THE TOPAZ 2 FLIGHT EXPERIMENT: WHAT WE WOULD LEARN

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Abstract

The Ballistic Missile Defense Organization (BMDO), through the New Mexico Alliance (NMA), is procuring several Russian TOPAZ 2 Space Nuclear Reactor Systems for test and evaluation in the United States. BMDO has examined the possibility of conducting a flight test of the TOPAZ 2 reactor. For a variety of reasons including budget pressures and Department of Defense (DoD) refocusing, BMDO has indefinitely deferred flight testing of the TOPAZ 2 reactor. In this paper, the value of flight testing is examined. It is postulated that a flight test mission can advance the understanding of space nuclear reactors in several key areas, including spacecraft system engineering, nuclear reactor system engineering, and spacecraft interaction modeling.

INTRODUCTION

In 1991, the Ballistic Missile Defense Organization (BMDO) began evaluating the possibility of performing a flight experiment to test the Russian TOPAZ 2 Space Nuclear Reactor System (SNRS) in orbit. As part of this effort, the New Mexico Alliance (NMA) began a preliminary safety assessment to determine whether the TOPAZ 2 SNRS could be launched in the United States (US) in a manner consistent with applicable US safety standards. NMA is a consortium including the US Air Force Phillips Laboratory, Los Alamos National Laboratory, Sandia National Laboratories, and the University of New Mexico. In conjunction, The Johns Hopkins University Applied Physics Laboratory (JHU/APL) began developing a mission and spacecraft concept for flight test and evaluation of the TOPAZ 2 SNRS.

In August 1992, APL conducted a Conceptual Design Review (CoDR) for a mission that became known as the Nuclear Electric Propulsion Space Test Program (NEPSTP). This mission had three primary goals:

1. Demonstrate and evaluate the TOPAZ 2 Space Nuclear Power System in space;
2. Demonstrate and evaluate Nuclear Electric Propulsion (NEP) technologies and techniques in space; and
3. Characterize the self-induced NEP environment.

In December 1992, NMA presented its Preliminary Safety Assessment (PSA) to the Interagency Nuclear Safety Review Panel (INSRP). NMA concluded that the TOPAZ 2 SNRS could be launched in a manner consistent with US safety standards if certain modifications were made to the reactor. Other safety issues raised were a matter of proper mission design and implementation of procedures.

In April 1993, APL conducted a Preliminary Design Review (PDR) for the NEPSTP mission that built upon the mission and spacecraft concept presented at CoDR. The PDR design reflected changes recommended by the safety team and by concerns regarding interference with ongoing and planned scientific space missions such as the Compton Gamma Ray Observatory (GRO). Since PDR, the program sponsor has indefinitely deferred the flight experiment for TOPAZ 2.

We believe that NEPSTP would be a cost effective experiment that would yield important and lasting contributions in the field of space nuclear power and nuclear electric propulsion. In this paper, we shall examine some of the areas in which NEPSTP could make significant contributions. This paper is organized in four major sections. Ihe first section is an overview of the TOPAZ 2 SNRS, the NEPSTP spacecraft, and the NEPSTP mission. In the second section, potential contributions in the fields of spacecraft and mission system engineering, including spacecraft processing, launch operations, mission planning, and mission operations are discussed. In the third section, the focus is on nuclear reactor system engineering and space nuclear reactor system controls and instrumentation. The final section discusses potential advancements in the fields of space vehicle interactions and plasma dynamics.

SPACECRAFT AND MISSION OVERVIEW

The NEPSTP spacecraft is divided into three primary systems: the Space Nuclear Reactor System, the spacecraft bus, and the Propulsion Module (PM). Figure 1 is a view of the operational configuration.

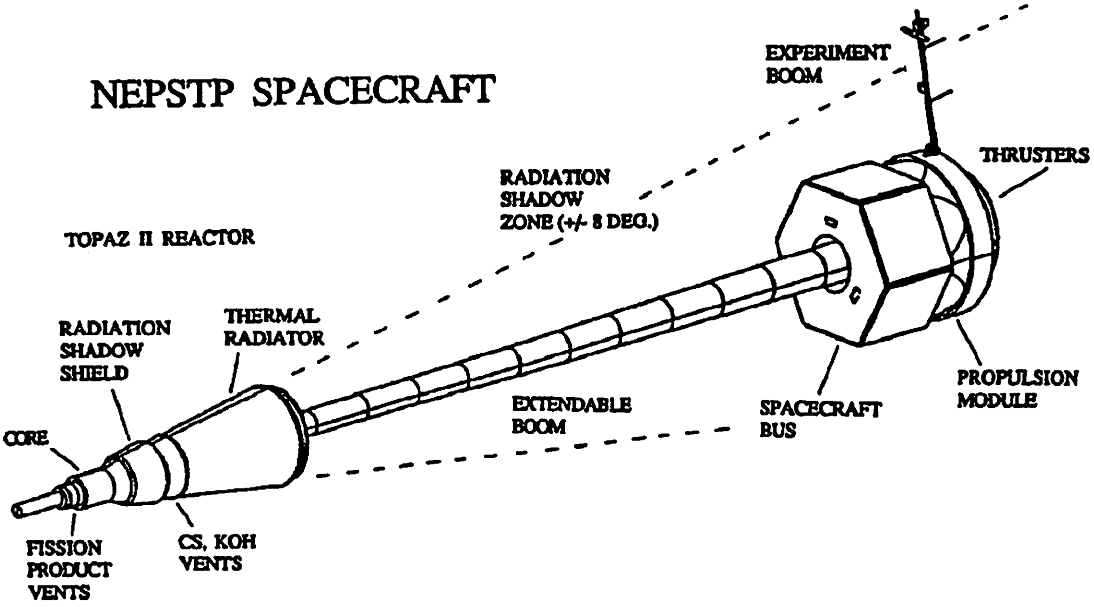

FIGURE 1. NEPSTP Spacecraft Orbital Configuration.

The TOPAZ 2 SNRS is a 115 kW_{th} reactor generating 4.5 to 5.5 kW_e power at 27 volts. The reactor system is 3.9 m high, 1.4 m in diameter at the base, and weighs approximately 1061 kg. TOPAZ 2 is designed for a three year mission life. TOPAZ 2 uses approximately 27 kg of uranium dioxide (UO_2) with 96% enriched U-235 in the form of toroidal fuel pellets. These pellets are stacked in 37 long single cell Thermionic Fuel Elements (TFEs) which generate power by thermionic emission. One of the significant benefits of the single cell TFE is that the ends are open and the fuel pellets can be easily inserted or removed. A related benefit is that the fuel pellets can be replaced by electrical heater elements so that the reactor can be tested electrically (without using nuclear fuel). The reactor is cooled by circulation of sodium-potassium (NaK) eutectic metal alloy, which is liquid at temperatures above -11°C. The NaK is pumped by an electromagnetic pump to a radiator, which ejects the waste heat at surface temperatures between 500°C and 600°C. The reactor also incorporates a radiation shield assembly, which is a stainless steel vessel filled with lithium hydride (LiH); the stainless steel attenuates the gamma radiation, whereas the LiH attenuates the neutrons. The spacecraft bus would be located within the shadow cone cast by this radiation shield.

The NEPSTP spacecraft bus would be separated from the reactor by a 10 m boom. In addition to the typical spacecraft subsystems, the spacecraft bus would contain a number of instruments for evaluating the self-induced environments of particles (neutrons, ions, atoms, and electrons), fields (electromagnetic and electrostatic), and waves (gamma rays and plasma waves). The instruments would include devices for measuring and characterizing the deposition of contaminants. All data would be recorded and downloaded to a ground station for analysis. The spacecraft would measure and record engineering parameters such as temperature, voltage, current, and acceleration to enable evaluation and characterization of reactor and thruster performance.

The Propulsion Module would carry a variety of electric thrusters and their Power Processing Units (PPU's), Flow Control Units (FCU's), propellant tanks, pressure regulators, and valves. All of the selected thrusters use xenon as a propellant. The international complement of thrusters would include the Russian SPT-100 Stationary Plasma Thruster and T-160 advanced technology SPT, the British T5-ITS electrostatic thruster, the Hughes Xenon Ion Propulsion System, and the NASA derated ion thruster.

The spacecraft would be launched into a nominal orbit of 5250 km at an inclination of 28.5°. After confirmation that the spacecraft has achieved a sufficiently high orbit, the reactor would begin operation and the reactor and spacecraft would be checked out. Nuclear Electric Propulsion (NEP) would be used to raise the orbit to an altitude of 40000 km. Life testing could be conducted on select thrusters. As the thrusters operate, their electromagnetic emissions, plasma characteristics, and contaminant deposition rates would be characterized by both local and remote sensors. In this fashion, a data base can be developed to aid spacecraft designers and mission planners for future NEP spacecraft.

SYSTEM ENGINEERING

Despite the significant efforts that have been made in developing space nuclear power systems, remarkably little work has been done in the area of system engineering for a reactor powered spacecraft. The self-induced environment resulting from the operation of a nuclear reactor in space is challenging for spacecraft designers; the radiation, thermal, and electromagnetic environments are considerably more severe than typical spacecraft design parameters. Designing, building, integrating, and testing the NEPSTP spacecraft would be extremely valuable, because it would require designers to find complete, pragmatic, cost effective solutions to the issues associated with reactor powered spacecraft. In this section, some of the system engineering problems that would be solved or at least explored by a flight TOPAZ mission will be discussed. Based upon the preliminary design work performed to date, all of these issues appear to be amenable to resolution. See Cameron and Herbert (1993) for more details regarding these problems and their solutions.

Radiation Hardness

Most existing "radiation hardened" spacecraft subsystems are not adequately hardened for the space reactor environment. Typical space systems are hardened against the anticipated doses, species, and spectra experienced in the ambient space environment; these environments include mostly electrons and protons, with little or no consideration of neutron or gamma radiation. Military spacecraft are hardened against a more applicable spectrum, however, they are generally designed to handle a limited number of high dose rate events, not high total doses. In the preliminary design phase of NEPSTP, it became apparent that most spacecraft subsystems would have to be reexamined to evaluate the hardness of the specific devices being utilized. In many cases, parts testing would be required to qualify existing designs. In designing a nuclear powered spacecraft, an optimal mix of separation distance, shielding, and device hardness would be used to operate in the anticipated environment. From preliminary design studies, a boom length of 10 m was selected for the NEPSTP mission. It is anticipated that designing for a total dose of 100 krad is sufficient (again, the actual species and spectra of anticipated energy must be considered). Spot shielding would be used in selected subsystems as deemed appropriate by modeling. The experience gained in developing subsystems for this environment, as well as the parts libraries and modeling tools developed or augmented, would be very valuable to the designers of future nuclear powered spacecraft and their subsystems.

Large Deployable Structures

In the conceptual design phase of the NEPSTP spacecraft, it became apparent that the most effective method to reduce radiation is to add separation distance between the reactor and the spacecraft electronics. Shielding effectiveness varies with the radiation type and energy spectrum, but *separation distance* decreases the dose rate over the entire energy spectrum by an inverse square relationship (as the reactor is not a true point source, this is an approximation). All spacecraft must fit within a launch vehicle fairing. The only way to achieve any meaningful separation distance is by using deployable structures, which create problems of their own. Many of these problems have been dealt with theoretically. The process of designing and fabricating the NEPSTP spacecraft would allow the community to gain hands-on experience with these issues.

The first problem is the development of a large deployable boom. Few applicable designs have ever been flown. Many existing designs can not be simply scaled for a variety of reasons, such as material limitations (fiberglass and aluminum cannot be used due to thermal considerations). Space reactor power systems are massive and compact structures relative to typical spacecraft subsystems. Large masses are difficult to deploy. Even in the "weightlessness" of space, inertia must be overcome by deployment mechanisms such as springs or motors.

Dynamics

Weight is always an issue when designing spacecraft, so lightweight structures are generally employed. Large, lightweight, deployable structures are flexible. The combination of large end masses and flexible structures leads inevitably to resonant modes. The dynamics and control of large flexible structures is a special discipline, mostly dealt with only in theory and modeling. Interactions between the spacecraft dynamics and the attitude control system must be well understood before flight. Resonant structural modes coupled to closed loop control systems can lead to oscillations if such problems are not anticipated. There is a concern that mechanisms for pointing a spacecraft, whether thrusters, wheels, or other means, would simply pump energy into resonant modes without imparting effective attitude control. Fortunately, the NEPSTP spacecraft has no stringent pointing, tracking, or stability requirements. This would make NEPSTP a good mission choice for gaining experience.

Power Transmission

Another significant design issue is power harnessing. In the case of TOPAZ 2, up to 6 kW of electrical power must be transmitted over the length of a 10 m boom. If the output voltage is 27 volts, the power harness must transmit more than 220 amperes of current a distance of 10 m with limited power losses. This implies that massive, stiff cables must be used. These cables must be stowed prior to launch and deployed with the boom in orbit; these cables add to the difficulty of deploying the boom. The power harness would also add inductance to the source impedance term, which effects the propagation and generation of electromagnetic interference on the power lines. These power lines would also provide a good coupling path for radiated electromagnetic noise, both transmitted and received. The transmission of high currents would generate strong magnetic fields, which would interact with the earth's magnetic field, creating disturbance torques for the spacecraft attitude control system. Again, experience gained in flying TOPAZ 2 would be useful to future reactor powered space missions.

Integration and Test

In addition to the issues apparent in *designing* a nuclear powered spacecraft, there are many unresolved issues related to integration and test. While many design issues have been examined closely, most integration and test issues have not yet been considered.

Reactor Qualification

One of the first integration and test problems is perhaps one of the least obvious: how do you qualify a nuclear reactor for space? Virtually all spacecraft subsystems are exhaustively tested on the ground; complete "end to end" testing is generally applied. Spacecraft engineering abounds with examples of unanticipated problems that were not discovered until after launch because no pre-launch testing was conducted to detect them. Space nuclear reactors do not lend themselves to ground testing in a fashion analogous to other spacecraft subsystems. A nuclear reactor destined to be launched cannot be used for nuclear gound testing at full power before launch. Once tested at rated power, a reactor would be too radiologically hot to be launched. An acceptable upper limit for pre-launch testing of a nuclear reactor may be on the order of tens of seconds at power levels on the order of a few watts. Additionally, nuclear ground testing is expensive and requires special facilities constructed for this purpose. Other typical space qualification tests such as vibration, acoustic, and shock would be considered hazardous with a fully fueled reactor.

In light of these limitations, it is necessary to develop a test regimen to qualify a reactor in a piecewise fashion for launch. For TOPAZ 2, six full nuclear ground tests of similar units have been conducted in Russia. The flight systems can be tested with electrical heaters to simulate full power operation. Zero power testing can be conducted at a criticals facility to verify the fuel loading height and the reactivity worth of the drums as a function of rotation angle. Vibration, acoustic, and shock testing can be conducted with simulated fuel (it is essential that the simulated fuel closely matches the actual fuel in mass and density for these tests to be valid). Launching and operating TOPAZ 2 in orbit would validate this testing approach and lead to improvements in future space reactor systems.

Reactor Integration

Once the reactor is qualified as a stand-alone subsystem, it must be integrated with the spacecraft. Many of the difficulties of integrating an SNRS with a spacecraft are greatly simplified by the fact that the TOPAZ 2 reactor can be fueled after spacecraft integration; there is no need to hoist, mate, and electrically test a fueled reactor. Nonetheless, there are some unique issues associated with this process. During the integration process, it is desirable to conduct a full operational test of the SNRS. Clearly, a nuclear test not be practical. Instead, a combination of simulators (for power and signals) and stimulators (for sensors) must be used in the integration process. As a minimum, a power supply under computer control must provide up to 6 kW of electrical power to the spacecraft. This computer controlled power source must vary its output power in accordance with the control drum rotation angles as commanded by the Reactor Control Unit (RCU). The RCU must receive the full complement of telemetry signals from the reactor to close the control loop. Some of these signals (control drum angular position, for example) can be received directly from the reactor. Others (such as neutron flux levels and coolant temperatures) must be simulated. All possible subsystems need to be tested out. The ionization chambers, for example, cannot be tested as part of an operational system, but must be tested and calibrated using an external neutron source. The full details of the test and integration plan remain to be worked out. This pathfinder operation, combined with the lessons learned, would be valuable to future space nuclear reactor testing.

Launch Site Issues

Some integration and test issues are unique to the launch site. By "launch site", we refer to the entire group of facilities found in the vicinity of the launch complex or "pad", including payload processing facilities and hazardous operations facilities normally meant for propellant loading and ordnance installation.

Fueling

Fueling of the TOPAZ 2 SNRS is a primary issue at the launch site; this entails installing UO_2 fuel pellets into the reactor core. The Russian designers of TOPAZ 2 developed simple and reliable techniques for fueling the reactor. The issue is the method of conducting such operations in facilities that were not designed for this purpose. New facilities specifically designed for reactor fueling could be constructed, but only at considerable cost. Instead, it is proposed to utilize an existing Hazardous Processing Facility for this operation. Plans, procedures, instrumentation, personnel protection criteria, and security measures (to prevent theft, loss, or diversion of Special Nuclear Materials) must be developed, reviewed, approved, signed off, and implemented. Once the fuel is inserted, some level of confirmation testing (up to or including "zero power testing") is anticipated to assure that the control drums are properly calibrated. Again, as this type of operation has not been performed in the US since 1965, this process would establish important precedents.

Final Pre-launch Preparations

After fueling, a number of operations must take place prior to launch, referred to here as final pre-launch preparations. These preparations include, but are not limited to, installation of the anticriticality device (ACD), loading of the fuel into the ACD, installation of the startup battery, installation of the arming and enabling plugs, and removal of the locking pins. Some of these activities would be performed in the payload processing facility, while others would be performed on the launch pad on the day of launch. One final pre-launch preparation is the preheating of the reactor system; this preheating allows the NaK coolant to remain liquid during launch and ascent until reactor startup. A pragmatic and cost effective process for pre-heating the reactor system must be developed. It is our belief that we have developed a practical solution that entails heating the reactor system with warm air.

Details as to the sequence, procedure, timing, and location of these pre-launch activities must be worked out well in advance and approved by the range safety organization at the launch site. As a pathfinder mission, NEPSTP would initiate new ways of thinking in the range safety community and establish precedents to be followed by subsequent nuclear reactor powered spacecraft. In the process, it is likely that we would identify features that should be built into or eliminated from future space nuclear reactors.

Launch and Ascent

Launch and ascent are the activities that would probably receive the most thorough review and closest scrutiny. Formal safety review by the INSRP is mandated by national policy. This process has already been initiated for NEPSTP. One of the important lessons already learned is that many of the established practices and procedures in place are geared towards missions using Radioisotope Thermoelectric Generators (RTGs). Many of these practices are being reconsidered in light of the differences between RTGs and reactors. At issue are practices concerning nuclear safeguards, the use of sonar location transponders, the requirements for assuring that the reactor remain subcritical during launch and ascent, the makeup and nature of standby emergency response teams, vehicle tracking requirements, orbit determination, and many others. Proposed solutions must be cleared by the review processes, INSRP and otherwise, which follow. It seems certain that subsequent space nuclear reactor launches would have to follow the approval precedents that would be established by NEPSTP as a minimum.

NUCLEAR ENGINEERING

In addition to the knowledge that would be gained about system engineering, the information gained about reactor design, materials, fabrication and performance under prelaunch, launch, startup, and operation would be considerable. Transfer of the TOPAZ technology would require close interactions between the Russian designers and developers of TOPAZ 2 and the US team responsible for safety, modifications, qualification, and test and integration.

To date, the US has only launched one nuclear reactor system, SNAP 10A, in April 1965. It was clear from the flight test that the information gained on space performance was significant. The most important insights gained from the launch of SNAP 10A related to the integration and performance of the space reactor with the experiments and the spacecraft power bus. The mission lasted 45 days, half of the planned mission. The exact cause of the premature system shutdown is unknown, but is believed to be the failure of a voltage regulator on the spacecraft. One of the achievements of a flight test of the TOPAZ 2 would be to show that there are no major science or engineering unknowns. In preparation for the launch, a team of Russian and US engineers and scientists would model the system behavior for both normal and off-normal conditions so that maximum understanding can be gleaned from the flight test. The flight test data would provide correlation of flight performance with ground testing, systems modeling, and analysis.

Different phases of the mission would answer questions about different aspects of the reactor system. One of the important findings of the launch phase would be confirmation of the thermal performance of the system during launch, the effect of solar heating, and the effectiveness of the thermal cover in maintaining the temperature profile of the NaK coolant.

Startup is the most demanding phase in terms of the mechanical and electrical operations required. In summary, this includes:

- spacecraft structural boom extension;
- insertion of the fuel by the anticriticality device in zero-G;
- operation of the three, independent safety drums and the nine interdependent control drums;
- switching on of the reactor control unit;
- transition from the startup battery to TFE power for the operation of the EM pump;
- cesium valve opening;
- startup battery electrolyte valve opening; and
- mechanical ejection of the thermal cover from the spacecraft.

Each of these events are imperative for a successful mission. In addition to each of the above functions, the response of the reactor to the startup transient is very important to understand and to compare to ground test data and analysis. The operation of instrumentation and monitoring equipment during the startup is also important.

Of particular interest to the US space power community are the operational characteristics of a nuclear reactor with a positive temperature coefficient. Incorporating a positive temperature coefficient is counter to the US design philosophy for nuclear reactors. It is interesting to note that the positive temperature coefficient has some unexpected safety advantages during the launch sequence as the beginning-of-life excess reactivity is greatly reduced relative to a reactor designed with a negative temperature coefficient.

On orbit, the steady-state operation of the TOPAZ 2 would demonstrate the viability of nuclear reactor power in space. Specifically, the demonstration of an autonomous reactor system operating for an extended period of time while meeting power requirements is imperative. Verifying analysis and ground test data and obtaining the experimental factors for code verification would be an important part of the orbital test program. Specifically, the parameters that would be measured and compared to calculated and observed values include the levels of fission products, cesium, and battery electrolyte released from the reactor system; the change in electrical output of the TOPAZ 2 as it goes from sunlight to shadow; the magnetic torque resulting from the interaction of the electric current produced by the pump with the earth's magnetic field; and the electrical resistance from the thermionic fuel elements to ground (the reactor vessel) over time.

Measurement of the radiation environment is important as there is no scattering due to associated test facilities. The true magnitude of fast and thermal neutrons and gamma radiation at the spacecraft can be determined and used to verify modeling techniques developed for use in later space missions. The spacecraft would have an articulating arm with neutron/gamma detectors to profile radiation levels at the edges of the shield shadow cone.

MISSION SCIENCE

The primary science activities associated with the NEPSTP program include:

- Evaluation of the performance of the TOPAZ 2 reactor in space;
- Evaluation of the performance and degradation of the electric thrusters;
- Evaluation of the self-induced environments that degrade performance of sensors and spacecraft subsystems.

As a secondary goal, the NEPSTP Program would conduct science of opportunity consistent with the primary goals. Included are evaluations of the earth's natural magnetospheric environment. "Science" in the context of the NEPSTP program is used in its broadest sense of developing predictive understandings of phenomena. The primary focus would be on phenomena of critical interest with regard to the future uses of nuclear electric propulsion.

The NEPSTP spacecraft, like all spacecraft, would be flying in a "self-induced" environment. That environment would consist of neutral gases (Xe from thrusters, cesium from the reactor, plus contaminants), plasmas (ionized from neutral gases, fission products), energetic particles, particulates, electric and magnetic fields, electromagnetic and plasma waves (from hardware and from plasma interactions), and reactor radiation effects. The induced environment is the result of interactions between the ambient environment, the contamination environment, and the spacecraft itself. It is important to understand the induced environment because it can have adverse effects on sensitive sensors and spacecraft subsystems.

The interactions of solar-powered or chemically propelled spacecraft with their environments have been studied extensively. Certain aspects are now well understood, for instance, contamination by chemical propulsion thrusters. Other aspects, such as spacecraft/plasma environment interactions, spacecraft charging, and the motions of plasma clouds about spacecraft are still active areas of research, however, much progress has been made. There is not a similar level of understanding of Nuclear Electric Propulsion (NEP) spacecraft interactions. The plasma and neutral plumes generated by the electric thrusters add a dramatic level of complexity to the interactions picture. The presence of the nuclear reactor, its efflux, and its associated magnetic fields adds further complexity. It should be noted that electric propulsion is one of the primary potential uses of the high power levels associated with space nuclear power. Finally, the long periods of thrusting needed to achieve useful changes in velocity mean that interaction effects that are subtle and difficult to diagnose over shorter periods can have long term cumulative consequences. The NEPSTP critical subsystems would be designed to tolerate expected levels of these environmental effects. However, it must be anticipated that the induced environment could degrade the performances of advanced sensors and of some spacecraft subsystems.

The induced environmental effects that are of potential concern to future uses of NEP technologies include:

- Direct and secondary radiation effects including systems and component degradations and sensors backgrounds;
- Spacecraft charging, differential charging, and discharging;
- Electromagnetic interference (EMI: from thrusters, discharges, and plasma waves);
- Surface Damage (contamination deposition, erosion and sputtering);
- Optical signature contamination (ion and neutral gas emissions); and,
- Communications degradation (attenuation, disruption, and data loss).

Because of the potential adverse effects of the induced environments on future missions, it is necessary that the NEPSTP spacecraft mission include an aggressive science program. This program must include a suite of instruments on the spacecraft, a comprehensive data analysis and evaluation program, a number of on-orbit operational experiments, and a comprehensive modeling effort to guide the instrument and spacecraft development program, and to incorporate data evaluations' results into prediction tools for future missions.

A prioritized list of 6 instruments for evaluating the induced environment includes:

1) neutron spectrometer;
2) gamma ray spectrometer/radiation dosimetry;
3) Langmuir probes/retarding potential analyzers;
4) materials experiment (for example, TQCM's);
5) plasma discharge/waves experiment; and
6) ion mass and energy spectrometer.

These investigations address the nuclear radiation environment, the plasma environment, the contamination environment, and the plasma waves and EMI environment. The ion mass spectrometer distinguishes between reactor and thruster components. In addition to these instruments that focus on the induced environment, the NEPSTP spacecraft would carry a sensitive electrostatic accelerometer for the evaluation of thruster performance.

For many measurement parameters it is critical that a spatial distribution of measurements be obtained. For example, the materials instrument and the radiation dosimetry instrument have multiple sensors distributed about the spacecraft. For other measurements the spatial distributions would be obtained with an articulated experiment boom. The boom is fixed in length (approximately 2 meters), is hinged near the aft end of the propulsion module, and is articulated in one dimension about that hinge over >180°. It would carry a neutron sensor (fast and thermal neutrons) to test the radiation shield performance and to measure low power neutron flux during reactor startup. The boom would be able to extend the neutron sensor beyond the radiation shadow cone (± 8° from the reactor symmetry axis). Additionally, the boom would carry sensors (Langmuir Probes, Retarding Potential Analyzers) to measure the spatial distribution of plasmas about the spacecraft. Angular variations in the plume would be measured by boom movement, and radial variations would be measured by multiple sensors along the boom length.

The NEPSTP Science Program would include a comprehensive modeling effort to provide a predictive understanding of the self-induced environment. The modeling would address the plasma, neutral and electromagnetic environment and its interaction with the spacecraft. Another model addresses the radiation environment from the reactor. The science program would also include several operational experiments, such as a communication experiment that propagates the telemetry link through the thruster plume, and a remote sensing experiment that examines the optical emissions due to the thruster from earth and space based assets.

We have documented here an aggressive science program included as a part of the NEPSTP mission. The science program would address reactor performance, electric thruster performance, and the character and effects of the self-induced environment. Consult Mauk et al. (1993) for details on the NEPSTP science program.

SUMMARY AND CONCLUSIONS

In this paper, we have presented many reasons, both scientific and engineering, establishing the value of conducting the Nuclear Electric Propulsion Space Test Program. NEPSTP is first and foremost a *pathfinder* mission for space nuclear reactors. It would establish techniques for testing, qualifying, integrating, and launching reactors for practical applications in space. The first US space nuclear reactor in orbit, SNAP 10A, produced 500 Watts of electric power. The TOPAZ 2 SNRS would generate over 5000 Watts of electrical power, an increase of an order of magnitude. Practical engineering development is based upon incremental advancements. The launch of TOPAZ 2 would be a good next step to get us back on the path towards the development and use of space nuclear power. We have discussed here the many things we would expect to learn; perhaps it should be observed that the most important things we learn are usually those things that we do not expect.

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