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Author(s): D. E. Trujillo

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Conceptual Design of the
Topaz II Anticriticality Device

David Trujillo, Darrell Bultman, R. Chris Potter, Leo Sanchez
Technical Engineering Support Group, MS G787
Los Alamos National Laboratory, Los Alamos, NM 87545
(505-667-7336)

Vladimir Egorovich Skobelev, CDBMB, Russia

Abstract

The Topaz II Flight Safety team requires that the hardware for the Russian-built reactor be modified to ensure that the reactor remains subcritical in the event of an inadvertent accident in which the reactor is submersed in wet sand or water. In April 1993, the American Flight safety team chose the fuel-out anticriticality device as the baseline for the hardware design. We describe the initial stages of the hardware design; show how the mechanism works; and describe its function, the functional and operational requirements , and the difficult design problems encountered. Also described, are the initial interactions between the Russian and American design teams. Because the effort is to add an American modification to a Russian flight reactor, this project has required unusual technical cooperation and consultation with the Russian design team.

INTRODUCTION

The Strategic Defense Initiative Organization (SDIO) has been investigating the possibility of launching a Russian Topaz II space nuclear power system in support of a Nuclear Electric Propulsion (NEP) Space Test Mission. Therefore, during the past year numerous nuclear safety-related analyses were conducted to assess the safety of a TOPAZ II flight reactor. The TOPAZ II flight safety team identified a major problem. If the reacter becomes immersed in water or saturated sand during a spacecraft launch failure or because of reentry, the reactor could, potentially, become supercritical. Such a problem could occur if the reactor falls in the ocean or onto a sandy beach or marsh area. The super criticality results from the extra reflection caused by the surrounding immersion water (or sand) and the moderation caused by the added water internal to the reactor. It may do so neutronically in excess of a criticality of $3. This potential problem is not acceptable; a hardware modification, in the form of a poison or partial fueling of the reactor, is needed.

In April 1993, the Topaz II Flight Safety team chose the fuel-out anticriticality device as the baseline hardware modification for maintaining the reactor at subcritical for all credible accidents. With this modification, enough fuel is kept outside the reactor during launch and until the reactor is in a safe orbit. Then the fuel is then inserted remotely back into the reactor, for normal reactor operation.

The Anticriticality Device is a major hardware modification needed for the safe flight of the Topaz II reactor. In initial design efforts, we identified all the requirements and criteria needed to deliver the hardware for testing and qualification. The American design team identified the problems and sorted through several feasible concepts, then presented these concepts to the Russian design team and the Topaz II flight safety team. The Russian design team initially preferred the poison concepts. But after several meetings, the American safety team decided to go with the fuel-out concept. Here, we present a summary of the problem and discuss the solutions, design criteria, requirements, and preliminary details and sketches of the ACD.

The Russian built Topaz II flight reactor has 37 Thermionic Fuel Elements (TFEs) that hold the fuel in the reactor core. Each TFE consists of an inner emitter tube and an outer collector tube. The inner emitter tube holds the 17-mm diam by 8-mm-high cylindrical fuel pellets, each of which as an 8 mm to 4.5 mm hole in the center of the fuel. Each TFE is open at the top to allow for fuel loading. After loading, the fuel is held down by a spring retaining rod and a clip that fastens to the top of each TFE.

The purposed American modification ACD (anticriticality device) holds the fuel out of four of the center TFEs during launch and until payload deployment. When called upon by a ground signal, the ACD remotely places the fuel from the four TFEs into the emitter tubes, and the reactor startup occurs. Before receiving this signal, it is not possible to load the fuel in to start up the reactor because no power is allowed to the ACD until the last booster separation operates the mechanical switch than provides the power to the ACD.

POISON VS FUEL OUT

Russian and American design teams studied two major methods for assuring anticriticality: inserting sufficient poison (in the form of B_4C rods) into the center hole of the fuel and keeping fuel out of the reactor. Some of the Russian scientists believe the poison method would be more reliable for reactor operation; it may, however, be less reliable for safety. Because of the different hole sizes in the fuel, it was determined that placing a poison into seven TFEs would require an additional 3-cm beryllium reflector outside the reactor and a new design for the drum and reflector steel retaining bands. A new fuel retaining rod design would also be required to allow a hole for the poison. The most difficult modification requirement, however, would be a mechanism to guarantee that the poison would remain with the fuel in all accident scenarios, yet which could easily be removed during deployment for reactor operation. No criteria were identified showing how long the mechanism would be required to protect the reactor from going super critical if the reactor were submerged in the ocean. Thus, the poison method seems to be less reliable than the fuel-out method for keeping the reactor sub critical. The fuel-out method will require the fewest modifications to the reactor. Conversely, placing fuel into the reactor will likely be somewhat more difficult than pulling the poison from the reactor, which makes the fuel-out method of reactor operation less reliable than the poison method for reactor operation. Discussions about these issues during meetings with the American Topaz II Flight Safety team led to their decision to make the fuel-out ACD the preferred concept. The engineering issues pertaining to both concepts are the number of modifications required for each method; survivability of the fuel during launch; how well the poison can be removed remotely; how well the fuel can be inserted remotely; materials compatibility; how many steps or operations are required; and what testing is required for qualification.

DESIGN PROBLEMS

A major problem with the ACD design is the lack of launch vehicle design load information. As of this writing no launch vehicle has been selected. Early in the project it was not certain how much space would be available for the ACD on the top of the reactor. If the Delta launch vehicle had been chosen, a maximum of 4 in. (102 mm) of vertical space may have been allowed. This limitation would have made both the poison and the fuel-out concepts very difficult to design. The initial design would have required a set of seven reels for winding the B_4C poison, shaped as beads, into a drum above the reactor in the allotted 4-in. (102-mm) vertical space. But meeting other mission requirements required that the Delta launch vehicle be excluded as an option. The remaining launch vehicles choices allow more space. The launch vehicle team has assured that at least 30 in. (762 mm) will be available for the ACD. Because the launch vehicle has not yet been determined, specific launch vibration and acceleration data are not confirmed for the design of materials. We will use launch data from an Atlas launch vehicle for our preliminary analyses and will adjust these data to the selected launch vehicle when that information becomes available.

The survivability of the fuel during launch is also a design concern. The Russians have assured us that the clamping force of about 20 kg keeps the fuel intact during launch, but we want to dynamically test the fuel-holding capability using real fuel if the opportunity arises.

TECHNICAL REQUIREMENTS

Design Goals

Our goals for hardware design are to produce qualified hardware that will ensure anticriticality under all credible accident scenarios. Neutronically, the ACD must maintain the reactor at subcritical prior to operation. The reactor and subsystems must survive the mechanical and structural loads encountered from normal and off-normal launch and deployment forces. The ACD modification must be compatible with operational and safety features and with launch vehicle and payload constraints. Other goals are to minimize the number of moving parts for simplicity and reliability. The new structural support must not interfere with the reactor components or their operations. Care must also be taken to assure material compatibility inside emitter tube; strength, thermal expansion, thermal expansion coefficients, hardness, etc. A plan must be formulated and a process undertaken that ensures the integrity of the new hardware through analyses and qualification tests

Functional and Operational Requirements

Prelaunch. The ACD must meet stringent design requirements before launch. All hardware components must meet material type and grade specifications with written traceable assurance for quality control. The tolerances for manufacture shown on the drawings must be met and certified. All components bought off the shelf as qualified must have the appropriate documentation showing the qualification standards used. The standards to be used for the design and testing of the ACD are as follows: Design Standards MIL-STD-1540B10 (October 1982), Military Standard, Test Requirements for Space Vehicles; and Design Handbook, DOD-HDBK-343 (USAF) (01 February, 1986), Military Handbook, Design, Construction, and Testing Requirements for one-of-a-kind Space Equipment. The ACD must be space-qualified through intensive dynamic testing as per the above standards. Included in the prelaunch requirements are requirements for safe transport from NMERI in Albuquerque to the launch site in Florida. An internal part of the ACD design and operation during prelaunch is the associated loading of fuel in the four TFEs, plus the loading of the fuel into the remainder of the reactor. Design reviews, safety reviews and testing reviews must be met and documented, as stated in the standards.

Launch and flight. The ACD will encounter the greatest of the acceleration and vibration forces capable of causing failure to connections or materials during launch and flight. Therefore, the designers of the ACD must pay careful attention to these forces. The ACD is required to survive theses forces without any material failure or alignment shift. When the last separation occurs between launch booster and the reactor/payload space system, the ACD can receive power via the mechanical switch that restricts the electrical power until that time. This is a safety switch whose purpose is to ensure that the ACD cannot insert the fuel into the reactor until a safe orbit is achieved.

Deployment. When the ACD is in a safe orbit, a ground signal will be given for the ACD to place the fuel into the reactor. The ACD is required to place the fuel into the TFEs for mission operation of the reactor. Failure to do so will disallow the reactor from operating and fail the entire mission. The fuel must then remain locked in place for the duration of the mission, which is approximately 3 years.

Design Criteria

The design criteria lists requirements and guidelines that must be followed in order to have a successful design.

1. Design the components for the 3-year lifetime of the experiment, with the understanding that the components may be in space for hundreds of years.
2. The design forces for the launch environment were derived from launch environment data (launch vehicle has not yet been selected).
3. Work as a team with neutronics personnel. Optimize hardware characteristics and neutronic properties.
4. Design moving parts of mechanism and fuel guide to allow fuel to freely move under zero gravity and space environment.
5. Design fuel-out anticriticality mechanism to ensure that fuel cannot enter the reactor in the event of an accident.
6. Design the structural frame to optimize material strength, weight, component strength, reduction of induced vibrations, and overall function.
7. Design holder fasteners for maximum strength, ease of assembly, noninterference with existing components, and security against dislodgment caused by vibrational forces.
8. Ensure that new hardware avoids the possible short-circuiting of a TFE or other electrical conductor. Ensure that conductive materials cannot gain an electrical path that would disrupt reactor performance.
9. Use safety wire or other sure fast connectors as securing fasteners.
10. Design electronic equipment for reliability and component compatibility and ensure that they can withstand the stress caused by vibration induced forces.
11. Design a monitoring sensor that communicates to an earth station the successful completion of the fuel loading so that startup of the reactor can commence.
12. The fuel out mechanism hardware size limit is not to exceed the following two sizes and conditions.
    a. The hardware envelope is not to exceed height of 33 in. (838 mm) in height by 11 1/2 in. (292 mm) in diam when measured from the highest point on the existing Topaz reactor.
    b. The fuel out mechanism hardware weight limit is 50 lb (22.7 kg). Not counting fuel, an additional 20 lb (9 kg) may be added for the quick connecting of the structural hardware, for a total of 70 lb ([illegible] kg)

14. The maximum and minimum times allowed for fuel insertion into TFEs 30 min (maximum) and 2 s (minimum).
15. Electronic and electrical power requirements must be coordinated with the Topaz flight safety team, APL and Phillips Lab. The sequence of events and the control of these events is of primary importance.

Hardware Descriptions for Fuel-Out Mechanism

Refer to the appropriate TOPAZ II documents for a description of the TOPAZ II reactor (see references). The hardware described herein is conceptual in nature and is the basis for the final design. Some of the components may change during the design as the design is being realized (see sketch below).

The hardware required for the **Fuel Out Mechanism** consists of the following:

1. A structural support frame, securely fastened to the TOPAZ II reactor, preferably using a new Russian welded design that supports the frame from the top ring outside the helium plenum. The frame and the ACD must be capable of withstanding acceleration forces and vibrations during spacecraft launch and deployment.
2. A fuel-out holder designed to interface with the TFEs (four, center plus 3 out of 6 from the inner ring). The holder incorporates spring hardware with a compressive force (~20 kg force) that clamps the individual fuel pellets together during launch. It also has a mechanical gate, which guarantees that the fuel cannot enter the TFEs during launch or in the event of an accident.
3. A fuel-out release mechanism that releases the 20 kg-load and opens a mechanical gate that allows the fuel to enter the TFE.
4. A hardware mechanism that inserts the fuel into the TFE to the correct location (pneumatic or direct electrical drive).
5. A locking mechanism that locks the fuel in place for the lifetime of the reactor.
6. The quick-connecting hardware that allows the fuel out anticriticality mechanism to quickly be fastened to the structural frame after the reactor (the other 33 TFEs' load of fuel) fuel is loaded.
7. The electronic and electrical hardware and/or harness required to transfer a signal that communicates with the Reactor Control Unit into an actuating command to begin the fuel loading operation and to load and lock the fuel, and the sensors required to confirm that the fuel loading is complete.

Hardware Design Analyses

Some of the following engineering analyses may be required to ensure reliability, strength, and operational function. These may be required at varying levels of detail.

1. Stress, materials optimization, and vibration analyses of the structural frame and the fasteners required to securely fasten the frame to the reactor.
2. Fuel material strength, suitability for holding fuel outside the reactor, stresses due to dynamic motion, and compatibility with TFE and other mechanisms.
3. Stress analyses on the fuel holder for survival of launch forces.
4. Quick-connecting hardware and fasteners may require stress analyses and vibration analyses.
5. The electronic control equipment requires matching power to control voltage check, manufacturers data review, and general review by electronic engineers.

Hardware Tests

Bench-top PrototypeTesting. During the design, it is necessary to know the friction force of the fuel (mock fuel) when the fuel is inserted into the TFEs. A benchtop prototype test is necessary to confirm what that force is. This information will aid us in predicting what happens in a zero-gravity environment. There are also questions of geometric fit with respect to the fuel and the TFE. This benchtop test will dictate the tolerances required for reliability and will confirm the effects of the design to keep the fuel from binding when inserted into the TFE. During this time, the testing of already qualified motors and actuators will begin, along with a history of their performance as related to this project. Where there are two methods for designing a fit or tolerance, both may be tried. In effect, this bench-top prototype testing procedure is a development phase that goes hand in hand with the design of the device. The information feeds back to the design and is used to improve the device.

Repetitive Testing. This test may be done on the benchtop or on one of the other reactors, such as the Ya-21 or V-71. In this test, a final version of the device will be mounted on the reactor or on a mockup of the reactor. The fuel (mock fuel) will be inserted dozens of times to show that the mechanism is reliable and capable of doing the inserting repetitively. A history will be kept and used for reliability purposes. The pass/fail criteria applied will require that more development be done if the device fails. When the device passes, it will be ready to be sent for qualification and dynamic testing. This testing is to ensure that the design works before the extreme dynamic forces are applied.

Qualification Testing. These tests will be done after the ACD design has been reviewed and approved and the development finalized. The tests will be done in conjunction with the other tests, required for the reactor main system, which are done by the testing team and the design team. These tests place the subsystem anticriticality device in the most extreme environments possible during launch and flight. They include temperature and vacuum testing that can be done without the reactor, and dynamic testing that will be done with the ACD mounted on the reactor. These tests will demonstrate the survivability of the ACD, and that the reliability, after the dynamic loads, have been applied as close as possible to the actual maximum forces credible during launch and flight. As with other testing, there will be a pass/fail criteria that either sends the device back for more development or qualifies the device for space.

Ground Critical Testing. This might be the only test permitted with the real fuel. The testing will be done in a critical facility, probably in Los Alamos. If real fuel is to be used, then semi repetitive testing may be warranted. A secondary goal is to use the ACD to place the fuel into the TFEs remotely, as required by regulations. Having the ACD on the reactor during ground criticals will also make the data reflect the actual flight system.

System Connection and Interface Testing. Because the bench top testing is not done with the associated spacecraft electronics and space mounted battery there will be a system check using the flight up electronics and ensuring the ACD works and is correctly hooked up. This may be done before shipment to the launch site and after system integration at and before launch at the launch site. There may be an additional test during critical testing if the proper electronic control systems are available

Expanded view of
the ACD showing
drive screw and
electric motor

ACD on proposed
Benchtop test stand

CONCLUSIONS

The design of the anticriticality device is underway. The baseline concept is to ensure that enough fuel is removed and held from the reactor during launch, flight, and deployment in a safe orbit. The fuel will be remotely placed into the reactor, and the reactor will be operated as planned. If the reactor and space craft should reenter before deployment in a safe orbit, there will not be sufficient fuel for the reactor to become super critical with the extra reflection and moderation caused by the immersion and submersion in ocean water or wet sand. Thus, the design is passive with respect to safety. Substantial testing must be performed prior to qualification of the hardware. The design issues are the survivability of the ACD and the fuel during launch and flight caused by the aggressive acceleration and vibration loads encountered. Reliability is a major concern, as it always is, on space hardware designs.

Acknowledgments

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