Proceedings of ICAPP '06
Reno, NV USA, June 4-8, 2006
Paper 6xxx

Options for Affordable Fission Surface Power Systems

Mike Houts, Steve Gaddis, Ron Porter, Melissa Van Dyke, Jim Martin, Tom Godfroy, Shannon Bragg-Sitton, Anne Garber, Boise Pearson

NASA Marshall Space Flight Center
VP31, MSFC, AL 35812
Tel: 256-544-8136:, Fax: 256-544-6696:, Email: Michael.g.houts@nasa.gov

Abstract – *Fission surface power systems could provide abundant power anywhere on the surface of the moon or Mars. Locations could include permanently shaded regions on the moon and high latitudes on Mars. To be fully utilized; however, fission surface power systems must be safe, have adequate performance, and be affordable. This paper discusses options for the design and development of such systems.*

I. INTRODUCTION

Nuclear fission systems could serve as "workhorse" power plants for the Vision for Space Exploration. In this context, the "workhorse" power plant is defined as a system that could provide power anywhere on the surface of the moon or Mars, land on the moon using a lander developed for early robotic missions (Robotic Lunar Exploration Program (RLEP) or other), and would be a viable, affordable option once power requirements exceed that which can be provided by existing energy systems.

A primary impediment to the use of surface fission systems is perceived development cost. The assumption is that because a system is "nuclear", it must be inordinately expensive to develop and utilize.

It is true that high power, cutting edge nuclear systems and facilities are expensive. For example, the 400,000 kWt, sodium cooled Fast Flux Test Facility (FFTF) was capable of burning mixed actinide fuel and had elaborate experimental capabilities, including large in-core test positions and hot cells. The facility cost $3B (FY06) to design, construct, and bring to initial operation. The Tennessee Valley Authority recently estimated that a single new terrestrial nuclear power plant (3,800,000 kWt / 1,371,000 kWe) would cost $2.2B (FY06) to complete. The high power, fast-spectrum Prometheus-1 NEP system for the previously proposed Jupiter Icy Moons Orbiter mission was designed to use refractory metals, a new fuel/clad system, and have a 20 year life. Cost estimates for that power system exceeded $3B.

In contrast, the required thermal power for a surface fission system had been identified as <400 kWt, roughly 1/10,000th that of a terrestrial power plant. Surface fission systems of this type may not require use of refractory metals, and could be designed to have a system operating environment similar to that of highly-developed terrestrial systems. Lifetime requirements could also be quite reasonable. Qualified fuel forms could be used.

A viable space reactor design must be safe and have adequate performance. Once those criteria are met, cost becomes the primary driver. This paper will discuss several attributes that could enable affordable surface fission power systems.

Fission is not an inherently expensive process. For example, a General Atomics TRIGA® Mark II research reactor with an initial power level of 2000 kW(t), and equipped for a planned future upgrade to 3,000-kilowatts was recently commissioned in the Kingdom of Morocco. The installation is capable of producing radioisotopes for medical, industrial and environmental uses, metallurgy and chemistry, implementation of nuclear analytical techniques such as neutron activation analysis and non-destructive examination techniques, as well as carrying out basic research programs in solid state and reactor physics. Total "turnkey" cost for the facility was < $50M.

II. BACKGROUND

Three organizations were heavily involved in Prometheus/JIMO reactor module design work. The Naval Reactors Prime Contractor Team (NRPCT) led the work for the final 13 months of the project. Los Alamos

National Laboratory led the government reactor module design effort prior to NRPCT involvement, and remained heavily involved with the NRPCT design team after the NRPCT assumed leadership. Sandia National Laboratories provided reactor module design support for the industry teams, including extensive support for the winning team (NGST).

In addition, Idaho National Laboratory currently has the DOE-NE charter for new reactor development activities. Potentially useful facilities at Idaho National Laboratory include the Advanced Test Reactor (ATR), hot cells, and fuel fabrication facilities.

In July, 2005 a team was assembled to assess the potential of using SNAP-derived technology to provide power on the surface of the moon or Mars. The team included individuals with direct SNAP and/or UZrH power system experience and participants from Glenn Research Center (GRC), Idaho National Laboratory (INL), Los Alamos National Laboratory (LANL), Marshall Space Flight Center (MSFC), and Sandia National Laboratories (SNL). The focus of the team was to devise a safe, affordable fission surface power system with adequate performance to be useful on VSE missions. The team primarily focused on non-refractory, pumped-NaK cooled, UZrH-fueled systems, although UO2 and U-Mo alloys were also considered as potential near-term fuel forms.

III. OBSERVATIONS

The affordability team generated several observations related to the affordable development and utilization of FSP systems. Observations include the following.

1. The system should be designed to fit on landers developed for robotic payload delivery using existing or near-term expendable launch vehicles. To accomplish this, unit mass was limited to <3000 kg.
2. The system should be designed using only well-characterized materials with irradiation databases. Refractory metals and exotic materials should not be used in the system.
3. The FSP system should use a nuclear fuel/clad combination with a significant database within or near the desired operating environment and operated to the desired fuel burnup. Fuel should be readily available using established processes or operational fuel lines.
4. The system should be designed to use uranium quantities, fuel forms, and/or enrichments that minimize security-related cost and schedule impacts.
5. The system should be designed to remain below the radiation damage threshold of structural materials used in the system.
6. The system can be designed to enable long-life. However, extreme lifetime requirements should not be placed on the first several units. This approach is analogous to the approach that was used in successfully developing long-lived radioisotope systems and naval reactors.
7. Minimize the need for new nuclear infrastructure. Use operational facilities for fuel fabrication, cold and warm criticality experiments, and any required ground nuclear testing.
8. Use simple, robust radiation shield designs with no materials development issues. Water may be a good option for FSP systems.
9. Design the system to allow materials and component testing in operational US facilities (e.g. ATR, HFIR, ACRR).
10. Take advantage of reactivity feedback coefficients, moderate lifetime, and moderate power level to simplify instrumentation and control.
11. Reduce system complexity.
12. Leverage off ongoing "balance-of-plant" development programs, e.g. Stirling engine development activities within NASA, industry and the DoD.

IV. ONGOING REACTOR MODULE TASKS

There are several ongoing tasks related to FSP reactor module development. These include FSP reactor module design, recapture of SNAP program UZrH hydrogen barrier technology, design of fuel validation experiments, and others. These tasks leverage off of previous experience and ongoing programs, and are important to demonstrating the viability of affordable FSP systems.

Three ongoing tasks at NASA's Marshall Space Flight Center are

1. development and testing of a representative alkali metal primary test circuit;
2. development and testing of instrumented thermal simulators; and
3. development and utilization of an affordable shield testbed.

These tasks are briefly described below.

IV.A. Alkali Metal Primary Test Circuit

The Alkali Metal Primary Test Circuit (AMPTC) is a key early step towards the design and development of an affordable "workhorse" fission surface power system. Data from the AMPTC will be useful for concept design and downselect activities. The AMPTC is a precursor to a joint GRC/MSFC Engineering Development Unit (EDU).

Information gained from AMPTC testing will be directly useful to EDU design, development, fabrication, and test.

The AMPTC will use highly realistic non-nuclear testing to obtain data associated with the thermal, structural, heat transfer, safety, and integrated system aspects of potential FSP systems. The required liquid metal fill machine and purification system are operational at the EFF-TF. Pumps and other loop components have been obtained. Primary coolant engineering for the AMTC has been completed. Initial AMPTC fill will occur in FY06. The AMPTC can be utilized with any alkali metal of interest. A description of the circuit (as configured for lithium testing) is given in Godfroy et al., 2006.

A picture of the AMPTC is shown in Figure 1.

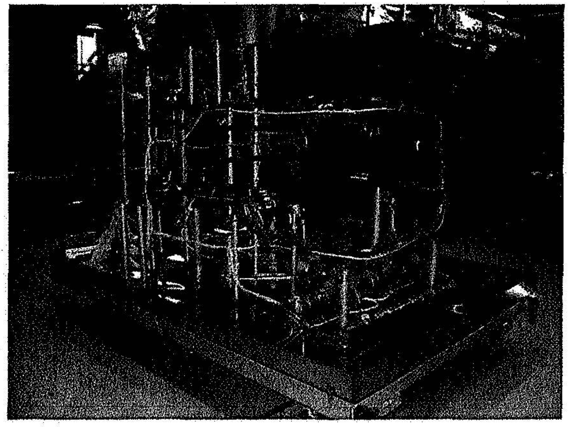

Figure 1. Alkali Metal Primary Test Circuit.

IV.B. Instrumented Thermal Simulators

Specialized thermal simulators are needed to maximize the information gained from non-nuclear testing, and the accuracy of that information. Thermal simulators optimized for use with difficult to access systems (e.g. pumped alkali metal) have been designed, and initial development testing completed. The simulators are being designed to accommodate thermocouples or fiber optic instrumentation, which will give direct information on reactor module temperature distribution and indirect information related to alkali metal flow distribution. The thermal simulators will also allow close matching of the total power and axial and radial power profiles that would be experienced by the actual flight system. The combined capability of the thermal simulators and the AMPTC will produce high fidelity data associated with the thermal, structural, heat transfer, safety, and integrated system aspects of potential nuclear surface power systems. This data will be used to reduce risk and improve designs associated with the EDU and actual flight systems.

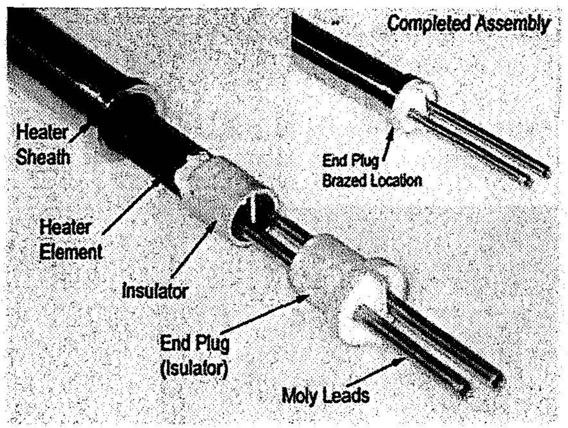

Figure 2. Thermal Simulator for Realistic non-Nuclear Testing of FSP systems.

IV.C. Affordable Shield Testbed

Most previous space reactor work has involved in-space systems operating with a high radiator temperature (>500 C for thermoelectric and thermionic power conversion). Many of these systems have also proposed operating at high thermal power, typically > 1000 kWt. The combination of high system temperatures, high thermal power, and microgravity operation resulted in the need for solid metal hydride shielding materials capable of long-term operation at high temperature in a high radiation field with significant internal heat generation. These metal hydride shields have been viewed as high risk and expensive to develop by previous programs.

Power conversion systems of current interest (Brayton or Stirling) typically operate with average radiator temperatures <200 C. Proposed surface power systems typically operate at power levels of 100 – 400 kWt. Gravity on the surface of the moon or Mars can be used to enhance heat transfer and provide confidence in the location of voids.

The combination of gravity, reduced system temperatures, and moderate power levels facilitates the use of a water neutron shield. The radiation attenuation performance of a water shield is comparable to that of an advanced lithium hydride shield. However, the water shield has the potential of being lower risk and lower cost for surface applications.

A testbed has been fabricated to validate water shield performance. The testbed is capable of measuring temperature distribution in the shield and providing visualization capability for natural circulation. The shield power input simulator matches the geometry and heat flux profile of the reactor. The testbed can be used for testing water shields associated with any nuclear surface power concept. Additional information related to water shield design can be found in Sadasivan et al., 2006.

A picture of the AST during assembly is shown in Figure 3. The reactor module / shield interface is shown in Figure 4.

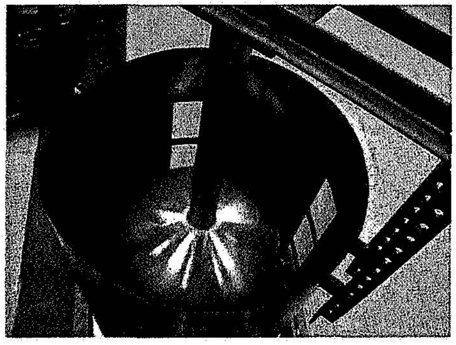

Figure 3. Assembly of the Affordable Shield Testbed

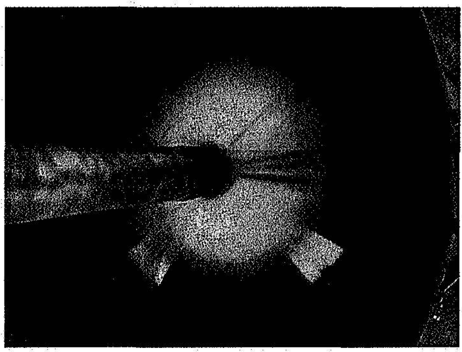

Figure 4. Reactor Module and Shield Interface Testing

V. CONCLUSIONS

Safe, affordable fission surface power systems can be designed that provide adequate performance while using established nuclear technology. While these systems will be more expensive than a typical university or research reactor, they should be significantly less expensive than large, sophisticated, world-class nuclear facilities that have been built in the past.

A modest, near-term investment can help ensure that affordable FSP systems are available when needed. For the reactor module, this includes validating potential fuel forms (leveraging off of GNEP activities), recapturing hydrogen barriers (to allow UZrH systems to be considered), adding fidelity to potential reactor module designs, adding fidelity to integrated system designs, design, development, fabrication and test of an engineering development unit (and/or precursors), and the development of affordable approaches to radiation shielding.

ACKNOWLEDGMENTS

The work reported in this paper was primarily funded by NASA MSFC. Additionally, internal support was provide by GRC, INL, MSFC, and SNL. The opinions expressed are those of the authors and not official NASA policy.

NOMENCLATURE

AMPTC	Alkali Metal Primary Test Circuit
AST	Affordable Shield Testbed
FSP	Fission Surface Power
GNEP	Global Nuclear Energy Partnership
GRC	Glenn Research Center
INL	Idaho National Laboratory
LANL	Los Alamos National Laboratory
SNL	Sandia National Laboratories

REFERENCES

1. Godfroy, T., A Garber, and J. Martin (2006) "Lithium Circuit Test Section Design and Fabrication", proceedings of Space Technology and Applications International Forum – STAIF 2006, edited by M.S. El-Genk, 2006 American Institute of Physics 0-7354-0305-8, pp 408 – 417.

2. P. SADASIVAN., R.J. Kapernick. and D.I. Poston (2006) "Thermal-Structural Design of a Water Shield for Surface Reactor Missions", proceedings of 2006 International Congress on Advanced in Nuclear Power Plants, Reno, NV, June 4-8, 2006.