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TOPAZ II SYSTEM DESCRIPTION

Susan S. Voss[1]

Abstract

The TOPAZ II single-cell thermionic space reactor power system was designed, built and tested by the former Soviet Union (Russia). It has been purchased by the United States (U.S.) for technology transfer, testing, and the possible integration and launch with a U.S. satellite. To support the program, ground facilities consisting primarily of Russian hardware, have been built in Albuquerque, New Mexico to perform non-nuclear ground testing of the system. The purpose of this paper is to provide a brief overview of the Russian TOPAZ II system.

Introduction

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 TFE terminal, 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 magnetic 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 1.

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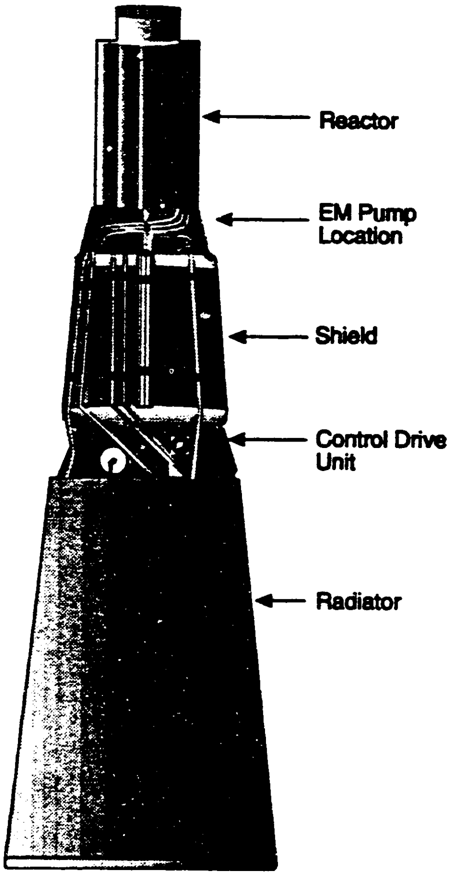

Figure 1. TOPAZ II Reactor System.

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. Important reactor system specifications are presented in Table 1.

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

TABLE 1. General TOPAZ II Reactor Power System Characteristics.

Lifetime	3 Years
Electric Power From the Reactor Terminal	4.5-5.5 (kW_e)
Electric Power to the Spacecraft Bus	<5.5 (kW_e)
Thermal Power BOL/MAX	115/135 (kW_{th})
Voltage	27 +/- 0.8 (volts)
Reactor System Mass (Excluding the ACS)	1061 (kg)
System Length	3.9 meters
Number of TFE Elements in the Core	37: 34 for Primary Power and 3 to Power the Pump
Reactor Coolant	NaK: 78 $^w/_o$ K and 22 $^w/_o$ Na
Reactor Coolant Inlet Temperature BOL/MAX	743/773 K
Reactor Coolant Outlet Temperature BOL/MAX	843/873 K
Coolant Mass Flow Rate BOL	1.3 (kg/sec)
Electromagnetic Pump	DC Conduction
Primary System Material	Stainless Steel
Reactor Neutron Spectrum	Epithermal
Reactor Fuel	UO_2
Fuel Enrichment	96%
Fuel Form	Pellets
Core Height	375 (mm)
Core Diameter	260 (mm)
Fuel Loading	27 (kg)
Reactor Height	920 (mm)
Reactor Diameter w/ Radial Reflectors	408 (mm)
Moderator	$ZrH_{1.85}$
TFE Emitter Material	Monocrystal Mo with ~3% Nb
TFE Emitter Surface Coating	95% W^{184}
TFE Collector Material	Polycrystal Mo
TFE Insulator Material	Monocrystal Al_2O_3
Reactor Control Drums	9 Be Drums with 120 degree segments of BC/SiC canned in Stainless Steel
Reactor Safety Drums	3 Safety Drums (same design as control drums)
Excess Reactivity BOL Cold	0.53-0.65
Power Monitors	2 Fission Chambers
Shield Half Cone Angle	8 degrees and 16 seconds
Neutron Shield Material	LiH
Gamma Shield Material	Stainless Steel
Radiation Dose Limits (4 m plane 18.5 m from reactor centerline)	1.0×10^{11} neutrons/cm^2 (E_n>0.1 MeV) and 5.0×10^4 roentgen
Total Cesium Supply	1 (kg)
Average Cesium Consumption per Day	0.5 (g/day)
Effective Radiator Surface	7.2 (m^2)
Number of Radiator Elements	78
Radiator Fin Material	Copper with black enamel coating

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) to 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. Each of the main subsystems is discussed in the following sections.

Reactor Subsystem

Reactor System Overview

The TOPAZ II nuclear reactor is a small zirconium hydride-moderated, epi-thermal reactor with in-core thermionic converters. The reactor contains 37 thermionic fuel elements (TFEs). Each TFE is fueled with highly enriched uranium dioxide (UO_2). The 37 TFE elements are located in vertical holes within the 5 cylindrical moderator blocks. The reactor power is controlled by the rotation of external beryllium drums, each containing a 116-degree segment of boron silicate carbide, which varies the amount of reflection versus absorption of the neutron flux. The coolant transfers the waste heat from the outer collector regions of each of the 37 TFEs to the radiator. The primary structural material of the TOPAZ II is stainless steel. Figure 2 provides a top view of the reactor.

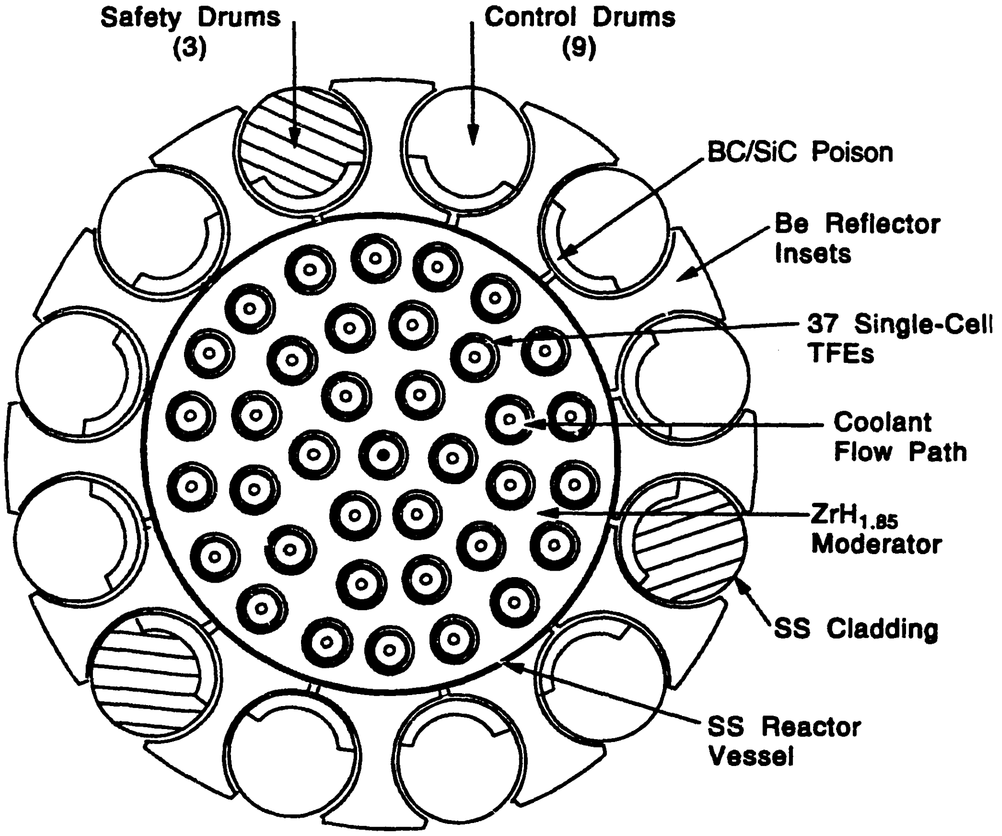

Figure 2. Top View of the TOPAZ II Reactor.

Thermionic Fuel Element

Fuel

The fuel contained within each TFE is highly enriched (96% U^{235}) UO_2 in the form of pellets, stacked within the cavity of the TFE emitter. Each fuel pellet is ~8 mm high with an outer diameter of 17 mm. Each fuel pellet has a central hole with a diameter of 4.5, 6.0 or 8 mm, depending upon the radial position of the TFE within the core. The central holes are used to help flatten the power profile in the radial direction. The total height of the fuel is 355 to 375 mm; the height of the fuel can be varied at the time of fuel loading to compensate for variations in fabrication that can affect the reactivity. The maximum temperature of the fuel is between 1773 and 1923 K, and the end pellet temperatures are 1573 K. Beryllium oxide (BeO) pellets on both ends of the fuel stack provide axial reflection within the TFE fuel region.

TFE Working Section

The working section includes the reactor fuel and the TFE components. The inner tube of a TFE is a monocrystal molybdenum emitter with 3% niobium added for additional strength. The fuel and BeO axial reflectors are placed within the emitter tube. The outer surface of the emitter has a surface layer of tungsten which increases the TFE emitter work function.

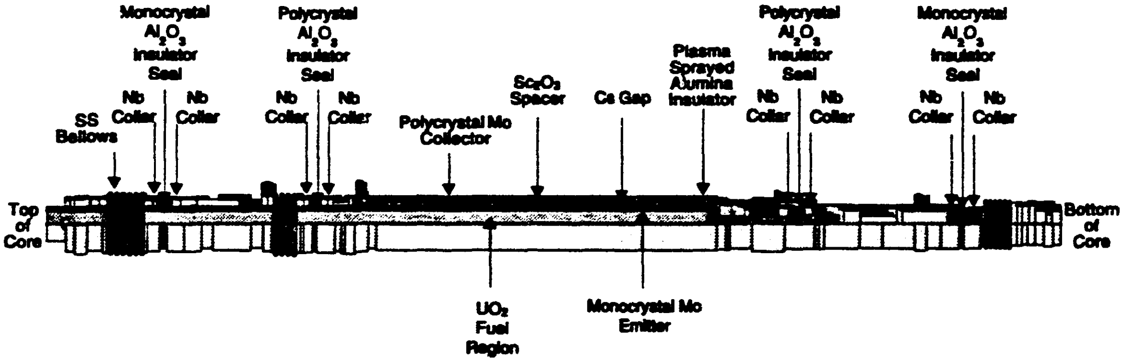

Figure 3. Single Figure of TFE.

External to the emitter is the interelectrode gap, which is formed by the emitter and collector surfaces. Helium is placed in the gap before reactor startup (to promote heat transfer during startup and prevent arc discharge at low cesium pressure), and is replaced with cesium during the reactor startup sequence. The collector is fabricated from polycrystal molybdenum. The outer surface of the collector is plasma sprayed with an alumina (Al_2O_3) electrical insulation. Scandium-oxide (Sc_2O_3) spacers are located between the emitter and collector surfaces in the interelectrode gap, to prevent the emitter from shorting to the collector because of emitter distortion caused by fuel swelling. The TFE working section is illustrated in Figure 4.

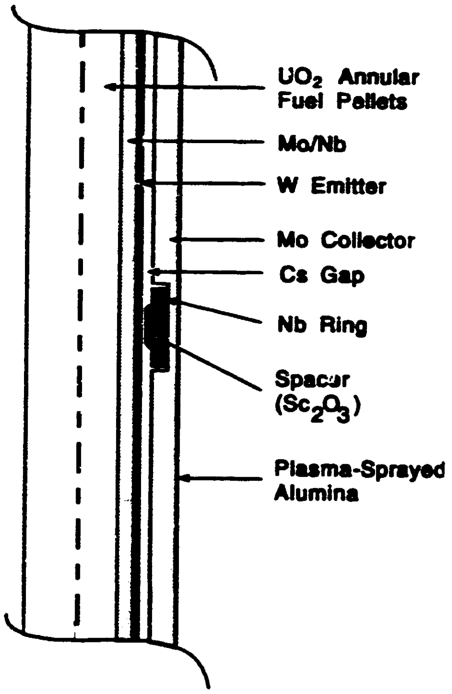

Figure 4. TOPAZ II TFE Working Section.

A helium gap is formed by the outer diameter of the collector insulator and the inside diameter of the inner coolant tube. The helium provides a good thermal conductor for the transfer of heat to the coolant, while maintaining electrical insulation of the TFE. The helium gap within the TFEs is open to the upper and lower helium plena, where the electrical leads of the TFEs are located. The TFE helium gap is connected to a bottle of helium located in the radiator region.

TFE End Sections

The TFE end sections provide the following functions:

- electrically isolate the working sections from the reactor frame;
- provide connections for the electrical leads;
- provide a mechanical attachment of the TFEs to the reactor vessel and
- provide bellows for the thermal expansion of the TFEs.

Radial Reflectors

The reactor is surrounded by a radial beryllium reflector, which is comprised of 12 rotating drums uniformly separated by 12 insets. The insets are hour-glass-shaped and fabricated from beryllium. Each of the twelve control drums has a 116-degree section of natural boron silicate carbide. Three of the twelve drums are connected to independent drive motors located at the top of the reactor. The remaining nine drums are connected to a ring gear and rotated by a single-drive motor through a single control drive shaft.

Two thin stainless-steel bands surround the radial reflectors - one near the top and one near the bottom of the reactor. The bands compress the reflectors against the reactor vessel and are designed to permit emergency ejection of the reflector assembly. They provide the only mechanical attachment of the reflectors to the reactor, other than the control drum tube sleeve bearings and the safety drive attachments.

Radiation Shield

The radiation shield is used to attenuate the neutron and gamma radiation. It is a truncated cone located behind the reactor and is lithium-hydride cast in a stainless steel vessel. There are five penetrations through the shield: two hot side coolant pipes, two cold side coolant pipes, and the single control drive shaft. The pipes and control drive shaft sleeve are welded into the shield prior to the casting of the LiH. The LiH is cast without any internal structural support other than the coolant pipes and control drive shaft. The coolant pipes are angled through the shield to reduce radiation streaming to the payload. Helium gas is maintained in the shield vessel to improve thermal conductivity from the LiH to the stainless steel shield vessel.

Primary Coolant Loop

The coolant loop removes excess heat from the reactor core and radiates it to space. The main components of the coolant loop are the piping and coolant, the EM pump, the volume accumulator, the gas absorber, the expansion bellows, the startup heaters, and the radiator. A brief description of each of the main components follows.

The coolant enters a plenum in the lower region of the reactor. It makes a single pass through the reactor core through the coaxial coolant region of each of the 37 TFEs. The coolant then enters the upper plenum of the reactor before continuing into two symmetric flow paths to the radiator header. The flow path is divided into two symmetric paths to provide equal kinetic moment. The coolant loop passes through the inside of the radiation shield at an angle to reduce streaming. There is insulation and a vacuum gap between the radiation shield tubes and the coolant pipes that pass through the radiation shield.

The coolant is transferred to the upper collector of the radiator and distributed through 78 small radiator tubes, by which the heat is rejected to space. The coolant flows through the radiator to the lower collector. Leaving the lower collector it is again split into two opposite and equal coolant flow paths. The cold-leg piping from the lower collector to the bottom of the shield is inside the radiator skirt. One of the two coolant paths branches into a flow path that surrounds the radial surface of the cesium unit to heat the unit during startup and nominal operation.

The coolant pipes again pass through the radiation shield at an angle to reduce radiation streaming. After leaving the shield, each of the two coolant paths branch into three coolant pipes; each set of pipes faces in opposite directions. The two sets of piping enter the pump in opposite directions to reduce torque on the spacecraft and to increase the EM pump efficiency. The coolant enters the EM pump through the six coolant pipes. The pipes entering and exiting the EM pump are electrically insulated from the reactor structure. The coolant enters through six inlets to the lower coolant plenum of the reactor before passing through the TFE flow channels. A gas absorber, zirconium getter is located in one of the two hot-side coolant pipes within the shield to remove oxygen from the coolant.

The cesium supply pipe intersects into one of the two hot-side pipes near the upper collector before entering the shield. The cesium supply pipe remains inside the coolant pipe up to the top of the shield, before entering the reactor vessel. A small copper bridge is attached to the cesium supply line from the upper collector to transfer heat from the radiator to the cesium unit during startup.

A volume accumulator is used to compensate for the expansion of the NaK during the system startup. It is attached to one of the two loops of the cold side of the primary coolant loop. Small expansion bellows are distributed throughout the primary coolant loop to provide expansion compensation during startup and thermal transients. A schematic of the primary coolant loop is shown in Figure 5.

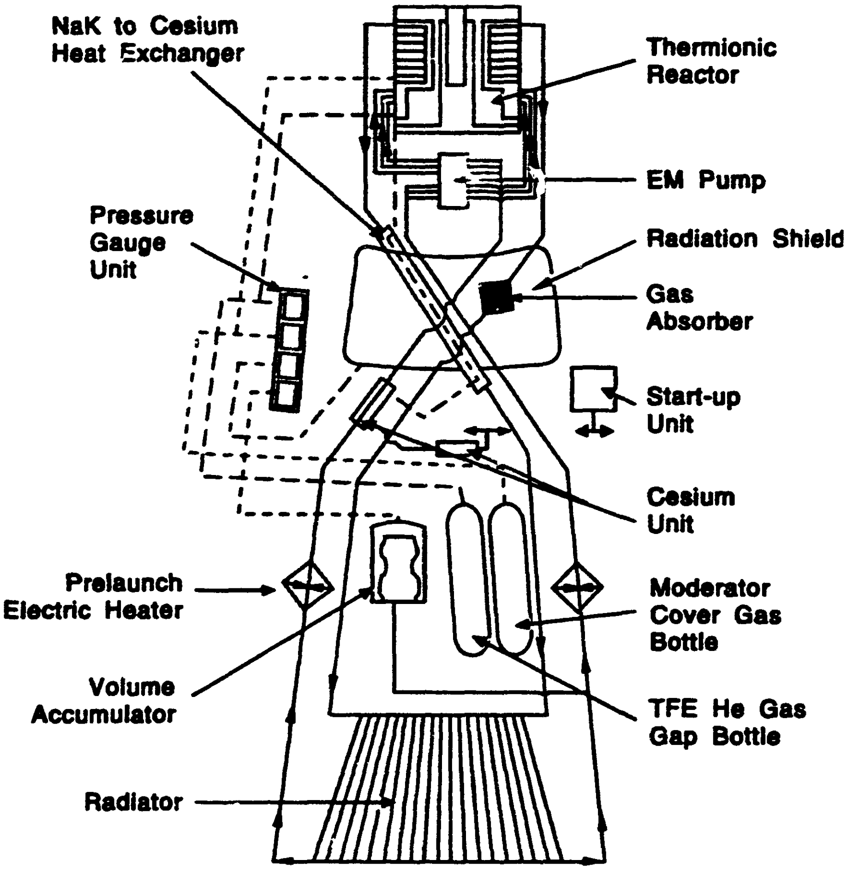

Figure 5. Primary Coolant Loop Flow Schematic.

Startup heaters ensure that the temperature of the NaK is high enough to prevent freezing during the prelaunch and launch phase of the mission. For the Russian mission scenario, this prelaunch temperature of the NaK coolant is 373 K. The electric startup heaters are attached externally to the two cold legs of the primary coolant loop. They are used only after the spacecraft has been integrated with the launch vehicle powered through an on-board detachable joint by the launch support station.

Cesium Supply System

The cesium supply system (CSS) provides cesium to the TFE interelectrode gap to reduce space charge effects between the emitter and the collector. The cesium unit is located between the radiation shield and the upper radiator collector and is attached to the coolant piping.

The circular portion of the cesium unit vessel is surrounded by one of the two cold legs of the coolant loop. This is done to provide heat to the CSS during startup, and to maintain a nominal operating temperature of 623 K. A copper bridge running from the upper radiator collector to the piping of the CSS transfers heat to the CSS during the startup sequence.

The main cesium pipe that runs from the CSS to the inlet plenum of the reactor intersects one of the hot legs of the primary coolant loop, near the bottom of the shield on the inside of the pipe. The cesium pipe is 12 mm in diameter, 1 mm thick, and is fabricated from stainless steel. The cesium pipe leaves the coolant pipe near the top of the shield region. The cesium pipe enters the cesium plenum at the aft end of the reactor where it is open to the interelectrode gap of the 37 TFEs. The cesium plenum is formed from the lower TFE helium plenum plate and the cesium plenum plate. A diagram of the cesium supply system is shown in Figure 6.

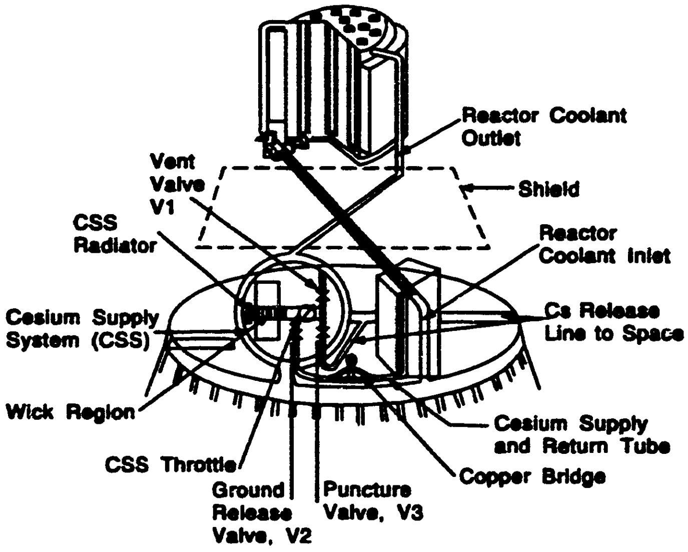

Figure 6. Cesium Supply System.

A single valve is opened in space during the startup sequence when the supply current reaches 40 to 60 amps. It is a puncture valve, that once opened cannot be closed again. Current is sent from the storage battery to open the valve. The valve is spring loaded and punctures a small steel membrane. The puncture valve must be opened to release the cesium and gaseous impurities into space during operation.

During the system startup, the temperature of the NaK coolant increases, and the temperature and the pressure in the CSS begin to rise. Cesium enters the interelectrode gap and mixes with the helium. This initiates the thermionic process within the TFEs. When the valve opens during the startup sequence, the helium diffuses from the interelectrode gap back through the cesium inlet pipe to space. The helium is then released to space through the throttle valve to the cesium release path. The release line branches into two opposite directions after leaving the CSS. The two cesium release lines run along the top region of the radiator where the initial helium, and then the cesium and contaminants are released directly to space.

Thermal Cover

The thermal cover is used during the prelaunch and launch sequence to reduce the heat loss from the TOPAZ II system on the launch pad and during the flight to orbit. It is important that the TOPAZ II coolant not freeze to allow coolant circulation necessary for operation of the system.

Primary Power System Structure

The three main structural and primary load bearing members of the TOPAZ II system are the reactor, the shield and the frame. The load bearing frame is illustrated in Figure 7.

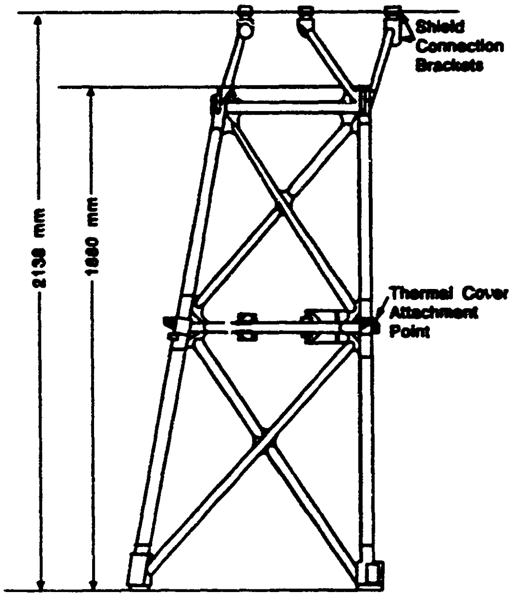

Figure 7. Frame.

Instrumentation and Control

The TOPAZ II instrumentation and control system provides the means of monitoring, controlling and telemetering system conditions. The control components employed to manage these activities are grouped under the name of automatic control system (ACS). The ACS has three functional systems, namely the automatic regulating system (ARS), the telemetry and command system (TCS), and the (electric) power supply system (PSS).

The ACS is a closed-loop feedback control system. It controls reactor system operations by receiving signals from various sensors (thermocouples, flux detectors, etc.) located on the reactor system. It uses this information to calculate the required actions necessary to put or maintain system parameters within their specified limits, and sends out command signals to perform the computed adjustments. The logic modules for reactor system control and telemetry, and the hardware needed to regulate and supply the spacecraft instruments with electric power are located within the spacecraft bus.

Conclusions

The U.S. and Russian specialists have worked closely and cooperatively in this highly successful technology transfer effort. A significant understanding of the TOPAZ II system has been garnered during the program. Continued collaboration between the two countries will provide further insight and comprehension of the design, development and testing of Russian space nuclear power technology.

Acknowledgments

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