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Important Technology Considerations For Space Nuclear Power Systems

March 1988

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Important Technology Considerations For Space Nuclear Power Systems

March 1988

U.S. Department of Energy
Assistant Secretary for Nuclear Energy

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(12-84)

United States Government **Department of Energy**

memorandum

DATE: March 4, 1988

REPLY TO
ATTN OF: NE-5C

SUBJECT: Technology White Paper

TO: All Recipients

Enclosed is a copy of the white paper Important Technology Considerations for Space Nuclear Power Systems. This paper describes the technical choices faced by space nuclear power system designers to meet the user requirements for this Nation's defense and research spacecraft. It is meant to assist those routinely dealing with the subject matter to provide a better understanding of the technical aspects of space nuclear power and use the document as a technical basis for conveying, in more general terms, these important and complex matters. I would like to express my thanks to those within the Space and Defense Power Systems organization of the Office of Nuclear Energy who participated in the preparation of this document.

Dennis A. Bitz
Deputy Assistant Secretary
for Space and Defense Power Systems
Office of Nuclear Energy

Attachment

IMPORTANT TECHNOLOGY CONSIDERATIONS FOR SPACE NUCLEAR POWER SYSTEMS

EXECUTIVE SUMMARY

PREFACE

This paper discusses the technology considerations that guide the development of space nuclear power sources (NPS) by the Department of Energy (DOE) to meet a wide variety of applications. The Department and its predecessor agencies have been developing NPS since the 1950s and producing NPS for spacecraft for the National Aeronautics and Space Administration (NASA) and the Department of Defense (DOD) since the early 1960s. No one nuclear power type, isotope or reactor, will suffice over the entire range of mission power required. Nor is one type of power conversion system, be it static or dynamic, the optimum choice for all space nuclear power system applications. There is a need for DOE, in partnership with its users, NASA and DOD, to develop a variety of types of space nuclear power sources -- isotope-static, isotope-dynamic, reactor-static, and reactor-dynamic -- to meet mission requirements well into the next century.

PURPOSE

The purpose of this paper is to discuss the important technology considerations which apply to space nuclear power systems, to explain the program choices made based on those factors, and to present the current status and direction of each of those programs.

[NOTE: Other white papers are available which cover the safety of space nuclear power systems as special topics. Discussions of safety also occur where appropriate in this paper, but the reader is advised to consult those papers for a more complete treatment of this important topic.][1]

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[1] These DOE white papers are:
"Flight Safety of Space Nuclear Power", issued jointly by DOE, NASA, and Office of Science & Technology, November 10, 1987.
"Radioisotope Power System Safety " (DRAFT), to be published in September 1988.

TECHNOLOGY CONSIDERATIONS COVERED IN THIS PAPER

The following outline presents in each column the main topics covered in each section of the main body and the appendix of this paper, for an easy and concise reference on what topics are covered and in what sequence.

Technology Issues

- Mass & volume
- Temperature & materials
- Reliability
- Safety
- Survivability

Program Issues

- Program Goals
- Schedule-Risk-Cost
- Life-cycle Costs

Program Decisions & Status

- Sub-kilowatt isotope(static)
- Kilowatt isotope (dynamic)
- Multi-kilowatt reactors
- Megawatt reactors

Appendix: General Features

- Heat Sources
  - Isotope
  - Reactor
- Power Conversion
  - Static
    - TE
    - TI
  - Dynamic
    - Rankine
    - Brayton
    - Stirling
- Heat Rejection
  - Closed
  - Open

SUMMARY OF TECHNOLOGY CONSIDERATIONS

Radioisotope and nuclear reactor systems share the common advantages of long-life, independence from the Sun, and the inherent capability to operate in high-radiation fields. However, they both share the common factor of assuring that they can be deployed and used safely in space. For isotope systems the primary safety concern is to assure that the Plutonium-238 fuel (Pu-238, a non-weapons-grade material) can be contained in all credible accident conditions during launch or reentry. For reactors the primary safety concerns are to assure that the reactor will not become operational, or critical, during any launch accident and that the radioactive fission products generated during operation in space are prevented from posing a hazard to the Earth's population. The latter criterion will be met by assuring that either the reactor is kept in space until the fission products have decayed to harmless levels or the reactor system can be kept intact during reentry, just as isotope heat source systems are.

The basic isotope fuel has a constant power density, so that mass and volume of those power systems are basically linear with increasing power. Reactor systems, however, have the potential for very high power density in the reactor itself. At lower power levels this potential is offset by the need for a minimum reactor system size and mass to become critical, but as power levels increase there is a net advantage in power density, and reactors become preferable to isotope and even non-nuclear power systems. Therefore, isotope systems are the preferred nuclear system at power levels up to about 10 kW_e, due to their small mass and size, and reactors are preferred above 10 kW_e.

Key factors in determining the cross-over point in the selection of reactors versus isotope systems are mass and volume. For isotope systems another consideration is the cost of the Pu-238 fuel, and that cost also influences whether the power conversion system should be static or dynamic. Below about 1 to 2 kW_e the isotope fuel mass is small enough that RTG systems are the clear choice because of the relatively elegant, mature, well tested (in space) thermoelectric (TE) technology, even though TE converters are currently only 6.5% efficient, with growth potential to 8% or so. Above 2 kW_e, however, the isotope fuel source should be linked to a dynamic converter (e.g., Brayton, Rankine, or Stirling cycles) to get efficiencies in the range of 20 to 30%, thereby economizing on the mass of Pu-238 fuel needed.

As power levels increase into the nuclear reactor range, the components that typically drive mass and volume reduction efforts are the radiator, which is used to reject the thermal energy that is not converted to electrical power, and the shield. (The radiator design is a function of operating temperature; the shield is principally dependent on the separation distance provided by the structural boom to the power source.) The amount of heat energy rejected by the radiator will be 70-80% of the total energy produced when dynamic converters are used and 90-94% for static converters. Since the radiator size is inversely proportional to the fourth power of the radiator temperature, that temperature is a crucial parameter in all space power system designs. Although they are less efficient and reject more thermal energy, proven TE technologies operate at much higher heat rejection temperatures than current dynamic processes, so that the overall reactor-TE system masses and volumes are lower than current reactor-dynamic systems. As power increases still further into the megawatt range, reactor-dynamic systems prove to be the only viable option, since the radiator mass and volume no longer dominate the power system size; all components are large at those power levels, and the more efficient dynamic systems are quite attractive, even at lower operating temperatures.

More efficient static conversion schemes, such as thermionics (TI) which potentially offer 10-12% efficiency, are also attractive candidates for reactor-static power systems. Because they operate at even higher peak temperatures than TE, they can have much higher heat rejection temperatures, therefore their radiator sizes could be smaller than for TE systems. Whichever system is selected, however, it must demonstrate the ability to operate with very high reliability over several years -- an important criterion for space nuclear power systems. The key issue then becomes the maturity of the competing technologies -what is the current state-of-the-art, and what are the prospects for developing a given technology within the schedule and cost constraints of the development program? At the time of the SP-100 technology selection in 1985, the decision was made that the constraint of demonstrating technological readiness by 1991 (then the target date) favored TE over TI. The technology base was clearly more mature, hence the development risks were lower. However, TI offered sufficient potential that a test program was begun to resolve the key technology issues to keep TI as a viable option for future space power systems.

At the very highest power levels, such as in the MW_e range for burst power applications, energy storage systems, open cycle systems, and modular design and construction become important options. Regardless of which approach is used, achievement of these very high power levels will require even more efficient systems, which will dictate the use of higher operating temperatures and more advanced material development. That is the challenge facing the multi-megawatt (MMW) space reactor program.

CONCLUSIONS

1. No single nuclear power source can span the wide range of power requirements of the variety of space applications now contemplated. Isotope systems are best suited for low power, for most applications below 10 kW_e, while nuclear reactor systems are more suitable above that general power level and have growth potential into the thousands of kW_e.

2. There is no clear-cut choice between dynamic and static conversion processes; each application brings different considerations of power, mass, volume, temperature, material development, reliability, and program goals and risks to bear on the choice of dynamic versus static power conversion. Dynamic power conversion methods offer two to four times the efficiency of static methods, but can add some complexities to other aspects of spacecraft design (e.g., the need to compensate for torque or jitter). For space nuclear power system designs the choices of heat source, power conversion method, and heat rejection system are highly interdependent. As in most other engineering challenges, what is optimum at the subsystem level does not necessarily lead to an optimum overall system.

3. Stringent spacecraft mass and volume restrictions force nuclear power system designers to develop systems with the best power-to-mass ratio possible. To use the lightest materials may force designers to use sub-systems which may be less than optimal. For instance, the most efficient thermodynamic energy conversion systems are those which operate through the largest temperature drop at a given high temperature. However, there is also utility in using the highest heat rejection temperature possible, since that yields great mass and volume payoffs at the higher power levels. Combining high-temperature operations at minimum mass requires extending the state-of-the-art, through significant material development time, extensive reliability testing, and the attendant high costs and program risks. There usually is not much schedule or cost latitude in such programs, consequently the technology decisions tend to be conservative.

4. The most efficient progression of space nuclear power systems from lowest power to higher power has been exhaustively studied and is currently judged to be: isotope-static, isotope-dynamic, reactor-static, and reactor-dynamic. Current DOE space nuclear power system programs are using and developing each

of these source-converter combinations. These programs are building upon over 30 years of spacecraft material development and power source design experience. If supported with appropriate resources, these space NPS will be developed in time to meet the Nation's ever-demanding space requirements now and into the next century.

5. Nuclear power sources may cost more per unit than other types of space power systems, but due to their intrinsic hardness may allow fewer satellites in a constellation, thereby cutting the launch and satellite costs needed to attain a given system capability at the required survivability level. This intrinsic hardness stems from their designs, which already include structural containers and perhaps shields, plus control components already hardened against the ionizing radiation of the nuclear power source. Nuclear powered spacecraft are more compact, therefore less detectable and more maneuverable, than non-nuclear power sources.

6. Spacecraft have the potential to tumble, lose their continuous communication with Earth stations, and perhaps not be able to receive corrective signals before their batteries are depleted. Space nuclear power sources could continue (isotopes unquestionably, and reactors consistent with fail-safe design criteria) to function reliably, independent of orientation and for sufficiently long periods, thereby enabling corrective actions directed from the ground to dampen the effects of that tumbling and possibly preventing the loss of the satellite.

IMPORTANT TECHNOLOGY CONSIDERATIONS FOR SPACE NUCLEAR POWER SYSTEMS

INTRODUCTION

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PURPOSE

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BACKGROUND

General: There are two basic types of NPS, radioisotope-driven systems and nuclear reactor powered systems. Due to the low-power needs of the past, the

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"Flight Safety of Space Nuclear Power", issued jointly by DOE, NASA, and Office of Science & Technology, November 10, 1987.

"Radioisotope Power System Safety " (DRAFT), to be published in September 1988.

U.S. experience with NPS in space is almost exclusively with radioisotope thermoelectric generators (RTG). One reactor was tested successfully in space in 1965; however, the program was essentially terminated by the early 1970s and was not reestablished until 1983. In contrast, 34 RTGs have been used to power 19 NASA and DOD space missions.

The **advantages** and **disadvantages** of each type of power source will be discussed below. Both isotope and reactor systems offer some common **advantages** -- attractive power-to-mass ratios in these higher power regimes, lifetimes of years, operation in radiation belt orbits or other hostile environments, and operation in shade or in regions far from the Sun. These attributes make space nuclear systems uniquely enabling power sources for important current and future missions.

The common **disadvantage** of space nuclear power systems is the unwarranted but persistent perception that nuclear power is unsafe and cannot be made sufficiently safe enough to warrant their use. This perception, of course, is contrary to the experience obtained in the launch and operation of several dozen space nuclear power sources to date. The fact is that substantial effort has gone and is going into the design and testing of these power systems, to insure that they are made safe and operated safely, so that they pose no undue risk to the exposed populations. To do any less would be highly irresponsible, however, we recognize that this misperception will be difficult to change in some quarters. Safety has been the primary design consideration of the power sources since the inception of space nuclear power systems. Protective component designs, using the highest quality materials, have evolved to insure immobilization of the fuel against all but the most improbable accidents. (The safety design philosophy for both system types is covered later, and the complete safety criteria, the safety review process, and the safety record to date are covered in the safety white paper.)

Isotopes Power Sources: Sophisticated space systems require a reliable source of electrical power. Many of the past U.S. space missions have relied upon solar cells or chemical systems such as batteries and fuel cells for power. However, certain specialized missions have required the unique capabilities that nuclear power sources provide. These missions have included those far from the Sun where solar intensity is too low and chemical power is not feasible for long duration flights, or for missions demanding high power or an increased level of survivability.

During the past 25 years, key **advantages** of using RTGs in space have been:

Space RTGs provide a compact source of electrical power with a good power-to-mass ratio. They have exhibited extremely high reliability over extended lifetimes of a decade or more. The relatively small exposed area of RTGs can reduce the overall size of spacecraft, simplify attitude control, and reduce structural interactions. RTGs are inherently designed to operate in radiation fields. Their general compactness make them attractive for satellites which must maneuver or which have tight tolerances on attitude control. RTGs enable spacecraft to be more autonomous; a single unit may meet a number of diverse system requirements. Radioisotope systems can be operated on the launch pad for system checkouts prior to launch or in the orbiting space shuttle.

(Another application of isotope energy is the radioisotope heater unit (RHU), which is used to heat selected components directly, without introducing electromagnetic interference.)

The main **disadvantage** of isotope systems, aside from the safety perception mentioned earlier, is the fuel cost. (However, if it is the only feasible power source, it may still be an economic choice. For example, the cost of the RTG power supplies used in spacecraft has never exceeded 10% of the cost of the spacecraft.) Plutonium-238 fuel can be considered costly and its production must compete with that of other special nuclear materials (SNM) produced by the Department of Energy. The arbiter of competing requirements for SNM is the joint DOD-DOE Nuclear Weapons Council; their decisions may affect NPS production schedules. However, it should be noted that SNM costs are covered in DOE overhead accounts, and the ownership of that material is retained by DOE.

Reactors: Space nuclear reactor development was pursued vigorously in the 1960s, but this program was terminated in the early 1970s because of the lack of missions and applications. When it became clear in the early 1980s that space power requirements would become large enough to warrant using reactors, a development program was begun by DOE in partnership with DOD and NASA.

The key **advantage** offered by space reactors is high power at an attractive power-to-mass ratio, with inherently highly survivable components.

Nuclear reactors are the principal candidates for spacecraft that will require larger amounts of electrical power (tens of kW_e and higher) for extended operations and possibly for burst-mode power requirements. Isotope-based NPS reach a fuel-cost-effectiveness limit at about 10 kW_e. At some power level the mass or size of solar arrays or chemical power systems also becomes unacceptably high, and reactors become necessary to satisfy these more demanding mission requirements.

Because they are designed to withstand their own radiation and thermal stress environments, reactors intrinsically are less vulnerable to external radiation damage. Since reactors emit ionizing radiation, the power processing and control systems are also designed to be hardened against radiation. Also by the very nature of their designs, nuclear reactors have vessels and radiation shields which can act as shields against laser attacks and electromagnetic pulse (EMP).

In addition to the safety questions mentioned earlier, the main **disadvantage** of space reactors at this stage is their development time and cost. Space nuclear reactors can require a substantial development and test program to demonstrate that they can meet more demanding safety, mass, reliability, and other performance requirements.

KEY TECHNOLOGY ISSUES

Introduction: The appendix to this paper presents a review of the general features of space nuclear power systems and includes the key considerations for choosing the power source, isotope or reactor, the type of conversion process (static or dynamic, and which of each), and the heat rejection system. This section presents the main technology factors which drive the choice of a suitable space nuclear power system to satisfy requirements specified by the users. The following section of this paper discusses the reasons for the technology choices made for each DOE program and reports the status of those programs.

Mass and Volume: These factors drive almost every aspect of spacecraft design, since a spacecraft (or a component or payload) is useless if it is too heavy or too large to be launched. **The single overriding figure of merit for space power systems of any type is power per mass, i.e., kW_e/kg, for the system.** (Figures 1 and 2 provide an overview of the mass of various nuclear power sources and their best power regimes.) Static isotope systems already developed provide 300 W_e (at beginning of mission, BOM) in 56 kg, for a power-to-mass ratio of 5.3 W_e/kg (or 187 kg/kW_e). Dynamic isotopes systems being designed and developed could provide up to 10 kW_e within about 1000 kg, or 10 W_e/kg (100 kg/kW_e). A goal for the SP-100 reactor is to provide power densities of 10 to 33 W_e/kg (100 kq/k_e to 30 kg/kW_e) over the power range 30 to 100 kW_e.

As it is for most spacecraft components, the search for lighter power systems is necessary. Overall system efficiency is the starting point in this search for the most compact and lightweight power source possible. In general for any energy conversion system, greater efficiency is obtained through using higher peak operating temperatures and greater temperature drops during the conversion process. Currently feasible static processes[2] convert from 6% to potentially 12% of the thermal energy into electrical energy, whereas present dynamic processes (e.g., Rankine, Brayton, or Stirling) offer conversion efficiencies of 20 to 30%. If efficiency were the only factor, dynamic processes clearly would displace static conversion schemes. However, the increased complexity and the reliability challenges that accompany dynamic hardware, particularly for reactors, usually add significant development time to the program in order to overcome those challenges.

The type of power source has definite mass implications. Shielding requirements for isotope sources are negligible (except for the most sensitive

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[2] Several other static, direct-conversion concepts, such as AMTEC (Alkali Metal Thermo-Electric Conversion), HYTEC (Hydrogen Thermo Electrochemical Converter), and MHD (Magneto-Hydro-Dynamic), have been proposed. They offer significantly better efficiency, but they are very advanced concepts which will require substantial development to realize that potential.

SPACE NUCLEAR POWER SYSTEMS
Power vs. Mass

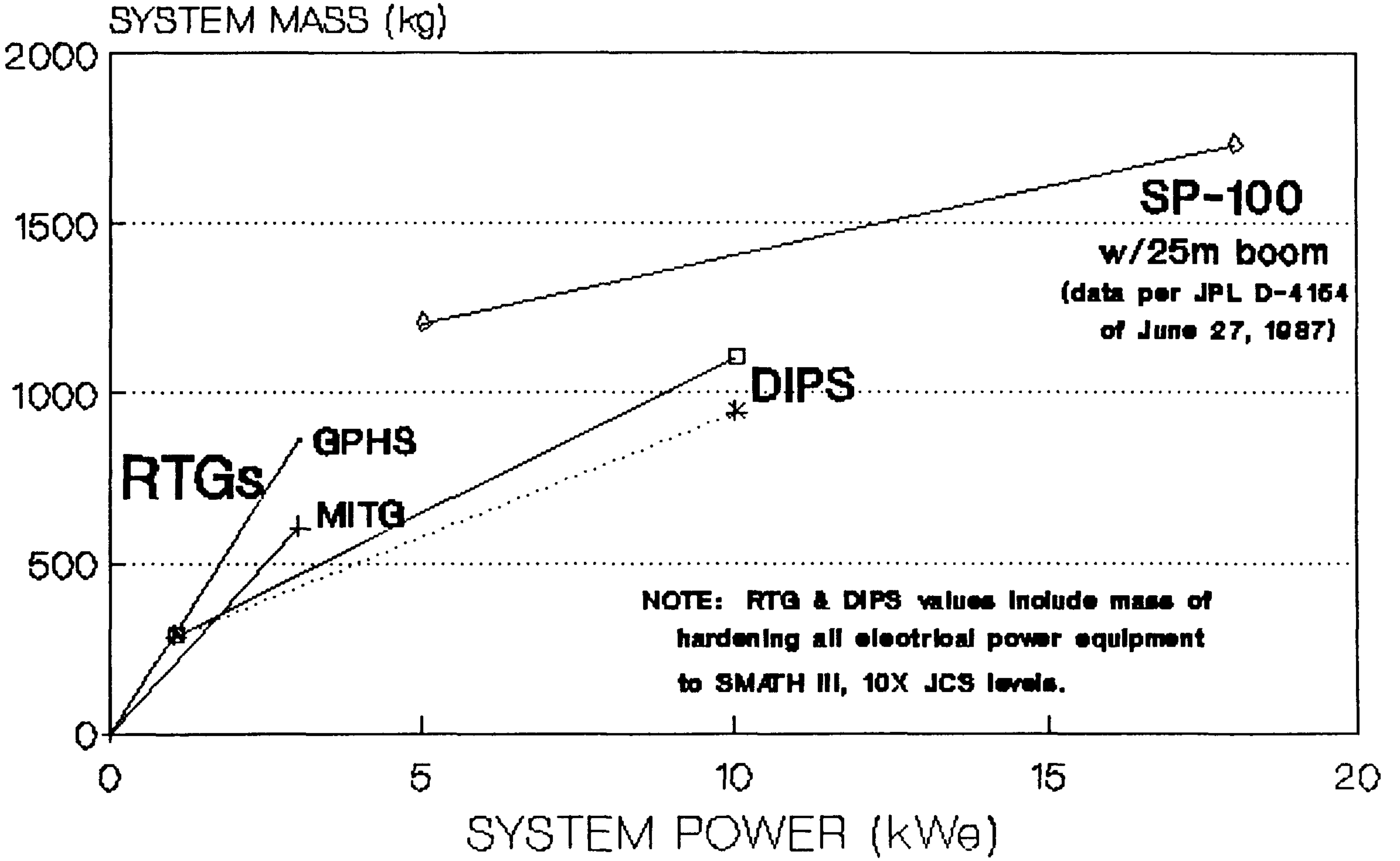

Figure 1

See next chart for 0-100 kWe power range

SPACE NUCLEAR POWER SYSTEMS
Power vs. Mass

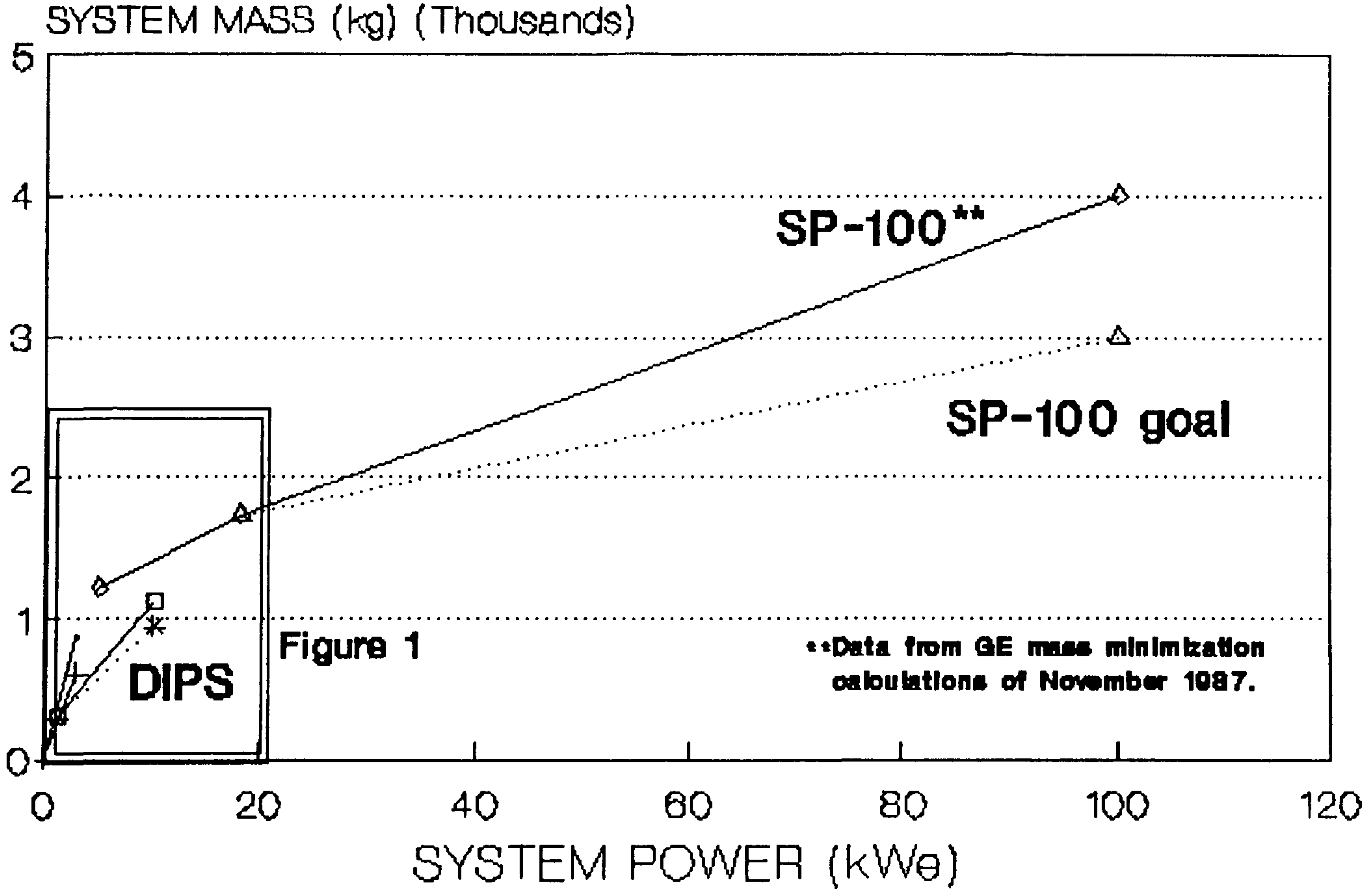

Figure 2

See previous chart for 0-20 kW details

instruments and experiments), whereas for reactors the shielding and separation boom can comprise 20 to 30% of the total system mass. The mass of isotope systems are generally linear with power. That is a distinct advantage over reactor systems at the lower power ranges, since reactors require a basic minimum mass. For a space reactor this would be about 1500 kg from low power to about 10 kW_e. As power increases the reactor core quickly shows economies of scale, but the shielding mass and heat rejection system mass begin to dominate the design. At 100 kW_e, for example, the shield mass (with a 25-m boom length) is almost 20% and the radiator 15% of the total 3000 to 4000-kg reactor system. Radiator size forces designers to look at higher operating temperatures, which implies more advanced materials and higher technological risk, all driven fundamentally by considerations of mass and size.

As mentioned above and explained in the appendix, the heat transport and rejection system can also add significant mass and volume to the power system. The radiator area required is proportional to the amount of energy to be rejected and inversely proportional to the fourth power of the temperature at which that heat rejection occurs. Hence there is a direct conflict between optimizing thermal efficiency through a low rejection temperature and optimizing the radiator design through a high rejection temperature. Dynamic power converters reject 10 to 25% less heat, which would reduce radiator size. However, current material fabrication constraints limit the peak operating temperature of dynamic components, leading to lower heat rejection temperatures, hence greater radiator size per kW_t rejected. At some point as power increases, particularly for burst-power applications of short duration, the radiator size and mass could become so large that one must consider using an open system, in which the working fluid is exhausted directly to space, eliminating the radiator completely; but, this now adds the problems of effluents which may affect other spacecraft functions and the new storage requirements for such expendable working fluids.

Another fundamental approach to reducing system mass for spacecraft which have peak power requirements is to use a separate energy storage system, chemical or kinetic, particularly for burst power applications. The stored energy would be used only for peak needs and restored gradually by the main power source in slack periods. The savings for dynamic isotope and reactors can be significant. In fact, for multi-MW_e reactors, such storage schemes may be the only feasible way to keep shielding and radiator masses to acceptable levels. However, current storage technology portends a significant mass burden as well.

One final caution on the overall power system size is appropriate. If the radiator panels get large enough, they have to be launched in a folded configuration and deployed in orbit; such panels are already as light as possible, so this may present a structural design challenge. Similarly, for MW_e-size systems, if fuel tanks are needed for large open-cycle systems, such power systems may have to be modular, launched in several vehicles, and constructed in space. Experience already gained in launching and deploying large, fragile solar panels and many chemical storage tanks over the years will be valuable in this regard.

Materials: Pushing the limits of technology to refine existing materials and to find and develop new ones is the major challenge for space nuclear reactor systems. Isotope system designers have made significant progress over the years, and therefore they are able to tap more state-of-the-art materials. (By state-of-the-art we mean the most modern, mature, producible technology.) Space nuclear power materials must meet stringent requirements for compatibility, durability, and demonstrated longevity in those high-radiation, high-temperature, and micro-gravity environments appropriate to each application.

The importance of temperature in many space NPS applications is a primary consideration of scientists and engineers designing power systems. For a given heat rejection temperature, the higher the operating temperature, the more efficient the cycle. Operating temperatures in turn are constrained by the materials available.

Among the static conversion choices, high-temperature (1800K) thermionic (TI) conversion promises better efficiencies, 10 to 12%, than thermoelectric converters, 6.5% to possibly 10%. However, a significant amount of material development and testing is required (and ongoing) to demonstrate reliable performance of such materials in a very strong radiation field. Thermoelectric (TE) systems operate at a lower temperature (1300K) and now provide 6.5% efficiency, but material development in progress seeks to extend this to 10% by 1993. Space RTGs since the mid-1970s have used the unicouple TE, making that a very well characterized technology. The SP-100 reactor will use the improved multi-couple technology now being developed as an outgrowth of the RTG technology. TI is being developed under a separate program, as discussed later.

For dynamic conversion processes, material compatibility is very important, particularly in the choice of working fluids. For example, an organic Rankine cycle for an isotope-driven system is quite attractive, but that fluid could decompose over time in the high radiation field of a nuclear reactor, consequently requiring systems which in all likelihood would have a large mass penalty. For reactor-Rankine systems liquid metals are better materials because they are a better thermal match to the higher operating temperatures available in a reactor. For the Brayton isotope system now under consideration, however, the chosen thermodynamic state points do not pose a materials challenge. Similar Brayton systems could be used with reactors, but with a mass penalty at the higher power levels of interest. To be more competitive, Brayton systems which can withstand higher turbine inlet temperatures are needed, and that poses significant technical challenges which are being addressed by the space nuclear power community.

Reliability: Long-duration space missions impose stringent reliability requirements on all systems, and the main power system is a vital component. For example, the types and extent of long-term materials and component development and testing that now lie ahead for TI, for multi-couple TE, and for the various dynamic converters being considered, are illustrated by the experience of RTGs using TE and show that such systems with proper development can perform in the severe environments of space for a decade or more. The challenge to the designers is to understand the failure modes very well through such testing and to incorporate the appropriate design solutions to meet the stringent reliability goals. Such solutions may involve redundant loops or building in excess capacity to meet all reasonable contingencies.

Safety: The primary safety design objective is to minimize the potential interaction of the radioactive materials with Earth's population and environment so there is no undue risk to the public health and safety. Extensive safety analyses and tests are conducted to insure that a given nuclear power source will satisfy this safety objective.

Every nuclear power source considered for use in space undergoes an extensive review process which is described in the DOE white paper, "Flight Safety for Nuclear Power". Expert staffs from DOD, DOE, and NASA are involved at each stage of the review process, and independent observers from the Nuclear Regulatory commission (NRC) attend the sessions. Additional independent safety reviews and assessments are performed by experts in the field and incorporated in the safety assessment process. The resulting independent flight safety evaluation is provided to the Office of the President before final approval of any launch containing a nuclear power source.

In the case of isotope sources, the design philosophy is to contain, immobilize, and recover if necessary the radioisotope fuel. These sources have been designed and tested to withstand the maximum credible combinations of explosions, projectile impacts (from a launch vehicle explosion), liquid or solid propellant fires, reentry heating, and land or water impact -- and still contain the Pu-238 full. For example, current isotope heat sources are modular, can serve as their own re-entry vehicle, have impact absorbing structure, and have a fire and fragment resisting casing, all to prevent release of the Pu-238 fuel under all accident conditions, and their potential consequences.

Space nuclear reactors will be designed to withstand similar environments. The safety philosophy for reactors is not to operate the nuclear reactor before launch to preclude the accumulation of radioactive fission products before reaching a safe operating orbit. The reactor design must insure that a subcritical configuration will be maintained under all credible pre-launch and post-reentry accident environments. Operation will not begin until the reactor has achieved a safe operating orbit. Any malfunction of the reactor, if used during initial operation in lower Earth orbit of a nuclear-electric propulsion system, would result in an immediate shutdown of the reactor until the problem was rectified, so that no appreciable amount of radioactive material will have been built up in low orbit. The reactor systems would be designed to insure that the reactor core could be cooled, by active or passive means, if the primary cooling system were to be disabled. After completion of its mission, the reactor will be shut down permanently using redundant systems functioning independent of other spacecraft systems. If not already in an orbit high enough to allow sufficient time for the radioactive fission products to decay to safe levels, the shut-down reactor will be raised to such a safe orbit.

<u>Survivability</u>: Survivability is a measure of how many space assets will remain after exposure to a given threat. A satellite is only as survivable, or as "hard", as its weakest critical component, and no component is more critical than the power system. Survivability of the power system is important both to military and civilian spacecraft; NASA spacecraft have been sent through the severe radiation belts of Jupiter, and communications satellites in have experienced performance degradation after periods in the radiation fields in near-Earth orbits. Given the increasing man-made threat to civil and military satellites in the future, survivability is receiving more attention from spacecraft designers than in the earlier period of the space program.

Nuclear power sources are intrinsically hardened automatically during the process of meeting other design requirements. Each source comes with a container, such as a radiator or structural supports, that can also act as a shield against laser attacks and externally generated electro-magnetic pulse (EMP). Because nuclear power sources emit ionizing radiation, the spacecraft designer has already had to provide radiation hardening in the design of the power processing and control system. Appropriate materials and designs can be used to protect against fragments without cutting off the source of power. The general compactness of nuclear power sources would also add to the survivability of satellites which must maneuver or which have tight tolerances on attitude control, such as surveillance systems. As the technology matures, nuclear-electric propulsion may also enable future spacecraft to move significant distances to avoid natural or man-made threats.

Nuclear power sources may cost more per unit than other types of space power systems, but due to their intrinsic hardness may allow fewer satellites in a constellation, thereby cutting the launch and satellite costs needed to attain a given capability at the required survivability level.

Nuclear power sources would also be useful if the spacecraft were to experience tumbling in orbit, since those systems do not depend on spacecraft orientation nor are they restricted by battery lifetime. That is important because it is possible to dampen the tumbling effect via ground commands to the spacecraft, but such signals must be sent continually to the craft in the hope that the antennae will pick them up while the craft is tumbling errantly. If those corrective signals are received in time to make corrections before the batteries run down, then the spacecraft may be saved. Otherwise, even when the signals do reach the spacecraft, it will be powerless to respond, the craft will return to earth prematurely (if in a near-Earth orbit), and that precious resource will be lost. With a nuclear power source, such corrective action could be attempted for months or years (depending on the decay period of the orbit and the fail-safe criteria for a reactor), with the assurance that the power source will be available for the spacecraft to respond.

This capability to correct spacecraft tumbling would exist without interruption with isotope-driven power sources. With reactors, however, a qualification is needed: when sufficiently aberrant conditions occur on the spacecraft (such as loss of communication), designers must provide automatic measures for reducing the power immediately, perhaps to zero in extreme cases, and for taking other fail-safe actions to prevent potential damage to the core during the emergency. Such safety provisions could recognize the need to maintain a minimum essential reactor power level to counter tumbling of the spacecraft, consistent with other safety threats to the reactor which might also be occurring.

PROGRAM ISSUES

Program Goals: Technology decisions for nuclear power system development are driven entirely by the goals of the specific program and their underlying assumptions. As the historical perspective is given below, these considerations must be kept in mind: Is this a research program, development program, or production program? What are the schedule demands? What level of technological risk is allowable, and will an intermediate success be essential to the program? Can we use state-of-the-art materials? Is there a potential fallback if needed?

Schedule-Risk-Cost: Given the preceding cautions, there are some dilemmas posed for space NPS development by the combination of schedule, allowable risk, and cost limitations (imposed by the user) which need to be understood. For example, it is far simpler, hence less costly and risky, to develop a space NPS targeted at a single power level rather than over a broad range of powers. Also, decisions made to meet near-term user program needs tend to avoid significant technology risks, whereas longer term research and development programs can consider more advanced technology approaches, with potentially higher payback in meeting user requirements, but at higher risk.[3] Such risk-benefit considerations of extending the technological state of the art are real and drive program decisions.

Life-Cycle Costs: Costs for research and development of space nuclear power systems are not necessarily determined in as easy and straightforward a manner as they would be in the private sector. Direct costs of contract efforts are not a problem; the difficulty arises in allocating properly the cost of the many DOE laboratories, field offices, nuclear fuel facilities, plus management overhead and the contribution of other agencies who participate in these joint DOD-NASA-DOE enterprises. A particularly difficult accounting problem arises in the cost of radioisotope fuel, which illustrates this point. Plutonium-238 is currently produced in the same DOE reactors which are used to produce other nuclear materials, such as tritium or Pu-239. Since these reactors operate at capacity to meet the demand, the cost of Pu-238 is really the opportunity cost

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[3] The SP-100 choices, discussed later, make an excellent case in point. Dynamic converters offer higher efficiencies but with a mass penalty currently. To reduce mass means investing in more material development, thereby increasing the risk, cost, and time for the program. Similarly, TI promises better performance than current, proven TE converters, but pursuing TI for this Nation's only near-term reactor development effort was judged by DOD, DOE, and NASA to be too risky to meet the early 1990s schedule.

of not producing other SNM, plus the processing that occurs to convert that isotope to a useful fuel form. In allocating such production costs one must acknowledge that if Pu-238 were not produced, those production reactors and processing lines would not be eliminated; they would typically be used to produce different critical materials, and the processing lines would produce other isotopes and elements. Therefore, the determination of the cost of the materials associated with research and development of space nuclear fuels and power systems is continuously under review within DOE to assure that life-cycle costs reasonably portray the value of the national resources which have been required to produce them.

PROGRAM DECISIONS MADE AS POWER LEVELS INCREASED

Having established the technological bases for making choices about space NPS, what follows is a summary of the NPS program decisions which were made by DOE to meet the evolving user needs at increasingly higher power levels.

Sub-kilowatt isotope (static) power sources: At the lowest end of the power range, below about 2 kW_e, radioisotope heat sources driving thermoelectric converters have proven to be the best NPS for space applications on a number of counts. They are simple, very reliable, lightweight and compact, and a singularly enabling power technology for many special applications of the past three decades. At such low power, reactors are not needed and in comparison would be considered too heavy and complex. Although the overall cost to DOE for producing Pu-238, from irradiating target material to the final fuel pellet form, is quite high, the amounts of fuel involved at low power make the fuel cost tolerable. Development of these heat sources and TE conversion has been ongoing since the beginning of the space age, hence the fuels and other materials have evolved continuously, to the point where this technology is as mature and low-risk as any space technology. Heat rejection is not a problem at this power level.

Program Status: DOE has developed the General Purpose Heat Source (GPHS) RTG which uses TE and is developing a Modular Isotope Thermoelectric Generator unit (MITG), which can be stacked to achieve the power level desired. Basic data is provided in the Table 1. The GPHS-RTGs are ready for NASA's Galileo and Ulysses missions in 1989 and 1991. The new MITGs should complete development in 1992.

TABLE 1: RTG Performance Data

Type RTG	Power Output (kWt)	BOM(kWe)	EOM(kWe)	System Mass(kg)	&Vol(m3)	Specific Power (We/kg)	T.E. Effic(%)
GPHS-RTG	4500	300	285	56	0.19	5.3	6.5
GPHS-MITG	3600	300	285	39	0.14	7.7	8.0

NOTE: BOM=beginning of mission; EOM=end of mission, assumes 7 years.

Kilowatt isotope (dynamic) power sources: At some point as power requirements increase, the mass of fuel needed for a system with a converter efficiency of 6.5% becomes excessive, and the higher efficiency of the dynamic systems becomes necessary and preferred, even though such systems are more complex than TE. That point is reached at about 1-2 kW_e and extends to about 10 kW_e.

The GPHS-RTG is the state-of-the-art radioisotope fuel source, producible and well tested for safety and performance, a very low-risk technology choice. However, which dynamic energy conversion cycle is best is still an issue. Stirling has been ruled out until it is further developed (and NASA is pursuing that for higher power), but the Brayton and organic Rankine cycles are being investigated by contractors, DOE, USAF, and NASA. Both of the latter cycles were widely used for terrestrial applications and were ground tested in the 1970s for less demanding requirements than those for space applications. Extensive component, subsystem, and system testing is still needed to meet reliability goals for space applications. The radiator size at low power levels is still manageable, and it can be made integral to the power subsystem or to the entire spacecraft.

Program Status: DOE in partnership with DOD is developing Dynamic Isotope Power System (DIPS) units targeted over the range of 1-10 kW_e which can be certified for first flight to meet user needs in the mid-1990s. These units, for example at 6 kW_e, could use up to 53 kg of Pu-238 each, and have a mass of up to 800 kg and a volume of about 0.8 cubic meters. A prime contractor has been selected, and a choice of Brayton or organic Rankine cycle will be made in early 1988, after which the final design and long-life component testing can begin. The heat source is the well characterized and developed GPHS. Materials being considered for dynamic systems already meet 10-year life requirements. If even greater efficiency is sought through higher temperature, more material development and testing will be needed. For the organic Rankine cycle this means more study of the degradation of the working fluid, toluene. For the Brayton cycle, studies of bearings and possibly of special turbine materials will be necessary. Heat rejection would be via heat pipes to a flat radiator (the current design), although a cylindrical radiator remains an option which would provide more hardness to the spacecraft. Overall the program costs are higher than they would be if a single power level were the target, since current criteria and requirements determine a need to test a number of units which span the range of 1 to 10 kW_e, to insure the high reliability (>98%) components essential for such systems. (However, if current criteria and requirements are changed, it would be possible to reduce the total cost of the DIPS demonstration project.)

Multi-kilowatt reactor power sources: At some point around ten kW_e, the dynamic isotope power system becomes too large and heavy for many applications, and the advantages of reactors begin to be attractive to the spacecraft designer. There are many more technical choices to be made among reactor concepts than for isotope systems.

The cautions offered previously, on the need to be ever-mindful of program goals and schedules in selecting technologies to develop, are most applicable to the SP-100 program decisions. The SP-100 program is structured in three phases and is targeted at the power range of tens to hundreds of kW_e. Phase I, the technology assessment and advancement phase completed by DOD, DOE, and NASA in 1985, included selection of a power system concept for engineering development and ground demonstration testing during the next phase. The demonstration power level was changed by the Interagency Steering Committee (DOD, DOE, and NASA) from 300 to 100 kW_e to meet evolving user needs. Phase II will demonstrate technology readiness by 1992, will define and analyze military and civil missions for SP-100, and will pursue advanced aerospace technologies which could enhance future SP-100 designs. Phase III could begin during Phase II (if desired) to prepare the first SP-100 system for launch and use in space. Given that timetable, the trade-offs between technological advancements and program risks became acute and drove several key choices.

Representatives of DOD, DOE, and NASA investigated four candidate reactor concepts, all of which used a compact, high-temperature, fast-neutron-spectrum reactor as the heat source; the difference was in the power conversion. There were two static (in-core TI and out-of-core TE) and two dynamic (Brayton and Stirling) processes considered during two years of system studies, fuel and material testing, component evaluation, and careful review of each design concept. The following provides the rationale used in the technology selection process and the joint decision made by DOD, DOE, and NASA for technology development and demonstration of the SP-100 space reactor.

An organic Rankine cycle was not considered further because there was no outstanding technical advantage or mass incentive over other systems, since it required a larger, relatively heavier radiator, and the complications of two-phase flow had not been tested in a zero-gravity space environment.

The TI concept offers a very compact power system with higher growth potential, and the DOE continues a separate TI technology development program, the Thermionic Fuel Element (TFE) verification program, geared to the power class over 2 MW_e. The TFE program focuses on the development and fabrication of materials that can withstand the high-temperature, high-radiation environment within the reactor core for a period of 5 - 7 years, and the development and verification of analytical models which predict accurately the emitter behavior over that operating lifetime. Primary issues include ceramic insulator performance, emitter deformation, and the design of the cesium reservoir. Component testing must occur in-core to simulate properly the operating environment, since the reactor core and the power conversion system are a fully integrated unit. At the time of the selection of the SP-100 power conversion system, there had not been a long-term demonstration of an in-core TI system in a fast-reactor environment, and a satisfactory demonstration by 1991, the schedule target at the time this decision was made, was judged to be difficult. The overall program risk for SP-100 if a TI conversion system were to be chosen would have been extraordinarily high, since the reactor core for an in-core conversion system would not be well suited for use with any other power conversion system, and TI technology was not verified. In short, there would be no fallback technology. This important consideration would obviously pose an insurmountable barrier to successfully meeting potential user schedules for testing and demonstrating the technology and the space reactor system.

The dynamic processes offer much higher efficiencies, as discussed earlier. Efficiency is a key consideration at low power for the relatively higher-cost isotope fuels, since greater efficiency reduces the thermal source energy, hence the fuel requirement. Space nuclear reactor designs, on the other hand, are driven more by mass and volume constraints. Therefore,to avoid a large mass penalty for radiators operating at low heat rejection temperatures, the highest possible operating temperatures are sought. That consideration places a great demand on current dynamic systems, which are decidedly limited by state-of-the-art materials. Static systems such as TE and TI do operate at suitably higher temperatures, and in reactors there is usually enough thermal energy available to permit even a low efficiency static conversion scheme to be considered, thereby enabling the use of existing technology. As will be described below, the trade-offs among mass, volume, and reliability for dynamic systems became too costly and risky for the SP-100 development program and its demonstration schedule, so a static conversion method (TE) was selected.

During Phase I of the SP-100 program two different Stirling and Brayton systems were designed and reviewed. One system of each type was based on stainless steel operating at 950 K, and the second one used a refractory alloy, Nb-1Zr, operating at up to 1350 K. Each material has advantages and disadvantages. For example, a stainless steel system would be simplest to fabricate and test, but it would also have a low heat rejection temperature which then increases the radiator size. Refractory systems allow higher temperature operation, including rejection temperature, leading to smaller but denser radiators. Therefore, materials for dynamic reactor systems need more development to make, to test, and to insure high levels of reliability. Testing and fabricating refractory components above approximately 650 K must be done in a vacuum, thereby complicating the testing and welding of intricate interfaces. Such considerations of fabricability and testing led to the conclusion that these dynamic technologies were not going to be mature enough in time to bear fruit for SP-100. As work on these systems progresses, such conversion systems can still be used in later SP-100 designs, providing growth potential to higher power levels.

Program Status: The SP-100 program is in the second year of the six-year Phase II, which will develop and demonstrate a generic reactor design at 100 kW_e. Initial reactor design will be completed in mid-1988. Designs for the two major system-level assembly tests, the Nuclear Assembly Test (NAT) and the Integrated Assembly Test (IAT), will be completed by early 1990. Hardware for those tests will be fabricated during 1990-91, in order to complete testing and other Phase II tasks by the end of 1992. Phase III (potential flight demonstration) awaits decisions by the users.

Because the Stirling cycle offers the highest system efficiency in the long run, NASA is continuing to develop that power conversion hardware. One NASA application would be to use an SP-100 reactor subsystem coupled to a Stirling engine to provide power for the NASA space station at about 300-500 kW_e after the year 2000, or for other planned missions, such as the Lunar Base.

Megawatt reactor power sources: The SP-100 program will demonstrate scalability up to about 1000 kW_e, or one MW_e, which could provide plenty of station-keeping power for many future applications. Above that power level, however, other reactor power systems become more attractive. The U.S. NERVA program, during the 1960s and concluding in the early 1970s, was an early effort in the megawatt power range, but just as for the SNAP program, that development effort was decades ahead of potential applications. In 1985 the multi-megawatt (MMW) Space Reactor Program was established as a joint DOD-DOE development program. The primary goal of this program is to identify at least one space reactor concept by 1992 that meets the high-performance, MMW power requirements of advanced defense applications, with all basic feasibility issues resolved. Civil applications, including nuclear-electric propulsion, will be clarified during this period as well. Power requirements are expected to range from tens to hundreds of MW_e for burst and perhaps continuous power applications.

The MMW Space Reactor Program is a multiple-phase program. Phase I, building on earlier definition, concept, and requirements studies, will result in the selection, evaluation, and conceptual design of six selected concepts and the identification of key technology issues for each concept. Phase II will analyze, design, and configure in detail the most promising two or three concepts from Phase I and resolve all corresponding technology feasibility issues for each candidate concept. DOD and DOE will then decide by the end of 1992 whether to proceed with any of the Phase II MMW space reactor technologies. If such a decision were made, a ground engineering system would be built and tested during Phase III through the mid to late 1990s; flight demonstration work could be conducted as Phase IV from the late 1990s to the turn of the century.

In March 1987, DOE completed preliminary work on the definition of the MMW reactor system concepts and requirements. Three distinct power system categories were selected to cover the broad range of power required by the many potential MMW reactor space applications. Category I systems concepts are primarily for short-duration, burst-type, open-cycle systems producing tens of MW_e in which effluents may be discharged to space during power system operation. Category II systems also must provide tens of MW_e for short-duration bursts, but with no effluents permitted (i.e., the system is closed). Category II reactor systems must have an integrated minimum life of one year, and must meet burst power requirements continuously or at least recharge to that level within a single orbit. Although Category II reactors will most likely be heavier than Category I designs, they may be essential if effluents are deemed intolerable and a continuous post-burst power or recharge capability is necessary for a given application. Category III concepts are geared toward far-term requirements, would provide hundreds of MW_e of burst power, and could be open or closed systems.

For the MMW reactor program to be successful, space reactor power sub-systems must be developed which are significantly lighter, more compact, and capable of operating at higher temperatures, in higher radiation environments, and at greater efficiencies. These substantial advancements in technologies and power levels will be a significant challenge, the largest of which will be reducing the total overall mass to levels that make launching MMW systems affordable. To that end parallel technology development efforts are already under way to develop and test new fuel forms and fuel fabrication techniques, and to conduct compatibility and performance testing of candidate refractory materials.

Program Status: Results of the initial evaluations were incorporated into a Phase I Request for Proposal (RFP) issued in July, 1987, to solicit the best concepts from industry. In late January 1988, six concepts were selected, and the contractors are expected to begin Phase I as early as April or May 1988. For each MMW reactor concept there will be preliminary system concept evaluations and analyses, trade-off studies, identification of technology feasibility issues, conceptual design configurations, and Phase II development proposals, all to be completed by the middle of 1989. Two or three concepts will advance to Phase II, during which will occur more detailed analyses and evaluations of the MMW reactor concepts, preliminary safety assessments, selection of specific components, resolution of technology feasibility issues, and planning the Phase III development and ground system engineering system. One concept will then advance for consideration by DOD and DOE for Phase III and Phase IV development.

CONCLUSIONS

1. No single nuclear power source can span the wide range of power requirements of the variety of space applications now contemplated. Isotope systems are best suited for low power, for most applications below 10 kW_e, while nuclear reactor systems are more suitable above that general power level and have growth potential into the thousands of kW_e.

2. There is no clear-cut choice between dynamic and static conversion processes; each application brings different considerations of power, mass, volume, temperature, material development, reliability, and program goals and risks to bear on the choice of dynamic versus static power conversion. Dynamic power conversion methods offer two to four times the efficiency of static methods, but can add some complexities to other aspects of spacecraft design (e.g., the need to compensate for torque or jitter). For space nuclear power system designs the choices of heat source, power conversion method, and heat rejection system are highly interdependent. As in most other engineering challenges, what is optimum at the subsystem level does not necessarily lead to an optimum overall system.

3. Stringent spacecraft mass and volume restrictions force nuclear power system designers to develop systems with the best power-to-mass ratio possible. To use the lightest materials may force designers to use sub-systems which may be less than optimal. For instance, the most efficient

thermodynamic energy conversion systems are those which operate through the largest temperature drop at a given high temperature. However, there is also utility in using the highest heat rejection temperature possible, since that yields great mass and volume payoffs at the higher power levels. Combining high-temperature operations at minimum mass requires extending the state-of-the-art, through significant material development time, extensive reliability testing, and the attendant high costs and program risks. There usually is not much schedule or cost latitude in such programs, consequently the technology decisions tend to be conservative.

4. The most efficient progression of space nuclear power systems from lowest power to higher power has been exhaustively studied and is currently judged to be: isotope-static, isotope-dynamic, reactor-static, and reactor-dynamic. Current DOE space nuclear power system programs are using and developing each of these source-converter combinations. These programs are building upon over 30 years of spacecraft material development and power source design experience. If supported with appropriate resources, these space NPS will be developed in time to meet the Nation's ever-demanding space requirements now and into the next century.

5. Nuclear power sources may cost more per unit than other types of space power systems, but due to their intrinsic hardness may allow fewer satellites in a constellation, thereby cutting the launch and satellite costs needed to attain a given system capability at the required survivability level. This intrinsic hardness stems from their designs, which already include structural containers and perhaps shields, plus control components already hardened against the ionizing radiation of the nuclear power source. Nuclear powered spacecraft are more compact, therefore less detectable and more maneuverable, than non-nuclear power sources.

6. Spacecraft have the potential to tumble, lose their continuous communication with Earth stations, and perhaps not be able to receive corrective signals before their batteries are depleted. Space nuclear power sources could continue (isotopes unquestionably, and reactors consistent with fail-safe design criteria) to function reliably, independent of orientation and for sufficiently long periods, thereby enabling corrective actions directed from the ground to dampen the effects of that tumbling and possibly preventing the loss of the satellite.

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APPENDIX to DOE White Paper: "Important Technology Considerations for Space Nuclear Power Systems"

GENERAL FEATURES OF SPACE NUCLEAR POWER SYSTEMS

Introduction: This appendix provides basic information on the two fundamentally different types of nuclear energy sources (radioisotope decay heat and nuclear fission energy), discusses the differences between static and dynamic power conversion schemes which might be used in space, provides the details on those static and dynamic processes which show the most promise for space nuclear power systems, and concludes with a discussion of heat rejection considerations, which can play a dominant role at the higher power levels.

Heat Sources: The basic principles behind the isotope and reactor systems are discussed below.

Radioisotope heat sources rely on the natural radioactive decay of certain materials to generate heat which can then be converted to electricity (thus far using thermoelectrics, described later). Of over 2000 possible radioisotope candidates, Pu-238 by far offers the best combination of half-life (87.6 years) and specific power (560 W_t/kg or 1.79 kg/kW_t). Although Pu-238 fuel cost can be quite high,[4] it can still be economical considering its mission-enabling attributes and demonstrated long mission life. Once the isotope fuel is manufactured it produces heat continuously, and although a radiation risk can be postulated, experience and rigorous testing programs show that the risk can be minimized or essentially eliminated, even under extreme accident conditions. Nuclear shielding is provided simply by the heat resistant cladding and structural material, which also acts as a protective barrier preventing the release of Pu-238. With no moving parts and their continuous energy production, isotope fuels intrinsically are very reliable heat sources.

Nuclear reactors operate using the fission process whereby neutrons induce the splitting of fissionable nuclei. This process releases considerable energy, most in the form of heat, some in the form of gamma and beta radiation, and more neutrons (which are crucial to sustaining the reaction). If enough fuel and other materials are assembled in an appropriate geometry, a chain reaction can be sustained, and energy can be released continuously over a wide range of power levels. Reactors may have few or many moving parts, as discussed later, but usually a coolant flow is involved, either to transfer the fission energy to the conversion system or to transfer waste heat to the radiators, or both. Since the control of reactors is much more complicated, and the choice of fuel forms is wider than for RTGs, there are more significant technology challenges to consider and overcome in space nuclear reactors versus isotope power sources.

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[4] See the comments on cost on p. 14.

Reactors do not present a potential radiation hazard until enough fissions have occurred to build up highly radioactive fission products, so the strategy is to defer full power operations until a stable orbit is reached. During operation significant shield mass is required to protect spacecraft components and any crew. At end-of-mission the spent reactor must be positioned carefully to eliminate hazards to future space operations. The plan is to place spent reactors in an orbit high enough to allow sufficient time for the radioactive fission products which have built up to decay to acceptable levels before any reentry.

Power Conversion Options: There are two basic categories, static and dynamic, to describe the mechanisms available to convert the nuclear energy, whether from isotope decay or fission of the nucleus, to electrical energy which the spacecraft requires. Static methods discussed here are Thermoelectrics (TE) and Thermionics (TI); dynamic methods covered are the Rankine, Brayton, and the Stirling cycles. (Other direct energy conversion schemes, such as Alkali Metal TE Conversion (AMTEC), Hydrogen Thermo Electrochemical Conversion (HYTEC), and Magnetohydrodynamics (MHD) are not yet considered to be sufficiently advanced to be considered viable space power conversion options for the near term. However, these schemes hold sufficient promise that they are being pursued by universities, the national laboratories, and the private sector. DOE continues to encourage and monitor research and development progress on all such technologies which may be applicable to space nuclear power systems.)

In general, for any ideal energy conversion cycle, the maximum theoretical efficiency is governed by the Carnot cycle efficiency expression[5]

Maximum Thermodynamic Cycle Efficiency = (TH-TL)/TH

where TH and TL refer to the highest and lowest temperatures in the cycle. Therefore, greater efficiency is obtained through higher peak temperatures if the low temperature is fixed; similarly, for a given peak system temperature, the lowest heat rejection temperature yields the greatest cycle efficiency. Therefore, operating temperatures are of vital importance as power system designers evaluate alternative power conversion options.

Static power converters operate with no moving parts, hence they offer high reliability, once the physical properties of the materials chosen are well

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[5] This relationship serves only as a first-order guide to assessing real devices. It applies directly only to thermodynamic cycles, in which a working fluid undergoes a special set of reversible thermodynamic processes which return the fluid to the initial state point, completing the "cycle". The static processes discussed here use no working fluids, and the dynamic processes are highly irreversible, or "non-ideal". For real devices, the concept of available energy is often useful, but that concept is related to Carnot efficiency, and it enables a comparison of actual efficiency versus that which is theoretically attainable.

characterized through extensive testing under realistic operating conditions. That is the constant materials challenge to researchers and developers. Having no moving parts means there is no rotating or reciprocating machinery which can break down (although static components may also fail), and there are no additional vibrations or unbalanced spacecraft torques induced by such static power systems. Furthermore, the dozens to thousands of small elements which comprise such converters (0.5 W_t per unicouple and potentially 2 to 2.5 W_t per multi-couple) provide excellent redundancy and avoid single point failure modes (but could have common mode failure), and that also tends to improve reliability. The chief drawback to these processes is their relatively low efficiencies; that puts an upper limit to their usefulness, particularly when combined with a higher-cost isotope fuel.

The two static power conversion candidates currently are thermoelectrics (TE) and thermionics (TI). Thermoelectrics use the same principle as the thermocouple, whereas thermionics operate at a much higher temperature to "bake" electrons off an emitter. Both systems use low-voltage cells, usually less than one volt each, connected in parallel-series circuits to provide the required operating voltage. Both TE and TI converters present certain technology challenges as described below.

The basic principle of thermoelectricity, discovered in 1826 by Thomas Johann Seebeck, is that an electromotive force (emf) or voltage is produced from temperature differences in two dissimilar metals where they are joined together to form a circuit. This Seebeck effect results from the diffusion of electrons across the junction of the two different metals. Semiconductor materials such as silicon-germanium offer better conversion efficiency than metals. Present TE technology operates near 1300K and achieves 6.5% efficiency; advances under way show promise for about 10% conversion efficiency by 1993. All space RTGs to date have used TE, as has the only U.S. space reactor flown (SNAP-10A), and the SP-100 reactor will use this proven and well characterized technology.

Thermionic conversion offers somewhat higher efficiencies (10-12%) than TE and operates at much higher temperatures, typically near 1850K. In this process the high-temperature emitter surface is separated by a narrow gap from a parallel collector surface which is held at a lower temperature. The emitter temperature must be high enough to give its electrons sufficient energy to escape from the surface and to flow across the gap to the collector. When the emitter and collector are connected through a load impedance, the electron flow results in an electrical current, generating a voltage across the cell. Several reactor concepts are based on the use of TI. The main technology challenge of TI is to develop materials which can maintain that gap geometry, which is critical to this approach, throughout many years of operation in that high-temperature and high-radiation environment.

Dynamic conversion processes use rotating or reciprocating machinery to improve the thermodynamic efficiency of the power conversion system to 20% - 30%. Better efficiency means that for the same power output the thermal energy and the waste heat are considerably lower, offering possible reductions in system cost and mass per kilowatt electric (kW_e) provided. At certain (low) power levels, it may even be a simpler system. However, adding such machinery often increases the piping and the controls, thereby complicating the reliability challenges that the system design, the materials development, and the testing programs must overcome. An important trade-off in optimizing the design of dynamic systems is between oversizing and increasing the number of engines needed to assure a given reliability for the system. The designer may choose to build in excess capacity in each loop and add more loops, with possible weight penalties, to meet the contingency of having one of the loops fail. Although it is possible to have a reliable dynamic system, it can be difficult to establish high enough reliability levels, for long-term power operation (several years) with high confidence. This results in a tradeoff between accepting higher reliability risk versus undergoing a lengthly and more costly testing program.

Three dynamic processes have received the most attention for space NPS; they are the Rankine, Brayton, and Stirling cycles. The Rankine and Brayton systems use rotating turbomachinery while the Stirling engine uses linear oscillators. (The linear motion avoids the need to counter the torques of rotating equipment, but still contributes to vibration.) In both the Rankine and Brayton cycles, a working fluid is heated and circulated through an integral turbine-alternator-pump/compressor assembly. (Development of suitable space-worthy bearings will be a challenge.) The fluid energy drives the turbine, which drives the alternator to produce electricity. The Rankine/Brayton working fluid next passes through a regenerator/recuperator and a condenser/gas cooler to reject the waste heat, and then is repressurized in the pump/compressor before returning to the heat source. The regenerator/ recuperator captures a portion of the waste heat to preheat the fluid before it returns to the heat source, thereby increasing overall cycle efficiency.

The development of organic Rankine cycles for space power (solar applications) dates back to 1960. The Rankine engine uses a condensable vapor such as toluene, an organic compound, hence the term "organic Rankine". Two-phased flow is involved. Typically, the liquid working fluid enters the vaporizer, where it is heated, and enters the turbine as a gas. That low energy vapor which does not condense in the recuperator or condenser must pass through a special fluid management process to insure that only liquid passes through the pump. In high pressure systems now being considered, two-phased flow occurs chiefly in the condenser. The principal advantage of the toluene Rankine cycle for space power is its component reliability due to its low operating temperature. The chief disadvantages of such Rankine systems are their relative complexity and the low heat rejection temperature, leading to larger, heavier radiators.

Brayton space power systems have been under development since 1962. The Brayton cycle is the basis for the familiar jet engine (which is an open-cycle version since the working fluid is exhausted). In a closed cycle a working fluid (which remains a gas throughout) which is used for space applications is a helium-xenon mixture. Helium has good heat transfer characteristics, and xenon's high molecular weight improves turbomachinery performance, reducing the number of turbine stages needed. The principal advantage of the Brayton cycle for space power is its simple design and higher efficiency, about 25% to

30%. Chief **disadvantages** of the Brayton cycle when used with reactors is the need to use refractory alloys, which tend to be brittle, in order to operate at the highest possible temperatures, and the requirement for batteries to drive the compressor for engine start-up.

Engines based on the Stirling cycle are attractive because they theoretically (See footnote on p. 24.) offer efficiencies as high as the most efficient ideal cycle, the Carnot cycle, between two temperatures, they use linear motion, and they do not have the start-up requirements that Brayton cycles do, as mentioned above. However, the linear motion is inherently low speed and the device therefore is heavier. Stirling engines have been under development for many years and have recently been considered for space power applications. Their principal features are an integral gas heat exchanger for heating and cooling and a free piston working as a linear alternator. The principal **advantages** of the Stirling cycle for space power are its potentially smaller size (at low power applications) and its high efficiency (30%) even at low temperatures. The chief **disadvantages** of the Stirling engine for space application are its lack of development compared to the other systems, its higher mass, the need to use brittle refractory materials, and the large liquid-metal-to-gas heat exchangers.

Finally, combined static-dynamic systems are possible by adding a TE topping or bottoming cycle to the heat source, to extract as much electrical energy as possible, although the primary contribution is made by the working fluid and machinery. These schemes could improve overall cycle efficiency by several percentage points. A topping approach may be attractive for organic Rankine cycles; and the bottoming approach might be useful for open systems, which do not use radiators.

<u>Heat Rejection Considerations</u>: Waste energy is rejected to space by thermal radiation. That process is governed by the Stefan-Boltzmann law, which states that the energy radiated per unit area varies directly with the **fourth** power of the radiation temperature. Total radiator area scales directly to the power to be rejected. As a result, there is a direct trade-off between cycle efficiency, which improves with lower heat rejection temperatures, and radiator size, which increases about ten-fold for a temperature decrease of from 1000K to 600K at a fixed power level. Therefore, as power increases the mass penalty for the radiators may force designers to choose a less efficient cycle and more expensive materials to achieve higher radiation temperatures, which cuts radiator mass.

Current RTGs, which use the general purpose heat source (GPHS), produce 4.4 kilowatts thermal (kW_t) to provide 0.3 kW_e, hence about 4.1 kW_t (or 93%) must be rejected. For this low amount of energy, the RTG radiator mass and size are tolerable, even though the radiator temperature is quite low, 566K. Using a dynamic conversion process with an isotope heat source extends the output power range to perhaps 10 kW_e, which at a 20% efficiency implies a heat rejection burden of 40 kW_t (or 80%). Dynamic components tend to limit the peak operating temperature, leading to lower heat rejection temperatures, hence to greater radiator sizes.

Similarly, reactors may use static or dynamic conversion processes, and since they may involve orders of magnitude more power output, their heat rejection requirements can quickly become a dominant consideration in the design process. For example, a reactor producing 100 kW_e even at 25% efficiency is rejecting 300 kW_t; using thermoelectrics (7%) it would be rejecting about 1300 kW_t. For spacecraft the mass penalty such heat rejection hardware portends is large. Therefore, this part of the power cycle can be just as important as heat source and power conversion considerations in selecting the best technology for space nuclear power systems.

Another heat rejection option is to exhaust the working fluid directly to space, eliminating the radiator completely. This approach is particularly attractive at high power (i.e., multi-MW_e) over short periods and is being considered for burst power applications. The problems with this approach are the need to store enough working fluid (usually cryogenic hydrogen) for the burst mode and the effluents which such open cycles produce. The storage is manageable, but the effluents (and their possible interaction with gases from other sources) could pose significant operational constraints for certain spacecraft applications.

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