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TITLE **RUSSIAN TOPAZ II SYSTEM TEST PROGRAM**

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kussian Topaz II System Test Program
(1970-1989)

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Abstract

The Russian Topaz II system is a space nuclear power system capable of producing 4.5 to 5.5 kWe for three years of continuous autonomous operation. To qualify the system for flight, the Russian Topaz II program extensively tested their systems over a 20-year period. Approximately 28 systems were fabricated for testing. During this period of time, there were two primary drivers that necessitated system changes: the evolution of the military user requirements, and failures during testing that resulted in modifications and follow-on systems testing. Therefore, the design, technology, and the materials used for the system were modified and improved. The Russian Topaz II systems test program was sub-divided into four major categories: thermophysical testing; mechanical testing, which included static load testing, dynamic testing, and impact/shock testing; nuclear ground testing; and cold temperature testing (CTT) to simulate prelaunch and launch temperature conditions. The systems testing was performed in a systematic manner to verify through ground testing the flight qualification of the Topaz II system. The purpose of this paper is to present an overview of the Russian Topaz II systems test program.

Introduction

In April 1992, a team of Russian specialists came to the United States (U.S.) to begin training U.S. specialists in the design, fabrication and acceptance and operational testing of the Topaz II nuclear power system. The Russian specialists were from the Kurchatov Institute of Atomic Energy (KIAE) in Moscow and the Central Design Bureau for Machine Building (CDBMB) in St. Petersburg, Russia. This was the beginning of an interactive, yet at times frustrating working relationship between the U.S. and the Russian specialists. The goal of the cooperation was to be the flight test of the Topaz II integrated with a U.S. spacecraft. The frustration came in understanding the difference between how the two countries manage programs, communicate with their customers, within Institutes and to the public, and their different approach to engineering and safety.

The systems test data presented in this report represents the cumulative work from over six weeks spent in Russia talking with their specialists, touring their facilities, reviewing their computer models, as well as innumerable meetings held within the U.S. As we continue to work together towards a common goal open issues will be answered. One of the specific goals of this work has been to trace the process by which the Topaz II has been flight qualified through systems testing.

Overview

The Topaz II program spanned from 1969 to 1989. During this same time, the Topaz I, a multi-cell thermionic system, was developed by the Red Star Institute outside of Moscow. Red Star is the technical institute that developed and flew 26 RORSAT satellites with small thermoelectric power units and two Topaz I systems. Early in the 1970s, the two institutes dissolved their cooperative effort and developed their systems independently until early in 1980 when Red Star was asked to work with the KIAE and CDBMB. Therefore, the Topaz II ran parallel to, but independent of the Topaz I and RORSAT development.

The following is a brief overview of the Russian systems tests, the designators used for naming the systems, and the four major program phases of the Topaz II.

The Russian Topaz II systems test program was organized into four major categories: thermophysical testing using electric heaters; mechanical testing, which included static load testing, dynamic testing, and impact/shock testing; nuclear ground testing; and cold temperature testing (CTT) to simulate prelaunch and launch temperature conditions. Information on the test facilities and the systems tested for each of the above systems tests is provided below.

The Russians used three designators to name their systems based upon the predicted and as-built quality of the system: Eh Ya, and V. An "Eh" system was intended to be a flight system, and could also be used for any of the other four types of systems testing depending upon why the system was fabricated and the as-built quality of the system. A "Ya" system could not be used for flight, but could be used for all other four types of systems testing. A "V" system was fabricated for either thermophysical or mechanical systems testing. A fourth type of system was the static mockup (SM), which was comprised of the three primary load bearing structures: the reactor, the shield, and the frame. The SM was used as part of the mechanical systems acceptance testing by statically loading the system structure.

A chronological listing of the Topaz II systems is provided in Table I. Major changes made between systems is presented below. The first generation of the Topaz II system (V-11 to Ya-22), were designed for one-year operation. They had 31 in-core thermionic fuel elements (TFEs), with a light-weight (190 kgs) radiation shield and were designed to be launched upright. In the second generation of systems (V-15 to Ya-26), the operational lifetime requirement was increased from one year to one and a half years. The first two generations of Topaz II TFEs used polycrystal molybdenum emitters, which caused extensive fuel swelling and a large fraction of the TFEs to short circuit during nuclear ground testing.

In the third generation of the Topaz II system (V-71 to Eh-42), the number of TFEs was increased to 37. The thermal power for nuclear ground testing was reduced and the operational lifetime goal was extended to more than one and a half years. The launch configuration was changed to the inverted design. The Russians continued with the lighter weight shield up to system E-41 when they changed to the heavier weight (390 kgs) shield to reduce the radiation levels to the spacecraft.

The fourth generation (Ya-21u to Eh-44), the lifetime was increased to 3 years at 4.5 to 5.5 kWe, with the heavy shield and in the inverted launch configuration. The volume of cesium (Cs) in the cesium unit was doubled for the Eh-44 flight unit to achieve the 3 year lifetime. The third and fourth generation systems used improved TFE emitter material of single-crystal molybdenum (Mo), and then changed to Mo with 3% niobium (Nb). The change in emitter material significantly increased the strength of the fuel cladding. The change in the TFE material, along with an increase in the number of TFEs, changes in the reactor fuel, and a decrease in the thermal power eliminated the problem of short circuits during nuclear ground testing.

The U.S. currently has tested both the V-71 and Ya-21u systems at the Thermionic System Evaluation Test (TSET) in Albuquerque using Russian test hardware integrated with U.S. hardware. The U.S. is also purchasing Eh-40, Eh-41, Eh-43, and Eh-44 systems. Eh-43 and Eh-44 are the potential flight units. The NEPSTP program will not choose the actual flight unit from the two systems until the systems have been filled with coolant, helium (He), cesium and other gases, and have completed the acceptance testing.

Table I: System Testing Summary Chart

Eh	GRP	System #	# of TFEs	Life	Launch	Test Stand	Date Begin	Date End	Test Time	General Description
										B: Baikal. MT: mechanical testing. CTT: cold temperature testing. Nuclear R or T: nuclear ground test Romashka or Tureavo. ZPT: zero power testing
1	1	Prototype 1	~2-3	1	Upright	B	7 23 71	2 3 72	3200	Development of system test methods and operation. Fabricated by the CDBMB. Electric heating testing. Did not have a complete set of TFEs.
2	1	Prototype 2	31	1	Upright	B	6 21 72	4 18 73	850	Development of technology for prelaunch operations and system testing. Electric testing. Fabricated by CDBMB
13	1	Prototype 3	31	1	Upright	B. MT. CTT	8 1 72	5 1 73	Not given.	Mechanical testing: transportation, dynamic, shock, and cold temperature testing. Reliability at freezing and heating. First unit fabricated in Estonia.
-20	1	Specimen 1	31	1	Upright	Nuclear - R	10 1 72	3 1 74	2500	Neutron physical characteristics and radiation fields. Zero power testing. Development of the nuclear tests methods. Fabricated in Estonia.
-21	1	Specimen 2	31	1	Upright	Nuclear R AND B				Neutron physical characteristics and radiation fields. Prelaunch operations. Nuclear test methods. Trial of stand systems. Fabricated in Estonia.
22	1	Specimen 3	31	1	Upright					Not fabricated. They were going to use Ya-21 design documents.
15	2	Serial 1	31	1-1.5	Upright	CTT and B	2 12 80			Cold temperature testing. Operation and functioning at freezing and heating. One set of design drawings. 2nd generation of TFEs. TFE 1 yr/system 1.5 yr.
16	2	Serial 2	31	1-1.5	Upright	MT	8 1 75	2 1 79	2300	Mechanical: transportation, vibration and shock. Electric system testing for serviceability after mechanical testing.
-23	2	Serial 3	31	1-1.5	Upright	Nuclear R	3 10/75	6 30 76	5000	Rev. of fuel loading, rad., and nuc. safety. Dev. of tech. prep. of nuclear tests. Study of unsteady-state conditions, and SS functioning. Disassembly. H loss
-31	2	Serial 4	31	1-1.5	Upright	Nuclear R	2 1 76	9 1 78	4600	Nuclear ground test. Startup with ACS. Steady-state functioning. Disassembly. Grp 2 TFEs lifetime limited to ~2 months due to fuel swelling and e/c shorting.
-24	2	Serial 5	31	1-1.5?	Upright	Nuclear T	12 1 78	4 1 81	14000	Steady state system testing. Disassembly. Significant TFE shorting.
-33	2	Serial 6	31	1-1.5	Upright					Already under fab at E.-needed new TFE design. No systems testing. Installed in Tureavo as a mockup. Used to establish transportation and handling procedures.
-25	2	Serial 7	31	1-1.5	Upright					Already under fab at Estonia. Not tested. Sent to Kraznoyarsk to be used as a mockup with the spacecraft.
-35	2	Serial 8	31	1-1.5	Upright					Already under fab at Estonia. Second stage of fab not completed. Used for some exp's on Baikal stand. Disassembled in Sosnovivord.
-26	2	Serial 9	31	1-1.5	Upright					Already under fab at E. Send to CDBMB for 2nd fab. TFE was burnt and damaged during 2nd fab stage. There was a notch between the TISA heater and emitter.
71	3	Serial 10	37	1.5	Inverted, Upright	B. CTT. Mech. ZPT	1 1 81	1 1 87	1300	Mech.: trans. (railroad), vib. and shock. CTT. Elec testing after MT. ZPT at KIAE. Interface w/s/c was modified.
-81	3	Serial 11	37	1.5	Inverted	Nuclear R	9 1.80	1 1 83	12500	Nuclear ground test. Leak in 2 coolant pipes 120 hours into testing. Plugged, and test continued. Steady state operation. Disassembly. PIE.
-82	3	Serial 12	37	1.5	Inverted	Nuclear T	9 1.83	11 1 84	8300	Nuclear ground test. Startup from ACS. Initial leak leading to large leak in the pump. LOCA. Steady state. Disassembly.
-37	3	Serial 13	37	1.5	Inverted					Quality not sufficient for flight. Static tests, including torsion tests.
-38	3	Serial 14	37	1.5	Inverted	Nuclear R	2 1 86	8 1 86	4700	Nuclear ground test and prelaunch simulation. Startup and operation from ACS. Steady-state. Disassembly.
-39	3	Serial 15	37	1.5	Inverted					Began fab in Estonia and changed some components. When finished, they changed system name and # to Eh-41 and 17. Main change in the reactor.
-40	3	Serial 16	37	1.5	Inverted		1 3 88	12 31 88		Cold temperature tests. No electric tests were done. Filled with NaK during the 2nd stage of fabrication.

Table I: System Testing Summary Chart

ms	GRP	System #	# of TFEs	Life	Launch	Test Stand	Date Begin	Date End	Test Time	General Description
-41	3	Serial 17	37	1.5	Inverted	B and MT	1/1/88			Mechanical: transportation (railroad), dynamic and impact. Leak testing done afterwards. Increased shield mass.
-42	3	Serial 18	37	1.5	Inverted		1/1/88			Error in welding during the fab at Tallinn. It was an error in a critical component, therefore they decided to not use this unit.
-2	4	Serial 19	37	3	Inverted	B	12/1/87	12/1/89		Electric testing. "u" means modified, ie. they used a modified TFE to get the longer lifetime. They modified the ends of the TFE, where they used
-43	4	Serial 20	37	3	Inverted	None	6/30/88			Flight unit. First phase of fab completed in Tallinn, 2nd phase not yet completed.
-44	4	Serial 21	37	3	Inverted	None				Flight unit. First phase of fab completed in Tallinn, 2nd phase not yet completed.
-45	4	Serial 22	37	3	Inverted	None				Partially fabricated flight unit. Components missing from system.
1 0		Static Mockup			Upright	MT	1/1/76	1/1/76		SM 0 was a mockup of the earlier launch configuration. It included the three primary load bearing systems: the reactor, the shield, and the frame. CDBMB.
1 1 1 2		Static Mockup			Inverted	MT	1/1/83	1/1/84		SM 1 and SM 2 were tested for an inverted launch configuration in 1983 and 1984 at Kraznoyarsk with a CDBMB representative present.

Systems Testing

The Russian Topaz II systems testing program obtained data on systems operation, nuclear characteristics, startup characteristics, unit strength under mechanical loads, temperature profiles under launch environments, and many other critical parameters necessary to prove to the military customer that the Topaz II system would meet the power and lifetime requirements. In general, the systems were tested under prototypic conditions.

In all, there were twelve thermophysical tests, four dynamic testing, four static testing, two shock and vibration, ten zero power testing, six nuclear ground tests, and four CTT. There is a tremendous amount of information and insight available from these tests that the U.S. team is just now beginning to study.

The Russian design and test philosophy appears to be similar to how the U.S. engineered systems during the 1960's, when the computer played less of a critical role in the development of advanced systems. The Russian specialists designed and tested components, subsystems, or systems. However, if during the testing, these components or systems did not meet the performance requirements or if they failed, the cause was determined and it was redesigned and modified. There appears to be more tolerance in the Russian engineering approach to failure and change, than in the U.S., where components, subsystems or systems are expected to perform correctly the first time. The Russian process allows for more change and growth over the length of the program.

The following is a brief overview of the purpose of each systems test, how it was performed, what systems were tested, and what were the major findings.

Thermophysical Testing

Thermophysical testing was completed as part of the process of filling the systems with gases and fluids, and as part of the system acceptance testing. All of the thermophysical testing was done at CDBMB, except for one of the nuclear ground tests where the preparation was completed at KIAE. The U.S. TSET facility in Albuquerque is also equipped with a complete test stand for performing thermophysical testing of the Topaz II units.

Thermophysical tests are done in a vacuum chamber at a pressure of 10^{-6} torr. The wall of the vacuum chamber is cooled with water to remove the heat released by the system. Testing is done with electrical heaters placed within the TFEs. This is an extremely useful feature of the Topaz II system allows for systems testing without performing a nuclear ground test.

During the initial phases, the system is operated for 1000 hours to out-gas the unit and to prepare for full power testing. This process can take several months to prepare the system, fill with Cs and flush the system with sodium-potassium (NaK) before filling with the final fluids and gases. Once the system has been fully prepared, it is brought up to power in steps to monitor the performance of the TFEs, the electromagnetic (EM) pump, the Cs unit, and other critical components, subsystems, and systems. During testing the position of the throttle on the Cs unit is set to provide the optimum Cs operating pressure. Also, during this phase, the system's "as-built" quality is quantified, and the type of testing the system will undergo is determined. For example, the Eh-41 unit was not used for thermophysical or nuclear ground testing but rather for mechanical testing because the Chief Designer determined it was not of high enough quality to be used for other systems testing.

The thermophysical test is also used for long-term systems testing and characterization for different operating conditions and for pretesting before a nuclear ground test. The Ya-81 unit did not undergo the 1000-hour non-nuclear thermophysical ground test prior to nuclear ground testing. During nuclear ground testing, there was a coolant leak early in the testing phase. If the non-nuclear thermophysical pre-test had been completed the complexity of the repair could have been greatly reduced.

The following systems underwent thermophysical testing: V-11, V-12, V-13, Ya-21, V-15, V-71, Ya-23, Eh-31, Ya-24, Ya-82, Eh-38, and Ya-21u. Ya-23, Eh-31, Ya-24, Ya-82, and Eh-38 underwent thermophysical testing prior to the nuclear ground tests. During these tests, there were a number of failures that required modifications to the systems. Information on the failures and modifications is presented in Voss 1994 "Topaz II Design Evolution." There were also many different operating modes that were studied and long-term, steady-state operation was also demonstrated. The U.S. program is continuing thermophysical testing at the TSET facility where the V-71 and the Ya-21u systems have been tested. Likewise, the Eh-43 and Eh-44 flight units will undergo system filling of fluids and gases, and acceptance testing at the TSET facility.

Mechanical Testing

The primary purpose of the mechanical tests was to verify the system strength and operability during launch and after separation through the application of mechanical loads on the system (Andrianov, V. 1993). Mechanical testing was sub-divided into three major categories: vibration testing, static load testing, and impact/shock testing. The vibration testing was done to simulate transportation and launch-induced vibrations. Static tests were performed for adequacy of structural integrity by applying concentrated loads to the primary load bearing structures. The impact/shock tests were done to simulate the separation phase of the launch vehicle from the satellite. The Topaz II systems did not undergo acoustic testing in Russia, but it is being considered by the U.S. test program.

Dynamic Testing

Before dynamic testing, a low-level dynamic test was completed by the manufacturer to determine if possible defects had been introduced in the system during manufacturing. The manufacturer was required by a State Standard to test at 20-30 Hz at an acceleration of 2 Gs for 30 minutes with the system in the launch position. Upon completion, the systems were shipped to CDBMB where further testing was coordinated by the Chief Designer.

The following is a short summary of the dynamic testing done on V-13, V-16, V-71, and Eh-41 (Voss and Rodriguez, 1993).

V-13: Testing was performed between August 1972 and May 1973. This was the first system to be fabricated at the Tallinn, Estonia plant where subsequent systems were also fabricated. It was designed for a one-year operational lifetime at 6 kWe. There were a total of 31 TFEs in the core, had the light-weight shield, and was designed and tested for an upright launch. Testing was done at the military customer's spacecraft facility in Kraznoyarsk. For safety purposes the coolant system was filled with alcohol rather than NaK during the dynamic testing. The V-13 system also underwent CTT.

V-16: Testing was done from August 1975 to March 1979. This was a second generation system designed for one and a half years of operation with 31 in-core TFEs, a light-weight shield, and was designed and tested for an upright launch. V-16 underwent dynamic testing with NaK coolant in the core and follow-on thermophysical testing to confirm that the system maintained its air-tight integrity and was still operational. The system operated for 2300 hours at power after dynamic testing.

V-71: Overall testing was done from 1981 to the present, while dynamic testing was performed from January through March, 1982. It was a third generation system with 37 TFEs, and an inverted launch configuration. Mechanical testing was performed to determine system adequacy with the spacecraft and the new thermal cover (TC) design for the inverted launch, and included NaK coolant. V-71 also underwent CTT, and thermophysical testing for 1300 hours. This is one of the units purchased by the U.S., which has been tested at the TSET facility.

E-41: Testing was done in 1988. This was the first unit to undergo testing that included system changes to achieve the three-year lifetime. Eh-41 system had 37 TFEs, the heavier shield (390 kgs), a mockup of a larger volume Cs unit, and was designed for an inverted launch. The mechanical testing was done on this system due to these system modifications. The customer also changed the required dynamic testing levels by an increased factor of 1.5 to 2 times the original accelerations.

There were a number of failures of the Eh-41 system during the dynamic testing due to the system modifications, in conjunction with the changes in the testing levels (Andrianov 1993). When there was a failure during the Eh-41 testing, the cause was determined, a change was made to the system, and testing continued. The flight units Eh-43 and Eh-44 may require similar modifications as those made to the E-41 during the dynamic testing. However, these evaluations have not yet been completed by the U.S. team. Eh-41 is one of the four units being purchased by the U.S. for follow-on mechanical tests.

Modal testing has been performed by the U.S. team on the V-71 system, and further modal testing and dynamic testing is being considered for other systems to ensure the flight units will be able to withstand the U.S. launch environment. There has been no dynamic or static testing for the system or launch configuration currently proposed by the U.S.; therefore dynamic testing by the U.S. will be required.

Static Testing

Static testing was done to determine structural adequacy and integrity. This was accomplished by applying concentrated loads simulating the loading in two perpendicular directions simultaneously. The loads were applied step-wise using pneumohydraulic jacks through transition elements attached to three load-bearing structures: the reactor, the shield, and the frame (Andrianov 1993). The static mockups were not complete systems, but rather were three load bearing structures without other components and subsystems attached. There were four systems tested: SM 0, SM 1, SM 2, and Eh-37 (Voss and Rodriguez 1993).

SM 0: SM 0 was tested for an upright launch configuration in 1976 at CDBMB using the light-weight shield (190 kgs).

SM 1 and SM 2: SM 1 and SM 2 were tested for an inverted launch configuration in 1983 and 1984 at Kraznoyarsk by the spacecraft designer with a CDBMB representative present. SM 1 had the lighter shield (190 kgs) and SM 2 had the heavier shield (390 kgs).

Eh-37: Eh-37 was fabricated to be a flight unit, but the as-built unit was determined by the Chief Designer to be of quality insufficient for further testing. Therefore it was used for a mechanical mockup. The primary purpose for the Eh-41 static test was to test the piping and other components under static conditions. Eh-37 testing was performed in 1987 at Kraznoyarsk.

The U.S. is considering repeating the static testing using the Ya-21u system to ensure that the launch loads and safety margin as defined for a U.S. launch can be met with the current load bearing structures in an upright launch configuration and to confirm the mathematical models.

Impact Testing

There is little data available on the Russian impact test program, except that test levels were 40 Gs for 0.004 seconds with a pulse shape of a half-sine function applied in three perpendicular axes. V-71 and Eh-41 were the two systems that were subjected to testing.

Nuclear Ground Testing

The purpose of the nuclear ground tests was to verify the nuclear performance and control parameters of the reactor, and to verify long-term operation of the system in a radiation environment. There were two test stands used for nuclear testing: the Romashka, located at KIAE in Moscow, and the Turaevo test stand at the Scientific Institute for Instrument Building of the Ministry of Atomic Energy, outside Moscow. A total of six nuclear power tests were completed. The following information has been taken from a comprehensive overview of the nuclear ground tests written by Nechaev in 1993.

The first three systems that were subjected to nuclear ground testing were Ya-23, Eh-31, and Ya-24 from 1975 to 1981. They were all designed for an upright launch, with 31 in-core TFEs. Each of the systems used the second generation TFE with the polycrystal Mo emitter, and early UO_2 fuel which had very high fuel swelling. This caused significant degradation and a large number of short circuits within the TFEs over the operating time of the nuclear ground tests. The Ya-24 system operated for the longest period, 14000 hours at the Turaevo facility.

The systems were then modified to include higher strength emitters, and UO_2 fuel that had reduced swelling. The next three systems tested were Ya-81, Ya-82, and Eh-38 from 1980 to 1986. Unlike the first three nuclear ground tests, the third generation TFEs did not experience shorting caused by fuel swelling.

Ya-81: This was the first system to be nuclear ground tested following major design changes to the Topaz II system. It was tested for a total of 12,500 hours and produced 4.5 kWe.

Because of a tight schedule the Russians did not complete the full 1000-hour thermophysical test before beginning the nuclear ground test. One hundred and fifty hours into the nuclear ground test a significant NaK leak occurred that caused the shutdown of the test until the cause of the leak could be determined. The V-71 system was undergoing thermophysical testing at about the same time and also had a coolant leak. Investigation into the cause of the leaks for both systems showed that small microcracks introduced into the radiator tubes during the manufacturing process were filled with the silver braze during the attachment of the copper fins to the tubes. During testing, the coolant washed away the silver braze opening up a leak path. By examining the fabrication x-rays, the Russian specialists were able to predict which radiator tubes had leaked and which may leak as the testing continued. They plugged the ends of the suspect radiator tubes and continued testing (Matveev 1993). Ya-81 testing was concluded after 12,500 hours due to a leak in the vacuum chamber's distilled water supply.

Ya-82: This system was tested from September 1983 to November 1984 for 8300 hours at the Turaevo nuclear test stand. The Ya-82 was started up autonomously nine times using the automatic control system with different startup parameters. The throttle on the Cs unit was initially set at an off-optimum position for the higher power operating range, and therefore caused problems during the early testing. Corrections were made and the testing continued. The system operated at 4.5 kWe at a reactor outlet temperature of ~530 °C and a thermal power of 108 kWth. Testing ended due to a large leak in the reactor coolant loop that caused voiding in the core for roughly five minutes at power. The response of the reactor to the loss of coolant caused the core to over-heat resulting in permanent shutdown of the system.

The response of the reactor to the loss of coolant was of considerable interest to the U.S. safety team; therefore the U.S. contracted with the Russian specialists to complete the post-test irradiation examination (PIE) on the Ya-82 TFEs, fuel, and moderator to determine the final physical state of the reactor following the accident. The Russian specialists at KIAE have completed outstanding work in this area during the past year. It is interesting to note that although the Russians had not performed PIE on the system due to limited resources at the time, the reactor components had been placed in storage for retrieval. The results of the PIE did show that the reactor shutdown resulted from the increased temperature in the moderator which caused cracking and spreading of the moderator into the vessel region (Degalsev 1993). Also, there was the general loss of hydrogen from the moderator from the ~one year of operation, which resulted in a general decrease of reactivity. This accident has shown the inherent shutdown of the Topaz II reactor under accident conditions.

E-38: This was the final nuclear ground test performed on the Topaz II program. Testing was performed from February 1986 to August 1986 at the Romashka facility. The ACS had been further modified since the previous nuclear ground tests. During the acceptance testing, the Cs unit had been overfilled with Cs, and had air ingress into the Cs line which caused large power oscillations during the first phase of testing. After the excess Cs was used, the power oscillations ended, and the reactor operated for 4700 hours at ~4.8 kWe. During the nuclear ground test there was a small coolant leak that was believed to have begun during the initial startup of the system and continued throughout the system operation. It appeared to be a small weeping leak that would open and seal during the transient periods. Over the four month period, enough NaK was lost such that after the reactor was shutdown the core was voided. The exact location, and cause of the leak was never determined.

The nuclear ground tests were an important component of the flight qualification program. Testing demonstrated the capability of the system to operate at 4.5 to 5.5 kWe for the three year lifetime without radiation damage to critical components or TFE shorting. The design and fabrication of the coolant loop was modified to reduce the possibility of a coolant leak. An overview of the modifications to the coolant loop is presented in Voss 1994.

Cold Temperature Testing

CTT was done to ensure that there was adequate heat storage capacity in the reactor system after pre-launch heating to keep the NaK coolant from freezing during the pre-launch, launch, and orbital ascent operations. The NaK coolant freezes between -5 to -11 °C depending upon the off-eutectic sodium-potassium composition.

The Russian pre-launch and launch scenario assumed that the reactor system was heated to 100 °C using startup heaters attached to the two cold legs of the reactor coolant loop. The heaters were powered by a ground station at the launch site. The system was disconnected from the launch facility and allowed to cool for two hours prior to launch. The Topaz II design has a thermal cover to reduce the heat loss prior to system operation. The time to reach the operating orbit was eight hours during which time the electromagnetic (EM) pump was switched on for ~90 seconds, a maximum of 11 times to distribute the heat stored in the reactor to other regions of the coolant loop. The Russian CTT simulated the above scenario for the pre-launch and launch environment.

Pre-launch simulation was performed at CDBMB where the reactor could be heated and allowed to cool. The systems were then transported to thermal vacuum facilities at the Research Institute of Chemical Machine Building in Zagorsk where the launch simulation was accomplished. The launch simulation was done both with and without the TC, and with and without simulated solar heating in the vacuum chamber. The Russians were able to conclude that preheating in conjunction with the TC would be adequate to ensure the coolant would not freeze prior to reactor startup, even under the worst conditions assuming no solar heating. Two of the systems were frozen and allowed to thaw without the aid of external heaters, but with only heat from the ambient environment. The Russians found there were no adverse effects to the systems after thawing, and they were able to pump the coolant in a sludge form.

Four systems underwent CTT: V-13, V-15, V-71 and Eh-40 (Kirillov 1993 and Blokvana 1993).

<u>V-13:</u> This system was tested from 8/1/72 to 5/1/73. The key finding was that the original design of the TC was not adequate and required additional insulation. V-13 was designed for an upright launch with alcohol rather than NaK coolant. Also, the TC ejection device was tested.

<u>V-15:</u> is system was tested during the early part of 1980, and included NaK coolant. The purpose of the test was to verify adequacy of the modified TC design, and found that it worked well. It was tested in an upright configuration, and the TC ejection device was also tested.

<u>V-71:</u> Underwent CTT during November of 1982. It was designed for an inverted launch. The CTT was required to verify the performance of the redesigned thermal cover and ejection device.

<u>E-40:</u> Underwent CTT during December and January of 1988 but no data has been made available.

The U.S. launch environmental requirements are not as severe as those of the Russians, and therefore the pre-launch heating requirements and the design of the thermal cover are being modified. Testing of the U.S. launch environment and configuration will require additional testing to verify the coolant will not freeze prior to reactor startup.

Summary

The Russian flight qualification program encompassed four specific types of systems testing: thermophysical, mechanical, nuclear, and cold temperature testing. The requirements of the Russian system evolved over me to be able to operate the system for three years at 4.5 to 5.5 kWe within the space environment. They also modified the launch configuration and test environment requirements. The system test program encompassed these changes as the program evolved. Therefore, it has been very important the U.S. understand the design, fabrication, testing, and evolution of the Topaz II systems to be able to determine what modifications, and testing are required for a U.S. launch. It has taken a tremendous amount of time and patience by both the Russian and the U.S. teams, to understand and transfer the information required for the program to move forward so successfully.

The Russian systems test data is applicable to and required for the U.S. flight qualification of the Topaz II. Areas where additional systems testing is required includes modifications made to the Topaz II (Haarman and Voss 1994), changes in the launch configuration, and differences in the launch environment. Areas where testing needs to be completed include: acceptance testing of the flight units, a 1000 hour duration high-temperature test, mechanical, static, dynamic and acoustic testing, reactor criticals, and cold temperature testing to simulate the U.S. launch environment.

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