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**UTILIZING A RUSSIAN SPACE NUCLEAR REACTOR FOR A UNITED
STATES SPACE MISSION: SYSTEMS INTEGRATION ISSUES**

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Abstract

The Nuclear Electric Propulsion Space Test Program (NEPSTP) has developed a cooperative relationship with several institutes of the former Soviet Union to evaluate Russian space hardware on a U.S. spacecraft. One component is the Topaz II Nuclear Power System; a built and flight qualified nuclear reactor that has yet to be tested in space. The access to the Topaz II reactor provides the NEPSTP with a rare opportunity; to conduct an early flight demonstration of nuclear electric propulsion at a relatively low cost. This opportunity, however, is not without challenges. Topaz II was designed to be compatible with Russian spacecraft and launch vehicles. It was manufactured and flight qualified by Russian techniques and standards and conforms to safety requirements of the former Soviet Union, not the United States. As it is desired to make minimal modifications to the Topaz II, integrating the reactor system with a United States spacecraft and launch vehicle presents an engineering challenge. This paper documents the lessons learned regarding the integration of reactor based spacecraft and also some insight about integrating Russian hardware. It examines the planned integration flow along with specific reactor requirements that affect the spacecraft integration including American-Russian space system compatibility.

INTRODUCTION

In 1992 and 1993, the Ballistic Missile Defense Organization (BMDO) funded the NEPSTP program to develop a satellite to evaluate electric propulsion technologies using an existing Russian Topaz II reactor as a power source. This work included mission and spacecraft design and all of the details associated with a space program. This included reactor launch approval, safety, integration and qualification, and launch operations. Such a mission would have several benefits to current reactor design efforts and future reactor based missions. As a pathfinder, the NEPSTP program could characterize the electromagnetic and plasma environments generated by a reactor and electric propulsion in orbit. This is important information needed for the design of electronic systems for future spacecraft utilizing reactors. Another benefit from a NEPSTP mission would be the identification of all the restrictions, logistics, analysis, safety requirements and approvals required to launch a reactor. The program has progressed to the preliminary design stage and has identified many of these special requirements and incorporated them into the program infrastructure. As part of this effort the integration, testing, and launch operations sequence has been developed. This sequence differs somewhat from traditional satellite ground processing due to the special requirements of space nuclear reactors and their launch approval.

This paper focuses on the integration issues and integration sequence of a reactor powered spacecraft. Future reactor based missions will face similar requirements and will likely benefit from the NEPSTP experiences. Some issues relate to accommodating an existing reactor based on a Russian design. Other issues are generic to all reactors. The spirit of this paper is to document the lessons learned on the NEPSTP program regarding the integration of space reactors and Russian hardware. It starts by briefly identifying the Topaz II interfaces and some implications of using Russian hardware. The program integration philosophy is described along with the flow of the spacecraft and reactor through their integration and test programs up through launch. The reader should refer to Cameron 1993, Polansky 1993, Marshall 1993, and Reynolds 1993, for detailed descriptions of NEPSTP system design, reactor qualification and acceptance test program, and safety issues.

TOPAZ II REACTOR & INTERFACES

Design of the Topaz II began in 1969 in the Soviet Union and its design evolved to its final configuration when the Russian program was scaled back in 1988. When the program ended, the Topaz II design was mature and considered flight qualified by the Soviet Union - though it was never launched. It was designed so it could be launched either right side up as shown or inverted. Figure 1 shows the final configuration and major spacecraft

interfaces of a Topaz II reactor unit. The reactor unit is almost four meters high and 1.5 meters in diameter at the base of the radiator. The total mass of the reactor unit in its launch configuration is 1061 kilograms.

The Topaz II has three major sections: the reactor core located at the top of the unit, the radiation shield located in the middle of the unit, and the thermal radiator located at the base of the unit. The reactor core contains thermionic fuel elements (TFE) which use heat from the reaction to generate electricity. The TFEs are designed so the fuel can be inserted and removed through openings in the top of the core. A benefit of this design is that the reactor system can be tested by inserting heaters into the TFEs instead of fuel. Another benefit of this design is that testing and processing can be performed with the reactor unfueled. By fueling the reactor just prior to launch, many of the special safety precautions associated with the fuel can be minimized. When operating, the reaction is monitored by measuring three parameters: neutrons, temperature, and electric current generated. The reaction is controlled by varying the amount of neutron reflector and absorber that faces the core center using nine rotating control drums ganged to a single control motor.

In Figure 1, half of the radiator section has been removed to show the truss structure that connects to the radiation shield. For the NEPSTP spacecraft, the truss is part of the structural load path for the reactor unit during launch. It also supports several gas and cooling components located within the upper radiator cavity. The lower portion of the cavity is empty. The base of this truss is used as an interface to the separation boom. Any boom and adapter hardware that interfaces with this truss must withstand temperatures up to 600 °C.

To interface the reactor with the spacecraft electronics, there are eighteen cables that hang below the radiator skirt approximately two meters. These cables interface with boom cables which route the signals to the spacecraft. The two meter pigtails are required to reduce the temperature of the interface connectors to something tolerable (120 °C). About half of the cables go to the Reactor Control Unit (RCU). The RCU is a microprocessor based unit that monitors the core sensors and makes adjustments to the control drums position. The other cables go to the power conditioning electronics, and to other spacecraft subsystems. The power conditioning electronics maintains a constant electrical load on the reactor TFE working section. The other subsystems are typical of other spacecraft -- relays, telemetry, and ordnance -- and are used to help startup, shutdown, and monitor the reactor system. A total wire count from these interface cables is as follows: 2 Wires at 00 AWG, 7 Wires at 10 AWG, 29 Wires at 20 AWG, 136 Wires at 22 AWG, and 4 Coax Wires.

FIGURE 1. Topaz II and Its Interfaces.

There are several other components of the system not shown in Figure 1: the Thermal Cover and the Start-Up Battery. The thermal cover blankets the reactor to conserve heat from launch to until the reactor starts up. This is to keep the NaK coolant from freezing. During start-up the cover is ejected using ordnance mechanisms. The Start-Up Battery is used to power the coolant system pump to periodically circulate the NaK to avoid cold spots in the system. This unit is used until the reactor has started up. Both systems are installed into the satellite during the final launch preparations, prior to encapsulating the satellite in the launch vehicle shroud.

IMPLICATIONS OF RUSSIAN HARDWARE -- DIFFERENT APPROACHES

The Russians develop space hardware using a different philosophy. Unlike the West, there is a limited amount of diagnostic tools to analyze designs before fabrication. Their approach is to build an item and then test the item. If the item breaks, the design is modified and then a new item is fabricated and retested. This process repeats until the

evolved item survives ground testing. This design is then used for the flight hardware. The Russians will design their components with factors of safety and margin but these margins are never tested in their qualification program. Typically, they will test the qualification unit to the anticipated environment and no higher. The Russian flight hardware typically receives only workmanship testing (low level vibration at a single frequency). In the United States, there is abundant computer resources and analysis software. The design is evaluated using computer software and analysis methods such as finite elements. Once the design is shown to survive the simulated environment with factors of safety and margin, it is fabricated and tested. In the U.S. the test levels are typically +6 dB above the anticipated flight levels for qualification hardware. This hardware is not flown. The flight hardware is built to the qualified design and tested to +3 dB above the anticipated flight environment. Test data is compared to the data from the analysis to insure that the models are correct and adequate margins exist. When using Russian hardware, these differences need to be taken into account when developing a qualification program for a satellite. For Topaz II, a new analysis and qualification program was initiated to prove the reactor would survive U.S. launch vehicle loads plus some margin.

Another important factor to consider is the Soviets use their own test specifications to qualify their hardware. Many times, the guiding test documents, similar to MIL-STD-1540B, are classified and unavailable. Even the hardware test reports are classified. The user may be forced to repeat tests just to obtain data to prove that the component is indeed qualified.

Many of the major NEPSTP integration issues dealt with adapting the Russian designed reactor into a U.S launch system. In the 1970s and 1980s, the Soviets had developed several spacecraft designs along with integration procedures using the Topaz II reactor system. In that program, the intended launch vehicle was the Proton rocket launched from the Baikonour Cosmodrome in Kazakhstan. In the NEPSTP program, we discovered several fundamental differences between Russian space designs and American space designs -- they appear subtle but they have large implications on the design and integration of the payload spacecraft:

1. Many Russian Spacecraft are Pressurized Chambers;
2. Russian Launch Sites are Inland;
3. Russian Launch Sites Do Not Environmentally Condition Payloads before Launch.

With each of the above items there was a difference in philosophy that caused the NEPSTP program to adopt a different approach from the Russian implementation. The following paragraphs identify the problems with each case and summarizes the new approach taken.

Russian spacecraft typically use pressurized vessels with a gas environment inside. These gas filled vessels provide convection heat transfer for cooling the electronics and transferring the heat to the outside environment via radiation. The use of pressure vessels greatly simplifies the thermal management but requires much more mass and volume to implement than western conduction/radiation designs. The reactor control system that was originally designed using the Russian philosophy. It is based on small scale integration discrete logic which made the unit large and heavy. Also, it relied on a pressure vessel with convective heat transfer for cooling their electronics. The unmanned U.S. spacecraft typically do not use pressure vessels and instead use conduction and radiation techniques for thermal control of their electronics. Because of mass and volume limitations and the desire to avoid building a pressure vessel for the Russian electronics, their electronics was replaced with a much smaller microprocessor based unit that retained all the functionality of the original design but used western thermal techniques.

Launches from the Baikonour Cosmodrome travel eastward over land all the way to orbit injection. The U.S. has an opposite approach and launches over water. Some analysis of the Topaz II reactor neutronics showed that the reactor could go critical if the launch vehicle failed and the payload landed in the ocean. To prevent this, a mechanism is required to fuel a portion of the core once the satellite is in a safe orbit. This approach differs from the Russian approach in which the reactor is launched with a full core. Because this mechanism is integrated with the satellite after fueling the core just prior to launch, the mechanism must be designed so it can be tested to show that it does indeed work and then reset to its safe configuration for launch.

The Proton rocket provides no temperature controlled air flow for the payload prior to launch so payload supplied equipment is required for any environmental control. In the Soviet Topaz II missions, ground support equipment was designed to heat and circulate the liquid metal coolant (NaK) in the reactor so that it would not freeze before the reactor starts up in orbit -- eight hours later. The Russians calculated a required launch temperature of 40 °C to prevent freeze up. With a two hour pull away of special umbilical connections and assuming worst case conditions

at the Cosmodrome (-50 °C with a 30 mile per hour wind), the reactor needed to be heated to 100°C. The heating and circulation technique selected by the Russians required an umbilical connector the size of a fire hose which carried currents up to 700 amperes. With the NEPSTP program, things are different. American launchers provide temperature controlled airflow up to the moment of launch. The launch to startup time is four hours -- not eight -- reducing the launch temperature from 40 °C to 35 °C. By soaking the entire payload at 35 °C, the need for the large umbilical and high current equipment is eliminated.

INTEGRATION PHILOSOPHY

The satellite is divided into four major modules: reactor unit, spacecraft bus, propulsion module, and separation boom. The satellite's stowed configuration is shown in Figure 2. At the bottom of the satellite stack is the propulsion module. It contains all the electric thrusters, gas thrusters, xenon propellant, and the electronics associated with the propulsion system. The next module is the spacecraft bus. It consists of six aluminum honeycomb pallets used to support the majority of the spacecraft electrical systems. Both the propulsion module and the bus are built up around the cylindrical structures of the satellite's primary structure. Due to a problem of low lateral stiffness of the reactor truss, the spacecraft structure is required to be as stiff as possible to keep the satellite stack lateral frequency compatible with the launch vehicle control requirements. In the propulsion module, the primary structure is a truncated cone. The cone interfaces with the launch vehicle adapter (1.65 meters diameter) and tapers down to the spacecraft bus primary structure, -- a pure cylinder (1.22 meters diameter). The separation boom assembly fits within the primary structure cylinder. When stowed, the boom assembly is two meters long and occupies a portion of the propulsion module structure and some volume under the reactor radiator skirt. At the top of the satellite stack is the Topaz II reactor unit. An adapter is used to connect the reactor truss to the boom assembly. During launch the reactor unit is secured to the spacecraft structure using explosive bolts that hold the adapter rigid to the spacecraft cylinder.

FIGURE 2. Stowed Configuration.

The integration philosophy of the program is to keep the satellite as modular as possible and to keep the interfaces between the modules as simple as possible. This approach was taken due to the special testing requirements of each component. The reactor unit requires special facilities at Phillips Lab, NMERI, Sandia, and Los Alamos for prelaunch functional and environmental testing as well as neutronics tests. The propulsion module requires a special vacuum chamber at NASA Lewis to test the electric thrusters. And the separation boom requires a zero-G suspension system to simulate the deployment conditions in orbit. With the NEPSTP program, most of the special tests will be performed during module testing and not during the all up satellite testing. During the module level tests, the electrical interfaces to the other spacecraft systems will be tested using engineering breadboards or actual flight hardware. When the module is integrated into the satellite, the interfaces will be retested. With this approach the satellite can avoid a lengthy test program and the need for new test facilities to accommodate such a large spacecraft.

The mechanical modularity is maintained by simple interfaces between each module. The interface between the propulsion module and the bus module uses a simple 1.22 meter bolt circle. The interface is designed to be adiabatic so heat transfer issues do not complicate the interface. When the tested propulsion module arrives at APL for integration with the spacecraft bus, a crane is used to lower the assembled bus module on to the propulsion module and the fasteners are installed. The separation boom assembly is a 1.22 meter diameter "bucket" that fits within the primary structure. Its interface also uses a simple 1.22 meter diameter bolt circle at the top end of the spacecraft bus cylinder. The end of the boom that connects to the reactor unit uses a 0.51 meter bolt circle to interface with the reactor unit adapter. Any special interfaces between the spacecraft structure, the boom assembly, and the reactor unit are isolated to this adapter. The flight adapter is easily transportable for fit checks with the other flight hardware around the country. By using simple bolt circle interfaces between the modules and using an adapter to secure the

reactor with the boom and the spacecraft, the coordination required for insuring module interfaces is greatly simplified.

Spacecraft Bus/Propulsion Module

The spacecraft bus will be developed at APL in Laurel, Maryland. The design of the spacecraft bus was based on maintaining the modularity philosophy down to the subsystem level. The components are placed on pallets by their subsystem: power, attitude, command and data handling, or experiments. Figure 3 shows an exploded view of the bus and its subsystem pallets. Each pallet has its own harness to connect the subsystem components together. There is also a system harness that interconnects the pallets and performs necessary functions such as grounding scheme, safety interlocks, power distribution and system testing. Commands and data are transferred between subsystems using a MIL-STD-1553 Bus. With this partitioned approach, the subsystem can be built up and tested individually prior to integration with the other subsystems.

- The attitude system pallet uses star cameras and gyros for attitude knowledge and uses the thruster systems of the propulsion module for attitude control. Communication with the propulsion module uses a second MIL-STD-1553 bus. A closed loop attitude simulator is used to stimulate the attitude sensors and monitor the control algorithm through the thruster commands.
- The command and data handling system uses one and a half pallets. It contains the command & telemetry processors, RF equipment and data storage. It is tested by traditional test practices at APL.
- The instrument pallet contains portions of the instrument suite used to evaluate the environment around the spacecraft. The instruments are selected to characterize how the reactor and the electric thrusters alter the natural environment. Testing of the instruments is based on different methods depending on the instrument. The satellites ground system architecture is designed so the experimenters' equipment can be connected and receive spacecraft and instrument data. With this design, the experimenters can use the equipment used to develop their instruments for data reduction after launch.
- The power system occupies two and a half pallets due to the large component count. The power pallet contains the Reactor Control Unit and the power shunting and conditioning equipment. All of the wires that connect to the reactor are routed to components in the power system. The interface connector bracket that interfaces with the boom cabling is actually part of the harnessing of the power system.

To test the power system, two different simulators are used instead of the reactor. The Dynamic Simulator is used to test the Reactor Control Unit (RCU) and the Source Simulator is used to exercise the spacecraft power electronics. The Dynamic Simulator mimics the signals from sensors of a reactor under operation and monitors the response of the RCU. The dynamic simulator operates 'closed-loop' to test the RCU control algorithm in a dynamic environment. Using a simulator allows the RCU to be tested in anomalous scenarios that would be difficult to create in a real environment. The Source Simulator mimics the power generation part of an operating Topaz II reactor unit. It is essentially a large 6000 watt power supply with all the electrical characteristics of reactor working section.

By using a modular approach, integration of a subsystem consists of mounting a pallet to the spacecraft bus frame and integrating the system harness with the pallet harness. The various simulators that are used to test the individual subsystems at the pallet level are also used for satellite level testing.

Separation Boom

A telescoping boom design was selected for NEPSTP. Early spacecraft design concepts had planar and three-dimensional scissors boom designs but they were dropped because of low torsional and lateral stiffness required by the satellite's attitude control system on orbit. Telescoping boom concepts are based on hollow concentric cylinders which are stowed one inside the other and deployed similar to a telescope. For NEPSTP, the required separation distance is ten meters. The selected design consists of six cylinders each two meters long. A bi-stem drive mechanism in the center of the telescoping cylinders is used to extend the boom. The cylinders use special locking pins to secure each section as it is deployed, starting with the largest cylinder and working down to the smallest. All of the cylinders are aluminum except for the two closest to the reactor. These two cylinders are stainless steel which are required for the 600 °C interface temperature at the reactor. The eighteen cables that connect the reactor unit

with the spacecraft are external to the telescoping cylinders. The advantage of external cabling is it allows for easy inspection to insure proper stowage. For cable stowage during launch, pockets were positioned around the outside of the telescoping cylinders. The cables were folded in a zig-zag fashion and stowed in the pockets. At the top of each cylinder, an extended member is used to secure the cabling to the boom along its deployed length.

FIGURE 3. Spacecraft Bus Exploded View.

The telescoping boom is oriented so the largest cylinder connects to the reactor end and the smallest cylinder connects to the spacecraft end. This geometry allows the reactor cable pigtails to be rigidly secured to the outer telescoping cylinder. The bi-stem motor mechanism is at the end attached to the spacecraft. Figure 4a shows the configuration of the stowed boom assembly with and its relationship with the reactor unit. Figure 4b shows the boom with one segment deployed to demonstrate the cable deployment from a stowage pocket.

The baseline plan is to perform much of the design and flight qualification testing of the boom at the module level. The pieces of the boom assembly would be integrated together: telescoping cylinders, bi-stem drive mechanism, cables, stowage pockets, and the bucket container. Functional testing would consist of attaching mass simulators representing the reactor and the spacecraft at each end of the stowed assembly and deploying the boom to its full extension and locked position. To do this, the boom-mass assembly has to be suspended in such a way to simulate zero-G. After the extension test, the boom assembly will be subjected to shock, random vibration and sine vibration in its stowed configuration. The boom also sees thermal cycling testing in a partially deployed configuration. To perform these tests, it is important that the boom assembly is designed to be retractable. Tooling is used to unlatch the locking pin mechanisms while the bi-stem mechanism is operated in reverse. After the environmental tests are performed, the boom assembly is delivered to the spacecraft for integration.

FIGURE 4a. Boom-Reactor Configuration - Stowed.

FIGURE 4b. Boom-Reactor Configuration - Partially Deployed.

Reactor Unit

In order to launch a Topaz II reactor requires three reactors: a pathfinder reactor, a test reactor, and the flight reactor. The pathfinder reactor is used to alleviate concerns about using Russian heritage hardware in an American test program. The pathfinder will be exposed the same environments that the flight reactor will see, including the launch, to demonstrate that the Russian design can be subjected to a MIL-STD-1540B test program and survive. If the pathfinder testing is successful, then a MIL-STD-1540B test program will be implemented using the test reactor and the flight reactor. The test unit will be used during environmental testing of the satellite and will be tested to proto-flight levels (+3 dB). The flight reactor will be tested by itself to acceptance levels (+0 dB). The test program for the different reactors is documented in Polansky (1993).

Preparation of the flight reactor begins with functional testing at the TSET facility at NMRI in Albuquerque, New Mexico. The unit is installed in the test chamber and functionally tested using heaters inserted in the core. This test lasts for 1000 hours and is used to detect any failures due to workmanship and infant mortality. The reactor is then shipped to Los Alamos for neutronics testing using the flight fuel. The reactor is then shipped to Sandia National Laboratories for acoustics, shock testing, and random and sine vibration. During the mechanical reactor testing, the various modified subsystems, like the core loading anti-criticality device and the thermal cover, will be exercised following the environmental exposures. The flight reactor is returned to the TSET facility to determine if the unit was damaged during the environmental exposure. Also as part of the TSET testing, the reactor cables are interfaced with portions of the power system electronics and the reactor control unit to determine if all the interfaces are correct. Following the functional testing, the unit is once again sent to Los Alamos for a final neutronics test. This test is used to measure any change in reactivity due to the addition of the anti-criticality device used to accommodate a launch over water. Following this final neutronics test, the fuel is removed and the reactor is transported to the launch site for integration with the spacecraft. In all of the neutronics test special care is taken to insure that the fuel pellets are always in the same position that they will be for launch.

Integration of Spacecraft-Boom-Reactor

The integration of a reactor with the rest of the satellite occurs twice. The first time is the integration of the test reactor with the spacecraft just prior to the satellite environmental testing. The second time is the integration of the flight reactor at the launch site about one month before launch. Once integrated, testing of the reactor unit is limited to testing motor rotation and measuring the state of various sensors at room temperature. The RCU can still be tested by connecting the Dynamic Simulator to the boom connector interface plate on the spacecraft. The process of the integration of the spacecraft, boom assembly, and reactor is shown in Figure 5.

The boom bucket is lowered into the spacecraft bus structural cylinder and fastened using the 1.22 meter bolt circle. The boom cabling, which is routed out the top of the bucket, is terminated at an interface connector plate. The boom is powered to deploy one segment. This exposes the reactor interface connectors. The reactor unit adapter is secured to the end of the boom using a 0.51 meter bolt circle interface. The reactor unit is then lowered near the adapter so that the reactor's connector pigtails can be secured to the boom segment. The reactor unit is then fastened to the adapter. A hydaset is used with the crane for fine control of the reactor's vertical position. The reactor unit is then lowered while the boom segment is retracted. During the retraction, care must be taken to insure that the length

of cabling is stowed correctly back into its stowage compartment. Once lowered, the reactor unit is secured to the spacecraft using explosive bolts to rigidly fasten the adapter to the spacecraft load cylinder.

FIGURE 5. Integration of the Spacecraft, Boom and Reactor Unit.

Functional & Environmental Testing

Satellite environmental testing begins at APL prior to the integration of a reactor. After the propulsion module and the separation boom are installed, the satellite will undergo baseline functional testing. The baseline test database is used as a reference for all future functional tests. Various simulators are used to exercise the different subsystems. The satellite will undergo ground station compatibility testing using hardwire connections between the spacecraft and the APL satellite tracking station. Alignments and self-susceptibility testing will also be performed at APL. The satellite will then be shipped to NASA Goddard Space Flight Center and integrated with the test reactor. The entire stack will undergo different structural tests: modal survey, shock, and acoustics testing. Following the structural testing, the test reactor is removed and sent back to the TSET facility to determine if it was damaged by the environmental exposure. The reactorless spacecraft will then undergo a month of thermal vacuum cycling and balance testing. Heaters will be used to simulate an operating reactor unit ten meters from the spacecraft. Following the thermal vacuum tests, the spacecraft will be shipped to Cape Canaveral Air Force Station for launch.

Launch Operations

The spacecraft and the flight reactor will arrive at the launch site about 45 days before launch. After ten days of unpacking and functional testing, the two units will be integrated using the procedure described earlier. Extensive interface testing and functional testing will be performed. Data from previous tests will be used for comparison to help insure proper interfaces and operation. About twelve days before launch, the final preparations begin: the reactor is fueled and the special water anti-criticality device is installed. Once in place the device is operated to confirm it can load fuel into the core when commanded. Special safety interlocks are used to inhibit reactor drum rotation while the device loads the core. The device is then reset to its fuel out position. At ten days before launch, the start up unit is installed into the reactor unit and the thermal cover is installed. At nine days before launch, the satellite is encapsulated in the launch vehicle shroud and the prepared payload is integrated with the launch vehicle. At five days before launch, the payload is thermally soaked to 38°C using an air duct umbilical provided by the launch tower equipment. This temperature soak continues up to the moment of launch. At the day of launch, the

ordnance and arming plugs are installed. The system is now relying on the interlocks associated with launch vehicle separation to prevent a reactor startup. At this point the satellite is ready for launch.

CONCLUSION

The use of Russian hardware in a U.S. spacecraft requires several modifications in both the design and the launch operations. These modifications are required due to differences in philosophies between the two space systems in areas of safety, launch procedure, spacecraft design, and launcher designs. The user must be aware of these differences and make changes when appropriate.

When launching reactor based spacecraft, many of the subsystems will require special testing. It is more efficient to perform this testing at the subsystem level than to coordinate and develop facilities for the full satellite. The key to a subsystem test approach is to have a modular spacecraft design.

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