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EVALUATING RUSSIAN SPACE NUCLEAR REACTOR TECHNOLOGY FOR UNITED STATES APPLICATIONS*

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Abstract

Space nuclear power and nuclear electric propulsion are considered important technologies for planetary exploration, as well as selected earth orbit applications. The Nuclear Electric Propulsion Space Test Program (NEPSTP) was intended to provide an early flight demonstration of these technologies at relatively low cost through extensive use of existing Russian technology. The key element of Russian technology employed in the program was the Topaz II reactor. Refocusing of the activities of the Ballistic Missile Defense Organization (BMDO), combined with budgetary pressures, forced the cancellation of the NEPSTP at the end of the 1993 fiscal year.

The NEPSTP was faced with many unique flight qualification issues. In general, the launch of a spacecraft employing a nuclear reactor power system complicates many spacecraft qualification activities. However, the NEPSTP activities were further complicated because the reactor power system was a Russian design. Therefore, this program considered not only the unique flight qualification issues associated with space nuclear power, but also with differences between Russian and United States flight qualification procedures.

This paper presents an overview of the NEPSTP. The program goals, the proposed mission, the spacecraft, and the Topaz II space nuclear power system are described. The subject of flight qualification is examined and the inherent difficulties of qualifying a space reactor are described. The differences between United States and Russian flight qualification procedures are explored. A plan is then described that was developed to determine an appropriate flight qualification program for the Topaz II reactor to support a possible NEPSTP launch.

Introduction

Both space nuclear power and nuclear electric propulsion are recognized as having the potential to dramatically improve both our access to space and its utilization. Space nuclear power offers significant increases in available power for spacecraft, independent of sunlight intensity. It is a key element of any large scale planetary exploration program and, in earth orbit applications, enables the use of high power active sensors, such as radar. Nuclear electric propulsion is recognized as having the capability to provide orbital agility in earth orbit applications, as well as dramatically improved performance over chemical propulsion systems in planetary exploration.

Despite the recognized potential of this technology, the United States has only minimal experience using space reactors and nuclear electric propulsion. The United States has launched 25 systems with nuclear power supplies; however, only one of these launches involved a space reactor. This was SNAP-10A, launched in 1965. All of the other systems that have been launched were radioisotope based systems. These systems possess a very limited capability for power growth and provide no experience with the unique environment produced by space reactors.

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The former Soviet Union has significant experience in the use of space reactors, having launched a total of 38 systems. Most of these systems (36 units) were Radar Ocean Reconnaissance SATellites (RORSATs), that utilized a thermoelectric space reactor power system. The other two launches were tests of Topaz I reactors, a system that has many design similarities to the Topaz II system employed in the NEPSTP.

Neither the United States nor Russia has an extensive experience base in the application of nuclear electric propulsion. The long term operation of both a space reactor power system and electric propulsion thrusters will produce an environment around the spacecraft that is currently not well understood. Before this technology can achieve widespread application, we must understand how the environment produced by a nuclear electric propulsion system might interfere with the spacecraft's primary mission.

It is clear that space reactors and electric propulsion devices can be built and operated in space. The vision of the NEPSTP was to show how these technologies could be effectively utilized in a space mission. In the spring of 1993, the restructuring of BMDO and budget pressures resulted in a reassessment of program priorities. The flight of the Topaz II was deferred in June 1993 and the NEPSTP was cancelled at the end of the fiscal year.

The primary goals of the NEPSTP were to:

- demonstrate and evaluate the Topaz II space nuclear power system in earth orbit,
- demonstrate and evaluate nuclear electric propulsion technologies and techniques in earth orbit,
- characterize the nuclear electric propulsion self-induced environment in earth orbit, and
- conduct additional scientific research consistent with cost and schedule goals.

The NEPSTP sought to achieve these mission goals in a cost effective manner through maximum use of existing technology. The key to the program was the availability of the Russian Topaz II reactor and existing electric thruster designs. However, existing components were proposed throughout the spacecraft to minimize cost and permit the option of an early launch date. The NEPSTP was not a technology development program.

NEPSTP Mission

The NEPSTP mission would have encompassed the following, as described in detail by Cameron and Herbert (1993). The mission could be launched on a medium-class launch vehicle such as an Atlas II or a Titan III. The launch is to a 5250 km circular orbit with a 28.5 degree inclination angle. Ground based assets are employed to provide independent confirmation that the vehicle is in an acceptable orbit. Ground signals then command the spacecraft to extend its primary boom to provide physical separation between the reactor and the spacecraft. After the boom has been extended, additional ground signals command reactor start-up. The reactor start-up takes approximately one hour and must be initiated within four hours of the vehicle launch to avoid freezing of the liquid metal coolant.

Scientific instruments, powered prior to reactor operation, are used to measure both the ambient environment and the interactions of the reactor with the spacecraft as the start-up proceeds. After several days of operation, the electric thruster evaluation begins. The different types of electric thruster designs are tested individually. Six different electric thruster designs are incorporated in the spacecraft. Each relies on electromagnetic or electrostatic forces to accelerate xenon ions to high velocities. Each thruster is operated for several thousand hours while its performance is monitored.

During thruster operation, the scientific instruments measure the thruster performance and its effect on the local environment. The spacecraft uses the continuous thrust produced by the electric thrusters to increase its altitude. The spacecraft orientation is such that thrust is along the spacecraft velocity vector. This causes the spacecraft to fly like an arrow as it slowly spirals higher in altitude. Periodically, the thruster operation is suspended to measure the decay of the plasma field generated by thruster operation. This lifetime testing continues until all thruster types have been evaluated.

When all mission objectives are satisfied, the reactor is shut down and any remaining propellants vented. The total mission duration was expected to be less than two years from launch.

Spacecraft Description

The NEPSTP spacecraft is shown in Figure 1 and described in detail by Cameron and Herbert (1993). The main section of the spacecraft is separated from the Topaz II reactor by an extendable boom. The boom provides the necessary distance between the reactor and the spacecraft electronics in order to reduce the radiation dose to acceptable levels. During launch, the reactor is rigidly secured to the spacecraft structure using explosive bolts. After achieving a sufficiently high orbit, the reactor is released and the boom is extended. In its orbital configuration, the entire spacecraft is approximately 15 meters long. The spacecraft launch mass is approximately 3500 kilograms; which includes 700 kilograms of Xenon propellant.

The spacecraft uses six instruments to evaluate the reactor performance, the thruster performance, and the local spacecraft environment. The nuclear electric propulsion spacecraft environment is unique as compared to all other spacecraft. Therefore, the sensors are used to measure not only the ambient environment, but the environment produced by the reactor and electric thruster operation as well. These instruments measure gamma and neutron radiation, plasma waves, surface contamination, etc. About half of the instruments are mounted on a honeycomb pallet as part of the spacecraft bus. The other half are mounted on an articulated boom that allows for measurements at different points around the spacecraft in order to sense the spatial variations of the parameters being measured.

TOPAZ II REACTOR DESCRIPTION

The Topaz II is a reactor power system that generates electricity from nuclear heat, using in-core thermionic conversion units. It was designed by the Russian team to meet the following system requirements:

- The mass of the power system must not exceed more than 1061 kilograms, not including the mass of the automatic control system.
- The system should provide 6 kW_e at the reactor terminals, at 27 volts, for a lifetime of 3 years. An operational reliability of 0.95 was a design goal.
- The system must have a shelf life, after fabrication, of 10 years or greater.
- Under no conditions should the reactor operate before achieving orbit.
- The coolant must not freeze before operation.

Additional general requirements were established for specified launch loads and unbalanced forces and moments.

The Topaz II power system consists of the following main subsystems: the reactor subsystem, the radiation shield, the primary coolant loop, the cesium supply system, the gas systems, the thermal cover, the primary power system structure, and the instrumentation and control system. The Topaz II power system is illustrated in Figure 2 and described in detail by Voss (1994a).

At the beginning-of-life (BOL), the reactor produces approximately 115 kW_{th}, for a conversion efficiency of 5.2%. The maximum thermal power is 135 kW_{th}. The Topaz II is cooled by a liquid metal eutectic of 22 weight percent ($^{w}/_{o}$) sodium and 78 $^{w}/_{o}$ (±3%) potassium (NaK). The coolant remains liquid during all phases of the Topaz II lifetime, excluding the end-of-mission shutdown.

The Topaz II reactor incorporates in-core single-cell thermionic fuel elements (TFEs). Electric heaters can

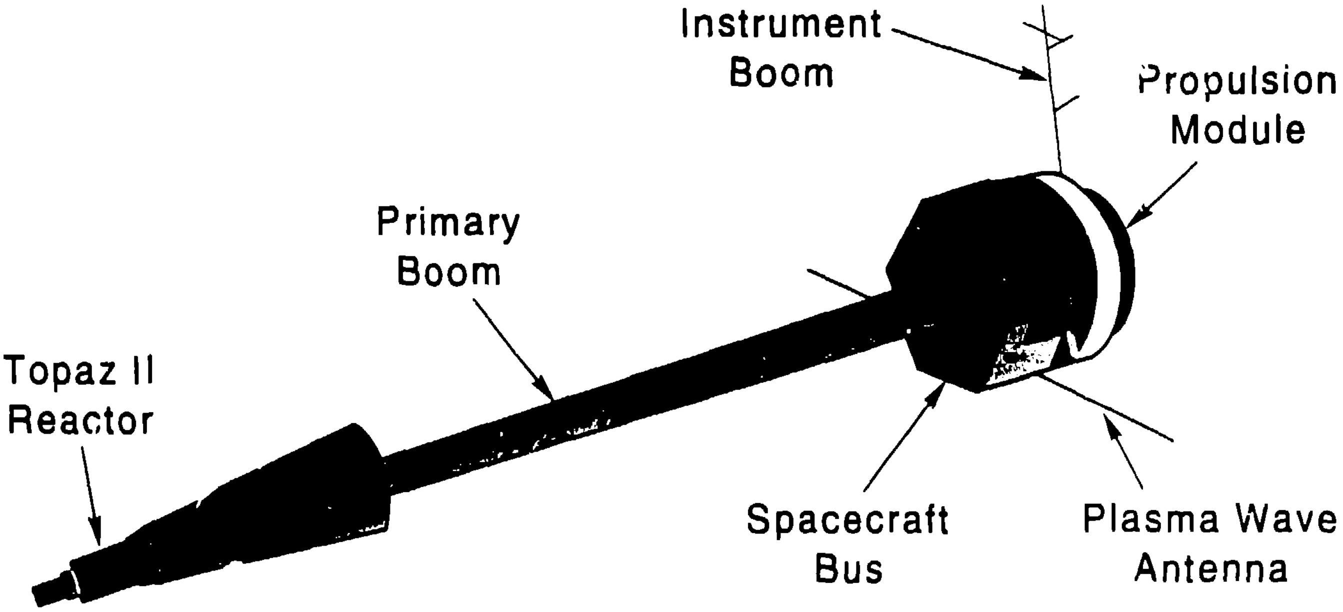

Figure 1. Orbital Configuration of the NEP Space Test Spacecraft.

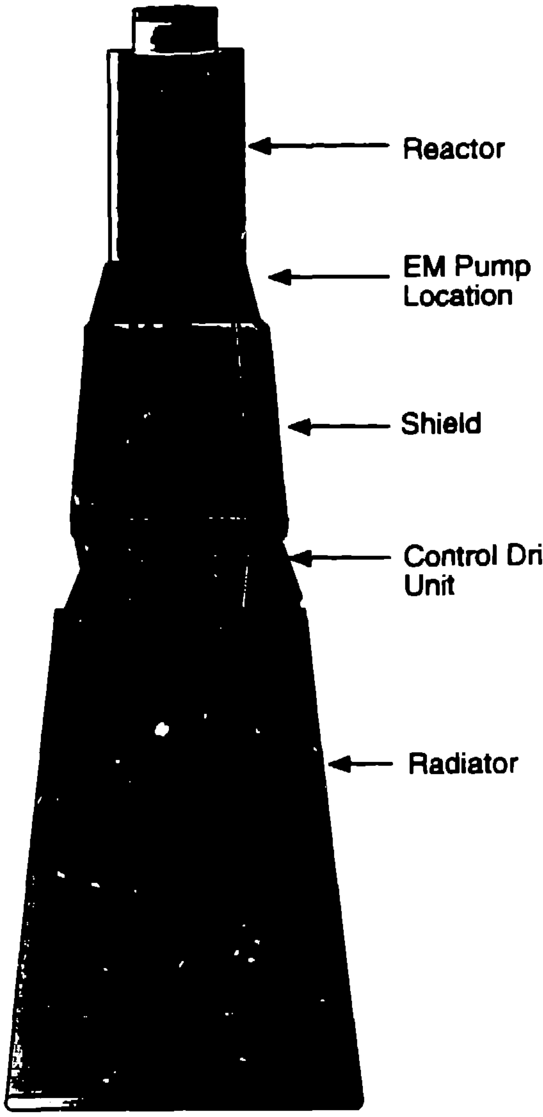

Figure 2. The Topaz II Power System.

be placed within the internal cavity of the TFEs (before loading fuel into the TFEs) and can simulate the heat generated by the reactor. This feature provides the unique advantage of allowing non-nuclear testing of the thermionic converters and the complete power system at close to nominal operating conditions. Testing with electric heaters in the TFE cavities allows the user to obtain the system operating parameters, and to check the fabrication and operation of the complete power system and control system before nuclear ground testing or operation in space.

The nuclear reactor contains 37 single-cell TFEs, that are fueled by UO_2 fuel pellets 96% enriched in U^{235}. Three of the TFEs are used to power the electromagnetic (EM) pump and the remaining thirty-four provide power to operate the Topaz II reactor and the satellite payload. The TFEs are set within axial channels within the $ZrH_{1.85}$ moderator blocks. The reactor core is 37.5 cm high and the diameter is 26.0 cm. A vessel of stainless steel contains the reactor core. The reactor core is surrounded by radial and axial beryllium (Be) reflectors. The radial reflector contains three safety drums and nine control drums. Each drum contains a section of boron silicate carbide neutron poison to control the reactor. During operation, the nuclear fuel heats the TFE emitters, which in turn generates an electric current. The waste heat is removed by the coolant system. The coolant flows past the outer surface of the collector boundary.

The radiation shield is attached by support legs to the lower end of the reactor. The shield is composed of a stainless steel shell that contains lithium hydride (LiH). The shell is thicker on its top and bottom, and serves both as a container for the LiH and to attenuate gamma radiation. The LiH is used to attenuate the neutron radiation. The radiation shield is designed to reduce the three-year accumulated radiation dose to 1×10^{11} neutron/cm^2 (for neutron energies >0.1 MeV) and 5×10^4 roentgen gamma at 18.5 meters from the centerline of the reactor core.

The reactor coolant system includes NaK coolant, a single EM pump, stainless steel piping, and a heat rejection radiator. The NaK coolant enters the reactor core through a lower plenum. It passes through the core and is heated from 743 to 843 K by the waste heat from the thermionic conversion process. After passing through the core, the NaK exits through an upper plenum and then flows through two parallel paths to the radiator inlet collector. The radiator consists of inlet and outlet collectors that are connected axially by 78 coolant tubes. Thin copper fins are attached to the outside of the coolant tubes. After flowing through the radiator, the NaK flows through two coolant pipes. They divide into three pipes each, before entering the pump. The EM pump, that is powered by three of the TFEs, pumps the NaK back to the reactor lower plenum.

The cesium supply system provides cesium to the TFE interelectrode gap. Cesium is necessary to suppress the space charge that occurs near the emitters of thermionic converters and it increases the efficiency of the TFE converter. During operation, the cesium from the reservoir is distributed to all the TFE interelectrode gaps. Cesium vents to space at a rate of 0.5 gram per day.

The Topaz II instrumentation and control (I&C) system provides the mechanism for monitoring, controlling, and telemetering power system conditions. Its major functions are: 1) to start up the power system, 2) to maintain operation of the system under nominal operating conditions, 3) to stabilize the voltage supplied to the payload, 4) to perform the commands supplied from the ground control station, 5) t shutdown the Topaz II power system, 6) to maintain safety control during land-based operations, 7) to telemeter performance data to the ground, 8) to shunt excess electrical power to ballast resistors, and 9) to charge the storage battery.

It will be necessary to make several modifications to the Topaz II reactor in order to launch it from the United States. The most significant modification is that the Russian automatic control system for the reactor must be replaced. The existing Russian system was not flight qualified, was massive, and required forced convection cooling. An effort is underway to replicate the functionality of the Russian system using microprocessor technology, integrated in a package that is consistent with United States spacecraft design.

Another significant modification that must be performed on the Topaz II reactor serves a safety purpose. Analysis indicates that this reactor may achieve nuclear criticality when immersed in and flooded with water. Because this violates United States safety practice, a modification is being considered to store a portion of the nuclear fuel outside the reactor core. A mechanism would then load this portion of the fuel into the reactor core after the spacecraft has achieved a sufficiently high orbit.

United States Qualification Program

In the United States, all space vehicles are subjected to extensive ground testing in order to ensure their successful operation. For Department of Defense programs, this testing program is normally governed by MIL-STD-1540B described in USAF (1962) and USAF (1985). This document establishes a uniform set of definitions and requirements for the ground testing of space vehicles. Under these requirements both space vehicles and their components are normally subjected to a variety of test environments, including static load, acoustic environment, pyrotechnic shock, random vibration, thermal vacuum, and pressurization.

The standard recognizes that these tests may serve a variety of purposes and defines a series of test levels: acceptance level (maximum predicted flight conditions), protoflight level (maximum predicted flight conditions + 3dB), and qualification level (maximum predicted flight conditions + 6 dB). Nonflight hardware is usually tested to qualification levels and actual flight hardware is usually tested at acceptance or protoflight levels. The standard also recognizes the uniqueness of many space programs and provides for tailoring of the test program as defined in MIL-STD-1540B, as appropriate for a specific program.

Additional guidance relevant to a program such as the NEPSTP is found in USAF (1986). This handbook provides additional guidance for "one of a kind" space experiments such as the NEPSTP. It recognizes that, in this type of program, the full qualification series intended for a production space vehicle may be inappropriate.

None of the standards for space vehicles are specifically designed for the launch of space nuclear reactors. Therefore, in addition to the spacecraft qualification requirements of MIL-STD-1540B, the NEPSTP will include guidance from various Department of Energy regulations concerning research nuclear reactors. In addition, the use of a space reactor imposes special qualification testing requirements on the space vehicle, in order to insure that it will function properly in the radiation fields produced by the reactor power system.

Russian Qualification Program

The Russians also have extensive ground testing procedures for space vehicles. Although the documents that define the details of the general procedures remain classified, much has been learned about the specific test program that was applied to the Topaz II and is described in detail by Voss, et al. (1994b). In general, the Russian test program philosophy is similar to the MIL-STD-1540B approach, in that both components and systems are tested for exposure to a variety of environments. However, important differences between the two qualification testing philosophies exist. Whereas, the United States requires extensive environmental testing of the actual flight hardware, Russian flight hardware generally receives only minimal environmental testing. Russian flight qualification relies on extensive testing of "similar" hardware from the same production line. The actual flight hardware is then only subjected to a low level workmanship test. The philosophy is to avoid stressing the actual flight hardware before the launch.

Another important difference between the Russian and United States approaches to flight qualification has to do with test levels. In the MIL-STD-1540B approach, the design margins of nonflight hardware are typically verified by testing to qualification levels. Actual flight hardware is then usually tested to acceptance or protoflight levels. Although the Russians perform extensive testing of the nonflight hardware, the test levels are generally only the expected environments from the launch (our acceptance levels). Although the Russians employ significant margins in their design, they typically do not verify these margins in their test program.

Space Reactor Qualification

In general, space reactors present several challenges in flight qualification. The most severe challenge is finding a meaningful method of performing functional testing on the ground. Full power nuclear operation is precluded, as this activity would build up a significant inventory of fission and activitation products, making the reactor too radioactive to handle for launch. Therefore, prelaunch nuclear testing is limited to extremely low power levels and relatively short durations and simply serves to verify that the neutronic performance of the reactor core is as expected. The first time that a space reactor power system will produce power from the heat of nuclear fission is in space, so some other technique must be developed to perform a functional test of the reactor.

In all tests involving the nuclear fuel, nuclear safety must be a primary consideration. If routine tests such as shock and vibration are to be performed with a fully fueled reactor core, then extensive analysis is required to insure that the test, or any potential accident environment at the test site, cannot cause a nuclear safety problem. Nuclear safeguards present an additional challenge. The highly enriched uranium fuel of space nuclear reactors must be protected from theft or diversion during transportation, storage, and testing. This can cause significant difficulties, as most facilities designed for routine environmental testing will not have security consistent with the requirements to safeguard the reactor fuel.

The combination of nuclear safety and nuclear safeguards concerns makes it very desirable to perform routine reactor qualification tests without the presence of the nuclear fuel. However, not all reactor designs permit the fuel to be readily removed and installed. In the designs that do, a mass mock-up of the reactor fuel that provides the same structural and mass properties as the nuclear fuel can be developed. The mock-up can then be used in the nonnuclear testing to significantly simplify the testing process. The nuclear fuel can then be qualified separately in a specialized test facility.

NEPSTP Flight Qualification

The NEPSTP faced many unique issues regarding qualification of flight hardware. In addition to the general complications posed by flight qualification of a space nuclear power system, this program considered flight hardware that was not designed for United States launch vehicles or the United States qualification testing process.

The Topaz II reactor was designed for launch on the Russian Proton launch vehicle. Comparisons of the Proton with the United States medium class launch vehicles considered by the NEPSTP, reveal similar dynamic environments. Therefore, the use of a United States launch vehicle to launch the Topaz II did not present any major obstacles.

The desire to employ a United States type qualification process on the Topaz II reactor was examined carefully. This reactor was designed for Russian flight qualification and therefore the flight hardware would not normally be subjected to environmental testing. Consequently, it must be determined if the Topaz II reactor can be expected to survive both environmental testing and the actual launch environment without degrading its ability to perform in space.

Despite the inherent difficulties of qualifying space reactors and the additional challenges posed by qualifying a Russian design by United States procedures, the Topaz II possesses features that are strong assets to the qualification program. The most important asset to flight qualification is that the single cell thermionic fuel element design of the Topaz II permits the reactor fuel to be easily installed or removed. This allows for all of the environmental testing to be performed on a reactor that substitutes mass simulant for the reactor fuel and avoids concerns of nuclear safety and safeguards.

The Topaz II design also permits electric heaters to be inserted in place of the nuclear fuel. The electric heaters simulate the heat produced by the nuclear fuel during reactor operation and permit a full systems level test of the power system in a nonnuclear test facility. These tests are currently being performed at the Baikal Test Stand of the Thermionic Systems Evaluation Test (TSET) facility described by Morris (1993). Combined with zero power critical tests performed in a nuclear test facility, these nonnuclear systems tests produce a high degree of confidence that the space reactor power system will operate as intended.

Another asset of the Topaz II reactor is that a relatively large number of units are available. There are currently two units in the United States undergoing tests in the TSET facility. Four additional units recently arrived from Russia. Two of these are flight quality units, one is a mechanical test unit, and one is a thermal test unit. This relative abundance of hardware permits a test program to be designed that presents minimum risk to the flight hardware.

It was the goal of the NEPSTP to qualify the Topaz II reactor as closely as possible to MIL-STD-1540B guidelines. This could be achieved by exploiting the inherent testability of the Topaz II reactor design and the relatively large amount of available hardware. The program test activity that is described in the following sections, begins early and seeks to answer key questions about the ability of the Topaz II reactor to survive a United States type flight qualification program. The results of this effort will be used to tailor the MIL-STD-1540B test requirements to the NEPSTP.

The Topaz Test Program

The Topaz II System Qualification Test Program is described in detail by Polansky, et al. (1993) and Schmidt, et al. (1994). The overall test program is illustrated by Figure 3 and includes the following systems:

V-71

The V-71 system was tested extensively in Russia before shipment to the Phillips Laboratory. The V-71 system was installed in the Baikal vacuum chamber and used to check out the Baikal test stand, train the American operators, and compare Russian test results with that obtained by Americans. The V-71 system was operated at heater power levels from 0 to 115 kWt and reactor NaK outlet temperatures from ambient to 790 K. The maximum electrical power produced by the work section (thermionic converters) was 4.5 kWe.

Work section power oscillations were observed and were attributed to variations in cesium vapor pressure due to argon gas entrapment in the cesium reservoir. The system was removed from the Baikal vacuum chamber and put in standby storage following Baikal test stand checkout and operator training.

Ya-21U

The Ya-21U system was also tested extensively in Russia before shipment to the Phillips Laboratory. The Ya-21U system was designated the "Pathfinder System" and is being used to demonstrate the viability of qualifying the Topaz II reactor to MIL-STD-1540B. The system is a prototype of the two flight systems, EH-43 and EH-44. A modal survey was performed on this system to verify the dynamic characteristics of Topaz II reactor systems.

The system was installed in the Baikal vacuum chamber and operated at heater power levels from 0 to 95 kWt and reactor outlet temperatures up to 520°C. The system was operated at steady-state power levels for a period of 1000 hours to demonstrate the integrity of the NaK system and to obtain baseline performance information for comparison with previous Russian test results and subsequent thermal vacuum tests which followed the mechanical tests.

Mechanical tests, to be performed at Sandia National Laboratories, include static loads, vibration, shock, acoustic, and determination of the center of gravity, and moment of inertia. Acceptance and proto-qualification test levels were selected, which represented the stresses expected for launches using American launch vehicles.

After the mechanical tests, the Ya-21U system was reinstalled in the Baikal vacuum chamber and the 1000 hour thermal vacuum tests repeated at a reactor outlet temperature of 840 K to demonstrate the robustness and durability of the reactor system, the integrity of the NaK system, and stable performance of the thermionic working section during the simulated orbital startup and steady-state operation.

Other non-intrusive experimental tests were performed during the first and second thermal vacuum tests to explore the stability of the Topaz II system while operating at non-optimum electrical loads and cesium pressures within the TFE interelectrode gap.

After completion of the "Pathfinder" thermal vacuum and mechanical test, the Ya-21U system will be delivered to the Los Alamos National Laboratory and used for non-nuclear demonstration of fuel loading and installation of the anticriticality device.

EH-40

The EH-40 system serves as a thermal-hydraulic engineering mockup of the Topaz II flight system. It has a functional heat rejection NaK system, was used and will be used for "cold-test" demonstration of the performance of thermal covers during prelaunch heating, launch, and orbital injection of the flight system. The "cold tests" will be performed to qualify the modified thermal cover and to assure that the NaK system will not freeze prior to reactor startup.

EH-41

The EH-41 systems serves as a structural engineering mockup of the Topaz II flight system. It will be used for mechanical testing and demonstration of the structural integrity of the flight system, anti criticality device, modified thermal cover, and other minor modifications required to adapt the Topaz II flight system to American launch vehicles.

Figure 3. Flow Chart for the Topaz Test Program.

EH-43 & EH-44

The EH-43 and EH-44 systems are the designated flight systems, to be used for potential flight demonstration or extended ground testing to demonstrate the long-life durability and performance of the Russian single-cell thermionic converter technology.

The flight systems will undergo modal tests, charging and purification of the NaK system, a 1000 hour thermal vacuum steady-state stability and NaK system integrity test, fuel loading and criticality tests, mechanical vibration, shock, and acoustic tests, and a short duration thermal vacuum system performance test.

Protoqual test levels will be used during performance of the flight system tests. Results of the flight system tests will be compared with Russian test results from other system tests and with results obtained during the Ya-21U Pathfinder test program.

Conclusions

The inherent difficulties of qualifying space reactors, combined with the additional complications of employing Russian space hardware posed challenges to the NEPSTP flight qualification program. A plan that exploits the testability that was designed into the Topaz II hardware and the relative abundance of this hardware was devised to qualify the reactor to MIL-STD-1540B requirements. The Pathfinder Program would have provided early test experience with the Topaz II and permitted the NEPSTP to determine how to tailor the United States MIL-STD-1540B requirements.

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