Autonomous Deep Space Operations of a Nuclear Powered Spacecraft

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INTRODUCTION

NASA's Prometheus program plans to build a series of deep-space probes for missions requiring Delta Vs in excess of 35 km/s. These missions, for the most part, will be remote sensing rendezvous, orbital and, eventually, sample-return missions to outer solar system destinations such as the moons of the gas giant planets and Pluto. With current ion thruster technology, mission times are projected to be 12 years at a minimum.

Description of the Actual Work

General Requirements for Autonomy

Autonomous Deep Space Operations research at Boeing is addressing the extent and what forms of autonomy will be required on Prometheus missions.

Results

Most of the vehicles under consideration for these missions will carry nuclear reactors providing energy to power conversion cycles such as Closed Bratyon, Sterling, or Rankine that have circulating working fluids, rotating equipment, heat pipes and high performance heat exchangers. These systems will have failure / degradation modes that will be on time scales which are short compared to the communication / response times available to the mission operators on Earth. Other aspects of the mission such as response to unexpected damage to the structure and subsystems, navigation in an N Body system with continuous low thrust, power management and distribution (PMAD,) communications, opportunistic revision of science priorities, etc., will all benefit from a well- designed autonomy capability. Since this is a multi-mission program, autonomous capability can be implemented in an evolutionary fashion. Near-term missions can be flown with an augmented (to account for the characteristics of the nuclear power generation systems) version of the autonomous fault detection identification and reconfiguration approach flown on NASA's Deep Space One mission. This will require a suitable regime of installed spares, reconfiguration capability, and model-based autonomous control systems [1]. The usual requirements to minimize the mass and volume on space systems still stand; however, the power limitation is relieved to some extent (reliable devices that use more power are heavier) by the nuclear generation capability. Current estimates of the thrust-to-weight ratio of Prometheus-style vehicles are much lower than earlier studies had specified and as such, there is a strong imperative to minimize the mass of the system. This gives the hard requirement that the autonomy and other subsystems must be implemented with minimum mass. Another imperative is to develop propulsion systems with high Isp to reduce propellant and vehicle mass.

Autonomous Reactor Control

The reactor / power conversion subsystem presents significant challenges. This system must function reliably for the entire mission. Some of the components are far too massive to be redundant and must be highly reliable with control capability based in part on the properties of materials. This is already done for thermal control purposes on deep-space satellites. The reactor control system can be implemented in layers. As in the experimental breeder reactor control system, the Prometheus reactor must be able to limit the peak core temperature. The next layer must be integrated with the power conversion system. Analog systems both, electronic and passive, would be used to protect the rotating equipment and to relay power transients to a power shunt to limit the effect on the reactor. The highest layer would be a digital system, which interfaces to the rest of the vehicle management system, serves to set reactor / power conversion system operational modes, and plant conditions, and to monitor system status. Both the digital and the analog systems require a minimized set of highly reliable sensors while in the case of the low-level systems; the control system and the sensors are one and the same. Off-axis measurement capability in the sensors allows the derivation of sensed parameters in the event of a failure of the primary sensor. Finally, the control system must be able to survive the input of random data without damaging the reactor / converter system, and it must not contain any accessible states that lock the reactor into a non-resetable condition. To this end, the control system must be simulated and exercised to a high degree of fidelity to identify such states prior to system launch.

[1] B. C. Williams et al, "Model – based Programming of Intelligent Embedded Systems and Robotic Space Explorers," in Proc. IEEE: Special Issue on Modeling and Design of Embedded Software, vol. 91, no. 1, pp. 212-237, 2003.

Control Element Options for Compact Fast-Spectrum Space Reactors

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INTRODUCTION

Compact, fast-spectrum fission reactors are being considered to power ambitious near-term space exploration. This paper examines control element options for 3 potential compact, fast-spectrum space reactor concepts.

Control Strategy: Internal Versus External

Internal control elements can present several major problems for space reactors because of the high temperature environment, the need for large internal vessel and shield penetrations, the potential for significant volume and integration issues, the requirement for long-life without maintenance, and in most cases a higher overall system mass. One of the favorable aspects of compact fast-spectrum reactors is the potential to control the reactor externally and eliminate the need for any in-core control/safety elements. Several factors determine whether internal control is needed for a specific design: criticality uncertainty margins, temperature defect reactivity, burnup reactivity loss, core diameter, core void fraction, etc. Several of these factors are highly dependent on the thermal power level of the core, thus as power increases, there is more likelihood that internal control/safety elements will be required.

Internal control elements should be avoided in early-generation space fission systems, because they add significant complexity to system design and development. The remainder of this paper proceeds with the assumption that external control is used.

Radial Reflector Material: Be vs BeO

The radial (i.e. external to the core "cylinder") reflector/control elements must use a primary material that has good neutronic performance, can withstand the thermal and radiation environments presented by the reactor, and can be fabricated and qualified within the time required. For this class of space reactors, good neutronic performance is defined by high reflection, low absorption, minimal moderation, low mass, and small thickness (translating to lower shield mass). Two materials that meet the above requirements are Be and BeO (although there may be other well-suited materials as well). The choice between Be and BeO is concept dependent – in most cases BeO provides a lower mass system, but Be provides lower technical risk (Be has better availability, fabricability, experience, and performance under irradiation).

Element Type: Movable Reflector or Drum

Movable reflectors control reactivity by adjusting the neutron leakage from the core; this is usually envisioned by sliding or pivoting the radial reflectors. Control drums are rotating reflector elements that have neutron absorber placed on one side of the cylinder. The choice of "sliders" or drums can be very concept dependent. In general, sliders result in lower system mass, but drums offer some integration and operational advantages, and account for all past space reactor flight experience.

DESCRIPTION OF THE ACTUAL WORK

A large number of criticality calculations were performed to complete this study. These calculations varied control element material, thickness, form, and position for 3 different reactor concepts. Control element worth was also calculated for various flooding conditions of the core internal and external gaps (including all coolant volumes). Each of the 3 concepts has similar core materials and geometries, but a different primary cooling mechanism: liquid-metal-(Li)-cooled, gas-(HeXe)-cooled, and heat-pipe-(Na)-cooled. A 500-kWt baseline design was developed for each concept; however, a description of these concepts is beyond the scope of this paper. These concepts will be documented in future references.

Criticality calculations were performed with MCNP4C using ENDF-B/VI cross sections. All

k_{eff} results are at room temperature at beginning-of-life (temperature and burnup reactivity effects have been calculated, but are not included here). The statistical error for the presented results is approximately 0.05%.

RESULTS

Three plots, Fig. 1, 2 and 3, are provided in this summary to display the general trends of the calculations. Figure 1 shows that BeO provides more reactivity per unit thickness than Be. Despite its higher density, BeO usually results in a lighter system; the reflector mass may be about the same, but the shield becomes lighter because of the smaller radius. Figure 2 displays k-eff vs reflector position for nominal and flooded conditions for the gas-cooled concept. For a cold-clean reactor, k-eff drops from 1.035 to 0.870 as the slider is withdrawn from 0 to 50 cm. The most restrictive of the flooded cases analyzed contained wet-sand (2/3 quartz, 1/3 water) in all internal and external voids. With the reflector in its fully stowed position k-eff is 0.985 – a small shutdown margin is acceptable because of the extremely low probability and low consequence of this event. Figure 3 contains a similar plot but for the heat pipe reactor using control drums. For this reactor k-eff drops from 1.035 to 0.935 as the drums as rotated 180 degrees. The worst-case flooded condition for this reactor contains water in the internal voids (heat pipes) and wet sand in external voids. In this case k-eff in the launch configuration is also 0.985.

CONCLUSION

The results presented, and several others not shown, will be used to select the optimum control element strategy for each of the reactor concepts. The "full" paper will discuss results in more detail, and take a more detailed look at the pros and cons of each control element strategy.

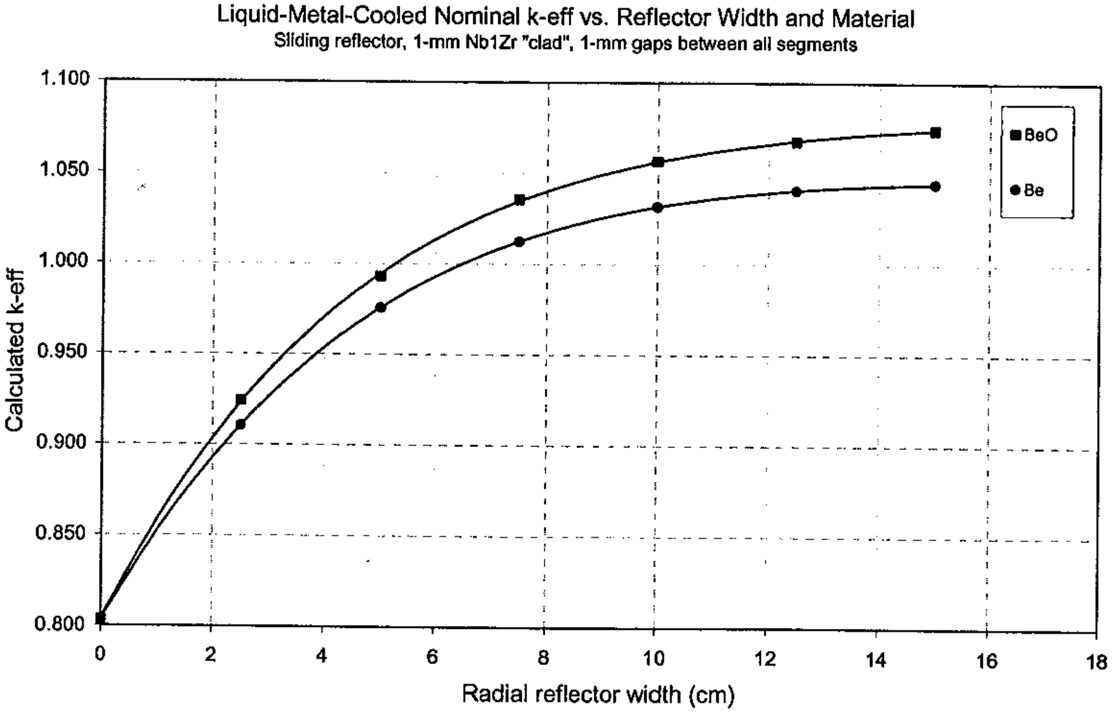

Fig. 1. Nominal reflector worth for liquid-metal-cooled concept.

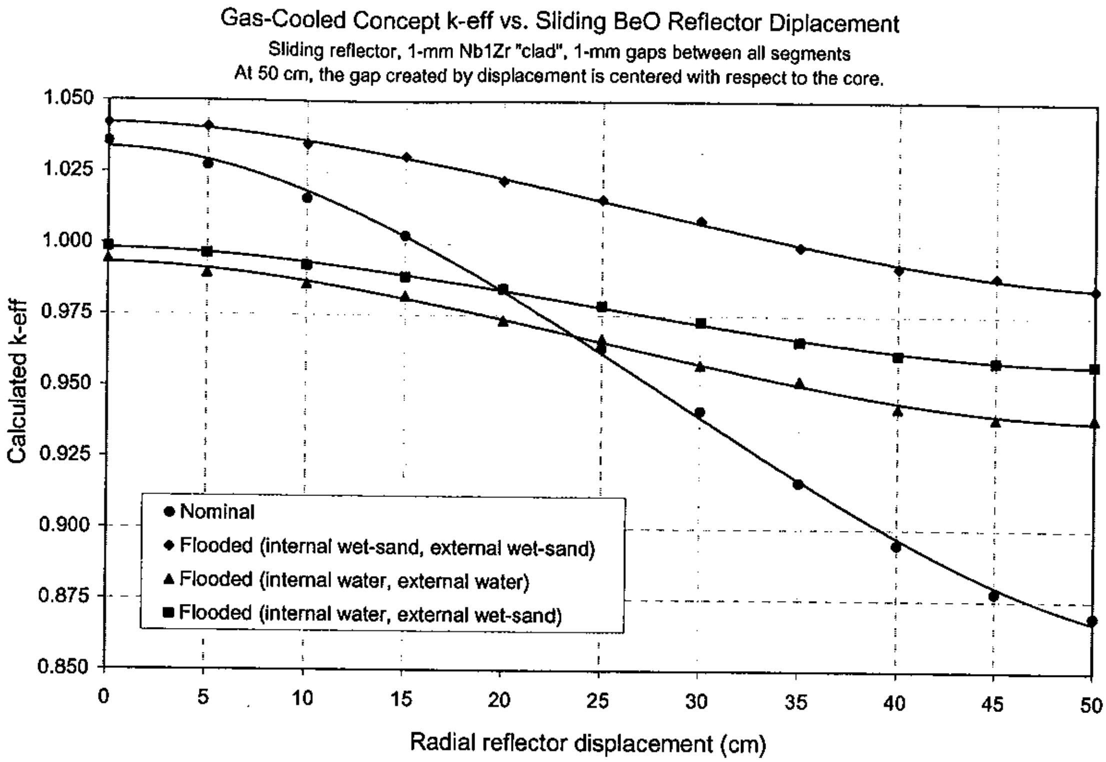

Fig. 2. Sliding reflector worth for gas-cooled concept.

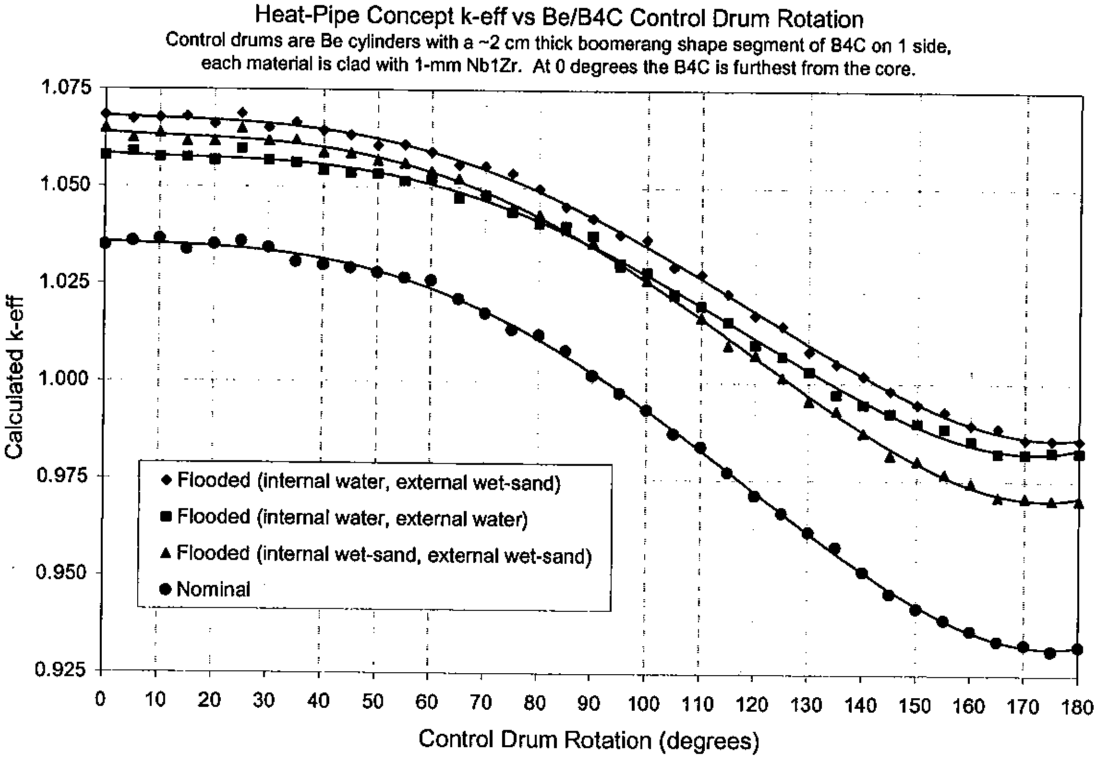

Fig. 3. Control drum worth for heat-pipe-cooled concept.

Space Nuclear Reactor Control Design Challenges, invited

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INTRODUCTION

The development of space nuclear power systems (SNPSs) pose nuclear design challenges that necessitate the integration of a wider range of design disciplines than for terrestrially operated systems. This paper focuses on thermal-structural design issues associated with reactor control elements envisioned for potential SNPS for use by NASA for robotic exploration of the solar system's outer planets. Control of an SNPS reactor core, as with terrestrially operated systems, requires precise placement of control elements to maintain the neutron chain reaction in a desired state. Because the SNPS will be operated in the vacuum of space, thermal management of heat deposited in control elements will play an important role in the reliability and lifetime of the reactor.

In 1953, Admiral Hyman G. Rickover[1] noted that an "academic reactor" can be characterized as being simple to build and operate, small, cheap, can serve a variety of purposes, will use mostly off-the-shelf components, and will require little development. An important distinction of "academic reactors" is that they exist only in the study phase of a program. Admiral Rickover goes on to point out that the characteristics of practical reactors, those that are in development, are very nearly the complement of those so called academic reactors. In 1953, issues of corrosion and water chemistry, among a plethora of other detailed design concerns affecting performance and safety, for compact pressurized water reactor cores significantly impacted system development schedule and overall system mass and complexity. It is with this historical perspective that NASA is considering the use of SNPSs to further enable robotic exploration of the outer planets in our solar system. As NASA transitions from the study phase to the development and eventual employment of such reactors, Admiral Rickover's comments from 50 year ago most certainly hold true today. Operating a nuclear reactor in the vacuum of space and at unprecedented power levels for a deep-space spacecraft will undoubtedly result in a new class of technical issues that will require resolution using a host of technical disciplines that have not been traditionally associated with the established nuclear industry. To illustrate this point, this paper examines potential technical issues regarding just one facet in the design of a space nuclear reactor: reactor control.

REACTOR CONTROL AND CONCEPT OF OPERATION

In terrestrial systems, nuclear reactor control is a well established discipline. Central power stations are static in their location; control by manipulation of neutron absorbing rods or chemical shim concentration in the coolant can be performed in real time; and plant protective functions in response to external factors are well defined. Reactors employed in naval propulsion applications enjoy a similar degree of well established concept of operations that ensure safety and performance.

Whereas Earth-based reactors operate in a fairly well defined envelope of conditions, a space nuclear power system will venture into the harsh conditions of deep space that have not yet been fully characterized and at a distance from Earth that precludes real-time communication with the spacecraft. The space nuclear reactor must be sufficiently robust to withstand launch loads and be designed such that the reactor can only be started deliberately. In addition, in the unlikely event of Earth re-entry, the system must be capable of impacting the earth intact and remaining subcritical under the full spectrum of impact environments.

The envisioned operating conditions and concept of operations will drive the design of the control system. For example, if the mission is designed such that the launch vehicle can accelerate the spacecraft to speeds in excess of 11.2 km/sec in order to escape Earth's gravitational field prior to reactor startup, then re-entry following reactor startup is not reasonably possible. On the other hand, if the reactor is deployed to high earth orbit and is operated during a spiral out to earth escape, then provisions for a perturbed orbit must be allowed for to preclude re-entry to Earth.

Once the system is started and is on its one-way trip to the outer reaches of the solar system, one must consider if it is desirable to vary the system power output or keep it at a constant full-power level. In addition, one must consider if a scram capability is desirable. Should the system scram, then some sort of auxillary power source, the analog of diesel back up power generators, needs to be available to allow for a system restart. Conditions that led to the scram in the first place may or may not be correctable, so the spectrum of upset conditions must be sufficiently well defined to establish the efficacy of a re-start capability in the first place.

Thermal and Structural Design Challenges

A reasonable estimate is that as much as three percent of the energy released in fission will be deposited in reactor non-fuel components and structures[2]. In the case of a compact space nuclear reactor core, this adds additional design considerations on maintaining the structural integrity of external neutron reflectors that are used for reactor control. This includes, but is not limited to:

- Launch and ascent environment considerations
- Coupled radiation transport and thermal-structural modeling
- Thermal management and heat rejection strategies

RESULTS

Reactor control and its relationship with thermal-structural design and mission definition issues provides one of many potential examples of complex, multidisciplinary tasks necessary for SNPS development. Along with these challenges are opportunities for cross-pollination across technical disciplines that could foster a broader understanding of the benefits of nuclear technologies.

REFERENCES

1. Rickover, H.G., *Journal of Reactor Science and Engineering*, June 1953
2. DUDERSTADT, J.J and HAMILTON, L.J., *Nuclear Reactor Analysis*, pp. 66-67, John Wiley & Sons (1976)