History of Soviet Topaz Reactors

- **First US Thermionic (TI) ideas, LASL, 1957**
- **USSR Scientists visit LASL in 1958**
- **First US Tests on TI principles, 1959**
- **First USSR tests on TI, 1961**
    - **Single TI cell ==> ENISY (later TOPAZ-II)**

Developed in early 60's at Sukhumi, 67 at the central Design Bureau for Machine building (CDBMB) in Leningrad. Later many organizations participated:

- ***Kurchatov Inst. of Atomic Energy-Moscow (Nuclear methods and analysis)***
- ***Scientific Ind. Assoc. Lutch-Podolsk (Developer of TFE's)***
- ***Sukhumi Inst. Tech. Physics-Sukhumi (Reactor automatic control system)***
- ***Res. Inst. Chem. Mach. Building-Zagorsk (thermal vacuum testing)***
- ***Sci. Inst. of Instr. Building-Moscow (Nuclear test facility)***
- ***Kraznoyarsk Spacecraft Designer-Kraznoyarsk (Mech. Testing and spacecraft integration)***
- ***Prometheus-St Petersburg (materials development, welding, liquid metals)***
- ***TOPAZ-II Manufacturing-Tallinn, Estonia (Actual construction)***

    - **Multi-Cell TI ==> TOPAZ (later TOPAZ-I)**

(Thermionic Experiment with Conversion in Active Zone, developed in Moscow by RED STAR, who also developed the "Bouk Reactor" [Beech Tree] which flew 33 RORSAT missions)

- **Russians first acknowledge "TOPAZ" in 1971**

• First Ground Test in 1971

• Cooperation between the two Russian groups lasted until early 70's, then was ceased because of differences in design philosophy

• USSR has flown at least two TOPAZ-I systems for a new generation of Ocean surveillance satellites,

Cosmos - 1818, 2/1/87, lasted 6 months
Cosmos - 1867, 7/10/87, lasted 1 year

Difference was W coating on Mo single crystal in Cosmos-1867 (in order to reduce the work function and reduce Cs consumption that limited Cosmos-1818 to 6 months operation)

• Near the end of 80's, USSR approached US company about possibility of purchasing Russian space equipment

• Offered for sale to U.S., Jan 1990
***** Will Sell 5 kW_e, "Flight Tested" for ≈8 $M***

• Sold 2 Topaz-2 reactors (minus fuel) to US for 13 $M. They were delivered Spring 1992

• First test of B-71 (electrical) completed in May 1993. Performed by Phillips Lab (PL), Sandia (SNL), Los Alamos (LASL), and Univ. New Mexico (UNM)

• Testing of the Ya-21 (thermal & vibration) started in Aug 93 and will be finished in CY 1994 (has already run for 1,000 hr's.)

• Clinton administration is considered buying 4 more Topaz-II reactors (w/o fuel) for 21 $M (never did it)

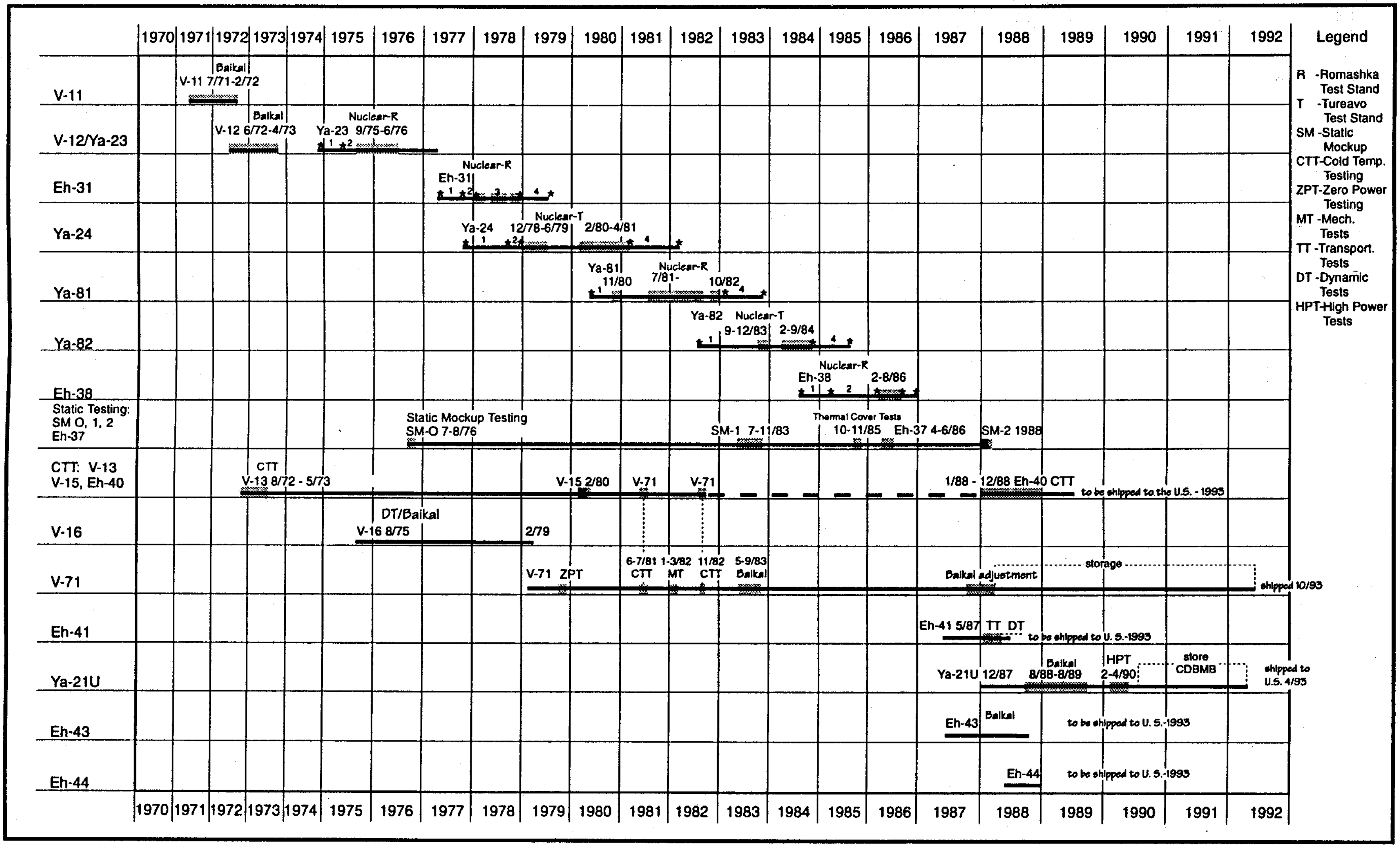


FIGURE 1. TOPAZ II System Tests.

TABLE 1. System Testing Summary Chart.

Name	#	System #	# TFE	Life (yrs)	Launch	Test Stand	Test Begin	Test End	Test Time	General Description
										B: Baikal, MT: mechanical testing, CTT: cold temperature testing, Nuclear R or T: nuclear ground test Romashka or Turaevo, ZPT: zero power testing.
V-11	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. Thermophysical testing. Did not have a complete set of TFEs.
V-12	1	Prototype 2	31	1	Upright	B	6/21/72	4/18/73	850	Development of technology for prelaunch operations and system testing. Thermophysical testing. Fabricated by CDBMB
V-13	1	Prototype 3	31	1	Upright	B, MT, CTT	8/1/72	5/1/73	----	Mechanical testing: transportation, dynamic, shock, and CTT. First unit fabricated in Estonia.
Ya-20	1	Specimen 1	31	1	Upright	Nuclear - R	10/1/72	3/1/74	2500	Neutron physical characteristics and radiation fields were studied. Zero power testing. Development of the nuclear test methods.
Ya-21	1	Specimen 2	31	1	Upright	Nuclear-R and B				Neutron physical characteristics, nuclear test methods and radiation fields were studied. Prelaunch operations.
Ya-22	1	Specimen 3	31	1	Upright					Not fabricated. They were going to use Ya-21 design documents, but they already knew they were going to change the TFE.
V-15	2	Serial 1	31	1-1.5	Upright	CTT and B	2/12/80			Cold temperature testing. First standardized design drawings. Second generation of TFEs. TFE 1 year/system 1.5 yr.
V-16	2	Serial 2	31	1-1.5	Upright	MT	8/1/75	2/1/79	2300	Mechanical: transportation, vibration and shock. Thermophysical testing for operability after mechanical testing.
Ya-23	2	Serial 3	31	1-1.5	Upright	Nuclear - R	3/10/75	6/30/76	5000	Fuel loading, radiation, and nuclear safety. Development of technical preparation for nuclear tests. Startup procedures established. PIE. Significant TFE shorting.
Eh-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. Significant TFE shorting.
Ya-24	2	Serial 5	31	1-1.5	Upright	Nuclear - T	12/1/78	4/1/81	14,000	Steady state system testing. Disassembled. Significant TFE shorting.
Eh-32	2	Serial 6	31	1-1.5	Upright					Already under fabrication at Estonia-needed new TFE design. No systems testing. Installed in Turaevo as a mockup. Used to establish transportation and handling procedures.
Ya-25	2	Serial 7	31	1-1.5	Upright					Already under fabrication at Estonia. Not tested. Sent to Kraznoyarsk to be used as a mockup with the spacecraft.
Eh-35	2	Serial 8	31	1-1.5	Upright					Already under fabrication at Estonia. Second stage of fabrication not completed. Used for some experiments on Baikal stand. .
Ya-26	2	Serial 9	31	1-1.5	Upright					Already under fabrication at Estonia. Send to CDBMB for second stage of manufacturing. TFE was burnt and damaged during second stage. There was a notch between the TISA heater and emitter.

Name	#	System #	# TFE	Life (yrs)	Launch	Test Stand	Test Begin	Test End	Test Time	General Description
V-71	3	Serial 10	37	1.5	Inverted/ Upright	B, CTT, MT, ZPT	1/1/81	1/1/87	1300	Mechanical: transportation (railroad), vibration, and shock. CTT. Electric testing after MT. ZPT at KIAE. Interface with s/c was modified for the inverted launch.
Ya-81	3	Serial 11	37	1.5	Inverted	Nuclear - R	9/1/80	1/1/83	12,500	Nuclear ground test. Early NaK leak. Plugged, and test continued. Steady state operation. Disassembled -PIE. 4.5 kWe/105 kWth @560-570°C.
Ya-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 and shutdown. Steady-state operation. Disassembled. 4.5 kWe/108 kWth @~530°C.
Eh-37	3	Serial 13	37	1.5	Inverted					Quality not sufficient for flight. Static tests, including torsion tests.
Eh-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 operation. Disassembly. 4.8 kWe/108 kWth @570°C.
Eh-39	3	Serial 15	37	1.5	Inverted					Began fabrication in Estonia and changed some components. When finished, they changed system name and # to Eh-41 and serial number to 17. Main change in the reactor.
Eh-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 second stage of manufacturing.
Eh-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 by 200 kgs.
Eh-42	3	Serial 18	37	1.5	Inverted		1/1/88			Error in welding during the fabrication at Tallinn. It was an error in a critical component, therefore they decided to not use this unit.
Ya-21u	4	Serial 19	37	3	Inverted	B	12/1/87	12/1/89		Electric testing. "u" means modified, i.e., they used a modified TFE to get the longer lifetime.
Eh-43	4	Serial 20	37	3	Inverted	None	6/30/88			Flight unit. First phase of manufacturing completed in Tallinn, Estonia. Second phase not yet completed.
Eh-44	4	Serial 21	37	3	Inverted	None				Flight unit. First phase of fabricated completed in Tallinn, Estonia. Second phase not yet completed.
Eh-45	4	Serial 22	37	3	Inverted	None				Partially fabricated flight unit. Components missing from system.
SM 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. Testing done at CDBMB.
SM 1 SM 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.

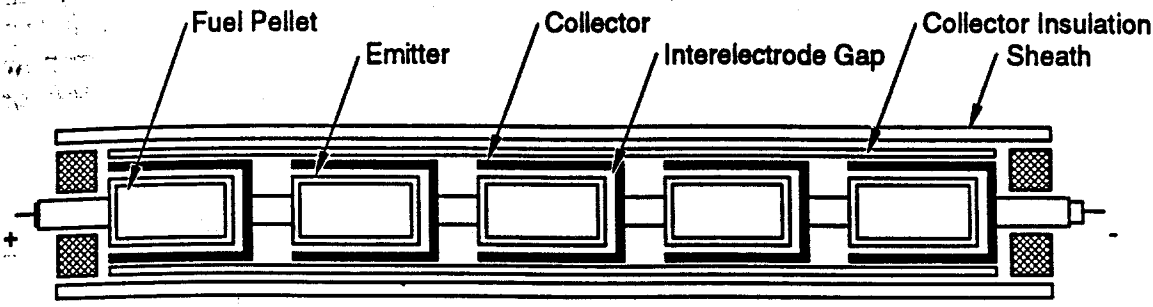


FIGURE 16. Basic Arrangement of the Multicell TOPAZ Thermionic Fuel Element (TFE) (Bennett 1989).

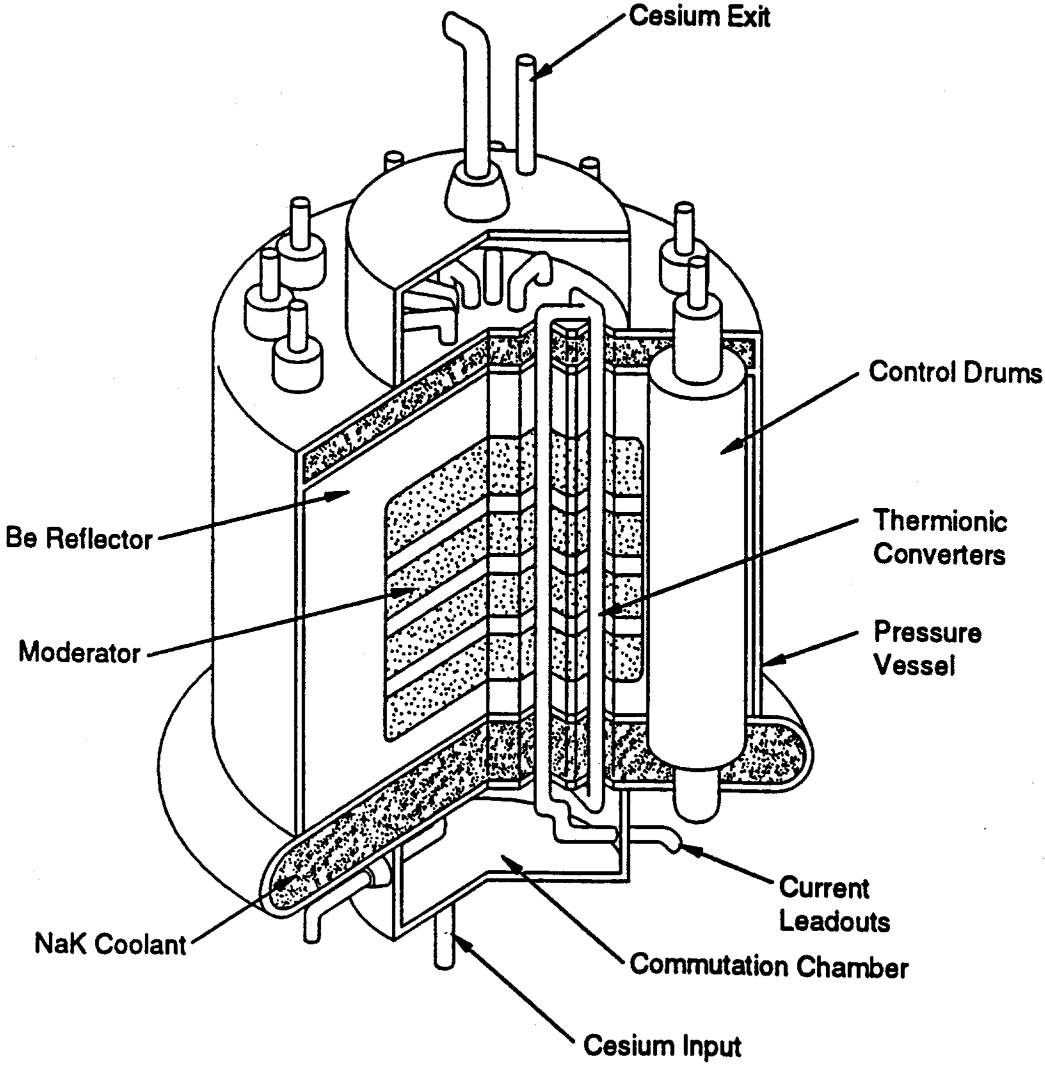


FIGURE 17. Configuration of the TOPAZ I Reactor (Bennett 1989).

Comparison of USSR and US Fission Space Reactors

Features	SNAP-10	Early Romaska	SP-100	TOPAZ-1	Later RORSAT
Flight Status	1965	65-?	Cancelled	87-?	67-?
Thermal-kW_t	45.5	40	2,000	150	<100
Elec. Power-kW_e	0.65	0.8	100	5-10	<5
Converter	T/E	T/E	T/E	T/I	T/E
Fuel	$U\text{-}ZrH_x$	UC_2	UN	UO_2	U-Mo
kg-^{235}U	4.3	49	140	12	25
Reactor Mass-kg	435	455	5,422	320	<390
Control	Be	Be	Be	Be/B_4C	Be
Coolant	NaK	None	Li	NaK	NaK
Reactor Type	Thermal	Fast	Fast	Thermal	Fast
	Temperature °K				
Core -max	858	2,173	1,650	N/A	N/A
Hot Junction	774	1,253	1,290	1,875	950
ΔT	152	315	448	1,000	N/A
T/E FOM-$(°K)^{-1}$	0.00058	N/A	0.0014	N/A	N/A

USSR Topaz-II Design Requirements

• Mass not to exceed 1061 kg (not including mass of automatic control system)

• Should provide 6 kWe at TFE terminal at 27 volts.

• Operating life of 3 years @ 95% reliability and have a shelf life (after fabrication) of 10 years.

• Reactor must not operate before achieving orbit.

• Coolant must not freeze before operation.

• Originally designed for GEO (36,000 km)

Topaz-II Components

1.) **Reactor**
2.) **Radiation Shield**
3.) **Primary Coolant Loop**
4.) **Gas Systems**
5.) **Thermal Cover**
6.) **Primary Power System**
7.) **I&C**

Picture

Table of parameters

***(*Note Overall Efficiency ≈ 5.2%)**

• Topaz-II incorporates in-core single cell TI fuel elements which can be replaced by electric heaters to test system before activated.

Top view of Topaz-II reactor

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

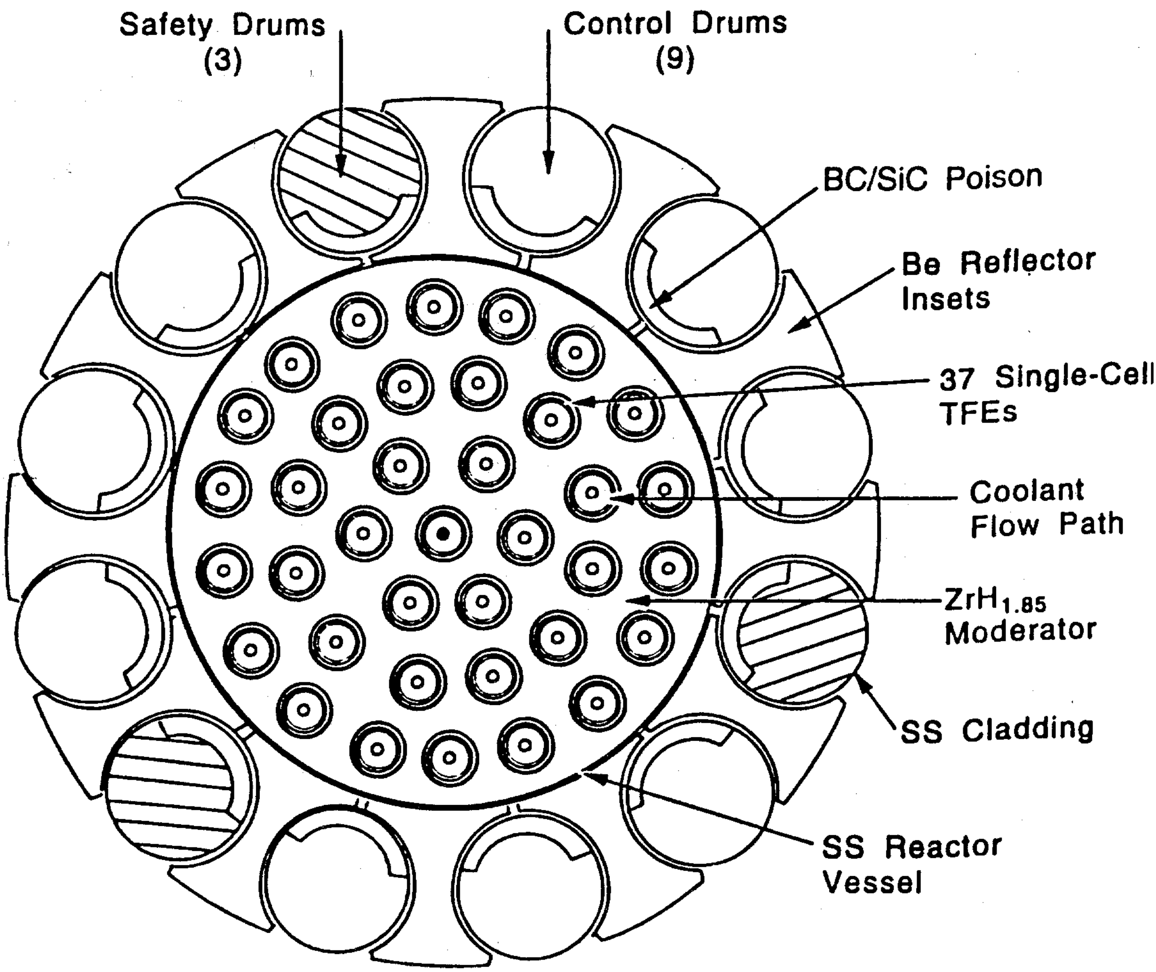
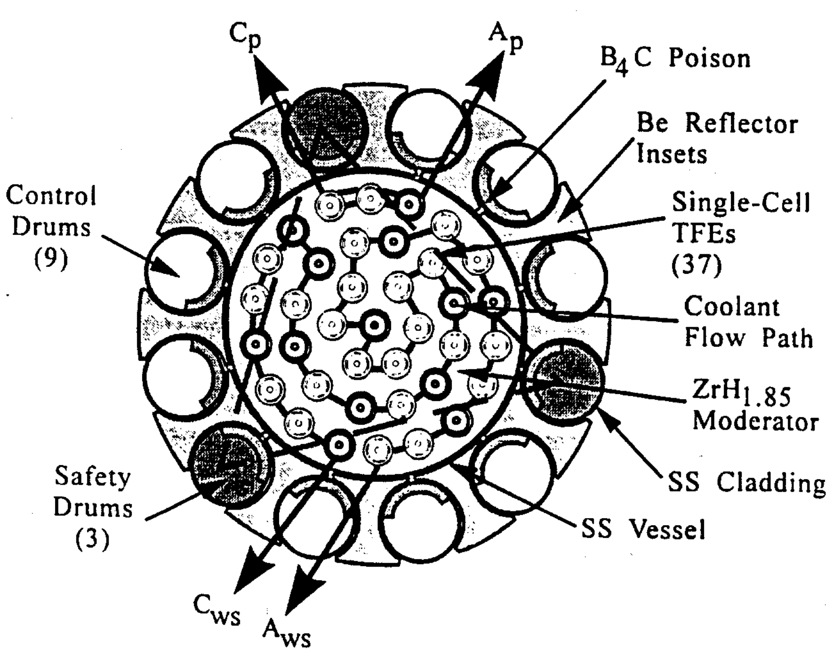


Figure 2. Top View of the TOPAZ II Reactor.



• Reactor contains 37 single-cell TFE's (3 for the EM pump, 34 to power system)

• Note $ZrH_{1.85}$ moderator block (special coating to keep from losing hydrogen)

• Note SS vessel

• Note 3 safety drums and 9 control drums

• Shield uses LiH and SS to reach radiation limits at 18.5 m for 3 years of 10^{11} n/cm^2, and 50,000 roentgen (γ) (had to increase mass from 190 to 390 kg in 1985 because of change in electronics).

Picture- Coolant flow path

• Found main contribution to LiH swelling is γ induced release of H to form H_2 bubbles

• Note single EM pump for NaK (ΔT 743=>843°K)

• SS piping and Cu fins for heat rejection

• Cs supply delivers Cs @ 0.5 g/day (had to increase the Cs inventory from 0.455 kg to 1 kg)

• Instrumentation & Control Functions
  - **Start-up power system (fast startup to 4.5 kW_e [98 kW_{th}/808 °K] in 65 minutes)**
  - **Maintain normal operating conditions**

• Stabilize voltage to payload
  - **Act on commands from ground control**

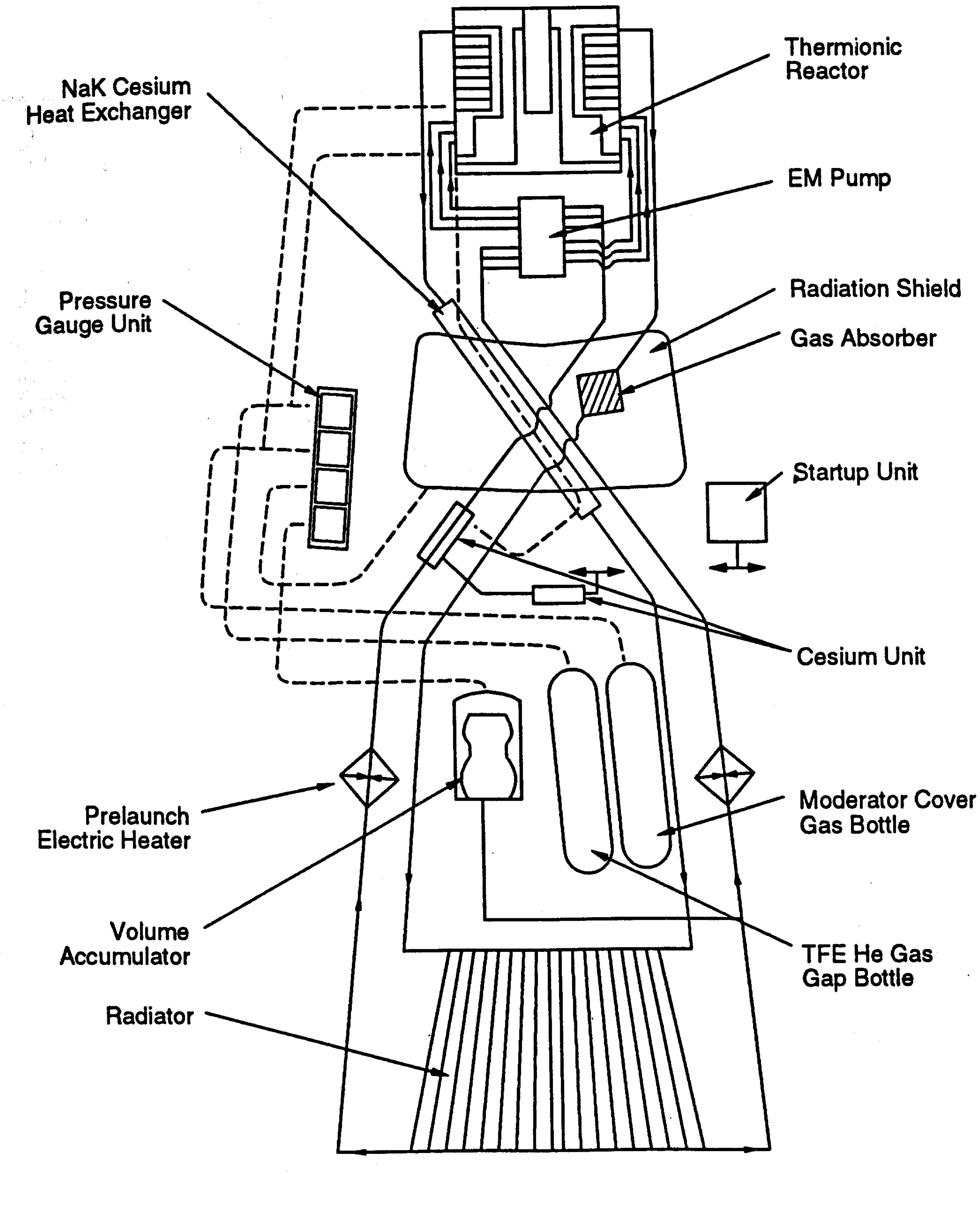


FIGURE 18. TOPAZ II Schematic (Topaz CoDR 1992).

- **Shut-down power system**
- **Safety control during land-based operations**
- **Telemeter performance data to ground**
- **Shunt excess power to ballast resistors**
- **Charge storage battery**

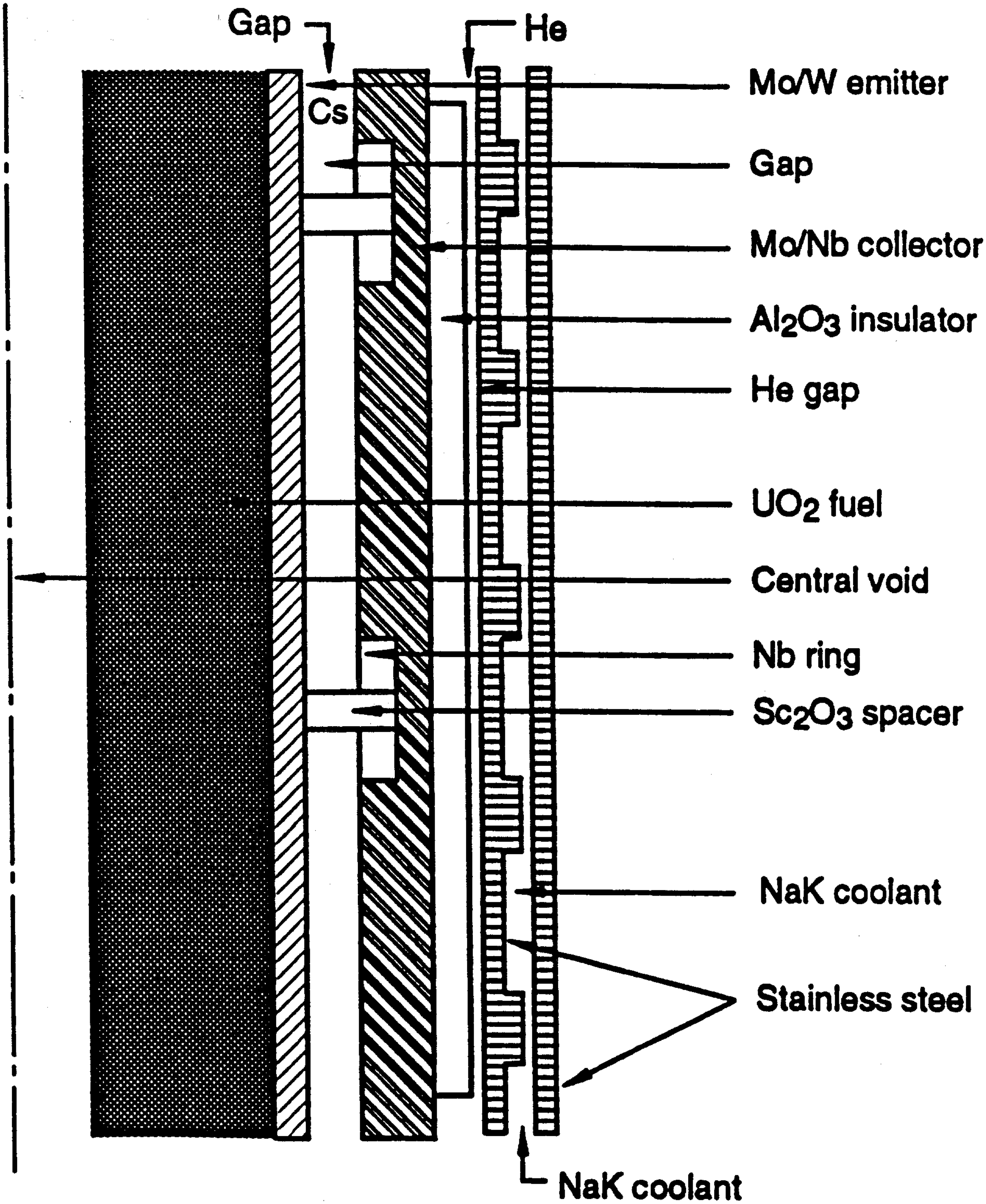
- **Fuel**
  - **96% ^{35}U in UO_2 with radial holes of 4.5,6, or 8 mm depending on location**
  - **Max fuel temp ranges from 1773 to 1923 °K**
  - **BeO pellets at both ends act as reflectors**
  - **Had to change from 31 to 37 TFE's and increase height of core to reduce power density, thus avoiding shorting due to swelling. They also increased the size of the inner hole to facilitate fission gas release as well as increasing the gap thickness.**

Picture TFE Working Section

- **Mono-crystal Mo has 3% Nb added to increase strength This decreased the emitter deformation by a factor of 2 (no longitudinal welds)**
- **Spacers (Sc_2O_3) prevent shorting due to fuel swelling**
- **Helium filled gap outside the collector insulator and the inner diameter of the coolant tube helps heat transfer and keeps electrical insulation**
- **Coolant pipes angled through shield to reduce streaming**
- **NaK is preheated on the pad to avoid freezing (note thermal cover to avoid premature cooling had to be increased to keep NaK,**

  MP = -13 °C ((9 °F)) from freezing in Feb)

TOPAZ-II TFE
Cross Section



• **<u>Safety Criteria</u>**

- **Reactor not operated prior to space deployment.**

- **Inadvertent criticality shall be prevented for both normal conditions and credible accidents**

(Reflectors are held together with steel bands which can be severed in case of an accident or melt on entry to the atmosphere)

- **Spacecraft radiological release to the space environment shall not result in a significant adverse effect on other spacecraft.**

- **Radiological release from spacecraft shall have insignificant effect on Earth**

- **On-orbit disposal shall be limited to sufficiently high orbits**

- **For any credible radiologically hot reentry accident, the reactor shall reenter essentially intact, or alternatively, shall result in essentially full dispersal of radioactive materials at high altitude.**

- **Planned radiologically hot reentry shall be precluded from mission profiles.**

Preliminary Nuclear Safety Analysis

- **Biggest problem appears to be inadvertent criticality when void spaces are filled with water.**

Solution: Use an "Anti-criticality" device to keep some of the fuel out of the core until orbit is achieved.

Topaz-II Excess Reactivity for Postulated Flooding Accident			
Reflectors	**Flood**	**Immerse**	**Excess Reactivity ($)**
Original Design			
on/Drums 0°	Water	Water	+3.46
on/Drums 0°	Water	Wet Sand	+4.00
off	Water	Water	+1.20
off	Water	Wet Sand	+4.78
With Anti-criticality Device			
off	Water	Wet Sand	-4.40

- **All other accidents and scenarios appear not to be significant or credible**

Comparison of Russian TOPAZ Reactors

Parameter	TOPAZ-I	TOPAZ-II
Electric Power-kWe	5-10	6
Therm. Power-kWt	130-150	115-135
Fuel	UO_2	UO_2
Fissile Mat., kg ^{35}U	12	up to 27
^{35}U Enrichment %	90	96
Moderator	ZrH_x	$ZrH_{1.85}$
Neutron Spectrum	Thermal	Thermal
Reflector	Be	Be
Reactor Mass-kg	320	1061
Emitter	Mo or W	Mo
Emitter T_{max}, °C	1450	1527-1827
Collector	Nb	Nb
Collector T, °C	650	470-570
Coolant	NaK	NaK
Coolant T, in/out	???	500/600