DOE/OR/00033--T701

AN OVERVIEW OF THERMIONIC POWER CONVERSION TECHNOLOGY

BY

MORGAN C WHITE

A THESIS PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE

UNIVERSITY OF FLORIDA

1996

DISCLAIMER

ACKNOWLEDGMENTS

First I offer a special thank you and extend a debt of gratitude to Dr. Samim Anghaie. Without his support and encouragement, this work would not have been possible. I thank him for being both a mentor and a friend.

General Atomics Technologies of San Diego, California, was also particularly helpful. The author spent a summer working with their Space Power Division during which the insights provided on working thermionic systems were invaluable. Special thanks go to Liz Bealman, Harlan Horner, Les Begg, Tom VanHagan and Joe Smith, Jr., for the countless hours they spent discussing and teaching me about thermionic systems.

This work was performed under appointment to the Nuclear Engineering Fellowship Program administered by Oak Ridge Institute for Science and Education for the U.S. Department of Energy. A special thank you goes to Sandra Johnson, Cheryl Terry and Jennifer Dalton of Oak Ridge for their smooth running of the fellowship program.

TABLE OF CONTENTS

LIST OF FIGURES

Abstract of Thesis Presented to the Graduate School
of the University of Florida in Partial Fulfillment of the
Requirements for the Degree of Master of Science

AN OVERVIEW OF THERMIONIC POWER CONVERSION TECHNOLOGY

By

Morgan C White

December 1996

Chairman: Dr. Samim Anghaie
Major Department: Department of Nuclear Engineering

Thermionic energy conversion is one of the many concepts which make up the direct power conversion technologies. Specifically, thermionics is the process of changing heat directly into electricity via a material's ability to emit electrons when heated. This thesis presents a broad overview of the engineering and physics necessary to make thermionic energy conversion (TEC) a practical reality. It begins with an introduction to the technology and the history of its development. This is followed by a discussion of the physics and engineering necessary to develop practical power systems. Special emphasis is placed on the critical issues which are still being researched. Finally, there is a discussion of the missions which this technology may fulfill. These three sections will give the reader enough background to begin

reading the myriad of technical documents available within this research area. The list of references concentrates mainly on research which has been conducted within the United States of America since 1960.

INTRODUCTION TO THERMIONIC ENERGY CONVERSION

Direct energy conversion is the process of turning raw energy, heat, into a more usable energy, electricity. This thesis will concentrate on thermionic energy conversion (TEC), a specific branch of the direct energy conversion technologies. Thermionic emission was first discovered by Thomas Edison and is the process heating a metal surface to produce electrons.

A basic understanding of the thermionic conversion process can be stated very simply. When heated, the electrons within any metal will exceed a barrier index energy such that electrons near the surface which are at energies higher than this barrier index are emitted from the surface. These electrons are subsequently collected onto another metal surface having a lower barrier index energy. The flow of electrons is the current in the system. The motive, or potential, is provided by the energy necessary to overcome the original barrier energy minus that lost when the electrons are collected. When the circuit is connected to a load, the energy conversion process is complete.

The concept of thermionic energy conversion is of interest for a number of reasons. In its basic form it is a simple, static system; i.e., it uses no moving parts. This leads to better inherent stability and maintainability than comparable dynamic systems. TEC can generate power from a wide range of heat sources with temperatures from 800 to 2600 K. This ability to utilize high temperature sources and the inherent property of thermionic emission (where the power density is proportional to the temperature squared) provide greater power densities and higher efficiencies than comparable concepts.

Thermionic converters are usually modular units of fairly small size and weight. Their size and modularity encourage research and development. It is relatively easy to fabricate individual units for testing under varied conditions and the results are scalable from the laboratory to practical systems. The modularity and ability to adapt to different system geometry also make it easier to integrate thermionic conversion into systems where size and shape are driven by other factors.

These characteristics and others make thermionic energy conversion a good option for missions with limited space or weight, with high temperature heat sources, or where maintenance and lifetime are critical factors. A more basic introduction to thermionic power conversion can be found in Ram93. This thesis is an in-depth overview of the thermionic technology available for these missions.

HISTORY OF U.S. THERMIONIC ENERGY CONVERSION RESEARCH

The study of thermionics within the United States of America began in 1957 with the creation of a practical cesiated thermionic converter with substantial power output capability. This original research was spawned from programs at Los Alamos National Laboratory , General Electric, and RCA among others. The first converter to show promising results was installed into the water moderated core of the Omega West Reactor in April of 1959 and, despite a rather large emitter-collector separation distance of approximately 6 mm, it produced a short circuit current and open circuit voltage of 35 A and 3.5 V respectively. With the publication of these results, there began a systematic investigation into the potential of this new technology. This section is devoted to describing the history of the programs which have developed thermionics into a working practical engineering task. Concurrent with the beginning of the U.S. effort and in the time since, research programs within many other countries have flourished. However, these programs will be mentioned only where they overlap or provide significant advancements to the U.S. programs.

The first effort to coordinate and develop U.S. thermionic research took place during the 1960s (Ran90a). During the heyday of the U.S. space program this effort focused on applications for space power systems and in particular nuclear power systems. Among the many programs during this time frame was the SNAP-2 reactor which was flight tested in 1965 (the only nuclear reactor the U.S. has ever orbited). The system was based around radiator-mounted Si-Ge thermoelectric converters (another direct power conversion technology) producing half a kilowatt of electric power. The original thermionics programs concentrated on integrating converters directly into a reactor core design similar to those of the SNAP program.

The in-core thermionic element design which resulted is commonly referred to as a "flashlight" type thermionic fuel element (TFE). This description refers to the cylindrical shape of the fuel element with the nuclear fuel in the center of the thermionic converter producing the electrical output all within the reactor core. From 1962 to 1968, research sponsored by NASA and the AEC concentrated on development of this fast spectrum, in-core "flashlight" type TFE for use in a 100 kWe space nuclear power system (SNPS). During this time frame, much of the research was focused on finding the best solutions to the materials problems involved in making a long-life converter.

Research broadened during the 1968 to 1972 time frame, as alternate concepts were explored for placing the thermionic converter outside the reactor core. These new studies looked at thermally coupling the thermionic converters to the reactor core either through radiative emissions or conduction. At this same time, in-core thermionics advanced to a multi-cell TFE design using tungsten-clad UO_2 emitters operating at 1800-1900 K. Prototypes of this design began experimental testing in 1970 and had met performance and lifetime objectives of 10,000 hour lifetime and two to five watts electric per square centimeter in multiple in-reactor tests by late 1972.

The next logical step was to build a full scale system. A request for proposals was announced detailing a desire for a 100 kWe space power system using a thermionic reactor. This sparked a competition between General Electric and General Atomics. However, even though the contract was won by General Atomics, the program was ill-timed. Changes by congress and the executive branch in national priorities were shifting funding out of the space power field. These changes resulted in the cancellation of all U.S. space reactor programs in early 1973. This was a major setback in thermionic research.

It should be noted that this change in U.S. policy had a significant impact on research into thermionics in many other countries. One example of this was the cancellation of a German project aimed at producing a 20 kWe SNPS for use in a direct broadcast television satellite. The project used an in-core thermionic reactor with UO_2 fueled molybdenum emitters operating near 1800 K and had achieved its goals for lifetime and performance. Even though the project was canceled when the U.S. declined to commit to providing a launch vehicle, it accumulated more than 23,000 hours of testing. The only bright star within thermionic research at that time was the USSR's TOPAZ project.

In 1970, the USSR orbited the first of three TOPAZ type thermionic space nuclear power systems. A second system was launched in 1972 and TOPAZ-3 followed in 1975. This system was comprised of a NaK cooled, Zr moderated fast-spectrum reactor utilizing a 5-cell "flashlight" type thermionic fuel element. It generated between 5 and 10 kWe with lifetimes between 3000 and 5000 hours. These remain the only thermionic reactor systems which have been flight tested.

The first relief for U.S. research projects came late in 1974 when NASA sponsored a joint effort at the Jet Propulsion Laboratory and Los Alamos National Laboratory. This effort was to research small nuclear reactor out of core, heat pipe fed thermionic systems. Heat pipes, a recent (1963) innovation of the Los Alamos laboratories, were designed to conduct heat from one location to another with as little temperature loss as possible. However, little funding was available and most research was limited to conceptual studies.

From 1973 to 1979, most of the major advances within thermionic research came from groups studying terrestrial applications under Department of Energy projects. These groups were concerned with developing a practical thermionic combustor (Mer80). Specifically, they were designing a flame fired thermionic conversion unit for use within conventional coal or gas power plants or any other manufacturing environment where combustion is used to produce high temperatures. Basic research during this time into the thermionic emission process and electron transport resulted in significant advances for the thermionic cell lifetime and performance.

In 1979, the Department of Energy, the Department of Defense and NASA launched a joint space power system study known as SPAR. The program used heat pipe technology to fed an out of core conversion system. Thermionics was chosen as the conversion technology to deliver power at levels over 100 kWe. This study was later broadened into the SP-100 program in 1982.

The SP-100 program goal was to design a 100 kWe space nuclear power system. General Atomics submitted essentially the same thermionic reactor design concept which had won the earlier contract in 1972 and it was given approval as part of the phase I effort within this new program. A three year effort (1984 to 1986) produced advances in understanding the system design but the final phase of the contract was awarded to a thermoelectric based design. However, a rebirth of the space program was being brought about because of interest in the national Strategic Defense Initiative.

A number of new programs were initiated under this initiative. The concept called for extremely high power space-based systems capable of sustained power outputs from 100s to 1000s of kWe with burst power outputs one to two orders of magnitude higher. Much of the basic research needed to develop a practical thermionic power system was carried out during this time.

Over the next decade, a number of major initives were undertaken (Dah93). The Thermionic Technology Program and the S-Prime Design TFE(1984 to 1986) focused on the emitter electrode and the insulator materials (Mil93 and Roc93). The Thermionic Fuel Element Verification Project (TFE VP) (1986 to 1994) focused on demonstrating performance and life-time characteristics of TFE components in a multi-MW reactor environment (Gen94, Sam87, Sam89 and Sam90). The Multi-megawatt Design Effort (1986 to 1994) evaluated several technologies to determine their ability to provide several megawatts of power for an SDI burst power space based defense platform. The Advanced Thermionic Initiative (1989 to 1993) concentrated on an advanced TFE with a single long cell design (Lam94).

Most of these programs included a third phase of their respective programs in which a prototype reactor would be built and flight tested. However, no recent U.S. program has been carried to this stage so we still have not gained any first-hand experience from flight testing a thermionic design. The TSET Program (1991 to 1996) sought to circumvent this lack of system engineering level data by studying the TOPAZ program. It focused on reviewing and integrating into the U.S. programs the information available from the Russian (former USSR) TOPAZ thermionic power system. Findings from the study include Agn94, Bel90, Bog90b, Bog90c, Bog90d, Mal95, Par94, Pon91 and Vib92.

In addition to these programs, many small business innovative research (SBIR) grants and several smaller scale USAF/DOD/DOE/SDIO/BMDO programs have continued research in new concepts and system integration. Due to the inherent ability to build and test thermionic converters at a unit level, much research has been done by individual researchers or small groups working outside the bounds of the large programs.

CRITICAL ISSUES IN THERMIONIC ENERGY CONVERSION

Background: The Basic Thermionic Cell

All power conversion systems have one goal in mind; to bring in raw energy and convert it into a more useful form. With this in mind, any thermionic converter can be reduced into a basic cell concept. A supply of energy is provided to the cathode, also called the emitter, in the form of heat. The Edison effect dictates that electrons gain energy reaching higher levels of excitement until the electrons close to the surface undergo thermionic emission. This occurs when the energy level of the electron exceeds the work function, equivalent to a binding energy, of the surface. The remainder of the thermionic converter cell is then dedicated to collecting and using these emitted electrons with minimal loss in bias (voltage) and minimal back current (flow of electrons back into the cathode).

After emission from the cathode, the electrons must traverse across a gap and be condensed onto an anode surface. This series of processes represents most of the key issues in making the thermionic conversion process viable. The remainder of the power conversion system is fairly simple in comparison. After the electrons are collected by the anode, the excess energy is taken from the collector to a heat sink.

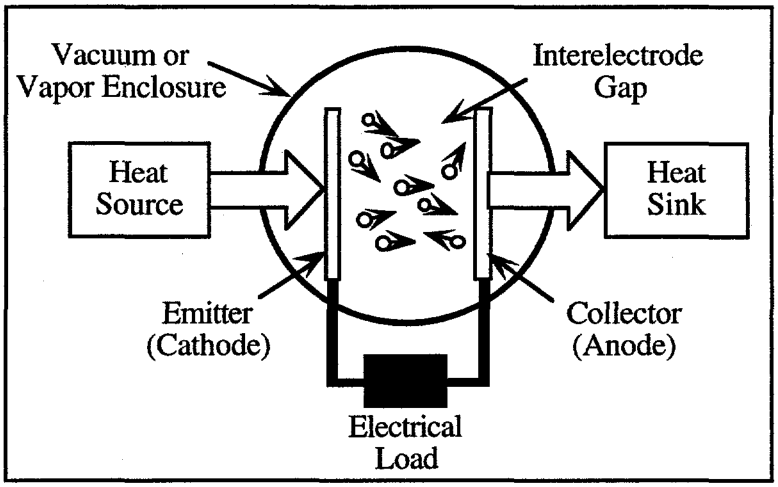

Figure 1. The basic thermionic cell.

The electrons are drawn through a circuit, usually a power conditioning system to transform the high current, low voltage signal into a more usable voltage-current range. The useful power having been extracted, the electrons are returned to the cathode to complete the circuit. The concept of the basic thermionic cell was introduced in by Drs. Hatsopoulos and Gyftopoulos in Hat73 and later refined in Hat79. Other full texts on this subject include Ang76, Bak78, Han67 and Kal89.

At this point the common units used to discuss thermionic systems should be introduced. These include mils (milli-inches) or micrometers (μm) for dimensions of thicknesses (note that 1 mil is 25.4 micrometers), inches or centimeters for other dimensions, amperes per square centimeter (A/cm^2) for current, electron volts (eV) for work functions, volts (V) for potential and Kelvin (K) for temperature. Thermionic energy conversion devices come in such a variety of sizes and shapes, the common dimensions and operating conditions will be discussed as each type of system is described.

Interelectrode Gap

With the basic cell in mind, it is time to examine the critical issues that make the engineering of thermionic converters challenging. The goal of thermionics is to produce electrical power. As such, the production of electrons and their transport across the gap becomes the

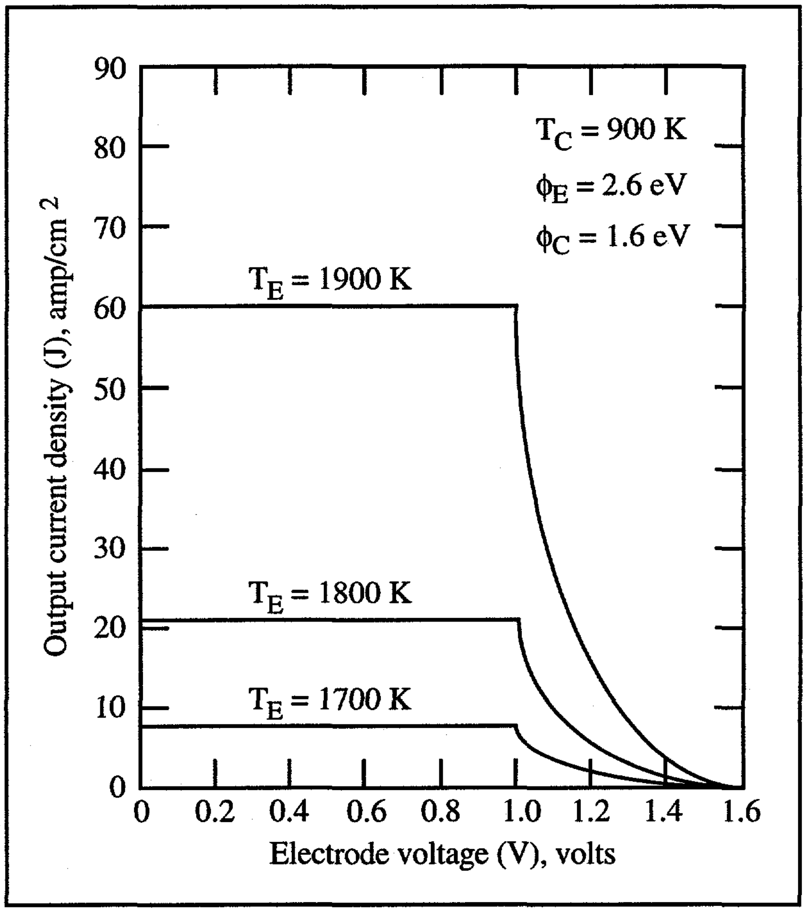

Figure 2. The effect of temperature on the J-V (Current-Voltage) curves for an ideal converter.

first key issue. It is important to optimize both the current, or number of electrons, and the voltage, or motive, that is produced.

The defining equation for computing the electron current leaving the surface of an emitter is credited to Richardson and Dushmann. This equation is derived from the Dirac's model of electron behavior and states:

$$J_S = AT^2 \exp\left(-\frac{\phi}{kT}\right)$$

(J_s is the saturation current leaving the surface, A is the Richardson constant:

$$A \equiv \frac{4\pi m_e k^2 e}{h^3} = 120 \frac{amp}{cm^2 K^2}$$

T is the material temperature, k the Boltzmann constant and ϕ is a material dependent work function). Notice that the output current density, and thus the final output power density, is dependent on the square of the temperature.

It is interesting to note here that no matter how complex the problems of transporting and collecting the electrons, the overall effect can be lumped into a generic "resistance" for the gap. This gap resistance can be introduced as a simple modifier in the derivation of the Richardson-Dushmann equation in combination with the material work function. The set of equations thus derived to describe the system can be used with fair accuracy in hand calculations. A full description of this concept can be found in *Thermionic Energy Conversion: Volumes I & II* by Drs. Hatsopoulos and Gyftopoulos (Hat73 and Hat79). However, the issues hidden in this generic term are worthy of further elaboration.

Space Charge Effects

First consider an emitter cathode isolated in a vacuum. The electrons emitted soon fill the space near the emitter surface with a highly charged negative electric field. This field builds up according to Poison's equation:

$$\nabla^2 \psi = -\frac{e^2 n_e}{\varepsilon_o}$$

where ψ is the electron motive, e the basic unit of charge, n_e the number density of electrons and ε_o the dielectric constant of vacuum. Since all the terms on the right hand side of the equation are always positive, it can be seen that the force on the electrons near the emitter surface increases directly with the number density of electrons. This effect is known as space charge. It severely limits the amount of current that can be produced from an emitter. All thermionic converters can be classified depending on how they reduce this effect.

Vacuum Thermionic Converters

The first broad category of thermionic converters are vacuum filled. These converters maintain a high vacuum on

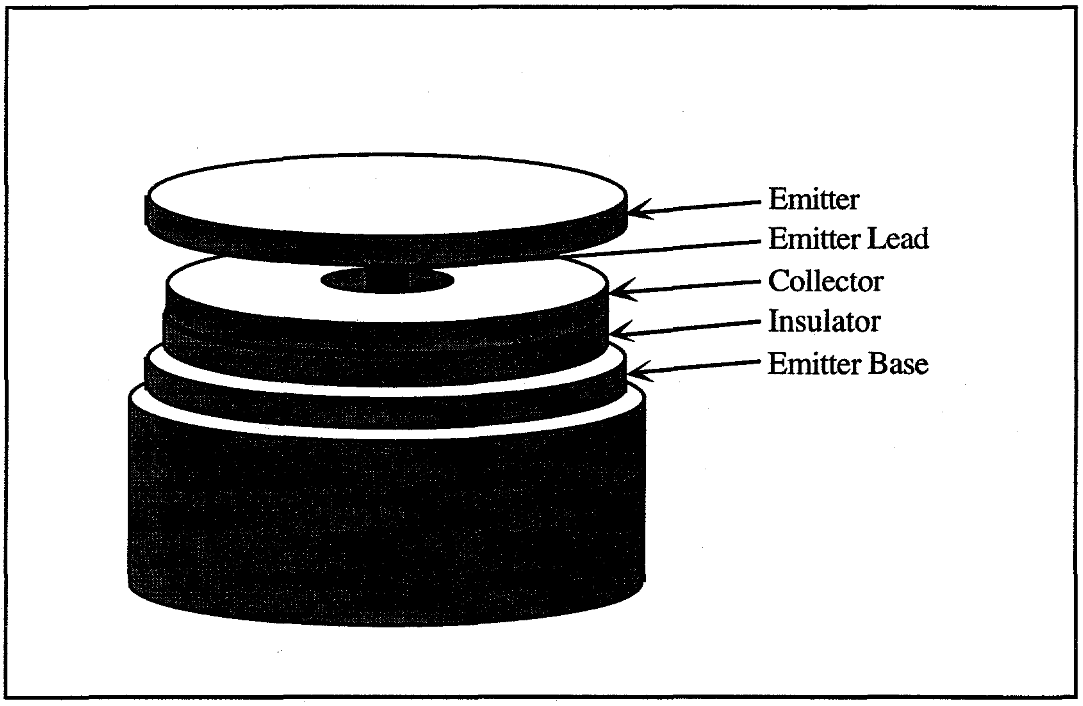

Figure 3. An example design of a close-spaced thermionic converter. (SAVTEC design by Lutch)

the interspacial gap and counter the space charge effect by controlling the gap size, the overall electric field within the gap or some combination of both.

Since the space charge effect depends directly on the number density of the electrons, one solution is too limit the number density of electrons. This can be done by using a very closed-spaced converter, e.g. less than one milli-inch separation between emitter and collector (Dic83, Fit93 and Nyr84). This has been accomplished to some extent by making use of the difference in materials coefficient of thermal expansion.

In close spaced converters, the spacing between the emitter and collector is maintained by the difference in thermal expansion of the two materials. As the support structure for either the emitter or the collector is heated up to operating temperatures, the thermal expansion of the material provides the spacing between the emitter and collector. However, it is a very difficult engineering task to maintain such an extremely close spacing at high operating temperatures without warping the surfaces involved causing short circuiting (see Figure 3). Practical converters of this type are typically half an inch in diameter.

A second method of reducing the space charge is to modify the electric field within the interelectrode gap. This can be accomplished by applying either an external magnetic or electric field. However, this adds to the system complexity by adding new sub-systems. This field is often generated by adding a third diode to the cell. Even if this is unnecessary, the amount of energy that is needed to create the field can have an adverse effect on the overall system efficiency.

Plasma Converters

The second category of converters are those in which the interelectrode gap is filled with a gas or vapor. The difference is that a vapor filled system derives the interelectrode material from the partial vapor pressure over a liquid or compound reservoir. A gas filled system derives the material from an external fully gaseous source.

This vapor or gaseous (from here forward referred to only as vapor) interelectrode material is then ionized, producing a positive field to counter the negative field of the space charge effect. In a vapor filled system these ions are produced either by surface ionization or volume ionization. Surface ionization occurs by a process similar to electron emission. This process can occur at either the cathode, the anode or an auxiliary electrode. Volume ionization is the production by inelastic collisions between free electrons and atoms within the volume. Though it is apparent that both surface and volume ionization will occur to some degree at all times, one effect is usually more dominant.

When ion production occurs mainly through surface ionization, the converter is said to be operating in the unignited, or extinguished, mode. If ion production is mainly by collisions within the volume, the converter is said to be operating in the ignited mode. A third method of ion generation is available whereby a high voltage arc is produced by an external source across the interelectrode gap. This creates a pulse of ions and the converter is said to be operating in a pulsed mode.

During operation the vapor filled system reaches an equilibrium plasma state where the conditions within gap are self regulating. If the balance of ions and electrons begins to shift towards ions, a positive electric field is felt by the emitter allowing a higher emission of electrons. If the balance shifts towards a higher density of electrons, the field becomes more negative and retards the emission of electrons. Local imbalances within the field are minimized due to the high mobility of the electrons in comparison to the ions.

The transition from the unignited mode to the ignited mode of operation is characterized by a steep drop in voltage followed by a sudden jump in current and voltage (see Figure 4). However, notice the overall higher voltage of the unignited mode over the ignited. Surface ionization is a thermal effect. Thus, the production of ions by surface ionization is only limited by the thermal energy available. As the thermal energy available also produces electrons, and produces them at a higher rate, the unignited mode eventually

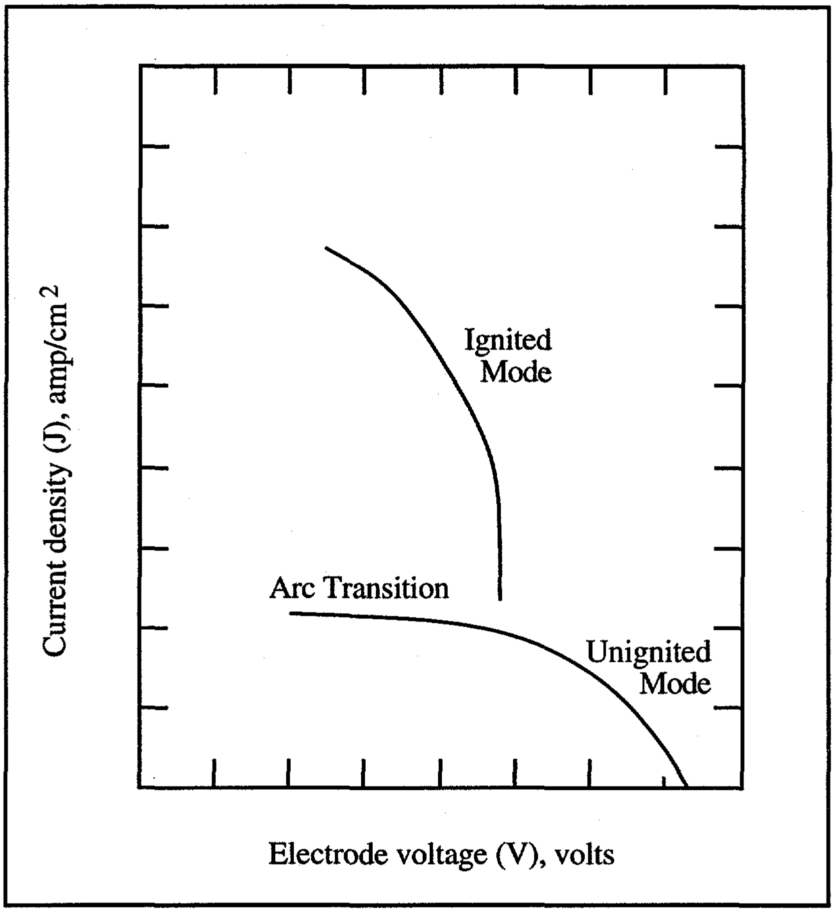

Figure 4. Unignited to ignited mode transition.

reaches a saturation level where the space charge effect again dominates.

However, as the density of the electrons increase within the gap, volume ionization begins to produce more ions. This is seen as a voltage drop as the electrons traversing the gap give up energy to the ionization process. As more of the electron motive is used for producing ions, a critical point is reached where the system becomes unbalanced. The converter "ignites" as the current from the emitter increases dramatically to balance the higher number of ions.

Once the converter has reached the ignited mode, it no longer takes as much energy to maintain the number density of ions and the system voltage is seen to increase. This energy can then be traded between ion production for higher currents or system voltage for powering external loads. Therefore, the current and voltage must be balanced to achieve an optimum operating condition.

Ultra-High Temperature Converters

Traditionally, the ignited mode of operation has been the mainstay of thermionic power conversion technology. However, recent advances in materials have seen operation of converters at high and ultra-high temperatures where surface ionization becomes more effective at space charge neutralization. This is due to the temperature squared dependence (see the Richardson-Dushmann equation in the basic cell section) of ion or electron emission from the surface.

This mode of operation, at ultra-high temperature, is also known as Knudsen operating mode. Its primary advantage over the ignited mode is that the electrons traverse the gap in direct flight. This saves approximately one-half of a volt of potential which is necessary to maintain volume ionization in the ignited mode of operation (Bab90). Thus, system efficiencies are much closer to the Carnot limitation for energy conversion at operating temperatures. In practical operations, this can represent an efficiency gain from 10-15% for ignited mode to 20-30% for Knudsen operating mode or possibly more. Issues concerning the Knudsen operating mode are discussed further in End88, End94, Kuz88 and Mor86a.

Heat Source

The next concern that must be addressed before material selection can begin is what heat source is being used. Thermionic systems have been proposed for use with combustion heat sources, solar concentrators, radioisotope thermal generators (RTGs) and nuclear fission reactors. Each involves a different set of system concerns which have a pronounced effect on material selection due to the unique engineering problems that must be solved. This section will set down the general problems faced by each type of system but defer discussion of the solutions until the next section.

Combustion systems face the hostile environment of open air, flame-fired combustion. The whole system, particularly the emitter, must be protected from the corrosive nature of the combustion gases and particles. As with solar thermionic systems, heat distribution is a design task. In this case, it is necessary to effectively spread a concentrated flame over the feed area of the emitter.

Solar powered thermionics is focused around the study of solar concentrators and thermal cavities. The primary advantage is the unlimited supply of free, weightless fuel, i.e. solar radiation. However, it has a number of disadvantages including the availability of solar radiation, due to distance or shadow effects, the necessity to concentrate the collected radiation and the non-uniformity of the focused radiation delivered to the solar thermal cavity.

Radioisotope thermal generators (RTGs) are the easiest heat source to incorporate into the thermionic system. They provide a very constant heat flow, both in uniformity of distribution and in temperature, with minimal side effects. The only disadvantage to RTGs is the lack of readily available material. This leads to a high fuel cost which prohibits large systems of this type.

The nuclear fission thermionic reactor system has been the subject of the majority of research to date. This is mainly due to thermionics strong ties with space power systems. Nuclear fission reactors are able to produce high power densities for extended times with minimal fuel and continuous heat source availability. The system is also able to operate in almost any location. The disadvantages of the nuclear fission heat source are the radiation effects, the non-uniformity of the distribution and the material compatibility issues.

Materials

There is no inherent limit on the production of energy from a thermionic energy conversion process. The limitations on lifetime come from the inability of materials to maintain their properties under the operating conditions required. The primary consideration in the selection of materials is the necessity to maintain thermionic emission properties as well as structural integrity over a finite lifetime. Again, it should be noted that the each class of converters--vacuum or vapor; solar, RTG, combustion, or nuclear; high temperature, ultra-high temperature, diode, triode, pulsed, etc.--have both unique and common concerns.

Vacuum Converters

Vacuum thermionic converters greatest challenge is to balance electron production against space charge limitations. There are three key elements necessary to achieve this goal. These include proper control over the work functions, maintaining the interelectrode gap distance and controlling the mass transfer between the collector and emitter.

The work functions of the emitter(ϕ_e) and collector(ϕ_c) are integral within a very non-linear system which dictates the power output. The balance must be struck between voltage and amperage produced. In doing this it is necessary to balance three goals: maximize the emitter thermionic electron emission by minimizing ϕ_e, minimize the collector thermionic electron emission by maximizing ϕ_c and maximize the system voltage by maximizing the difference $\phi_e - \phi_c$. More information on surface work functions can be found in references Aga90, Che80, Cho93, Cul90, Dan80, Dav80, DCr93c, Des90, Des92, Fom66, Gor90a, Gor90b, Gub88, Gun80, Jas80, Kal92, Ken90, Kor90b, Kor90c, Kor92, Kuz90, Lee94, Mag94, Ram87a, Ram87b, Ras64, Ras92, Sav90, Sen89, Smi84, Sto80, Tru88, Viz90, Wal90, Wol83, Yar92b and Yas90.

The interelectrode gap spacing is a struggle to maintain structural integrity. Cycling within a thermionic system can produce changes in temperatures of as much as 2000 K. This can produce extreme stresses on the materials if their thermal expansion properties are not well matched. Experiments to fabricate high strength emitters have been conducted by Amm89, Bol90, Dav90, DCr93b, Gro89, Luo93, Mor83, Mor84, Mor85, Mor88, Ran90b, Tit89 and Tsa90

Some of the innovative ways to maintain this small spacing (on the order of a few to several hundred micrometers) include rigid structures, ceramic spacers and floating gaps. Rigid structures approach the problem in a brute force manner. However, this often leads to warping of the emitter or collector due to the high induced stresses. Ceramic spacers encounter similar problems in that they are a brute force method. One of the failure modes induced by the this method is shorting due to the turning up of a small sliver of either emitter or collector material which then bridges the gap. Floating gaps are designed to minimize stresses at operating temperatures by designing around the thermal expansion properties of the various materials. In this way, high stress is only a problem during temperature cycling. Other novel ideas to reduce space charge within the interelectrode gap are discussed in Fit90, Lee90, Lun88, Mai83 and Zhe90a.

The most subtle issue which must be addressed is mass transfer (Kor90d, Lub90 and Pon93). This effect is primarily due to the vapor pressure of materials at high temperatures. Though these vapor pressures are relatively small, over significant lifetimes there is often a significant mass migration of material from the emitter across the gap. This material slowly coats the surface of the collector. As the effective collector work function increases, the typical effect is a decrease in overall system performance.

With the previous discussion in mind, tungsten and rhenium have become the emitter materials of choice. Both have suitable work functions which can be optimized through grain orientation or doping. They have high creep resistance, high melting temperatures and low vapor pressures. Most other promising candidates lack either the creep resistance or low vapor pressure which are essential to long life converters. Collector materials operate at much lower temperatures and stresses and are therefore usually chosen more to match a specific work function. As such, the options are many and varied.

Plasma Converters

Vapor filled thermionic converters balance the same factors as vacuum converters but with the added reduction in the space charge effect by ionizing a gas within the interelectrode space. This involves several changes to the system. The surface work functions are changed due to partial coverage by the vapor. The space charge effect is reduced through ion interactions lessening the need for such close interelectrode gap spacing. Chemical compatibility becomes a concern for all materials which border the interelectrode space.

The vapor ions undergo a process of deposition and ionization from both surfaces. As more ions are deposited on a surface, the effective work function of that surface shifts towards the work function of the vapor material. By understanding the processes involved it is possible to compute a surface coverage and an effective surface work function. With proper optimization this effect can be used to tune the work functions to more precisely control the thermionic processes.

The introduction of ions into the interelectrode gap gives greater flexibility in the gap spacing. The reduction in space charge produces wider gaps at the same emission levels or higher electron emission at the same spacing as with vacuum systems. This gives an additional parameter which can be used when designing the system. Wider gaps mean less problems due to warping of emitter or collector components and extension of component lifetimes. Maintaining the same tolerances gives higher performance which reduces system and fuel inventory size.

Material chemical compatibility becomes an issue because cesium is the material of choice for plasma converters. Cesium has the lowest ionization potential of any element. This is balanced by the fact that this leads to a high chemical potential which makes cesium corrosive to most other elements. However, tungsten and most of the collector materials used are very resistant to corrosion by tungsten. The remaining materials surrounding the interelectrode gap can be specified such that this is not an issue.

The vapor pressure within a thermionic system must be closely controlled for optimal efficiency of the converter. In the case of ignited mode thermionics, this means maintaining from one to ten torr of cesium within the interelectrode gap. Ultra-high temperature Knudsen converters need less cesium but it must still be maintained at a few tenths of a torr.

The cesium vapor pressure is maintained by one of two reservoir types: an external liquid reservoir or an integral compound reservoir (see Figure 5). An external liquid reservoir can hold vast quantities of cesium such that closed or open loop cesium supply is possible. However, it requires

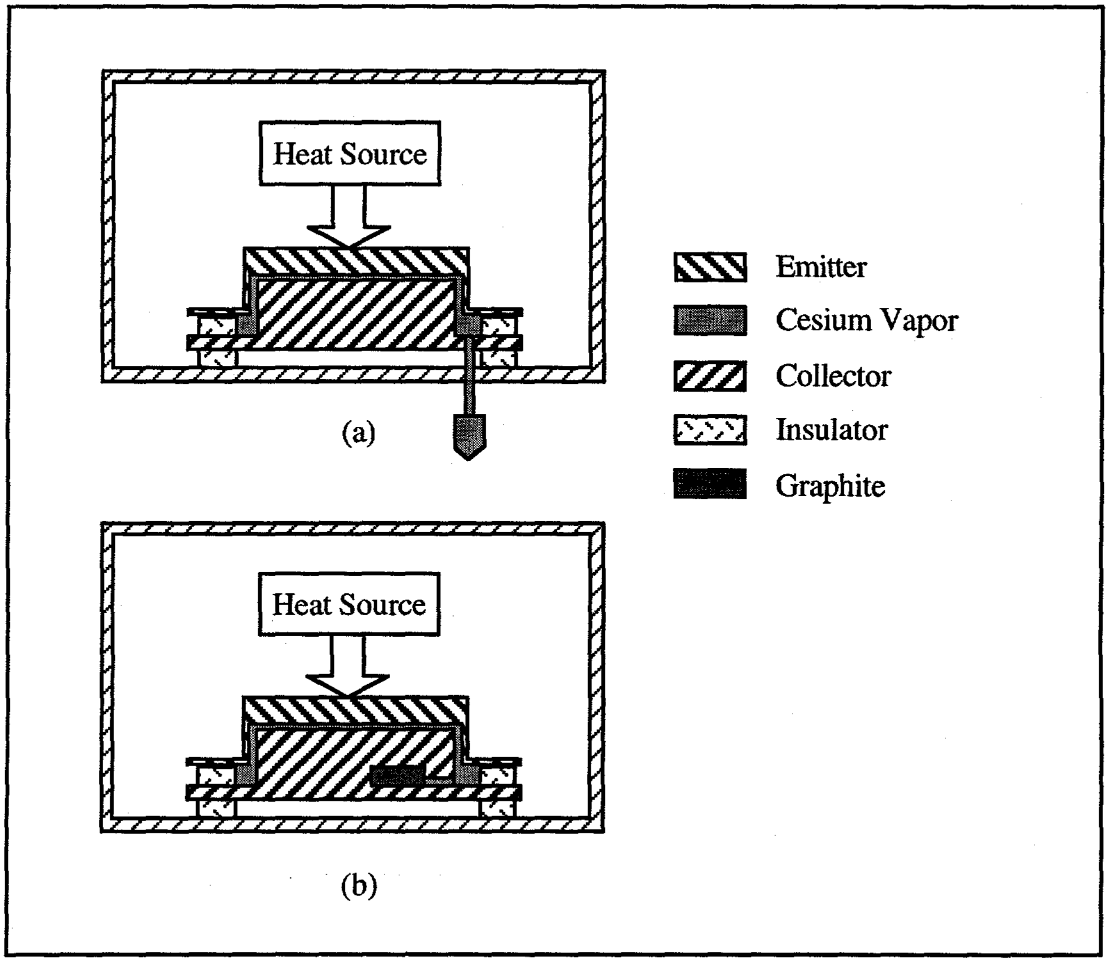

Figure 5. Two examples of cesium reservoirs: (a) an external, electrically heated liquid reservoir, and (b) an integral, conductively heated cesium-graphite compound reservoir.

many additions to the basic thermionic cell. An external tank must be provided along with the heaters and control system to see that it maintains the correct cesium pressure. An integral reservoir makes use of the cesium compounds Cs_xC_y which can control the cesium pressure by means of temperature and vapor pressure. The disadvantage to this system is it must be closed loop and it does not provide a large cesium reservoir in case of leakage from the interelectrode gap.

Another vapor material that should be mentioned is barium. There have recently been a number of studies using barium in addition to cesium within the interelectrode gap. This has a two-fold effect. The first is better control over the emitter and collector work function due to better control over the deposition of cesium and barium on the materials. The second effect is better ion retention within the interelectrode gap due to the reduced mobility of the ions by collision with barium atoms. The critical issues related to vapor control systems and their effect on the system are discussed in DCr93a, Kal89, Mis94, Ras90, Sin93, Smi90, Uso93b, Vel92 and Wit93.

Combustion Converters

A thermionic combustor must isolate the converter from the corrosive gases of a combustion atmosphere while maintaining a heat conduction path to the emitter. This has led to the construction of a hot shell which encloses the thermionic conversion unit. These are normally constructed

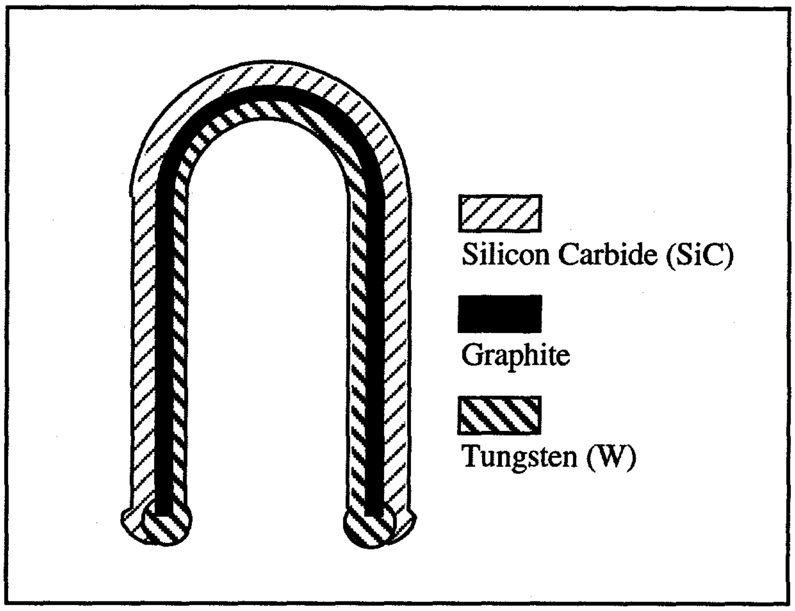

Figure 6. Cross-sectional view of a SiC/Graphite/W "Hot Shell".

in either a hemispherical or torispherical geometry to match the geometry of the normal burner which they will replace, hence the name thermionic combustor.

The outer layer of the hot shell must be very resistant to corrosion from the combustion gases. Early experiments used superalloys to form the outer layer of the shell (Gub86). They were bonded to the emitter either by brazing or explosive bonding. However, the difference in thermal expansion coefficients often causes separation of the layers. Additionally, above 1500 K transport of hydrogen and other trace elements to the emitter occurs causing changes in thermionic emission properties.

The solution has been to use chemical vapor deposition (CVD) techniques to form a trilayer shell. A graphite shell about 40 to 50 mils thick is machined (see Figure 6). This provides a solid base for structural properties. The emitter material, usually tungsten or a tungsten-rhenium compound, is deposited (10 to 15 mils thick) onto the inner surface to form the emitter. Silicon carbide is then deposited to form the outer layer (10 to 15 mils thick). Prototype combustors of this type have been successfully tested for over 5000 hours with negligible transfer of elements past the silicon carbide layer (Goo80, Goo81 and Hen80).

The other concern for combustion thermionics is proper heat distribution to the emitter. The long lifetimes so far have come from one inch diameter converters. Heat conduction within the shell and emitter of these smaller converters is such that the emitter temperature remains near uniform. Additionally, the stresses to the collector and emitter are of lesser concern for smaller diameter converters. Both emitter/collector deformation failure and performance loss due to non-uniformity of emitter temperature are issues for larger diameter converters. However, these concerns can be overcome to a degree by careful design to control heat distribution and stress within the converter.

A final area of concern within thermionic combustors is the ceramic to metal seal at the insulator. Typically aluminum oxide has been used as the insulating material. This insulator usually plays a key role in maintaining the spacing between the emitter and collector. As such, it is important to maintain the brazed seal between the metal and ceramic to insure that failure due to shorting does not occur. This is a fabrication issue which has not been discussed in detail within the thermionic research community.

Solar Converters

The greatest challenge in solar energy thermionic converters is the proper concentration and distribution of the solar energy flux. Typical values of solar flux are on the order of tenths of a watt per square centimeter. Therefore a theoretical 100 kWe system with an overall efficiency of 10% needs roughly 7 million square centimeters (that is a three meter diameter mirror) of collector area.

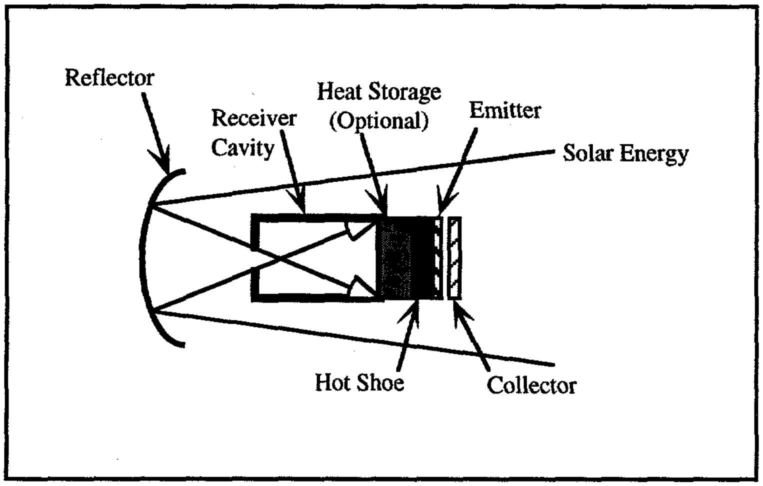

Figure 7. Schematic of a solar thermionic power system.

The process of focusing and distributing solar energy has been studied intensively but few experiments directly involving thermionics have been done. The two broad approaches to focusing the energy are reflectors and lenses. Each has advantages and disadvantages in weight, size, structural integrity and focal ability. Practical efficiencies for collecting and focusing the solar flux range from 80 to 95%. Distribution of the focused beam is done by the receiver.

The receiver for a solar thermionic conversion unit is typically a cavity with a small aperture opening. The focus of the beam is usually set to coincide with the aperture such that the opening is as small as possible. This is important to minimize the back radiation and thus energy losses from the cavity. The design of the cavity (its shape) and its subsequent integration with the converter is an area still open for new innovations. Proposed designs include concepts from multiple cavities each with their own thermionic converter which is heated directly by the focused beam to large cavities lined with thermionic converters heated by secondary radiation within the cavity.

Solar thermionics also suffer from the disadvantage of a source which is not constant. For a variety of reasons, solar radiation is usually available only for certain periods of a cycle. For example, a converter may receive energy for 60 minutes of every 90 minute orbit or for 12 hours of the day. This can lead to thermal cycling which causes stress and may deform the active converter area causing a short. Additionally, it also creates times when no power is available unless it was stored.

Two options exist to solve the thermal cycling and need for constant energy problem. The first option is to attach a thermal reservoir between the receiver and the emitter. This can be done by taking advantage of the high latent heat stored during a phase transition of a material. The material is chosen such that the transition temperature is just above the desired operating temperature of the converter. The other option is to design the converter to withstand the expected deformations and store the electrical energy produced.

RTG Converters

Radioisotope thermal generators are the easiest heat source to integrate into a thermionic conversion unit. RTG heat sources can be integrated easily into planar or cylindrical converter desings. The only concern in integrating the heat source is chemical compatibility between the heat source and the emitter. This can be solved by putting a cladding material between them, e.g. creating a cylindrical converter with space for a replaceable RTG heat source in a thermionic battery. Radiation effects from the RTG on the converter are negligible.

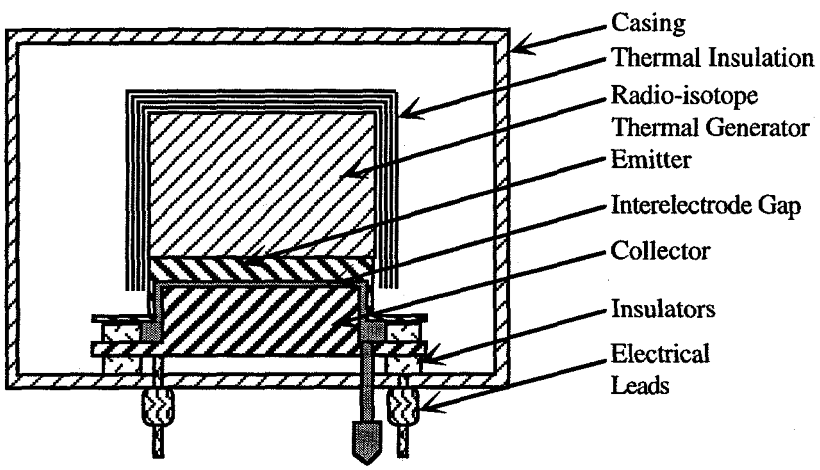

Figure 8. An example of a conductively-coupled radioisotope thermal generator thermionic power system.

Nuclear Fission Reactor Converters

Thermionic converters can be integrated into nuclear fission reactors either within the core (in-core) or external to the core (ex-core). In-core thermionics are cylindrical in design such that the emitter, collector and other converter components are built around the fuel rod. This type of design is known as a thermionic fuel element (TFE). Ex-core thermionic converters are located outside the core boundary and are either radiatively or conductively coupled to the core.

In-Core Thermionic Fuel Elements

Thermionic fuel element reactors present a number of unique problems. These issues center around chemical, thermal and nuclear compatibility with the fuel. The issues directly effect the converter performance and are the limiting factor for the lifetime of the TFE. There have been a number of excellent studies on the life limiting factors for TFEs including Beg84, Bog90a, Can89, Dun85, Fit86, Gon90c, Gon93, Hol72, Hol84, Hou94, Men90, Nik90a, Gen94, Sam87, Sam89, Sam90, Tsa93, Vec89, Yan72.

A thermionic fuel element is built around the fuel rod. The first step is to clad the fuel with a layer (a few tens of mils) of the emitter material. This imposes the requirement that the two materials be chemically and thermally compatible.

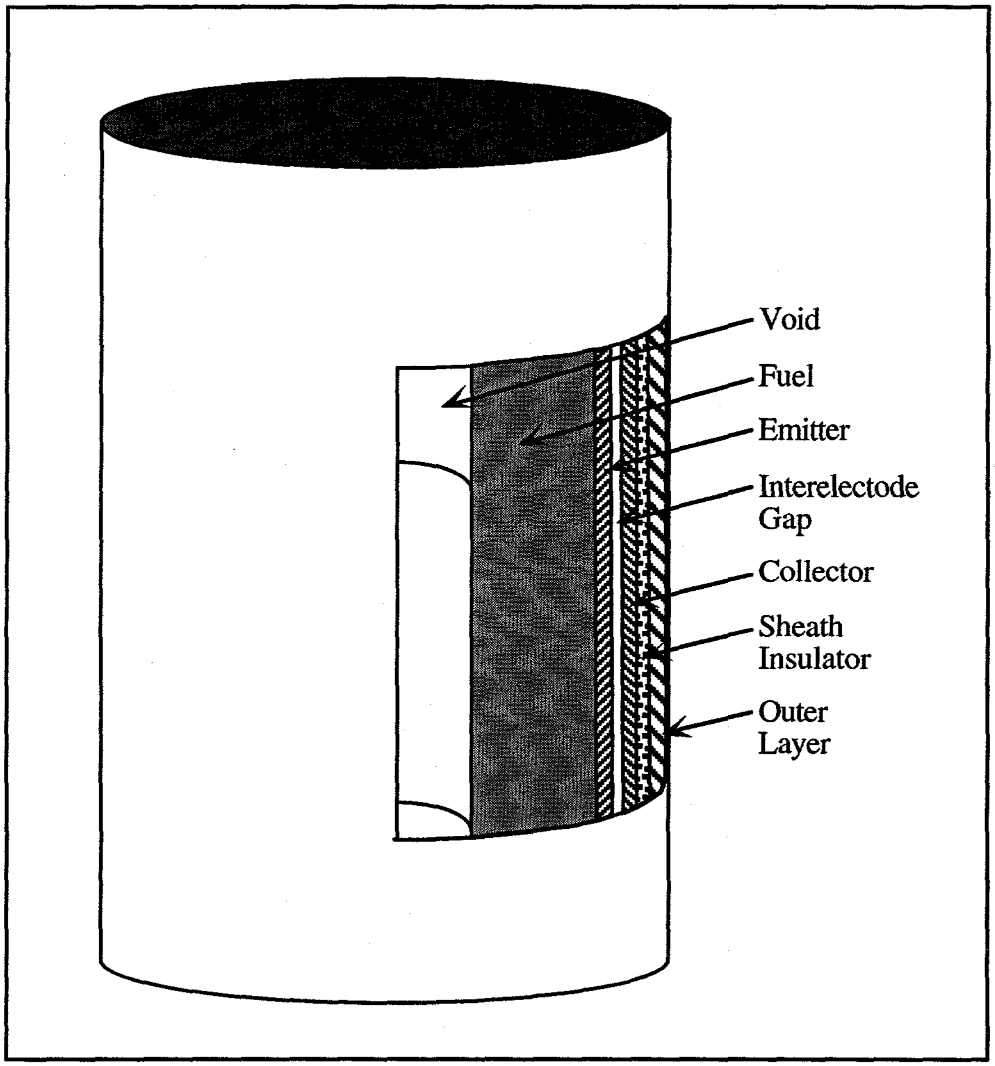

Figure 9. Cut-away view of a section of a thermionic fuel element (TFE).

Chemical compatibility is important for two main reasons. Mass migration from the fuel to the emitter can lead to performance losses due to work function changes in the emitter material. Also, the introduction of other elements to the emitter material can lessen the structural integrity of the emitter leading to deformation and possible shorting. Analysis of various fuel and emitter compatibilities has been made by Deg90a, Gon90a, Gon94, Kaz90, Kuc90b, Lan90, Lun86, Nik90b and Plo90.

Thermal effects include effects caused by differences in thermal expansion and conduction. A high variation in thermal expansion coefficients can cause the emitter to peel away from the fuel. This can cause emitter deformation either directly from stresses created as the fuel expands or from "thermal ratcheting." Thermal ratcheting is caused by variations in the axial temperature distribution causing fuel to redeposit (the fuel typically operates in regimes where the vapor pressure is significant) in the warmer central region. During thermal cycling this can cause significant stress on the emitter cladding. Deformation and subsequent shorting of the converter can result.

Fuel swelling and the bladder effect can also cause emitter deformation. Fuel swelling occurs due to the build-up of fission products within the fuel over time (Beg90 and Deg90b). This increase in total volume of the fuel must be planned for in the design. The bladder effect is due to the fission product gas pressure. A number of the fission

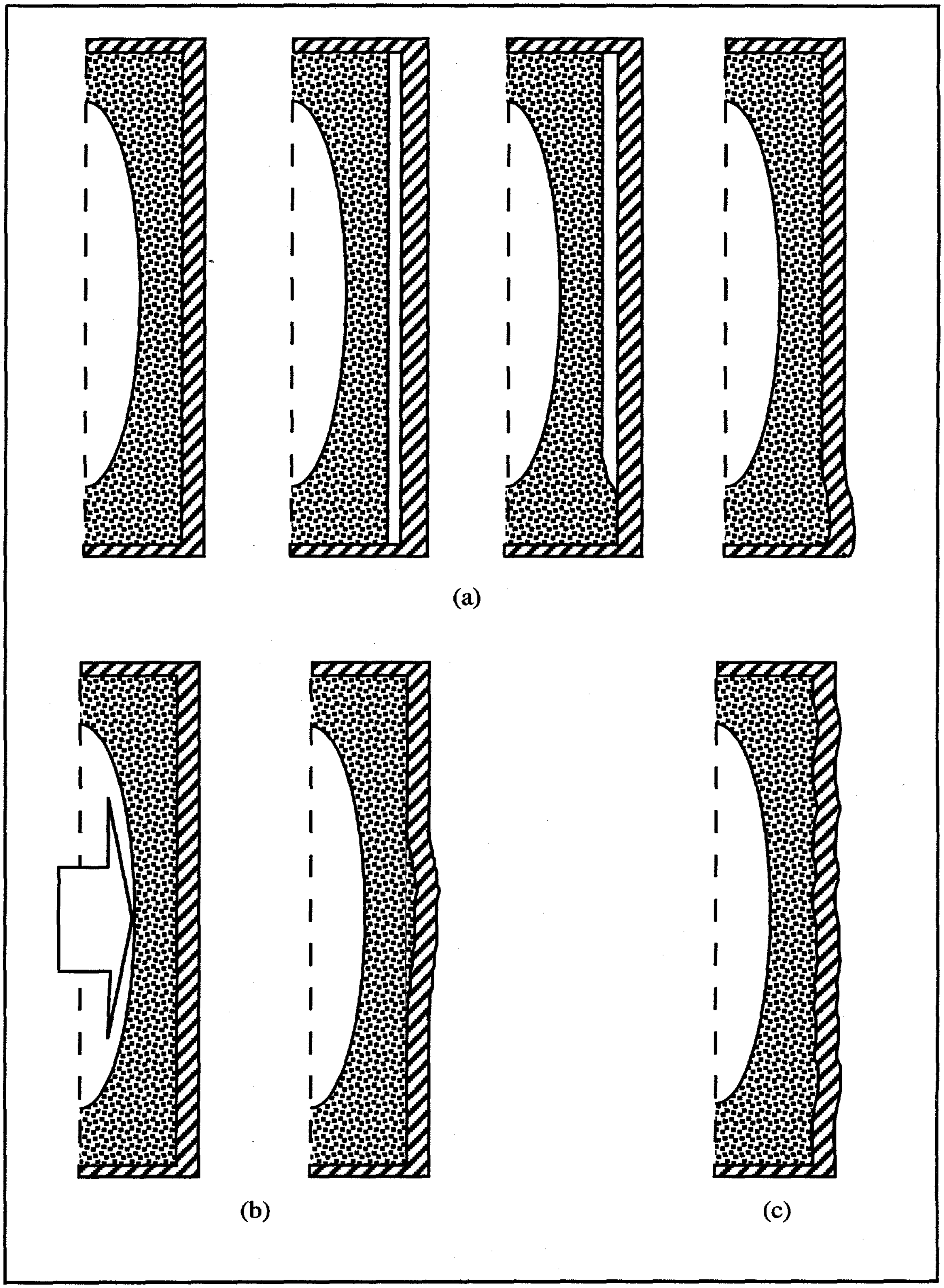

Figure 10. TFE deformation due to fuel interaction occurs by three primary methods: (a) thermal ratcheting, (b) ballooning, and (c) fuel swelling.

products produced are gaseous and if they do not have a way to easily migrate out of the fuel region area, they can produce tremendous radial pressure on the fuel. Two methods have been suggested to counter this problem. The first controls the porosity of the fuel and the second alleviates the pressure by using a snorkel to vent the gases.

Thermal conduction within the fuel also affects the converter performance. The thermionic process is best optimized when the emitter has a uniform temperature distribution. It is therefore important to flatten the axial power distribution or provide enough thermal conduction to achieve the same effect.

Another crucial nuclear related issue is that of reactivity (the measure of how long a nuclear fission reactor can produce heat). By introducing the thermionic converter into the core area, the fuel volume fraction has been decreased. Additionally, materials which may be strong neutron absorbers have been introduced into the core. This creates a decrease in the reactivity available for lifetime or power distribution flattening which may be countered by an increase in the fuel inventory.

An operating nuclear reactor core is a hostile environment for materials. The effects of neutron bombardment on many materials include loss of structural integrity and changes in electrical properties. Due to the close tolerances demanded by the thermionic conversion process, the key structural materials should be insensitive to neutron embrittlement. Maintaining the electrical resistance of the insulators within the system is vital.

There are two main insulators in a thermionic fuel element: the insulator sheath and the insulator seal (Bri85, Fed93, Ser90a, Smi80, Tra90, Uso93a, Vas91 and Wu94). The sheath insulator separates the collector from the rest of the system. It is under a maximum 2000 volt per centimeter electric field (approximately 50 volts of potential on a few tenths of a millimeter of material). The moderately high electric field and the very high operating temperature combine to make electrolysis a concern for degradation of insulator performance.

The insulator seal serves to isolate the emitter and collector and in some designs functions as a structural support member. It sees on the order of one volt of potential and thus does not suffer from any electrolysis effects. However, both insulators are also subjected to a high fast neutron fluence.

The insulators also suffer volumetric swelling effects due to neutron bombardment. Aluminum oxide has been the standard insulator in thermionic converters but it suffers from neutron induced swelling. Yttria oxide is radiation resistant but suffers from electrolysis degradation. Recent studies have shown that yttria aluminum garnet or YAG ($Y_3Al_5O_{12}$) has shown promise at minimizing both of these effects. However, most converters continue to use aluminum oxide matched with niobium collectors (they have similar

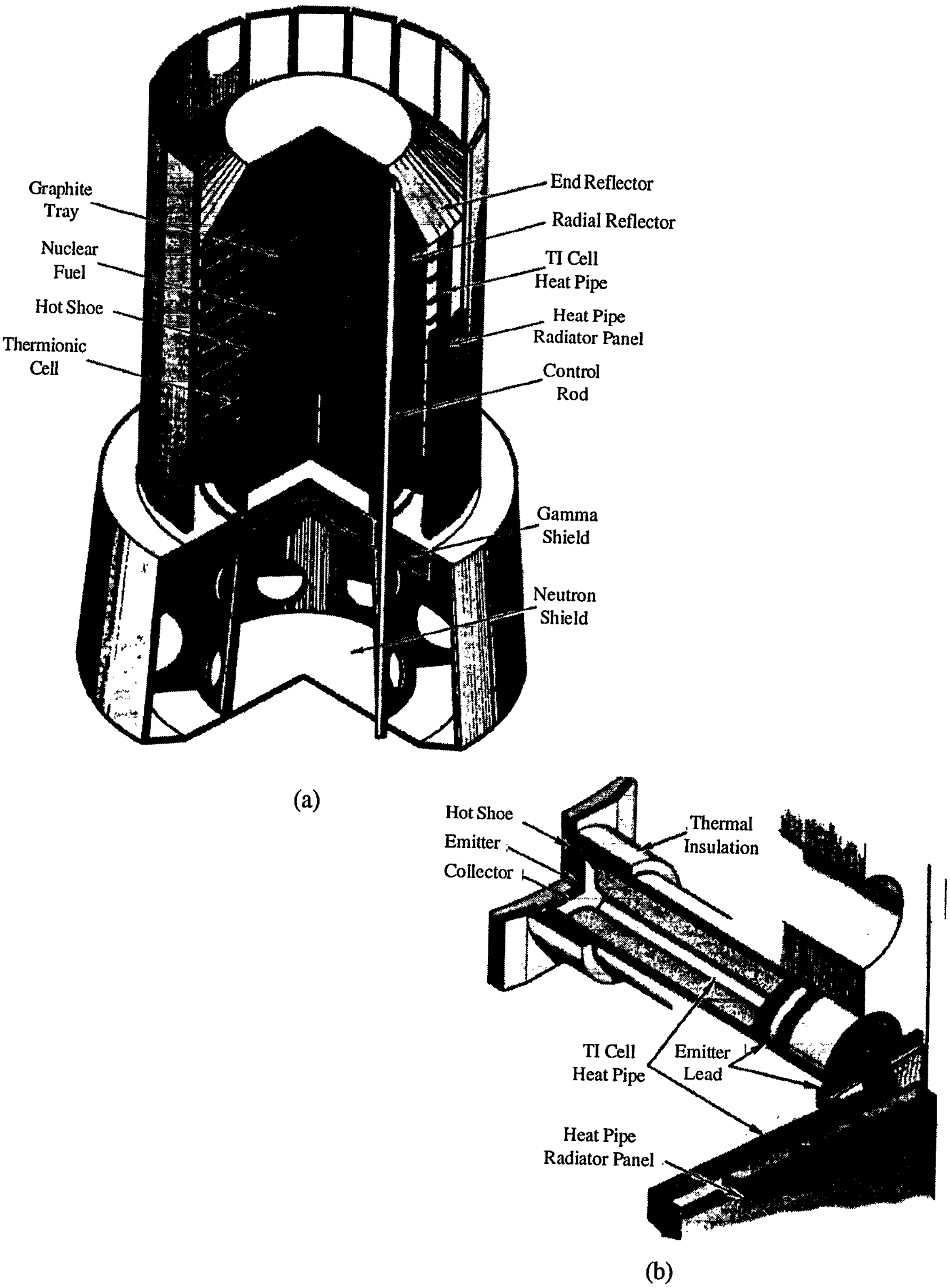

Figure 11. An example of a radiatively-coupled, ex-core thermionic power system. (STAR-C design by General Atomics Technologies)

expansion characteristics) and design around the expected degradation.

Uranium dioxide, tungsten, niobium and aluminum oxide have proven to be an effective and workable set of materials in TFEs. There is no material transfer from the fuel to the emitter. Tungsten and niobium provide good work functions in a low pressure cesium vapor atmosphere. The thermal expansion coefficients are within acceptable ranges and the poor thermal conductivity of uranium dioxide can be circumvented by flattening the power distribution. Other materials and designs may prove valuable in future TFE converters but these have and can provide near term solutions.

<u>Ex-Core Thermionic Fuel Elements</u>

Ex-core thermionic reactor systems are similar to in-core systems except that they do not suffer from the fuel related compatibility issues (Jen94, Roc93 and Tha94b). One important gain for ex-core systems is that the radiation induced problems are similar to in-core systems but at a much reduced level. The new challenge for ex-core systems is moving the heat from the core to the converters.

Several options exist for transferring the heat from the core to the converters. Sodium potassium (NaK) coolant loop systems are the easiest conceptualize. Heat pipe thermionic reactors function in a similar manner but make use of the low temperature drop across the heat pipes. These are both conductively coupled systems. A radiatively coupled system has been proposed using graphite trays to conduct the heat radially outward from the center of the core to the edges. The radiation from the core then heats a set of hot shoes which are conductively coupled to the thermionic emitters.

Power Conditioning

The final challenge in thermionic energy conversion is providing usable electric power. A typical single thermionic cell produces from a few to a few tens worth of current per square centimeter at half to one and a half volts. This high current, low voltage power source suffers high ohmic losses and is not immediately useful for most needs. It is therefore important to quickly convert this source into a more usable energy supply.

The most common method to convert the power coming out of the cells is too link them in a series-parallel fashion (McV81). Specifically, chains of converters are linked in series to provide a higher overall voltage. These chains are also cross-linked in parallel with each other to provide redundancy within the circuit in case of a short in one cell. However, this output is usually passed through another power conditioning unit to provide the final form of electricity for the system.

The pulsed thermionic systems offer two other solutions to the power conditioning problem (Ant93, McV90, Nik90c and Ras86). Pulsing the converters at a high enough rate results in a near continuous power supply that can be conditioned via the series-parallel method. However, the large currents are good candidates for an inductively coupled system. In this case, all the converters are linked to a common potential and each converter is linked to the output load through induction (i.e. a miniature transformer). By pulsing sets of converters at specified intervals with preset windings, an AC current of any arbitrary voltage can be produced directly.

APPLICATIONS OF TEC TECHNOLOGY

Now that all the components necessary for a working system have been discussed, the next step is to apply the solutions to specific applications. Two broad categories of application areas will be discussed: terrestrial and extraterrestrial. The discussion will focus on missions thermionic power systems could fulfill and the parameters inherent in performing those mission.

Terrestrial Applications

The major interest in terrestrial applications has been to make more efficient use of the high temperatures produced during combustion (Huf83, Kle92, Nik92, Nik94 and Nyr84). In particular, most industrial and power production facilities produce heat at much higher temperatures than they actual need. For these systems, thermionics represents a means to maximize system efficiency. The dual or combined thermionic system takes heat produced at high temperature as its input and returns electricity and heat at the appropriate lower temperature for further use within the system.

One of the areas this would be of great use is in combustion power production facilities (Dic80a, Dic84, Fit81a, Fit81b, Goo82b, Goo83, Goo84, Mis80, Mis81, Mis82, Mis83, Mis84 and Yar92a). In particular, gas turbine systems usually produce heat at over 2400 K but due to material limitations, the gas temperature at the turbine input must be below 1400 K. Coal fired and other power production facilities have similar limitations. Numerous studies have been conducted in this area showing that the overall system efficiency can be improved on the order of 2 to 10 percent.

These studies all make use of the thermionic combustor concept where the thermionics package is self-contained within the burner unit. The lower increases in efficiency, 2 to 5 percent, are typically older units where normal burners have been replaced with thermionic combustors. In these units, fuel savings justifies the conversion costs within one to three years. In combustion furnaces which are designed and optimized for thermionic combustors, the increase in overall system efficiency can be as much as 10 percent. The same type of results apply to approximately 60 percent of industry which use high temperature flue gases (greater than 800 K).

The other terrestrial area of interest is small or remote power systems. Many systems call for a small battery to supply low voltage, low current power for extended periods of time. These systems are a good match for a RTG thermionic unit with its small size and consistent, constant power output. Lifetimes on this type of low power system can be very long due to the low temperature regime and thus low stress on the thermionic conversion package. Remote power

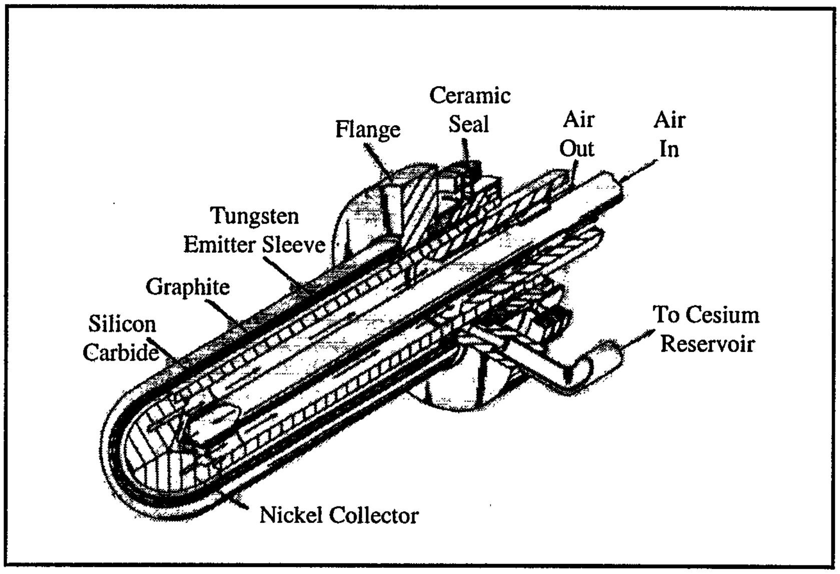

Figure 12. A hemispherical thermionic combustor with a silicon carbide hot shell.

systems are portable units where weight and lifetime are the key issues. The solution to these problems in the terrestrial environment is similar to the extraterrestrial concepts.

Extraterrestrial Applications

Space power systems require optimization for weight and size. The high cost per kilogram and the limited space available for boosting these systems into orbit or beyond determine the maximum power output available to the mission. Therefore, thermionic systems provide a number of advantages over other power systems (And91, Bri82, Fit73, Fit94, Huf82, Jos86, Ken88, Kir86, Mah81, Mor82, Sny86, Wet83, Wet85, Zha93 and Zub94).

These advantages include higher system performance, higher power density and higher waste heat temperature. For the equivalent electric output, high system performance reduces the need for input heat energy. This translates to smaller collectors for solar systems, less material needed for a RTG or a smaller fuel inventory for a fission reactor. The higher power density produces similar reductions in size and weight. However, the higher waste heat rejection temperature is the most important advantage.

The only means to reject waste heat in space is radiation. Because heat loss by radiation is proportional to the fourth power of the temperature, it is important for the thermal cycle to have as high a heat sink temperature as possible. Thermionics fulfills this requirement with collector temperatures that can be optimized in the range from 800 to 1400 K. This vastly reduces the size of the radiator, which has traditionally been one of the largest subsystems in weight and size.

Thermionic space power systems can be effective at low power outputs but excel at higher levels. Solar and RTG powered thermionics are capable of producing power systems in the watts to kilowatts regime but this area has been traditionally covered by photovoltaics or thermoelectric systems. These technologies have produced mature, proven systems which have been in operational use since the 1960s. However these systems are limited in their scalability to the power production regime of below the megawatt regime. Additionally, thermionic systems are comparable or better beginning at the power production level of tens of kilowatts and above.

Thermionic fuel element reactors have been extensively studied due to their compactness and ability to produce high power output. Reactors are inherently compact due to the high power density available from nuclear fuel. Integrating the power conversion package into the core (i.e. through TFEs) helps further minimize the overall size of the system. It does this by minimizing the space used for power conversion and by making better use of the available heat through direct coupling to the fuel. The high power output is a product of the high heat source temperatures available from nuclear fission and the high efficiencies and power density this generates in thermionic conversion.

Thermionic power systems are therefore the best choice for missions which require a high electric power output. These applications include direct broadcast and telecommunications satellites which can provide larger coverage areas with smaller receiver options. More power can be distributed over a larger bandwidth for faster or more detailed communications. Weather and reconnecience satellites can use more powerful radar imaging systems to provide greater image resolution. With the addition of electric propulsion thrusters, satellites can be quickly and efficiently placed in new orbits including fast transitions from low earth orbit (LEO) to geosychronous earth orbit (GEO).

The main motivation behind high power space systems during the 1980s was the desire for a spaced based defense system. The concept called for megawatt power supplies capable of burst power an order of magnitude higher. This systems would be capable of tracking inter-continental ballistic missiles and disabling them through the use of either a laser or particle beam.

Other missions include space exploration and habitats. Space exploration satellites will benefit from thermionic power systems for all the same reasons as earth bound satellites. In addition, nuclear fission power sources enable high power satellites enable longer and more in depth missions for the exploration of the outer solar system. Future space stations and lunar or Mars bases will need large power supply systems which again are ideal candidates for thermionic power conversion. Overall, any system which can benefit from higher available electric power is a possible mission for a thermionic conversion system.

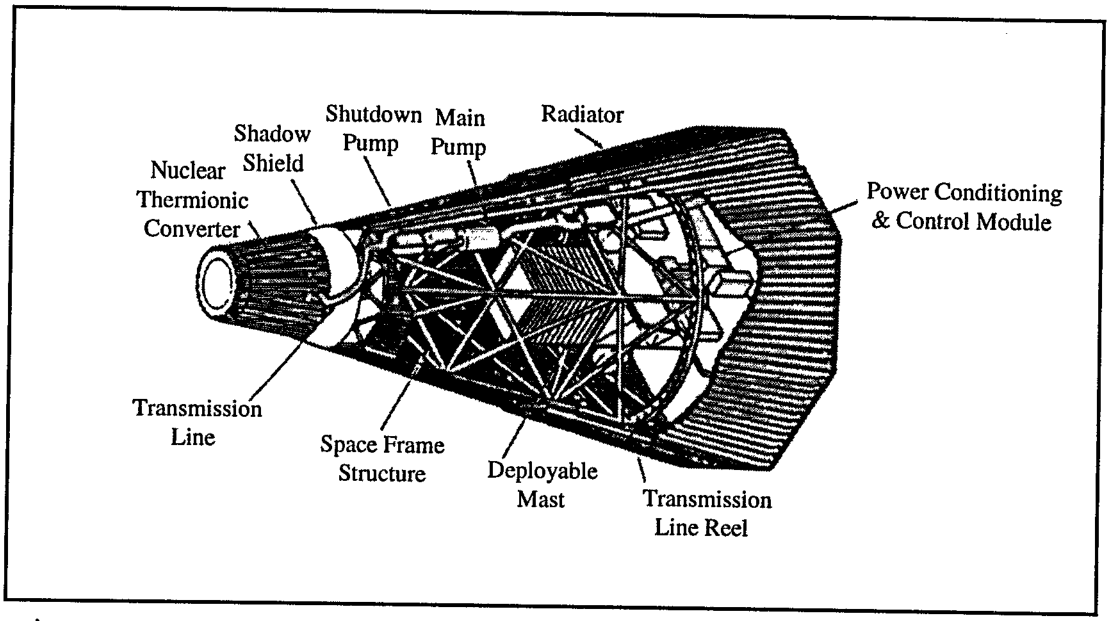

Figure 13. An example of a deployable space nuclear power system. (Courtesy of General Atomics Technologies)

CURRENT AND FUTURE DIRECTIONS IN THERMIONIC RESEARCH

With the end of the cold war in the early 1990s, congress and the executive office began rethinking and restructuring the research and development goals for the country. As with the shift in orientation during the 1970s, this one brought about the ending of many projects before they completed their full proposals. Thermionic research has been tied in with government sponsored space power system research to such an extent that the overall health of this research community is dependent on government support.

Before the end of the major programs, thermionics was ready to show its potential through flight level testing. Specifically, all the engineering of the sub-systems for a complete thermionic system have been developed. Also, extensive research has been done for the next generation of thermionic converters. All of this technology is presently being converted into "off-the-shelf" concepts.

The "off-the-shelf" concept is to continue research at the component level. This basic research is cheaper and easier to fund than major programs. The goal is to create components that can be easily integrated into a system design. However, this whole concept overlooks the fact that system level design is often difficult and all the subcomponent research and validation is incomplete without system level data to prove system validity.

The integration of components into at least prototype systems should be a primary goal of future thermionic research. While the technology has been demonstrated to some degree by the TOPAZ program, the issues and difficulties of manufacturing and integrating an advanced system will remain unknown until such time as a prototype is constructed and tested. This goal will not be undertaken by the industrial community without government support due to the risk involved. However, with this done, thermionics can be put forth to the industrial community as an operational system capable of expanding space systems capabilities dramatically.

This should respark interest in the technology among the major industrial researchers. Within the program for testing a prototype system, a facility for system level testing will have to be constructed. This facility can then serve as a testbed for new concepts. In today's markets, ideas which are years down the road are taking a back seat to what is available now. Advanced nuclear power thermionic conversion systems are available today. Next generation converters are not far behind. Demonstration of these technologies at full scale within their specific mission applications could open up a whole new era of space exploration and commercial use.

It should be noted here that thermionic research has also produced or helped further several other technologies. Multi-foil insulation is commonly used in thermionic systems to shield parts of the system from the high emitter temperature. Chemical vapor deposition (CVD) is used for forming emitters with very precise grain structures. It has also been used for manufacturing trilayer hot shell technology for thermionic combustors and heat pipes for use in atmospheric conditions. The study of the thermionic emission process has lead to a better understanding of electron production for use in everything from free electron lasers to better electron beams for microscope or lithography purposes. On top of these, there is also the whole wealth of data which has been gathered on high temperature material properties.

CONCLUSIONS

The main purpose of this thesis is to show that the state of the art in thermionic research is a mature technology. The basic research necessary to develop and produce working thermionic system is available today. A space power system in the kilowatt to megawatt range of electric power production with a 7 to 10 year lifetime could be orbited within a few years. A full scale thermionic combustor system capable of giving up to 10 percent efficiency gains in numerous industrial processes could be running in as less than two years.

The next generation of thermionic conversion units are showing even higher performance. Recent results with cesium-barium vapor converters and Knudsen ultra-high temperature converters have shown the potential to have twice the efficiency of the units available today. In addition, since they are working at much higher temperatures, the corresponding output power density will be much higher (due to the output current density being proportional to the square of the operating temperature). It it these high power density options which make thermionics promising for future space missions where high power in a compact unit are vital.

However, the current research outlook within the thermionic community is in a downtrend. Thermionic power conversion's close association with space power systems has meant that the funding for the major research programs has been through national initiatives. These initiatives have all stopped short of their final flight phases.

For thermionics to really become a workable system, a full scale prototype must be demonstrated under flight conditions. The commercial use of these systems will not occur until (1) they show that they can meet the parameters and goals established for the different missions, (2) they are proven reliable, and (3) the political issues involved with launching a space-based nuclear power system are decided. To some degree, these first two issues have been addressed. However, without the third requirement, thermionics will remain only a novel concept. Until such time as the government takes the lead and sets in place the standards for such systems, thermionics cannot advance and the industry cannot begin to look at turning out commercially viable thermionic space power systems.

LIST OF REFERENCES

Aga90 Agafonov, V. R. & Yarygin, V. I., "Research of Thermionic Converter Emitter Properties in Model Experiments with Surface Control," Proc. 25th Intersoc. Energy Conv. Engr. Conf., 1990, vol. 2, pp. 322-325.

Agn94 Agnew, P., "Topaz-II Materials and Thermionics Research," Proc. 11th Symposium on Space Nucl. Power System, 1994, vol. 1, pp. 71-74.

Amm89 Ammon, R. L. & Buckman, R. W., "Fabrication of High Strength Tungsten Fiber-Reinforced High Conductivity Copper Composite for Application in Space Power Systems," Proc. 6th Symposium on Space Nucl. Power System, 1989, vol. 1, pp. 261-263.

And91 Andreev, P. V., Gryaznov, G. M., Zhabotinsky, E. E., Zaritsky, G. A., Nikonov, A. M. & Serbin, V. I., "The Conceptual Design and Main Characteristics of Long Lifetime Thermionic SNPS with Thermal Reactor," Proc. 8th Symposium on Space Nucl. Power System, 1991, vol. 1, pp. 367-372.

Ang76 Angrist, S. W., Direct Energy Conversion, Allyn and Bacon, Inc., Boston, 1976.

Ant93 Antonov, E. E., Korchevoy, Yu. P. & Podolukh, I. Ya., "Relaxation Characteristics of Cs-N2 TEC with Pulsed Ionization," Proc. 28th Intersoc. Energy Conv. Engr. Conf., 1993, vol. 1, pp. 1.511-1.516.

Bab90 Babanin, V. I., Ender, A. Ya., Kolyshkin, I. N., Kuznetsov, V. I. & Sitnov, V. I., "Aspects of the Knudsen Thermionic Converter," Proc. 7th Symposium on Space Nucl. Power System, 1990, vol. 1, pp. 97-102.

Bak78 Baksht, F. G., Dyuzhev, G. A., Martsinovskiy, A. M., Moyshes, B. Ya., Pikus, G. Ye., Sonin, E. B. & Yur'yev, V. G., Thermionic Converters and Low-Temperature Plasma, Technical Information Center/U.S. Department of Energy, 1978.

Bak90 Baksht, F. G. & Kostin, A. A., "Theory of Grid Controlled Elements," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Beg84 Begg, L. L., Wetch, J. R. & Nelin, C. J., "Thermionic Fuel Element Endurance Enhancement," Proc. 19th Intersoc. Energy Conv. Engr. Conf., 1984, vol. 4, pp. 2276-2281.

Beg90 Begg, L. L., Yevsikov, V. V. & Zheng, C., "Thermionic Fuel Clad/Emitter with Long Life Potential," Proc. 7th Symposium on Space Nucl. Power System, 1990, vol. 1, pp. 315-318.

Bel90 Belevtzev, A. V., Kumskoy, V. V. & Sviridenko, I. P., "The Heat and Electrotechnical Characteristics Investigation on Laboratory Models of Electrogenerating Elements for the Thermoemissional Converting Reactor 'TOPAZ'," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Bog90a Bogush, V. B., Borodastov, S. V., Devyatchenok, G. S., Leontev, V. V., Lekhachev, Y. I., Raskach, V. N. & Khmelevski, M. Ya., "Deformation Behaviour Modelling of the High Temperature Fueled Emitters," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Bog90b Bogush, V. B., Borodastov, S. V., Likhachev, Y. I., Raskach, V. N., Syshchikov, L. A., Khmelevski, M. Ya. & Chkauseli, V. F., "Deformation Analysis of Fueled Emitters from Multicell Electric Power-Generating Channels of the 'TOPAZ' Reactor," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Bog90c Bogush, V.B., Gryaznov, G. M., Zhabotinsky, E. E., Makarov, A. N., Serbin, V. I., Trukhanov, Yu. L. & Bologov, P. M., "The Main Principles of Design, Ground and Flight Tests of SNPS Within 'TOPAZ' Program," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Bog90d Bogush, V. B., Likhachev, Y. T. & Sheherbanova, G. N., "Stessed State Analysis of Collector Package of Multicell Electric Power-Generation Channel from 'TOPAZ' Reactor," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Bol90 Bolonkin, V. S., Vizgalov, A. V., Ruzhnikov, V. A., Sibir, E. E. & Sidelnikov, V. N., "Identification of Internal Parameters of the Experimental Thermionic Converter with Hexahedral Tungsten

Electrodes," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Bri82 Britt, E. J. & Fitzpatrick, G. O., "Direct Conversion Nuclear Reactor Space Power Systems," Proc. 17th Intersoc. Energy Conv. Engr. Conf., 1982, vol. 4, pp. 1894-1901.

Bri85 Britt, E. J., Desplat, J. L., Gulden, T., Chin, J. & Cone, V., "Long-Life Insulators for In-Core Thermionics," Proc. 20th Intersoc. Energy Conv. Engr. Conf., 1985, vol. 3, pp. 3.499-3.512.

Can89 Cannon, N. S., Lawrence, L. A. & Veca, A. R., "Postirradiation Examination of Thermionic Fuel Element Specimens," Proc. 6th Symposium on Space Nucl. Power System, 1989, vol. 1, pp. 251-255.

Car94 Carpenter, S. A., Brennan, K. M., DeBoskey, D. A. & Deveny, M. E., "IDEAs: Integrated Design Environment Algorithms--A Precursor to Systems Engineering in Virtual Reality," Proc. 11th Symposium on Space Nucl. Power System, 1994, vol. 2, pp. 575-580.

Che80 Chen, H. K., Swanson, L. W. & Davis, P. R., "Cesium Adsorption on the Zr/O/W(100) Surface," Proc. 15th Intersoc. Energy Conv. Engr. Conf., 1980, vol. 3, pp. 2334-2337.

Cho93 Choong, P. T., Ravi, K. V., D'Cruz, L. A. & Hatch, G. L., "Chemical Vapor Deposited Diamond for Low Temperature Thermionic Electrode Applications," Proc. 28th Intersoc. Energy Conv. Engr. Conf., 1993, vol. 1, pp. 1.555-1.560.

Cox86 Cox, C. M., Miller, W. C. & Mahaffey, M. K., "Preliminary Site Design for the SP-100 Ground Engineering Test," Proc. 21th Intersoc. Energy Conv. Engr. Conf., 1986, vol. 3, pp. 1942-1943.

Cul90 Culin, M. V., Ischakov, C. A. & Yarygin, V. I., "Nuclear Microanalyses of Surface and Near-Surface Characteristics Life Change of Thermionic Converter Electrodes," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Dah93 Dahlberg, R. C., Begg, L. L., Smith, J. N., Hatch, G. L., McVey, J. B., Rasor, N., Fitzpatrick, G. O., Allen, D. T., Lieb, D. P. & Miskolczy, G., "Review of Thermionic Technology: 1983 to 1992," Proc. 10th Symposium on Space Nucl. Power System, 1993, vol. 1, pp. 223-234.

Dan80 Danielson, L. R., "Development of a Low Work Function Zr/O/W(100) Emitter," Proc. 15th Intersoc. Energy Conv. Engr. Conf., 1980, vol. 3, pp. 2338-2341.

Dan90 Danilin, V. A., Konoplev, E. E., Muravin, E. L. & Nikolaev, V. S., "Metal-Ceramic Leucosapphire Units Having the Mininum Technology Stress," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Dav80 Davis, P. R., Chambers, S. A. & Swanson, L. W., "The Adsorption of Cesium on Lanthanum Hexaboride Surfaces," Proc. 15th Intersoc. Energy Conv. Engr. Conf., 1980, vol. 3, pp. 2327-2330.

Dav90 Davis, P. R. & Mackie, W. A., "Thermionic Projection Microscope Investigations of TEC Electrode Surfaces," Proc. 25th Intersoc. Energy Conv. Engr. Conf., 1990, vol. 2, pp. 362-367.

DCr93a D'Cruz, L., Desplat, J. L., Hatch, G. L. & Rasor, N. S., "Tests of a Cesium Vapor Control, Circulation and Purge System," Proc. 28th Intersoc. Energy Conv. Engr. Conf., 1993, vol. 1, pp. 1.517-1.523.

DCr93b D'Cruz, L., Desplat, J. L., Hatch, G. L., Miskolczy, G. & Lieb, D. P., "Preliminary Testing of a Planar Thermionic Converter with Uranium Oxide Pellets in the Tungsten Emitter," Proc. 28th Intersoc. Energy Conv. Engr. Conf., 1993, vol. 1, pp. 1.531-1.536.

DCr93c D'Cruz, L. A. & Jacobson, D. L., "High Temperature Effective Work Function Variations at Surfaces of Dilute Solution Tungsten-Base Alloys Containing Iridium," Proc. 28th Intersoc. Energy Conv. Engr. Conf., 1993, vol. 1, pp. 1.567-1.572.

Deg90b Degaltsev, Yu. G., Kuznetsov, V.F. & Ponomarev-Stepnoi, N.N., "Modelling of Thermionic Fuel Elements Gas Swelling Based on Diffusion Approach for Their Lifetime Prediction," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Deg90a Degaltsev, Yu. G., Kostochka, N. V., Kuznetsov, V. F., Ponomarev-Stepnoi, N. N. & Slabcky, V. D., "Uranium Dioxide Fuel of the Single-Cell TFE Processes After-Reactor Analysis," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Des90 Desplat, J. L., Hatch, G. L. ,Rasor, N. S. & Lamoreaux, R., "Oxygen Dispenser for Thermionics," Proc. 25th Intersoc. Energy Conv. Engr. Conf., 1990, vol. 2, pp. 316-321.

Des92 Desplat, J. L., "Tests of a Zirconium Dioxide Electrolytic Cell in a Thermionic Diode," Proc. 27th Intersoc. Energy Conv. Engr. Conf., 1992, vol. 3, pp. 3.523-3.528.

Dic80a Dick, R. S., Banda, B. M. & Starr, J. W., "Design Study of a Coal-Fired Thermionic (THX)-Topped Power Plant," Proc. 15th Intersoc. Energy Conv. Engr. Conf., 1980, vol. 3, pp. 1775-1782.

Dic80b Dick, R. S., McVey, J., Britt, E. J. & Fitzpatrick, G. O., "Collector Temperature Effects on the Performance of Advanced Thermionic Converters and Nuclear Electric Propulsion Systems," Proc. 15th Intersoc. Energy Conv. Engr. Conf., 1980, vol. 3, pp. 1766-1772.

Dic83 Dick, R. S., McVey, J. B., Fitzpatrick, G. O. & Britt, E. J., "High Performance, Close-Spaced Thermionic Converters," Proc. 18th Intersoc. Energy Conv. Engr. Conf., 1983, vol. 1, pp. 198-201.

Dic84 Dick, R. S., "Thermionic Cogeneration Burner Assessment," Proc. 19th Intersoc. Energy Conv. Engr. Conf., 1984, vol. 4, pp. 2307-2312.

Dun85 Dunlay, J. B., Smith, E. A., Holland, J. W. & Horner, M. H., "Experimental Investigation of Fueled Thermionic Emitter Deformation," Proc. 20th Intersoc. Energy Conv. Engr. Conf., 1985, vol. 3, pp. 3.495-3.498.

ElG93 El-Genk, M. S. & Xue, H., "Two-Dimensional Transient Analysis of an Electrically Heated Thermionic Fuel Element," Proc. 28th Intersoc. Energy Conv. Engr. Conf., 1993, vol. 1, pp. 1.493-1.498.

ElG94 El-Genk, M.S. & Xue, H., "Two-Dimensional Steady State and Transient Analysis of Single-Cell Thermionic Fuel Elements," Nuclear Technology, vol. 108, Oct., 1994, pp.112-125.

End88 Ender, A. Ya. & Sitnov, V. I., "Collector Emission Influence on Characteristics of Knudson Thermionic Converter," Proc. 23th Intersoc. Energy Conv. Engr. Conf., 1988, vol. 1, pp. 585-590.

End94 Ender, A. Ya., Kuznetsov, V. I., Sitnov, V. I., Solovyov, A. V., Ogloblin, B. G., Luppov, A. N. & Klimov, A. V., "Ultra-High Temperature Thermionic System for Space Solar Power Applications," Proc. 11th Symposium on Space Nucl. Power System, 1994, vol. 2, pp. 861-867.

Fed93 Fedik, I. I., Vybyvanets, V. I. & Izhvanov, O. L., "Electrical Insulation Characteristics of TOPAZ II TFE Ceramic Insulators," Joint Russian-American Enterprise Inertek, NMERI, Alburquerque, NM, 1993.

Fit73 Fitzpatrick, G. O., Yates, M. K. & Schwarzer, D., Development of a Thermionic Reactor Space Power System: Final Summary Report, GA-A12608, General Atomics Technologies, San Diego, CA, June, 1973.

Fit81a Fitzpatrick, G. O., Britt, E. J. & Dick, R. S., "High Temperature Cogeneration with Thermionic Burners," Proc. 16th Intersoc. Energy Conv. Engr. Conf., 1981, vol. 2, pp. 1951-1955.

Fit81b Fitzpatrick, G. O., Britt, E. J., Dick, R. S., Lohneiss, R. F., Sederquist, R. A. & Lehman, S. J., "Thermionic Converters for Increased Performance in Gas Turbine Power Plants," Proc. 16th Intersoc. Energy Conv. Engr. Conf., 1981, vol. 2, pp. 1962-1967.

Fit86 Fitzpatrick, G. O. & Huffman, F. N., "Thermionic Fuel Element Verification Issues," Proc. 21th Intersoc. Energy Conv. Engr. Conf., 1986, vol. 2, pp. 1318-1319.

Fit90 Fitzpatrick, G. O. & Allen, D. T., "Thermionic Converter: Normal and Transparent Collectors," Proc. 25th Intersoc. Energy Conv. Engr. Conf., 1990, vol. 2, pp. 283-289.

Fit93 Fitzpatrick, G., Lawless, J., Nikolaev, Y., Yeremin, S., Klinkov, A. & McVey, J., "Demonstration of Close-Spaced Thermionic Converters," Proc. 28th Intersoc. Energy Conv. Engr. Conf., 1993, vol. 1, pp. 1.573-1.580.

Fit94 Fitzpatrick, G. O. & Allen, D. T., "Cascaded Thermionic Converters Applied to Space Nuclear Power Systems," Proc. 11th Symposium on Space Nucl. Power System, 1994, vol. 2, pp. 819-828.

Fom66 Fomenko, V. S., Handbook of Thermionic Properties: Electronic Work Functions and Richardson Constants of Elements and Compounds, Plenum Press Data Division, New York, 1966.

Foo87 Foote, J. P., Morris, D. G. & Olszewski, M., "Encapsulated Sink-Side Thermal Energy Storage for Pulsed Space Power Systems," Proc. 22th Intersoc. Energy Conv. Engr. Conf., 1987, vol. 3, pp. 1940-1945.

Gen94a TFE Verification Program Final Report: Conceptual Design, GA-A21590, General Atomics Technologies, San Diego, CA, March, 1994.

Gen94b TFE Verification Program Final Report: Converter Performance, GA-A21591, General Atomics Technologies, San Diego, CA, March, 1994.

Gen94c TFE Verification Program Final Report: Insulator Seal, GA-A21592, General Atomics Technologies, San Diego, CA, June, 1994.

Gen94d TFE Verification Program Final Report: Sheath Insulator, GA-A21593, General Atomics Technologies, San Diego, CA, July, 1994.

Gen94e TFE Verification Program Final Report: Fueled Emitter, GA-A21594, General Atomics Technologies, San Diego, CA, July, 1994.

Gen94f TFE Verification Program Final Report: Cesium Reservoir and Interconnective Components, GA-A21595, General Atomics Technologies, San Diego, CA, March, 1994.

Gen94g TFE Verification Program Final Report: Thermionic Fuel Element Performance, GA-A21596, General Atomics Technologies, San Diego, CA, June, 1994.

Gen94h TFE Verification Program Final Report: TFE Design Package, GA-A21597, General Atomics Technologies, San Diego, CA, June, 1994.

Gon90a Gontar, A. S., Gutnik, V. S., Zaitsev, V. A., Levedev, A. M., Lubimov, D. Y. Mitrofanov, V. Y. & Nikolaev, Yu. V., "Fuel for Thermionic Fuel Elements," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Gon90b Gontar, A. S., Nelidov, M. V., Nikolaev, Yu. V., Podogov, Yu. N., Solovyov, L. N., Sotnikov, V. N. & Shulepov, L. N., "Problems of the Thermionic Fuel Element Development," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Gon90c Gontar, A. S., Nelidov, M. V. & Nikolaev, Yu. V., "Deformation Behavior of a Thermionic Fuel Element

Under Conditions of Thermal Cycling with a Small Temperature Change," Proc. 25th Intersoc. Energy Conv. Engr. Conf., 1990, vol. 2, pp. 290-293.

Gon93 Gontar, A. S., Gutnik, V. S., Nelidov, M. V. & Nikolaev, Yu. V., "Swelling of Uranium Dioxide and Deformation Behavior of the Fuel Element at High Temperature Irradiation," Proc. 28th Intersoc. Energy Conv. Engr. Conf., 1993, vol. 1, pp. 1.549-1.553.

Gon94 Gontar, A. S., Kucherov, R. Ya., Lapochkin, N. V. & Nikolaev, Yu. V., "Thermionic Fuel Element with Carbide Fuel," Proc. 11th Symposium on Space Nucl. Power System, 1994, vol. 2, pp. 845-850.

Goo80 Goodale, D. B., Reagan, P., Miskolczy, G., Lidb, D. & Huffman, F. N., "Combustion Performance of CVD Silicon Carbide Thermionics Diodes," Proc. 15th Intersoc. Energy Conv. Engr. Conf., 1980, vol. 3, pp. 2095-2097.

Goo81 Goodale, D. B., Reagan, P. & Miskolczy, G., "Characteristics of CVD Silicon Carbide Thermionic Converters," Proc. 16th Intersoc. Energy Conv. Engr. Conf., 1981, vol. 2, pp. 1974-1978.

Goo82a Goodale, D., Lieb, D. & Neale, D., "Solar Thermionic Energy Converter Experiment," Proc. 17th Intersoc. Energy Conv. Engr. Conf., 1982, vol. 4, pp. 1924-1928.

Goo82b Goodale, D., Reagan, P., Lieb, D. & Huffman, F., "Thermionic Converters for Terrestrial Applications," Proc. 17th Intersoc. Energy Conv. Engr. Conf., 1982, vol. 4, pp. 1913-1917.

Goo83 Goodale, D., Lieb, D., Miskolczy, G. & Moffat, A., "Combustion Converter Development for Topping and Cogeneration Applications," Proc. 18th Intersoc. Energy Conv. Engr. Conf., 1983, vol. 1, pp. 192-197.

Goo84 Goodale, D. B. & Miskolczy, G., "Combustion Converter Design Evolution," Proc. 19th Intersoc. Energy Conv. Engr. Conf., 1984, vol. 4, pp. 2270-2275.

Gor90a Gorodetsky, D. A., Melnik, Y. P., Usenko, V. A., Yas'ko, A. A. & Yarygin, V. I., "Adsorption of Cesium on Molybdenum(110)," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Gor90b Gorodetsky, D. A., Melnik, Yu. P., Sklyar, V. K., Yas'ko, A. A., Vizgalov, A. V. & Yarigin, V. I., "Structure and Work Function of Polyhedral Tungsten Emitter Covered with a Platinum Film," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Gri90 Gridnev, A. A., "Calculation of Irradiation Characteristics of Uranium Dioxide," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Gro89 Grobstein, T. L., "Creep Behavior of Tungsten-Fiber Reinforced Niobium-Based Alloy Metal Matrix Composites," Proc. 6th Symposium on Space Nucl. Power System, 1989, vol. 1, pp. 194-198.

Gry90 Gryaznov, G. M., Novikov, A. B, .Sveshnikova, N. N. & Serfin, V. I., "Thermionic Plasma Switching Elements," Proc. 25th Intersoc. Energy Conv. Engr. Conf., 1990, vol. 2, pp. 300-304.

Gub86 Gubbels, G. H. M., Metselaar, R., Penders, E. & Wolff, L. R., "Combustion Heated Thermionic Energy Converter," Proc. 21th Intersoc. Energy Conv. Engr. Conf., 1986, vol. 2, pp. 1343-1345.

Gub88 Gubbels, G. H. M. & Wolff, L. R., "A Thermionic Energy Converter with a Molybdenum Alumina Cermet Emitter," Proc. 23th Intersoc. Energy Conv. Engr. Conf., 1988, vol. 1, pp. 617-619.

Gun80 Gunther, B. & Huffman, F. N., "Characteristics of a Cesiated W(110) Electrode Annealed in Oxygen," Proc. 15th Intersoc. Energy Conv. Engr. Conf., 1980, vol. 3, pp. 2103-2106.

Han67 Hansen, L. K., "Ion-Current and Schottky Effects in Thermionic Diodes," Journal of Applied Physics, vol. 38, Oct., 1967, pp. 4345-4354.

Hat73 Hatsopoulos, G. N. & Gyftopoulos, E. P., Thermionic Energy Conversion: Volume I Processes and Devices, The MIT Press, Cambridge, 1973.

Hat79 Hatsopoulos, G. N. & Gyftopoulos, E. P., Thermionic Energy Conversion: Volume II Theory, Technology and Application, The MIT Press, Cambridge, 1979.

Hen80 Henne, R., Bradke, M. V. & Weber, W., "Progress in the Development of Small Flame Heated Thermionic Energy Converters," Proc. 15th Intersoc. Energy Conv. Engr. Conf., 1980, vol. 3, pp. 2089-2094.

Hol72 Holland, J. W., "Thermionic Fuel Element Development Status Summary," Proc. 3rd Int. Conf. of Thermionic Elec. Power Generation, 1972, vol. 2, pp. 469-476.

Hol84 Holland, J. L. & Yang, L., "Technology Status of Thermionic Fuel Elements for Space Nuclear Power," Proc. 19th Intersoc. Energy Conv. Engr. Conf., 1984, vol. 4, pp. 2282-2292.

Hou94 Houts, M. G., Wharton, W. R., Begg, L. L. & Lawrence, L. A., "Technical Accomplishments of the Thermionic Fuel Element Verification Program," Proc. 11th Symposium on Space Nucl. Power System, 1994, vol. 2, pp. 997-1008.

Huf82 Huffman, F., Reagan, P., Miskolczy, G. & Merrill, O., "Thermionic Technology Infrastructure for Space Power," Proc. 17th Intersoc. Energy Conv. Engr. Conf., 1982, vol. 4, pp. 1908-1912.

Huf83 Huffman,F., "Overview of Terrestrial Thermionics," Proc. 18th Intersoc. Energy Conv. Engr. Conf., 1983, vol. 1, pp. 179-185.

Huf88 Huffman, F. N. & Haq, Z., "Preliminary Investigations of a Thermotunnel Converter," Proc. 23th Intersoc. Energy Conv. Engr. Conf., 1988, vol. 1, pp. 573-580.

Isa90 Isaew, V. I., Kovalev, V. P., Ryabinkin, V. I. & Filatow, A. S., "The Development of Accumulation Method in Leak Detection," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Jas80 Jaskie, J. & Jacobson, D., "Thermionic Emission and Surface Composition of the Y-B System," Proc. 15th Intersoc. Energy Conv. Engr. Conf., 1980, vol. 3, pp. 2331-2333.

Jen94 Jensen, R. R., "Materials Performance Issues in the Design of Fuel Elements for Externally Fueled Thermionic Hybrid Systems," Proc. 11th Symposium on Space Nucl. Power System, 1994, vol. 2, pp. 1525-1534.

Jos86 Josloff, A. T. & Chiu, W. S., "Operational Aspects of Spacecraft Using Space Reactor Power Systems," Proc. 21th Intersoc. Energy Conv. Engr. Conf., 1986, vol. 3, pp. 1938-1941.

Kal89 Kalandarishvili, A. G., Working Medium Sources for Thermionic Power Converters, Trans. on Cesium Sources for Thermionic Converters, 1989.

Kal90 Kalinin, G. M., Ivanov, A. D. & Korostelev, A. B., "Perspective Structural Materials for Nuclear Power Propulsion System of Space Complexes," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Kal92 Kalandarishvili, A. G. & Kashiya, V. G., "Characteristics of Cylindrical Thermionic Converters with Niobium Polycrystal-Based Collectors at High Temperatures of Electrodes," Proc. 27th Intersoc. Energy Conv. Engr. Conf., 1992, vol. 3, pp. 3.461-3.464.

Kar90 Karabut, A. B., Kucherov, Ya. R. & Savvatimova, I. B., "Cold Fusion Observation at Gas-Discharge Device Cathode," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Kaz90 Kazantsev, G. N., Moseyev, L. I., Cvchinnikov, I. J. & Polyakin, V. V., "Investigation of Uranium Dioxide of Prestoichiometric Composition," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Ken88 Kennel, E. B. & Perry, M. S., "Advanced Thermionic Nuclear Electric Propulsion for Leo to Geo Transfer in 14 Days," Proc. 23th Intersoc. Energy Conv. Engr. Conf., 1988, vol. 1, pp. 597-600.

Ken90 Kennel, E. B., Donovan, B. D. & Ramalingam, M. L., "Thermionic Emitter Pure Metal and Alloy Approaches: Comparison and Contrast," Proc. 7th Symposium on Space Nucl. Power System, 1990, vol. 1, pp. 92-96.

Kes88 Keshishian, V., Gay, R. L. & Meyer, R. D., "Space Reactor Shield Technology," Proc. 23th Intersoc. Energy Conv. Engr. Conf., 1988, vol. 1, pp. 219-224.

Kir86 Kirpich, A., Biddiscombe, R., Chan, J. & McNamara, E., "Comparison of Concepts for a 300 kWe Nuclear Power System," Proc. 21th Intersoc. Energy Conv. Engr. Conf., 1986, vol. 3, pp. 1933-1937.

Kle92 Klepikov, V. V.,Yarigin, V. I.,Kuptsov, G. A.,Veltkamp, W. B. & Wolff, L. R., "Design of a TECTEM Prototype," Proc. 27th Intersoc. Energy Conv. Engr. Conf., 1992, vol. 3, pp. 3.451-3.454.

Kob90 Kobyakov, V. P., Kozlov, O. F., Uvarov, V. I., Tsetskhladze, Sedmale, G. P., Sedmalis, U. Ya. & Tsimdinsh, R. A., "Amorphous Coverings for Protection and Electroinsulation of Columbium Alloys at Heightened Temperature," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Kor90a Koryukin, V. A., Mosevitshii, I. S., Obrezumov, V. P. & Stepennov, B. S., "Emission Properties of Electrodes of One-Cell Thermionic Fuel Elements in Operating Life," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Kor90b Koryukin, V. A., Mosevitskii, I. S., Obrezumov, V. P. & Stepennov, B. S., "Work Function Properties of Electrodes of One-Cell Thermionic Fuel Element in Operating Life," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Kor90c Koryukin, V. A. & Obrezumov, V. P., "The Influence of Oxygen and Carbon Monoxide Adsorption on Emission Characteristics of Thermionic Fuel Element Electrodes," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Kor90d Koryukin, V. A. & Obrezumov, V. P., "Dynamics of Changes in Thermionic Energy Converter Collector Properties Under Condition of Mass Transfer in the Interelectrode Gap," Proc. 25th Intersoc. Energy Conv. Engr. Conf., 1990, vol. 2, pp. 332-339.

Kor92 Koryukin, V. A. & Obrezumov, V. P., "Thermionics of Molybdenum Monocrystals Being Implanted by Cesium and Barium Ions," Proc. 27th Intersoc. Energy Conv. Engr. Conf., 1992, vol. 3, pp. 3.543-3.547.

Kuc90a Kucharkin, N. E., Ponomarev-Stepnoi, N. N. & Usov, V. A., "Reactor-Converter 'Romashka' and the Perspectives of Its Development," Proc. 7th Symposium on Space Nucl. Power System, 1990, vol. 1, pp. 400-405.

Kuc90b Kucherov, R. Ya., Khromov, Yu. F., Lebedev, A. M., Shulepov, L. N., Krayuhin, V. I. & Zhmurov, S. A., "Possibilities of High Temperature Uranium Nitride Vented Fuel Element Development," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Kuz88 Kuznetsov, V. I. & Ender, A. Ya., "Nonlinear Theory of Oscillations in Low-Pressure Thermionic

Converter," Proc. 23th Intersoc. Energy Conv. Engr. Conf., 1988, vol. 1, pp. 581-584.

Kuz90 Kuzmina, R. V., Men'kin, L. I. & Pyshkin, V. P., "Investigation of Deposition of Different Iodine Forms on Structural Materials," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Kva90 Kvasnikov, L. A., Miagkov, K. G., Yakushin, M. I., Vizgalov, A. V., Savvov, R. V. & Yarygin, V. I., "The Emission Ununiform Investigation of Thermoemission Reactor-Converter Polyfacet Emitter Shells Using Thermoelectron Emission Microscopy Method," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Lam94 Lamp, T. R. & Donovan, B. D., "Energy Conversion Programs at Wright Laboratory," Proc. 11th Symposium on Space Nucl. Power System, 1994, vol. 2, pp. 1159-1164.

Lan90 Lanin, A. G., Zubarev, P. V. & Vlasov, K. P., "The Main Characteristics of Materials Used in Fuel Assemblies of High-Temperature Gas Reactors," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Lee90 Lee, C., Leib, D. & Miskolczy, G., "Performance of Thermionic Converters with Structured Emitters and Collectors," Proc. 25th Intersoc. Energy Conv. Engr. Conf., 1990, vol. 2, pp. 294-299.

Lee93a Lee, C. M. & Miskolczy, G., "Design Study of the Emitter Stem for the S-PRIME Thermionic Fuel Element," Proc. 28th Intersoc. Energy Conv. Engr. Conf., 1993, vol. 1, pp. 1.543-1.548.

Lee93b Lee, H. H. & Klein, A. C., "Analysis of Topaz-II Reactor Performance Using MCNP and TFEHX," Proc. 28th Intersoc. Energy Conv. Engr. Conf., 1993, vol. 1, pp. 1.537-1.542.

Lee94 Lee, H. H., Dickinson, J. W., Klein, A. C. & Lamp, T. R., "Comparison of Tungsten and Molybdenum Based Emitters for Advanced Thermionic Space Nuclear Reactors," Proc. 11th Symposium on Space Nucl. Power System, 1994, vol. 2, pp. 701-706.

Lew90 Lewis, B. R., Pawlowski, R. A. & Klein, A. C., "Advanced Thermionic Reactor Systems Design Code," Proc. 25th Intersoc. Energy Conv. Engr. Conf., 1990, vol. 2, pp. 305-309.

Lew91 Lewis, B. R., Pawlowski, R. A., Greek, K. J. & Klein, A. C., "Advanced Thermionic Reactor Systems Design Code," Proc. 8th Symposium on Space Nucl. Power System, 1991, vol. 1, pp. 222-227.

Lub90 Lubimov, D. Yu., Bobkov, B. N., Lavrentyev, E. A. & Panov, A. S., "Modelling of the Mass-Transfer Processes in an Interelectrode Gap of a Thermionic Converter," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Luc94 Luchau, D. W., Follis, H. D., Schreiber, C. A., Izhvanov, O. L., Vibivanets, V. I., Androsov, V. N. & Shadrin, E. O., "Thermionic Fuel Element Test Rig: Testing of Single Cell Thermionic Fuel Element Technology," Proc. 11th Symposium on Space Nucl. Power System, 1994, vol. 2, pp. 1031-1036.

Lun86 Lundberg, L., "Compatibility Studies on SP-100 Fuel, Cladding and Lithium," Proc. 21th Intersoc. Energy Conv. Engr. Conf., 1986, vol. 3, pp. 1944-1949.

Lun88 Lundin, J., Pettersson, J., Moller, K. & Holmlid, L., "Observation of Negative Ions of Cesium from Thermionic Converters and in Desorption from Metal Surfaces," Proc. 23th Intersoc. Energy Conv. Engr. Conf., 1988, vol. 1, pp. 591-596.

Luo93 Luo, A., Park, J., Jacobson, D. L., Tsao, B. H. & Ramalingam, M. L., "Particle Strengthened Molybdenum for Space Power Applications," Proc. 28th Intersoc. Energy Conv. Engr. Conf., 1993, vol. 1, pp. 1.561-1.566.

Mag94 Magera, G. G. & Davis, P. R., "The Coadsorption of Cs and Ba Onto the (110) Surface of Mo," Proc. 11th Symposium on Space Nucl. Power System, 1994, vol. 2, pp. 1153-1158.

Mah81 Mahefkey, T., "Thermionic Application for Future Air Force Space Power Systems," Proc. 16th Intersoc. Energy Conv. Engr. Conf., 1981, vol. 2, pp. 1979-1981.

Mai83 Main, G. L. & Lam, S. H., "Effects of Reflections and Trapped Ions on the Thermionic Emitter Sheath," Proc. 18th Intersoc. Energy Conv. Engr. Conf., 1983, vol. 1, pp. 215-220.

Mai87 Main, G. L., Bouwmans, R., Ridderbusch, G. L., Hamm, D., Dansereau, J. P. & Coleman, W. P., "A Time Dependent Model of a Thermionic Energy Converter Using a Three Scale Asymptotic Analysis of the Electrodde Plasma Boundaries," Proc. 22th Intersoc. Energy Conv. Engr. Conf., 1987, vol. 3, pp. 1935-1939.

Mai90 Main, G. L. & Larson, G., "Two Dimensional Modeling of a Proposed Auxiliary Ionization Scheme for Thermionic Convertors," Proc. 25th Intersoc. Energy Conv. Engr. Conf., 1990, vol. 2, pp. 368-372.

Mal95 Malloy, W. & Roma, W.(ed), TOPAZ International Program: Lessions Learned in Technology Cooperation with Russia, Booz-Allen & Hamilton, Inc., 1995.

McV81 McVey, J. B., Britt, E. J., Fitzpatrick, G. O. & Dick, R. S., "The Design of Series-Parallel Connected Thermionic Converter Arrays," Proc. 16th Intersoc. Energy Conv. Engr. Conf., 1981, vol. 2, pp. 1968-1973.

McV90 McVey, J. B., "Improved Pulsed Ionization Thermionic Converters for Nuclear Power Applications," Proc. 25th Intersoc. Energy Conv. Engr. Conf., 1990, vol. 2, pp. 357-361.

McV92 McVey, J. B. & Rasor, N. S., "The TECMDL Thermionic Converter Computer Model," Proc. 27th Intersoc. Energy Conv. Engr. Conf., 1992, vol. 3, pp. 3.505-3.512.

Men90 Men'kin, L. I., Kim, E. V. & Chebotcov, V. A., "In-Pile Tests of Gas Fission Product Release from Fuel-Element of a Research Nuclear Plant," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Mer80 Merill, O. S., "The Changing Emphasis of the DOE Thermionic Program," Proc. 15th Intersoc. Energy Conv. Engr. Conf., 1980, vol. 3, pp. 1773-1774.

Mil93 Mills, J. C., Determan, W. R., Dahlberg, R. C. & Van Hagan, T. H., "S-PRIME/TI-SNPS Program Summary," Proc. 28th Intersoc. Energy Conv. Engr. Conf., 1993, vol. 1, pp. 1.487-1.492.

Mir90 Mironov, V. S. & Sidelnicov, V. N., "Maximum Permissible Output Characteristics of TEC," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Mis80 Miskolczy, G., Wang, C. C., Margulies, A. E. & Fusegni, L. J., "Thermionic Topping of Combined Cycle Powerplants and Cogeneration Applications," Proc. 15th Intersoc. Energy Conv. Engr. Conf., 1980, vol. 3, pp. 1783-1787.

Mis81 Miskolczy, G., Wang, C. C., Lieb, D. P., Margulies, A. E., Fusegni, L. & J.Lovell, B. J., "Thermionic Combustor Application to Combined Gas and Steam Turbine Power Plants," Proc. 16th Intersoc. Energy Conv. Engr. Conf., 1981, vol. 2, pp. 1956-1961.

Mis82 Miskolczy, G. & Lieb, D., "Cogeneration Using a Thermionic Combustor," Proc. 17th Intersoc. Energy Conv. Engr. Conf., 1982, vol. 4, pp. 1918-1923.

Mis83 Miskolczy, G., Goodale, D., Moffat, A. L. & Morgan, D. T., "Thermionic Cogeneration Burner Design," Proc. 18th Intersoc. Energy Conv. Engr. Conf., 1983, vol. 1, pp. 186-191.

Mis84 Miskolczy, G., Goodale, D., Moffat, A. & Gentile, A., "Design and Construction of Thermionic Cogeneration Burner Module," Proc. 19th Intersoc. Energy Conv. Engr. Conf., 1984, vol. 4, pp. 2260-2264.

Mis94 Miskolczy, G., Witt, T., Lieb, D., McVey, J. & Hatch, L., "Design of Cesium Reservoir Critical Component Experiment for S-Prime," Proc. 11th Symposium on Space Nucl. Power System, 1994, vol. 2, pp. 1009-1016.

Mor82 Morris, J. F., "Direct-Energy-Conversion Implications of Space Nuclear Reactors," Proc. 17th Intersoc. Energy Conv. Engr. Conf., 1982, vol. 4, pp. 1902-1907.

Mor83 Morris, J. F., "Ultralloys for Nuclear Thermionic Conversion," Proc. 18th Intersoc. Energy Conv. Engr. Conf., 1983, vol. 1, pp. 208-214.

Mor84 Morris, J. F., "Better, Cheaper In-Core Thermionic Energy Conversion (ICTEC) with Pre-1973 Ultralloys," Proc. 19th Intersoc. Energy Conv. Engr. Conf., 1984, vol. 4, pp. 2293-2299.

Mor85 Morris, J. F. & Jacobson, D. L., "TEC and Ultralloys for High-Power Space Systems," Proc. 20th Intersoc. Energy Conv. Engr. Conf., 1985, vol. 3, pp. 3.521-3.530.

Mor86a Morris, J. F., "Aspects of Cs, Ba Knudsen Ultrahigh-Temperature TEC," Proc. 21th Intersoc. Energy Conv. Engr. Conf., 1986, vol. 2, pp. 1331-1336.

Mor86b Morris, J. F. & Jacobson, D. L., "Material Considerations for Ultrahigh-Temperature Thermionic Conversion in Space Nuclear Power," Proc. 21th Intersoc. Energy Conv. Engr. Conf., 1986, vol. 2, pp. 1326-1330.

Mor88 Morris, J. F. & Jacobson, D. L., "Thermionic Conversion and Alloys for High-Temperature Nuclear Space Power," Proc. 23th Intersoc. Energy Conv. Engr. Conf., 1988, vol. 1, pp. 607-612.

Nik90a Nikolaev, Yu., Zubarev, P. V., Karetnikov, I. A., Yastreckov, A. A., Solovyov, V. F., Zagrjazkin, V. H. & Repiy, V. A., "Refractory Metals for Thermionic Fuel Elements of NEP," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Nik90b Nikolaev, Yu. V., Khromov, Yu. F., Khromonozhkin, V. V., Lyutikov, R. A., Izvanov, O. L., Galkin, E. A. & Zaitsev, V. A., "Some Characteristics of Fuel Compositions: UO2, UZr(CN), U(Zr, Nb, Ta)C, UCS," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Nik90c Nikolaev, Yu. V., Vasilchenko, A. V., Golubev, M. P., Gontar, A. S., Gordinskiy, V. L., Eryomin, S. A. & Kucherov, R. Ya., "Electrogenerating Channel for High-Voltage Thermionic Reactor," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Nik92 Nikolaev, Yu. V., Kucherov, R. Ya., Maraginsky, R. N. & Kuznetsov, P. P., "A Terrestrial Solar Power Plant with Direct Energy Conversion," Proc. 27th Intersoc. Energy Conv. Engr. Conf., 1992, vol. 3, pp. 3.433-3.436.

Nik94 Nikolaev, Yu. V., Vasilchenko, A. V., Eryomin, S. A. & Lapochkin, N. V., "Thermionic Fuel Element for High-Voltage Thermionic Nuclear Power Plant," Proc. 11th Symposium on Space Nucl. Power System, 1994, vol. 2, pp. 851-860.

Nyr84 Nyren, T., Korringa, M., McVey, J., Sahines, T. & Fitzpatrick, G. O., "Design and Testing of a Combustion-Heated Nineteen-Converter SAVTEC Array," Proc. 19th Intersoc. Energy Conv. Engr. Conf., 1984, vol. 4, pp. 2300-2306.

Par92 Parker, G. J., Hitchon, W. N. G., Lawler, J. E. & McVey, J. B., "Development of a Self-Consistent Kinetic Plasma Model of Thermionic Energy

Converters," Proc. 27th Intersoc. Energy Conv. Engr. Conf., 1992, vol. 3, pp. 3.513-3.518.

Par94 Paramonov, D. V. & El-Genk, M. S., "Comparison of a Topaz-II Model with Experimental Data from the V-71 Unit Tests," Proc. 11th Symposium on Space Nucl. Power System, 1994, vol. 2, pp. 829-844.

Plo90 Plosukhin, B. G., Zyryanov, A. P., Baskakov, E. P., Shestakov, S. A. & Dobrynskikh, A. G., "In-Core Irradiation Effect and Oxygen-Nitrogen Impurity Influence on Hydrogen Permeability of Austenitic Steel and High Nickel Alloys," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Pon91 Ponomarev-Stepnoi, N. N., Nikolaev, Yu. V., Degaltsev, Yu. G., Stepennov, B. S. & Nikitin, V. P., "Thermionic Fuel Element of Power Plant TOPAZ II," Joint Russian-American Enterprise Inertek, NMERI, Alburquerque, NM, 1991.

Pon93 Ponomarev-Stepnoi, N. N., Usov, V. A., Vybyvanets, V. I. & Koriukin, V. A., "Mass Transfer in Interelectrode Gap and Its Impact Upon Electrode Properties and TFE Characteristics," Joint Russian-American Enterprise Inertek, NMERI, Alburquerque, NM, 1993.

Ram87a Ramalingam, M. L. & Jacobson, D. L., "Thermionic Emission Characteristics of Thoriated Tungsten, Rhenium Alloys," Proc. 22th Intersoc. Energy Conv. Engr. Conf., 1987, vol. 3, pp. 1929-1934.

Ram87b Ramalingam, M. L. & Jacobson, D. L., "Thermionic Emitter Material Characteristics at Elevated Temperatures," Proc. 22th Intersoc. Energy Conv. Engr. Conf., 1987, vol. 3, pp. 1949-1954.

Ram93 Ramalingam, M. L. & Young, T. J., "The Power of Thermionic Energy Conversion," Mechanical Engineering, Sept., 1993, pp. 78-83.

Ran90a Ranken, W. A., "Historical View of Thermionic Reactor Development," Proc. 7th Symposium on Space Nucl. Power System, 1990, vol. 1, pp. 393-399.

Ran90b Ranken, W. A., "Low Power Moderated Thermionic Reactor with Heat Pipe Cooling," Proc. 7th Symposium on Space Nucl. Power System, 1990, vol. 1, pp. 406-414.

Ras64 Rasor, N. S. & Warner, C., "Correlation of Emission Processes for Adsorbed Alkali Films on

Metal Surfaces," Journal of Applied Physics, vol. 35, Sept., 1964, pp. 2589-2600.

Ras86 Rasor, N. S., "Second-Generation Thermionic Reactor (TRICE)," Proc. 21th Intersoc. Energy Conv. Engr. Conf., 1986, vol. 2, pp. 1337-1346.

Ras90 Rasor, N. S. & Desplat, J. L., "The Cesiator: A Device for Cesium Vapor Control and Impurity Purge," Proc. 25th Intersoc. Energy Conv. Engr. Conf., 1990, vol. 2, pp. 310-315.

Ras91 Rasor, N. S., "Thermionic Energy Conversion Plasmas," IEEE Trans. on Plasma Science, 1991, vol. 19, pp. 1191-1208.

Ras92 Rasor, N. S., "Physical-Analytical Model for Cesium/Oxygen Coadsorption on Tungsten," Proc. 27th Intersoc. Energy Conv. Engr. Conf., 1992, vol. 3, pp. 3.529-3.536.

Roc90 Driver Fuel-Thermionic Fuel Element Power System: Volume I - Technical Proposal, RI/RD90-143P-1, Rocketdyne Division, Rockwell International Corporation, May, 1990.

Roc93 Rochow, R. F. & Stansberry, M. D., "Fuel Element Design Considerations for the SEHPTR 40 kWe Thermionic Nuclear Reactor," Proc. 28th Intersoc. Energy Conv. Engr. Conf., 1993, vol. 1, pp. 1.643-1.647.

Roc93 S-Prime Thermionic Space Nuclear Power System Design and Technology Demonstration: Technical Progress Report, DOE Contract AC03-92-SF19138, Rocketdyne Division, Rockwell International Corporation, October, 1993.

Sam87 Samuelson, S. L., Dahlberg, R. C., Huffman, F. N. & Brehm, R. L., "Thermionic Fuel Element Verification Program," Proc. 22th Intersoc. Energy Conv. Engr. Conf., 1987, vol. 3, pp. 1946-1948.

Sam89 Samuelson, S. L. & Dahlberg, R. C., "Thermionic Fuel Element Verification Program--Summary of Results," Proc. 6th Symposium on Space Nucl. Power System, 1989, vol. 1, pp. 439-444.

Sam90 Samuelson, S. L. & Dahlberg, R. C., "Thermionic Fuel Element Verification Program--Summary of Results," Proc. 7th Symposium on Space Nucl. Power System, 1990, vol. 1, pp. 77-84.

Sav90 Savvov, R. V., Skrebova, Z. B., Yarygin, V. I. & Chramushin, N. I., "Life Change of Thermionic Converter Collector Surface Characteristics," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Sch94 Scheglov, A. S., Sinyavshiy, V. V. & Allen, D. T., "Influence of Emitter-Collector Axial Asymmetry on the Temperature Distribution in a Thermionic Converter," Proc. 11th Symposium on Space Nucl. Power System, 1994, vol. 2, pp. 1165-1170.

Sen89 Senor, D. J., Thomas, J. K. & Peddicord, K. L., "Niobium-1%Zirconium Property Correlations for Electrical Resistivity, Thermal Conductivity, Thermal Expansion, Specific Heat, and Hemispherical Total Emittance," Proc. 6th Symposium on Space Nucl. Power System, 1989, vol. 1, pp. 205-208.

Ser90a Sernyaev, G. A. & Shehurin, V. N., "Irradiation Influence on Al-Be Alloys Mechanical Properties," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Ser90b Sernyaev, G. A. & Shehurin, V. N., "Main Causes, Behavior and Level of Beryllium Radiation-Damage in a Wide Range of Radiation Temperatures and Neutron Fluences: Beryllium Swelling and Spontaneous Cracking Under Low-Temperature Radiation," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Shi80 Shimada, K., "Heat Flux at the Thermionic Collector," Proc. 15th Intersoc. Energy Conv. Engr. Conf., 1980, vol. 3, pp. 2112-2116.

Sid90 Sidelnicov, V. N., "The Main Physical Effects of Uniform TEC," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Sin93 Sinutin, G. V., Smolin, A. L., Dorf-Gorsky, I. A. & Elchaninov, A. A., "Features of Thermionic NPS Cesium System Operation with a Wick Vapor Source," Joint Russian-American Enterprise Inertek, NMERI, Alburquerque, NM, 1993.

Smi80 Smith, M. D., Manda, M. L. & Britt, E. J., "Utilization of Low Temperature Insulators and Seals in Thermionic Converters," Proc. 15th Intersoc. Energy Conv. Engr. Conf., 1980, vol. 3, pp. 2098-2102.

Smi84 Smith, E. A. & Huffman, F. N., "Characteristics of Two Thermionic Converters with Oxide Collectors," Proc. 19th Intersoc. Energy Conv. Engr. Conf., 1984, vol. 4, pp. 2265-2269.

Smi90 Smith, J. N., Heffernan, T., Speidel, T., Lawrence, L. & Cannon, S., "Evaluation of Poco Graphite as a Cs Reservoir," Proc. 7th Symposium on Space Nucl. Power System, 1990, vol. 1, pp. 415-419.

Sny86 Snyder, H. J., "Star-C Space Thermionic Advanced Reactor Compact," Proc. 21th Intersoc. Energy Conv. Engr. Conf., 1986, vol. 2, pp. 1320-1325.

Sta80 Stark, G., Saunders, M. & Lieb, D., "Thermionic Converter Output as a Function of Collector Temperature," Proc. 15th Intersoc. Energy Conv. Engr. Conf., 1980, vol. 3, pp. 2107-2111.

Sto80 Storms, E. K., "Thermionic Properties of the Molybdenum Boron System," Proc. 15th Intersoc. Energy Conv. Engr. Conf., 1980, vol. 3, pp. 2324-2326.

Sve92 Svensson, R. & Holmlid, L., "Temperature Studies and Plasma Probing of a Rydberg Matter Collector in a Thermionic Energy Converter," Proc. 27th Intersoc. Energy Conv. Engr. Conf., 1992, vol. 3, pp. 3.537-3.542.

Tha93 Thayer, K. L., Ramalingam, M. L. & Young, T. J., "Performance Simulation of an Advanced Cylindrical Thermionic Fuel Element with a Graphite Reservoir," Proc. of the 28th Thermophysics Conference, 1993.

Tha94a Thayer, K. L., Ramalingam, M. L. & Young, T. J., "Sensitivity Analysis on a Cylindrical Thermionic Converter," Proc. 11th Symposium on Space Nucl. Power System, 1994, vol. 1, pp. 297-302.

Tha94b Thayer, K. L., Ramalingam, M. L., Young, T. J. & Lamp, T. R., "Life Testing and Diagnostics of a Planar Out-of-Core Thermionic Converter," Proc. 11th Symposium on Space Nucl. Power System, 1994, vol. 2, pp. 1017-1024.

Tit89 Titran, R. H., "Long-Time Creep Behavior of Nb-1%Zr and PWC-11," Proc. 6th Symposium on Space Nucl. Power System, 1989, vol. 1, pp. 189-193.

Tra90 Trama, K., Stevens, F., Lonergan, B., Witt, T. & Miskolczy, G., "Ceramic Composites for Thermionic Fuel Elements," Proc. 25th Intersoc. Energy Conv. Engr. Conf., 1990, vol. 2, pp. 340-345.

Tru88 Trujillo, V. ,Merrigan, M. & Ranken, W., "Characterization of Compliant Thermal Conductive Tungsten Material for Thermionic Element Application," Proc. 23th Intersoc. Energy Conv. Engr. Conf., 1988, vol. 1, pp. 601-606.

Tsa90 Tsao, B. H., Ramalingam, M. L. & Donovan, B. D., "Creep Considerations of a (W-Re-Hf)C Alloy for Thermionic Fuel Element Application," Proc. 25th Intersoc. Energy Conv. Engr. Conf., 1990, vol. 2, pp. 326-331.

Tsa93 Tsao, B. H., Ramalingam, M. L., Young, T. J. & Donovan, B. D., "Fission-Product Gas Pressure Analysis in the ATI-TFE," Proc. 28th Intersoc. Energy Conv. Engr. Conf., 1993, vol. 1, pp. 1.499-1.504.

Uso93a Usov, B., Nikolaev, Yu., Vybyvanets, V., Kozlov, O., Uvarov, V. & Tsetskhladze, D., "Researches of the TFE Insulation Characteristics of the TOPAZ II Assembly: Stability of Ceramic Insulating Materials in the TFE Interelctrode Space Environment," Joint Russian-American Enterprise Inertek, NMERI, Alburquerque, NM, 1993.

Uso93b Usov, V. A., Kalandarishvili, A. G., Stepennov, B. S., Kashiya, V. G. & Tsakadze, L. M., "Working Medium Sources Based on Layered Graphite-Cesium Compounds for Autonomous Thermionic Fuel Elements," Joint Russian-American Enterprise Inertek, NMERI, Alburquerque, NM, 1993.

Van90 Van Dam, S. A. & Ramalingam, M. L., "Application of a One-Dimensional TEC Code to the Characterization of a Lanthanum-Hexaboride Diode," Proc. 25th Intersoc. Energy Conv. Engr. Conf., 1990, vol. 2, pp. 346-351.

Vas91 Vasilchenko, A., "Characteristics of Single-Crystal Alumina Electrical Conductivity in Vacuum and Cesium Vapor," Joint Russian-American Enterprise Inertek, NMERI, Alburquerque, NM, 1991.

Vec89 Veca, A. R., Horner, M. H., Dunlay, J. A., Trama, K., Ranken, W. A., Cannon, N. S. & Lawrence, L. A., "Irradiation Testing of Components for Thermionic Fuel Elements," Proc. 6th Symposium on Space Nucl. Power System, 1989, vol. 1, pp. 256-259.

Vel92 Veltkamp, W. B., van Kemenade, H. P. & Sampers, W. F. J., "Combustion Heated Thermionic Systems," Proc. 27th Intersoc. Energy Conv. Engr. Conf., 1992, vol. 3, pp. 3.443-3.450.

Vel93 Veltkamp, B. & Van Kemenade, E., Combustion Heated Thermionic Systems: Thermionic Energy Conversion Short Course, Eindhoven University of Technology, Netherlands, 1993.

Vib92 Vibivanets, V. I. & Stepennov, B. S., "TOPAZ II (V-71 and YA-21U) TFE Design, Fabrication and Performance Analysis to Justify the Demonstration Tests Modes," Joint Russian-American Enterprise Inertek, NMERI, Alburquerque, NM, 1992.

Viz90 Vizgalov, A. V., Gulin, M. V., Mironov, V. S., Savvoy, R. V., Sibir, E. E. & Skrebova, Z. B., "Thermionic Converter with All Single Crystal W(110)-W(110) Electrodes," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Vla90 Vlasov, V. V. & Degal'tsev, Yu. G., "Post-Reactor Studies of Helium Migration Processes in Beryllium," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Vui90 Vuivuivanetz, V. I., Gontar, A. S., Gordinsky, V. L., Dementiev, L. N., Eremin, S. A., Izhvanov, O. L. & Korobov, A. V., "Experimental Development of a Single-Element Thermionic Power Generated Channel Through Thermal and Reactor Tests," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Vya90 Vyakhorev, V. G., Glagolev, A. E., Nilov, N. A., Oleinikov, P. P., Ordyntsev, V. A. & Taubin, M. L., "Nondestructive Control Methods and Means of Structural Elements of Nuclear Power Plants," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Wal90 Wall, R. N. & Jacobsen, D. L., "Effective Work Function of Tungsten, Osmium Alloys," Proc. 7th Symposium on Space Nucl. Power System, 1990, vol. 1, pp. 85-90.

Wet83 Wetch, J. R., Rasor, N. S., Britt, E. J. & Fitzpatrick, G. O., "Thermionic Space Reactors Overview," Proc. 18th Intersoc. Energy Conv. Engr. Conf., 1983, vol. 1, pp. 170-178.

Wet85 Wetch, J. R., Begg, L. L. & Koester, J. K., "Static and Dynamic High Power, Space Nuclear Electric Generating Systems," Proc. 20th Intersoc. Energy Conv. Engr. Conf., 1985, vol. 3, pp. 3.513-3.520.

Wit93 Witt, T. & Lieb, D., "S-PRIME Cesium Reservoir Design and Modeling," Proc. 28th Intersoc. Energy Conv. Engr. Conf., 1993, vol. 1, pp. 1.505-1.510.

Wol83 Wolff, L. R., Gubbels, G. H. M., Metselaar, R., Danielson, L. R., Saunders, M. & Huffman, F., "Development and Evaluation of Directionally Solidified Cermet Electrodes for Thermionic Energy Converters," Proc. 18th Intersoc. Energy Conv. Engr. Conf., 1983, vol. 1, pp. 202-207.

Wol88 Wolff, L. R., "Status Report on the Dutch Thermionic Energy Conversion Research," Proc. 23th Intersoc. Energy Conv. Engr. Conf., 1988, vol. 1, pp. 613-616.

Wol94 Wold, S. K., Izhvanov, O. L., Vibivanets, V. I. & Schmidt, G. L., "Topaz-II Thermionic Fuel Element Testing," Proc. 11th Symposium on Space Nucl. Power System, 1994, vol. 2, pp. 1025-1030.

Wu94 Wu, W. Y., Patuwathavithane, C. & Zee, R. H., "Radiation Induced Conductivity in Ceramics Insulators for Thermionic Systems," Proc. 11th Symposium on Space Nucl. Power System, 1994, vol. 2, pp. 1147-1152.

Yan72 Yang, L., "Material Development for Thermionic Fuel-Cladding Systems," Proc. 3rd Int. Conf. of Thermionic Elec. Power Generation, 1972, vol. 2, pp. 873-894.

Yar92a Yarygin, V. I., Vizgalov, A. V., Klepikov, V. V., Tulin, S. U., Ruzhnikov, V. A., Wolff, L. R. & Veltkamp, W. B., "Progress in the Field of Terrestrial Thermionics," Proc. 27th Intersoc. Energy Conv. Engr. Conf., 1992, vol. 3, pp. 3.437-3.442.

Yar92b Yarygin, V. I., Vizgalov, A. V., Skrebova, Z. B. & Rodichev, I. K., "The Emitter Envelopes for Power Intensive Thermionic Fuel Elements," Proc. 27th Intersoc. Energy Conv. Engr. Conf., 1992, vol. 3, pp. 3.519-3.522.

Yas90 Yastrebkov, A. A., Repi, V. A. & Lepeshenkov, E. K., "Structural Perfection of Engineering Materials on the Base of Single Crystals of Refractory Metals," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

You92 Young, T. J., Ramalingam, M. L. & Tsao, B. H., "Orientational Effects on the Performance of a Heat Pipe Coupled Thermionic Converter," Proc. 27th

Intersoc. Energy Conv. Engr. Conf., 1992, vol. 3, pp. 3.455-3.460.

You93 Young, T. J., Thayer, K. L. & Ramalingam, M. L., "Thermal Transients During Startup in a TFE Lead with Graphite Reservoirs," Proc. 28th Intersoc. Energy Conv. Engr. Conf., 1993, vol. 1, pp. 1.525-1.530.

Zha93 Zhabotinsky, E. E., Gryaznov, G. M., Servin, V. I., Andreev, P. V., Galkin, A. Ta., Nikonov, A. M. & Zaritsky, G. A., "Prospects of Thermionic Nuclear Power Systems for Space Power and Propulsion Complexes," Proc. 28th Intersoc. Energy Conv. Engr. Conf., 1993, vol. 1, pp. 1.593-1.598.

Zhe88 Zheng, C., Begg, L. L., Lawless, J. L. & Britt, E. J., "An Analytical Method to Predict In-Core Thermionic Emitter Temperature and Current Density Profiles," Proc. 23th Intersoc. Energy Conv. Engr. Conf., 1988, vol. 1, pp. 567-572.

Zhe90a Zherebtsov, V. A., Kiriutchenko, A. I., Kononova, Z. I., Lebedev, M. A., Mironov, V. S. & Sibir, E. E., "Influence of Hydrogen Admixture in Interelectrode Spacing on the TEC Operation," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Zhe90b Zherebtsov, V. A., Lebedev, M. A., Soboleb, A. A. & Talanova, V. D., "Effects of Diatomic Gas Impurities on Energy Losses in TEC," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Zhe90c Zherebtsov, V. A., Lebedev, M. A., Lukyanov, A. A. & Sobolev, A. A., "Chemical Composition of Cesium Plasma with Simple Molecular Gas Impurities," Proc. 25th Intersoc. Energy Conv. Engr. Conf., 1990, vol. 2, pp. 352-356.

Zhu90 Zhurin, S. V., Surkov, L. Ya., Syshikov, L. A. & Yudakov, G. A., "Post-Reactor Examination of Ground Prototype of 'TOPAZ' NPS with Multielement TFE," Proc. of the Annv. Spec. Conf. on Nuclear Power Engr. in Space, 1990.

Zub94 Zubrin, R. M., "Beyond Electric Propulsion: Non-Propulsive Benefits of Nuclear Power for the Exploration of the Outer Solar System," Proc. 11th Symposium on Space Nucl. Power System, 1994, vol. 2, pp. 725-732.

BIOGRAPHICAL SKETCH

Morgan Curtis White [redacted] son of Virginia Leslie White and Robert Coleman White. He graduated as Valedictorian from Fernandina Beach High School and received both the National Merit and Florida Undergraduate Scholarship. Arriving at the University of Florida in fall of 1990, he has since completed his Bachelor of Science in Nuclear Engineering degree with highest honors in 1994. He was awarded a Department of Energy Nuclear Engineering Fellowship and entered graduate school. While pursuing his Master of Science degree, he interned with General Atomic Technologies of San Diego, California, working with their Space Power Division. He plans to continue his graduate education here at the University of Florida.