Options for Development of Space Fission Propulsion Systems

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Abstract. Fission technology can enable rapid, affordable access to any point in the solar system. Potential fission-based transportation options include high specific power continuous impulse propulsion systems and bimodal nuclear thermal rockets. Despite their tremendous potential for enhancing or enabling deep space and planetary missions, to date space fission systems have only been used in Earth orbit. The first step towards utilizing advanced fission propulsion systems is development of a safe, near-term, affordable fission system that can enhance or enable near-term missions of interest. An evolutionary approach for developing space fission propulsion systems is proposed.

INTRODUCTION

The fission process was first reported in 1939, and in 1942 the world's first man-made self-sustaining fission reaction was achieved. Creating a self-sustaining fission chain reaction is conceptually quite simple. All that is required is for the right materials to be placed in the right geometry - no extreme temperatures or pressures required - and the system will operate. Fission systems operate independently of solar proximity or orientation, and are thus well suited for deep space or planetary surface missions. In addition, the fuel for fission systems (highly enriched uranium) is virtually non-radioactive, containing 0.064 curies/kg. This compares quite favorably to current nuclear systems (Pu-238 in radioisotope systems contains 17,000 curies/kg) and certain futuristic propulsion systems (tritium in D-T fusion systems contains 10,000,000 curies/kg). An additional comparison is that at launch a typical space fission propulsion system would contain an order of magnitude less onboard radioactivity than did Mars Pathfinder's Sojourner Rover, which used radioisotopes for thermal control. The primary safety issue with fission systems is avoiding inadvertent system start – addressing this issue through proper system design is quite straightforward. The energy density of fission is comparable to that of D-D fusion and higher than the charged particle energy density of D-T fusion.

The potential capability of fission propulsion systems is compared with that of existing and futuristic propulsion systems in Table 1. As shown in Table 1, the energy density in fissile fuel is seven orders of magnitude greater than that of the best chemical fuels. Put another way, completely fissioning a piece of uranium the size of a coke can would yield 50 times more energy than burning all of the chemical fuel contained in the space shuttle main tank. If properly harnessed, the energy density in fissile fuel far exceeds that required to enable rapid access to any point in the solar system. Fission systems are the nearest-term option for high efficiency, high thrust in-space propulsion.

Although several hundred thousand kilograms of highly enriched uranium has been declared "excess", there is still significant expense involved with fabricating fuel pins for space fission systems. The cost estimate given in Table 1 was provided by Chidester, 2000, and includes all costs associated with providing fissile fuel pins for a solid core space fission system. Likewise, it may be possible to extract up to 30 kg of tritium from waste that has accumulated over the past several decades from heavy-water cooled terrestrial nuclear power plants. Although this waste tritium may be available for on the order of $30M/kg (Wilms, 2000), producing new tritium is projected to be much more expensive. The Department of Energy's ongoing tritium production program has a cost goal of $100M per kg of tritium produced (Lisowski, 1998).

In Table 1, engineering "Q" is defined as the ratio of the total energy generated in the reaction chamber/volume to the energy that must be recycled outside the chamber to sustain the reaction. An engineering "Q" of 1.0 would thus represent the case where all of the energy generated in a given reaction is used to sustain the reaction, and the only energy left over for propulsion is low-quality waste heat from system inefficiencies. An engineering "Q" much greater than 1.0 is thus required for a propulsion system to be potentially attractive. Pulsed fusion systems driven by fission primaries are considered to be fission systems. Because of the early stage of fusion propulsion research, no attempt has been made to demonstrate even a low (Q > 0.0001) engineering Q in non-fission-driven fusion systems. Both fission and fusion systems have adequate fuel energy density to theoretically enable rapid access to any point in the solar system. Although the charged-particle energy density of fission is comparable to that of D-T or D-D fusion, it has proven difficult to design fission systems that use charged particles directly as propellant. The primary potential advantage of fusion systems is thus the theoretical ability to more easily use charged particles directly as propellant. Primary advantages of fission systems compared to fusion systems are the high technology readiness level of certain fission systems and the relative ease of generating a self-sustaining fission reaction. The scarcity of Helium-3 and the scarcity/hazards of tritium will limit their use as fuels. Many proposed D-T space fusion propulsion concepts cannot breed adequate tritium onboard to sustain operation, and thus tritium would have to be launched from Earth. In addition, waste heat generated by tritium production in D-T fusion propulsion systems that do propose breeding tritium onboard severely limits the potential performance of those systems. From an overall architecture standpoint, D-D fusion may thus be the best potential fusion option, assuming a light-weight, high engineering "Q" D-D fusion propulsion system can be devised.

TABLE 1. Comparison of Fission Propulsion to Existing (Chemical) and Futuristic (Fusion) Propulsion Options.

Parameter	LoX/H2	D-D Fusion	D-T Fusion	D-He3 Fusion	Fission
Theoretical Fuel Energy Density (J/kg)	$1.6x10^7$	$8.8x10^{13}$	$3.4x10^{14}$	$3.5x10^{14}$	$8.2x10^{13}$
Demonstrated Fuel Energy Density (Operational System, J/kg)	$1.6x10^7$	0	0	0	$> 2x10^{13}$
Charged Particle Energy Density (J/kg)	0	$7.8x10^{13}$	$6.8x10^{13}$	$3.5x10^{14}$	$7.2x10^{13}$
Neutron Energy Density (Potential for Radiation Damage, J/kg)	0	$1.0x10^{13}$	$2.7x10^{14}$	0 + (D-D)	$2.1x10^{12}$
Demonstrated Engineering Q (Energy Out / Energy Recycle to Sustain Rx)	∞	Not Attempted	Not Attempted	Not Attempted	∞
Fuel Cost	Low	Low	≈$100M/kg T	High	≈ $0.1 M/kg
Fuel Availability	High	High	Low	Low	High
Fuel Heat Generation During Storage	0	0	325 W/kg T	0	< 0.001 W/kg
Radioactivity at Launch	0	0	$1x10^7$ Ci/kg T	0	0.064 Ci/kg

A POTENTIAL APPROACH TO FISSION PROPULSION SYSTEM DEVELOPMENT

Despite the relative simplicity and tremendous potential of space fission systems, the development and utilization of these systems has proven elusive. The first use of fission technology in space occurred 3 April 1965 with the US launch of the SNAP-10A reactor. There have been no additional US uses of space fission systems. While space fission systems were used extensively by the former Soviet Union, their application was limited to earth-orbital missions. Early space fission systems must be safely and affordably utilized if we are to reap the benefits of advanced space fission systems.

Table 2 gives a partial list of major US space fission programs that have failed to result in flight of a system (Angelo, 1985). There are a variety of reasons why these programs failed to result in a flight. The fact that so many

programs have failed indicates that a significantly different approach must be taken if future programs are to succeed. In many cases, space reactor programs were cancelled because the proposed mission was cancelled. However, in many of those cases mission cancellation was partially due to the fact that the reactor required by the mission was taking too long and costing too much to develop.

Terrestrial fission systems have been utilized by the government, universities, industry, and utilities for over 50 years. In addition, technology development directly related to space fission systems has been progressing for over 40 years. Near-term fission systems must capitalize on this experience. The development of new nuclear technology has historically been costly and time consuming. Nuclear technology developed by previous programs should thus be utilized, and no new nuclear technology should be required. This means that all in-core components should operate within demonstrated fuel burnup capability and demonstrated neutron damage limits for the given reactor environment (temperature, chemistry, power density, etc.). The construction of new nuclear facilities or the extensive modification of existing facilities has historically been costly and time consuming. Near-term fission systems should thus use only existing nuclear facilities in their development. No new or significantly modified facilities should be required. Flight qualification of any space system requires an extensive test program. Near-term fission system flight units must thus be highly testable. Because of the expense and difficulty associated with performing realistic full-power ground nuclear tests, previous programs have considered the option of foregoing full-power ground nuclear testing in favor of a flight test. For example, in Josloff, 1993 (referring to the SP-100 program) it is stated that "There has been recent interest among government agencies in establishing an early flight mission that would provide the catalyst needed to enable confident planning for subsequent operational missions. This first flight would validate the total system performance, obviate the need for costly ground nuclear testing, demonstrate safety features and facilitate safety approval through the INSRP process for the subsequent operational missions." Full power nuclear ground test facility requirements may also dictate that the unit tested on the ground be significantly different than the actual flight unit. Any differences between what is tested and what is flown will limit the benefit from full-power ground nuclear tests. Highly testable systems that utilize established nuclear technology incur the least technical risk if full power ground nuclear testing is not performed. The ability to quickly and affordably establish the safety and reliability of any proposed space fission system will be critical to its programmatic success.

Additional innovative approaches will have to be used to ensure that the next space fission system development program results in system utilization. Safety must be the primary focus of the program, but cost and schedule must also be significant drivers. System performance must be adequate, but the desire to make performance more than adequate should not be allowed to drive system cost and schedule. Near-term space fission systems must be safe, simple, and as inexpensive to develop and utilize as possible.

TABLE 2. Partial list of major US Space Fission Programs that Have Failed to Result in Flight of a System.

• Solid-Core Nuclear Rocket Program • Medium-Power Reactor Experiment (MPRE) • Thermionic Technology Program (1963-1973) • Space Nuclear Thermal Rocket Program • SP-100	• SNAP-50 / SPUR • High-Temperature Gas-Cooled Electric Power Reactor (710 Reactor) • SPAR / SP-100 • Flight Topaz • DOE 40 kWe Thermionic Reactor Program	• Advanced Liquid Metal Cooled Reactor • Advanced Space Nuclear Power Program (SPR) • Multi-Megawatt Program • Thermionic Fuel Element Verification Program • Air Force Bimodal Study

Initial research related to a potential near-term, low-cost space fission system is underway at NASA's Marshall Space Flight Center (MSFC). Contributors to the effort include Department of Energy National Laboratories, universities, industry, and other NASA centers.

The primary near-term fission system under investigation is the Safe Affordable Fission Engine (SAFE). Three SAFE systems are currently being considered – the 30 kWt SAFE-30 (stainless steel), the 300 kWt SAFE-300 (molybdenum), and the 120 kWt SAFE-300s (stainless steel). All SAFE cores use fuel pins conductively coupled to

heatpipes. Power generated in the fuel pins is conducted to the heatpipes and transported to an ex-core heat exchanger. The heat exchanger is used to transfer power to a Stirling or Brayton engine, depending on the power level and mission application. Full power can be generated even following multiple heat pipe failures. Propellant can also be channeled directly through the SAFE core to provide thermal propulsion. Although the SAFE can operate in a thermal propulsion mode, it is at a low thrust-to-weight ratio (<0.1) and a low specific impulse (<750 s) compared to more traditional Nuclear Thermal Rockets (NTRs) that were proposed and developed for use on human missions. The SAFE thermal propulsion capability might be useful for advanced robotic missions aimed at landing on small asteroids or moons, or other missions where a thrust-to-weight ratio significantly higher than that achievable by electric propulsion is required at certain phases. However, the SAFE is not well suited for directly propelling a crewed vehicle. Details of the SAFE-30 and SAFE-300 designs are presented in Poston, 2001.

Research related to the SAFE has been ongoing at MSFC since 1998. Initial efforts were focused towards demonstrating the performance of a module suitable for use in a high temperature / high performance system. The test series was successful, demonstrating module block temperatures of 1750 K and isothermal heat pipe operation at 1450 K. In addition, multiple restarts of the module were performed, as well as a fast start in which the module block and heat pipe were taken from room temperature to operating conditions in less than one hour.

Following the module tests, an unfueled SAFE-30 core was fabricated by Los Alamos National Laboratory and sent to MSFC for testing. Although all MSFC tests are non-nuclear, the core is designed to operate at 30 kWt if fuel (UO_2) is added to the pins and the core is surrounded by a neutron reflector / control system. Primary heat transport tests have been highly successful. Following tests of the primary heat transport system, a Stirling engine will be coupled to the core. Electricity from the Stirling engine will then be used to drive an advanced ion thruster, completing an end-to-end demonstration of nuclear electric propulsion. A picture of the high temperature module test is shown in Figure 1. A picture of a full-core SAFE-30 primary heat transport test is shown in Figure 2.

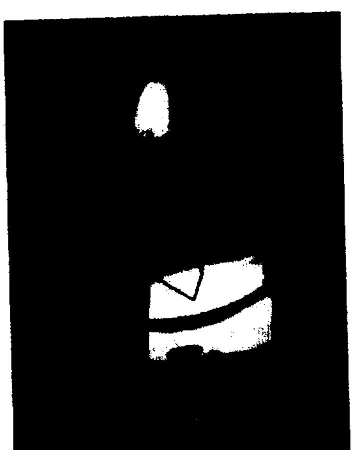

FIGURE 1. High Temperature SAFE Module Test

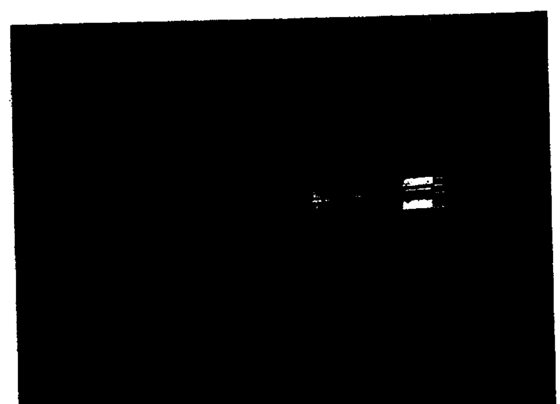

FIGURE 2. SAFE-30 Primary Heat Transport Test

HIGH SPECIFIC ENERGY FISSION PROPULSION SYSTEMS

The specific energy of fissile fuel is $8x10^{13}$ J/kg. For systems requiring a year of operation at full thrust without refueling, the minimum theoretical specific mass is thus $4x10^{-4}$ kg/kW. In an actual system, structure, heat removal, energy conversion, waste heat rejection, radiation shielding, and other subsystems will significantly increase specific mass. However, it may still be possible to devise high efficiency (Isp > 3000 s) fission propulsion systems with a specific mass in the 0.1 to 1.0 kg/kW (energy into propellant) range. Such systems would enable rapid access to any point in the solar system.

Initial research on these systems could involve non-nuclear simulations of vapor or droplet core fission reactors. Advanced energy conversion subsystems including MHD energy conversion and high-temperature Brayton cycles

could be investigated. Flowing UF_4 (or other fuel-form) loops could be constructed (using natural or depleted uranium) to validate thermal hydraulic predictions and investigate high temperature materials compatibility.

A concept proposed by NETECH (Anghaie, 2000) appears promising. One configuration of the system uses a flowing UF_4/KF mixture coupled with radiation-enhanced MHD power conversion. The system has several attractive characteristics, including the following:

1. System can be launched with fuel removed from core, thus precluding any possibility of inadvertent start.
2. Fuel can be removed from the core following operation.
3. Electricity generated by system can be used to drive high power thrusters with minimal power processing.
4. The system has excellent operational characteristics, including a strong negative temperature coefficient of reactivity.
5. The system may be capable of achieving specific powers in excess of 1.0 kW/kg at power levels above 50 MWe.

Waste heat from the system is rejected at 1500 K, reducing the mass of the waste heat rejection system. The system operates at up to 4 MPa pressure. Vessel wall operating temperatures may exceed 1600 K, thus a hermetically sealed refractory metal pumped loop will be required. In addition, the predicted performance and lifetime of the radiation-enhanced MHD energy conversion system needs to be verified.

NUCLEAR THERMAL PROPULSION SYSTEMS

Extensive research and development related to Nuclear Thermal Rockets (NTRs) was conducted between 1955 and 1973, primarily within the Rover/NERVA program. Twenty-one full engine tests were performed, and significant milestones achieved. Significant milestones include the following (Koenig, 1986):

1. System operation for 40 minutes at a hydrogen exit plenum temperature above 2500 K (Pewee). This temperature capability would enable an Isp of 870 s if integrated with a modern engine cycle / nozzle (Borowski, 2000).
2. System operation for 60 minutes at an equivalent vacuum Isp of 730 s (NRX-A6).
3. System operation at an overall reactor specific power of 440 kW/kg (Phoebus-2A).
4. Multiple restart capability of a single engine (XE, 28 restarts).

Modern NTRs based on the graphite matrix fuel technology developed and tested during the Rover/NERVA program could potentially be developed with acceptable technology risk. Although new or significantly modified test facilities would be required for system tests, there is high confidence that 1 hr operation at 2500 K mixed hydrogen exhaust temperature can be attained with the previously developed graphite matrix fuel. Because of the high power densities associated with NTRs, realistic full thrust tests of actual flight units will be impossible to perform. Extensive full power nuclear testing of "duplicate" units will be required for flight qualification.

Once NTR development and test capability is established, development of more advanced systems could be initiated. For example, extremely high temperature (>3000 K) fuels capable of enabling specific impulses well in excess of 900 s may be feasible. It may also be possible to develop "bimodal" fuels capable of high temperature, short duration operation interspersed with moderate temperature, long-duration operation. Missions that would be enabled by a bimodal NTR are discussed in Borowski, 2001.

RECOMMENDATIONS FOR FUTURE RESEARCH

Research should continue on near-term, affordable fission systems. These systems are characterized primarily by the use of existing nuclear technology, the use of existing nuclear facilities, and a very high level of testability. The focus of this research should be on demonstrating that fission propulsion systems can be developed and utilized in a safe, timely, and affordable fashion. In addition, critical path research and facility development related to more advanced fission systems should be initiated. Promising systems include high specific power vapor core / MHD systems and Nuclear Thermal Rockets.

ACKNOWLEDGMENTS

Unless otherwise referenced, the research reported in this paper was funded by and performed at NASA's Marshall Space Flight Center.

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