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AN ASSESSMENT OF SPACE REACTOR TECHNOLOGY NEEDS AND RECOMMENDATIONS FOR DEVELOPMENT

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Abstract

In order to provide a strategy for space reactor technology development, the Defense Nuclear Agency (DNA) has authorized a brief review of potential national needs that may be addressed by space reactor systems. A systematic approach was used to explore needs at several levels that are increasingly specific.

- Level 0 - General Trends and Issues
- Level 1 - Generic Space Capabilities to Address Trends
- Level 2 - Requirements to Support Capabilities
- Level 3 - System Types Capable of Meeting Requirements
- Level 4 - Generic Reactor System Types
- Level 5 - Specific Baseline Systems

Using these findings, a strategy was developed to support important space reactor technologies within a limited budget. A preliminary evaluation identified key technical issues and provide a prioritized set of candidate research projects. The evaluation of issues and the recommended research projects are presented in a companion paper.

INTRODUCTION

Effective in FY 1996, Defense Nuclear Agency (DNA) has assumed responsibility for the TOPAZ International Program (TIP) from the Ballistic Missile Defense Organization (BMDO); DNA has managed the TIP program for BMDO during FY 1995. In the absence of a flight program, DNA is redirecting the TIP toward a broader-based R&D program. DNA authorized a brief review of potential national needs that may be addressed by space reactor systems. Using these findings, a strategy was developed to support important space reactor technologies within a limited budget. A preliminary evaluation was also conducted to identify key issues and provide a prioritized set of candidate research projects to be undertaken as part of the DNA program. The evaluation of issues and the recommended research projects are presented in a companion paper (Wiley and Marshall 1996).

SYSTEMATIC NEEDS ASSESSMENT

A systematic approach has been developed to review national needs that may require space reactor capabilities. This review was also used to explore reactor technologies and to suggest an R&D strategy to address reactor technology needs. A top down approach was used, as follows:

- Level 0 General Trends and Issues;
  - Defense related
  - Important civilian sector trends
- Level 1 Generic space capabilities to address trends/issues;
  - Space based
  - Advanced propulsion
- Level 2 Requirements to support capabilities;
  - Electrical power systems
  - Propulsion systems

DISCLAIMER

- Level 3 System types capable of meeting requirements (conventional, nuclear);
- Level 4 Generic reactor system types best suited to meet requirements;
- Level 5 Specific baseline systems.

Level 0: General Trends and Issues

A number of important trends and issues for the defense and civilian sectors were identified that may ultimately require space reactor capabilities. The defense related trends and issues include:

D1 - Regional conflicts, such as the Gulf War;
D2 - Proliferation of weapons of mass destruction;
D3 - Increasing cruise missile threat to U.S. cities and to naval forces;
D4 - Increased U.S. reliance on smart weaponry;
D5 - Ability to conduct all-conditions combat;
D6 - Threats from international terrorism;
D7 - Increasing concern for launch capability vulnerability due to a limited variety of heavy-lift launch vehicles (access to space);
D8 - Budget constraints on using space assets as a force multiplier (due to high launch and deployment costs).

Important civilian sector trends include:

C1 - International competition for space delivery services;
C2 - Continued space science and exploration, including exploration of the moon, Mars, and the outer planets;
C3 - Global concerns, such as civilian air traffic control, weather predictions, and environmental monitoring;
C4 - Advanced broadcasting and communication needs, such as direct broadcast TV;
C5 - International drug trafficking.

Defense trends D1 through D6 and civilian trends C2 through C5 may be addressed by advanced space based capabilities. Defense trends D7 and D8 and civilian trends C1 and C2 may be addressed by advanced propulsion capabilities.

The trends and issues identified above were selected from a much longer list. The trends met the criteria of being important and of possibly requiring space reactor capabilities. This selection does not mean that only space reactors can be used to address these issues, or that space capabilities provide the best solution. The list simply identifies national issues that may be addressed by capabilities that require space reactors. In addition to the references given under level 2, the most important references for level 0 include: (BMD *Monitor* 1995, Garell 1994, Kelly 1993, and AIR University 1994). Technology advances have established a trend toward smaller, lighter satellites requiring less power. This trend runs counter to the trends listed. The significance of the trend toward smaller low-power systems will be discussed under level 2.

Leve l: Generic Space Capabilities

Space Based Capabilities

All of the Level 0 trends and issues could be at least partly addressed by space capabilities. Potential space capabilities and the trends and issues they may address are presented in Tables 1 and 2.

TABLE 1. Space-Based Capabilities that Could Address Level-0 Defense Trends and Issues.

Trends →	D1	D2	D3	D4	D5	D6
↓ Space-Based Capabilities	Regional Conflicts	Proliferation of Weapons of Mass Destruction	Cruise Missile Threat	Smart Weapons	All Conditions Combat	International Terrorism
Advanced Surveillance	✓	✓	✓	✓	✓	✓
Advanced Science Satellites & Probes						
Advanced Surface Power						
Advanced Processing, Communi-cation	✓	•	✓	✓	✓	•
Advanced Earth Monitoring					✓	

✓ = Clear Application • = Possible Application

TABLE 2. Space-Based Civilian Capabilities that Could Address Level 0 Civilian Trends and Issues.

Trends →	C2	C3	C4	C5
↓ Space-Based Capabilities	Space Science/Exploration	Global Concerns	Civilian Broadcasting/ Communication	Drug Trafficking
Advanced Surveillance		✓		✓
Advanced Science Satellites & Probes	✓			
Advanced Surface Power	✓			
Advanced Processing, Communication		•	✓	•
Advanced Earth Monitoring		✓		

✓ = Clear Application • = Possible Application

Advanced surveillance capabilities, such as a space based radar system could obtain information on battlefield conditions information for regional conflicts, all-conditions combat and may enhance smart weaponry capabilities. Advanced surveillance could also detect cruise missile threats, monitor both authorized and unauthorized air traffic (air traffic control, drug trafficking, remote Lear-jet terrorist attack, etc.) and obtain evidence of weapons of mass destruction production (trends D1 though D6, C3 and C5).

Advanced science satellites and probes can be used for space science and exploration and may require significant power for some missions. Advanced surface power capabilities will be required to meet the high power requirements of human habitation on the moon or Mars (trend C2).

Advanced processing and communication capabilities could provide space acquired and processed battlefield information broadcast to mobile forces, without the need for ground based processing. Space based high volume, high rate communication may be of value for civilian broadcasting and communication (direct broadcast TV, information superhighway) and for other trends indicated in Tables 1A and 1B (trends D1 through D6 and C3 through C5). An advanced Earth monitoring capability could include advanced meteorology for both combat and civilian purposes (D5 and C3).

Advanced Propulsion

A list of potential advanced propulsion capabilities that may address space transportation issues is presented in Table 3. The capabilities include high-thrust/high-specific Impulse (Isp) systems, very high Isp/low thrust (electric propulsion) systems, bimodal high Isp/moderate thrust systems, and dual use very high Isp/low thrust systems. These systems can provide a Low Earth Orbit (LEO) to Geostationary Earth Orbit (GEO) tug or electric power plus propulsion capability (for LEO/GEO transfer, station keeping, station change). Multiple-use capabilities (tug, bimodal, dual use) could reduce costs for military missions and increase U.S. competitiveness for space delivery services. A LEO to GEO tug could also increase launch vehicle options because launch vehicles would only be required to place payloads in LEO, thus addressing military access to space issues. Hence, trends D7, D8, and C1 will be addressed by these capabilities. High thrust, high Isp or very high Isp (low thrust) capabilities will most likely be required for piloted missions to Mars and for other ambitious space exploration missions (C2).

TABLE 3. Advanced Propulsion Capabilities that Could Address Space Transportation Trends and Issues.

	Trends	D7	D8	C1	C2
Propulsion Only	Advanced Propulsion Capability	Access to Space for Military	Budget Constraints	Competition for Space Delivery	Continued Space Science
	High Thrust, Isp	✓	✓	✓	✓
	Very High Isp, Low Thrust	✓	✓	✓	✓
Propulsion and Electrical Power	Bimodal High Isp, Moderate Thrust	✓	✓	✓	✓
	Dual Use High Isp, Low Thrust	✓	✓	✓	✓

Level 2: Requirements to Support Capabilities

In the absence of a defined mission, it is difficult to establish a list of specific system requirements. In order to obtain some bounds on the range of potential requirements, the power or propulsion requirements from studies for specific applications were reviewed for each of the capabilities identified in Level 1. This review used references; (Ball 1994, Herrera and Kennedy 1993, Lenard and Walker 1994, Peterson 1994, SMCXP 1991, Weiss 1995, NASA and DoD 1992, and Bennett et al. 1993). These references provided projections of power or propulsion requirements for specific systems for each capability. These requirements were then judged for their applicability to near-term, mid-term, or far-term systems (referred to as generation 1,2, and 3 respectively). Because of the significant uncertainty in when these capabilities will be needed, no attempt was made to quantify what is meant by a first, second, or third generation; instead, they are defined only by a range of successively more demanding requirements.

Ranges of power and propulsion requirements are presented in Tables 4 and 5. Although other requirements will be established for specific missions (reliability, lifetime, etc.), other requirements were either not sufficiently resolved or not sufficiently important to our objectives to be included in this exercise. As previously mentioned, advances in technology have established a trend toward smaller, lighter satellites requiring less power. As a consequence, some of the projected requirements may be reduced. In addition, some of these capabilities may never be pursued. On the other hand, the need for other, now unforeseen, capabilities with demanding requirements may develop and requirements for some of the projected capabilities may not be significantly affected by technology advances. The requirements presented in Tables 4 and 5 should be viewed as approximate ranges of requirements for a variety of potential future space capabilities.

TABLE 4. Ranges of Electrical Power Requirements to Support Capabilities.

		Capabilities Supported Requiring Electrical Power				
Generation	Required Power	Advanced Surveillance	Science Satellites	Surface Power	Processing Communications	Earth Monitoring
1	1-10 kWe	✓	✓	✓	✓	✓
2	10-150 kWe	✓	✓	✓	✓	✓
3	150 kWe - >1 MWe	✓	?	✓	?	✓

TABLE 5. Ranges of Propulsion Requirements to Support Capabilities.

				Advanced Propulsion Capabilities Supported			
Propulsion Type	Generation	Required Power	Isp (sec)	High Thrust	High Isp	Bimodal	Dual Use
Thermal	1	200 kWth -10 MWth	800 - 900	✓		✓	
	2	10 MWth - 100s MWth	900 - 1000	✓		✓	
	3	100 MWth - 1000 MWth	1000 - 1100	✓		✓	
Electrical	1	5 - 10 kWe	1000s		✓	*	✓
	2	10 -150 kWe	1000s		✓	*	✓
	3	150 kWe - >1 MWe	1000s		✓	*	✓

* Electrical power needed, but not for propulsion

Level 3: System Types to Support Requirements

Several types of systems have been assessed for their ability to meet the requirements presented in Level 2. These include solar power (photovoltaic and thermal), nuclear isotopic sources, nuclear reactors (electrical power, bi-modal, and thermal propulsion), and chemical rockets. The assessment was based on previous studies (e.g., Buden and Albert 1987) in which system mass was a dominant concern. For high-Isp/high- thrust propulsion, the potential for achieving high-Isp and thrust was also a deciding factor. Other issues (such as development requirements and safety) were also considered.

The results of this assessment are presented in Table 6. Reactor electrical power systems (including electric propulsion) are scored low relative to solar for first generation systems because, in most cases, they provide no clear mass advantage and present greater development and public acceptance challenges.

A bimodal reactor system, however, could provide sufficient economic incentive to merit development and use; consequently, bimodal systems were scored medium (M) for applicability. Electrical power space reactors become strong contenders to meet generation 2 requirements, especially at the high end of the power range, because their system mass advantage generally becomes significant above ~50 kWe. For generation 3, space reactors become the most logical (and perhaps only) choice.

For high-thrust/high-Isp propulsion, nuclear reactor thermal propulsion is the only choice. Chemical rockets cannot provide the indicated Isp and electric propulsion cannot provide high thrust. Although only nuclear thermal propulsion can provide the high-Isp/high-thrust specified, first generation systems may not show enough of an advantage relative to chemical rockets (low Isp) to merit a high (H) score. Hence, (M) was awarded for nuclear thermal propulsion for generation 1 and (H) was awarded for generations 2 and 3.

TABLE 6. Applicability of System Types to Meet Requirements.

		Importance for Electrical Power (Including Electric Propulsion)			Importance for Thermal Propulsion		
	(Isp) Power →	1 - 10 kWe	10 - 150 kWe	150 kWe - >1 MWe	(800-900s) 0.2 - 10 MWth	(900-1000s) ~100's MWth	(1000-1100s) ~1000 MWth
	Potential Power or Propulsion System ↓	Generation 1	Generation 2	Generation 3	Generation 1	Generation 2	Generation 3
	Solar Power	H	M	L	?	---	---
N	**Isotopic**	M	---	---	---	---	---
U	**Reactor**	L	M	H	---	---	---
C L	**Bimodal Reactor**	M	H	H	M	H	H
E A R	**Thermal Propulsion Reactor**	---	---	---	M	H	H
	Chemical Rocket	---	---	---	---	---	---

H = High M = Medium L = Low

Level 4: Types of Reactor Systems

Given that there will be a need for space reactor systems, the next step is to determine which types of reactor systems are best suited for development. Typically, types of reactor systems are defined by the type of power conversion used (e.g., thermionic, thermoelectric). A number of criteria were used to assess a best choice for electrical power reactor systems, such as technical maturity, breadth of application, near-term applicability. However, in the absence of a defined mission, and given the early stage of development of the numerous options, no clear choice based on the best power conversion system choice emerged.

TABLE 7. Generic Reactor Power System Type Defined by Most Common Features.

	System Material			Primary Coolant			Coolant Transport			Fuel			Fuel Geometry			Clad Matrix			Moderator			Power Conversion							Balance of System			
Electrical Power System Type	Stainless Steel	Super Alloy	Refractory Metal	NaK, Na, K	Li	He - Xe	EM or TEM Pump	Heat Pipe	Compressor	UO_2	UN	Other	Pin	Block	Other	Stainless Steel	Refractory	Other	Zr H_2	None	Other	Thermionic	Thermoelectric	AMTEC	HX/Brayton	Stirling	Direct Brayton	Other	Radiator	Shield	I + C	
Low-Temperature Liquid Metal Cooled System	X	X		X			X	X		X	X	X	X	X	X	X			X	X	X	X	X	X	X	X		X	X	X	X	
High-Temperature Liquid Metal			X		X		X	X			X	X	X	X	X		X	X		X		X	X	X	X	X		X	X	X	X	Electrical Power
Cooled System Gas Cooled System		X	X			X			X	X	X	X	X	X	X	X	X	X	X	X	X				X		X		X	X	X	
Solid Core Reactor				H_2			Turbo Pump			X	X	X		X	X	X	X	X	X	X	X	Nozzle							X	X	X	Thermal Propulsion

A second attempt to explore options defined systems by their most common features (Table 7). Note that the electrical power system options are defined by the type of coolant used: Low Temperature Liquid Metal (LTLM), High Temperature Liquid Metal (HTLM), and Gas Cooled Electric Power Reactors, and Hydrogen cooled Nuclear Thermal Propulsion (NTP) reactors. This approach has the advantage of emphasizing generic technologies that can be developed to benefit a variety of options. In the absence of a clear choice for a power conversion option, this approach avoids defining a power conversion choice when a best choice is not known. On the other hand, it leaves too many options to be developed with a small budget.

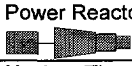
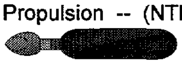
Level 5: Specific Baseline Systems

Three baseline systems were chosen to avoid dilution of scarce funding, while keeping other options open. However, these baseline systems could not be chosen from the above assessment, because none of the technologies clearly stood out as best choices. In order to make a selection, two other criteria were considered:

1. Continue development of technologies in which a significant base has been recently established in order to make the most effective use of scarce funds, or
2. Develop new technologies a level of technical maturity equal to the more developed technologies.

Given the scarcity of available funds, option (1) seemed to be the more practical and was used to select three baseline systems, they are: an in-core, single-cell, thermionic system (TI) based on the TOPAZ-II program, a multi-couple thermoelectric system (TE) based on the SP-100 program, and a cermet core thermal propulsion reactor (CP) based on the bimodal (NEBA-1) program. These choices are illustrated in Table 8.

TABLE 8. DNA Recommended Baseline Systems.

Baseline	System Type Represented	Justification Based on Budget Constraints; Build on Most Recent and Significant Base
In-Core TI Single Cell Thermionic Reactor	Low-Temperature Liquid Metal Cooled Power Reactor -- (LTLM) 	• Established TSET Facility and Program (System, Component, Basic Research Capabilities) • Extensive Development Work • Closely Related (Multi-Cell) Flight Experience
Thermoelectric TE Conductively Coupled Multi-couple Reactor System	High - Temperature Liquid Metal Cooled Power Reactor -- (HTLM) 	• Recent SP-100 Program Experience • Extensive Development Work • Closely Related (Unicouple, Radiatively Coupled) Flight Experience
Low Power CP UO_2/W Cermet, H_2 Cooled Propulsion Reactor	Nuclear Thermal Propulsion -- (NTP) 	• Recent Bimodal Program Experience • Development Requirements Moderate • Some Application to Gas-Cooled Power Reactors

Note that low-temperature and high-temperature liquid-metal-cooled systems and nuclear thermal propulsion system types are represented by these baselines. Gas cooled power reactor systems were not chosen because there is no recent program to build upon, only a few options are supported by development of a gas cooled power reactor, and some of the gas cooled technologies are, to a degree, addressed by the other baseline technologies.

It is important to emphasize that the selection of baselines does not imply a selection of the best technology. The best technology for future missions has not been determined. Other existing promising technology programs (e.g. AMTEC, Brayton) should be tracked or leveraged as appropriate. At periodic intervals, a reassessment should be made to determine whether a new baseline selection would be more appropriate.

CONCLUSIONS

- A number of important defense and civilian trends and issues have been identified that may be addressed by space capabilities;

- These are expected to require significant advances in power or propulsion;
- Space reactor systems may play a role for the first generation of these capabilities and are expected to be essential to support more advanced space capabilities;
- The choice of baselines was based upon the need to best utilize scarce funding by building on recent programs;
- In-core thermionic, multi-couple thermoelectric, and cermet core thermal propulsion systems are recommended as the baseline system to represent several broad classes of space reactor systems; and
- Other promising technology programs should be tracked or leveraged to support development of a broad technology base.

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