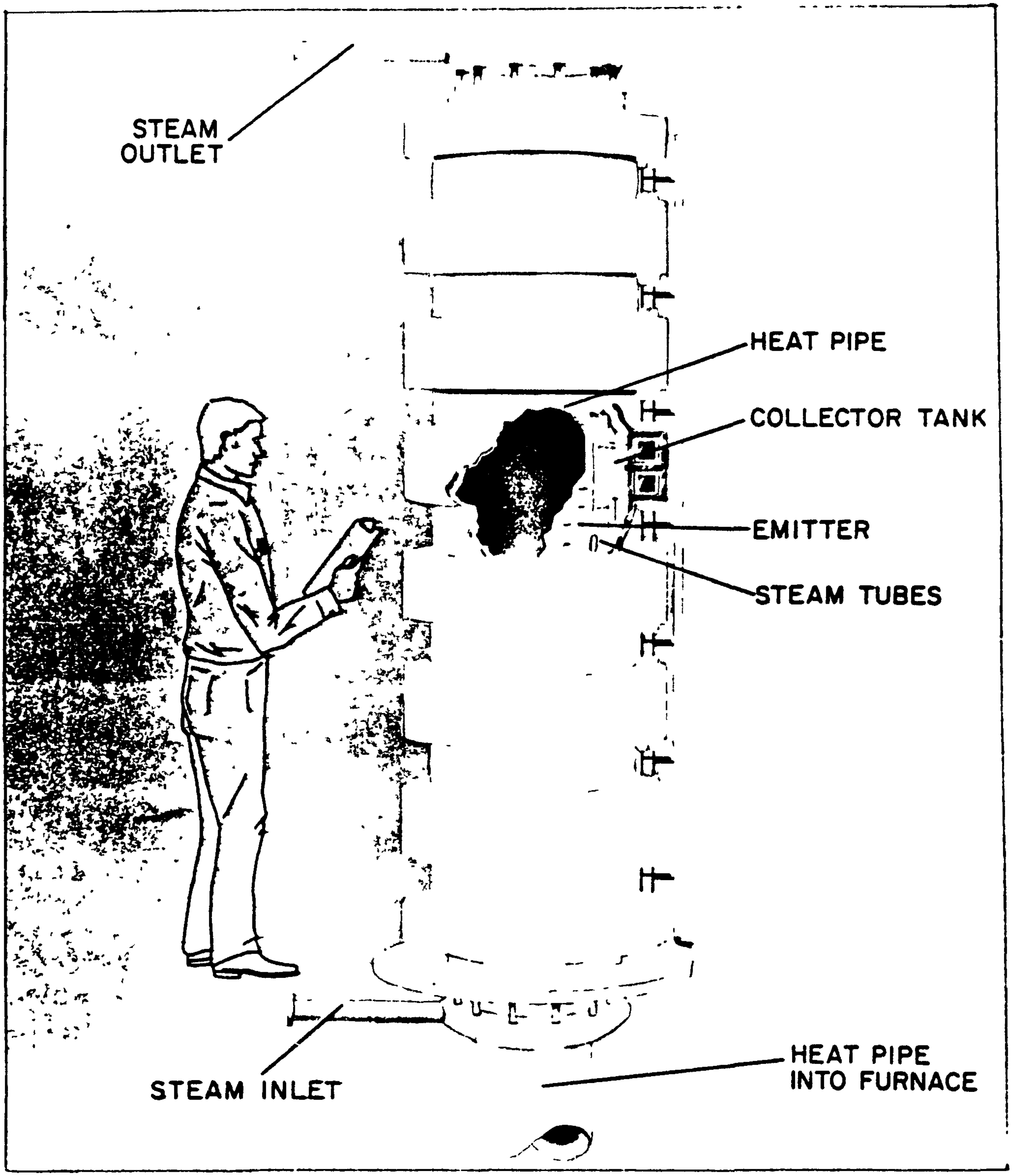

Exhibit B-2.2

Typical THX Module

and mechanically independent emitters. The small size and independence of the individual elements permits extremely close spacing between emitter and collector, resulting in pronounced increases in device efficiency. Still another approach has involved the use of auxiliary ion sources (i.e., in devices such as the "plasmatron") to overcome the energy losses caused by interelectrode space charge. A combination of such an auxiliary ion source with inert gas plasmas and oxide-modified electrode surfaces appears especially promising.

2.4 Overview of Accomplishments

The "Executive Summary," Part A of this report, summarizes the accomplishments of the Advanced Thermionic Technology Program, and, of course, the main body of the report, Parts C, D, and E, describe those accomplishments in detail. Without repeating that material, it is, nevertheless, useful at this point to give a brief, non-technical overview of what the Program has achieved, and what remains unresolved if thermionic technology is to become a commercially accepted means of producing energy.

First generation, flame-fired, hot-shell thermionic converters have been designed, realistically fabricated (i.e., with procedures relevant to a mass production situation), and tested. The technology has shown continual and dramatic improvement throughout the history of the Program in terms of achievable operating temperatures, lifetimes, and cost per unit of output. Operating temperatures in excess of 1700 K and a lifetime of 12,500 hours have been demonstrated. Most impressive has been the improvement of roughly a factor of 20 in the cost per kilowatt which has been achieved during the Program. Confidence has also been established that these converters can be feasibly mass-produced at a cost which can make them competitive with more conventional technologies.

Less progress has been made in integrating these individual first generation converters into the larger arrays necessary for their use in practical electrical systems. None of the arrays tested within the Program has as yet been large enough to demonstrate as much as a single order of magnitude increase in power output over that of an individual converter, although, it should be noted, exhaustive attempts to produce large arrays have not yet been undertaken.

Since some of the applications considered would require the power output of up to 10^6 individual converters, it seems probable that only lower output applications (i.e., such as cogeneration systems) will be commercial possibilities in the immediate future. This conclusion is further supported by the fact that the lifetimes so far demonstrated for converters, while showing impressive gains during the Program, are still far less than the periods normally considered the useful lifetimes of utility generating stations as a whole. Demonstration of significantly longer converter operating lifetimes will inherently be a time-consuming process even if achieving such further gains proves to be easy technically. Hence, it is likely that terrestrial development of this technology in the next few years will focus most heavily on cogeneration applications. Designs specifically tailored for cogeneration are already among the most highly developed of the first-generation converters.

System studies conducted during the Program, both for cogeneration and utility applications, have established the technical compatibility of thermionics with industrial processes and conventional generating technologies. The studies have also shown the economic promise of thermionics in these applications, especially when second- or third-generation converters become available. However, energy costs have proven to be highly dynamic in recent years, and the systems studies have focused more on engineering measures of economic attractiveness (e.g., installed cost per kilowatt) and on energy savings than on comprehensive investment analyses. Consequently, the need for continuing studies in this area as thermionic technology matures can be anticipated.

A great deal of understanding has also been acquired by the Program about the technical problems that will have to be addressed in order to produce the next generation of converter. Laboratory converters have shown remarkable improvements over the first-generation devices in performance measures such as barrier index and scale of output, but these advanced converters generally remain laboratory devices, with the kind of design evolution which marked the development of the first-generation hot shell converters barely begun. Indeed, several of the promising approaches being pursued are mutually exclusive, while others can potentially be combined. Thus, it is very much an open question which of these approaches will eventually come to dominate the second generation, although at present the combination of: 1) an inert gas plasma in the interelectrode space; 2) an auxiliary source of ions; and, 3) electrode surfaces with properties modified by the presence of oxides appears especially promising. Much clearly productive research can also be anticipated on advanced converter technology.

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