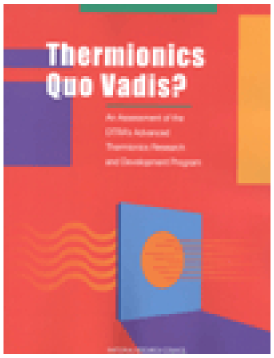

Thermionics Quo Vadis? An Assessment of the DTRA's Advanced Thermionics Research and Development Program

Committee on Thermionic Research and Technology, Aeronautics and Space Engineering Board, National Research Council

ISBN: 0-309-50965-3, 84 pages, 8.5 x 11, (2001)

Thermionics Quo Vadis?

An Assessment of the DTRA's Advanced Thermionics Research and Development Program

Committee on Thermionic Research and Technology

Aeronautics and Space Engineering Board
Division on Engineering and Physical Sciences
National Research Council

NATIONAL ACADEMY PRESS
Washington, D.C.

NATIONAL ACADEMY PRESS 2101 Constitution Avenue, N.W. Washington, DC 20418

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This study was supported by Contract No. DTRA01-00-C-0001 between the National Academy of Sciences and the Defense Threat Reduction Agency. Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the organizations or agencies that provided support for the project.

International Standard Book Number: 0-309-08282-X

Available in limited supply from: Aeronautics and Space Engineering Board, HA 292, 2101 Constitution Avenue, N.W., Washington, DC 20418, (202) 334-2855

Additional copies available for sale from: National Academy Press, 2101 Constitution Avenue, N.W., Box 285, Washington, DC 20055, (800) 624-6242 or (202) 334-3313 (in the Washington metropolitan area), <http://www.nap.edu>

Printed in the United States of America

THE NATIONAL ACADEMIES

National Academy of Sciences
National Academy of Engineering
Institute of Medicine
National Research Council

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce M. Alberts is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Wm. A. Wulf is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Kenneth I. Shine is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Bruce M. Alberts and Dr. Wm. A. Wulf are chairman and vice chairman, respectively, of the National Research Council.

COMMITTEE ON THERMIONIC RESEARCH AND TECHNOLOGY

TOM MAHEFKEY, *Chair*, Consultant, Atlanta, Georgia
DOUGLAS M. ALLEN,* Schafer Corporation, Dayton, Ohio
JUDITH H. AMBRUS, Space Technology Management Services, Bridgewater, New Jersey
LEONARD H. CAVENY, Aerospace Consultant, Fort Washington, Maryland
HAROLD B. FINGER, Consultant, Chevy Chase, Maryland
GEORGE N. HATSOPOULOS, Thermo Electron Corporation, Waltham, Massachusetts
THOMAS K. HUNT, Advanced Modular Power Systems, Inc., Ann Arbor, Michigan
DEAN JACOBSON, Arizona State University, Tempe, Arizona
ELLIOT B. KENNEL, Applied Sciences, Inc., Cedarville, Ohio
ROBERT J. PINKERTON, Spectrum Astro Corporation, Gilbert, Arizona
GEORGE W. SUTTON, NAE, ANSER Corporation, Arlington, Virginia

Staff

DOUGLAS H. BENNETT, Study Director, Aeronautics and Space Engineering Board
GEORGE LEVIN, Director, Aeronautics and Space Engineering Board
ALAN ANGLEMAN, Senior Program Officer
ANNA L. FARRAR, Administrative Associate
BRIDGET EDMONDS (July 2, 2001, until December 27, 2001), Senior Project Assistant
MARY LOU AQUILO (June 12, 2000, until July 2, 2001), Senior Project Assistant
JAN BERGER (September 1, 2001 until October 26, 2001), Project Assistant
VIKTORIA HERSON (January 28, 2000, until June 12, 2000), Project Assistant

*The full committee served from April 19, 2000 until December 27, 2001. Mr. Allen served on the committee from April 19, 2000, until June 20, 2001.

AERONAUTICS AND SPACE ENGINEERING BOARD

WILLIAM W. HOOVER, *Chair*, United States Air Force (retired), Williamsburg, Virginia
A. DWIGHT ABBOTT, Aerospace Corporation (retired), Los Angeles, California
RUZENA K. BAJSCY, NAE, IOM, National Science Foundation, Arlington, Virginia
WILLIAM F. BALLHAUS, JR., NAE, Aerospace Corporation, Los Angeles, California
JAMES BLACKWELL, Lockheed Martin Corporation (retired), Marietta, Georgia
ANTHONY J. BRODERICK, Aviation Safety Consultant, Catlett, Virginia
DONALD L. CROMER, United States Air Force (retired), Lompoc, California
ROBERT A. DAVIS, The Boeing Company (retired), Seattle, Washington
JOSEPH FULLER, JR., Futron Corporation, Bethesda, Maryland
RICHARD GOLASZEWSKI, GRA Inc., Jenkintown, Pennsylvania
JAMES M. GUYETTE, Rolls-Royce North America, Reston, Virginia
FREDERICK H. HAUCK, AXA Space, Bethesda, Maryland
JOHN L. JUNKINS, NAE, Texas A&M University, College Station
JOHN K. LAUBER, Airbus Industrie of North America, Washington, D.C.
GEORGE K. MUELLNER, The Boeing Company, Seal Beach, California
DAVA J. NEWMAN, Massachusetts Institute of Technology, Cambridge
JAMES G. O'CONNOR, NAE, Pratt & Whitney (retired), Coventry, Connecticut
MALCOLM R. O'NEILL, Lockheed Martin Corporation, Bethesda, Maryland
CYNTHIA SAMUELSON, Opsis Technologies, Springfield, Virginia
WINSTON E. SCOTT, Florida State University, Tallahassee
KATHRYN C. THORNTON, University of Virginia, Charlottesville
ROBERT E. WHITEHEAD, NASA (retired), Henrico, North Carolina
DIANNE S. WILEY, The Boeing Company, Long Beach, California
THOMAS L. WILLIAMS, Northrop Grumman, El Segundo, California

Staff

GEORGE LEVIN, Director

Preface

Generating electricity from a heat source using no moving mechanical parts is the ultimate goal of the Defense Threat Reduction Agency's thermionics program. However, developing thermionic energy conversion devices has proven difficult, although much progress has been made. In spite of initial success during the late 1960s and intermittent funding since that time, for a variety of reasons no thermionic system has yet been developed in the United States that can be used today on Earth or in space. The ability of humankind to reach farther and farther into the solar system and beyond is determined, in part, by our ability to generate power in space for spacecraft use.

Thermionic energy conversion has been pursued since the advent of the space age by virtue of its intrinsic attributes as a compact, high performance space power system candidate. While the revolutionary missions that spawned interest in thermionics 40 years ago have yielded to an evolutionary approach to space utilization and exploration, potential future revolutionary missions prompt interest in maintaining and supporting development and examination of this potential technology option today.

Progress in the technology was substantial during the 1960s but waned in the early 1970s due to a shift in space technology funding priorities. The advent of the Strategic Defense Initiative (SDI) and space exploration initiatives in the late 1970s rekindled interest and investment in thermionics. However, that investment diminished again in the mid 1990s, not as a result of lack of progress, but because of changes in national technology investment priorities. Today, the thermionic technology base and infrastructure stand close to extinction. Only a modest $1.5 million to $3 million per year is directed toward sustaining the technology.

Two complete 5 kilowatt-electric nuclear reactor thermionic systems have been developed and flown in space by the former Soviet Union for experimental purposes, but no follow-up Russian or U.S. development on a high power thermionic system has taken place for a variety of reasons. Among them, the political nature of funding priorities involves decisions based on technology considerations, specifically concerning competing technologies that might accomplish the same system-level mission goals as thermionic systems.

The Committee on Thermionic Research and Technology started by asking a difficult question: In light of past efforts and the lack of apparent success in developing a fully functioning system and uncertain requirements, why do thermionics at all? This report is written to answer that question in view of potential future needs and applications while recognizing the existing technological risks as well as the currently available alternative power conversion technologies, in the context of the present, congressionally mandated, DTRA thermionics technology program (see Appendix A for the statement of task).

This study was sponsored by DTRA and was conducted by the Committee on Thermionic Research and Technology appointed by the National Research Council (see Appendix B).

This report has been reviewed by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the authors and the National Research Council in making the published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. The committee wishes to thank the following individuals for their participation in the review of this report:

Henry W. Brandhorst, Jr., Space Power Institute, Auburn University,
Lee S. Mason, NASA Glenn Research Center,
Gerald D. Mahan, NAS, Applied Physical Sciences, and
Mohamed S. El-Genk, University of New Mexico, Institute for Space and and Nuclear Power Studies.

Although the reviewers listed above have provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release.

The review of this report was overseen by Simon Ostrach, Case Western Reserve University. Appointed by the National Research Council, he was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

The committee also wishes to thank others whose efforts supported this study, especially those who took the time to participate in committee meetings and the thermionics workshop held in La Jolla, California.

Tom Mahefkey, *Chair*
Committee on Thermionic Research and Technology

Contents

Tables, Figures, and Boxes

TABLES

FIGURES

BOXES

Executive Summary

In 1995, the Defense Nuclear Agency, now a part of the Defense Threat Reduction Agency (DTRA), was assigned management responsibility for the remnants of the thermionics research and development programs of the Ballistic Missile Defense Organization (BMDO) and the U.S. Air Force (USAF). The main thrust of the combined program was a cooperative U.S.-Russian project called the TOPAZ International Program, which was based on the Russian TOPAZ nuclear thermionic power system. (TOPAZ is a Russian acronym meaning thermionic power from the active zone.) The TOPAZ International Program was terminated in 1996 in response to (1) findings made by the General Accounting Office and a study by the National Research Council (NRC 1996) questioning the relevance of the unfueled TOPAZ system testing, (2) the absence of a Department of Defense (DoD) and NASA requirement for near-term space nuclear power systems, and (3) a pressing need to prioritize resources. Most of the remaining thermionic technology projects being conducted by BMDO and the Air Force Research Laboratory (AFRL) were terminated or phased out shortly thereafter.

Congress subsequently directed DTRA to establish a modest, technology-focused thermionics program. The DTRA program incorporated a variety of projects performed by industry, universities, two Russian institutes, and a Department of Energy (DOE) laboratory. In 1999, after 3 full years, DTRA sought an independent assessment of its stewardship of the advanced thermionics research and development program and of the technical progress of the program. The NRC accepted the charge of performing this assessment.

The statement of task for this study required the NRC to perform the following tasks:

- Evaluate DTRA's prior and present sponsored efforts.
- Assess the present state of the art in thermionic energy conversion systems.
- Assess the technical challenges to the development of viable thermionic energy conversion systems for both space and terrestrial applications.
- Recommend a prioritized set of objectives for a future research and development program for advanced thermionic systems for space and terrestrial applications.

An additional task was to conduct a workshop for the interim discussion of technical challenges and a strategy for meeting those challenges. The results of the workshop are incorporated into this report.

PROGRESS IN THERMIONIC RESEARCH

Despite being limited by modest funding, DTRA has made good progress since its redirection to a technology program in 1996. Given the funding limitations and uncertainties, the industry and university participants generally have performed admirably. The committee was especially impressed by the technical accomplishments in the cooperative work conducted by U.S. and Russian researchers on single-crystal refractory metal alloys research under the auspices of the DTRA program.

Nevertheless the committee believes that, despite these accomplishments, the overall goals of the present program are too broad and diverse to be accomplished given the projected budget constraints. The committee also notes that the thermionic technology program is not encompassed by the primary mission statement of the DTRA organization. This being so, the committee believes that the program could be more effectively planned, managed, coordinated, and conducted by the AFRL.

OVERVIEW AND ASSESSMENT OF THE DTRA THERMIONICS PROGRAM

The present DTRA thermionics program consists of three major elements, namely the nuclear power in-core thermionic technology element, performed primarily by General Atomics and several subcontractors; the microminiature thermionic converter element performed by DOE's Sandia National Laboratories; and the theory and theory model validation element, performed by the DTRA staff and consultants. Table ES-1 summarizes the tasks conducted under the DTRA thermionics program.

From fiscal year 1996 to 1999, DTRA also sponsored a portion of the thermionic generator testing conducted under the USAF's Solar Orbital Transfer Vehicle program. The DTRA thermionics program includes both basic and applied research as well as engineering development and demonstration efforts.

TABLE ES.1 Major Elements of the DTRA Thermionics Program

Major Thermionic Program Element	Subelement	Subtask	Responsible Research Group
Nuclear power in-core	Conductively coupled/multi-cell thermionic fuel element (TFE)	Trilayer insulation design, development, and device testing	General Atomics in collaboration with Russian research facilities
	Oxygenated thermionic converters	Oxygenated electrode testing	General Atomics in collaboration with Russian research facilities
		Oxygen mass transport	Russian research facilities
	High-creep strength fuel clad development	Single-crystal alloy domestic fabrication and creep testing; closed chemical vapor deposition process	Auburn University in collaboration with Russian research facilities
	Advanced thermionic converter: close-spaced converter	Device development and testing	Russian research facilities
	Advanced thermionic converter: low emissivity converter development	Design and proof of concept	Russian research facilities
Microminiature thermionic converter (MTC)	Proof of performance and theory validation	Low work function coating development device testing	Sandia National Laboratories with New Mexico Engineering Research Institute test support
Thermionic theory and model validation	Thermionic space reactor system mass model	RSMASS-T system model upgrade	DTRA staff
	Thermionic theory and theory validation	Vacuum converter theory development and surface effects modeling	DTRA staff and consultants

Of the three major elements that make up the DTRA thermionics program, the committee recommends that the microminiature thermionic converter (MTC) effort and the theory and validation efforts be discontinued. While the MTC effort can be appreciated for its innovation and its attempts to eventually provide some potential technology spin-off to other fields in the future, the committee does not believe that the promise of the MTC concept can ever be realized without unreasonable amounts of funding.

Likewise, in the committee's opinion, the theory and validation task has a relatively low probability of additional success, and the potential end results do not warrant further expenditures at this time in light of limited available funding.

By contrast, many of the tasks under the nuclear in-core portion of DTRA's thermionic technology program do show promise, and the committee believes that many of those elements in the program should be continued. However, the activities associated with the oxygenated thermionic converter subtask should not be continued. Although they are categorized under the nuclear in-core portion of DTRA's thermionic technology program, the remaining tasks in the thermionics program can be broken down into two broad application areas:

- Space applications
  —Solar power
  —Nuclear power
- Terrestrial applications.

The committee found no firm requirements or need for thermionic systems within DoD or NASA, and thermionic system-level technology is not developed to the point that it is available for mission commitment at this time. However, potential applications may be defined beyond the next decade. The committee believes that the system performance advantages offered by thermionic energy conversion are attractive for future high power space missions employing solar concentrating heat sources or, in the longer term, nuclear reactor heat sources. Because of the unique nature of thermionic systems, the committee believes that a thermionic program should continue to be supported.

Key Finding: Thermionic systems are unique for three reasons: (1) the inherently high power density of the conversion mechanism itself, (2) the systems' high heat rejection temperature, typically 1000 K, which allows thermionic systems to use compact radiators with relatively low masses, and (3) the systems' potential to operate in a higher power "surge mode" for sustained periods over a small fraction of their programmed life. The combination of these three advantages could allow for potentially significant advances in system power level density (kilowatts per kilogram).

SOLAR THERMIONIC SYSTEMS

Although solar thermionic development was explored briefly by NASA in the 1960s, research was curtailed in the early 1970s in favor of solar photovoltaic battery systems. However, standard power requirements for satellites have since increased from several kilowatts to tens of kilowatts. In this range, a solar thermionic system appears to offer advantages in terms of stowed payload volume and mass. Space-based solar thermionic systems, such as the high-power, advanced, low-mass (HPALM) solar thermionic converter proposed by General Atomics, potentially offer competitive specific power.[1] It should be noted that no such system exists at present.

The HPALM concept is an energy conversion system for use with spacecraft operating where solar energy is available. The concept involves the use of an inflatable solar concentrator to focus solar energy onto a thermionic converter to supply power to a spacecraft.

The feasibility of solar thermionic systems is based in part on the demonstrated NASA planar converter and generator technology of the 1960s, namely the solar electric converter used under the Solar Energy Technology (SET) program. Under that program, converters operating at 25 watts per square centimeter and 0.7 volts demonstrated 15,000 hours of life through several hundred thermal eclipse cycles. The individual generators developed under the SET program provided 150 watts of electrical power.

Since then, substantial progress on large, oriented space structures, particularly inflatable structures not related to thermionics research and development, has raised the possibility of using large solar concentrators in space. The committee recommends that the sponsoring agency[2] direct the near-term thermionics research

[1]Specific power is defined as the power per unit mass, or kilowatts per kilogram.

[2]The term "sponsoring agency" is used to reflect the recommendation that the program be transferred from the DTRA to the AFRL.

and development toward a solar thermionic application that could provide mid to high tens of kilowatts (roughly 30 to 70 kilowatts) of electrical power to a client spacecraft. In particular, the program should be aligned with the HPALM concept.

The committee conducted a detailed review of the relatively unsuccessful New Mexico Engineering Research Institute (NMERI) string thermionic assembly research testbed (START) efforts. The tests consisted of connecting strings of electrically connected thermionic converters, forming thermionic generators, to validate a system-level power conversion concept for the AFRL Solar Orbital Transfer Vehicle (SOTV) program.

The committee decided that the tests should be reviewed because of the conclusions apparently drawn from the inconclusive tests. The testing team concluded that the poor test results indicated problems with the converter technology. Based on available documentation, however, the committee believes that serious test procedural problems may have been to blame and that no conclusions should be made about thermionic converter performance based on those tests.

NUCLEAR POWER THERMIONIC SYSTEMS

A 1998 report of the National Research Council's Committee on Advanced Space Technology (NRC 1998) stated as follows:

> Advanced space nuclear power systems will probably be required to support deep space missions, lunar and planetary bases, extended human exploration missions, and high-thrust, high-efficiency propulsion systems. A major investment will eventually be needed to develop advanced space nuclear power sources. . . . Unless NASA supports R&T in areas such as innovative conversion methodologies or innovative packaging and integration, future space nuclear power systems will probably be more expensive and less efficient.

For some missions that will require high power and long life, or where nuclear power is a critical requirement, the potential performance advantages of nuclear thermionic space power are compelling for electric propulsion missions. In terms of lifetime and device-level power output, coupled with their low mass, compactness, and surge mode capability, thermionic systems are attractive, and the nearly unique features of this technology could satisfy future space power requirements for 20 kilowatts up to megawatts of electric power.

In some cases, fully developed thermionic technology may be mission enabling. However, the committee also acknowledges that the technical risks in developing a functional thermionic system are high. The technical uncertainty surrounding an operational system that could achieve the desired performance is especially high for power systems that use thermionic converters powered by in-core nuclear reactors.

The most challenging and expensive feasibility issues for nuclear thermionic systems are clearly those related to the integration of the converter into the nuclear reactor core. These issues include nuclear fuel swelling, which causes structural deformation and electrical short circuits in the thermionic converter, and radiation damage to converter insulator materials. At present, any thermionic fuel element using nuclear fuel would be life limited due to nuclear fuel swelling. This limitation currently makes nuclear thermionic systems impractical for missions with a requirement for long operational life. The original Russian TOPAZ reactor program demonstrated a 1 year life operational capability in space. The U.S. thermionic fuel element verification program projected system life to be greater than 3 years; however, no such system has been built. There is no capability in the United States to test nuclear thermionic fuel materials for fuel swelling issues because those fast-spectrum test facilities were deactivated. A possible alternative to reestablishing test facilities in this country is to coordinate with Russia in future thermionic materials testing.

Given the very high cost of developing and deploying space nuclear reactors, the committee does not recommend pursuing thermionic technology solely for use with nuclear power sources in the near term. Instead, the thermionics research and technology program should have the development of a thermionic space nuclear capability as a long-term goal. A challenge to balancing near- and long-term plans is to identify technologies that can be adapted to both solar and nuclear thermionic applications.

TERRESTRIAL THERMIONIC SYSTEMS

Terrestrial thermionic applications are specifically mentioned in the statement of task for this study, even though such applications have received little attention from any research organization in the past two decades. The committee found no significant interest in terrestrial military or commercial fossil-fuel-based thermionic systems. Past interest had been motivated by a desire to increase energy conversion efficiency and reduce pollution. The committee believes that this lack of interest is a result of the high cost of thermionic systems and the fact that neither long-term reliability nor the systems themselves have been proven. There is currently no incentive in the marketplace to develop terrestrial thermionic systems in spite of rising fuel costs, significant power shortages, and environmental pollution.

SUMMARY AND CONCLUSIONS

Although thermionic systems have the potential to satisfy many future power system needs, other power conversion technologies are also being developed. In relation to these other potential technologies, the committee believes that thermionic technology may offer equal or superior merit for specific missions. The future sponsor should continue to evaluate and develop the possibilities of thermionic systems despite the challenge of preserving, continuing, and advancing this technology in the near term.

The following recommendations are presented in order of priority. The first recommendation, to move the thermionics program from the DTRA to the Air Force Research Laboratory (AFRL), is listed as the primary recommendation strictly from a programmatic point of view. The committee urges those working within and managing the thermionics program on a daily basis to concentrate on recommendations two through seven, which are offered by the committee in order to strengthen the program on a technology level.

Recommendation 1. The United States Congress and the Administration should transfer responsibility for the technical management of the Defense Threat Reduction Agency's thermionics program to the Air Force Research Laboratory. Doing so would enhance the technical continuity for the technology and place the program in an agency responsible for developing power systems and conversion technologies. As the focal point for thermionic research, the Air Force Research Laboratory should attempt to establish cooperative activities with other government agencies, such as the Department of Energy, the Naval Research Laboratory, NASA, and the Air Force Office of Scientific Research.

Recommendation 2. The sponsoring agency should generate a long-term plan to focus activities related to both solar and nuclear applications for thermionic technology.

Recommendation 3. The sponsoring agency should concentrate its near-term thermionic development work on a space-based solar thermionic power system, such as the high-power, advanced, low-mass (HPALM) concept.

Recommendation 4. The sponsoring agency should concentrate longer-term thermionic development work on those areas of nuclear thermionic power systems related to materials development, converter development, and radiation effects on materials in order to achieve high power and long life for such systems.

Recommendation 5. The sponsoring agency should reestablish an adjunct basic research program on electrode surface physics, plasma, and materials processes relevant to thermionic energy conversion. This program should be funded separately from the thermionics research program.

Recommendation 6. The sponsoring agency should discontinue the microminiature thermionic converter (MTC) program, the close-spaced vacuum converter tasks, the oxygenation effects research, and all current theory and theory validation work.

Recommendation 7. When working on a system-level solar thermionic design, the sponsoring agency should reexamine the string thermionic assembly research testbed (START) tests in order to record lessons learned. The reexamination should begin with a retest of the original, individual converters to differentiate between problems due to the converter design and generator configuration and those due to the test setup. The sponsoring agency should gather an independent group of experts to devise testing methodologies so as not to repeat past mistakes.

REFERENCES

NRC (National Research Council). 1996. *Assessment of the TOPAZ International Program*. National Academy Press, Washington, D.C.

NRC (National Research Council). 1998. *Space Technology for the New Century*. National Academy Press, Washington, D.C.

1

Introduction

BACKGROUND

In 1995, the Defense Nuclear Agency, now a part of the Defense Threat Reduction Agency (DTRA), was assigned management responsibility for the remnants of the thermionics research and development programs of the Ballistic Missile Defense Organization (BMDO) and the U.S. Air Force The major thrust of the new combined program was a cooperative U.S.-Russian project called the TOPAZ International Program (TOPAZ is a Russian acronym meaning thermionic power from the active zone). The TOPAZ program was terminated in 1996 in response to (1) findings by the General Accounting Office and a study by the National Research Council (NRC 1996) questioning the relevance of the unfueled TOPAZ system testing, (2) the absence of a Department of Defense (DoD) and National Aeronautics and Space Administration (NASA) need for near-term space nuclear reactor power systems, and (3) pressure to prioritize resources. Most of the remaining thermionic technology projects being conducted by BMDO and the Air Force Research Laboratory were terminated or phased out shortly thereafter.

Congress subsequently directed DTRA to establish a modest, technology-focused thermionic program. The DTRA program incorporated a variety of projects being performed by industry, universities, several Russian institutes, and a Department of Energy (DOE) laboratory. In 1999, after 3 full years of planning and management, DTRA sought an independent assessment of its stewardship of the advanced thermionics research and development program and the technical progress of the program. The NRC accepted the charge of performing this assessment.

The statement of task for this study, which appears in Appendix A, required the NRC to perform the following tasks:

- Evaluate DTRA's prior and present sponsored efforts.
- Assess the present state of the art in thermionic energy conversion systems.
- Assess the technical challenges to the development of viable thermionic energy conversion systems for both space and terrestrial applications.
- Recommend a prioritized set of objectives for a future research and development program for advanced thermionic systems for space and terrestrial applications.

An additional task was to conduct a workshop for the interim discussion of technical challenges and a strategy for meeting those challenges. The meetings and workshop included participants from nongovernmental organizations, industry, and academia. The results of the workshop are incorporated into this report.

To accomplish these tasks, the NRC's Aeronautics and Space Engineering Board established the Committee on Thermionic Research and Technology, consisting of 11 members. Brief biographies of the committee members are presented in Appendix B.

APPROACH

The committee first met with DTRA representatives in May 2000 to clarify the objectives and purposes of the study. DTRA representatives attended and participated in all subsequent open meeting activities. The study was conducted independently, in keeping with NRC procedures and government contracting regulations.

At the second meeting in June 2000, the committee met with all of the government thermionic research and development organizations and potential technology user organizations, including NASA, DOE, and DoD. The committee was also briefed on current and potential NASA and DoD mission and system applications for thermionic technology, including envisioned power requirements. Earth-based (terrestrial) applications and commercial power technology development activities were assessed based on discussions with commercial power industry representatives and a recent NRC study on the DOE's renewable energy program (NRC 2000).

During the information gathering phase of the study, the committee received technical briefings from all of the researchers in the United States currently sponsored by the DTRA program. The committee also sponsored a 2-day thermionic technology workshop in La Jolla, California, in August 2000. At that workshop, the committee presented an overview of the major tasks to representatives of the thermionics community. In turn, the committee received additional technical briefings and suggestions for recommendations from the thermionics community, some of which the committee ultimately adopted.

All written materials presented to the committee during the course of this study, including materials presented at the workshop, are maintained on file as a matter of public record at the NRC.

The information gathering phase of this study also included a complete review of three earlier NRC studies related specifically to thermionics, *Advanced Nuclear Power Sources for Portable Power in Space* (NRC 1983), *Advanced Power Sources for Space Missions* (NRC, 1989), and *Assessment of the TOPAZ International Program* (NRC 1996).

A related report, *Renewable Power Pathways: A Review of the United States Department of Energy's Renewable Energy Programs* (NRC 2000), and discussions with commercial power industry representatives, aided the committee in evaluating terrestrial applications and national commercial power technology development activities.

ORGANIZATION OF THIS REPORT

The seven recommendations in this report are prioritized as presented in the executive summary. However, in the main body of the report, they are placed with the relevant subject matter topics and discussion, rather than in prioritized order.

The committee found that many of the technology program elements that the DTRA is currently funding should be discontinued. For the purpose of this study, the remaining program elements fall into three broad categories discussed in Chapters 4, 5, and 6, respectively:

1. Space solar power applications,
2. Space nuclear power applications, and
3. Terrestrial applications.

Chapter 2 of this report presents the conclusions of the study. Thermionic systems offer the potential to satisfy many future power system needs. However, thermionics is but one candidate in a field of many, several of which are also in as austere funding situation as thermionics. The committee believes that in relation to these other technologies, thermionic technology has worth and should continue to be developed. However, the committee acknowledges that preserving, continuing, and advancing this technology in the near term will be extremely challenging.

The committee praises the technical quality and accomplishments of the cooperation between U.S. and Russian researchers under the auspices of the DTRA program. At the same time, the committee is concerned that there is a possibility of undesired transfer of technology from the United States to China through the Russian researchers. It has been reported that China is engaging in thermionic research and development.

The committee believes that a firm understanding of the technical and programmatic history of past thermionic activities, of the technology's successes and failures, and of programmatic and national policy issues is essential for planning the future direction of the program. Accordingly, Chapter 3 briefly reviews thermionic energy conversion principles and history and discusses thermionic system attributes as they relate to potential applications in future missions. Although it found no firm requirements for thermionics for any DoD- or NASA-approved missions, the committee believes that the system performance advantages offered by thermionic energy conversion could be utilized in future high power space missions employing a solar-concentrator or nuclear reactor heat source. In some cases, fully developed thermionic technology may be mission enabling. The committee also acknowledges that the technical risks in developing a functional thermionic system are high. The technical risk and uncertainty are especially high for power systems that use thermionic converters powered by nuclear reactors. Given the tremendous cost of developing and deploying space nuclear reactors, the committee does not recommend pursuing either short-term thermionic technology solely for use with nuclear power sources or system development activities until a mission is identified that will require such a power source.

Should a high power mission, one requiring a nuclear reactor in space, be identified, the demonstrated capabilities of thermionic systems, coupled with their intrinsic low mass and compactness, could satisfy future space power requirements in the low to mid tens of kilowatts to megawatts.

Chapter 3 also summarizes the demonstrated state of the art of thermionics technology as related to space and terrestrial applications. Much of the existing technology base supporting the feasibility of system application has already been demonstrated, particularly for solar applications as demonstrated by NASA's Jet Propulsion Laboratory (JPL) Solar Energy Technology (SET) program. The remaining development issues within the arena of solar thermionics are significant, but those problems have been clearly defined as a result of past efforts.

The most challenging and expensive technology feasibility issues are those that are related to integration of the converter into the nuclear reactor core and that are mostly dependent on structural deformation induced by nuclear fuel swelling. The structural deformation (or creep) results in electrical shorting in the converter and radiation damage to converter insulator materials. Both problems raise questions about the suitability of a thermionic system for an extended space mission life of 10 years or more.

Chapter 4 reviews the potential use of thermionics in conjunction with power systems that use concentrated solar energy. First considered in the 1960s, development of solar thermionics was curtailed in the early 1970s owing to the competitive advantages of solar photovoltaic battery systems and their ability to satisfy the prevalent need at that time for hundreds of watts up to a few kilowatts of electrical power. As potential power requirements grow into the 30-plus kilowatt range, solar thermionic systems appear to offer stowed payload volume advantages, competitive specific power capabilities, and the ability to operate in higher natural radiation orbital environments than most other energy conversion systems.[1] The feasibility of such solar thermionic system concepts is based in part on the demonstrated JPL planar converter and thermionic generator technology of the 1960s, especially those technologies generated under the JPL SET program. Under that program, converters operated at 25 watts per square centimeter and 0.7 volts with a demonstrated life of 15,000 hours. Progress in large, oriented space structures, particularly inflatable structures, has also contributed greatly to solar thermionic feasibility.

Chapter 5 presents a review of thermionic technology as it relates to space nuclear reactor power systems. The demonstrated performance of the short-life Russian TOPAZ thermionic space reactor system is discussed, as are the accomplishments of the Thermionic Fuel Element Verification program sponsored by the Strategic Defense Initiative during the mid 1990s. The key remaining technology issues are described, as are arguments for nuclear in-core thermionics versus nuclear out-of-core conversion systems.

Chapter 6 covers terrestrial applications of thermionics. Even though these applications have received little attention in the past two decades, the committee was specifically tasked with identifying them. In response, the committee has included a brief summary of past terrestrial efforts; however, the committee found no current interest for terrestrial military thermionic systems or commercial fossil-fueled thermionic systems. The desire to increase power conversion efficiency and decrease pollution motivated past system concepts, but there is currently no market incentive to develop terrestrial thermionic systems in spite of rising fuel costs, significant power shortages, and environmental pollution. The committee believes that this lack of interest is a result of the high cost of thermionic systems and the fact that neither long-term reliability nor the systems themselves have been proven. By contrast, combined cycle gas turbine systems that have a proven long life, high efficiency, and reliability are being used.

In Chapter 7, the committee assesses progress made under the current DTRA program in certain key areas. The committee believes that the DTRA program has made good progress, especially in light of the limited funding since the program's redirection toward technology development from the previous TOPAZ Inter-

[1]Specific power is defined as the power per unit mass, or kilowatts per kilogram.

national Program system-level approach. In general, industry and university participants in the present program have performed admirably given the uncertainties surrounding funding.

Appendix A contains the DTRA statement of task, and brief committee member biographies are presented in Appendix B. Appendixes C and D contain supporting material on electric propulsion and list the acronyms used in the report, respectively.

REFERENCES

NRC (National Research Council). 1983. *Advanced Nuclear Power Sources for Portable Power in Space*. National Academy Press, Washington, D.C.

NRC (National Research Council). 1989. *Advanced Power Sources for Space Missions*. National Academy Press, Washington, D.C.

NRC (National Research Council). 1996. *Assessment of the TOPAZ International Program*. National Academy Press, Washington, D.C.

NRC (National Research Council). 2000. *Renewable Power Pathways: A Review of the United States Department of Energy's Renewable Energy Programs*. National Academy Press, Washington, D.C.

2

Conclusions Regarding the Current DTRA Program

THE MISSION OF THE DEFENSE THREAT REDUCTION AGENCY

Thermionics, as a technical entity, is in danger of disappearing. The infrastructure and technology base will disappear unless continued support is provided. Both applied research and basic research are required to maintain the technical infrastructure and attract competent researchers.

The biggest challenge to maintaining a strong thermionics technology program is finding an interested user. The only potential users for thermionics-based technology that the committee has identified are described in Chapter 3. In addition, there seems to be little interest in or enthusiasm for thermionics within the Defense Threat Reduction Agency (DTRA) itself. This is understandable, because the goals of a thermionics research and development program do not coincide with the stated mission of the DTRA.

> The Defense Threat Reduction Agency safeguards the United States and its friends from weapons of mass destruction (chemical, biological, radiological, nuclear and high explosives) by reducing the present threat and preparing for the future threat. DTRA's work covers a broad spectrum of activities—shaping the international environment to prevent the spread of weapons of mass destruction [WMD], responding to requirements to deter the use and reduce the impact of such weapons, and preparing for the future as WMD threats emerge and evolve.[1]

Thermionics technology and devices have traditionally been closely tied to nuclear power applications. As a result, early on there was an indirect link between thermionics and the DTRA mission statement in that research in thermionics was able to employ Russian nuclear specialists. However, in recent years, thermionics technology has been increasingly applied to other, non-nuclear applications. As a result, the goals of the thermionics research and technology effort are no longer compatible with the DTRA mission statement.

Finding: The thermionics research and development effort does not fit within DTRA's current mission.

In discussions with the committee, representatives from the Air Force Research Laboratory (AFRL) indicated an interest in expanding their role in thermionic research and development. In fact, they are currently working in thermionics with the solar orbital transfer vehicle (SOTV) and the high-power, advanced, low-mass (HPALM) concepts as discussed in Chapter 4. This interest in thermionics is logical since the AFRL has the mandate to develop future power supplies for the Air Force, and thermionics could potentially play a role.

The committee believes that it is prudent for the AFRL to assume all responsibilities for thermionic research and development on behalf of the federal government for the following reasons:

- The AFRL has the mandate to work with power conversion technologies, one of which is thermionics.
- The responsible parties at AFRL have expressed an interest in developing thermionic technology.
- The AFRL is already supporting thermionic efforts at a low level.

Recommendation 1. The United States Congress and the Administration should transfer responsibil-

[1]The DTRA mission statement is available online at <http://www.dtra.mil>.

ity for the technical management of the Defense Threat Reduction Agency's thermionics program to the Air Force Research Laboratory. Doing so would enhance the technical continuity for the technology and place the program in an agency responsible for developing power systems and conversion technologies. As the focal point for thermionic research, the Air Force Research Laboratory should attempt to establish cooperative activities with other government agencies, such as the Department of Energy, the Naval Research Laboratory, NASA, and the Air Force Office of Scientific Research.

By transferring thermionics research and development to the AFRL, the federal government would establish one thermionics focal point, for the AFRL could then become the thermionics community coordinator and employ the existing Space Technology Alliance (STA) and the Interagency Advanced Power Group (IAPG) to coordinate efforts and disseminate information. The STA is a U.S. government forum for increasing collaboration across government, industry, and academia. The alliance comprises eight government organizations: the departments of the Air Force, Army, and Navy; the Ballistic Missile Defense Organization; the Defense Advanced Research Projects Agency; the Department of Energy (DOE); the National Aeronautics and Space Administration (NASA); and the National Reconnaissance Office. IAPG is a U.S. government forum whose goal is to increase collaboration in power technology research and development activities across the government. The IAPG operates the Power Information Center, which distributes summaries of current and past projects in power technology to member organizations.

To achieve this aim, the AFRL, or other sponsoring agency, could establish interagency collaborations on thermionics with NASA, the DOE, the Naval Research Laboratory, and the Air Force Office of Scientific Research.[2]

WORK CONDUCTED UNDER THE DTRA PROGRAM

In general, the committee found that most of the research and development sponsored by the DTRA has been good. The benefits in the materials regime are especially apparent as discussed in Chapter 7. The DTRA has accomplished what appears to be solid results in the single-crystal research area, largely by sponsoring research conducted by Russian research institutes.

Finding: DTRA-sponsored efforts in thermionics have yielded respectable technical results at a relatively modest funding level.

However, in general the DTRA thermionics research and development program is attempting to accomplish too many things given the modest levels of funding that are available. The committee appreciates the efforts of the DTRA management team to date and understands that DTRA is attempting to create a technology base of useful elements that other programs or initiatives might use in the future (see Table 2.1). The committee believes, however, that other system programs or mission initiatives will not consider using thermionic power system technology since the technology is largely undemonstrated at the level of a complete power system. Also, future needs for any power conversion technology will be driven by the potential requirements of future mission systems. Since the far-term continuation of a thermionics program is contingent upon the technology actually being used, the committee strongly believes that future thermionics research and development should be localized around a potential sponsor effort. The committee has kept this philosophy in mind when constructing the recommendations in this report.

Finding: The present DTRA program is spread among too many different areas to allow a large impact in any one area.

The DTRA thermionics technology program has been affected by the method of funding and by the manner in which the program has been administered. Since the program has been funded by so-called congressional plus-up funds, there is no long-range funding plan. As a result, no long-range plan for technology has been put in place and pursued that would result in the technology being available on a system level in the foreseeable future. The committee found that there is a general lack of continuity and coordination of funding for the current thermionics research program.

The current program tends to focus on component technology and performance enhancement as the easi-

[2]The term "sponsoring agency" is used to reflect the recommendation that the program be transferred from the DTRA to the AFRL.

TABLE 2.1 Major Elements of the DTRA Thermionics Program

Major Thermionic Program Element	Subelement	Subtask	Responsible Research Group
Nuclear power in-core	Conductively coupled/multi-cell thermionic fuel element (TFE)	Trilayer insulation design, development, and device testing	General Atomics in collaboration with Russian research facilities
	Oxygenated thermionic converters	Oxygenated electrode testing	General Atomics in collaboration with Russian research facilities
		Oxygen mass transport	Russian research facilities
	High-creep strength fuel clad development	Single-crystal alloy domestic fabrication and creep testing; closed chemical vapor deposition process	Auburn University in collaboration with Russian research facilities
	Advanced thermionic converter: close-spaced converter	Device development and testing	Russian research facilities
	Advanced thermionic converter: low emissivity converter development	Design and proof of concept	Russian research facilities
Microminiature thermionic converter (MTC)	Proof of performance and theory validation	Low work function coating development device testing	Sandia National Laboratories with New Mexico Engineering Research Institute test support
Thermionic theory and model validation	Thermionic space reactor system mass model	RSMASS-T system model upgrade	DTRA staff
	Thermionic theory and theory validation	Vacuum converter theory development and surface effects modeling	DTRA staff and consultants

est way to structure a program with limited resources and little assurance of continued funding. However, a system oriented approach would be useful in identifying the major technology needs and tradeoffs early on. For example, the operating temperature regime of solar thermionic converters may be determined by factors such as the characteristics of the solar concentrator rather than by the limitations of the converter per se. Similarly, additional lifetime issues may be determined by factors such as thermal stresses caused by sunlight or eclipse transitions in orbit. The system oriented approach is particularly important for the case of advanced solar concentrator thermionic systems, which may present challenges that are significantly different from those presented by their nuclear counterparts.

Combining this system oriented approach with improved record retention and knowledge capture, which are discussed below, will mean that other nonthermionics related work could take advantage of the advances made to date even if program funding were eliminated in the future.

Recommendation 2. The sponsoring agency should generate a long-term plan to focus activities related to both solar and nuclear applications for thermionic technology.

KNOWLEDGE CAPTURE

The committee found that the DTRA thermionics program has no formal mechanisms to ensure that the results of current work will be available to future researchers, including non thermionics researchers who may have interest in specific aspects of the DTRA research program. From experience, the committee knows that even with fairly large program efforts, research results can be lost due to inadequate record keeping and high personnel turnover. The amount of knowledge capture, or the lack thereof, appears to be independent of how complete any one research and development project may be but depends, rather, on the amount of knowledge captured during the process. One way to avoid the loss of hard-earned research results is through publication in peer reviewed journals.

The thermionics program can benefit greatly from peer reviewed publications. To establish a true sense of a thermionics community, the sponsoring agency should encourage researchers and commercial developers in thermionics to broaden their sphere of interaction. Technology programs in general are strengthened by peer interaction and especially constructive peer criticism.

To date, the researchers working under the DTRA thermionics program have not, with few exceptions, actively engaged in peer review. For example, the committee found it difficult to gather data on the string thermionic assembly research testbed (START) tests, and much of the data was not recorded, only alluded to.

Finding: By having papers published under the thermionics research and development program peer reviewed, and by establishing a formal documentation and hardware storage protocol, the future sponsor will help prevent loss of hard-earned research and development knowledge.

FUTURE THERMIONIC WORK WITH RUSSIA

Collaboration between the U. S. and the former Soviet Union has significantly enhanced the U.S. technology base in the area of high temperature materials and thermionic conversion. Much of this collaboration involves Auburn University and General Atomics in the area of materials research.

In addition to materials and thermionic conversion, dialogue in the area of nuclear safety has also developed. This dialogue, though not necessarily pertinent to the performance of thermionic converters, is certainly important and beneficial for the international spacefaring community (Booz-Allen and Hamilton 1993). Similarly, Russian technologists have expressed the desire to collaborate on ways that nuclear technology, and in particular thermionic nuclear technology, can enhance an international human mission to the Moon or even Mars, should such a mission take place (Ponomarev-Stepnoi et al. 1992). American specialists visited nuclear test facilities in Russia and discussed the possibility of collaboration. The conclusion of a report generated from that trip was that there could be beneficial collaborations with the Russians in certain technology areas (DOE 1992).

The ability to perform high quality nuclear testing in fast neutron flux is considered to be vital to the development of nuclear thermionic systems or other types of space nuclear power and propulsion systems. Russia may still be able to provide such testing capability today. However, expanded collaboration between the United States and Russia has not occurred since the Space Exploration Initiative was canceled in 1993, and that effort was focused on the human exploration of the Moon and Mars.

Despite the potential for positive results from continuing or expanded thermionic research and development collaboration with Russia, the committee has some concerns about the possibility of technology transfer to China. In-core thermionic fuel element testing was carried out by the Institute of Atomic Energy in Beijing in the 1980s (Shengquan 1984). In 2000, a TASS announcement from Moscow indicated that Russia and China had discussed collaborative efforts on nuclear reactors for Chinese satellites (FBIS 2000).

Finding: Past involvement with the Russians in thermionic research has been beneficial, particularly in the area of materials research for thermionic electrodes and insulators. Future work with Russia should include testing the effects of radiation on material due to the lack of nuclear radiation test capability in the United States.

Finding: The collaboration between General Atomics, Auburn University, and research facilities in Russia has been successful in advancing the U.S. thermionics research program. The involvement of Russia may also be beneficial in the future because of its capabilities for testing thermionics device-related technology in its fast neutron irradiation reactor test facilities.

REFERENCES

Booz-Allen and Hamilton, Inc. 1993. *Topaz International Program—Lessons Learned in Technology Cooperation with Russia.* Contract SD1084-93-C-0010.

DOE (Department of Energy). 1992. *Report of the United States Space Nuclear Power and Propulsion Team: An Examination of the Space Nuclear Power and Propulsion Activities of the Commonwealth of Independent States*. DOE, Washington, D.C., October 6.

FBIS (Foreign Broadcast International Service). 2000. *FBIS-CHI-2000-0530*. May 30.

Ponomarev-Stepnoi, N.N., Pavshoock, Vladimir A., and Usov, Veniamin A. 1992. "NPS Options for Lunar Bases Power Supply," *American Institute of Physics Conference Proceedings* 246 (1): 440-445.

Shengquan, Cao. 1984. "Thermionic Converter for Space Reactor Description," *Chinese Journal of Nuclear Science and Engineering* 4(3):227-232.

3

Overview of the Technology

DEVICE PHYSICS

Thermionic energy conversion is a process that converts heat directly into electrical power. In its most elementary form, a thermionic converter consists of two metal electrodes separated by a narrow gap (see Figures 3.1 and 3.2). One of the electrodes, called the emitter, is held at a high temperature, typically 1800 to 2000 K. The other electrode, called the collector, is held at a lower temperature, typically 900 to 1000 K. The emitter emits electrons into the gap and the lower temperature collector absorbs them. The binding energies of the emitter and collector surfaces that act on electrons are known as the work functions of the electrode surfaces. The electrons absorbed by the collector produce a usable electrical current as they return to the emitter through an external circuit. Electrical power is produced by virtue of the potential difference between the emitter and collector.

A thermionic converter is a static device that has no moving mechanical parts. The device operates at high temperatures, generates high power, and occupies only a small volume. For these reasons, thermionic converters have been considered potentially useful as power

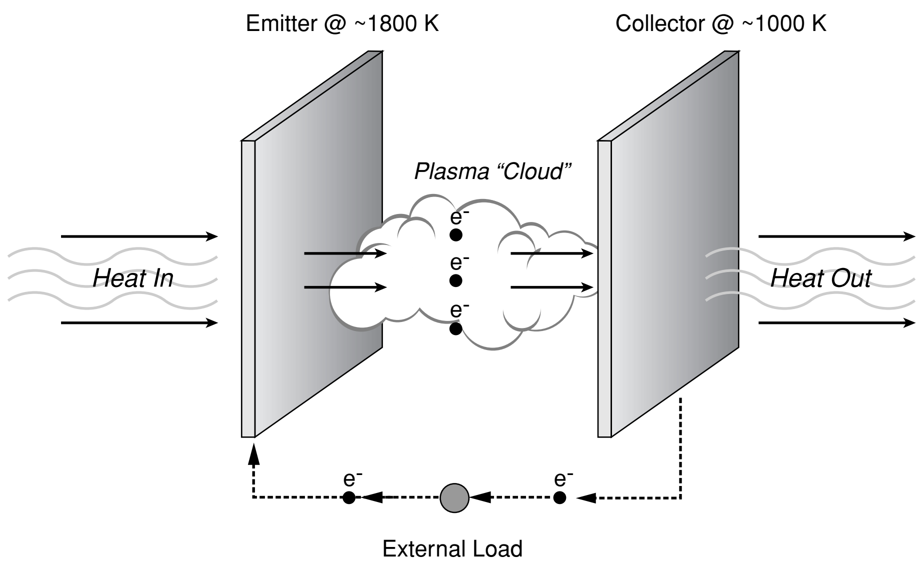

FIGURE 3.1 Basic thermionic converter schematic.
SOURCE: L. Begg, General Atomics, presentation to the Committee on Thermionic Research and Technology, August 2000.

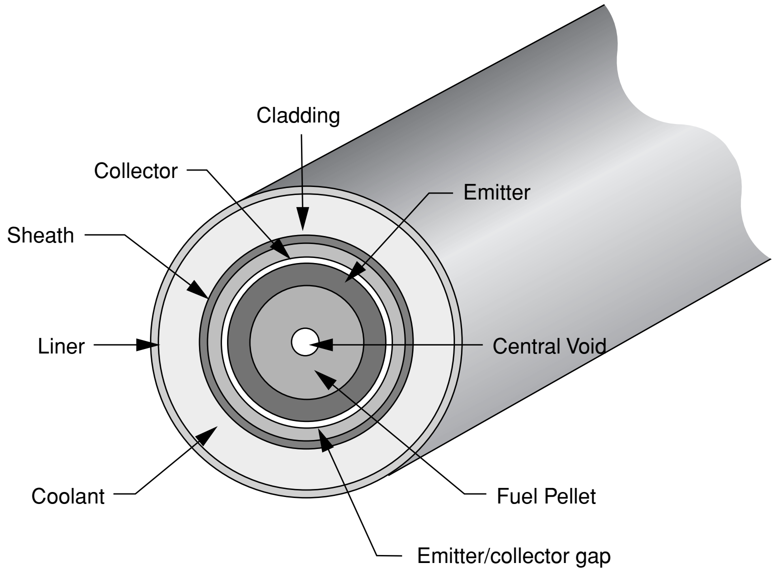

FIGURE 3.2 A cross sectional view of a thermionic fuel element (TFE). The nuclear fuel is located in the middle of the TFE and radiates heat outward.
SOURCE: Oregon State University, Nuclear Engineering and Radiation Health Physics, Department of Nuclear Engineering.

sources for use in space as well as for high temperature terrestrial power systems that generate large amounts of excess heat, such as coal or natural gas fired power plants. The United States, France, Germany, Sweden, Holland, and Russia have pursued thermionic research and development since the early 1960s. More recently China has begun investigating thermionic conversion technologies. Research is still ongoing in Russia, Sweden, and China. The committee does not know the current status of thermionics research in France, Germany, or Holland.

Efficient operation of a thermionic converter requires an emitter surface with a relatively low work function of 3 electron volts or less and an even lower collector work function of 1.5 electron volts or less.[1] The converter must also have the right charge transport conditions in the interelectrode gap, the area between the emitter and collector surfaces, to allow electrons to flow from the emitter to the collector.

Historically, emitters with low work functions were made for vacuum tubes by coating a metallic surface with compounds such as barium-calcium-strontium oxide. Such a technique proved to be impractical for thermionic converters because these compounds evaporated, limiting converter life to a few hundred hours.

Another problem relating to the operation of a practical thermionic converter is that the emitted electrons passing through the interelectrode gap create a negative voltage barrier in the gap. When electrons leave the emitter surface, they sense the negative space charge in the interelectrode gap and are forced to return to the emitter surface. In this way, the flow of current is obstructed. The negative space charge of the electron gas in the interelectrode gap must be suppressed to allow sufficient current to flow.

One solution to the negative space charge problem is to make the interelectrode gap small enough to be less than the mean free path of the emitted electrons. One type of thermionic device, the vacuum converter, obtains practical output currents by reducing the interelectrode spacing to a few micrometers (~5). The gap is small enough so that the electrons do not have the opportunity to collide with one another or to accumulate in the gap where they can create a space charge. The electrons are absorbed by the collector before this can happen.

The principal technical challenge in making such devices is maintaining the extremely close spacing required. A mechanically stable electrode support structure also conducts too much heat from the emitter.

[1]The work function of a material is defined as the amount of energy required for an electron with a certain energy to overcome and escape the binding attractive charge, or surface potential, of a material's surface.

Vacuum converters, while possible to construct, have proven to be impractical as power producing devices.

Typical thermionic converters have a significantly larger separation between the emitter and collector, but use cesium in the gap to nullify the negative space charge effect. Figure 3.3 illustrates the change in output voltage as a function of the distance between the emitter and collector in a cesium environment. The graph presents data generated by the Jet Propulsion Laboratory (JPL) Solar Energy Technology (SET) program team in approximately 1967. The data are for an ignited mode converter, and the peak performance is at the optimum spacing of approximately 3.5 mils (88.9 micrometers). The voltage output is lower on the right side of the graph as a result of an increasing negative space charge. The smaller spacing between the emitter and collector, as represented on the left side of the graph, results in a lower voltage output. The linear output at very low spacing, also at the left, is equivalent to the performance of a close-spaced vacuum thermionic converter.

The solution to the negative space charge problem and device spacing problems is provided by the introduction of cesium vapor into the interelectrode gap. Cesium vapor accomplishes two things. First, a layer of adsorbed cesium is formed on both the emitter and collector surfaces that reduces the surfaces' work functions and improves converter efficiency. Second, the cesium vapor is ionized and forms a plasma in the interelectrode gap. The positive ions neutralize the negative space charge of the electron gas.

There are several operational modes of the cesium plasma, two of which are considered to be important. In the unignited mode, also called the "Knudsen mode" when operating at low pressures and the "diffusion mode" when operating at higher pressures, the plasma is maintained by thermal ionization of cesium vapor contacting the hot emitter surface. This method requires no internal electrical power losses for plasma production. The unignited mode requires a very high emitter temperature, typically greater than 2200 K, as well as a low cesium pressure, typically 0.1 torr. The system has an interelectrode gap separation of approximately 0.2 millimeters.

The ignited mode, also called the arc mode, is a mode in which the plasma is maintained by impact ionization of interelectrode cesium vapor atoms by a highly energetic and very hot electron gas. The electron gas is heated by ohmic electrical power dissipation in the plasma to a temperature of greater than 3200

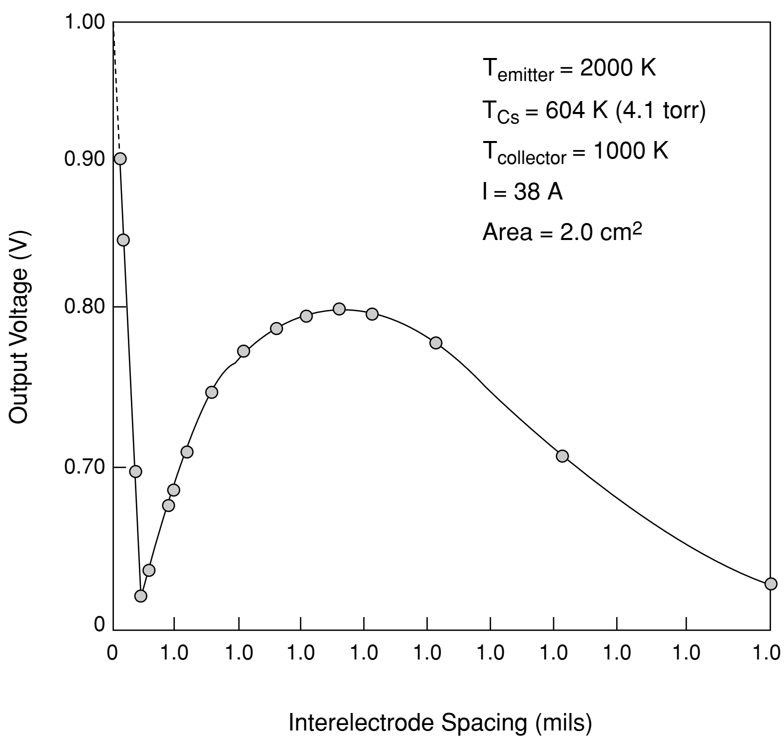

FIGURE 3.3 Solar thermionic output voltage based on emitter-collector spacing.
SOURCE: Jet Propulsion Laboratory, Solar Energy Technology program unpublished data, circa 1967.

K in this non-equilibrium process. This mode requires an emitter temperature of between 1600 and 2000 K and a relatively high cesium pressure of 1 torr. The interelectrode gap for this mode also has a moderate spacing, approximately 0.3 millimeters. The arc potential drop required to maintain the hot plasma is minimized at approximately 0.5 volts. This is the drop in voltage of the device resulting from maintaining the high temperature of the plasma. To date, only the ignited mode of operation has been used for practical applications. Figure 3.4 illustrates the voltage and current density characteristics for the various converter configurations.

The high temperature of the emitter can be maintained by any high temperature heat source. For terrestrial applications, thermionic converters may potentially be used with coal or gas fired electrical plants, as discussed in Chapter 6. For space missions, two heat sources could power thermionic converters: solar and nuclear.

A solar thermionic system, as described in Chapter 4, would consist of a solar concentrator that heats the emitter using the Sun's energy. A nuclear system can use thermionic converters located either inside the nuclear core, called "in-core systems," or outside the nuclear core, called "out-of-core systems." Both nuclear in-core and out-of-core systems consist of a reactor, which generates heat; a thermionic converter, which uses the heat to produce electrical power; and a radiator, which rejects waste heat. However, the out-of-core system also requires a core-to-converter heat transport mechanism, such as a heat pipe assembly or pumped liquid metal recirculating system, to deliver the thermal energy to the thermionic converter since the converters are not in direct contact with the heat in the reactor core.

In-core thermionic converters use thermionic fuel elements that contain both the thermionic converter (or converters) and the nuclear fuel. The most common design consists of a fuel rod that is placed inside a hollow cylindrical thermionic fuel element. The heat is transferred to the emitter on the inside of the hollow cylinder, and the exterior of the cylinder is the collector.

POTENTIAL APPLICATIONS AND COMPETING TECHNOLOGIES

Thermionics has been considered as a candidate for space power systems in the regime between a few kilowatts and multi-megawatts. The unique nature of thermionic systems could lead to a lighter, more compact

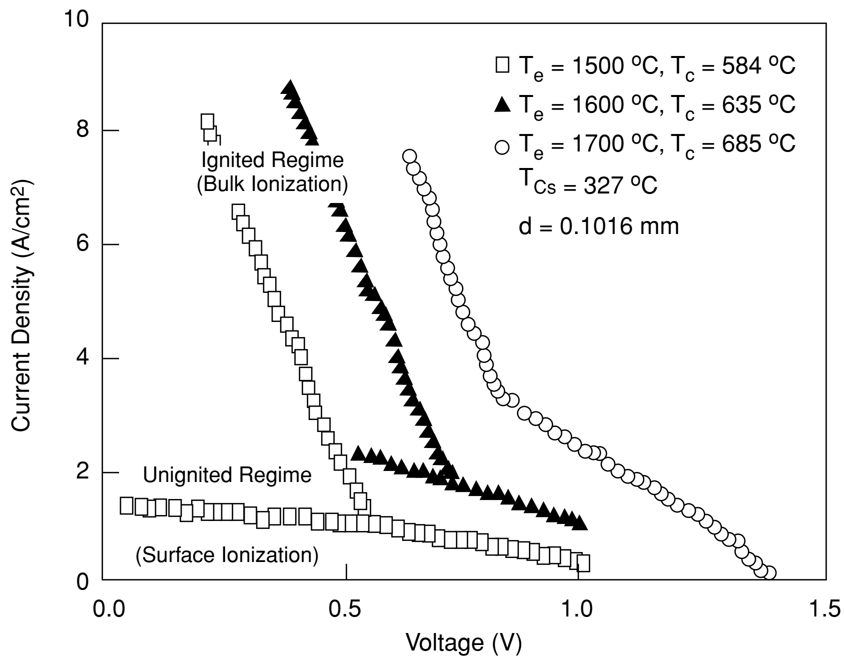

FIGURE 3.4 The current-voltage curve of a typical thermionic converter. T_e, emitter temperature; T_c, collector temperature; T_{Cs}, cesium reservoir temperature; d, electrode spacing.

power conversion system, as detailed in this section. However, the success of such a system will depend entirely on technologies that have not yet been developed. Chapter 4 details the advantages of a lightweight solar thermionic system if lightweight power conditioning electronics, a lightweight concentrator, a high temperature receiver, and a heat pipe radiator can be developed. Potential missions for thermionic power systems are listed in Table 3.1.

A lightweight power system with minimum volume is desirable for launch purposes. The approximate cost to launch a spacecraft is $6,000 to $10,000 per kilogram to reach low Earth orbit (LEO) and $20,000 to $40,000 per kilogram to reach a geosynchronous Earth orbit (GEO) depending on the launch vehicle type. Making the power conversion system smaller increases the volume and mass allocation available for mission payload on the launch vehicle.

Many other energy conversion systems have been explored to satisfy potential requirements for space-based power systems. Currently, there is little consensus within the power technology community on which power conversion system would be best for missions that travel beyond Mars or toward the Sun inside the orbit of Venus. There is very clear consensus that solar arrays are the best power conversion technology to use for spacecraft orbiting Earth or traveling to Mars and Venus.

Thermionics has also been considered for Earth-based, or terrestrial, power generation systems, but to a much lesser extent. These systems would convert thermal energy to electrical energy using a thermionic conversion device. The ability of thermionic devices to operate at higher temperatures than conventional turbine engines might make thermionics attractive for niche applications.

The following sections describe general applications for thermionics and contrast thermionic power conversion with competing technologies that achieve the same goal.

Space Power Applications

Almost all space missions to date have required some form of power onboard a spacecraft. The amount of power needed by these missions in the past, present, and future varies widely depending on the mission. Spacecraft operate as close as low Earth orbit, only

TABLE 3.1 Potential Missions for Solar and Nuclear Thermionic Power Systems

	Mission							
	Near-Term, Space-Based Radar	Far-term Space-Based Radar	Space Transportation/ Electric Propulsion	Manned Space Exploration	Lunar, Planetary Surface Power	Advanced Communications	Space-Based Electric-powered Weapons	Advanced Deep Space Telescope
Power required (kW)	3 to 10s	100s	5 to 100s	100s to 10 MW for cargo support missions	100s to 1,000s	10s to 100	1,000s	10s to 100
Location	LEO	High orbit	Orbit transfer, deep space	Mars to deep space	Lunar and planet surface	LEO to GEO	LEO to GEO	LEO
Application for solar thermionics	√	√	√ Orbit transfer and deep space	√ Cargo and robotic missions		√	√	√
Application for nuclear thermionics		√	√ Deep space	√ Manned missions	√		√	

hundreds of miles above Earth's surface, and as far away as the outer planets and beyond. In the future, space missions may include a lunar base and a human mission to Mars.

The power required for spacecraft ranges from watts to tens of kilowatts today and may require hundreds of kilowatts, even megawatts, in the future. The length of time that peak power is required also depends on the mission type. Some missions may require a few seconds burst of high power, while other missions may be conducted for decades, requiring continuous power for the entire mission life.

A variety of power system technologies can be used to satisfy this broad range of needs. Figure 3.5 depicts the general applicability of a particular power system to a given power level and mission duration regime. The separate areas shown in the figure represent the areas where different power conversion technologies have the greatest benefit. For example, chemical systems, such as primary single use batteries, fuel cells, and combustion turbo alternators, are useful for relatively short lived missions. Solar photovoltaic systems using rechargeable batteries are in wide use today. Solar-heated, dynamic conversion systems are rarely used and are based on different thermodynamic cycles, such as the Brayton, Rankine, and Stirling cycles, and alkali metal thermal electric converters (AMTEC) and thermionic converters. Finally, nuclear reactor- and radioisotope-heated dynamic and direct converters are listed. Thermoelectric and thermionic systems fall in this final category.

The shape of the boundaries between areas varies depending on the importance of power system mass, volume, cost, reliability, and system integration issues. Safety issues and other power system selection criteria can also affect the boundaries of the areas in Figure 3.5.

Figure 3.6 groups similar candidate power systems together in relation to their applicable regimes, showing selection criteria for one type of power system. Power system specific mass, defined as total mass divided by total power produced, is plotted versus power output for mission durations in the 5 to 10 year range. These optimum specific mass regimes were determined by plotting the results of the many space power system design studies conducted between 1960 and the 1990s.

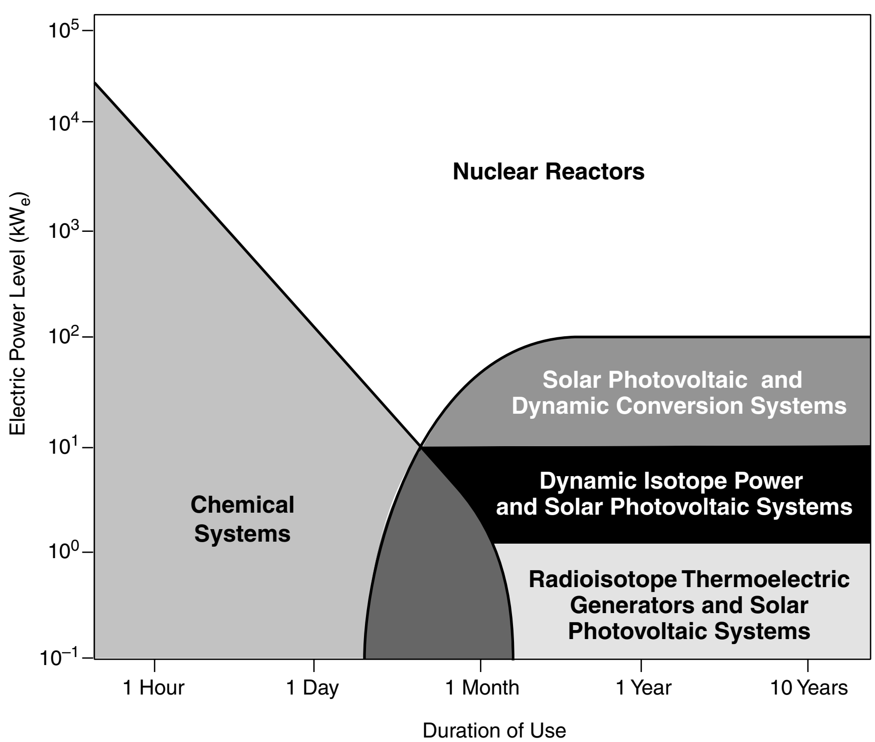

FIGURE 3.5 Power system options for specific mission durations.

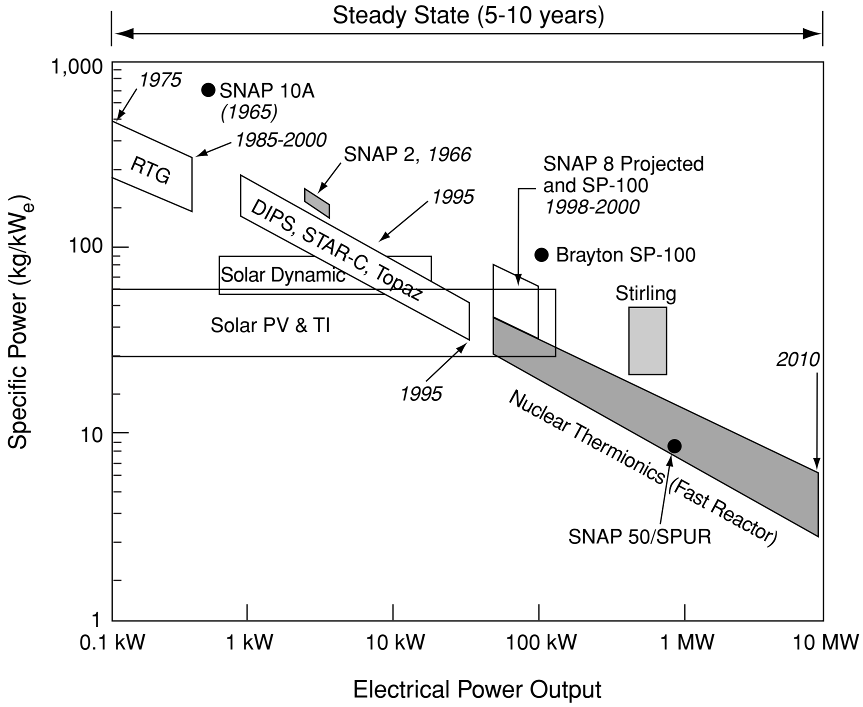

FIGURE 3.6 Inverse specific mass versus electrical power output.

Figure 3.6 demonstrates the wide potential applicability of both nuclear-heated thermionic systems and, to a lesser extent, solar-heated thermionic systems. The ability to scale these technologies to larger power systems is also important.

Over the past four decades, several design studies considered thermionics as the power source. Generally, the main advantage of both nuclear and thermionic systems is their potential for high specific power, particularly at high power output levels. By contrast, radioisotope thermoelectric generators are not generally scalable above 1 kilowatt due primarily to high fuel costs and limited supply of isotopes. Some have suggested that by using more efficient dynamic converters coupled to radioisotope heat sources, those heat sources could be expanded to supply 1 to 2 kilowatts of power. However, these changes would introduce life and reliability issues that would require more investigation.

The highly modular nature of thermionic converters represents a potentially significant, yet subtle, cost benefit when establishing a reliability database as compared to dynamic conversion devices. This situation is also true for the equally modular photovoltaic cells. However, there is a cost penalty on the front end to develop thermionic systems for in-core thermionic fuel elements. The cost of testing in-core for issues such as fuel swelling and radiation effects on materials can be significant.

Solar dynamic power systems were included in the early International Space Station (ISS) design. These power systems were ultimately not pursued, in part because the dynamic converters themselves were not fully developed and lacked a significant life test database. The ISS development team selected photovoltaic battery systems, accepting, when they did so, the tradeoff between the perceived lower technical risk associated with a proven technology despite the potential limitation, at that time, of not being able to scale photovoltaics up to the 75 kilowatts power requirement. Also, maintenance issues on dynamic systems were a concern. However, the team was limited in its choice since there were no other flight-demonstrated power conversion technologies available that had the promise to achieve such power levels.

The data shown in Figure 3.6 exclude any out-of-core nuclear thermionic concepts, whose application overlaps the application of in-core thermionic systems. Also, the ability of some categories of nuclear out-of-core systems to scale to high power levels is limited compared to that of nuclear in-core systems.

Most of the specific power advantages of nuclear thermionics are a result of the converter's potential ability to operate within a nuclear core. When manufactured as part of a nuclear fuel rod, the thermionic converter can eliminate both heat transport temperature drops and the need for additional heat transport hardware to convey the heat from the core to the converter. A thermionic energy converter is the only converter, static or dynamic, that has been designed to operate inside a nuclear core. This benefit allows the overall power generation system to be more compact and potentially less complex.

However, there are also issues with materials and fuel swelling. The high temperature, electric field, and radiation environment inside the nuclear core can severely affect the lifetime of materials. Also, as fission gas products build up inside the reactor, the nuclear fuel swells and mechanically stresses the containment walls. If the nuclear fuel is part of a thermionic fuel element (TFE), the resulting mechanical deformation can cause an electrical short in the TFE.

All power system cooling in space is usually accomplished by radiative cooling. Therefore, the high heat rejection temperature associated with thermionics gives the system another benefit. The high heat rejection temperature allows for a compact, lightweight radiator. As system power levels increase, the mass of the thermal radiator scales linearly with power, and as the reciprocal of the absolute temperature raised to the fourth power.[2] As a result, as the power level increases on a traditional space-based nuclear reactor, the radiator becomes a significant contributor to the total system mass.

With a thermionic nuclear reactor system, however, the high heat rejection temperature allows for a smaller heat rejection radiator to be used. Even when compared to most other nuclear power conversion candidate technologies that operate outside the nuclear core yet have higher efficiencies, a nuclear in-core thermionic system is still often more desirable in terms of specific mass. For example, a thermionic system operating at 10 percent efficiency must reject 125 percent more heat than a 20 percent efficient dynamic nuclear power system, such as a Brayton, Rankine, or Stirling dynamic converter. However, the dynamic converter rejection heat radiator must be nearly an order of magnitude larger owing to the inverse fourth power scaling of radiator area as a function of temperature. As a result, dynamic nuclear power system radiators are not readily scalable to very high power levels. At megawatt power levels, the mass of the heat radiator would most likely dominate system mass. Another way to view this situation is that the thermionic system takes advantage of the temperature to the fourth power rule by using a higher heat rejection temperature and a smaller radiator.

When scaling a nuclear reactor core to provide more heat, a fairly small increase in the overall size of the core will yield significant results since the mass of a cylindrical core simply scales in proportion to the radius squared. An increase in core size therefore yields more heat energy to drive a thermal conversion system. All reactor systems, when looking simply at the nuclear core, scale easily to supply larger amounts of heat energy, which in turn can provide more thermal power.

However, the peripheral hardware of the converter systems receiving the thermal output from the nuclear reactor scale more linearly with the increase in overall heat energy, so that scaling to higher energy power systems results in an unfavorable increase in overall system mass.

This high temperature heat rejection characteristic allows thermionic system radiators to be intrinsically compact. A future thermionic system could have mass and payload integration advantages over most power conversion candidates. The notable exception is the liquid metal Rankine cycle, which also rejects heat at a high temperature. Development of liquid metal Rankine cycles ceased in the 1970s, at a low level of development, with the demise of the U.S. space nuclear power program.

Another intrinsic advantage of thermionic system radiators used in space, relative to low temperature systems, is the potential ability of the thermionic radiator to survive a small meteoroid impact as well as attack by space-based weapons that use high speed orbiting pellets, laser systems, or other potential threats. The radiator system has higher survivability because it can be more easily armored and constructed to be highly redundant through the use of heat pipes in case parts of the radiator system are disabled. The armoring can be added to the high temperature system with a much smaller mass penalty than a low temperature system would incur. To armor a larger radiator system that is

[2]Put another way, mass is proportional to the radiator area. Also, the heat transfer rate is proportional to the area of the radiator multiplied by the temperature of the radiator raised to the fourth power.

used on low temperature systems is much less feasible because of the additional mass that armoring would add to the overall system. Also, the smaller size of a high temperature thermionic radiator decreases the probability of the system being hit. These potential survivability advantages apply only to other comparable high temperature systems. A complete discussion of survivability is beyond the scope of this report.

A less obvious thermionic radiator advantage not shared by its lower temperature competitors is the ability of a thermionic system to use sodium heat pipes for radiator heat transport. In addition, the temperature range of a thermionic system is nearly optimal for sodium heat pipe operation. Selection of an adequate radiator heat pipe fluid for 500 to 600 K radiators is difficult, but is often ignored when considering low temperature systems. A sodium heat pipe has a very high transport capacity, which allows for a lighter weight and less complex radiator assembly.

Finally, the power density that can be attained by a thermionic converter system as the temperature of the system increases is very impressive. The device output increases exponentially with only moderate increases in temperature on the order of a few hundred degrees and with minimal technical risk. This increase in device power density as a function of temperature is shown in Figure 3.7.

The very high temperature thermionic regime shown in Figure 3.7 reflects U.S. and Russian experimental data. The data demonstrate that thermionics potentially offers a tenfold gain in power density compared to current technology if higher temperature fuels, more creep resistant electrode materials, and fuel cladding materials can be developed. The advantage of higher system power density is that, again, an overall lighter system is possible than with current systems. However, Figure 3.7 does not take into account lifetime issues that need to be resolved to make thermionics a viable system-level technology.

There is a potential limit on the ability of solar photovoltaic and other solar concentration approaches to scale to very high power scenarios. The area of solar

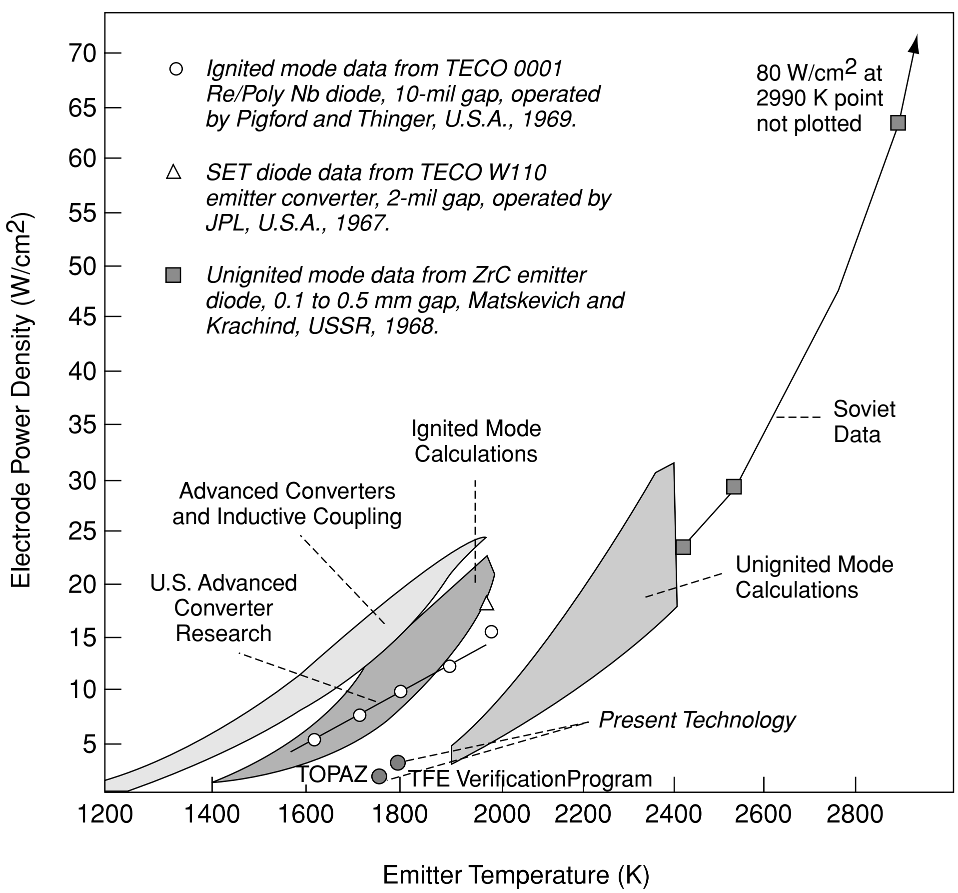

FIGURE 3.7 Increase in power density of a nuclear thermionic system as a function of temperature.

array and concentrator systems scales roughly linearly with power; however, the structural mass to support the array or concentrator does not. The increase in the mass required to support such a structure for very high power levels might not be practical for launch unless there are unforeseen advances in lightweight structural materials.

Most experts in the power system community acknowledge that there is a maximum limit for solar power systems; however, that exact practical limit is not known. Nuclear thermionic systems offer reduced mass, volume, and surface area, which may become increasingly important when space power needs approach and exceed 100 kilowatts. Nuclear thermionics has the potential to scale to these higher powers, where, as discussed in the next section, they could be very useful for specific space missions.

A unique benefit for electric propulsion systems is that nuclear powered and some solar powered thermionic systems, designed to operate over normal capacity at the beginning of the system's operational life, can operate in a surge power mode (also referred to as peak power mode). For example, in the regime shown in Figure 3.7, the emitter temperature can be increased from 1800 K to 2100 K to double the power for a relatively short time of 30 to 90 days. To configure a system to operate in a surge mode requires that all components be designed to achieve equilibrium at a higher temperature. This type of operation also requires spacecraft designers to accept a somewhat shorter vehicle operating lifetime. Such surge mode operation can be used to decrease the time required for orbit positioning or transfer. In this dual mode operation, electric propulsion can be combined with other mission requirements resulting in a synergistic benefit. This operational scenario is described in more detail in Chapter 4.

Key Finding: Thermionic systems are unique for three reasons: (1) the inherently high power density of the conversion mechanism itself, (2) the systems' high heat rejection temperature, typically 1000 K, which allows thermionic systems to use compact radiators with relatively low masses, and (3) the systems' potential to operate in a higher power "surge mode" for sustained periods over a small fraction of their programmed life. The combination of these three advantages could allow for potentially significant advances in system power level density (kilowatts per kilogram).

Comparison of Thermionics with Other Power Conversion Technologies

The location of thermionic technology within the spectrum of space energy conversion systems can be determined only by comparing and contrasting it with the other available and emerging technologies. Eight commonly discussed technologies have supplied spacecraft with power or offer the potential to do so in the future. Of the eight, only five have actually been flown in space. These flight demonstrated power conversion technologies are compared in Table 3.2.

The power conversion systems that have flown on spacecraft are listed below:

- Photovoltaic—Systems are still in widespread use;
- Radioisotope thermoelectric generator (RTG)—Used infrequently;
- Fuel cells—Still in use for specialized, short duration missions such as the space shuttle;
- Thermoelectric nuclear reactor—Used in up to 30 Russian spacecraft and 1 experimental U.S. spacecraft, but no longer in use; and
- Thermionic nuclear reactor—Used in two Russian missions in the late 1980s, but no longer in use.

The systems that are in development but have not flown in space are as follows:

- Dynamic (solar or nuclear), including Rankine, Brayton, and Stirling cycle converters;
- Alkali metal thermal to electric converters (AMTEC; see Box 3.1);
- Magnetohydrodynamic (MHD) converters.

Photovoltaic systems with battery storage are the most commonly flown space power systems. They have been in use since the late 1950s and have flown on more than a thousand missions. Systems have been designed to supply up to 75 kilowatts of electricity and for up to 15 years of life.

A second power conversion technology to be placed in space is the radioisotope thermoelectric generator. RTGs are small devices designed to supply less than 1 kilowatt for greater than 10 years. These devices have been used on deep space probes, as well as on several long-life instruments left on the Moon during the Apollo program. RTGs have also been used extensively in the Russian space program.

TABLE 3.2 Comparison of Flight Demonstrated Power Conversion Technologies

Technology	Beginning of Life W/kg	Beginning of Life kg/kW	Power Level (kW)	Recurring Cost ($/Watt)	Year	Life (yr)	Comments
Photovoltaic (PV)[a,b]	14.85	67.36	10	1,130			
Solar array[c]	50.00	20.00		700	2000	15	Must have sunlight
Battery (kWh/kg)	19.50	51.28		180	1999	15	Must have electric energy storage
PV conditioning electronics	481.06	2.08		250	2000	15	Good between Mars and Venus Degrades 1-2%/yr, sensitive to radiation Deep Space 1, Hughes 702 Battery is 30% DoD 60 kWh/kg NiH_2 SPV
Thermoelectric[d,e] Radioisotope thermoelectric generator (RTG)	5.30	188.68	0.3	133,000 plus Pu^{238}	1997	30	Highly survivable against natural radiation and space-based weapon attacks Heat source degrades 0.8%/yr from Pu^{238} half-life Converter degrades 0.8%/yr Cassini
Fuel cells (alkaline)[f]	51.00	19.61	7	825	1981	0.3	Requires fuel resupply
Fuel (Wh/kg)	1550.00	0.65		plus fuel			Requires fuel storage, tank weight included Does not need sunlight Orbiter Requires maintenance between flights
Nuclear thermionic[g]	4.17	239.81	5	5000 plus fuel	1987	1.0	Highly survivable Cosmos 1818 and 1867, Topaz I

[a]0.56 watt-hours of energy storage required for every watt of load power needed in a low Earth orbit (LEO).
[b]1.75 watts of solar array power required for every watt of load power needed in a LEO.
[c]Allen, Douglas M., and D.M. Murphy. 1998. "An Update on the Deep Space 1 Power System: SCARLET Integration and Test Results," *Proceedings of the 33rd Intersociety Engineering Conference on Energy Conversion,* American Nuclear Society, Albuquerque, N. Mex., August 2-6, 1998.
[d]Mehner, Arthur, U.S. Department of Energy, e-mail communication, July 28, 2000.
[e]Bennett, Gary, e-mail communication, July 15, 2000.
[f]Loyselle, Patricia, Thomas Maloney, and Henry Cathey, Jr. 1999. "Design, Fabrication, and Testing of a 10 kW-hr H2-O2 PEM Fuel Cell Power System for High Attitude Balloon Applications," *34th Intersociety Energy Conversion Engineering Conference Proceedings,* Society of Automotive Engineers, Inc., August 1999.
[g]National Research Council. 1996. *Assessment of TOPAZ International Program.* Committee on the TOPAZ International Program. National Academy Press, Washington, D.C.

The third power conversion system to have been used in space is the fuel cell. Fuel cells are typically used for short duration missions. They are compact systems with no deployed devices such as photovoltaic arrays although small waste heat radiators are sometimes used. Fuel cells combine aqueous hydrogen and oxygen to yield water as a waste product. These systems have been used on manned space flight programs since the early days of those missions and are still in use today on the space shuttle.

Nuclear thermionic generators are the only other power conversion devices to have been flown on operational spacecraft. Two Russian experimental satellites, Cosmos 1818 and Cosmos 1867, used thermionic conversion systems to supply their power. Cosmos 1818 and 1867 operated in space for approximately 142 days and 342 days, respectively (Ponomarev-Stepnoi et al. 2000).

Ground demonstration is one technology development step below flight testing. This development level is for technologies that are not mature enough for space flight, but it is intended to demonstrate the promise of a new technology in a flight-like configuration and environment. Other heat engine systems in addition to static

BOX 3.1
Alkali Metal Thermal to Electric Converter

Alkali metal thermal to electric converters (AMTECs) are thermally powered electrochemical concentration cells that convert heat energy directly to DC power from any fuel source capable of generating 970 to 1170 K. The converter has no moving parts and efficiencies ranging from 15 to 25 percent depending on operating temperature and specific design features.

In operation, an alkali metal such as sodium or potassium ionizes and is driven through an ion-permeable beta-alumina solid electrolyte membrane by a temperature-induced pressure differential. On the cathode at the low pressure side, the alkali metal evaporates, travels as a vapor to a heat sink where it condenses, and then is returned to the high pressure zone by a fine capillary artery or an electromagnetic pump. The charge separation produces electrical power at the anode and cathode surfaces of the ceramic membrane. With its moderate upper operating temperatures and heat sink temperatures from 373 to 623 K, AMTEC is suitable for cogeneration or topping cycle applications.

Thermodynamically, AMTEC operates as a heat engine. However, in contrast to Stirling, Brayton, and Rankine dynamic cycles, AMTEC systems have no moving parts and are temperature sensitive but relatively insensitive to the choice of heat source.

AMTECs that have been ground demonstrated include the dynamic Brayton cycle, the Rankine cycle with an organic working fluid, and the Stirling cycle. However, these systems have not flown or been demonstrated in a flight configuration or adequately life tested. Table 3.3 compares some of the ground demonstrated power conversion technologies.

The least mature level of development is projected performance based on theoretical or partially demonstrated performance. Closed cycle MHD falls into this category. There have been several planned MHD ground demonstrations, but these tests were for terrestrial systems, not space flight systems. The technology is being considered for possible use on future orbit-raising vehicles that move satellites from low Earth orbit to geosynchronous Earth orbit. Table 3.4 characterizes the advances projected to be made with power conversion systems.

There are five top-level criteria that a systems engineer considers when selecting a technology as a power source for space flight:

1. Weight,
2. Cost,
3. Volume needed on the launch vehicle,
4. Deployed area or boom length, and
5. Risk and availability.

These criteria must be well defined before choosing a power source. The availability of sunlight is another key issue and one that is mission specific, which generally relates to what energy sources are available where a mission is to operate. Some missions may operate where there is little to no usable sunlight, such as around the outer planets. Where no sunlight is available, a nuclear heat source is most likely the only option available to power a spacecraft. This option requires a heat-to-electric converter such as thermoelectric, thermionic, AMTEC, or a heat engine using a Brayton, Rankine, or Stirling cycle.

Yet another set of missions to which nuclear power may be best suited are missions that very closely approach the Sun, where the vehicle must contend with extreme heat and very intense solar conditions.

HISTORY OF THERMIONIC SYSTEMS AND DEVELOPMENT

The ability of a device to supply usable electrical power from heat, thus converting the heat energy to electrical power with no moveable mechanical parts, is a potentially important process. One sure process, thermionics, has been investigated as a potential power supply since the 1950s by many different individuals and companies. To make clear the extent of the research carried on in thermionics to date, this section describes previous efforts to develop thermionic power systems and highlights the major accomplishments of each project.

Early efforts, beginning in the 1960s, involved both solar and nuclear in-core reactor system configurations. Solar thermionic developments were abandoned in the early 1970s, while nuclear thermionic research continued sporadically from the 1960s through the 1990s.

Jet Propulsion Laboratory Solar Energy Technology (SET) Thermionic Program

JPL initiated a solar thermionic converter life evaluation and generator test program in 1961. The activities taking place under the SET program included the following:

- Performance testing on over 135 thermionic converters;

TABLE 3.3 Comparison of Ground Demonstrated Power Conversion Technologies

Technology	Beginning of Life W/kg	Beginning of Life kg/kW	Power Level (kW)	Recurring Cost ($/Watt)	Life (yr)	Comments
Solar dynamic Brayton[a,b]	3.0	333.33	2	5,000	6-15	Highly survivable against natural radiation and space-based weapon attacks Demonstrated at the system level
Radioisotope Stirling[a,b]	4.0	250.00	0.11	2,000	6-15	Highly survivable against natural radiation and space-based weapon attacks Under development Demonstrated at the converter level
Radioisotope AMTEC[c,d,e]	5.7	175.44	0.1	3,500	1.2	Highly survivable against natural radiation and space-based weapon attacks Demonstrated at the converter level

[a]Mason, Lee S. 1999. *Technology Projections for Solar Dynamic Power*. NASA TM-1999-208851. National Aeronautics and Space Administration, Washington, D.C.
[b]Mason, Lee S. 2001. *A Comparison of Brayton and Stirling Space Nuclear Power for Power Leads from 1 Kilowatt to 10 Megawatts*. NASA TM-2001-210593. National Aeronautics and Space Administration, Washington, D.C.
[c]Sovie, Ronald J. 1999. *Space Power Systems Technology to Meet National Needs*. American Institute of Aeronautics and Astronautics, Reston, Va.
[d]Hunt, Thomas, Advanced Modular Power Systems, Inc., e-mail communication, March 14, 2001.
[e]Cockfield, Robert. 2001. "Radioisotope Power System Options for Future Planetary Missions," paper presented at 2001 Space Technology and Applications International Forum, Albuquerque, N. Mex., February 2001.

- Extended life testing on 10 planar converters for a total of over 68,000 hours from 1967 to 1969, with converters experiencing hundreds of thermal cycles;
- Building of at least four generators with four-converter configurations and testing them calorimetrically in the laboratory; and
- Testing of the four-converter generator geometry with a Sun tracking, 9.5 foot diameter parabolic mirror.

Most SET converters were tested in the 1900 to 2000 K emitter temperature range, with life routinely exceeding 7,000 to 11,000 hours while maintaining efficiencies between 7 and 10 percent. One converter test had a demonstrated life of 20,000 hours, or 2.3 years, while producing 25 watts per square centimeter on the converter surface. The converter in question experienced less than 5 percent power density degradation. The 150 watt generators in the SET program demonstrated efficiencies in the range of 9 to 11 percent, while operating at approximately 1700 K. The converter power densities ranged from 17 to 22 watts per square centimeter. The SET program was terminated in the early 1970s.

The committee found that researchers working under the U.S. Air Force and DTRA String Thermionic Assessment Research Testbed program, as discussed in Chapter 7, had difficulty trying to recapture the generator design and test experience from the SET program work.

The Atomic Energy Commission's Thermionic Reactor and Fuel Element Programs

The Atomic Energy Commission (AEC), which was replaced by the Department of Energy (DOE), initially ventured into thermionic development in 1959, funding the Los Alamos National Laboratory. In 1964, the AEC began funding General Electric and General Atomics to develop an integrally fueled thermionic fuel element. In 1970, General Atomics was selected to continue development of the thermionic fuel element and to construct a thermionic test reactor. The program included designing thermionic power systems for both space and remote terrestrial applications, as well as developing fabrication methods for single-cell and multicell thermionic fuel elements and a thermionic critical reactor experiment. A test reactor at General Atomics (TRIGA), the Mark III thermal spectrum

TABLE 3.4 Comparison of Projected Power Conversion Technology Capabilities

Technology	Beginning of Life W/kg	Beginning of Life kg/kW	Power Level (kW)	Recurring Cost ($/Watt)	Years to Maturity	Comments
Photovoltaic[a,b,c]	33.65	29.7134		633		Assumes a 500 nm (926 km) orbit with a 33 min eclipse
Solar array[d]	200.00	5.00	30	300	5	35% efficient solar cells on communications satellite
Battery (30.0 Wh/kg)	54.55	18.33		133		30% depth of discharge at 100 Wh/kg lithium-ion battery
PV conditioning electronics	665.00	1.50		200		
Thermoelectric RTG[d]	8.00	125.00	TBR	Unknown	20	Costs do not include plutonium-238
Fuel cell (PEM)[e,f,g]	181.00	5.52	20	Unknown	7-10	Potential life increase to 1.14 years
Fuel (Wh/kg)	1550.00	0.65				Power density may be as high as 1000 W/kg and 2500 Wh/kg
Solar thermionic[a,h]	31.15	32.10				Assumes a 500 nm (926 km) orbit with a 33 min eclipse
Thermionic converter[i]	106.00	9.43	50	Unknown	10	
Thermal storage[j]	48.64	20.56		133		90% depth of discharge at 213.9 Wh(thermal)/kg manganese oxide
Control electronics	665.00	1.50		200		
Concentrator mass[k]	600.00	1.67				
Nuclear thermionic[d]	33.78	29.60	100	Unknown	7-10	
Solar dynamic						
Brayton[l,m]	11.50	86.96	10	2,500	5	
Stirling[l,m]	15.00	66.67	10		5-10	
Nuclear dynamic						
Brayton reactor[l,m]	40.00	25.00	100	Unknown	5-10	
Brayton reactor[l,m]	100.00	10.00	1,000		10-20	
Stirling radioisotope[l,m]	8.00	125.00	0.1	20,000	5	Costs do not include plutonium-238
Stirling radioisotope[l,m]	10.00	100.00	1		5-10	
Stirling reactor[l,m]	30.00	33.33	100		10-15	
AMTEC						
Radioisotope AMTEC[n]	11.20	89.29	0.1	Unknown	5	
Solar AMTEC[o]	49.00	20.41	3	Unknown	10-15	

[a]There is a requirement for 0.56 watt-hours (Wh) of energy storage for every watt of load power needed in a low Earth orbit (LEO).
[b]There is a requirement for 1.75 W of solar array power for every watt of load power needed in a LEO.
[c]There is an array scaling factor of 1.75 included in the calculation of the specific power to accommodate required battery recharge energy, recharge efficiency, and electrical bus power conditioning efficiency.
[d]Sovie, Ronald J. 1999. *Space Power Systems Technology to Meet National Needs.* American Institute of Aeronautics and Astronautics, Reston, Va.
[e]Loyselle, Patricia, Thomas Maloney, and Henry Cathey, Jr. 1999. "Design, Fabrication, and Testing of a 10 kW-hr H_2-O_2 PEM Fuel Cell Power System for High Altitude Balloon Applications," *34th Intersociety Energy Conversion Engineering Conference Proceedings,* Society of Automotive Engineers, Inc., August 1999.
[f]Bradley, Karla F., Johnson Space Center, telephone and e-mail communication, 2000.
[g]Fellner, Joe. 2000. "Electrochemical Power/Energy Storage for Diode Lasers," *Proceedings of the 13th Annual Solid State and Diode Laser Technology Review.* Air Force Research Laboratory, August.
[h]There is a requirement for 1.73 W of thermionic converters for every watt of load power required in a LEO.
[i]Begg, Lester, General Atomics, presentation to the committee, 2000.
[j]Assume 213.8 Wh (thermal)/kg manganese oxide, 15% thermionic converter efficiency, and 20% penalty due to structure, insulator, and heat exchanger mass.
[k]Assume 80% inflatable concentrator optical efficiency, 0.27 kg/m^2 for inflatable concentrator, which includes the torus, reflective canopy, inflation system, and pointing and tracking hardware.
[l]Mason, Lee S. 1999. *Technology Projections for Solar Dynamic Power.* NASA TM-1999-208851. NASA, Washington, D.C.
[m]Mason, Lee S. 2001. *A Comparison of Brayton and Stirling Space Nuclear Power for Power Leads from 1 Kilowatt to 10 Megawatts.* NASA TM-2001-210593. NASA, Washington, D.C.
[n]Schock, A., H. Noravian, C. Or, and V. Kumar. 1999. "Recommended OSC Design and Analysis of AMTEC Power System for Outer-Planet Missions," Space Technology and Applications International Forum. American Institute of Physics, Melville, N.Y.
[o]Hunt, Thomas, Advanced Modular Power Systems, Inc., e-mail communication, March 14, 2001.

nuclear reactor, was built that was capable of testing up to 15 in-core thermionic fuel elements simultaneously. The chain reaction of the TRIGA reactor is sustained primarily by thermal neutrons, those fast neutrons that have collided with other material in the core to achieve a lower energy state. Thirty-seven thermionic fuel elements were tested in-core between 1962 and 1973. Converters operating at full power at 1900 K in the nuclear core achieved lifetimes of 12,500 hours. The program was terminated in 1973, when all AEC, NASA, and DoD activities related to space nuclear reactors were discontinued. To date, the DOE, and the AEC before it, have invested over $1.5 billion in nuclear reactor programs such as SNAP-2, SNAP-10A, SNAP-50, and SNAP-8, and in other reactor and dynamic energy converter programs. Nuclear thermionic activities were also included in these programs. At the conclusion of the nuclear program in 1973, only NASA Lewis Research Center continued to fund thermionic research. However, that organization terminated thermionic research in the late 1970s. For a detailed history of the space nuclear energy program, see NRC (1983).

The SP-100 Program and the Thermionic Fuel Element Verification Program

From 1973 to 1979, the national space nuclear power program conducted very little research and development, and the USAF, NASA, and DOE allocated very little funding for thermionic technology development. In addition, NASA Lewis abandoned its in-house thermionic research facility and its considerable thermionic materials development program.

In 1979, a joint DoD and Energy Research and Development Administration (ERDA) study group assessed potential DoD missions. That assessment led to a modest $1 million to $2 million per year technology program at Los Alamos National Laboratory. The program at Los Alamos focused on a heat pipe cooled thermoelectric concept called the space power advanced reactor (SPAR). Other advanced reactor types were also investigated by DOE, but at low levels of effort.

In 1981, NASA agreed to collaborate with DOE on reestablishing a high power space nuclear reactor program. NASA's interest was based on several potential missions that would require 100 kilowatts or more of electrical power. This power range was the same as the range DoD was interested in at the time. As a result of the combined interest, the SPAR program was redirected and renamed SP-100 when DoD joined the program. DOE led the reactor development effort, and NASA coordinated efforts on the power conversion and radiator development. NASA was not considering thermionics at the time. In 1983, the Defense Advanced Research Projects Agency (DARPA) joined the SP-100 program as the DoD representative to the triagency group composed of DOE, DoD, and NASA. DARPA was replaced by the Strategic Defense Initiative Office (SDIO) in 1986.

When a ground engineering system development effort was initiated, candidate reactor power systems for full development included thermionics, thermoelectrics, Brayton cycle, and Stirling cycle configurations. The thermoelectric system was selected partly in the belief that a reactor developed for the relatively low temperature thermoelectric system would also apply to the Brayton and Stirling cycle configurations as those two technologies matured. After considerable discussions with the thermionics community, SDIO, in conjunction with DOE, began an adjunct thermionics program to the SP-100 program. This second program was aimed at verifying the potential of the in-core thermionic reactor to satisfy envisioned SDIO missions, which extended into the megawatt power requirement regime. The program was named the Thermionic Fuel Element Verification (TFEV) program.

Based on the past accomplishments of the DOE thermionic fuel element program, the life of thermionic reactors was projected to be about 1 year. The objectives of the TFEV program were established to address this life limitation. Researchers understood that the life limits were related to fuel swelling. Fuel swelling is caused by the accumulation of fission gas in the bulk fuel, which distorts the emitter and eventually results in an electrical short between the emitter and collector surfaces of the fuel elements. Radiation damage on materials was also a concern. Accordingly, the TFEV program had the following largely experimental demonstration and evaluation goals:

- Predictive fuel swelling and emitter distortion validation;
- Assessment of radiation damage and effects on insulators, seals, and cesium reservoir materials; and
- Revalidation of prior test data on thermionic fuel element life obtained in the neutron flux TRIGA thermal reactor.

A variety of candidate insulator, seal, and cesium reservoir materials were tested in a fast reactor radiation spectrum. In some cases, the materials were subjected to accelerated testing to the equivalent of 15 years of life. Multiple in-core, fueled emitter tests were conducted to validate fuel swelling, fission gas liberation rates, and the resultant clad distortion predictions.

Polycrystalline alumina proved to be sufficiently stable at high temperatures and electric fields to perform as a thermionic insulator and seal material for 7 to 10 years. Graphite proved to be an adequately stable cesium reservoir matrix material. At a temperature of 1800 K, computer models were able to predict a consistent relationship between fuel swelling and emitter distortion when up to 2 percent of the nuclear fuel atoms had fissioned. This was twice the system design requirement.

Thermionic fuel element manufacturing methods were recovered from work conducted 15 years earlier. The fast spectrum, nuclear thermionic fuel element was demonstrated to last up to 12,000 hours, and projected to last to 18,000 hours based on observed distortions. Contamination of the cesium interelectrode gap by fission gas resulted in acceptable degradation. The TFEV program validated the potential of in-core thermionic reactor systems to meet mission life requirements ranging from 3 to 7 years, and there were indications that longer life might be possible.

Russian Thermionics Research and Development Efforts

Efforts in the former Soviet Union have contributed greatly to the technology of thermionic energy conversion and to space nuclear power in general. The former Soviet space program has flown more than 30 thermoelectric reactor systems and at least 2 thermionic reactor systems. By contrast, the United States flew only one nuclear reactor, SNAP-10A, in 1965.

In contrast to the U.S. program, the Soviet thermionics reactor capability has been supported by a diverse, broadly based technology program that resulted in the launch of two spacecraft. The major research groups working on the technology in the former Soviet Union were the following:

- Russian Research Institute Kurchatov,
- Institute of Physics and Power Engineering at Obninsk,
- Scientific Production Association Red Star,
- Scientific Production Association Energiya,
- Scientific Research Association Luch,
- Central Design Bureau for Machine Building,
- Sukhumi Physical Technical Institute,
- Ioffe Physical Technical Institute, and
- Institute of Nuclear Physics at Almaty.

Major development was carried out in a number of areas, including the nucleonic theory of compact thermionic space reactor design, the control theory of nuclear thermionic reactors, high temperature materials, high temperature nuclear fuel, single-crystal refractory metals, radiation degradation studies, and thermionic converter physics. These programs are impressive in terms of their breadth, as well as their depth in demonstrating the feasibility of space nuclear thermionic systems.

While the United States has made impressive strides in photovoltaic research that the Russians have not matched, the former Soviet Union did produce many noteworthy technical achievements in thermionic technology. Specific areas in which the former Soviet Union appears to have outstripped the U.S. efforts are detailed below.

Single-Crystal Refractory Metal Alloy Development

Several thermionic single-crystal emitter alloys were successfully developed in the former Soviet Union, including alloys of tungsten and molybdenum. No such capability existed in the United States until after 1990. The principles of single-crystal alloy production were well known in 1990 in the United States because single-crystal technology in other alloy systems had been extensively investigated in connection with high performance aircraft engines. However, researchers in the United States never considered the single-crystal refractory metal series for use in thermionics. Since single-crystals have no grain boundaries, using alloys of single-crystal material for high temperature thermionic emitter cladding is believed to limit diffusion of unwanted materials through the emitter cladding.

Low Elastic Modulus Nuclear Fuel to Accommodate Fission Gas Swelling

The U.S. philosophy in reactor design has generally been to use high modulus nuclear fuels to resist emitter cladding swelling induced by fission product gases. Emitter swelling can be a life-limiting degradation mechanism in an in-core thermionic reactor. The Russian approach has been to vary the stoichiometry of uranium and oxygen to minimize the modulus of the fuel. In this way, the nuclear fuel plastically deforms to accommodate the change in cladding geometry. In addition, Russian thermionic fuel elements are designed to vent the fission gas. As a consequence, the fuel is unable to exert force on the cladding wall, and emitter clad distortion is minimized (Gontar 1990).

Resistively Heated High Temperature Refractory Metal Heat Source Development

In the United States before 1990, it was assumed that thermionic nuclear power systems would be launched without any prior acceptance testing of the complete flight unit power system since such prelaunch testing creates radioactive fission products, thus complicating safe launch procedures. Later, Russian researchers demonstrated that a system could be tested using non-nuclear heating. By testing the converter system using electrical heating, researchers could acceptance-test a thermionic converter system on the ground without having to address the added complexity of using nuclear fuel. Refractory metal heaters, such as those developed by the Russians, allow a thermionic system to be tested electrically.

Because U.S. thermionic reactor advocates had not appreciated the benefit of refractory metal heat sources for acceptance testing on the ground, they did not work to develop such sources. Russian researchers, on the other hand, paid considerable attention to qualifying and partial acceptance testing (electrical heating only) on Earth and worked to develop refractory metal heat sources (Vybyvanetz et al. 1990).

Stainless Steel Containment of Zirconium Hydride Moderator

A significant difference between Russian and U.S. reactor design philosophy concerns the use of a neutron moderator. The Russian preference has been to use a neutron moderating material, such as zirconium hydride. The use of such a material results in a more compact nuclear reactor core and shield and dramatically reduces the critical mass of enriched uranium required. The thermal reactors can reach critical mass with as little as 10 to 12 kilograms of fuel, whereas most fast reactor cores require well over 100 kilograms. The thermal stability of zirconium hydride is limited, however, since the hydrogen tends to dissociate from the zirconium at high temperatures. If the hydrogen were allowed to diffuse into the thermionic converter interelectrode gap, a rapid corrosion cycle or embrittlement could occur. High temperature diffusion barrier coatings have evidently been used to prevent hydrogen diffusion into the thermionic converter, but such work has not been pursued in the United States.

Single-Crystal Sapphire Thermionic Insulators

The use of single-crystal sapphire as a thermionic insulator was virtually unknown in the United States prior to 1990. Because there are no grain boundaries in the insulator, electrolytic transport is greatly reduced. As a result, such insulators are considered to be more stable under the combined effects of high temperature, electric fields, and radiation.

Single-Crystal Hexagonal Tungsten Thermionic Emitter Elements

This technology has been demonstrated only in the laboratory and not in operational systems. The hexagonal shape, as opposed to the customary cylindrical shape, permits the emitter to exhibit only the 110 crystal plane. This orientation may increase electron emission and improve efficiency relative to polycrystalline tungsten.

Low Work Function Oxygen-Impregnated Niobium Alloys

The development of low work function niobium-oxygen-cesium thermionic collector surfaces (1.3 electron volts at 900 K has been claimed) may result in higher output voltage and conversion efficiency in thermionic converters. However, because of oxygen depletion, experimental converters have not achieved the anticipated benefit to date.

U.S.-Russian Cooperation: TOPAZ International Program

In the mid 1960s, the former Soviet Union initiated a full scale program to develop and test in-core thermionic reactors using UO_2 fueled thermionic fuel elements (Ponomarev-Stepnoi et al. 2000). Unlike the programs in the United States, which focused mainly on thermionic component technology, the Soviet program developed entire reactor systems. Two competing design teams were allowed to build space reactor systems. One design used multicell thermionic fuel elements, while a second design used single cell thermionic fuel elements. The latter design had less potential to evolve into a high power system because of its inherent low voltage. But the single cell design was simpler than the multicell design. The single cell design also demonstrated the technology of advanced low-modulus nuclear fuel combined with creep resistant, single-crystal emitter claddings, which was intended to result in long lifetime for the nuclear reactor system. Ultimately, the multicell system was flown. In the United States, the Russian acronym TOPAZ (meaning thermionic power from the active zone) is commonly applied to both designs. However, today, the multicell design is apparently the only design being considered for development.

REFERENCES

Gontar, A.S. 1990. "Problems of the Thermionic Fuel Element Development," pp. 164-165 in *Proceedings of Anniversary Specialist Conference on Nuclear Power Engineering in Space*, May 15-19, New Mexico.

NRC (National Research Council). 1983. *Advanced Nuclear Power Sources for Portable Power in Space*. National Academy Press, Washington D.C.

Ponomarev-Stepnoi, N., V. Talyzin, and V. Usov. 2000. "Russian Space Nuclear Power and Nuclear Thermal Propulsion Systems," *Nuclear News* 43(13):33-46.

Vybyvanetz, V.I., et al. 1990. "Experimental Development of Single Cell Thermionic Fuel Element in Thermal and Reactor Tests," pp. 312-313 in *Proceedings of Anniversary Specialist Conference on Nuclear Power Engineering in Space*, May 15-19, New Mexico.

4

Solar Thermionics

As part of the mandate from the Defense Threat Reduction Agency, the committee looked carefully at missions that might use thermionic power conversion in space. In short, there are no current or near-term missions for space that require a thermionic energy conversion system. Furthermore, thermionic technology has not been developed to the point where it is ready for an end user. However, the committee believes that one thermionic energy conversion subsystem using concentrated solar energy may be suitable for use in the far term.

Development of thermionic converters for space has been directed predominantly at applications that use a nuclear heat source. However, a few programs have been undertaken using a solar heat source that concentrates solar energy into a central receiver.

The first major program to consider a solar thermionic heat source was the Solar Energy Technology (SET) program at the Jet Propulsion Laboratory (JPL) in the 1960s. More recently, the U.S. Air Force (USAF) and NASA have considered in a limited way both solar thermionic power systems and hybrid propulsion and power systems. The hybrid systems would first use solar energy and a solar concentrator for thermal propulsion to raise a satellite from low Earth orbit to final orbit, such as to a geosynchronous orbit. Once the vehicle is on station, the same solar concentrator heat receiver would be used as a heat source for a thermionic power system.

In this chapter, the committee discusses potential missions that could use concentrated solar energy as the heat source for a thermionic power conversion system in both standard and hybrid systems.

POTENTIAL SOLAR THERMIONIC MISSIONS

Solar thermionic converters do not involve many of the problematic technical issues associated with nuclear thermionic conversion, nor does solar conversion technology have to contend with the social controversy surrounding the use of nuclear power systems. Most notably, in the technical regime, solar heated converter lifetimes can be very long compared with in-core nuclear thermionic systems, which must overcome the effects of a harsh radiation environment and fuel swelling. Historically, the problems associated with thermionic power systems have been the size and mass of the solar concentrator, in the case of solar thermionics, as well as the complexity and cost of developing an entirely new spacecraft power system in both cases, solar and nuclear. However, recent advances in solar concentrators have mitigated those problems to a large extent.

The primary benefit envisioned with a solar thermionic space power system, such as the high-power, advanced, low-mass (HPALM) system discussed in the next section, is that such a system could deliver high electric power, from 20 to 100 kilowatts, in a low stowed volume, lightweight package. At the projected performance parameters, a 50 kilowatt solar thermionic system would take up less room on the launch vehicle and weigh about the same as a solar array of current design for a 20 kilowatt communications satellite. It is in this high power range that solar thermionic systems have the potential to perform better than other power conversion systems. Below 20 kilowatts, however, solar thermionics would most likely not be competitive when compared to the industry standard, photovoltaic battery systems. Of course, for missions where there is little or no available sunlight, such as outer planet exploration, solar powered conversion systems are not feasible.

Based on current preliminary studies, the committee believes that a solar thermionic power system could possibly facilitate the launch of non-nuclear spacecraft with up to 100 kilowatts of onboard power in a single launch with a standard U.S. launch vehicle. This achievement would more than double the power available from current photovoltaic systems, although future photovoltaic systems may also offer competitive performance. The key is to develop and demonstrate a long life solar thermionic power system that meets or exceeds the performance goals set for the HPALM system described in the next section.

The committee believes that the following types of missions fit the criteria for using solar thermionic systems if the thermionic technology has been developed to a point where it is demonstrated and readily available:

- Space transportation using electric propulsion,
- Advanced high power communications, and
- Space-based military applications.

Electric Propulsion

Space transportation using electric propulsion is perhaps the most interesting and compelling of these potential solar thermionic missions. In typical chemical propulsion systems, combustion provides propulsion energy to accelerate the propellant. In electrical propulsion systems for space, electrical energy provides the electromagnetic and electrostatic fields as well as the heat to accelerate the propellant. The solar thermionic power conversion system could be used in a dual mode power and electric propulsion configuration. The power conversion system is first used for electric propulsion to maneuver a spacecraft into the proper orbit. Once the vehicle is on station, the system could then be used for the mission power requirements. Therefore, the power conversion system has two modes of operation, propulsion and power supply, hence the term "dual mode." Electric propulsion should not be confused with traditional rocket engines or rocket launches from Earth to space. Electric propulsion is not used to place the spacecraft in orbit but, rather, to maneuver the vehicle once it is in space.

One unique benefit for electric propulsion systems is that nuclear powered and some solar powered thermionic systems designed to operate over normal capacity at the beginning of life, can operate in a surge power mode (also referred to as peak power mode). For example, in Figure 3.7 in Chapter 3, if the emitter temperature is increased from 1800 K to 2100 K, the output power can be doubled for a relatively short time, 30 to 90 days. To configure a system to operate in a surge mode requires that all components be designed to achieve equilibrium at a higher temperature. This type of operation could require spacecraft designers to accept a somewhat shorter vehicle operating lifetime. Such surge mode operation can be used to decrease the time required for orbit positioning or transfer. In this dual mode operation, electric propulsion can be combined with other mission requirements to achieve a synergistic benefit.

A wide range of missions could potentially take advantage of recent advances in electric propulsion systems. Electric propulsion uses fuel 4 to 10 times more efficiently than chemical propulsion and 2 to 4 times more efficiently than solar thermal propulsion.

With the smaller volume and mass afforded by a solar thermionic electric propulsion system, a number of configuration scenarios can be imagined. For instance, smaller, less expensive booster rockets might be used for launch, or more satellites might be launched per boost vehicle. Or, a larger on-orbit, station-keeping fuel payload might be allowed, which would extend the lifetime of a spacecraft on orbit.

The committee believes that spacecraft designers may require that many new high altitude spacecraft, such as satellites in geosynchronous orbits, be inserted above the Van Allen belt by their launch vehicles in order to avoid payload exposure to radiation. From that point, electric propulsion could be used to raise the vehicle to a final orbit. Currently, spacecraft are inserted directly into geosynchronous orbit, but this practice significantly limits the cargo space and mass available for payload.

The committee believes that the spacecraft design community may make use of high power, low mass applications that solar thermionics has the potential to offer. Higher available power levels would enable shorter insertion times when using electric propulsion in the manner described above.

Appendix C contains details of spacecraft mission considerations and describes a concept for a commercial system coupling high power to electric propulsion for orbit transfer in order to reduce operational costs. A 100 kilowatt electric propulsion system made up of four 25 kilowatt thrusters is compared with the total impulse of the Thiokol Star 75 motor, a state-of-the-art solid propellant space motor. Based on cost estimates for a thermionic power system, cost savings on the order of $100 million could be realized by satellite operators. The savings associated with dual mode operation could also be substantial. This cost analysis, of course, assumes a fully operational and tested system that would require a substantial investment to develop.

Finding: Solar thermionic power systems may enable dual mode operation: electric propulsion for orbit raising and orbit maintenance and electric power for satellite payloads while on station.

Civilian Applications

Recent commercial space activities indicate a trend of placing larger and larger satellites into geosynchronous orbits. The geosynchronous market continues to grow, with larger satellites with higher power levels being built every year. Twenty years ago, aerospace companies were launching geosynchronous satellites that required 1 to 3 kilowatts of electric power. Presently, the standard power requirement for geosynchronous communications spacecraft is approximately 10 kilowatts. Satellites requiring 20 to 25 kilowatts are now being designed for possible use within 3 years.[1]

A solar thermionic system could meet the need for potential future growth in the industry, while allowing the industry to explore even higher power applications that could benefit the consumer. For instance, as satellite broadcast power increases, consumers can use smaller and smaller receiver dishes on the ground.

Space-Based Military Applications

Space-based radar systems have been studied extensively by the military over the past few decades. Most of these studies have recommended a combination of low orbits and low duty cycles. This combination is probably recommended based on the prohibitively large size and mass of traditional power systems required by a more advanced space-based radar system capable of broad coverage, detection of small targets, and frequent contact updates of multiple targets. Such missions require on the order of 100 kilowatts of available electric power. A solar thermionic system could drastically change the feasibility of such a mission. The higher power levels a solar thermionic system could allow for an affordable space-based radar system that improves on the mission performance now provided by airborne radar systems, such as the Airborne Warning and Control System (AWACS) and optical and Long Wave Infrared (LWIR) systems.

HIGH-POWER, ADVANCED, LOW-MASS CONCEPT

For a solar power conversion system using thermionics, solar energy is concentrated into a heat receiver using either reflective or refractive optics. This heat receiver then serves as the heat source for a group of thermionic converters that provide power to the spacecraft.

As presented to the committee by General Atomics, the HPALM concept uses a large off-axis, inflatable parabolic reflector to focus solar energy into a 2000 K heat receiver that is radiatively coupled to the thermionic devices (see Figure 4.1). The program is based on a concept developed in part by General Atomics. An AFRL program to study the HPALM design concept started in mid 2000.

In one approach being evaluated, the cylindrical thermionic converters are designed with an inverted multicell. In this design, the emitter is on the outside and the collector is in the center of the cylinder. This is a nontraditional approach to designing a cylindrical thermionic device. In traditional designs, the collector is outside the cylinder and the heat is generated internally, as it is with a nuclear thermionic fuel element (TFE), and then removed by cooling systems attached to the outside surfaces of the TFE.

In the HPALM concept, the thermionic element is inverted. Heat will be applied to the outside of the thermionic element cylinder, and heat pipes will be used to remove the waste heat, at approximately 1100 K, from the collector surface inside the cylinder. General Atomics anticipates reaching efficiencies of 20 to 25 percent for the converters. According to General Atomics, the conceptual system is sized to provide 50 kilowatts of

[1] Space Systems Loral announced in January 2001 that it can provide a new standard bus for geosynchronous satellites that is capable of delivering "up to 30 kW" with a photovoltaic power system.

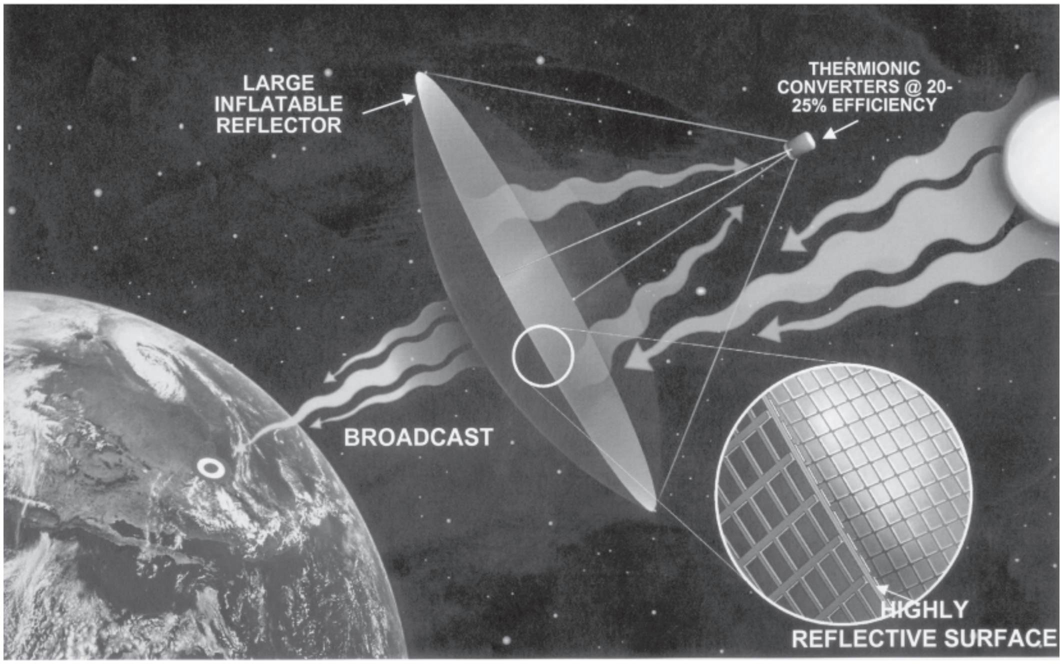

FIGURE 4.1 Artist's rendition of the HPALM solar thermionic concept.
SOURCE: L. Begg, General Atomics, presentation to the Committee on Thermionic Research and Technology, August 2000.

electricity and has a calculated performance of 106 watts per kilogram and 80 kilowatts per cubic meter in a stowed configuration ready for space launch.

The HPALM concentrator consists of an off-axis inflatable dish with a thin film reflector for low mass and low stowed volume for launch. The concept is based on inflatable space structure development that has been sponsored by NASA and AFRL over the past several years. The highlight of this work, which is not directly related to the HPALM concept, was the deployment of a large inflatable antenna structure from the space shuttle in 1997. Large area, thin film solar reflectors have been flown a number of times and are now included in the Hughes Corporation's concentrator solar arrays for some communications satellites. An inflatable concentrator configured specifically for the HPALM system does not, however, exist at this time. If an inflatable concentrator is not successfully developed, then the projected performance capability, as presented under solar thermionic systems in Table 3.4 (Chapter 3), would not be as appealing due to the increase in mass required for a noninflatable concentrator.

Another important component of the HPALM power system is the heat receiver. This unit would be designed to capture the solar energy from the concentrator through a small aperture. The concentrated solar rays would be partially absorbed and internally reflected to different surfaces. The reflected rays bounce between surfaces and are partially absorbed during each reflection process. This process repeats until essentially all of the solar energy is absorbed inside the heat receiver. The aperture would be kept small to minimize both heat loss and the loss of reflected solar energy back out of the aperture. Refractory or carbon materials can be used to absorb the heat at the working temperature of the receiver. An integral heat receiver with thermal storage designed for use with a 2000 K HPALM system does not exist at present, although the technology has been demonstrated at 1100 K by both NASA and the USAF. One final, yet important, aspect of the HPALM design is the mechanism used to transfer heat energy from the solar receiving cavity to the thermionic converter. The heat from the graphite block receiver is radiated to the emitter in General Atomic's version of the concept. The HPALM concept does not call for any dynamic mechanical systems to transfer the heat energy.

Committee Analysis

The committee suggests that the eventual sponsoring agency align a thermionics research and development program to coordinate with the HPALM program.

Recommendation 3. The sponsoring agency should concentrate its near-term thermionic development work on a space-based solar thermionic power system, such as the high-power, advanced, low-mass (HPALM) concept.

The committee makes this recommendation based on the understanding that the HPALM system is designed around a thermionic converter power supply; therefore, successful completion of a thermionics research and development program would be a major HPALM program priority.

The committee finds the HPALM concept interesting for a number of reasons. The calculated performance as presented by General Atomics is approximately twice as good as that of current solar array technology in terms of stowed volume and mass, since the system would make use of a lightweight inflatable concentrator. From a power density perspective, the HPALM system is estimated to provide between 23 to 33 watts per kilogram, which is comparable to photovoltaic systems. A solar power thermionic system providing 50 kilowatts of electrical power could have many interesting potential applications. For instance, a 50 kilowatt HPALM system may enable electric propulsion used to raise satellites to middle and high orbits. The committee anticipates that HPALM performance should improve as the system design is refined. However, it should be acknowledged that comparing the performance of a future thermionic concept system to the current capabilities of a photovoltaic system is not entirely valid. Only when a detailed thermionic system has been designed or built can it be compared to a then-current photovoltaic system.

Based on space vehicle market trends over the past 10 years, the 50 kilowatt design proposed for the HPALM concept appears to be a potentially viable option. The solar thermionic system also appears to have a power density advantage when scaling to higher power levels, while a photovoltaic system has the advantage when scaling down. Compared with a photovoltaic space power system, a solar thermal system starts with a higher percentage of fixed mass. Thermionic generators are usually multikilowatt devices, and both the pointing system and the pressurization system for the inflatable structures, as proposed for the HPALM system, have the desirable trait of scaling nonlinearly relative to the increase in power production.[2] Therefore, the power density of solar thermionic power systems will most likely increase as they are scaled to higher power levels.

Finding: A solar thermionic conversion system can likely be designed, built, and flight demonstrated using known technology. However, since the lifetime, mass, efficiency, and cost of such a system are uncertain, they need to be addressed in future technology programs.

Technical Challenges

It is important to note that all of the committee's assessments of solar thermionic power system technology are based on projected capabilities. Until the potential of such a system is proven, these assessments represent what might be possible. Even though there are potential positive benefits from a solar thermionic system, a number of technical challenges would have to be addressed before such a system could be definitively endorsed.

Another aspect of developing a new power system concept, such as a solar thermionic system, is that detailed design information must be available to the satellite designer before the system can be considered for use. Although the technology exists so that the components of a solar thermionic power system can be developed, no one has developed a detailed, peer reviewed design of a complete system. The committee expects that a HPALM program at AFRL may fill this need.

The committee identified several areas where technical issues must still be resolved. The list should not be considered to be inclusive.

- Power conditioning,
- Energy storage,
- Thermionic converter configuration,
- Cavity/receiver heat flux uniformity, and
- Pointing, tracking, and reacquisition.

The last two are not discussed in the text that follows.

Power Conditioning

An important consideration that has not been addressed in the HPALM concept description is power

[2]The area of an inflatable solar concentrator is proportional to the radius of the concentrator squared ($A \propto r^2$). Thus, a 10 percent increase in solar concentrator radius results in a 21 percent increase in concentrator area and energy collected.

conditioning. Thermionic converters tend to produce low voltage and high current while operating at high temperature. This particular configuration presents an especially difficult problem for a high power system on a spacecraft. Current high power spacecraft, 10 to 20 kilowatts, use bus voltages of 50 to 160 volts to minimize the mass of power conductors. The committee expects that as power levels increase from 20 to 100 kilowatts, voltages will continue to increase to as high as 270 or 300 volts.

A thermionic system such as HPALM is likely to have a much smaller voltage than this future specification even with all of the converters connected in series. The need to handle the high currents that would be characteristic of a high power thermionic system would require large diameter conductors. Such conductors can act as a source of heat leaks from a high temperature device.

Also, power conditioning systems would be very heavy, which is not a desirable property for space launch. For example, a recent power conditioning unit developed for a 5 kilowatt Hall-effect propulsion system that converted 28 volts to 300 volts weighed approximately 25 kilograms. These power conditioning issues can thermally impact both the performance of the energy converter and nearby components on the satellite.

Finding: Power conditioning technology issues are inherent to a space-based power conversion system. So far, this issue has not been addressed by the DTRA-sponsored thermionics program.

Energy Storage

For any satellite power conversion system, energy storage must be considered to meet peak power demands and to provide power when the primary power system is not operational, such as prior to system startup during launch and deployment. For solar power systems, energy storage must be considered when the satellite is shadowed by Earth. There are two basic options for storing energy: batteries or thermal energy storage.

Battery system storage, the current baseline for the HPALM concept, is the same energy storage scenario used for photovoltaic power systems. When batteries are used, the solar power system is oversized to generate extra power during the sunlit portion of the orbit. The extra power is stored as electrochemical energy in a battery to provide power to the spacecraft during eclipse periods when sunlight is not available.

One technology now being developed is lithium ion batteries, which deliver up to 100 watt hours per kilogram. A portion of a battery's energy between 40 and 80 percent is normally used during each eclipse. The amount used is driven by the required lifetime for the batteries since they last longer if they use less of their energy during each discharge cycle.

Thermal energy storage is an alternative approach to energy storage, an approach that may be more attractive than batteries for the HPALM program. A thermal energy storage device would be incorporated into the heat receiver, and energy for operating the spacecraft during eclipse would be stored in a phase change material. Such a material melts as heat is added, then refreezes when the heat is used during eclipse. This process allows the energy conversion device to operate continuously, even during eclipse. The thermal energy storage material must be selected for minimum mass, which can be achieved in part through a high heat of fusion. The material must also have a melting point that matches the operating temperature of the heat receiver. The material is enclosed in a heat exchanger containment system that enables the heat to transfer between the heat receiver and the thermionic fuel elements.

One candidate high temperature material that has been tested is silicon, which has a heat of fusion of 1.80 megajoules per kilogram. However, the melting point of silicon is 1673 K, which is compatible with a thermionic energy conversion system but is well below the heat receiver temperature of 2000 K proposed for HPALM. If the HPALM system used the new baseline of 1673 K to match the melting temperature of silicon, there would be a 30 percent decrease in power generation efficiency in the thermionic converters. A higher temperature material therefore needs to be identified if thermal storage is to be considered. The committee suggests that manganese oxide, with a melting point of approximately 2000 K and a heat of fusion of 0.77 megajoules per kilogram (213 watt-hours per kilogram), may be a promising alternative. However, it should be noted that should such a concept be implemented into a full system, the overall performance of the system with energy storage would be significantly lower.

For a thermal energy storage system, the usable heat of fusion of the pure material is reduced by the inefficiency of the electrical energy conversion process. This reduction in the heat of fusion is typically fivefold. In the case of manganese oxide, the resulting energy storage system performance would be about 20.56 kilograms per kilowatt for the case illustrated in Table 3.4. This performance compares favorably with lithium ion batteries, which have been demonstrated to provide 18.33 kilograms per kilowatt. Since batteries can actually use only a fraction of this amount, thermal storage may add to the attractiveness of a solar thermionic system. However, this is an area that needs more investigation.

An added benefit of using thermal energy storage is that both the heat receiver and the thermionic converters are kept at a constant temperature throughout the life of the spacecraft. Without a heat receiver, the solar energy would be concentrated on different parts of the heat receiver cavity at different points of an orbit, thus creating hot spots in the cavity. If there is no thermal energy storage system to act as a buffer between the concentrated solar energy and the thermionic converters, they may produce different amounts of power depending on the amount of solar energy directed on any one converter. Unevenly heated converters would mean a significantly more complex power source. The use of isothermal heat pipe cavities has also been demonstrated as a method of avoiding hot spots in the cavity.

Another problem with having orbit-induced hot spots in the receiver cavity is thermal-induced mechanical stress. Varying temperature gradients resulting from solar energy concentration could shorten the life of power system components. A thermal energy storage system could eliminate deep thermal cycling for system components and increase the life and reliability of the system. However, such a system may not be practical for satellites placed in geosynchronous orbit due to the very long eclipse times.

Finding: A phase change design for thermal energy storage should be considered as part of solar thermionic system development.

Thermionic Converter Configuration

A final consideration that concerns the committee is that the initial HPALM design includes the use of cylindrical thermionic devices. The HPALM concept proposed by General Atomics uses radiative coupling between a cylindrical heat receiver and a ring of several cylindrical converters that stand out from the receiver like spokes from a wheel hub. An alternative configuration could use planar thermionic converters to couple more directly to the outer surface of the receiver. It is not clear why the cylindrical converter design was the only converter configuration considered for evaluation in the HPALM system. The cylindrical TFE would offer more surface area for the emitter and collector and less surface area for the receiver. However, past solar thermionic designs have used a planar configuration that, in the SET program, for instance, has demonstrated very good performance and lifetime.

Finding: It is not yet known if the performance goals of obtaining a high power solar thermionic system based on the HPALM concept are technically feasible.

Finding: For the solar thermionic HPALM concept as presented by General Atomics, there are no obvious advantages to using a cylindrical geometry rather than a planar geometry for the thermionic fuel element.

To summarize, the committee's assessment is that a space solar power system is the most promising near-term application for thermionic technology. However, while it is the most promising application, success is not certain. The history of spacecraft performance demonstrates that it is difficult to compete with photovoltaic power systems. Although photovoltaics have been used since the late 1950s, no other technology has been able to replace this technology as the power source of choice for Earth orbiting satellites. Significant progress continues to be made in photovoltaic converters. For instance, triple junction solar cells can now deliver up to 29 percent efficiency.

The key to competing with and potentially replacing photovoltaics as the space power source of choice is to optimize solar-to-electric thermionic system design and quickly demonstrate the capability of the thermionic technology. Success requires a near-term focus with an aggressive system engineering approach.

SOLAR ORBITAL TRANSFER VEHICLE PROGRAM

The primary goal of the Solar Orbital Transfer Vehicle (SOTV) program being conducted by the AFRL is to develop an orbit transfer propulsion system using concentrated solar energy to heat hydrogen. A SOTV could be used to raise a client spacecraft's orbit, that is, to transfer its orbit to a higher elevation. The transfer vehicle could then detach and return to a lower orbit for refueling. Alternatively, the transfer vehicle could remain attached to the client satellite and use the solar concentrator and a thermionic conversion system as a power supply for the satellite.

The program is in the proof-of-concept phase, and researchers are conducting experiments to verify component performance. Orbit transfer vehicles appear in the USAF Space Command Strategy Master Plan, but no orbital transfer vehicle has been constructed thus far, and no funds have been budgeted to do so (see Figure 4.2).The SOTV program is the only active program other than HPALM that the committee has identified that is considering thermionics as a power conversion mechanism. However, the committee does not advocate aligning a thermionics research and development program with the SOTV program. The primary focus of the SOTV program is on proving the viability of the hydrogen propulsion system. The committee understands that the limited availability of funding drove this decision and that a critique of the SOTV program in relation to the HPALM concept is beyond the scope of this committee's responsibility. While not intending for this report to cast any doubt on the performance or capability of the SOTV program, the committee does feel obligated to identify the best potential match for thermionics technology.

The committee was interested in the thermionics testing done to date under the SOTV program. Specifically, the DTRA and AFRL sponsored three tests of thermionic element arrays at the New Mexico Engineering Research Institute (NMERI) of the University of New Mexico to demonstrate the readiness of the technology for the SOTV system. The tests were termed the string thermionic assembly research testbed (START) tests. The committee felt it needed to review the tests in detail since the poor START test results indicated that there was some fundamental failure of the thermionic converter technology.

STRING THERMIONIC ASSEMBLY RESEARCH TESTBED TESTS AT THE NEW MEXICO ENGINEERING RESEARCH INSTITUTE

The SOTV program is a follow-on to the hydrogen fueled Integrated Solar Upper Stage (ISUS) Orbital Vehicle program started in 1994, and the START tests were initiated under that program. Because the ISUS concept vehicle would need very high temperatures for the hydrogen fuel propulsion, thermionics was selected as an appropriate power conversion technology since thermionics also requires a high temperature heat source.

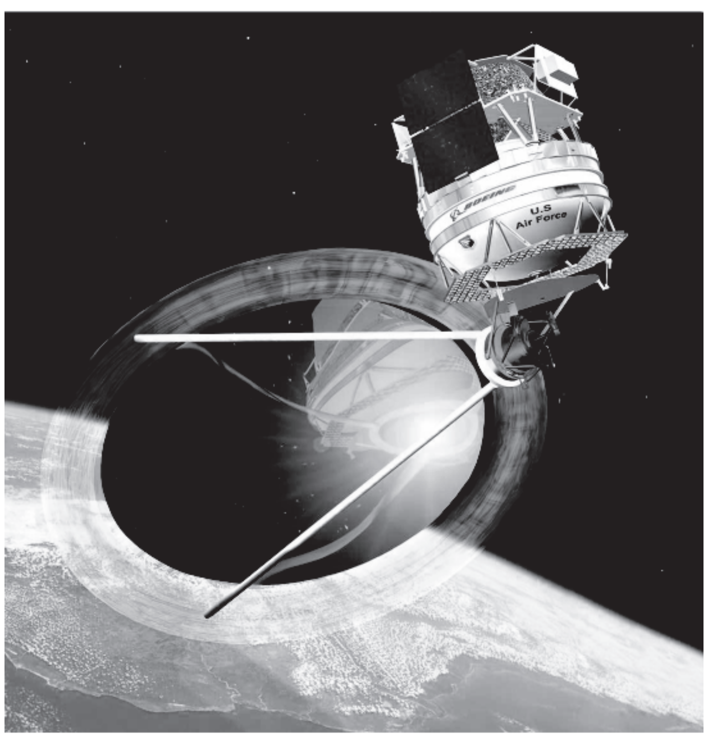

FIGURE 4.2 Artist's rendition of a solar orbital transfer vehicle.

The START tests were designed to evaluate thermionic power conversion for use with a future SOTV spacecraft. Of special interest to the committee was the conclusion from these tests, namely, that there were too many technical difficulties to make thermionics a viable power conversion technology. In fact, the committee believes that the SOTV program's shift in focus toward propulsion technology may be due in part to the poor START test results. Thermionic power conversion is still being considered as a possible power source in the SOTV program, but the technology is now in competition with Stirling engines, concentrating solar arrays, and other alternatives.

The committee examined the START tests in detail and found problems with the testing, analysis, design, and test fixture fabrication in the START series that should be carefully accounted for in any future tests. Because these problems bring into question the validity of the data that were collected, the committee determined that the viability of thermionic power conversion technology should not be judged based on these tests.

Finding: The string thermionic assembly research testbed (START) test series should not be used as a basis for evaluating the viability of thermionic power conversion technology.

When the ISUS orbital vehicle program was initiated, a contract was awarded to Babcock and Wilcox to develop a test fixture with a string of 8 series-connected thermionic converters to be used in the first test phase. A string of 16 series-connected converters was ordered to be used in a second test phase. The first test of the 8 series-connected thermionic converters was intended to identify any first-phase problems with the converter test setup prior to initiating the second phase. Other groups involved at various times during the testing were General Atomics, NMERI, and Loral Electro Optical Systems (now a part of Lockheed Martin Corporation).

As a consequence of various technical difficulties with the test equipment and procedures, a total of four tests were conducted under the START test series instead of the originally planned two tests. At the end of the four tests at NMERI, a total of 26 converters had been tested in strings of 8 or 16 converters connected in series. The primary objective of the test series was to demonstrate the performance of series-connected converters in a flight-like environment. However, even with the extra tests, every attempt to operate a string of thermionic converters connected in series ended in failure during the START tests. As a result, there was no opportunity to test the string of diodes in a flight-like environment.

The committee is very concerned about these results. Other tests detailed in this chapter have proven that thermionic converters can successfully operate for very long lifetimes both when operated individually and when connected in series.

One such test was performed by JPL under its SET program in 1967, during which four converters were connected in series (see Box 4.1). A second test was performed by General Atomics in a TRIGA reactor with a six cell TFE and again with a three cell TFE. There have been two Russian TOPAZ reactors flown with thermionic converters wired into 28 volt output configurations. Converters from a TOPAZ reactor were

BOX 4.1
The Solar Energy Technology Thermionic Program

Some past thermionic testing made significant progress in the development of thermionic technology. The committee believes that some of the difficult lessons learned may be lost if the documentation is not carried forward. If the knowledge gained from those tests is lost, future generations of researchers may have to rediscover it, wasting limited resources in the process.

The Solar Energy Technology (SET) program, initiated by the Jet Propulsion Laboratory (JPL) in 1962, is an example of successful tests of thermionic converters developed by Thermo Electron and Loral Electro Optical Systems (now part of Lockheed Martin Corporation). By 1968, the SET program had produced high pressure, ignited mode converters with a stable life of over 10,000 hours and an output power density of 20 watts per square centimeter at 1 volt for an emitter temperature of 2000 K. This project pioneered the development of cesium-compatible, ceramic-metal seals and other materials technology employed extensively in all later thermionic work.

One such test, performed by JPL in 1967, included four converters connected in series. The performance predicted from the individual converter data was approximately 20 percent greater than what was attained when the START converters were tested as a series-connected array. This loss was found to be caused by increased spacing between the collector and emitter, which was in turn due to a difference in the thermal expansion behavior of the converter when it was placed in a receiver block versus when the converter was in an emitter block (Rouklove 1967).

also electrically tested in the United States during the TOPAZ International Program discussed in Chapter 3. Finally, a planar thermionic converter similar to the converters used in the START tests, and built by the same manufacturer that constructed the START test thermionic devices, demonstrated 24,000 hours of life in a test completed in 1994 (Thayer 1994).

Previous experience in testing thermionic devices indicates that converters can be made to work in series-connected circuits to develop a usable voltage level. The committee therefore recommends that the future sponsoring agency look closely at the START tests in order to identify and make use of the lessons learned and increase the probability of a successful test in the future. To aid in this effort, the committee identified several areas that should be given attention in any future tests:

- As with any difficult test program, additional time and financial resources should be included in any future test plan to accommodate problems that will inevitably arise. Technical difficulties, and the time and resources required to deal with them, should be considered as a part of the standard operating procedure for any high risk, experimental scenario.
- Some members of the thermionic device design and manufacturing team should be involved in the system tests. In this way, their expertise can be used early in the test cycle to minimize errors, help overcome testing obstacles, and avoid previously identified mistakes.
- The test fixture should be tested and characterized to make certain that performance requirements are met before fitting the thermionic devices into the fixture. For instance, temperature stability characteristics and temperature gradients in the heating elements should be clearly identified.
- Any future test setup should account for a high electromagnetic interference environment, because the high temperature test fixtures used in previous thermionic experiments generated a large amount of such interference.

The committee believes that the sponsoring agency should conduct an independent test of the original START test converters. First, the sponsoring agency should determine conclusively if the devices still work or if they are no longer functioning, as shown by the results at NEMERI. If the results of the reevaluation of the converters are different from those of NEMERI, an effort should be made to understand why there are differences. Any discrepancies between the two sets of data must be resolved so that the true test issues and device design issues can be identified.

Once the core issues are identified, the sponsoring agency should gather a group of experts to look closely at the START tests. This group should document proper test methods needed to have a successful test in the future.

Recommendation 7. When working on a system-level solar thermionic design, the sponsoring agency should reexamine the string thermionic assembly research testbed (START) tests to record lessons learned. The reexamination should begin with a retest of the original, individual converters to differentiate between problems due to converter design and generator configuration and those due to the test setup. The sponsoring agency should gather an independent group of experts to devise testing methodologies so as not to repeat past mistakes.

REFERENCES

Rouklove, Peter. 1967. "Thermionic Converter and Generator Tests," Jet Propulsion Laboratory research documents, Pasadena, Calif.

Thayer, Kevin. 1994. "Life Test and Diagnostics of a Planar Out-of-Core Thermionic Converter," paper presented at the Eleventh Symposium on Space Nuclear Power, Albuquerque, N. Mex., January.

5

Nuclear Thermionics

A 1998 report published by the National Research Council's Committee on Advanced Space Technology (NRC 1998) stated as follows:

> Advanced space nuclear power systems will probably be required to support deep space missions, lunar and planetary bases, extended human exploration missions, and high-thrust, high-efficiency propulsion systems. A major investment will eventually be needed to develop advanced space nuclear power sources. . . . Unless NASA supports R&T in areas such as innovative conversion methodologies or innovative packaging and integration, future space nuclear power systems will probably be more expensive and less efficient.

For some space propulsion missions that require high power, or where nuclear power is a critical requirement, the potential performance advantages of a nuclear thermionic system are compelling. The demonstrated state of the art of thermionic systems in terms of lifetime and device-level power output, coupled with their low mass and compactness, make this technology attractive and suggest that it could satisfy future space power requirements in the low to mid tens of kilowatts to megawatts.

In some cases, fully developed thermionic technology may be mission enabling. However, the committee acknowledges that the technical risks in developing a functional thermionic system are high. The technical uncertainty in developing an operational system that could achieve the desired performance is especially high for power systems that use thermionic converters powered by nuclear reactors.

There is no capability in the United States to test nuclear thermionic fuel materials for fuel swelling issues because those fast-flux test facilities were deactivated. A possible alternative to reestablishing test facilities in this country is to coordinate with Russia in future thermionic materials testing.

As discussed in Chapter 4, the committee recommends orienting the near-term thermionics research and development program toward a solar thermionics conversion technology aimed at competing with other energy conversion technologies available today, such as solar photovoltaics. Basic research and long-term planning, however, should be oriented to establish a technology base that could be used by a future space mission requiring nuclear power. This chapter details the current state of nuclear thermionic research and the path that should be followed to establish a long-term nuclear thermionic capability.

Recommendation 4. The sponsoring agency should concentrate longer-term thermionic development work on those areas of nuclear thermionic power systems related to materials development, converter development, and radiation effects on materials in order to achieve high power and long life for such systems.

LESSONS LEARNED FROM TOPAZ

The history of the TOPAZ International Program work is recounted briefly at the end of Chapter 3. The statement of task required the committee to review the work conducted under the joint U.S.-Russian TOPAZ International Program. A previous National Research Council report on the TOPAZ program reviewed the work conducted under that program (NRC 1996). No further work has been conducted under the program since it was canceled.

In 1995, the Defense Nuclear Agency (DNA), which has since then become a part of the Defense Threat

Reduction Agency (DTRA), requested that the National Research Council examine and assess the TOPAZ International Program that the DNA was then conducting. The DNA asked for an assessment of the following:

- The status of the program at the time;
- The value of continuing the ongoing activities as they related to developing operational space nuclear power systems;
- The possible effects of discontinuing certain elements of the program;
- The state of the TOPAZ reactor technology in relation to the equivalent U.S. technology;
- The value of establishing revised goals for the program; and
- Steps DNA could take to serve the national interest more effectively, including continuing, modifying, expanding, or discontinuing the program.

Representatives of various organizations in DoD, DOE, and NASA, together with Russian interests, U.S. industrial companies, and private individuals, participated in the 1996 deliberations on the TOPAZ International Program. Since the TOPAZ International Program was devoted to thermionic system advancement, the 1996 report's assessment is relevant in many respects to the current examination requested by DTRA. Although no work has been conducted in the United States related to the TOPAZ International Program since the program was discontinued in 1996 and the TOPAZ hardware was returned to Russia, many of the factors considered by the previous committee and the conclusions it reached are still valid. The conclusions of the 1996 report, and the current committee's observations, are summarized below.

- *Support of high power, long lifetime nuclear systems.* The 1996 TOPAZ committee stated that one objective of a U.S. thermionics program should be to advance critical technologies that could support potential future high power, long lifetime space nuclear reactor systems. However, at that time the program did not have sufficient funds to advance the critical technologies required for such a nuclear system. Those funds are still not available.
- *User applications.* The 1996 TOPAZ committee emphasized throughout its report that there were no dedicated users or then-current applications for thermionic or nuclear technology. The 1996 committee also found that there were no planned or confirmed mission-directed activities within the TOPAZ International Program. While the Solar Orbital Transfer Vehicle program may address this issue with respect to solar thermionic systems, there is still no confirmed mission for a nuclear thermionic system.
- *Knowledge capture.* The 1996 TOPAZ committee found that the TOPAZ International Program had no formal mechanisms to record and archive the technical knowledge gained from the space power nuclear reactor technology efforts so that it would be accessible for future efforts. There is still no formal archival method being used today in the DTRA thermionics program.
- *Collaboration.* The TOPAZ committee found that an integrated and collaborative interagency approach that existed in earlier nuclear power development programs, such as SP-100, had broken down.
- *Role of government.* The 1996 TOPAZ committee found that there is a role for the government in research and development for thermionics because U.S. companies often do not have sufficient economic motivation to maintain the scientific and engineering staffs or facilities to support continued work on high risk, long-term projects such as thermionics. The situation has not changed since 1996.

All of the points made by the TOPAZ committee in 1996 are relevant to the current situation in the DTRA thermionics program. In contrast to the previous committee, the current committee, as already stated, recommends that emphasis be placed on solar thermionics research as a near-term goal and that nuclear thermionics research, as advocated by the 1996 NRC committee, be viewed as a long-term goal.

The current funding situation is analogous to the funding that existed for the TOPAZ International Program in 1995 and 1996: that is, year-to-year funding mandated by Congress limits the efforts. The conclusions listed above should help guide future thermionics work aimed at space nuclear power.

The 1996 TOPAZ committee considered six program options that ranged from terminating the TOPAZ program to revisiting the possibility of conducting a flight test and revamping the overall program. The TOPAZ International Program was canceled shortly after the committee's report was released, and no further work has been conducted.

The following is a paraphrased account of some of the recommendations from the 1996 report that would be relevant to a future nuclear thermionics program in the United States:

• The overriding objective of thermionic research should be to advance the critical technologies for high-power, long-lifetime U.S. space nuclear reactor power systems.

• The U.S. government should support a single, comprehensive, integrated thermionics program rather than a collection of uncoordinated programs. Funding at the level of $15 million to $20 million per year would be required to develop a space nuclear reactor program.

• The nuclear portion of an integrated thermionics program should focus on fast-spectrum reactors using in-core multicell thermionics aimed at high-power, long-lifetime systems rather than thermal-spectrum, single-cell systems. An integrated thermionics program should also include other power conversion approaches, including thermoelectrics and out-of-core thermionics.

• An integrated thermionics program should cooperate with Russian institutes involved in thermionic development to benefit from their experience and testing facilities. In-core lifetime testing is not readily available in the United States owing to the declining availability of domestic irradiation test facilities.

• A thermionics program should include the participation of U.S. industry to help establish and benefit from a strong, long-term knowledge base.

• A thermionics program should initiate cooperation among DoD, NASA, and DOE and should include multiagency funding to provide continuing support.

NUCLEAR THERMIONIC TECHNOLOGY DEVELOPMENT

In Recommendation 3 (see Chapter 4), the committee states that the thermionics research and development program should be directed in the near term toward the development of a solar thermionic system. Long-term thermionic program goals, however, should be directed toward establishing and maintaining an option for a nuclear thermionic system, a position stated in Recommendation 4 above in this chapter. Balancing two sets of requirements to meet these short- and long-term goals will not be easy. It will not, for example, be possible for the sponsoring agency to design a solar thermionic system that simultaneously addresses issues such as the radiation damage to materials and mechanical stress caused by nuclear fuel swelling. However, for a viable nuclear thermionic system to be built, those are exactly the issues that must be addressed.

Despite the difficulty, the committee believes that the sponsoring agency should work to develop a technology base that can advance systems that will meet both sets of requirements. However, the area where the two technologies overlap is difficult to define, so the sponsoring agency needs to carefully decide which specific technologies or systems will be developed.

The committee feels that the cylindrical inverted multicell (CIM) thermionic converter, proposed by General Atomics in conjunction with the HPALM system (described in Chapter 4), and the conductively coupled multicell (CC/MC) thermionic fuel element, also proposed by General Atomics, may be specific examples of technologies that can be used for solar thermionic applications and adapted to nuclear thermionic applications in the future. The following discussions of the CC/MC and CIM are not meant to indicate that these technologies are the perfect (or the only) technologies that can be developed for use in both nuclear and solar conversion systems. Rather, these technologies should be considered indicative of the type of devices that offer promise of being compatible with both heat source systems.

Conductively Coupled, Multicell Thermionic Fuel Element

A traditional multicell thermionic fuel element (TFE) consists of thermionic converters connected in series. Each element is loaded with nuclear fuel and both ends of the element are sealed. The nuclear fueled "flashlight" TFE, which was the baseline for most in-core reactor concepts in the United States as well as the former Soviet Union, is a stack of these individual thermionic converters connected in series to form a thermionic generator. Each fueled thermionic converter gives the impression of a standard D-cell sized battery, hence the term "flashlight configuration." General Atomics has performed most of the work on flashlight TFEs in the United States.

By the early 1990s, program planners and researchers realized that the ability to conduct nonnuclear ground testing of flight units prior to launch would be useful for acceptance or flight qualification testing. Unfortunately, conventional sealed thermionic cells used in the thermionic flashlight generator are difficult to heat-test electrically because of the mechanical design of the TFE.

Moreover, nuclear heating is not practical for flight system verification on the ground. When units are tested for flight qualification on the ground, radioactive fission products are produced in the nuclear core. Having these products in the nuclear core during a rocket launch creates additional complications for launch safety assurance. A predecessor of the only U.S. nuclear reactor to fly in space, SNAP-10A, was ground tested. The second, untested unit was then flown on the experimental space mission.

Radiative coupling is one way around the dilemma of not being able to test a TFE individually prior to combining it with the nuclear heat source. With a TFE designed for radiative heating, a vacuum gap electrically isolates the nuclear fuel from the thermionic converters. An electrical heat source is then used to mimic the radiative heat properties of a nuclear heat source. In this way, each individual TFE and the entire energy conversion subsystem can be tested before loading the reactor with nuclear fuel. The reactor can then be fueled relatively late in the checkout process before launch.

The major disadvantages of using radiative electrical heat testing are that the radiative heating introduces an additional temperature gradient between the heat source and thermionic emitter due to the vacuum gap between the two. This situation requires that the fuel maintain a temperature roughly 200 K higher than the emitter surface to compensate for the gap.

An alternative approach for a design that keeps the thermionic converter separate from the nuclear fuel is conduction coupling. There, the heat from the nuclear fuel is transferred conductivly using a ceramic insulator that electrically isolates the fuel from the emitter. As is the case for radiatively coupled converters, the conduction coupled converter can be heated electrically by placing a heating element inside the hollow center of the cylindrical thermionic converter to replicate the heating properties of nuclear fuel. This is the method that General Atomics proposes to use with its CC/MC concept.

Although conceptually simple, using a heat-conducting medium between the nuclear fuel heat source and the thermionic emitter is a challenge because of the combination of high temperature, voltage gradient, and nuclear radiation, which cause electrolytic dissociation of most ceramic insulators.

Russian research offers a possible solution. It has shown that scandia (Sc_2O_3) insulators offer extraordinary high temperature capability. An emitter trilayer may be fabricated with a fuel cladding layer, followed by a scandia insulator layer and then the thermionic emitter. However, the lifetime for a device such as a CC/MC has not been conclusively demonstrated, especially under the combined influence of temperature, voltage gradient, and irradiation (Streckert et al. 2000a, b).

Since the CC/MC was designed to be heated by sources other than nuclear fuel, it could be used with some other method of transporting heat into the CC/MC cylinder, such as with a heat pipe assembly. However, the addition of a heat pipe system to a solar concentrator, for example, may negate some of the potential weight advantages of the solar thermionic system. So, although such a system is possible, the system tradeoffs to make such a system viable need to be examined before any final conclusions can be made.

Finding: The conductively coupled multicell (CC/MC) thermionic fuel element, as proposed by General Atomics, needs to be evaluated for nuclear in-core use by resolving radiation-induced fuel swelling and insulator degradation issues before the concept can be declared viable.

Cylindrical Inverted Multicell

The cylindrical inverted multicell (CIM) thermionic converter is essentially an inverted version of the CC/MC device and was proposed specifically for use with the HPALM concept (see Figure 5.1). So while one challenge with the CC/MC device may be to find a suitable solar candidate mission, a challenge with the CIM device is to find a suitable nuclear candidate application.

In the CIM thermionic converter, the heat is applied externally, where the emitter is located, and the waste heat is removed from the hollow interior of the cylinder. This conceptual device is intended for use with the HPALM system and is, therefore, inherently capable of being tested using an electrical heater. The CIM converter would be immersed in the heat receiver of the HPALM system, so a comparable nuclear system could be the space thermionic advanced reactor compact (Star-C) concept as was proposed by General Atomics. The STAR-C concept is a nuclear reactor in which the heat from the uranium carbide nuclear fuel is captured by a graphite block. The CIM thermionic converter could be placed into this graphite block so that the CIM is heated radially inward. One potential advantage of this design is that, since the nuclear fuel is not in contact with the CIM, fuel swelling issues may not be as

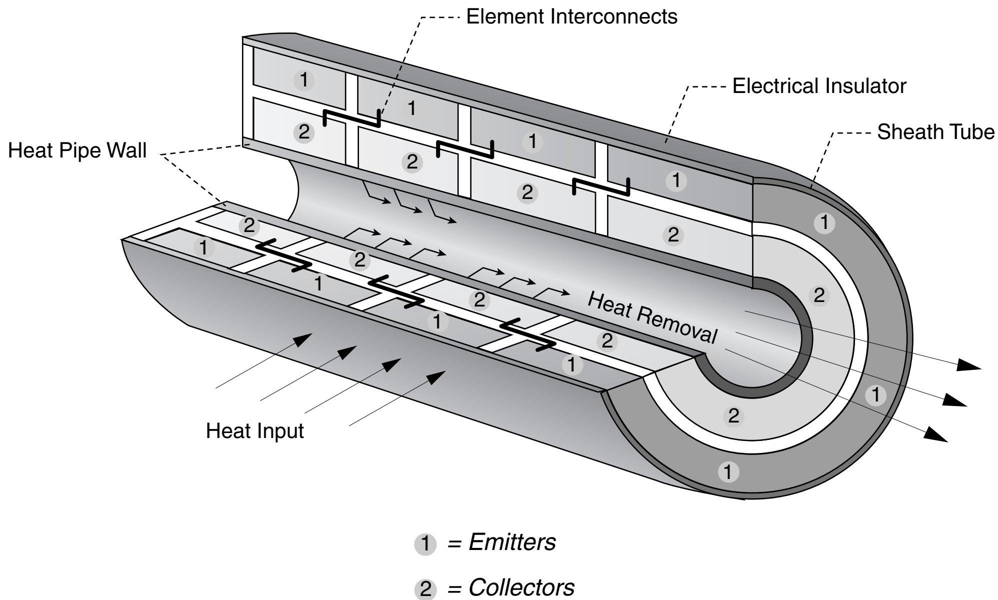

FIGURE 5.1 Cylindrical inverted multicell cross section.
SOURCE: L. Begg, General Atomics, presentation to the Committee on Thermionic Research and Technology, August 2000.

large a concern for the thermionic converter portion of the device. However, the CIM would still be inside the nuclear core, and so any development would have to contend with radiation damage to materials just as would the CC/MC development. This configuration could introduce the added complexity of carbon diffusion into the thermionic device.

Finding: Both the inverted thermionic element and the planar thermionic converter that could be used the HPALM concept are compelling, but the system has not been built or tested.

Finding: The cylindrical inverted multicell (CIM) thermionic fuel element, as proposed by General Atomics, needs to be proven for solar conversion applications. The same technology, if chosen for use with a nuclear in-core system, needs to be evaluated for nuclear in-core use by resolving radiation-induced insulator degradation issues before the concept can be considered viable.

POTENTIAL SPACE NUCLEAR THERMIONIC MISSIONS

Nuclear heat conversion is an alternative to solar heat conversion for providing power to a spacecraft. Nuclear power applications can be divided roughly into those with low and high power requirements. Low power requirements can be satisfied by radioisotope power systems that generate a few kilowatts of power at most. High power requirements, near or exceeding 100 kilowatts, may require the use of nuclear reactors, depending on the specific mission.

In general, thermionic converters would not be used with radioisotope heat sources because other conversion devices are better suited to operate at the lower temperatures typical of radioisotope heat sources.

The decision to use a nuclear power source on a spacecraft will generally be driven by compelling mission requirements. To date, the United States has only flown one reactor in space. There have been other missions that use nonreactor-based radioisotope power. All of the spacecraft that have flown beyond the orbit of Mars have been powered by radioisotope power sources because there is simply not enough sunlight for photovoltaic arrays. Figure 5.2 illustrates that the solar energy available decreases rapidly as an interplanetary spacecraft flies to the outer planets of the solar system.

Currently, there are no planned or approved space missions that use a nuclear reactor. Smaller spacecraft, such as NASA's planned Europa orbiter and the Pluto/Kuiper Express, meet the criteria for needing a nuclear power source. However, both spacecraft require a fairly

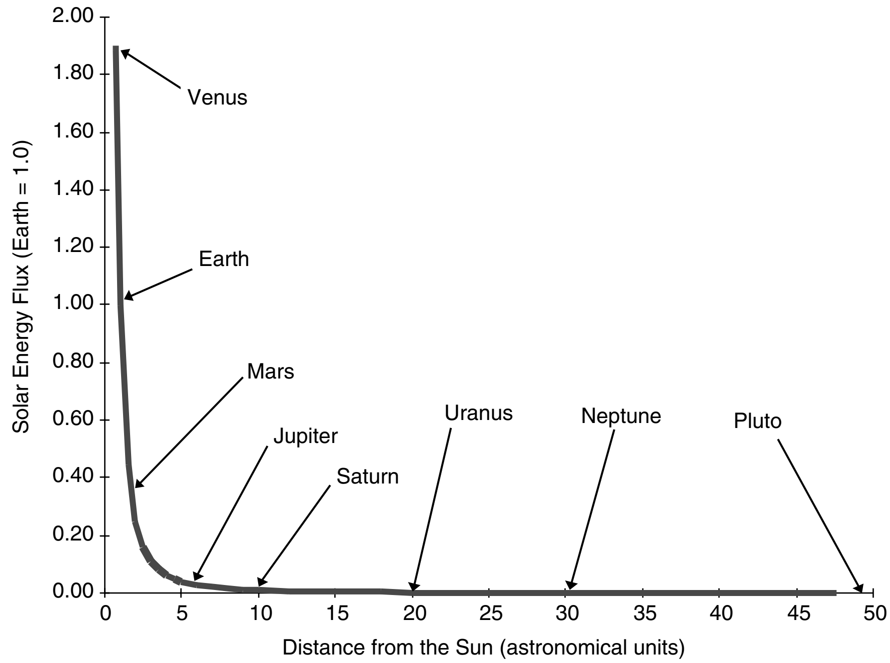

FIGURE 5.2 Solar energy flux as a function of distance from the Sun.

small amount of power and could therefore make use of the smaller radioisotope power systems. In addition, the Pluto/Kuiper Express program at NASA has been canceled at the time of this report's publication. A number of potential future missions have been postulated that would use nuclear reactors based on the following conditions:

- *High power*. Nuclear power is the only practical source of continuous, high power levels in space (more than 100 kilowatts), especially where solar energy is not adequately available. This is due to an economy of scale effect: little size or mass is added as power levels increase.
- *Self-sufficiency*. Nuclear power sources make the spacecraft more independent of potentially unreliable external solar or chemical heat sources. For example, a nuclear power source can be used for missions to the outer planets where there is not sufficient solar energy for a solar-powered system. Or, for missions on the Martian surface, a nuclear power system would not be affected as much by dust storms that reduce the available sunlight.
- *Survivability*. Nuclear power sources are generally less vulnerable to external radiation (e.g., the radiation belts around Earth and Jupiter) and to other potentially hostile environments, such as meteoroids, Martian dust storms, space weapons, and extreme temperatures such as those experienced on the lunar surface.

Examples of missions that are considered for nuclear reactor use include human and cargo missions to Mars, human lunar or planetary bases in harsh conditions, electric propulsion missions to the outer planets, and missions to the outer planets with high power science instruments or high information data rates.

Some of these missions combine a reactor power system with a high power electric propulsion system for enhanced deep space travel. The dual mode systems are described briefly in Chapter 4 for a solar thermionic power system, and Appendix D discusses the potentially significant benefits of combining a lightweight power system with emerging electric propulsion technology.

Some future military missions may have a need for nuclear reactor systems. These include high power radar systems and space-based electric weapons. However, current studies of these types of missions indicate that they can be accomplished with nonnuclear power systems. Most space-based radar concepts being studied use a combination of low orbits and low duty cycles to reduce the continuous power level required by the vehicle to between 4 and 30 kilowatts. This requirement can currently be met by state-of-the-art solar power systems.

None of the approved NASA far-term missions seem to require power that cannot be provided by solar arrays or advanced radioisotope power sources. The exception is the establishment of a lunar base and a human mission to Mars, mentioned above, which have not been approved but are being considered.

Rationalizing the development of nuclear power supplies for spacecraft is difficult, especially in the near term, because of the absence of current missions and the effects of other factors associated with nuclear development, such as cost, development risk, and potential nuclear safety issues. These risks (or perceived risks) have halted the development of space-based nuclear reactors. However, most studies that explore the concept of space bases and their power requirements assume the future availability of nuclear power.

The advanced conversion technologies that are currently being pursued by various government agencies, as discussed in other sections of this report, are aimed primarily at solar energy and isotope heat sources with heat to electric conversion via:

- Free piston Stirling engine,
- Brayton engine,
- Alkali metal thermal to electric converter (AMTEC),
- Thermophotovoltaics, and
- Advanced thermoelectric generators.

Should a permanent human mission to the Moon or Mars be authorized and a nuclear heat source for the power be selected, thermionic conversion might well be able to compete with these conversion technologies. While NASA and DOE are sponsoring development work on the other conversion systems, the DTRA program is the only U.S. program working on thermionic converters in relation to space nuclear power. The committee believes that the research on thermionic converters should continue so that there will be a technology base on which future nuclear power reactor system development programs can draw.

Finding: The current thermionic research and development program sponsored by the DTRA is the only thermionics work being conducted today in the United States related to space nuclear power. However, the program does not include efforts to address nuclear issues related to incorporating the technology into a reactor system, namely radiation-induced fuel swelling or radiation damage to converter materials for use with nuclear in-core systems.

While the DTRA program is important because it is the only funded effort in this area, there are limits to what the program can realistically accomplish given the relatively meager funding. Also, if the sponsoring agency follows this committee's recommendation to establish a U.S. thermionic research program that focuses on near-term solar thermionic applications, the program will be limited in its ability to achieve a nuclear thermionic capability.

Previous thermionic technology programs have identified as a problem the fuel swelling that occurs over time in an in-core thermionic fuel element. Not only is DTRA not examining fuel swelling effects, but there is also no materials or device testing being conducted in nuclear environments, presumably due to cost and the lack of fast-flux test facility availability in the United States. The absence of nuclear in-core testing could invalidate any nuclear thermionic design that is developed by the current program.

BIBLIOGRAPHY

Degaltsev, Yu. G., et al. 1987. "Behavior of High Temperature Nuclear Fuel Under Irradiation," *Atomizdat*.

NRC (National Research Council). 1998. *Space Technology for the New Century*. National Academy Press, Washington, D.C.

NRC (National Research Council). 1996. *Assessment of the TOPAZ International Program*. National Academy Press, Washington, D.C.

Streckert, Holger H., et al. 2000a. "Development and Testing of Conductively Coupled Multi-Cell TFE Components," American Institute of Physics Conference Program 504, Space Technology and Applications International Forum-2000, Albuquerque, N. Mex., Jan. 30-Feb. 3.

Streckert, Holger H., et al. 2000b. "Development of a Cylindrical Inverted Thermionic Converter for Solar Power Systems," American Institute of Physics Conference Program 504, Space Technology and Applications International Forum-2000, Albuquerque, N. Mex., Jan. 30-Feb. 3.

6

Terrestrial Applications

The consideration of the potential applicability of thermionic conversion to non-space, or terrestrial, applications can presently be divided into two broad categories, namely, commercial power production and special-purpose military applications. However, the attributes that make thermionics attractive for space power systems are not as compelling in terrestrial applications. Cost and long-life reliability considerations for terrestrial applications generally dominate decision making for terrestrial applications, whereas for space applications, mass, compactness, and efficiency tend to be the ruling criteria.

COMMERCIAL POWER PRODUCTION

In the early 1960s, the American Gas Association and the U.S. Army started funding programs to develop fossil fuel powered thermionic converters. The material silicon carbide emerged as the preferred coating for emitters to protect them from air and combustion products. Because emitter materials, such as tungsten, had thermal expansion coefficients different from that of silicon carbide, cracking and separation problems were severe. These problems were not overcome until the 1980s. By that time, there was no funding available to demonstrate the practicality of fossil fuel powered thermionic devices.

Due to the Arab oil embargo and the increasing awareness of environmental issues related to energy production, terrestrial thermionic research and development received modest funding during the 1970s and 1980s. Since fossil fuel combustion temperatures can be much higher than allowable steam turbine operating temperatures, thermionic devices have the potential to increase overall power plant efficiency when used as a high temperature topping cycle. That is, the elevated combustion temperature of burning coal or other fossil fuels could heat the thermionic converters. The heat rejected by the thermionic devices could then be used to power the steam turbines. However, most of the power generating systems being constructed and ordered today are gas turbine systems, some using a combined cycle steam generation bottoming cycle with high efficiency. In this case, the exhaust of the gas turbine is used to generate steam. The potential benefits of thermionic topping cycles include reductions in waste heat, pollutants, and plant cooling water requirements. However, thermionic topping cycles have not been commercialized due to high capital and operating costs as well as the expense of developing initial prototypes. Some small market thermionic applications were explored in Europe, where fuel generally costs more than in the United States, but those efforts were abandoned because of unfavorable cost tradeoffs.

Finding: The committee could not identify any financially viable terrestrial applications that could make use of thermionic power conversion.

SPECIAL PURPOSE MILITARY APPLICATIONS

The military has a continuing need for improved transportable field power sources for remote sites. These systems have requirements ranging from a few watts to several hundred kilowatts in the case of futuristic airborne energy weapons. For lower power requirements, advanced battery concepts are being pursued. For mid and high power requirements, alternatives to diesel-generator systems are under development. Thermionics can be used with combustion heat sources, but thermionic systems are less efficient than turbines or fuel cells.

Cost-effectiveness is also a significant issue. None of the military organizations responsible for the development of terrestrial military power sources are currently examining thermionics, presumably for the same reasons that the technology is not being pursued for commercial purposes, namely, the availability of other approaches that cost less and that are more efficient.

Finding: Thermionic technology is not being pursued for special-purpose military applications primarily because of the technology's high cost and low efficiency.

7

Assessment of Progress

The Defense Threat Reduction Agency thermionics program sponsors a number of different efforts aimed at establishing a technology base for potential future users of this technology. As detailed in Chapter 2, the effort is spread among too many different projects within present funding constraints. However, even given the fairly large number of projects for the modest yearly funding available, the program does not sustain thermionic science and basic research related to electrode materials, plasma physics, and surface physics. The committee believes that the overall DTRA effort would be more successful if it were to emphasize a basic research program in electrode and materials processes relevant to thermionic energy conversion.

Recommendation 5. The sponsoring agency should reestablish an adjunct basic research program on electrode surface physics, plasma, and materials processes relevant to thermionic energy conversion. This program should be funded separately from the thermionics research program.

The term "adjunct" in the recommendation above refers to basic research that does not use DTRA contract funds. These non-DTRA contract funds might include funds from Small Business Innovation Research, the National Science Foundation, the Air Force Office of Scientific Research, NASA, and so on. Naturally, the future sponsor of thermionics research cannot dictate to the other agencies how to spend such funds: however, if they present the potential benefits of such a research program, the future sponsor may be successful.

The current funding mechanism, so-called congressional plus-up money, also negatively affects technology development, particularly at the university level. It is difficult for researchers to guarantee funding for graduate students for the duration of their degree program which spans multiple years. Because funding uncertainty, faculty and students often hesitate to participate in thermionic research.

Finding: Without stable, multiyear funding, university researchers hesitate to take part in thermionics research efforts, and the thermionics community misses the opportunity to leverage university-based research.

MATERIALS AND DEVICE RESEARCH

Single-Crystal Refractory Metals

Single-crystal refractory thermionic electrodes were tested in the early U.S. programs including the Solar Energy Technology program. The use of single-crystal refractory metal alloys was pioneered in the former Soviet Union (Gontar et al. 1996). According to research conducted there, single crystals offer three important advantages over their polycrystalline counterparts: (1) improved creep resistance, resulting in lower emitter cladding distortion and longer lifetime; (2) improved resistance against material diffusion, another factor important for long life; and (3) high bare work function, which produces a low cesiated work function, resulting in higher efficiency (Drake 1998). This advantage is primarily for planar converters.

Collaborative efforts involving Scientific Research Association (SRA) Luch, Auburn University, and General Atomics have tended to support these conclusions. Accordingly, the committee perceives that this collaboration has significantly enhanced the U.S. state of the art in the area of high temperature metallurgy, as well as in thermionic device technology.

Finding: The collaboration between the Defense Threat Reduction Agency thermionics program and Russian research facilities is ongoing and has been successful.

Auburn University Materials Work

The DTRA has sponsored research at Auburn University through General Atomics that concentrates on the fabrication methods and underlying science in the fabrication, processing, and characterization of refractory alloy single-crystals. This work has proven to be successful and is one of the major success stories associated with the thermionics technology program. The committee learned in June 2001 that the U.S. Army will be providing funding to Auburn University to expand the single-crystal work discussed here to other non-thermionic applications.[1] Auburn researchers are exploring three approaches: (1) electron beam float zone, (2) flow chemical vapor deposition (CVD), and (3) closed-cell CVD.[2]

The electron beam float zone method is considered a brute force approach to single-crystal fabrication, where the refractory alloy bar stock is melted and resolidified by sweeping a segment of the molten material up or down the specimen axis. There are several difficulties associated with this approach. The electron beam float zone method requires that the alloys be melted at high temperature (more than 3400ºC for tungsten), which is difficult to do with the systems currently in place.

However, researchers at Auburn University have overcome many of the challenges and have successfully fabricated single-crystal alloys in small amounts of niobium, molybdenum, rhenium, and tungsten using this method. The growth facility at Auburn University is capable of processing the highest melting point tungsten alloys with diameters up to half an inch. Selected high temperature mechanical properties of the processed alloys have been examined and the effect of grain boundaries and solute additions identified.

[1]United States Army Solicitation Number DAAE30-01-Q-0820.

[2]The Russians had a leading role in the development of single-crystal technology on which Auburn University researchers have based much of their work (DOE 1992).

CVD methods allow researchers to grow single-crystalline layers of refractory metals on a metal substrate at a much lower operating temperature than is needed with the electron beam float zone method. Conventional CVD technologies depend on flow-through methods, in which fresh vapor phase reactants are continuously passed over the surface to be coated.

CVD single-crystal alloy production was a true collaborative effort between Auburn University and General Atomics. Two chemical reduction reactions were used: one with the tungsten hexachloride and the other with tungsten hexafluoride. Researchers were able to grow layers of pure tungsten on molybdenum substrates using both reactions.

To reduce the amount of waste associated with the corrosive vapors used in CVD processes, a closed-cell CVD concept was investigated. A closed-cell CVD process gives only small volumes of waste products, and these can be condensed within the CVD cell. Auburn has demonstrated the feasibility of employing a closed-cell CVD process for depositing pure tungsten into molybdenum substrates with the following attributes:

- Environmental friendliness (no exhaust vapor),
- Low cost and potentially significant raw material savings, and
- Ease of operation owing to the low operating process temperature and the absence of exhaust.

The closed-cell approach is relatively simple in an experimental configuration. However, the thermodynamic characteristics of the system are significantly more complex than those of the flow CVD system. These complexities are due to significant variations in the temperature and pressure of the reaction gases in the system. Researchers are continuing to investigate the correlation between crystal growth characteristics, thermodynamic parameters, and properties in this closed system.

General Atomics informed the committee that some work has been reported in Russia where a single-crystal tungsten wire was fabricated that had a final-diameter to start-diameter ratio of 30:1. General Atomics is currently trying to replicate this large-diameter CVD work.

While General Atomics has made some progress on CVD single-crystal tungsten, it is working to develop CVD single-crystal tungsten alloys. Single-crystals have several advantages over polycrystalline metals because grain boundaries are eliminated. High temperature creep strength is enhanced, grain boundary diffusion is eliminated, and the highest bare work function of the crystal can be exposed on the emitter and collector faces, producing optimum cesiated performance. These factors are all available in planar converter geometries. In cylindrical geometries, a single-crystal electrode will provide enhanced mechanical properties, but the work function will vary around the circumference. Russian CVD work indicates that some possible improvements in work function may be realized by using cylindrical geometries with single-crystals, but the exact amount of improvement has either not been determined, or the Russian researchers have not revealed their results.

Uniaxial creep test data were obtained during the first year of funding on single-crystal tungsten-tantalum. The DTRA anticipates using tungsten-tantalum nuclear fuel cladding for the thermionic converter heat source. If the single-crystal is used with a nuclear fuel heat source, the material will be subject to biaxial stresses. DTRA management proposed that biaxial verification experiments be conducted on single-crystals. As a result, the General Atomics subcontract to Auburn University includes a task to test the biaxial creep properties of tungsten-tantalum single-crystals at high temperature.

In biaxial creep testing, a closed-end tube made of the material to be tested is internally pressurized using a static, inert gas. The test assembly is heated to the desired temperature in a diffusion pump vacuum chamber using a 5 kilowatt heat source. The diameter of the tube is measured periodically using a noncontacting laser micrometer system. Auburn researchers will subject each sample to different stress levels from 6,000 to 20,000 pounds per square inch in a stepwise manner with a set temperature. Two axial measurements will be made periodically to determine creep rates. The tests are expected to be complete shortly after this report is published in late 2001.

Committee's Assessment of the Single-Crystal Research

Single-crystal materials can improve thermionic converter performance. As Figure 7.1 shows, increased bare work function results in higher efficiency and higher optimum power density. A work function of 5.6 corresponds to single-crystal rhenium, and one of about 5.0, to polycrystalline tungsten.

As bare work function increases, cesiated work function decreases (Figure 7.2). Thus, to maximize work function differences between emitter and collector, the highest collector bare work function is desirable.

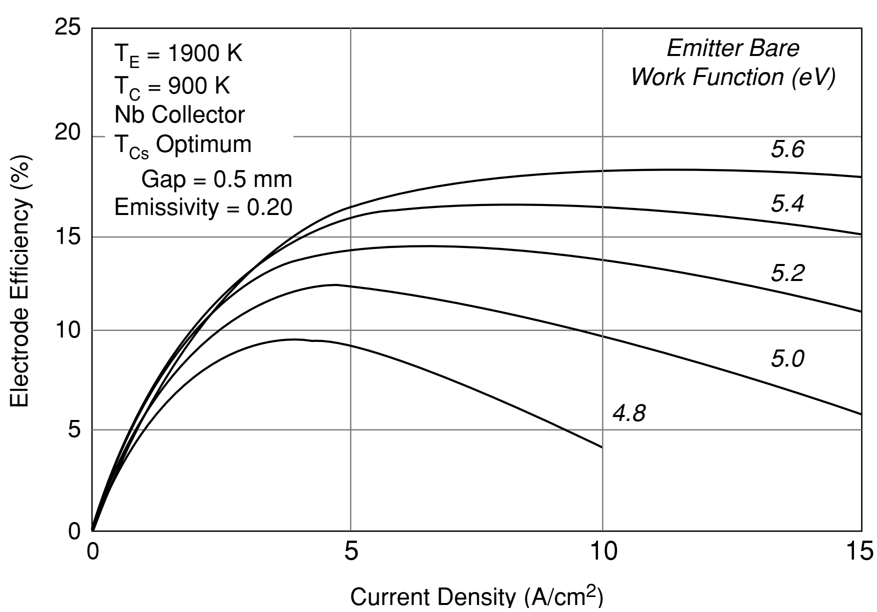

FIGURE 7.1 Effect of emitter bare work function on performance, using computer code TECMDL. SOURCE: General Atomics.

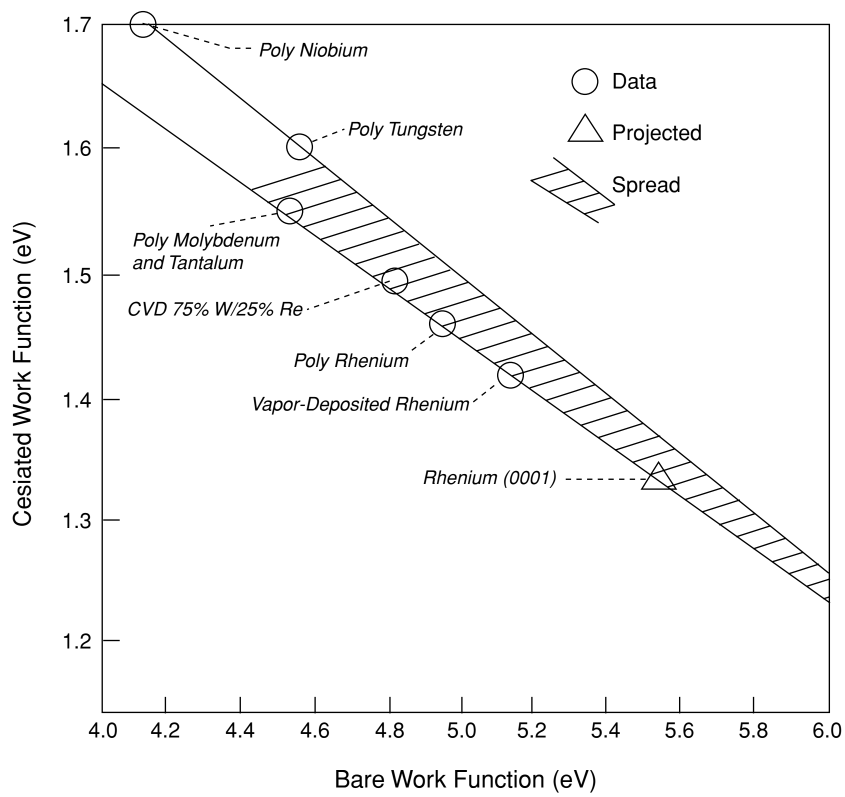

FIGURE 7.2 Cesiated work function versus bare work function.

The research being conducted in single-crystal refractory metals is a critical technology area for any future thermionic program. The research also has the potential for significant spin-off applications into numerous other areas. Industry alone cannot sustain these technologies without recruiting new interested personnel from the university ranks. University research must be supported not only to provide technical knowledge continuity but also to gain advocates, now and in the future, for the complex and wide ranging technologies associated with thermionic energy conversion.

General Atomics has the primary experience in the cylindrical converter and trilayer technology. There are clear materials issues that must be addressed and solved in order to achieve the anticipated performance. In the United States, cylindrical CVD techniques used in the past produced textured polycrystalline structures with high work function grain exposure on the electrode surface. There are several ultimate tradeoffs that must be evaluated between the geometrically simple, demonstrated planar converters on the one hand and the more complex and untested cylindrical converters on the other.

Oxygenation

Previous work established that oxygenation of emitter and collector surfaces in a thermionic converter can be a useful technique for improving thermionic performance (Figure 7.3). An oxygen layer on the surface creates a very high work function. A cesium monolayer on the oxygenated surface will result in a very low work function surface. The work function is less than 1.3 electron volts at 900 K or about 0.2 electron volts lower than cesiated niobium.

Another advantage of oxygenation is that the cesium pressure in the space between the emitter and collector is reduced. Lowering the pressure might lower plasma losses. In the conventional nonoxygenated converter, the output voltage is reduced by about 0.5 volts due to electron scattering losses in the plasma, thus diminishing the electrical output by 30 to 40 percent (Drake 1998, Begg 1998).

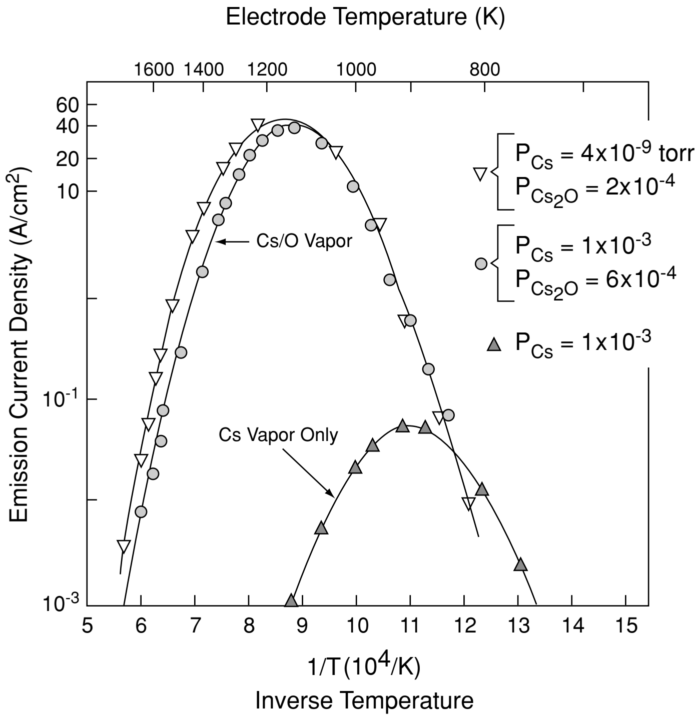

FIGURE 7.3 Effects of cesium oxide vapor on converter performance.

The committee, however, has heard concerns raised about the long-term stability of oxygenated electrode systems. Since oxygen is known to attack refractory metals, the long-term effects of even trace amounts of oxygen need to be carefully monitored over the operating lifetime of any thermionic device under test. Also, the benefits of oxygenation on system design, thermionic fuel element performance, and overall life have not been clarified. These issues must be addressed before benefits of oxygenation can be conclusively established, and the committee believes that the benefits are difficult to justify.

Finding: The benefits of oxygenation in enhancing converter efficiency are difficult to justify in view of the technical risks associated with system design, thermionic fuel element performance, and overall life.

Thus, oxygenation should not be incorporated into advanced technology development programs at this time, but it might be considered as a legitimate activity for basic research or possibly future applied research.

CLOSE-SPACED VACUUM CONVERTER

One of the features of the DTRA thermionics program is research on close-spaced thermionic converters being carried out by SRA Luch, the primary subcontractor in Russia.

In theory, the efficiency of the thermionic converter increases significantly as the gap approaches zero, because in an infinitesimally small converter space, there is no opportunity to build up space-charge. Hence, the barrier potential is nearly zero, and energy conversion efficiency is primarily limited by conduction and radiative losses.

However, once the gap size increases beyond a few microns, the electron barrier potential can no longer be ignored, and it is necessary to provide charge neutralization with a plasma such as cesium.

The physics behind this effect is not at all new. Vacuum mode converters have been investigated since the 1950s. In the past, such converters were judged to be impractical from an engineering point of view, owing to the difficulty of maintaining the extremely small tolerances that are required, substantially less than 1 micron.

The close-spaced converter effort has resulted in the manufacture of a thermionic converter with a 6 micron gap, which the committee feels was an impressive accomplishment. The converter apparently worked well during tests at SRA Luch. However, when it was shipped to New Mexico Engineering Research Institute, a cracked housing prevented the unit from being tested. After repair, poor performance was observed. This poor performance may have been due to partial shorting from contaminants in the gap region. The DTRA management's intent now is to revalidate the test and to design and build a three-cell, close-spaced converter module.

It appears that the close-spaced converter project has been carried out with great competence and skill. However, the committee feels that a successful project will not provide enabling technology for a long-life nuclear thermionic reactor, because the close-spaced converter device cannot be easily integrated into a thermionic nuclear reactor core. Also, the project goals are directed toward conversion efficiency and performance rather than long life.

The close-spaced vacuum diode concept as presently envisioned must be a planar arrangement, so efforts on cylindrical thermionic converters are not applicable. Thus, the technology is not likely to be used with in-core thermionic fuel element type reactors, although it might be used with other core concepts (STAR-C or Romashka-derivative) or solar thermionic cells.

As mentioned above, the performance of the test converter that was transported from Russia to New Mexico was less than expected, probably owing to the presence of a foreign particle in the gap, which caused partial shorting. Such particles may have been liberated during transport, and launch vibration might cause similar problems for spaceborne versions of such a converter. However, the exact cause of the electrical short was never conclusively identified.

Also, there are significant concerns about mass transport and electrode distortion, either of which could be inherently life limiting. The vacuum converter must have very clean electrodes at all times. Even a small deposit could result in a short circuit in the converter. Evaporation and redeposition of even a few atomic layers could change the single-crystal nature of the surfaces. Thus, even if there are performance enhancements available from single-crystal surfaces, the long-term stability of closed-spaced converter performance is in doubt.

Thus the potential advantage of the close-spaced thermionic converter is its improved conversion efficiency. However, this improvement requires extraordinarily tight tolerances in machining the surface of the converters, similar to the requirements for machining laser mirrors, for example. In addition, the converter is subject to several failure modes that make long-term reliability questionable. Making such a converter practical for spacecraft use could be very difficult, and the benefits might not outweigh the risks.

THEORY AND THEORY VALIDATION

One of the three major tasks within the DTRA research and development program is thermionic device theory development and theory validation. The theory development and validation work is aimed at characterizing the effects of emitter and collector surface reflection effects, characterizing non-uniform surface work function effects (a.k.a. patch effects), and optimizing a thermionic system mass model.

A novel portion of the research, specifically the patch effect investigation, has been tied closely to the Microminiature Thermionic Converter (MTC) program, as is discussed below. Unfortunately, this theory development is of little importance to the overall program.

Also, the system mass modeling does not add significantly to the overall understanding of thermionic devices or systems. The committee believes that this work has already been conducted by many others and is satisfactorily complete for the present. The committee does not understand the need to explore the underlying principles of thermionic theory any further since the existing theory base is complete enough to work experimentally on developing thermionic components and systems.

Other than as related to the MTC, the current modeling work being conducted at Sandia National Laboratories does not appear to extend theoretical understanding of the current thermionic theory. Also, the patch effect explanation has been hypothesized to explain certain experimental observations. The committee believes that this explanation is but one of many potential explanations for the experimental observations. If the program were well funded, the committee would support the high risk, relatively low return patch effect research exercise. However, given the limited amount of funding for the thermionics program as a whole, the committee recommends that all theory and theory validation activities be discontinued.

MICROMINIATURE THERMIONIC CONVERTER

The DTRA-sponsored MTC program is another one of the major program elements in the overall DTRA effort and is slated to receive a significant percentage of the limited funds of the DTRA program. The effort is directed toward the development of a converter using semiconductor-scale fabrication technology with the hope that extremely small emitter-collector gaps can lead to economical, high efficiency conversion. Also, unlike the close-spaced converter concept, the MTC would be a very small chip-scale device. By manufacturing the converters on a micron scale or smaller using electronic device fabrication technology, they could potentially be very small. Just as millions of electronic devices can be fabricated on a single silicon wafer, it could conceivably be possible to place millions of thermionic converters on a small surface. The committee's investigations have led it to conclude that the funding for this portion of the DTRA thermionics program should be redirected toward more basic research objectives as discussed elsewhere in this report. The rationale for this recommendation is discussed below.

Research is in progress at Sandia National Laboratories to develop scandate-based MTCs with high energy conversion efficiencies using semiconductor integrated circuit fabrication methods. These converters are of the vacuum type. Analysis shows that in theory such converters operating at emitter temperatures of about 1200 K, collector temperatures of 700 K, and interelectrode gaps of between 1 and 5 microns could produce attractive power densities and conversion efficiencies, but practical manufacturing methods and dimensional tolerances have never been demonstrated.

Extensive work on vacuum converters was conducted by Hatsopoulos and Kaye in the late 1950s, in which they used electrodes coated with barium-strontium oxides. The lowest work function achieved was 1.75 electron volts, and that for only very short periods of time. To offset evaporation loss of the barium and thus maintain an effective coating at the emitter surface, they used tungsten emitters impregnated with mixed barium and strontium carbonate These did produce 1 watt per square centimeter at about 1500 K for a few hours, having achieved an emitter work function of about 2.1 electron volts and a collector work function of about 1.8 electron volts. After that, however, converter performance deteriorated substantially because barium that evaporated from the emitter condensed on the collector (Hatsopoulos and Kaye 1958a,b). The discovery of surfaces with work functions of less than 1.6 electron volts that are stable over a useful period of time would greatly benefit not only MTC but all types of thermionic converters, whether vacuum or cesium based. Such a discovery, however, would not necessarily mean that vacuum converters, with or without the extremely close electrode spacing proposed for the MTC devices, are practical. The committee believes that beyond addressing the electrode work function issues, it would be extremely difficult to maintain, for any reasonable period of time, a temperature difference of nearly 1000 K between two surfaces held apart by a miniaturized spacer that is a few microns thick.

A number of advantages are claimed for the MTC concept. Relative to dynamic energy conversion systems, conventional thermionic systems, and other static conversion systems, MTCs claim the presumption of low maintenance, silent operation, long life, and compactness. In many cases, modularity and simplicity of assembly can also be expected. It is hoped that MTCs would be able to operate at high efficiency using a relatively low temperature heat source. And, very importantly, MTC devices might be manufactured inexpensively using integrated circuit chip manufacturing methods to achieve the extremely close tolerances needed.

The current program consists of several efforts, including the following (Rightley 1998a,b):

- Development of electrode coatings to improve the emitter and collector properties, since the structural materials suitable for integrated circuit manufacturing methods are not those normally used for thermionic converters,
- Analysis of MTC device configurations, and
- Testing of MTC cells.

There are a number of technical issues associated with the MTC program. These are discussed in the following subsections.

Electrodes

As outlined above, the efficiency gains and lower operating temperatures postulated for the MTC configuration appear to depend on substantial improvements in both the emitter and collector work functions. Achievement of these advances via coatings such as barium is problematic since barium and other candidate materials tend to evaporate rapidly at operating temperatures above about 1000 K. This means that the barium surface coating would require resupply from within the solid coating. Further, deposition of the lost barium on the cool collector surface degrades the critical properties of the collector. The committee deems it unlikely that the MTC device would have a long enough life under these conditions. Scandium oxide cathodes produced by a sputtering process at Sandia do not yet meet the required work function properties. Electrode investigations using thin film layers of low vapor pressure materials may offer the best opportunity for achieving useful improvement in electrode properties (Zavadil et al. 1999).

Theoretical analyses of electron reflection from metal surfaces with and without adsorbed cesium or coadsorbed cesium and oxygen suggest that physical modifications of the electrode surface might allow the full, low work function capability of these coatings to be realized (Rasor 1998). However, the committee questions whether these theoretical benefits can be realized.

Analysis

The MTC's device configuration has been modeled but the data taken to date do not appear to support the analytical results. Vacuum converters of the conventional type were analyzed in the 1950s and, for the converters of that time, gave good agreement with experiment (Hatsopoulos and Kaye 1958a,b).

The current modeling work does not appear to extend theoretical understanding. With respect to model validation by experiment, while inexpensive manufacture using fully developed integrated circuit methodologies might be feasible, fabrication and testing of small numbers of experimental converters would be expensive. Given likely funding limits, the prospects are poor for obtaining adequate data with which to validate the MTC analysis from feasible experiments, even if this effort were to be the major funded effort of the entire DTRA thermionics program.

Thermal Control

The conversion efficiency of individual converters is measured as the ratio of the electric output power to the heat actually delivered into the diode. Regardless of the conversion efficiency, the utility of an MTC-based conversion system depends on the way in which the heat available for conversion can be forced to feed primarily the thermionic converter portion of the device while minimizing the thermal losses from the external surfaces of the converter. These losses can occur by radiative transfer across the gap and by parasitic thermal conduction transfer around the converter edges from the hot side to the cold side of the system as a whole. As noted above, the necessary level of thermal transport control tends to become much more difficult for physically small systems such as MTC. More specifically, the MTC configuration has the two electrode surfaces, differing in temperature by approximately 500 K, separated by approximately 1 micron. This situation creates a temperature gradient of 5×10^5 K per millimeter in the connecting structure. Removal of the parasitic heat from the collector is expected to be difficult, given the thermal power density the collector will receive. In the opinion of the committee, sustaining such an enormous gradient with tolerable thermal conduction losses is not credible.

MTC Experiments

A diode with an extremely low power was demonstrated at Sandia (King et al. 1999). The device had a peak power of approximately 1.2 milliwatts per square centimeter with the temperature of the emitter at 1173 K and the temperature of the collector at 973 K. This power density value is less than conventional thermionic technology capability by a factor of approximately 1000. Power density values were minuscule compared to those reported for vacuum converters as long ago as 1956. The committee was told that the critical problem leading to these weak results was nonuniform emission from the emitter electrode such that only a small fraction of the total cathode area was contributing to the output power. Unfortunately, both the validation of this hypothesis and the development of methods to overcome the difficulty, if it is proven to be correct, are likely to be expensive given the limited funding for the thermionics program. While the performance of electrodes in complete converters is the ultimate test, diode manufacture at the MTC scale will be inexpensive only when it becomes standardized and the major benefits of integrated circuit production methods can be used. Producing and testing enough single converters on the scale needed to produce critical electrode performance data will be expensive.

It is the opinion of the committee that, at this time, program funding should not be spent on electrode analysis validation, particularly when no method to correct performance problems is available.

Finding: The device being developed in the microminiature thermionic converter (MTC) effort has low efficiency, and the explanation and understanding of the surface physics are incomplete.

MTC Electrode Materials

The rationale for the MTC configuration depends not only on the presumed low manufacturing cost using integrated circuit manufacturing techniques, but also on very substantial advances in durable electrode work function properties. The search for such materials has been thoughtfully and extensively pursued in a number of laboratories over the years without the constraint of compatibility with integrated circuit fabrication methods and materials. Even if low work function electrode materials can be fabricated inexpensively and made compatible with the integrated circuit industry fabrication methods used to form the main structure of the MTCs, the same electrode materials should also be helpful in forming more conventional thermionic fuel elements. In the case of conventional thermionic fuel elements (TFEs), the space charge limitations of higher gap spacing are compensated for by the use of Cs vapor. Therefore, even if an MTC device became practical, the gains in low work function materials would probably allow conventional TFEs to outperform the MTC device.

Competing Technologies

Even if it is assumed that the several major technical hurdles identified above can be overcome, very small scale (on the scale of a chip or radioisotope heater unit) MTCs still face stiff competition from thermal electric generators. At 1 to 100 watts, MTCs also face strong competition from AMTEC and free-piston Stirling, which appear to have fewer material problems at the temperature levels proposed for the Sandia converters.

Ultimately, the experimental data from the MTC program do not support the theoretical predictions. Not only are postulated low work function emitters not yet functional, they also are not expected to be so in the near future. Finally, while it is assumed that integrated circuit fabrication methods will lead to low cost production, the fact remains that fabrication of stable, small gap converters has not been demonstrated for near-term experiments, and these devices do not have the right characteristics for long-term, low cost production given material constraints such as directional etching, compatible layer chemistry, and so on.

Recommendation 6. The sponsoring agency should discontinue the microminiature thermionic converter (MTC) program, the close-spaced vacuum converter tasks, the oxygenation effects research, and all current theory and theory validation work.

REFERENCES

Begg, Lester L. 1998. "In-Core Thermionic Technology Development Program," Paper IECEC-98-402, *Proceedings of the 33rd Intersociety Engineering Conference on Energy Conversion,* American Nuclear Society, Albuquerque, N. Mex., August 2-6, 1998.

DOE (Department of Energy). 1992. *Report of the United States Space Nuclear Power and Propulsion Team: An Examination of the Space Nuclear Power and Propulsion Activities of the Commonwealth of Independent States*. DOE, Washington, D.C., October 6.

Drake, T.R. 1998. "DoD's Advanced Thermionics Program: An Overview," Paper IECEC-98-404, *Proceedings of the 33rd Intersociety Engineering Conference on Energy Conversion,* American Nuclear Society, Albuquerque, N. Mex., August 2-6, 1998.

Gontar, A.S., et al. 1996. "Fuel Elements of Thermionic Converters," Special Issue on Technology, *Journal of the Franklin Institute* 333A:(2-6).

Hatsopoulos, G.N., and J. Kaye. 1958a. "Analysis and Experimental Results of a Diode Configuration of a Novel Thermo Electron Engine," *Proc. I.R.E.* 46(9):1574-1579.

Hatsopoulos, G.N., and J. Kaye. 1958b. "Measured Thermal Efficiencies of a Diode Configuration of a Thermo Electron Engine," *Journal of Applied Physics* 29(7):1124-1125.

King, D.B., J.R. Luke, and F.J. Wyant. 1999. "Results from the Microminiature Thermionic Converter Demonstration Testing Program," *Proceedings of the Space Technology and Applications International Forum*, CP458. American Institute of Physics, Melville, N.Y.

Rasor, N.S. 1998. "The Important Effect of Electron Reflection on Thermionic Converter Performance," Paper 211, *Proceedings of the 33rd Intersociety Engineering Conference on Energy Conversion,* American Nuclear Society, Albuquerque, N. Mex., August 2-6, 1998.

Rightley, Gina. 1998a. "Summary Results of MTC Diode Studies," Sandia National Laboratories memo, October 13.

Rightley, Gina. 1998b. "Summary Results of RHU/MTC System Studies," Sandia National Laboratories memo, September 29.

Zavadil, K.R., J.H. Ruffner, and D.B. King. 1999. "Characterization of Sputter Deposited Thin Film Scandate Cathodes for Miniaturized Thermionic Converter Applications," *Proceedings of the Space Technology and Applications International Forum*, CP458. American Institute of Physics, Melville, N.Y.

BIBLIOGRAPHY

Marshall, A.C. 1998. "An Advanced Thermionic Theory for Development of High Performance Thermionic Energy Conversion Diodes," Paper 212, *Proceedings of the 33rd Intersociety Engineering Conference on Energy Conversion,* American Nuclear Society, Albuquerque, N. Mex., August 2-6, 1998.

Marshall, A.C. 1998. "An Advanced Thermionic Theory: Recent Developments," *Proceedings of the Space Technology and Applications International Forum.* American Institute of Physics, Melville, N.Y.

Marshall, A.C. 1998. " An Equation for Thermionic Currents in Vacuum Energy Conversion Diodes," *Applied Physics Letters* 73:2971-2973.

Appendixes

Appendix A

Statement of Task

The ASEB [Aeronautics and Space Engineering Board] will assemble a committee with expert knowledge in thermionic direct energy conversion, space power supplies, and associated technologies to conduct an independent technical assessment of DTRA's thermionic direct energy conversion research and technology program. The committee will assess the results of the earlier work in the area of thermionics that was conducted under the jointly managed Russia/United States project, TOPAZ. Advances in the state of the art resulting from this earlier thermionics technology work will be identified and evaluated. Assessments will be made of the most critical technical challenges remaining in the development of viable thermionic direct energy conversion systems. Specifically, the study will:

1. Evaluate DTRA's earlier work in the area of thermionic energy conversion and assess its impact on the state of the art of thermionics technology.
2. Assess the present state of the art of thermionic energy conversion systems.
3. Assess the technical challenges to the development of viable thermionic energy conversion systems.
4. Recommend a prioritized set of objectives for a future DTRA research and development program for advanced thermionic systems for space and terrestrial applications.
5. Conduct a workshop for the interim discussion of major technical challenges and appropriate research and development responses.

The ASEB will draw upon other elements of the NRC, as appropriate, in conducting this study. A final report will be issued at the end of the study.

Appendix B

Biographical Sketches of Committee Members

TOM MAHEFKEY, *Chair*, retired from the Air Force Wright Laboratory in 1995 after 33 years as an engineer, scientist and research manager. Before retiring, he was deputy division chief for technology in the Propulsion Laboratory's Aerospace Power Division. Dr. Mahefkey was instrumental in establishing the Thermal Energy/Heat Pipe and the Thermionics laboratories within the Air Force Wright Laboratory. Dr. Mahefkey is also an experienced educator, having held the rank of adjunct professor of mechanical engineering at the University of Dayton, Wright State University, University of Kentucky, Ohio State University, and the Air Force Institute of Technology. Since retiring in 1995, Dr. Mahefkey is serving as a consultant to several firms in the areas of heat transfer and energy conversion. Dr. Mahefkey's areas of expertise include thermionics, energy conversion, and heat transfer, and he has published extensively in these areas.

DOUGLAS M. ALLEN is currently the site manager for Schafer's Dayton, Ohio, office responsible for managing technical support contracts and developing new business with Wright-Patterson Air Force Base and the National Aeronautics and Space Administration (NASA) Glenn Research Center. From 1992 to 1998 Mr. Allen was program manager for Schafer's Systems Engineering and Technical Assistance contract supporting the Ballistic Missile Defense Organization (BDMO) Innovative Science and Technology program, leading independent technical review teams and assessing technology, progress, schedules, costs, and alternatives for BMDO on a wide variety of advanced technology and space experiment programs. Mr. Allen's areas of expertise include system integration, thermal management, power conditioning and control electronics, advanced materials and coatings, and space flight qualification testing.

JUDITH H. AMBRUS retired from National Aeronautics and Space Administration (NASA) Headquarters in 1996 with 30 years of government service. She served the first 15 years at the Naval Surface Warfare Center (formerly Naval Ordnance Laboratory), where she was engaged in battery research and technology, the last 5 years heading up the Electrochemistry Branch. After transferring to NASA Headquarters, she served as program manager for chemical and thermal energy conversion, including thermionic technology, in the Office of Aeronautics and Space Technology. In this capacity, she managed all NASA-sponsored research and technology activities in this technology area, including the initiation and management of the space nuclear reactor program (SP-100). In the Engineering Division of the Space Station Office, she managed the power, propulsion and life support elements during Phase B of that program. As assistant director for space technology, she managed planning for the utilization of the International Space Station for technology development and later for commercial research and development. Since her retirement, she has been serving occasionally as consultant in the general area of space technology management.

LEONARD H. CAVENY has been an aerospace consultant since retiring in 1997 from the Ballistic Missile Defense Organization (BMDO), Science and Technology Office, where he had served as director since August 1995. While in BMDO from 1985 to 1997, Dr. Caveny led the directorate that initiates and manages fundamental research and development of high-risk technology. Between 1984 and 1985, Dr. Caveny was a staff specialist in the Office of the Deputy Undersecretary for Research and Advanced Technology at the Pentagon. Between 1980 and 1984, he was program manager for energy conversion in the Air Force Office of Scientific Research, Aerospace Sciences Directorate in Washington, D.C. Between 1969 and 1980, Dr. Caveny was a senior member of the professional staff in the Department of Aerospace and Mechanical Sciences at Princeton University. Dr. Caveny's areas of expertise include propellants, propulsion, power, high temperature materials, sensors, and space systems. Dr. Caveny serves on the National Research Council panel to evaluate proposals in the area of advanced propulsion research and development for the Air Force Office of Scientific Research.

HAROLD B. FINGER served as a member of the National Research Council Committee on the TOPAZ International Program, which issued its report in 1996. He has been working as a consultant since his retirement in May 1991 from the U.S. Council for Energy Awareness, where he had served as president and CEO since January 1983. Between 1972 and 1983, Mr. Finger was with the General Electric Company (GE) serving as general manager of the Center for Energy Systems in Washington, D.C., manager of the Electric Utility Engineering Operation in Schenectady, New York, and then staff executive of GE's Power Systems Strategic Planning and Development at corporate headquarters in Fairfield, Connecticut. From 1967 to 1969, he served as associate administrator for organization and management at the National Aeronautics and Space Administration (NASA) and, from 1969 to 1972, as assistant secretary for research and technology at the Department of Housing and Urban Development. Between 1958 and 1969, Mr. Finger held several senior management positions in the fields of space power and nuclear energy programs and space nuclear propulsion in both NASA and the Atomic Energy Commission (AEC). From 1960 to 1967, Mr. Finger managed the Space Nuclear Propulsion Office (joint NASA/AEC), which was responsible for nuclear rocket propulsion development, while also serving as director of space power and nuclear systems (NASA), and in 1965 he was appointed director of the Space Nuclear Systems Division (AEC), all positions that he held concurrently. Mr. Finger's management skills and technical expertise were instrumental in the timely and successful development of the SNAP 27 Radioisotope Thermoelectric Generator system that powered the scientific instruments on the surface of the Moon in the Apollo lunar exploration program. Mr. Finger's special areas of expertise relevant to this study include management of the development of conventional space electrical power systems, space nuclear power supplies, nuclear propulsion systems, and terrestrial energy systems analysis and planning. He is on the board of the National Housing Conference and is a member of the American Nuclear Society and a fellow of the National Academy of Public Administration and of the American Institute of Aeronautics and Astronautics. Mr. Finger is also president of the NASA Alumni League.

GEORGE N. HATSOPOULOS is chief executive officer of Thermo Electron Corporation, Waltham, Massachusetts, and a pioneer in the development of thermionic technology. After graduating from the National Technical University of Athens, Dr. Hatsopoulos attended the Massachusetts Institute of Technology (MIT), where he received his bachelor's, master's, engineer's, and doctorate degrees, all in mechanical engineering. He served on the MIT faculty from 1956 to 1962 and continued his association with the Institute until 1990, serving as senior lecturer. Dr. Hatsopoulos is a member and former chairman of the American Business Conference and a member of the executive committee of the National Bureau of Economic Research and the Corporation of MIT, and he was also a member of the board of directors of Bolt Beranek and Newman, Inc., from 1990 to 1996. He is also a board member of several other organizations, including the National Research Council's Board on Science, Technology, and Economic Policy; the Concord Coalition; the Congressional Economic Leadership Institute; the American Council for Capital Formation Center for Policy Research; and College Year in Athens, and he serves as a trustee to the Maliotis Foundation. From 1982 through 1989, Dr. Hatsopoulos was a member of the board of the Federal Reserve Bank of Boston, serving as chairman from 1988 through 1989. He also served as a member of the Governing Council of the National Academy of Engineering from 1988 to 1994. He is a fellow of the American Academy of Arts and Sciences, the American Institute of Aeronautics and Astronautics, the American Society of Mechanical Engineers, and the Institute of Electrical and Electronics Engineers. Among his academic and professional honors, Dr. Hatsopoulos received the Heinz Award in 1996 for helping enhance technology, the economy, and employment. He also received the Pi Tau Sigma Gold Medal Award in 1961 for outstanding achievement in the field of engineering for the years 1950 to 1960, the honorary degree of Doctor of Science from New Jersey Institute of Technology in 1982, Doctor of Humane Letters from the University of Lowell in 1991, and Doctor of Science from Adelphi University in 1994. Dr. Hatsopoulos is principal author of *Principles of General Thermodynamics* (1965), and *Thermionic Energy Conversion* Volume I (1973) and Volume II (1979). He has published over 60 articles in professional journals.

THOMAS K. HUNT is the chief executive officer and chief scientist of Advanced Modular Power Systems, Inc. (AMPS) in Ann Arbor, Michigan. He attended the California Institute of Technology where he received his master's and Ph.D. degrees in physics. From 1964 to 1989, he was a staff scientist at the Ford Motor Company Scientific Laboratory, conducting basic research first in superconductivity and liquid helium and then in energy conversion. Since 1979, he has performed and directed research on advanced energy conversion systems, first at Ford and then at the Environmental Research Institute of Michigan, where he served as a department manager for 3 years. Dr. Hunt founded AMPS in 1991 and has conducted and led research in alkali metal thermal to electric converters since that time. Dr. Hunt's areas of expertise relevant to the committee include direct thermal-to-electrical energy conversion and high temperature materials. He is a member of the Management Advisory Board of the Center for Space Power at Texas A&M University and has served on the board of directors of Automated Analysis Corporation. He has published over 75 technical papers and holds 7 patents in the field of energy conversion.

DEAN JACOBSON is a consultant and a professor (emeritus) of Arizona State University. He has served as a professor and as director of science and engineering of materials in the university's Ph.D. program. Dr. Jacobson's principal areas of research have included high temperature materials, alloy design, material corrosion, failure analysis, thermionic emission phenomenon. thermal energy storage, heat pipes, laser-material interaction, and thermophysics. He has authored, or co-authored, 132 publications in these fields.

ELLIOT B. KENNEL is vice president and director of research and development at Applied Sciences, Inc, Cedarville, Ohio, specializing in aerospace materials development and solid state physics. Prior to November 1990, Mr. Kennel was at Wright Patterson Air Force Base, where he was responsible for research and development activities in support of thermionic energy conversion for space power supplies, and other aerospace power technologies. He holds several patents in the areas of electron emission devices and nanomaterials.

ROBERT J. PINKERTON is currently with Spectrum Astro, Inc. where he is the lead power system engineer for the Space Based Infrared System (SBIRS) Low Program. He has been with Spectrum Astro since June 2000. Previously, he was with the Motorola Corporation, Chandler, Arizona, where he was the lead power system engineer for the Iridium program. Between March 1988 and May 1998, Mr. Pinkerton was with the Lockheed Martin Company where he held several lead engineer positions in the Space Station Freedom and the International Space Station programs and led several proposal efforts. Between 1984 and 1988 Mr. Pinkerton was with the Martin-Marietta Aerospace Company, Denver, Colorado, where he was an electrical power system design and analysis lead engineer in the Magellan program. Mr. Pinkerton's areas of expertise include: conventional space electrical power systems, satellite avionics, and space power system integration and operation.

GEORGE W. SUTTON (NAE) is a principal engineer with ANSER Corporation, Alexandria, Virginia, and since 1996 has been a member of the ANSER team supporting the Ballistic Missile Defense Organization (BMDO) for interceptor technology and high-energy lasers. Dr. Sutton's areas of technical expertise include plasma physics, magnetohydrodynamic electrical power generation, and thermionic and thermoelectric direct energy conversion. Dr. Sutton's technical publications include *Engineering Aspects of Magnetohydrodynamics, Engineering Magnetohydrodynamics,* and *Direct Conversion*. Dr. Sutton was chairman of the AIAA Plasmadynamic Technical Committee and was general chairman of the Aerospace Sciences Meeting. He is a member of the National Academy of Engineering.

Appendix C

Electric Propulsion Considerations

Electric propulsion can benefit the deployment of large payloads for orbit transfer. The mass and volume saved by using an electric propulsion system allows for the use of smaller launch vehicles or allows more satellites to be placed on a larger launch vehicle. Alternatively, more station keeping fuel can be carried for a single spacecraft, which would extend the on-station lifetime of the spacecraft. Ultimately, the benefit of electric propulsion, or any propulsion system, relies on the impact of the propulsion system on total mission cost.

For some space missions requiring high power, the power system cost and mass can be partially offset by using electrical propulsion for orbit transfer and station keeping. Electric propulsion typically uses its fuel 4 to 10 times more efficiently than chemical propulsion. This efficiency results in a significant reduction in the mass of fuel required to complete certain space maneuvers. However, using electric propulsion systems requires that a spacecraft take more time to be placed into a final orbit. The increased amount of time it takes to reach orbit introduces other issues such as increased exposure to radiation while the spacecraft is in the Van Allen belt.

The wide variety of electrical propulsion applications complicates the generalization of the benefits. Thus, for the sake of discussion, this appendix uses an example of how coupling power and electric propulsion significantly reduces mass and cost. Combining mission power requirements with electric propulsion for orbit raising or station keeping maneuvers creates a dual mode system, that is, a system that can satisfy more than one mode of operation.

Of the various power systems that can provide dual mode operation, thermionic electric propulsion systems are unusual in that they can be designed to operate in a surge mode where the emitter temperature is increased from 1800 K to 2100 K. This temperature increase doubles the power output. This surge mode would be used during the propulsion portion of the mission, which raises an orbit. The surge in propulsion could be active for a relatively short time, from 30 to 90 days. The surge mode operation would result in a minor decrease in total expected life of a mission base-lined to last 7 years. The main advantage of surge mode operation is that it can be used to decrease the time required for orbit positioning or orbit transfer. However, primary orbit transfer using electric propulsion is still in the planning stage.

APPLICATIONS

Defense satellites must often be able to deal with contingencies such as changing inclination to observe a particular region on a timely basis, moving to a lower orbit to gain a better view of an area, moving to a higher orbit to avoid offensive damage, or maneuvering evasively to frustrate offensive measures. Electric propulsion would be one way to accomplish tasks such as these.

However, electric propulsion is not appropriate for all DoD space missions. In a launch on demand situation where there is an urgent need to replace or deploy space assets, chemical propulsion would be the likely candidate for orbit transfer. For standard launches where the time it takes for a spacecraft to arrive on orbit is important or for on-station maneuvering, the cost per kilogram to place a spacecraft on orbit is likely to be a key parameter. In this case, the cost to place a spacecraft on orbit includes such items as total propulsion cost, booster system requirements, command and control costs during orbit raising, and contingency for spacecraft loss because of propulsion failures.

The trend to high power for several classes of satellites is causing electric propulsion to be considered. Commercial satellites are typically designed and programmed to perform for very specific lifetimes. The principal electric propulsion application for commercial satellites is station keeping using only the available power used for the main mission power (Sackheim and Byers 1998).

An Example: Cost Savings Achieved by Dual Mode Operation

Of the several electric propulsion systems competing for high power and orbit transfer applications, two offer high efficiency and long life at attractive specific impulses: gridded ion engines and Hall effect thrusters.[1] Both devices accelerate noble gases, such as xenon and argon, to velocities in the 10 to 40 kilometers per second range. Xenon is safe, dense, and easily stored at ambient conditions. The Hall thruster is used here to illustrate electric propulsion payoff. A 25 kilowatt Hall thruster can be expected to operate as follows:

- I_{sp} = 15,680 meters per second (1,600 seconds),[2]
- Efficiency = 62 percent (58 percent after lead losses and power processing),
- Thrust: F ~ 1.6 Newtons (0.36 pounds force),
- Xe flow = 0.12 grams per second.[3]

The changes in velocity for station keeping are less demanding than changes in velocity encountered during orbit transfer. Station keeping changes in velocity can be accomplished by a variety of mature electric propulsion systems, including:

- Arcjets,
- Electrothermal monopropellant systems, and
- Pulsed plasma thrusters.

Although arcjets are not as efficient as Hall thrusters, they have the cost advantage of using hydrazine fuel, which is already required to be onboard the spacecraft for other propulsion (Sackheim and Byers 1998).

To achieve a mass and cost comparison, a 100 kilowatt electric propulsion system made up of four 25 kilowatt Hall thrusters is fueled to match the total impulse of the Thiokol Star 75 motor, a state-of-the-art solid propellant space motor.[4] To a first order approximation, the propulsion mass saved by the electric propulsion system will be considered as revenue producing payload. The Star 75 is 1.9 meters in diameter and contains 7,518 kilograms of propellant. The rocket provides approximately 200 kilo Newtons (45,000 pounds force) of thrust over 105 seconds. The cost is approximately $3.5 million. The equivalent electric propulsion system using four 25 kilowatt Hall thrusters and powered by a 100 kilowatt electric system would thrust at a combined total of 6.4 Newtons for about 33 days.

Economies of Scale

To place a kilogram of payload into low Earth orbit (LEO) costs between $6,000 and $10,000. The cost to reach geosynchronous Earth orbit (GEO) is at least $20,000 per kilogram and may go as high as $40,000, depending on the mission. When a chemical propulsion system is used, 60 to 70 percent of the mass that reaches LEO is the propulsion system needed to get the payload to GEO. Most of the mass consists of the propulsion system propellant. Using electrical propulsion, the ratio of propulsion mass to payload mass can be reversed. There are additional benefits if the power used for electric propulsion during orbit raising is also available and required for the main mission, thus creating a dual mode system. However, the lower thrust of the electric propulsion systems increases the orbit transfer time from hours to weeks. A LEO to GEO (1,500 to 36,000 kilometer) transfer with a 29 degree plane requires a satellite velocity increase of 3,500 meters per second using chemical propulsion and 4,050 meters per second using electric propulsion. The greater change in velocity required for electric propul-

[1]The rocket engine figure of merit is specific impulse (I_{sp}), which in SI units is the velocity of the propellant exiting the nozzle. Meters per second is equivalent to thrust per rate of mass discharge or newtons per kilogram-second.

[2]A lower I_{sp} is selected to shorten trip time.

[3]Xe is xenon, the propellant generally used for gridded ion engines and Hall effect electric propulsion.

[4]Total impulse is the integral of thrust over the thrusting time.

sion is a result of the persistent gravity from the longer time spent in LEO.

For the purposes of this example, the costs of propulsion and power were estimated using assumptions for large constellations of communications satellites, for example Teledesic, where economies of scale come into play. Also, for missions in LEO, the losses in altitude due to gravity will reduce these benefits slightly. A satellite using an electric propulsion system takes longer to reach GEO so the effect of gravity acts on the spacecraft for a longer period of time.

The costs per launch are as follows:

- Star 75 solid rocket motor: $3.5 million,
- Electric propulsion system + 100 kilowatt space power system: approximately $9 million + $33 million = $42 million.[5]

Using the figure stated earlier, $20,000 per kilogram to reach a GEO orbit, the savings are as follows:

- *Case 1*. When the 100 kilowatt power source is used for electric propulsion only, the approximately 3,000 kilogram savings in mass yields approximately $60 million in additional payload for an approximate $21 million net savings.
- *Case 2*. When the 100 kilowatt system is used for both propulsion and primary mission power once on station, the approximately 6,000 kilogram savings in mass yields approximately $120 million worth of additional payload for an approximate $114 million net savings.

The savings for the dual mode operation are substantial. Such savings are an integral part of the advocacy for more economical and higher space power.

SPACE APPLICATIONS

Even before the 1960s space race, the advantages of electric propulsion for deep space probes were recognized. However, neither power nor electric propulsion adequate for prescribed missions was available. Nuclear power, which is a candidate for certain missions that travel beyond Earth orbit, would enable electric propulsion systems to be used. During the 1970s and 1980s, NASA made considerable progress on several electric propulsion systems centered on the use of gridded ion engines and magnetoplasmadynamic (MPD) thrusters. In both the United States and Great Britain, research and development also concentrated on producing flight qualified ion engine systems in the thrust range of less than 5 kilowatts by the mid 1990s.

The MPD engines would be suitable for large power systems producing more than half a megawatt. However, these systems are currently not developed to a point where they could be used.

Gridded ion engines could potentially be useful for deep-space probes. The power requirements for these missions are generally low, in the hundreds of watts. If high power is not required for the mission, placing a high power system onboard the spacecraft for electric propulsion is usually not justified.

The gridded ion engine offers potential advantages. These engines can operate at the lower levels of power that might be used on certain deep space missions. However, such missions would take several months to build the velocity needed to arrive at the far reaches of the solar system in a reasonable number of years. Gridded ion engines also provide higher efficiency by operating at a higher specific impulse, in the range of 40 to 60 kilometers per second.[6]

TABLE C.1 Performance of Chemical and Electrical Propulsion Systems

Typical Space Engine	Specific Impulse (km/s)
Chemical	
Solid propellant for spacecraft maneuvering	2.8
Storable liquid (N_2O_4 and MMH[a])	3.3
Cryogenic oxygen and hydrogen	4.3
Electric	
Gridded ion engine	20 to 40
Hall thruster	10 to 25

[a]Monomethylhydrazine.

[5]If the same 100 kilowatt system is onboard acting as a primary power system, some of these costs will be offset by the dual mode performance of such a system.

[6]Thrust is fuel flow rate times exit velocity of the fuel. For constant power, reducing the flow rate permits the fuel to be accelerated to higher velocity, or higher specific impulse.

BIBLIOGRAPHY

Caveny, L.H., ed. 1984. "Orbit-Raising and Maneuvering Propulsion: Research Status and Needs," *AIAA Progress Series in Astronautics and Aeronautics*, Vol. 89, January.

Sackheim, R.L., and D.C. Byers, TRW Space and Electronics Group. 1998. *AIAA Journal of Propulsion and Power* 14(5):669.

Appendix D

Acronyms

AEC—Atomic Energy Commission
AFRL—Air Force Research Laboratory
AMTEC—alkali metal thermal to electric converter
BMDO—Ballistic Missile Defense Organization
CC/MC—conductively coupled multicell (thermionic converter)
CIM—cylindrical inverted multicell (thermionic converter)
CVD—chemical vapor deposition
DARPA—Defense Advanced Research Projects Agency
DNA—Defense Nuclear Agency
DoD—Department of Defense
DOE—Department of Energy
DTRA—Defense Threat Reduction Agency
GEO—geosynchronous Earth orbit
HPALM—high-power, advanced, low-mass (solar thermionic system)
IAPG—Interagency Advanced Power Group
IPPE—Institute of Physics and Power Engineering (Russia)
ISS—International Space Station
ISUS—Integrated Solar Upper Stage (Orbital Vehicle program)
LEO—low Earth orbit
JPL—Jet Propulsion Laboratory
MHD—magnetohydrodynamic
MPD—magnetoplasmadynamic
MTC—microminiature thermionic converter
NASA—National Aeronautics and Space Administration
NMERI—New Mexico Engineering Research Institute
NRC—National Research Council
RTG—radioisotope thermoelectric generator
SRA—Scientific Research Association
SDIO—Strategic Defense Initiative Office
SET—Solar Energy Technology (program)
SNAP—Space Nuclear Auxiliary Power (program)
SOTV—Solar Orbital Transfer Vehicle (program)
SPAR—Space Power Advanced Reactor (program)
STA—Space Technology Alliance

STAR-C—space thermionic advanced reactor–compact
START—string thermionic assembly research testbed (tests)
TFE—thermionic fuel element
TFEV—Thermionic Fuel Element Verification (program)
TOPAZ—thermionic power from the active zone (a Russian acronym)
TRIGA—training (test) reactor isotope General Atomics
USAF—U.S. Air Force