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NUCLEAR SCIENCE

Usefulness of Space Power Research to Ground-Based Nuclear Reactor Systems

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The Honorable Robert A. Roe
Chairman, Committee on Science,
Space and Technology
House of Representatives

The Honorable Manuel Lujan, Jr.
Ranking Minority Member
Committee on Science, Space
and Technology
House of Representatives

As requested, we are providing information on the usefulness of the Department of Energy's space nuclear reactor research to developers of advanced terrestrial (ground-based) nuclear power systems. Specifically, this report presents the results of our survey of nuclear systems experts regarding the usefulness of space nuclear power systems technology for the development of advanced terrestrial reactor systems and a discussion of possible challenges to the actual transfer of space reactor technology.

We are sending copies of this report to appropriate congressional committees; the Secretary of Energy; the Secretary of Defense; the Administrator, National Aeronautics and Space Administration; and the Director, Office of Management and Budget. We will also make copies available to others upon request.

Major contributors to this report are listed in appendix V.

Sincerely yours,

Keith O. Fultz

Keith O. Fultz
Senior Associate Director

Executive Summary

Purpose

In the mid-1980s, the Department of Energy (DOE) adjusted its nuclear reactor research and development efforts to meet the growing need for nuclear power in potential civil and military space missions, including the Strategic Defense Initiative (SDI). In doing so, DOE officials stated that some results of their space power systems research may be useful to the development of civilian terrestrial (ground-based) reactors. However, others are more skeptical about the potential usefulness.

To learn if DOE's space nuclear power systems research will also benefit the development of civilian terrestrial nuclear power systems, the then Chairman and the current Ranking Minority Member, House Committee on Science, Space and Technology, requested that GAO obtain information on the potential for related technology transfer. To do this, GAO queried experts in nuclear power and related technologies on the potential usefulness of space nuclear power systems research to the development of terrestrial nuclear power systems for civilian use.

Background

DOE is participating in two programs to research and develop technology for space nuclear power systems. The SP-100 Space Power Program, which was initiated in 1983, is a joint effort of DOE, the Department of Defense's (DOD) SDI Organization, and the National Aeronautics and Space Administration (NASA) to develop and demonstrate technology capable of providing up to 1 megawatt (1,000 kilowatts) of electric power for potential future civilian and defense space missions. The Multimegawatt Space Nuclear Power Program, which is funded by DOE and the SDI Organization, was initiated in 1985 to specifically develop and demonstrate a nuclear power system that will meet SDI's requirements for electric power ranging from tens to hundreds of megawatts. SDI is a research program to develop technologies needed for a defense against a ballistic missile attack.

Results in Brief

GAO's survey of 139 experts in space and terrestrial nuclear power systems shows that the knowledge gained from much of DOE's space power systems research is expected to be useful to advanced liquid metal- and gas-cooled terrestrial reactor development. Furthermore, knowledge gained in generic areas, such as reactor instrumentation and control, may also be useful for improving water-cooled systems. However, some potential benefits may have limited applicability. For example, there are design differences in space reactor power systems and terrestrial reactor systems that would not allow direct one-for-one transfer of hardware component designs. In addition, the extent to which some potential benefits will be realized will depend on how various constraints to using this technology, such as restrictions on information dissemination, are handled.

Principal Findings

Usefulness of Space Power Research to Terrestrial Reactors

Experts surveyed identified various areas in which space reactor systems technology is expected to be useful for the development of advanced terrestrial nuclear reactors. Most of these experts believe that knowledge gained from the following research areas may be useful: fuel and fuel systems, materials, heat transport, instrumentation, control methodology, safety, reliability, and modeling and analysis techniques. For example, most of the respondents said that knowledge gained in nuclear power system instrumentation and control is expected to be very useful for improving the safety and efficiency of both future and existing terrestrial systems.

However, survey respondents also identified limitations to the technology that can be transferred. They cautioned that while space power research knowledge can be useful to terrestrial reactor development, little one-for-one transfer of space power hardware component designs is likely because of different design requirements. In addition, space power technology is less likely to benefit existing commercial reactors, since these are water-cooled reactors and space power concepts involve liquid metal- and gas-cooled systems. The respondents also stated that the SP-100 will be less likely than the more advanced Multimegawatt program to produce technology that will be useful to designers of terrestrial reactors.

Challenges to Achieving Successful Transfer of Technology

The respondents to the survey also identified a number of constraints that will affect the extent to which space power technology is successfully transferred. For example, DOE plans to classify key information from the space nuclear power systems research programs as restricted or national security data. In addition, institutional problems —including industry regulatory and licensing issues, financial and economic concerns, and public perception problems—may discourage investors and developers from accepting and using new technology. Finally, the extent of transfer will depend on the continuance of a space power research program to develop the new technology and the maintenance of a viable advanced terrestrial reactor program to accept the technology. Research and development supporting both programs has been curtailed or delayed because of reduced funding levels.

Recommendations

This report provides information on the potential use of space power systems technology by developers of civilian terrestrial nuclear power systems. It contains no recommendations.

Agency Comments

GAO requested comments on a draft of this report from DOE, DOD, and NASA. The three organizations generally concurred with the report's contents. (See ch. 1 and apps. III and IV.)

Contents

Figures

Abbreviations

DOD	Department of Defense
DOE	Department of Energy
GAO	General Accounting Office
MMW	Multimegawatt Space Nuclear Power Program
NASA	National Aeronautics and Space Administration
RCED	Resources, Community, and Economic Development Division
R&D	research and development
SDI	Strategic Defense Initiative
SDIO	Strategic Defense Initiative Organization
SP-100	SP-100 Space Power Program

Introduction

Nuclear power is one of the key sources of this nation's energy supply. Until recently, the Department of Energy (DOE) concentrated its nuclear reactor research and development (R&D) efforts on improving the efficiency of terrestrial (ground-based) reactors for civilian use. However, in the mid-1980s, DOE adjusted its advanced reactor R&D efforts to meet an emerging need for large amounts of electrical power in potential civilian and defense space missions. DOE currently has two space nuclear reactor programs to develop the technology for producing electrical power in the hundreds-of-kilowatt and multimegawatt ranges.

Although DOE's near-term efforts will focus primarily on supplying nuclear reactor power technology for the Department of Defense's (DOD) Strategic Defense Initiative (SDI)[1] and potential civil space applications, DOE has told the Congress that some of the technology developed for space nuclear power systems will also have applicability to future civilian terrestrial nuclear power systems. For example, DOE believes that the knowledge gained from developing special fuels, high-temperature materials, and control systems for space reactors will be useful in developing advanced terrestrial reactors. However, other witnesses in congressional hearings, some scientists in media interviews, and other DOE officials have expressed skepticism about the potential for this technology transfer. In addition, DOE has stressed that the primary purpose of space power research is to support potential space missions, and while auxiliary benefits are desirable, according to DOE, "the absence of any such auxiliary benefits should not be construed as reason to not conduct space nuclear power research."

The House Committee on Science, Space and Technology, while supportive of the space reactor program, wants to know if knowledge gained from DOE's space power R&D will be useful for terrestrial reactor development. In a May 20, 1986, letter, the then Chairman and the current Ranking Minority Member of the Committee requested that GAO obtain opinions from experts in nuclear reactor and related technologies concerning the potential for technology transfer from DOE's space reactor R&D programs to its terrestrial reactor R&D program. This was one of four space power program issues that the Committee wanted us to examine; the other three were addressed in a report issued in December 1987.[2]

[1]SDI is a DOD research program to develop technology needed for a defense against a ballistic missile attack.

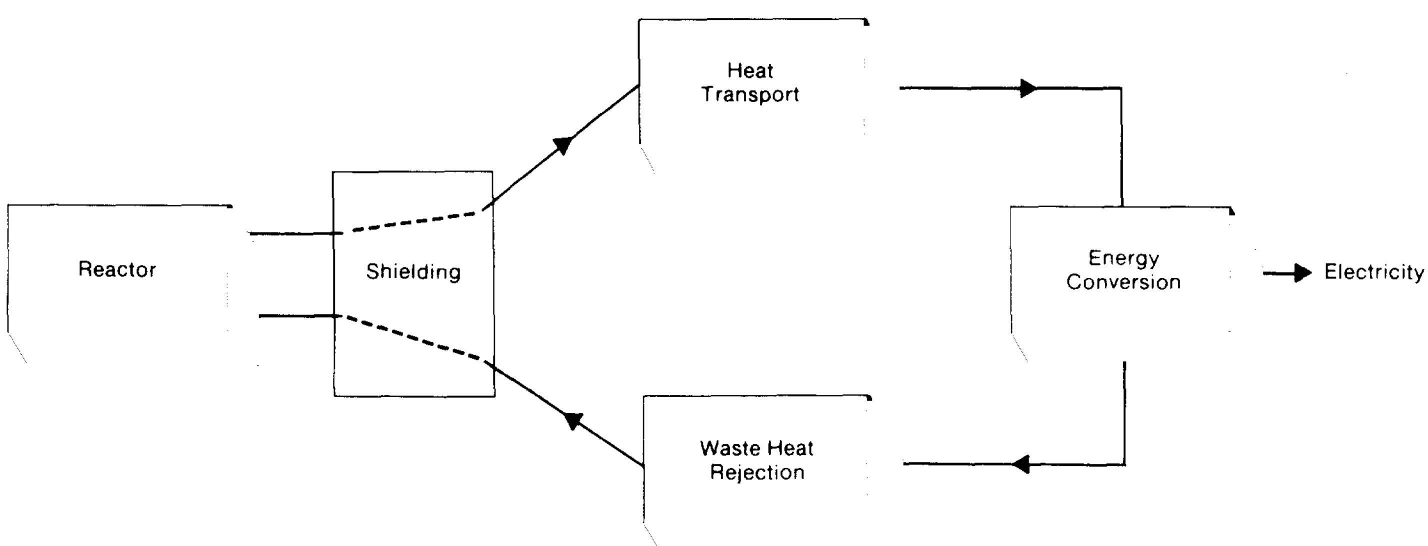
[2]Nuclear Science: Challenges Facing Space Reactor Power Systems Development (GAO/RCED-88-23, Dec. 2, 1987).

This chapter provides background information on nuclear power systems and DOE's two space power systems programs. The chapter also contains information on the objectives, scope, and methodology used in our study.

Nuclear Power Systems

Nuclear power systems, like more conventional nonnuclear power sources, generate heat energy that is converted to electric power. All nuclear reactor power systems consist of several subsystems: (1) a nuclear reactor, (2) a heat transport system, (3) an energy conversion subsystem, (4) a waste heat rejection subsystem, and (5) radiation shielding. (See fig. 1.1.)

Figure 1.1: Diagram of a Nuclear Power System



Nuclear reactors use the fissioning of uranium to generate heat. To convert this heat to electricity, a fluid (coolant) passes through the reactor core, absorbs the heat, and is pumped to an energy converter, where the heat is transformed into electricity. Not all of the heat that is produced in the reactor can be transformed into electricity. Excess heat must be rejected from the system. For example, space reactors use elaborate, lightweight heat rejection systems to radiate residual waste heat into space. Shielding made of concrete and other materials for terrestrial reactors or lightweight shielding in the case of space reactors provides protection to people and equipment from radiation generated during the fission process.

Space Power Systems

The difficulties of providing large amounts of nuclear power in space demand that existing technologies be advanced and that new technologies be explored and developed for nuclear fuels and fuel systems, materials, heat transport, energy conversion, instrumentation, and control. These technologies must enable nuclear space power systems to operate reliably, safely, autonomously, and continuously, with high performance characteristics for long periods of time—10 years for some missions. In addition, space power systems that are expected to be used to support defense activities, such as SDI, must be survivable against enemy attack. DOE is currently working on two space power systems it hopes will meet the rigors of operating in space. Both of DOE's nuclear space power programs—the SP-100 Space Power Program (SP-100) and the Multimegawatt Space Nuclear Power Program (MMW)—are building upon the vast knowledge gained from historical terrestrial nuclear reactor R&D efforts and knowledge gained from previous space reactor efforts during the period between the 1950s and the early 1970s.

DOE's SP-100, which was started in 1983, is a joint effort of DOE, DOD's Strategic Defense Initiative Organization (SDIO), and the National Aeronautics and Space Administration (NASA) to develop and demonstrate a low-weight nuclear power system providing tens and hundreds of kilowatts of electric power. The concept selected includes a small (about 1 cubic foot) lithium metal-cooled reactor to generate heat, which is converted directly into electricity through use of static (motionless) thermoelectric cells made of silicon-germanium. Special fuel, materials, subsystems, and components are expected to allow the SP-100 system to operate at required high temperatures with reliability greater than 95 percent over the 10-year operational lifetime of the system. Currently, DOE is ground-testing an SP-100 system that supporters hope will be flight-tested in the mid-1990s.

The objective of MMW, initiated in 1985, is to identify at least one space nuclear power system concept by 1992 that, alone or in combination with a nonnuclear power system, meets SDI power requirements. The SDI mission requires a wide range of power. For example, preliminary power estimates include (1) tens of kilowatts up to a few megawatts of electric power for continuous mode operation (7-year lifetime), (2) up to 20 megawatts for alert mode operation (intermittent power usage), and (3) 100 to 1,000 megawatts for burst mode operation (200 to 2,000 seconds). DOE's MMW must make technological advancements far beyond those expected from SP-100 in order to meet SDI program objectives. The MMW system's need for high operating efficiencies combined with high operating temperatures (2,000 degrees to 3,500 degrees Fahrenheit) requires enhancements and advancements in reactor fuels, materials and components, thermal management, energy conversion and storage, safety, shielding, instrumentation, and control.

DOE has contracted with private industry to develop conceptual designs for the MMW system. Starting in late 1989, DOE will select a number of these designs for further development. Power systems concepts being studied for possible use include both gas- and metal-cooled reactors and static and dynamic (rotating equipment, i.e., turbines) energy conversion systems.

Terrestrial Nuclear Power Systems

Terrestrial nuclear power systems are named or classified by the type of coolant used. The U.S. commercial power community almost exclusively uses water-cooled reactors.[3] DOE has a research and development program involving water-cooled reactors and an advanced civilian reactor research and development program involving gas- and liquid metal-cooled reactors. Research in metal- and gas-cooled reactors may form the basis for future generations of commercial reactors. The objective of these DOE programs is to research, develop, and demonstrate technology that will be useful for improving and advancing the civilian use of nuclear power.

Objectives, Scope, and Methodology

This report is in response to a request by the former Chairman and the current Ranking Minority Member of the House Committee on Science, Space and Technology to obtain information on the potential for transfer of technology developed in DOE's space power system programs. The request, modified in subsequent meetings, asked that we query experts in nuclear power and related technologies on the potential usefulness of space nuclear power systems research to the development of terrestrial nuclear power systems for civilian use.

[3]A reactor was built in 1979 in Fort St. Vrain, Colorado, to demonstrate the high-temperature, gas-cooled concept. However, because of operational problems, it has operated intermittently for a total of about 38 months in the past 8 years. The other 97 operating commercial nuclear power plants are water-cooled.

To answer this request, we (1) identified a frame of reference for comparing nuclear space power systems and nuclear terrestrial power systems, (2) identified a group of experts to query, (3) developed a data collection instrument to gather information from these experts, and (4) analyzed the results.

We selected 11 major systems and components of space nuclear power systems as a frame of reference in making our inquiries about the potential usefulness of space reactor research to terrestrial reactor development. These 11 major systems and components are also common to all terrestrial nuclear reactor power systems: fuel and fuel systems, materials, heat transport, energy conversion, instrumentation, control methodology, safety, reliability, fabrication, facilities, and modeling and analysis.

To identify a group of experts to query, we requested DOE, DOD, NASA, nuclear industry associations, and nuclear engineering departments at selected universities to recommend individuals with expert knowledge in 1 or more of the 11 major systems and components. We then called these experts to confirm their area of expertise and asked them to recommend other individuals with appropriate expertise. As a result, we identified 139 experts for our survey.

We cannot say that the results of our questionnaire survey represent the opinions of the entire universe of nuclear and related systems experts. We do not know the size of this universe. In addition, gradations and stratifications of expertise within this universe make a statistical projection of the results extremely difficult. However, we used a consultant to (1) review the list of prospective respondents to ensure a proper mix of expertise and to ensure that both the terrestrial reactor community and the space reactor community were fairly represented and (2) help develop data collection questionnaires and analyze responses. The consultant's analysis of the experts' responses to our questionnaires is reflected primarily in appendix I.

We used two questionnaires to survey the opinions of the 139 experts. The first questionnaire was open-ended, permitting spontaneous, somewhat unguided responses. We asked the experts to comment on the potential for research advances in each of the 11 major component and system areas to produce technology that might be useful to terrestrial reactor development. We also asked the experts to specify the subcomponents and subsystems within major areas that would be useful to terrestrial power systems. We asked these experts to use a progressive scale to rate this usefulness, from little or no usefulness to somewhat, moderately, very, or extremely useful. In addition, we asked the experts to identify situations, policies, and processes that they believe may facilitate or interfere with actual transfer of space power systems technology. We analyzed the responses to this first questionnaire and then developed a second similar, but more detailed and specific, questionnaire with close-ended quantifiable responses. We used mainly the responses to this final questionnaire to report the quantitative results of our survey of these experts (mainly ch. 2). The narrative responses to our first questionnaire were also used to expand on or clarify these quantitative responses where necessary (mainly ch. 3). In the text of our report, we refer to those responding to our survey as "those surveyed." (See app. II for the results of our second questionnaire.)

We also visited DOE, SDIO, and NASA headquarters and DOE field operations offices and facilities to obtain additional information concerning the potential for the transfer of space power systems technology, the processes and procedures for technology transfer, and possible constraints to technology transfer. We visited DOE's San Francisco Operations Office in Oakland, California; the Multimegawatt Project Integration Office at DOE's Idaho Operations Office in Idaho Falls, Idaho; Argonne National Laboratory-West in Idaho Falls, Idaho; the Oak Ridge National Laboratory in Oak Ridge, Tennessee; and DOE's Office of Scientific and Technical Information in Oak Ridge, Tennessee. In addition, we attended the fourth and fifth Symposia on Space Nuclear Power Systems in Albuquerque, New Mexico. Because of the limited scope of our study, we did not review any of the internal controls used by DOE's management to monitor its programs and functions.

Two other GAO reports contain information that has a bearing on this study. As mentioned earlier, this is the second report that we have produced for the Committee on DOE's space power system programs. The first, Nuclear Science: Challenges Facing Space Reactor Power Systems Development (GAO/RCED-88-23, Dec. 2, 1987), described the origin, organization, administration, and technical and funding challenges of SP-100 and MMW. Our report Energy R&D: Changes in Federal Funding Criteria and Industry Response (GAO/RCED-87-26, Feb. 9, 1987) also contains information bearing on the potential use of space reactor technology by civilian commercial reactors. This study noted the following:

- DOE's R&D efforts have shifted from satisfying primarily the needs of the civilian sector for advanced reactors to meeting the space and terrestrial power needs for the military. This shift has led to sharp reductions in long-term civilian R&D.

- The private sector has also reoriented much of its R&D efforts away from advanced reactors to meet near-term objectives, such as the economic improvement of the present light-water reactor plants.
- Representatives of major reactor vendors are pessimistic that much of the nuclear power R&D being done for the military will be applicable to civilian reactors.

We conducted our study between June 1987 and May 1988 in accordance with generally accepted government auditing standards.

We requested comments from DOE, DOD, and NASA on a draft of this report. All three organizations concurred with the report's contents. DOE, in particular, stated, "Overall, the report is well done and we concur with its contents." The written comments from DOE and DOD are presented in appendixes III and IV, respectively. NASA's comments were provided orally. Minor technical corrections and suggested editorial changes have been incorporated where appropriate.

Space Nuclear Power Research Expected to Be Useful to Designers of Terrestrial Reactor Systems

According to our survey results, technology gained from DOE's SP-100 and MMW is generally expected to be useful to those planning future advanced terrestrial nuclear power systems and those considering certain modifications to enhance the efficiency and safety of existing systems. The opinions of the respondents varied slightly, depending on their affiliation or nonaffiliation with the space power programs and/or their role in the nuclear industry.

Our survey also identified some limitations to the applicability of space power research in the 11 major system and component areas we examined. For example, differences in design requirements may limit terrestrial use of some designs for space power hardware components; space power research may have little applicability for water-cooled terrestrial reactors, except for advances in instrumentation and controls; and SP-100 is not as likely as MMW to produce technology useful to terrestrial reactor development.

This chapter discusses the views of the experts we surveyed on (1) the applicability of space power research to terrestrial reactor systems designs and (2) some of the limitations of space power research.

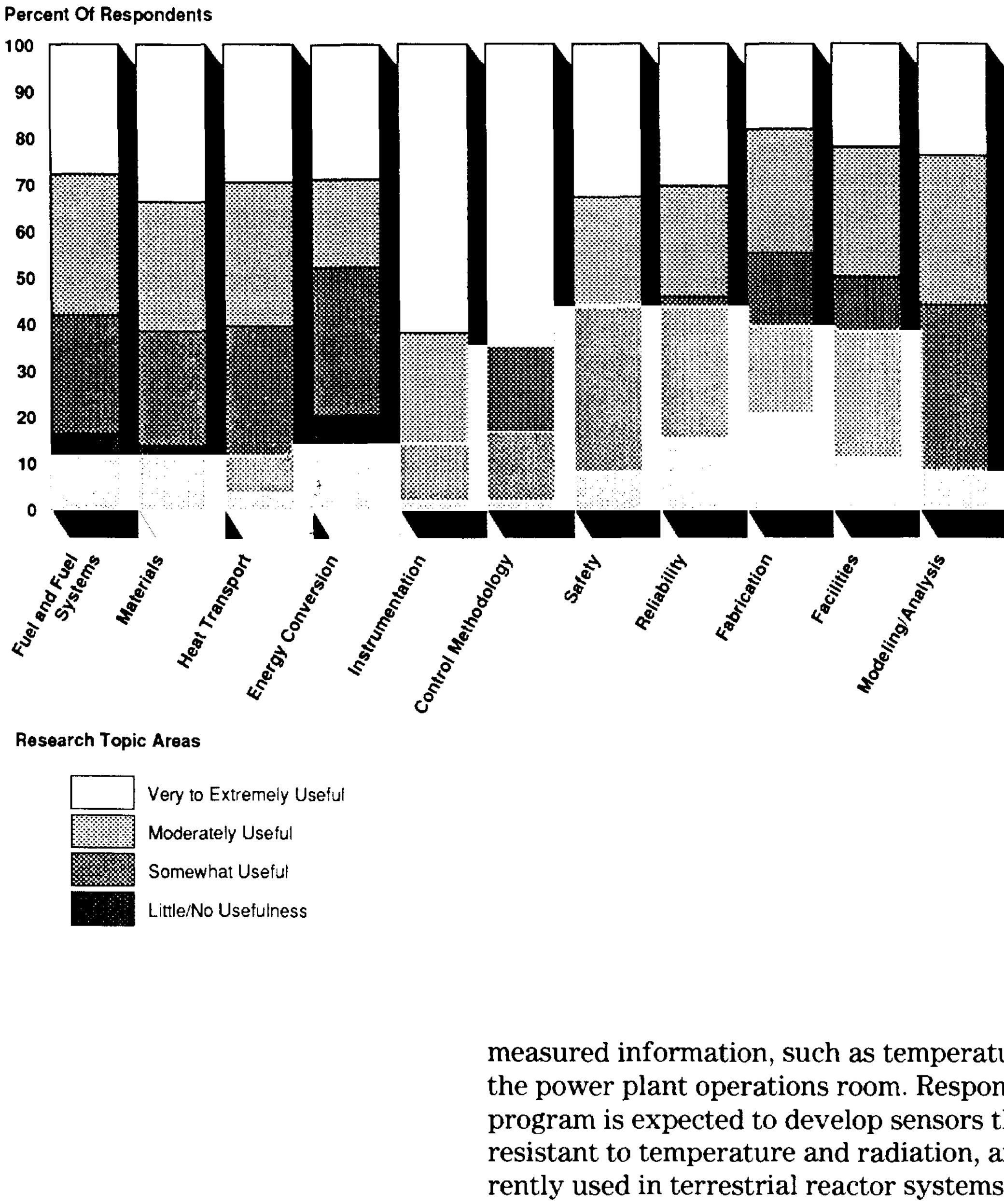
Applicability of Space Power Research to Terrestrial Reactor Systems Design

Among the 11 major system and component areas we examined in SP-100 and MMW, research advances and breakthroughs in 8 areas—fuel and fuel systems, materials, heat transport, instrumentation, control methodology, safety, reliability, and modeling and analysis—can be expected to be at least moderately useful to designers of advanced terrestrial reactor systems, according to most of our respondents.[1] Although the other areas—energy conversion, fabrication, and facilities—were rated lower, most respondents expect that research advances in these areas will be somewhat useful for future terrestrial reactor development.

As figure 2.1 shows, instrumentation and control may prove the most fruitful for designers of terrestrial systems. Those surveyed believe that instrumentation and control technology from space power systems research may be very useful for improving the sensing and transmitting of reactor operating data and improving reactor systems safety and efficiency, not only for future terrestrial reactors but also for existing reactors. Nuclear power plants contain elaborate instrumentation networks consisting of sensors (measuring devices) and cables for transmitting

[1]Of the 139 experts surveyed, 118 (85 percent) responded to our two questionnaires—72 percent to the first and 76 percent to the second. Some respondents returned one survey but not the other.

Figure 2.1: Experts' Opinion On The Usefulness Of Space Nuclear Power Systems R&D To The Development Of Terrestrial Nuclear Reactors



measured information, such as temperature and power intensity, back to the power plant operations room. Respondents said the space power program is expected to develop sensors that respond faster, are more resistant to temperature and radiation, and last longer than sensors currently used in terrestrial reactor systems. They also said that the space power program is exploring improved cabling and other means, such as fiber optics and telemetry, for transmitting sensor data. In addition, respondents stated that space power research in advanced computer systems to control reactor operations may be very useful to terrestrial designers seeking to improve reactor safety and efficiency. Appendix I discusses in detail how specific space power research results in these eight areas are expected to be most useful to terrestrial developers.

Responses Vary by Affiliation

Figure 2.1 presents the opinions of all respondents as a group. Opinions varied slightly according to respondents' space program affiliation and their role within the nuclear R&D industry. Most respondents have experience in both space and terrestrial power systems, and their affiliations cover the range of scientific communities—government, private industry, and colleges and universities. Similarly, they are diverse in their experience with nuclear power systems: they write R&D proposals; approve and/or manage R&D projects; conduct or review research; provide technical advice; or are involved with terrestrial power plant operations. About 80 percent conduct or review research results. Twenty-one respondents work for companies that are vendors responsible for marketing the results of reactor systems' research. Seventy-six percent of the respondents are involved with SP-100 and/or MMW, and the remaining 24 percent exclusively focus on terrestrial projects.

Table 2.1 shows that for the areas of fuel systems, heat transport, energy conversion, and facilities research, the median responses of those affiliated with SP-100 and/or MMW were a little more optimistic about potential commercial applications than those not affiliated.

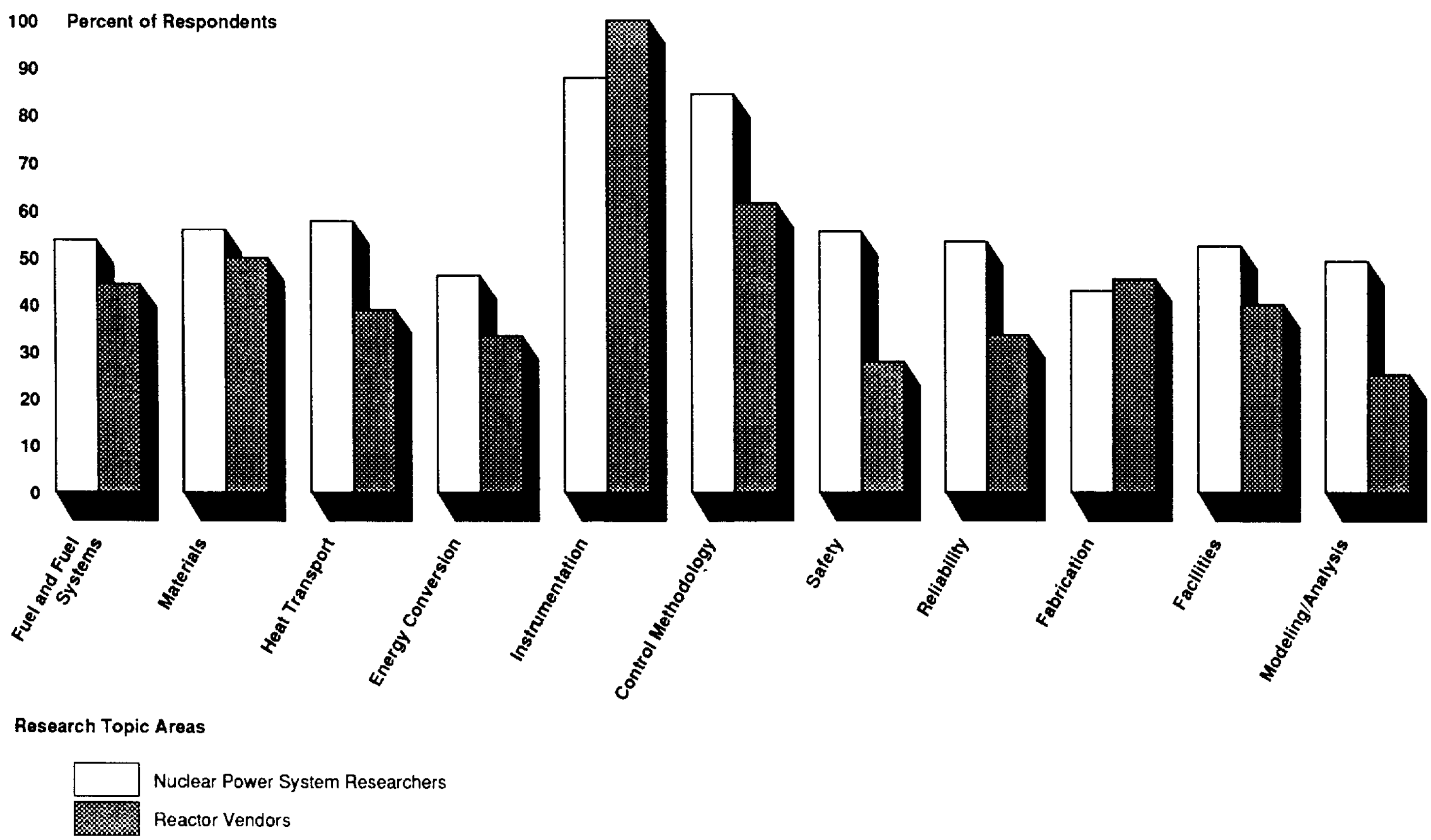
Table 2.1: Comparison of Median Responses From Those Affiliated and Not Affiliated With SP-100 and MMW

	Usefulness of SP-100 and MMW technology to terrestrial power systems	
Topic area	**Affiliated**	**Nonaffiliated**
Fuel systems	3	2.5
Materials	3	3
Heat transport	3	2.5
Energy conversion	2	1.5
Instrumentation	4	4
Control methodology	4	4
Safety	3	3
Reliability	3	3
Fabrication	2	2
Facilities	3	1.5
Modeling and analysis	3	3

Note: 1—little/no use; 2—somewhat useful; 3—moderately useful; 4—very useful

As figure 2.2 shows, those involved directly in space or terrestrial power research were also more optimistic about the terrestrial application of space power research than vendors who have to market such systems. Major vendors had been somewhat pessimistic, as well, in congressional hearings on the potential use of space and defense research results by terrestrial power systems developers. We believe it is significant that the opinions of the vendors were, however, unanimously optimistic concerning the potential use of space power instrumentation research by terrestrial reactor system designers.

Figure 2.2: Percentage of Vendors And Researchers Believing That Specified Space Power Systems Research Would Be At Least Moderately Useful To Terrestrial Reactor Development



Note: "At least moderately likely" means responses fell in the range of "moderately" to "extremely" likely.

Limits to the Potential Usefulness of Space Power Research to Terrestrial Systems

Technology gained from research in space nuclear power systems may prove useful, but there will be some limitations to the technology that can be transferred, according to our survey results. Respondents concluded the following:

- Differences in reactor design requirements will result in little one-for-one transfer of some space power hardware components for terrestrial use.
- Designers of terrestrial water-cooled reactors will find research technology for space nuclear power systems to be less useful than will designers of terrestrial metal- or gas-cooled reactors.
- SP-100 will be less likely than MMW to produce as much technology that will be useful to designers of terrestrial reactors.

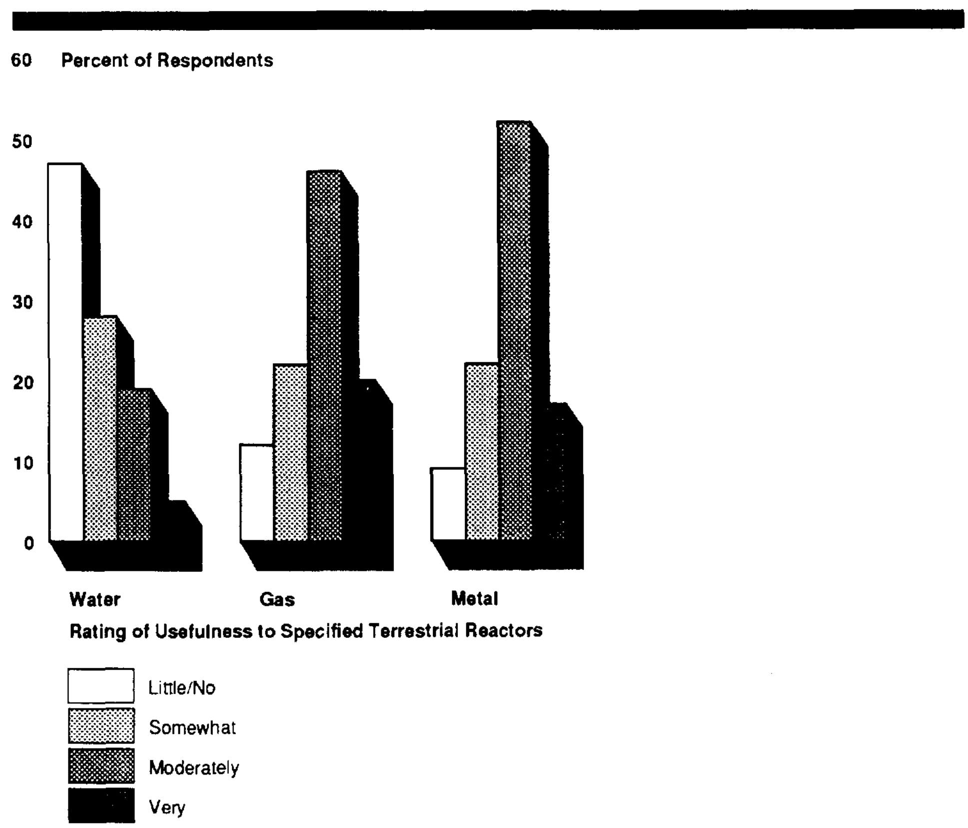
Design Differences May Limit Direct Transfer

While space technology may prove useful to designers of terrestrial nuclear power systems, experts cautioned that there may be little one-for-one correspondence between some space power and terrestrial hardware components because of differences in specific design requirements. For example, while weight is not a strong consideration in terrestrial designs, weight is crucial in space nuclear power systems because of stringent power-to-mass requirements and the logistical difficulties and cost of putting massive objects into space. As a result, SP-100 and MMW must develop components and materials that are more compact and lighter than those in terrestrial systems and that are able to operate at temperatures two to three times higher to achieve required performance at minimal weight. Because stringent design constraints for space power systems are also costly to achieve, these specifications may make space power technology somewhat costly for terrestrial systems, even though improved designs may mean improved efficiency.

Metal- And Gas-Cooled Reactors Expected to Benefit Most

Research on space nuclear power systems is expected to be beneficial mainly to advanced reactor systems, according to our survey results. That is, most respondents believe that technology from research on space nuclear power systems can be expected to be at least moderately useful to terrestrial metal- and/or gas-cooled reactors (see fig. 2.3), since space power research involves liquid metal and gas concepts. Less than one-fourth of the respondents believe this would be true for terrestrial water-cooled reactors, although respondents believe that existing and future water-cooled reactors may also benefit from technology improvements in generic areas, such as instrumentation and control, to improve safety and efficiency. The respondents stated that most other technology for water-cooled reactors is well developed and fixed at this point.

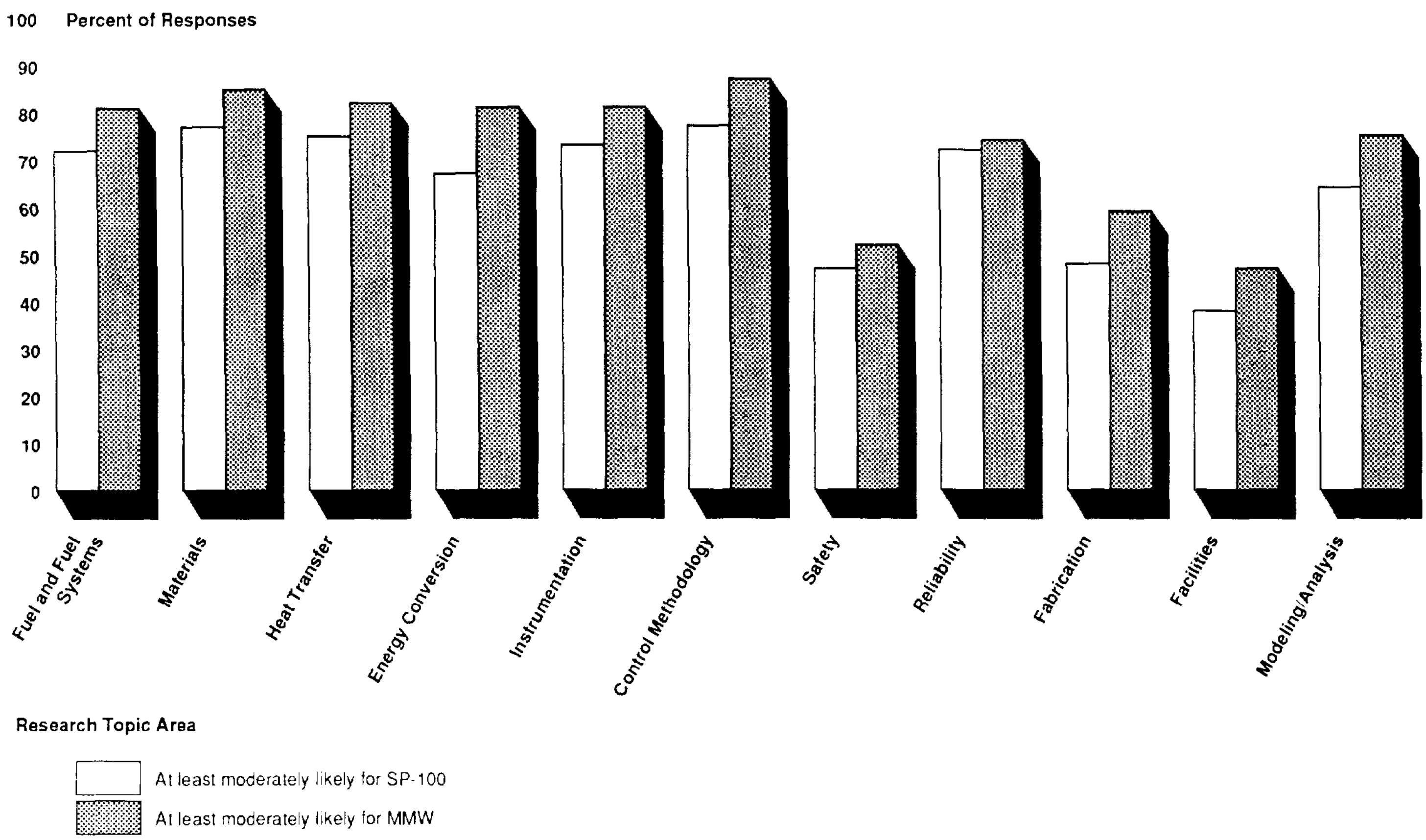
Figure 2.3: Usefulness of Space Nuclear Power Research to the Development of Specified Civilian Terrestrial Reactors



MMW More Likely to Advance Technology

Most respondents also believe that SP-100 will not produce technology that can be as useful to terrestrial reactors as that from MMW. (See fig. 2.4.) This result occurs because, according to DOE officials, the SP-100 project is near-term, with modest technology improvement objectives. MMW is longer-term, with more demanding design and performance requirements than SP-100, and thus has a much greater potential for technology improvements. For example, the MMW system must operate over a larger range and at higher power levels and temperatures to meet more stringent performance-to-weight ratios. In addition, it is expected that, unlike SP-100, MMW technology may use a dynamic energy conversion system to help meet SDI's power range requirements. Higher power ranges and dynamic energy conversion systems are more attractive to designers of terrestrial commercial nuclear power than the lower power range and static conversion used by the SP-100 system.

Figure 2.4: Comparison Of The Likelihood Of Technical Advancements From SP-100 And MMW Research



Note: "At least moderately likely" means responses fell in the range of "moderately" to "extremely" likely.

Challenges to Achieving Successful Transfer of Space Power Systems Technology

Although much of the knowledge gained from research on space power systems is expected to be useful to terrestrial power systems, experts surveyed raised a number of issues they believe pose challenges to the successful transfer of this technology. They stated that the extent to which expected benefits will be achieved depends in large part on whether

- the technology developed will be widely disseminated or retained by DOE as restricted data,
- solutions to institutional problems materialize to rejuvenate a declining nuclear industry, and
- funding will exist over the long term to fully realize technology development.

Over 90 percent of the experts we surveyed are concerned that government agencies will restrict access to space power systems technology. However, many of these experts also believe that even if the information is made available, it may not be used because the existing nuclear industry's problems with regulations, licensing, financing, and public perception discourage developers and investors from taking the economic risks of accepting new technology. The experts also believe that reduced program funding may prevent SP-100 and MMW from achieving some expected technical advancement, while DOE budget shifts may leave the civilian reactor research program unable to accept and apply this new technology.

DOE Must Weigh the Value of Information Restriction Versus Dissemination

Concerns about restrictions on the dissemination of information about space power systems may be well-founded, since DOE has taken action to classify "key information" from SP-100 and MMW as restricted or national security data.[1] DOE officials said that this action has been taken to prevent dissemination of this information to adversarial competitors. Only those within SP-100 and MMW who have a need to know will have access to these key research results.

DOE's classification action may affect the dissemination of some expected key technical advancements that the experts we surveyed said would be useful to the civilian nuclear power program. Consequently,

[1] "Key information" is information that reveals aspects, features, or attributes of space reactor power systems concepts or technologies that are innovative, not obvious, unexpected, or difficult or time-consuming to duplicate, and permit either a significant technical advancement or resolution of a significant technical problem.

DOE's research and development programs for advanced terrestrial reactors may not have the full benefit of useful space power research results until the results are declassified.[2]

DOE officials told us that most of their current SP-100 efforts—mainly support of ground engineering tests—use available technologies. Thus, according to these officials, most of the current SP-100 research does not warrant classification as restricted or national security data. However, they said that some information may be controlled as "applied technology." DOE labels some significant R&D information as applied technology to withhold its public dissemination, specifically to help prevent its disclosure to foreign countries. DOE's other space power research effort, MMW, is expected to produce more significant technical advances and breakthroughs than SP-100, and thus, MMW information is expected to be more heavily classified and protected from dissemination.

Although DOE is taking action to classify key technical advancements and breakthroughs from the space reactor research programs, DOE officials are aware of the benefits of transferring such technology. DOE officials have stated to the Congress that pertinent technology from the space power systems programs would be transferred to other DOE and private sector programs having a need for it. As a result, DOE officials will have to reconcile the need to classify or otherwise limit dissemination of the results of SP-100 and MMW research with the need for timely dissemination of research results that may be useful to the development of U.S. terrestrial power systems.

Institutional Problems That Challenge Acceptance of New Technology

Even if information about space power systems is freely shared, the civilian nuclear power community may be slow to use this new technology because of regulatory and licensing issues, financial and economic concerns, and public perception problems, according to some experts surveyed.

These experts stated that government agencies and the private sector must work together to revive the nuclear industry for the good of the U.S. economy. They said that compliance with the current regulatory process governing nuclear power plant licensing and operations is costly, time-consuming, and confusing. The Nuclear Regulatory Commission, which is responsible for nuclear safety and quality assurance for

[2]Technology from the space nuclear reactor program of the 1950s to early 1970s was also classified initially. It was eventually declassified in 1973 and made available to those who were interested.

commercial nuclear applications, has issued over 2,000 regulatory guidelines, letters, bulletins, orders, notices, and standards that utility companies must comply with to be licensed, to operate, and to adopt new technology. According to DOE, this regulatory framework is continually being changed and added to, making it difficult for the utility companies to plan.

Some of the experts also stated that the nuclear industry has become less financially attractive to investors, vendors, and power plant operators in recent years. For example, according to DOE statistics, the average time to complete a nuclear plant has increased from 7 years for plants coming on-line in the early 1970s to more than 14 years, on average, for those entering operation in 1985. Recent project times have ranged from 9 to 20 years. In addition, the cost of U.S. nuclear plants has increased nearly 10-fold.[3] As a result, the commercial nuclear industry is in a no-growth posture, with no new plants being ordered.

In addition, the industry must overcome its public perception problems. According to DOE, most people see the advantages for nuclear power as an energy source but are not willing to have nuclear power plants built near their homes. Until the public's perception and acceptance of commercial nuclear power improves, the industry is not likely to invest in building new systems. Some experts stated that the commercial sector will take few risks, given the current institutional environment for the nuclear industry. They added that any new technology proposed for eventual commercial use must be well-demonstrated, profitable, acceptable to regulatory agencies, and supported by government funding.

Funding Availability Will Challenge Successful Development and Transfer of Technology

To develop and transfer technology successfully, program decisionmakers will need to ensure that adequate funding exists over the long term and that a viable terrestrial research and development infrastructure (people and programs) capable of accepting the technology is maintained. However, reduced levels of project funding have affected the development of both SP-100 and MMW. Of the approximately $415 million requested by DOE, DOD, and NASA for SP-100 during fiscal years 1986-89, about $258 million (62 percent) was received. According to DOE officials, the reduced levels have caused key development activities to be pursued with a higher degree of risk. MMW, which will build on and go beyond SP-100 technology, has experienced more significant reductions in

[3] According to DOE, power plant construction cost per kilowatt (1,000 watts) of generated electric power capacity increased from $388 in 1971 to $3,776 in 1987.

project funding levels. Of the approximately $123 million requested for MMW by DOE and DOD during fiscal years 1986-89, about $74.7 million (61 percent) was received. As a result, MMW program planners have put off some technology developments. Because technology research and development time frames for both programs have been stretched out and some technology may not be pursued, some experts responding to our survey are concerned whether and when the technology originally expected from SP-100 and MMW will be realized.

While reduced funding levels will affect the space reactor programs, reduced funding levels in advanced terrestrial reactor programs also raise concern about whether these programs will be able to accept and apply transferable technology. DOE funding for advanced reactor programs declined by several hundred million dollars between fiscal years 1981 and 1986 and has continued to decline significantly since fiscal year 1986. DOE's budget actions in fiscal year 1987 to emphasize space and defense power needs mainly affected the advanced terrestrial reactor program for liquid metal- and gas-cooled reactors and other longer-term programs, rather than the nearer-term light-water reactor programs. By the end of fiscal year 1989, funding for the advanced terrestrial reactor R&D program will have dropped nearly 37 percent since fiscal year 1986. DOE's space and defense power systems, despite reduced funding levels, will have increased by about 350 percent during this same period. (See table 3.1.)

Table 3.1: Comparison of DOE Funding for the Advanced Reactor Systems and Space and Defense Power Systems

Dollars in millions

Fiscal year	Advanced reactor R&D[a]	Space and defense power R&D[b]
1986	126.8	$20.2
1987	75.1	47.6
1988	92.6	75.2
1989	80.5 (−37%)	91.0 (+350%)

[a]Funding specifically for liquid metal and gas reactor systems dropped from $63.5 million in 1986 to $40 million for 1989.

[b]DOE's funding for SP-100 and MMW increased from $17.8 million in 1986 to $68.5 million for 1988 and $66.0 million for 1989.

In a related 1987 study, we found that industry planned to pick up little of the advanced reactor R&D curtailed by DOE. Lower demand for nuclear power has led to the virtual elimination of an advanced terrestrial reactor market in the United States. Rather than invest in the advanced reactor market, the nuclear industry has devoted an increasing share of its resources to nearer-term developments, largely because of projected reliance on existing light-water reactors well into the next century. Consequently, a portion of the industry's infrastructure supporting the capability to do R&D for advanced reactor technologies is being disbanded.[4]

Observations

In the mid-1980s, DOE reduced the funding levels for its civilian advanced terrestrial reactor R&D programs and at the same time established support for R&D in space and defense reactor power system programs. In doing so, DOE was confident that some technology from space power systems research would benefit terrestrial reactors as well. However, DOE stressed the importance of support for space power research regardless of any auxiliary benefits that may or may not be realized.

Our survey results show that there are opportunities for technology transfer from DOE's space power programs to terrestrial reactor systems R&D programs. Advanced liquid metal- and gas-cooled reactors are expected to be the main terrestrial reactor beneficiaries of space power R&D. However, all types, including existing water-cooled reactors, may benefit from advances in instrumentation and control, although, as we described in chapter 2, there are understandable limitations to transferring some of the space power technology.

However, as discussed in this chapter, a number of circumstances exist that challenge the extent to which technology transfer may actually occur. DOE may be in a primary position to influence some of these determinants to successful technology transfer, such as expeditiously disseminating space power research results to the terrestrial community and funding the space and advanced terrestrial programs at levels that ensure program viability. However, DOE has less immediate influence over other determinants that deal with public and private institutional issues. Consequently, whether and how DOE and others in the government and the private sector address these challenges to technology transfer will ultimately determine the successful transfer of space power system technology.

[4]Energy R&D: Changes in Federal Funding Criteria and Industry Response (GAO/RCED-87-26, Feb. 9, 1987), pp. 40-42.

Specific Space Power Research Results That Are Expected to Be Most Useful to Terrestrial Systems Development

This appendix discusses the relevance of the specific space power research that the respondents to our survey believe may be most useful to designers of terrestrial reactors. Expected space nuclear power research developments are underlined.

Fuels and Fuel Systems

The cost of nuclear power is strongly affected by the amount of electricity that can be generated by a particular amount of fuel, fuel fabrication costs, and refueling costs. The lifetime of the fuel in a reactor core results from a number of design compromises. In commercial U.S. power reactors, the fuel consists of uranium oxide pellets sheathed in zirconium alloy rods. The fuel life is limited by the buildup of fission products and by radiation damage to the zirconium cladding and the uranium oxide pellets.

Consequently, space power research that would lead to the development of reactor fuel with <u>improved fission product retention at high temperatures and high power densities</u> would benefit any new commercial power reactor.[1] Improved fission product retention would allow for better control of radioactive materials and a longer fuel lifetime; high temperatures would facilitate improved efficiency; and high power density would contribute to the development of smaller reactors for a given power level. However, the behavior of reactor fuels under these extreme conditions is very hard to predict. Thus, any information gained from the space reactor program's <u>high-temperature testing</u> and <u>high-power-density experience</u> would help the commercial reactor sector even if the fuel type was not identical.

Materials

The allowable limits of operation of any technological device ultimately depends on the materials used to construct it. Improvement in any material's capabilities usually translates into improved design and better economics.[2]

The space reactor program will employ higher operating temperatures than are currently used in the civilian nuclear program. It therefore will

[1] Fission products tend to escape from the fuel more readily at higher temperatures, thus increasing the radioactivity of the other parts of the reactor system. Power density is a measure of the rate of heat generated per unit volume of reactor core.

[2] The U.S. nuclear power program is based on the use of materials that have been very thoroughly documented, with a long history of commercial availability and usage. Thus, the introduction of any new material, no matter how economically beneficial, may require extensive testing and documentation before regulatory approval can be expected.

need to develop materials for bearings, contact surfaces, and fuel cladding that are able to withstand high temperatures. These materials can potentially improve the lifetime of terrestrial systems. The development of high-temperature bearings would have the most impact on advanced gas or liquid metal reactors because the temperature of water-cooled reactors tends to be limited by the properties of water itself. Although there exist metal alloys with much better high-temperature properties than those currently used, many of these alloys are often difficult to fabricate because they are brittle or difficult to weld. The development of "workable" high-temperature alloys would allow a new class of materials to be used and would afford increased design freedom for new commercial reactors.

Heat Transport

Heat transport refers to the actual physical process by which the heat generated in the reactor core is carried to external systems, where it is converted to useful output. The heat transport system is a subsystem of the total energy conversion process. Heat transport technologies proposed for the space reactor program share a technological base with second-generation liquid metal reactors and gas-cooled reactors proposed for civilian use.[3] Thus, expected space power research into experimental liquid metal-coolant circulation loops or an experimental gas-coolant circulation loop would be the source of much-needed data on heat transfer and fluid circulation properties for terrestrial reactors. As in the research planned for space power, the driving force for the circulating fluid is likely to be an electromagnetic pump for the liquid metal reactor and a high-performance, high-temperature gas circulator for the gas-cooled reactor. High-reliability pumps and circulators are essential if commercial acceptability is to be achieved. The U.S. technology database is not nearly as well advanced in liquid metal- or gas-cooled systems as it is in water reactor systems; consequently, construction and operation of test facilities would add to our knowledge of liquid metal cooling technology in general and, in particular, would address those issues of mass transfer, erosion, and corrosion that can only be determined by long-term operation of well-instrumented test facilities.

Another feature of some nuclear systems is the rejection of excess heat from the power conversion cycle through another cooling fluid. This heat is transferred from one fluid to another in high-temperature two-fluid heat exchangers. Space reactor research advances in construction

[3]Heat transport in all operating commercial U.S. power reactors relies on the circulation of pressurized water or steam, which has little relevance to the space reactor program.

techniques for such exchangers would bring benefits in reliability and reduced cost for second-generation reactors.[4]

Nuclear Instrumentation

Nuclear plants contain a large number of complex, interacting systems. Instrumentation refers to the whole network of measuring devices (sensors) and transmitting schemes used to transfer information from the hardware to the control room. Current practice uses instrumentation placed in reasonably accessible locations and derives information about inaccessible or highly stressed locations by inference. Instrumentation resistant to high temperatures could be used to directly monitor the more critical portions of the plant. A commercial nuclear power plant employs literally thousands of different sensors measuring such diverse quantities as neutron flux in the core (an indication of generated power) and the chemical properties of the cooling water. In current nuclear plants, the electrical signals generated by these sensors are brought to the control room via a network of individual electric cables. These cables are expensive, take up valuable room, and are vulnerable to damage.

The first need is for improved sensors. For example, improved neutron flux sensors are essential because they directly monitor the intensity of nuclear power generation, are almost always in the least accessible places, and are located in high-radiation zones. Advanced (high-temperature, wide-range, high-fluence) neutron monitors expected from the space reactor program would facilitate the use of a minimal number of detectors because each would cover a wide monitoring range.[5] Fast-response neutron detectors from space reactor research would fill an important gap because sensitive detectors that are now in use tend to respond slowly. The neutron detectors and some of their associated electronics are necessarily in a radiation zone, and radiation-hardened (resistant to radiation) systems would have a longer lifetime. In addition, long-life thermocouples would reduce the need for frequent replacement of this commonly used sensing device.

Other potential space systems instrumentation developments concentrate on improved transmission of sensor data. For example, improvements are expected via improved cabling and insulation, the application

[4]The SP-100 space reactor system uses a heat exchange technology employing "heat-pipes" to transfer excess heat from one fluid to another and to radiators, which in turn radiate this heat into space.

[5]Flux monitors measure the intensity of neutron radiation, which is a measure of the rate of the fission process. Fluence is a measure of the total neutron exposure in a given location.

of multiplexers, which can combine information from many sensors over a single data link, and fiber optic data transmission, which promises to combine the information-carrying capacity of many cables into a single optical fiber. The optical fiber would also be much less sensitive to electrical interference. In addition, the telemetric instrumentation of space power systems would eliminate the need for cabling by sending information by radio signal. Finally, self-diagnostic instrumentation would use modern control theory to continually assess the state of the sensors in order to send the best possible information back to the control room, while auto-reconfigurable instrumentation would go a step further to automatically compensate for malfunctioning instruments.

Control Methodology

Control methodology refers to the general design decisions for regulating the reactor system—manual versus automatic, digital versus analog, partially or fully computerized. Commercial U.S. nuclear power plants rely on control technologies introduced 20 to 30 years ago. For the most part, these plants use analog and manual control with operator input from analog instruments.

Because the current U.S. technology for reactor control is old, any advance in control methodology resulting from the space nuclear program would pay off in simplicity and reliability of operations. The control issue is generic to all types of reactors; thus, any technology improvement could be useful to both existing and proposed terrestrial reactors. Space reactors require remote operation with minimal opportunity for operator intervention and equipment replacement. This type of operating mode could also improve operation of existing terrestrial reactors. Digital control systems would tap the high reliability and accuracy of modern computerized instruments and actuators. The use of distributed control systems (individual control systems located in various parts of the reactor system) would minimize the need for expensive communications networks; self-diagnostic control systems would be aware of their own errors and compensate for them; and fault-tolerant computers in these control systems could minimize the impact of any potential control system failure. Adaptive control techniques refer to the practice of modifying the control strategy in response to the actual status of the system. In effect, adaptive control methods make allowances for change in the plant caused by wear and possibly individual component failure.

Together, these developments would constitute a control system capable of operating with minimal or no operator intervention. The development and demonstration of such autonomous control hardware and software would be an important step in attempting to persuade the licensing authorities that such control methodologies are an improvement over the current manual schemes. In addition, the development of devices to improve the interface between operators and reactor systems would be important because the task of operating a nuclear power station requires the integration of a large amount of information. Thus, the use of advanced computer systems, such as artificial intelligence and expert systems, to assist the operator in dealing with this complexity could improve plant safety and efficiency.

Safety

The need for safety in nuclear power reactors is self-evident. The real issues lie in deciding how safe is "safe enough" and ensuring that the reactor has attained the claimed safety level.

Current light-water reactors achieve their exceedingly low risk levels by the technique known as "defense-in-depth." All important safety functions are provided with redundant backup systems so that if one system fails another can be brought in to perform its job. In addition, there are other systems that are responsible for mitigating the consequences of the unlikely failure of redundant systems. For example, the reactor vessel is expected to contain the effects of the failure of fuel in the reactor core, and the containment vessel is expected to contain the effects of a failure of the reactor vessel.

Systems relying on defense-in-depth are necessarily very complex. The potential space reactor developments likely to affect current safety analyses are improved analytic techniques, particularly in thermal hydraulics (the study of fluid behavior under heat conditions), which would improve the ability to predict behavior in the event of an irregular operation, and improved probabilistic risk analysis techniques to aid in estimating the true hazards. Defense-in-depth also depends on maintaining equipment in good repair; remote maintenance and repair methods facilitate this goal while simultaneously reducing the operational radiation dose to plant staff. Fault-tolerant controls would minimize the safety impact of both control system and operator failure. Improved methods to preserve structural integrity would minimize the probability of defense-in-depth systems failing in the event of an accident. Another important contribution of space power research would be advances in safety design methods, which would greatly reduce the complexity of defense-in-depth systems while simultaneously simplifying the analysis of plant risks.

Reliability

Because nuclear power plants are very complex, they often have malfunctioning components and subsystems. Component reliability plays an important role in determining availability of plant power, which in turn affects the economics of operating the power plant.

The experts we surveyed believed that the following space reactor research to improve reactor system components and subsystems could contribute to the improved reliability of terrestrial power systems. High-temperature tribology (friction between materials and surfaces) concerns the lubrication of severely stressed bearing surfaces, one of the major contributors to equipment failure. Experience in the fabrication and testing of high-reliability materials has a potentially important impact, especially as the current generation of reactors ages and effects due to corrosion and fatigue become more important. Other items, advances in automated operation and advances in high-reliability software, both attack the issue of operator errors. High-reliability software will be essential if we are to develop computer aids for reactor operators and, eventually, fully computerized control systems.

Modeling/Analysis

Nuclear systems require complex nuclear codes (computer programs) to predict their behavior and guide their design. Because of the complexity and cost of nuclear systems, there is far greater reliance on numerical analysis and less reliance on construction of prototypes than in most other industries. The accuracy of the analytical tools thus plays a proportionately greater role. Current design capabilities are limited as much by the analytic tools being used as they are by the lack of detailed data.

The space power systems research involving reactor cores should enhance modeling capability. Because these cores must operate under more highly stressed conditions and at higher power levels and must undergo faster transient changes than commercial reactors, the numerical codes required for analysis must improve over existing ones. The experimental verification of neutron kinetics codes (computer programs modeling the behavior of neutrons in an operating reactor) will enhance confidence in existing accident analyses, as will the ability to analyze the stresses during transient operation. The need to investigate extreme conditions is also expected to lead to improved thermal-hydraulics codes and models for fuel performance. These tools will enable us to extend current design limits with more confidence and predictability. In addition, improved ability to predict fuel lifetime through modeling will cut plant operations costs through improved planning.

The space reactor program is also expected to lead to improved reliability analysis because of the necessity for space reactors to operate for long periods of time without maintenance. Improved reliability analysis will allow designers to identify the weak points of current designs and to predict where improvements will have maximum impact on the reliability of the total system. Such capability, leading to better designs, can be expected to produce eventual operational and economic benefits for utility companies.

Summarized Questionnaire Responses Regarding the Potential for Space Power Technology Transfer

This appendix summarizes the experts' responses to our final questionnaire regarding factors affecting space power systems technology transfer (part I), the potential for technology transfer (part II), and the overall potential usefulness of space power technology to terrestrial reactor development (part III). The questions for these parts were developed from the experts' narrative responses to our initial questionnaire. In part II, respondents were asked to rate the usefulness of specific space power research to terrestrial reactor system development. Appendix I discusses the relevance of these responses.

Note: GAO comments supplementing those in the report text appear at the end of this appendix.

Part I

See comment 1.

FACTORS AFFECTING TECHNOLOGY TRANSFER

7. In your opinion, how much, if at all, would each of the following design features of nuclear space reactors increase or decrease the likelihood of technology transfer? (Check one box for each feature.) (60-71)

	Greatly Increase 1	Somewhat Increase 2	Neither Increase Nor Decrease 3	Somewhat Decrease 4	Greatly Decrease 5
1. Increased safety/reliability	34	48	18		
2. Low power	6	18	42	24	10
3. Small size	14	31	33	19	4
4. Remote operation	17	52	26	3	2
5. Low maintenance	33	51	16		
6. High efficiency	26	46	27	1	
7. Design simplicity	39	40	19	2	
8. Modular design	34	45	19	2	
9. Scalable technologies	39	41	20		
10.Refractory materials	16	36	36	10	3
11.High temperature operation and tolerance	24	44	24	8	1
12.Other (specify):					

8. In your opinion, how much, if at all, would each of the following business and economic issues affect the use of transferable technologies by the terrestrial reactor community? (Check one box for each issue)

ID (1-3)
CD8 (4)
(5-13)

	Little or No Effect 1	Somewhat Affect 2	Moderately Affect 3	Greatly Affect 4	Extremely Affect 5
1. Exclusivity/proprietary rights to certain types of information	6	19	29	27	20
2. Stability/source of supply	16	16	25	33	9
3. Licensing/regulatory requirements	11	11	18	35	25
4. Construction time	23	14	16	29	18
5. Operator training requirements	20	29	32	14	5
6. Investment risk	14	6	12	34	35
7. Production costs	12	11	18	39	19
8. Size of market	16	11	18	32	24
9. Other (specify):					

9. In your opinion, to what extent, if at all, will each of the following government actions, policies or practices increase or decrease the likelihood of technology transfer? (Check one box for each item.) (14-22)

	Greatly Increase 1	Somewhat Increase 2	Neither Increase nor Decrease 3	Somewhat Decrease 4	Greatly Decrease 5
1. Security classification of significant technical advancements and breakthroughs from space R&D programs	2	3	3	35	58
2. Current regulatory and licensing policies/procedures for terrestrial reactors	2	9	26	38	24
3. Provisions in Technology Transfer Act assigning responsibility for transfer to labs	9	35	29	17	9
4. Current patent right waiver laws, policies, and regulations	7	26	46	19	2
5. Economic incentives for tech. transfer to contractors	26	63	8	4	
6. National lab dominance in space reactor R&D programs	3	22	24	30	20
7. Involvement of terrestrial researchers in space R&D	22	53	22	3	
8. Involvement of commercial firms in space reactor R&D	38	52	10	1	
9. Other (specify):					

10. In your opinion, to what extent, if at all, would each of the following government interventions facilitate or interfere with technology transfer? (Check one box for each intervention.) (23-36)

	Greatly Facilitate 1	Somewhat Facilitate 2	Neither Facilitate Nor Interfere 3	Somewhat Interfere 4	Greatly Interfere 5
1. Emphasize technology transfer during all stages of space nuclear power programs	26	63	10	1	
2. Initiate/maintain effort to disseminate information early (e.g., publications, symposia, etc.)	30	61	9	1	
3. Provide economic or other incentives for adopting new technology	42	52	6		
4. Increase/provide stable funding for space reactor R&D	47	40	12	1	
5. Increase funding for basic research	25	44	30	1	
6. Sponsor parallel terrestrial program to develop a small reactor	43	38	12	4	3
7. Formal DOE/DOD/NASA agreement on technology transfer responsibilities/strategies	17	54	26	3	
8. Sponsor commercial ground demonstration programs using space reactor technology	44	39	10	5	2
9. Use terrrestrial nuclear power at U.S. defense bases/control centers	40	39	17	2	1
10. Establish/clarify national nuclear energy policy	60	25	14	1	
11. Provide incentives to retain U.S. nuclear infrastructure--people and programs	45	40	12	1	2
12. Provide R & D review by regulatory agencies	3	30	29	30	9
13. Increase export control limitations on new technologies	1	10	33	49	8
14. Other (specify):					

See comment 2.

11. In your opinion, how much, if at all, would each of the following situations or events facilitate or interfere with (1) space reactor R&D efforts, (2) terrestrial reactor development, and (3) technology transfer? (Enter one number from the following rating scale for each topic.) (37-69)

Rating Scale:
1 = Greatly Facilitate
2 = Somewhat Facilitate
3 = Little or No Effect
4 = Somewhat Interfere
5 = Greatly Interfere

	Space R&D*	Terrestrial R&D*	Technology Transfer*
1. Catastrophic terrestrial power plant failure	4	5	4
2. Less than catastrophic terrestrial power plant failure	4	4	3
3. Space reactor accident causing Earth contamination	5	4	4
4. Space reactor accident with no Earth contamination	4	3	3
5. Anti-nuclear public sentiment	4	4	4
6. Pro-nuclear public sentiment	2	2	2
7. Depletion or long duration shortage of fossil fuels	3	1	2
8. Reduced cost of fossil fuels	3	4	3
9. Increased cost of fossil fuels	3	2	3
10. Proof of adverse environmental effects (e.g., CO_2 greenhouse) due to fossil fuel burning	3	2	2
11. Other (Specify):			

*Median response.

12. It is obvious that technology transfer can be helped or hindered by numerous factors. However, these factors will not all have equal weight or importance in determining whether or not transfer will occur. Consider each of the following general factors which could affect technology transfer. In your opinion, which ones are most likely to affect technology transfer from the space reactor programs to terrestrial reactor development?

Indicate your answer by ordering each factor from the most (1st) to least (7th) important. Select the factor which you think is most likely to affect technology transfer. Rank this first by circling 1st. Do the same for all the remaining categories, ranking them 2nd, 3rd, 4th, 5th, 6th, and 7th. Each rank number, from 1st to 7th, should be used only once.
(70-76)

FACTORS	IMPORTANCE						
1. Demand for nuclear energy	1st	2nd	3rd	4th	5th	6th	7th
2. Economics (see, e.g., Q.10)	1st	2nd	3rd	4th	5th	6th	7th
3. Relevance/usefulness of results to existing or planned terrestrial systems	1st 43%	2nd	3rd	4th	5th	6th	7th
4. Design features of space reactors (see, e.g., Q.7)	1st	2nd	3rd	4th	5th	6th	7th
5. Government practices/interventions (see, e.g., Q.8,9)	1st	2nd	3rd	4th	5th	6th	7th
6. Ease/complexity of implementing the transfer	1st	2nd	3rd	4th	5th	6th	7th
7. External events (see, e.g., Q.11)	1st	2nd	3rd	4th	5th	6th	7th

Part II

POTENTIAL FOR TECHNOLOGY TRANSFER

The space reactor program will require advances in a number of areas. In some cases, the advances will be narrowly confined ones as, for example, cyclic stress testing of a particular refractory alloy or the design of a zero-gravity liquid metal pump. Other advances may be more generally applicable as, for example, extensions of PRA techniques or development of self-testing sensors. The following section contains advances that respondents to the first questionnaire thought might reasonably be expected to flow from the space reactor program. The purpose of this second questionnaire is to elicit from you some insight into which areas have greatest potential for terrestrial nuclear reactor application.

See comment 3.

The likelihood of a particular development depends, of course, on the future of the space reactor program. For purposes of this section of the questionnaire, please assume that the listed technical advancements are equally likely to occur.

See comment 4.

Please answer the questions for those topics about which you are at least moderately knowledgeable. Skip those topics about which you have less knowledge, and add any topics you believe are applicable.

Based on responses to our first questionnaire, we have eliminated from this questionnaire (or merged with other topics) the topics of shielding, energy storage, maintenance and heat rejection. If you feel strongly about topics we eliminated, please include your opinions about them under the "Other" category at the end of this section.

FUELS AND FUEL SYSTEMS

ID (1-3)
CD9 (4)

Are you at least moderately knowledgeable about this topic? [X] Yes (5)

[ ] No (SKIP THIS TOPIC)

Listed below are the specific developments in this topic area that experts believed might occur as a result of space nuclear reactor power systems R&D. Please assume that all of the developments are equally likely to occur. Then select the number from the rating scale below that comes closest to your response to the following questions:

1. How useful would the development be to light water, high temperature gas, and liquid metal civilian reactor development? (Enter one number for each reactor type.)

2. What is the likelihood that the development will actually transfer from the space programs to terrestrial reactor development? (Enter one number.) (6-65)

Rating Scale

1 = Little or no usefulness/likelihood
2 = Somewhat useful/likely
3 = Moderately useful/likely
4 = Greatly useful/likely
5 = Extremely useful/likely
6 = No Basis to Judge

	Usefulness to Civilian Reactors			Likelihood of Actual Technology Transfer
	Water 1a	Gas 1b	Metal 1c	2
1.Advanced cladding materials	2	2	3	3
2.Cermet fuel	1	2	3	2
3.Graphite matrix fuel	1	4	1	2
4.High temperature, high burnup testing	2	3	3	3
5.High power density experience	1	2	3	2
6.Homogeneous fuels	1	1	1	1
7.Improved design for high reliability	2	3	3	3
8.Improved fabrication techniques	2	3	3	3

FUELS AND FUEL SYSTEMS (continued)

	Usefulness to Civilian Reactors			Likelihood of Actual Technology Transfer
	Water 1a	Gas 1b	Metal 1c	2
9. Improved fission product retention at high temperatures and high power densities	2	4	3	3
10. Improved fuel performance model	2	3	3	3
11. Mixed fuels - Pu/U	2	2	3	2
12. Nitride fuel	1	1	3	2
13. Particle fuel	1	4	1	2
14. Pebble bed fuel	1	4	1	2
15. Testing of advanced fuels	2	3	3	3

3. Considering all of the potential advances listed above, in your opinion, how useful, overall, will advances in this topic area be to terrestrial reactor development? (Check one.) (66)

1. [ ] Little or No Use
2. [ ] Somewhat Useful
*3. [X] Moderately Useful
4. [ ] Very Useful
5. [ ] Extremely Useful

4. In your opinion, what is the overall likelihood of technology transfer in this topic area? (Check one.) (67)

1. [ ] Little or No Likelihood
2. [ ] Somewhat Likely
*3. [X] Moderately Likely
4. [ ] Very Likely
5. [ ] Extremely Likely

*Median response.

MATERIALS

ID (1-3)
CDA (4)

Are you at least moderately knowledgeable about this topic? [X] Yes (5)

[_] No (SKIP THIS TOPIC)

Listed below are the specific developments in this topic area that experts believed might occur as a result of space nuclear reactor power systems R&D. Please assume that all of the developments are equally likely to occur. Then select the number from the rating scale below that comes closest to your response to the following questions:

1. How useful would the development be to light water, high temperature gas, and liquid metal civilian reactor development? (Enter one number for each reactor type.)

2. What is the likelihood that the development will actually transfer from the space programs to terrestrial reactor development? (Enter one number.) (6-65)

Rating Scale

1 = Little or no usefulness/likelihood
2 = Somewhat useful/likely
3 = Moderately useful/likely
4 = Greatly useful/likely
5 = Extremely useful/likely
6 = No Basis to Judge

	Usefulness to Civilian Reactors			Likelihood of Actual Technology Transfer
	Water 1a	Gas 1b	Metal 1c	2
1. Composites: carbon/carbon	1	3	1	2
2. Composites: Ceramic-based	1	3	2	2
3. Composites: metal matrix	1	2	3	2
4. Composites: oxidation resistant	2	3	2	2
5. Development of "workable" high temperature alloys	1	3	3	3
6. Development of Nb-1Zr metallurgy	1	2	3	2
7. Fabrication/testing of ceramics	1	2	2	2

MATERIALS (continued)

	Usefulness to Civilian Reactors Water 1a	Gas 1b	Metal 1c	Likelihood of Actual Technology Transfer 2
8. Fabrication/testing of refractories	1	3	3	3
9. High temperature bearings and contact surfaces	1	3	3	3
10.High temperature fuel cladding materials	1	3	3	3
11.Improved thermoelectric materials	1	1	1	1
12.Refractory alloys	1	3	3	2
13.Refractory insulators	1	2	2	2
14.Structural ceramics	1	3	3	2
15.High temperature dielectrics	1	2	2	2

3. Considering all of the potential advances listed above, in your opinion, how useful, overall, will advances in this topic area be to terrestrial reactor development? (Check one.) (66)

1. [ ] Little or No Use
2. [ ] Somewhat Useful
*3. [x] Moderately Useful
4. [ ] Very Useful
5. [ ] Extremely Useful

4. In your opinion, what is the overall likelihood of technology transfer in this topic area? (Check one.) (67)

1. [ ] Little or No Likelihood
2. [ ] Somewhat Likely
*3. [x] Moderately Likely
4. [ ] Very Likely
5. [ ] Extremely Likely

*Median response.

HEAT TRANSPORT

ID (1-3)
CDB (4)

Are you at least moderately knowledgeable about this topic? [X] Yes (5)

[_] No (SKIP THIS TOPIC)

Listed below are the specific developments in this topic area that experts believed might occur as a result of space nuclear reactor power systems R&D. Please assume that all of the developments are equally likely to occur. Then select the number from the rating scale below that comes closest to your response to the following questions:

1. How useful would the development be to light water, high temperature gas, and liquid metal civilian reactor development? (Enter one number for each reactor type.)

2. What is the likelihood that the development will actually transfer from the space programs to terrestrial reactor development? (Enter one number.) (6-53)

Rating Scale

1 = Little or no usefulness/likelihood
2 = Somewhat useful/likely
3 = Moderately useful/likely
4 = Greatly useful/likely
5 = Extremely useful/likely
6 = No Basis to Judge

	Usefulness to Civilian Reactors			Likelihood of Actual Technology Transfer
	Water 1a	Gas 1b	Metal 1c	2
1. Electromagnetic pumps	1	1	4	3
2. Experimental liquid metal loops	1	1	4	3
3. Experimental gas loops	1	4	1	3
4. Far off-normal experiments (e.g., boiling liquid metals)	1	1	3	2
5. High performance, high temperature gas circulators	1	4	1	3
6. High heat-flux models	1	3	3	3

HEAT TRANSPORT (continued)

	Usefulness to Civilian Reactors			Likelihood of Actual Technology Transfer
	Water 1a	Gas 1b	Metal 1c	2
7. High temperature heat pipes	1	2	2	2
8. High temperature pipes and valves	1	3	3	3
9. Improved heat transfer correlations	2	3	3	3
10. Liquid metal cooling technology	1	1	4	3
11. Knowledge of mass transfer, erosion and corrosion in liquid metal and hot gas systems	1	3	4	3
12. High temperature two fluid heat exchangers	1	3	3	2

3. Considering all of the potential advances listed above, in your opinion, how useful, overall, will advances in this topic area be to terrestrial reactor development? (Check one.) (54)

1. [ ] Little or No Use
2. [ ] Somewhat Useful
*3. [x] Moderately Useful
4. [ ] Very Useful
5. [ ] Extremely Useful

4. In your opinion, what is the overall likelihood of technology transfer in this topic area? (Check one.) (55)

1. [ ] Little or No Likelihood
2. [ ] Somewhat Likely
*3. [x] Moderately Likely
4. [ ] Very Likely
5. [ ] Extremely Likely

*Median response.

ENERGY CONVERSION

ID (1-3)
CDC (4)

Are you at least moderately knowledgeable about this topic? [X] Yes (5)

[_] No (SKIP THIS TOPIC)

Listed below are the specific developments in this topic area that experts believed might occur as a result of space nuclear reactor power systems R&D. Please assume that all of the developments are equally likely to occur. Then select the number from the rating scale below that comes closest to your response to the following questions:

1. How useful would the development be to light water, high temperature gas, and liquid metal civilian reactor development? (Enter one number for each reactor type.)

2. What is the likelihood that the development will actually transfer from the space programs to terrestrial reactor development? (Enter one number.) (6-53)

Rating Scale

1 = Little or no usefulness/likelihood
2 = Somewhat useful/likely
3 = Moderately useful/likely
4 = Greatly useful/likely
5 = Extremely useful/likely
6 = No Basis to Judge

	Usefulness to Civilian Reactors			Likelihood of Actual Technology Transfer
	Water 1a	Gas 1b	Metal 1c	2
1. Solid state energy conversion	1	1	2	2
2. Improved direct conversion efficiency	1	2	2	2
3. Advanced thermionic convertors	1	1	2	2
4. Advanced MHD generation technology	1	2	2	2
5. Advanced thermoelectrics	1	1	2	2
6. Ceramic turbine blades	1	4	2	3
7. Ceramic heat transfer structures	1	3	2	2
8. Experience with liquid metal Rankine cycle	1	1	3	2

ENERGY CONVERSION (continued)

	Usefulness to Civilian Reactors			Likelihood of Actual Technology Transfer
	Water 1a	Gas 1b	Metal 1c	2
9. High power Stirling engines	1	2	2	2
10. High temperature Brayton cycle machines	1	4	1	3
11. High temperature gas turbines	1	4	1	3
12. Hydrogen turbomachinery	1	2	1	2

3. Considering all of the potential advances listed above, in your opinion, how useful, overall, will advances in this topic area be to terrestrial reactor development? (Check one.) (54)

1. [_] Little or No Use
* 2. [X] Somewhat Useful
3. [_] Moderately Useful
4. [_] Very Useful
5. [_] Extremely Useful

4. In your opinion, what is the overall likelihood of technology transfer in this topic area? (Check one.) (55)

1. [_] Little or No Likelihood
*2. [X] Somewhat Likely
3. [_] Moderately Likely
4. [_] Very Likely
5. [_] Extremely Likely

*Median response.

NUCLEAR INSTRUMENTATION

ID (1-3)
CDD (4)

Are you at least moderately knowledgeable about this topic? [X] Yes (5)

[_] No (SKIP THIS TOPIC)

Listed below are the specific developments in this topic area that experts believed might occur as a result of space nuclear reactor power systems R&D. Please assume that all of the developments are equally likely to occur. Then select the number from the rating scale below that comes closest to your response to the following questions:

1. How useful would the development be to light water, high temperature gas, and liquid metal civilian reactor development? (Enter one number for each reactor type.)

2. What is the likelihood that the development will actually transfer from the space programs to terrestrial reactor development? (Enter one number.) (6-53)

Rating Scale

1 = Little or no usefulness/likelihood
2 = Somewhat useful/likely
3 = Moderately useful/likely
4 = Greatly useful/likely
5 = Extremely useful/likely
6 = No Basis to Judge

	Usefulness to Civilian Reactors			Likelihood of Actual Technology Transfer
	Water 1a	Gas 1b	Metal 1c	2
1. Advanced (high temperature, wide range, high fluence) flux monitors	3	4	4	3
2. Auto-reconfigurable instrumentation	3	3	3	3
3. Fast response neutron detectors	2	3	3	3
4. High temperature instrumentation (flow meters, pressure sensors, etc.)	2	4	4	4
5. Improved cabling, insulation	3	4	4	4
6. Long-life thermocouples	3	4	4	4

NUCLEAR INSTRUMENTATION (continued)

	Usefulness to Civilian Reactors			Likelihood of Actual Technology Transfer
	Water 1a	Gas 1b	Metal 1c	2
7. Radiation-hardened detectors	4	4	4	4
8. Radiation-hardened electronics	3	4	4	4
9. Self-diagnostic instrumentation	4	4	4	4
10.Telemetric instrumentation	3	3	3	3
11.Fiber-optic data transmission	3	4	4	4
12.Multiplexers	3	4	4	4

3. Considering all of the potential advances listed above, in your opinion, how useful, overall, will advances in this topic area be to terrestrial reactor development? (Check one.) (54)

1. [_] Little or No Use
2. [_] Somewhat Useful
3. [_] Moderately Useful

*4. [X] Very Useful

5. [_] Extremely Useful

4. In your opinion, what is the overall likelihood of technology transfer in this topic area? (Check one.) (55)

1. [_] Little or No Likelihood
2. [_] Somewhat Likely

* 3. [X] Moderately Likely

4. [_] Very Likely
5. [_] Extremely Likely

*Median response.

CONTROL METHODOLOGY

ID (1-3)
CDE (4)

Are you at least moderately knowledgeable about this topic? [X] Yes (5)

[_] No (SKIP THIS TOPIC)

Listed below are the specific developments in this topic area that experts believed might occur as a result of space nuclear reactor power systems R&D. Please assume that all of the developments are equally likely to occur. Then select the number from the rating scale below that comes closest to your response to the following questions:

1. How useful would the development be to light water, high temperature gas, and liquid metal civilian reactor development? (Enter one number for each reactor type.)

2. What is the likelihood that the development will actually transfer from the space programs to terrestrial reactor development? (Enter one number.) (6-37)

Rating Scale

1 = Little or no usefulness/likelihood
2 = Somewhat useful/likely
3 = Moderately useful/likely
4 = Greatly useful/likely
5 = Extremely useful/likely
6 = No Basis to Judge

	Usefulness to Civilian Reactors			Likelihood of Actual Technology Transfer
	Water 1a	Gas 1b	Metal 1c	2
1. Adaptive control techniques	3	3	3	3
2. Application of artificial intelligence and expert systems	3	4	4	3
3. Development and demonstration of autonomous control hardware and software	3	3	4	3
4. Digital control systems	4	4	4	3
5. Distributed control systems	3	3	3	3

CONTROL METHODOLOGY (continued)

	Usefulness to Civilian Reactors			Likelihood of Actual Technology Transfer
	Water 1a	Gas 1b	Metal 1c	2
6. Fault tolerant computers	4	4	4	4
7. Improved operator interfaces	4	4	4	4
8. Self-diagnostic control systems	4	4	4	4

3. Considering all of the potential advances listed above, in your opinion, how useful, overall, will advances in this topic area be to terrestrial reactor development? (Check one.) (38)

1. [_] Little or No Use
2. [_] Somewhat Useful
3. [_] Moderately Useful
*4. [x] Very Useful
5. [_] Extremely Useful

4. In your opinion, what is the overall likelihood of technology transfer in this topic area? (Check one.) (39)

1. [_] Little or No Likelihood
2. [_] Somewhat Likely
3. [_] Moderately Likely
* 4. [x] Very Likely
5. [_] Extremely Likely

*Median response.

SAFETY

ID (1-3)
CDF (4)

Are you at least moderately knowledgeable about this topic? [X] Yes (5)

[_] No (SKIP THIS TOPIC)

Listed below are the specific developments in this topic area that experts believed might occur as a result of space nuclear reactor power systems R&D. Please assume that all of the developments are equally likely to occur. Then select the number from the rating scale below that comes closest to your response to the following questions:

1. How useful would the development be to light water, high temperature gas, and liquid metal civilian reactor development? (Enter one number for each reactor type.)

2. What is the likelihood that the development will actually transfer from the space programs to terrestrial reactor development? (Enter one number.) (6-53)

Rating Scale

1 = Little or no usefulness/likelihood
2 = Somewhat useful/likely
3 = Moderately useful/likely
4 = Greatly useful/likely
5 = Extremely useful/likely
6 = No Basis to Judge

	Usefulness to Civilian Reactors			Likelihood of Actual Technology Transfer
	Water 1a	Gas 1b	Metal 1c	2
1. Advances in passive safety design methods	3	3	3	3
2. Benchmark tests	2	2	2	2
3. Fault-tolerant controls	3	3	3	3
4. Gradual degradation	2	2	3	2
5. Improved analytic techniques--neutronics	2	2	2	3
6. Improved analytic techniques--thermal-hydraulics	2	3	3	3

SAFETY (continued)

	Usefulness to Civilian Reactors			Likelihood of Actual Technology Transfer
	Water 1a	Gas 1b	Metal 1c	2
7. Improved probabilistic risk analysis techniques	3	3	3	3
8. Improved seismic codes (based on high-g codes)	2	2	2	2
9. Methods to preserve structural integrity	3	3	3	3
10. Remote maintenance and repair methods	3	3	3	3
11. Utilization of Integrated Design Methodology	3	3	3	2
12. Criticality prevention devices or techniques	2	2	2	2

3. Considering all of the potential advances listed above, in your opinion, how useful, overall, will advances in this topic area be to terrestrial reactor development? (Check one.) (54)

1. [ ] Little or No Use
2. [ ] Somewhat Useful
*3. [X] Moderately Useful
4. [ ] Very Useful
5. [ ] Extremely Useful

4. In your opinion, what is the overall likelihood of technology transfer in this topic area? (Check one.) (55)

1. [ ] Little or No Likelihood
2. [ ] Somewhat Likely
* 3. [X] Moderately Likely
4. [ ] Very Likely
5. [ ] Extremely Likely

*Median response.

RELIABILITY

ID (1-3)
CDG (4)

Are you at least moderately knowledgeable about this topic? [X] Yes (5)

[_] No (SKIP THIS TOPIC)

Listed below are the specific developments in this topic area that experts believed might occur as a result of space nuclear reactor power systems R&D. Please assume that all of the developments are equally likely to occur. Then select the number from the rating scale below that comes closest to your response to the following questions:

1. How useful would the development be to light water, high temperature gas, and liquid metal civilian reactor development? (Enter one number for each reactor type.)

2. What is the likelihood that the development will actually transfer from the space programs to terrestrial reactor development? (Enter one number.) (6-41)

Rating Scale

1 = Little or no usefulness/likelihood
2 = Somewhat useful/likely
3 = Moderately useful/likely
4 = Greatly useful/likely
5 = Extremely useful/likely
6 = No Basis to Judge

	Usefulness to Civilian Reactors			Likelihood of Actual Technology Transfer
	Water 1a	Gas 1b	Metal 1c	2
1. Advances in automated operation	3	3	3	3
2. Advances in high reliability software (develop, verify, validate)	3	3	4	3
3. Fabrication and testing of high reliability materials	2	3	3	3
4. High temperature tribology	1	3	3	3
5. Improved design techniques	2	2	2	3
6. Increased lifetime of high temperature and high dose components	2	3	3	3

RELIABILITY (continued)

	Usefulness to Civilian Reactors Water 1a	Gas 1b	Metal 1c	Likelihood of Actual Technology Transfer 2
7. "Life-cycle" approach to QA	2	3	3	2
8. Lifetime testing experience	2	3	3	3
9. QA/QC techniques	2	3	3	2

3. Considering all of the potential advances listed above, in your opinion, how useful, overall, will advances in this topic area be to terrestrial reactor development? (Check one.) (42)

1. [_] Little or No Use
2. [_] Somewhat Useful
*3. [X] Moderately Useful
4. [_] Very Useful
5. [_] Extremely Useful

4. In your opinion, what is the overall likelihood of technology transfer in this topic area? (Check one.) (43)

1. [_] Little or No Likelihood
2. [_] Somewhat Likely
* 3. [X] Moderately Likely
4. [_] Very Likely
5. [_] Extremely Likely

*Median response.

FABRICATION

Are you at least moderately knowledgeable about this topic? [X] Yes (44)

[ ] No (SKIP THIS TOPIC)

Listed below are the specific developments in this topic area that experts believed might occur as a result of space nuclear reactor power systems R&D. Please assume that all of the developments are equally likely to occur. Then select the number from the rating scale below that comes closest to your response to the following questions:

1. How useful would the development be to light water, high temperature gas, and liquid metal civilian reactor development? (Enter one number for each reactor type.)

2. What is the likelihood that the development will actually transfer from the space programs to terrestrial reactor development? (Enter one number.) (45-64)

Rating Scale

1 = Little or no usefulness/likelihood
2 = Somewhat useful/likely
3 = Moderately useful/likely
4 = Greatly useful/likely
5 = Extremely useful/likely
6 = No Basis to Judge

	Usefulness to Civilian Reactors			Likelihood of Actual Technology Transfer
	Water 1a	Gas 1b	Metal 1c	2
1. Fabrication methods for fuel systems	1	3	3	3
2. Fabrication methods for high temperature heat pipes	1	2	2	2
3. Fabrication methods for refractories	1	3	3	3
4. Fabrication methods for thermoelectric and thermionic materials	1	1	2	2
5. Modularized manufacturing	2	2	3	2

FABRICATION (continued)

3. Considering all of the potential advances listed above, in your opinion, how useful, overall, will advances in this topic area be to terrestrial reactor development? (Check one.) (65)

1. [ ] Little or No Use
*2. [X] Somewhat Useful
3. [ ] Moderately Useful
4. [ ] Very Useful
5. [ ] Extremely Useful

4. In your opinion, what is the overall likelihood of technology transfer in this topic area? (Check one.) (66)

1. [ ] Little or No Likelihood
* 2. [X] Somewhat Likely
3. [ ] Moderately Likely
4. [ ] Very Likely
5. [ ] Extremely Likely

*Median response.

FACILITIES

ID (1-3)
CDH (4)

Are you at least moderately knowledgeable about this topic? [X] Yes (5)

[ ] No (SKIP THIS TOPIC)

Listed below are the specific developments in this topic area that experts believed might occur as a result of space nuclear reactor power systems R&D. Please assume that all of the developments are equally likely to occur. Then select the number from the rating scale below that comes closest to your response to the following questions:

1. How useful would the development be to light water, high temperature gas, and liquid metal civilian reactor development? (Enter one number for each reactor type.)

2. What is the likelihood that the development will actually transfer from the space programs to terrestrial reactor development? (Enter one number.) (6-25)

Rating Scale

1 = Little or no usefulness/likelihood
2 = Somewhat useful/likely
3 = Moderately useful/likely
4 = Greatly useful/likely
5 = Extremely useful/likely
6 = No Basis to Judge

	Usefulness to Civilian Reactors			Likelihood of Actual Technology Transfer
	Water 1a	Gas 1b	Metal 1c	2
1. Cleaning and purification facilities for liquid metals	1	1	3	2
2. Development of fuel fabrication and test facilities	1	3	3	2
3. Development of heatpipe fabrication and test facilities	1	2	2	2
4. Development of high-temperature creep test facilities	1	3	3	3
5. Development of testing equipment and material performance data in high radiation and temperature	2	3	3	3

FACILITIES (continued)

3. Considering all of the potential advances listed above, in your opinion, how useful, overall, will advances in this topic area be to terrestrial reactor development? (Check one.) (26)

1. [ ] Little or No Use
2. [ ] Somewhat Useful
*3. [X] Moderately Useful
4. [ ] Very Useful
5. [ ] Extremely Useful

4. In your opinion, what is the overall likelihood of technology transfer in this topic area? (Check one.) (27)

1. [ ] Little or No Likelihood
2. [ ] Somewhat Likely
* 3. [X] Moderately Likely
4. [ ] Very Likely
5. [ ] Extremely Likely

*Median response.

MODELING/ANALYSIS

Are you at least moderately knowledgeable about this topic? [x] Yes (28)

[_] No (SKIP THIS TOPIC)

Listed below are the specific developments in this topic area that experts believed might occur as a result of space nuclear reactor power systems R&D. Please assume that all of the developments are equally likely to occur. Then select the number from the rating scale below that comes closest to your response to the following questions:

1. How useful would the development be to light water, high temperature gas, and liquid metal civilian reactor development? (Enter one number for each reactor type.)

2. What is the likelihood that the development will actually transfer from the space programs to terrestrial reactor development? (Enter one number.) (29-72)

Rating Scale

1 = Little or no usefulness/likelihood
2 = Somewhat useful/likely
3 = Moderately useful/likely
4 = Greatly useful/likely
5 = Extremely useful/likely
6 = No Basis to Judge

	Usefulness to Civilian Reactors			Likelihood of Actual Technology Transfer
	Water 1a	Gas 1b	Metal 1c	2
1. Advanced computing and computers	3	3	3	3
2. Improved reliability analysis	3	3	3	3
3. Improved thermal-hydraulics codes	2	3	3	3
4. Models for fuel performance	2	3	3	3
5. Models for fiber-reinforced materials	1	3	2	2
6. Neutronics of small leaky cores	1	1	2	2

MODELING/ANALYSIS (continued)

	Usefulness to Civilian Reactors			Likelihood of Actual Technology Transfer
	Water 1a	Gas 1b	Metal 1c	2
7. Reactor core analysis	2	3	3	2
8. Stress analysis in transient operation	2	3	3	3
9. System-level design optimization codes	2	2	3	2
10.Verification of neutron kinetics codes	2	2	3	2
11.Advanced vectorized computer modeling	2	2	2	2

3. Considering all of the potential advances listed above, in your opinion, how useful, overall, will advances in this topic area be to terrestrial reactor development? (Check one.) (73)

1. [ ] Little or No Use
2. [ ] Somewhat Useful
*3. [X] Moderately Useful
4. [ ] Very Useful
5. [ ] Extremely Useful

4. In your opinion, what is the overall likelihood of technology transfer in this topic area? (Check one.) (74)

1. [ ] Little or No Likelihood
2. [ ] Somewhat Likely
* 3. [X] Moderately Likely
4. [ ] Very Likely
5. [ ] Extremely Likely

*Median response.

Part III

SUMMARY

ID (1-3)
CDI (4)

1. Overall, in your opinion, how likely is it that any space nuclear reactor power systems R & D will result in significant scientific breakthroughs or technological advancements? (Check one.) (5)

	A;	B;	C%
1. [_] Little or no likelihood	6;	3;	17
2. [_] Somewhat likely	23;	25;	17
3. [_] Moderately likely	19;	12;	44*
4. [_] Very likely	34*;	37*;	22
5. [_] Extremely likely	19;	24;	—

2. Overall, in your opinion, how useful would any advancements that did occur as a consequence of space nuclear reactor power systems R & D be to the development of civilian terrestrial reactors? (Check one.) (6)

	A;	B;	C%
1. [_] Of little or no use	9;	9;	11
2. [_] Somewhat useful	33;	33;	33
3. [_] Moderately useful	31*;	28*;	44*
4. [_] Very useful	24;	28;	11
5. [_] Extremely useful	2;	3;	--

3. Overall, in your opinion, how likely is it that technology transfer will actually occur from space nuclear reactor power systems R & D to civilian terrestrial reactor development? (Check one.) (7)

	A;	B;	C%
1. [_] Little or no likelihood	14;	11;	22
2. [_] Somewhat likely	35;	36;	33*
3. [_] Moderately likely	25*;	23*;	33
4. [_] Very likely	19;	21;	11
5. [_] Extremely likely	6;	7;	—

4. Comments. Please use this space to provide any additional comments you may have concerning this technology transfer issue. We also encourage you to send us any additional information (documents, studies, papers, etc.) that you believe may be pertinent to this issue. (8)

KEY

A = All respondents.

B = Respondents affiliated with space power programs.

C = Respondents not affiliated with space power programs.

NOTE: Percentages may not add to 100 because of rounding.

*Median response.

5. Please write your name and telephone number below in case we need to contact you for clarification of your responses to this questionnaire. (Names and affiliations will not be published in our final report.)

Name: ____________________

Phone: ____________________

Thank you for your cooperation.

GAO Comments

1. For questions 7-10, presented on pp. 36-39, numbers represent the percent of respondents giving the indicated response. Numbers may not add to 100 percent because of rounding. Questions 1-6 were used to determine the respondents' expertise and work affiliation and therefore are not included in this appendix.

2. Numbers presented in this table represent median responses.

3. Respondents were also asked the likelihood of actual transfer of this technology (question no. 2). In answering this question the respondents assumed that space power research results would be freely disseminated.

4. Responses entered for part II, on the following pages, are median responses.

Comments From the Department of Energy

Department of Energy
Washington, DC 20585

OCT 13 1988

Mr. Keith O. Fultz
Senior Associate Director
Resources, Community, and
Economic Development Division
U.S. General Accounting Office
Washington, DC 20548

Dear Mr. Fultz:

The Department of Energy (DOE) appreciates the opportunity to review and comment on the General Accounting Office (GAO) draft report entitled "Nuclear Science: Usefulness of Space Power Research to Ground-Based Nuclear Reactor Systems."

Overall, the report is well done and we concur with its contents. Corrections and suggested editorial changes are being provided separately to Mr. James H. New.

DOE hopes that these comments will be helpful to GAO in their preparation of the final report.

Sincerely,

for

Lawrence F. Davenport
Assistant Secretary
Management and Administration

Comments From the Department of Defense

DEPARTMENT OF DEFENSE
STRATEGIC DEFENSE INITIATIVE ORGANIZATION
WASHINGTON, DC 20301-7100

30 September 1988

TA

Mr. Keith O. Fultz
Senior Associate Director
Resources, Community, and
Economic Development Division
U. S. General Accounting Office
Washington, DC 20548

Dear Mr. Fultz:

This is the Department of Defense (DoD) response to the General Accounting Office (GAO) draft report. "NUCLEAR SCIENCE: Usefulness of Space Power Research to Groundbased Nuclear Reactor Systems." dated September 2, 1988 (GAO Code 301772/OSD Case 7756.

The DoD has reviewed the report and concurs with the GAO findings and conclusions. The Department appreciates the opportunity to comment on this draft report.

Sincerely,

EUGENE FOX
Major General, USA
Acting Deputy Director

Major Contributors to This Report

Resources, Community, and Economic Development Division, Washington, D.C.	Keith O. Fultz, Senior Associate Director, (202) 275-1441 James H. New II, Group Director Emi Nakamura, Assignment Manager Jack H. Paul, Evaluator-in-Charge Duane G. Fitzgerald, Nuclear Engineer Carolyn Boyce, Social Science Analyst Carol H. Shulman, Reports Analyst
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