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The Soviet Space Nuclear Power Program

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Directorate of Intelligence

The Soviet Space Nuclear Power Program [redacted]

A Research Paper

This paper was prepared by [redacted] Office of Scientific and Weapons Research. Comments and queries are welcome and may be directed to [redacted]

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SW 91-10074X
October 1991

The Soviet Space Nuclear Power Program [redacted]

Summary

Information available as of 17 August 1991 was used in this report.

The Soviet space nuclear power program has concentrated on developing nuclear reactors to provide electric power and on developing reactors to heat propellant for nuclear rockets. As early as 1971, the Soviets were using a low-power reactor to generate about 2.5 kilowatts of electric power to operate a Radar Ocean Reconnaissance Satellite. This program apparently ended in 1988, probably because concern about accidental nuclear reactor reentry outweighed the value of the short-lived satellite. [redacted]

If the need arose, the USSR has the capability to use low-power reactors in space at any time. [redacted] 25X1, E.O.13526 [redacted]

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Efforts to develop higher power output space reactor systems, [redacted] had funding sharply reduced. Although we believe termination is unlikely, the space nuclear reactor will not make significant progress unless stable sources of funding are found. Soviet scientists are urgently seeking support from other countries, particularly the United States, for these programs. These scientists see foreign support as a source of much-needed hard currency and as a means of locking in Soviet Government funding. [redacted]

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Within 10 years the Soviets could produce a thermionic reactor with [redacted] Research is under way that could lead to fast reactors using in-core multicell thermionic converters and gas-cooled reactors coupled to turbines producing from hundreds to a few thousand kilowatts of electricity. The lack of funding has limited work on these systems to component tests. [redacted]

The Soviets have pursued development of nuclear reactors for rocket propulsion for more than 30 years, but progress has been slow. [redacted] 25X1, E.O.13526 [redacted]

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The Soviet Space Nuclear Power Program

Introduction

The Soviet Union established nuclear power for space applications as a goal in the early 1950s. The Soviets moved quickly in the development of low-power nuclear reactors for electric power production in space. By late 1971, they began routinely using a system producing approximately 2.5 kilowatts of electricity (kWe) to power a military satellite known to the US Intelligence Community as the Radar Ocean Reconnaissance Satellite (RORSAT).

Work on high-power reactors for space applications and on nuclear rocket technology proceeded more slowly. Near-full-scale testing of nuclear rocket fuel did not begin until 1975. Although Soviet claims about nuclear rocket fuel development are impressive, neither the nuclear rocket nor the high-power reactor effort has moved beyond the component testing phase.

Space Electrical Power Generation

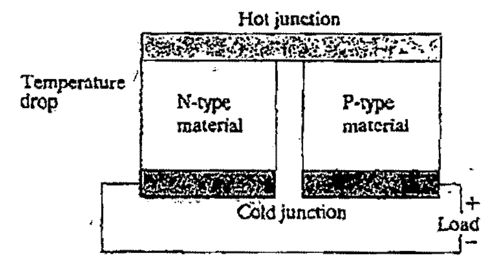
Thermoelectric Energy Conversion

In the 1950s the Soviets began to develop nuclear reactors with thermoelectric energy conversion for space applications (see inset). Soviet scientists apparently pursued parallel programs, which may have used the same thermoelectric material but had no other common features. The Romashka reactor never developed beyond demonstrating technology, and the competing program became the power source for the Soviet RORSAT. (Romashka is Russian for "daisy," so called because of the flower-like arrangement of its radiator fins.)

Romashka. On 14 August 1964 the Soviets began testing the Romashka—a simply designed, fast reactor with thermoelectric energy conversion—at the

Thermoelectric Conversion

Thermoelectric Converter



In 1821, Thomas Seebeck discovered that voltage is produced by dissimilar materials in a temperature gradient—a phenomenon known as the thermoelectric effect. Few practical applications existed until the 1950s, when semiconducting thermoelectric materials were developed. As heat is applied to a P-N[a] semiconductor junction, electrons move from the hot to the cold end of the N-type material, and positive charges move from the hot to the cold end of the P-type material (see figure). This charge movement creates a voltage. Thermoelectric converters are low-efficiency devices; only 2 to 5 percent of the supplied energy is converted to electricity. They are also highly reliable, simple, and durable, which makes them attractive for space applications.

[a] The term P-N refers to the two types of semiconducting material. In P-type material, current flows by movement of positive charges (holes). In N-type material, current flows by movement of negative charges (electrons).

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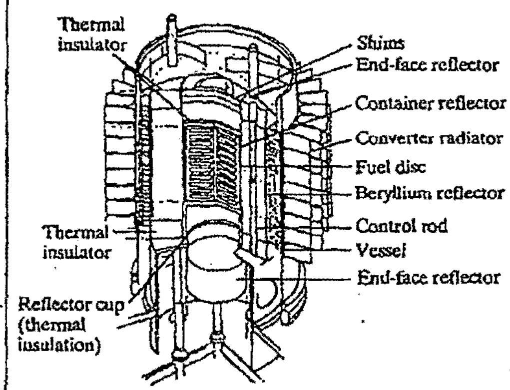
Institute of Atomic Energy *imeni* Kurchatov (IAE) in Moscow. The Romashka was fueled by uranium dicarbide (UC_2) contained in 11 plate-like graphite containers. These plates were surrounded by a monolithic radial beryllium reflector. A key feature was a layer of graphite cladding between the fuel containers and the beryllium reflector and another layer between the outside of the reflector and the converters. The graphite prevented chemical reactions between the reflector and fuel and the reflector and the silicon-germanium (SiGe) thermoelectric converters. Material compatibility was a major concern in the Romashka program. [redacted] the first Romashka never reached criticality because the materials reacted so poorly when the reactor was heated to operating temperature. [redacted] the Romashka that began operating in 1964 was actually the second Romashka. [redacted]

The design goal for Romashka was 1,000 hours of operation, but it actually accumulated 15,000 hours before being shut down for examination in 1966 (see figure 1). In 1977 [redacted] 25X1, E.O.13526 [redacted] a "new Romashka" had been developed. [redacted] 25X1, E.O.13526 [redacted] and the "new Romashka" was apparently the last. In the early 1970s, I. D. Morokhov published a paper describing a Romashka with a thermionic converter (see inset). The idea of a thermionic Romashka reappeared in a 1990 paper presented at the Seventh Symposium on Space Nuclear Power Systems, but this was nothing more than a revisit of the earlier 1970s concept. [redacted]

RORSAT. The Soviet RORSAT used a nuclear reactor to power a conventional, real aperture radar. The RORSAT was developed to locate and track US carrier battle groups. The relatively low-power radar limited the maximum RORSAT operational orbit to less than 300 kilometers (km). The Soviets have stated that a reactor was the only feasible power source for this satellite series. They claim that solar arrays capable of providing several kilowatts of electrical

Figure 1
Design Parameters of Romashka Reactor

Romashka Reactor



Characteristics	
Power level	
Thermal	28.2 kW
Electrical	0.46-0.475 kW
Reactor	
Core height	351 mm
Core diameter	241 mm
Moderator	None
Reflector	Beryllium
Coolant	None
Control	Four beryllium and boron control rods
Fuel	
Composition	Uranium dicarbide (UC_2)
Enrichment	90-percent uranium-235
Uranium mass	49 kg
Converter material	Silicon germanium (SiGe)
Operating temperature	
Core maximum	1,900° C
Converter hot-junction maximum	815° C
Converter cold-junction maximum	585° C
Total system mass	450 kg (without control-rod drive)
Specific mass	Over 980 kg/kW

[redacted] [redacted]

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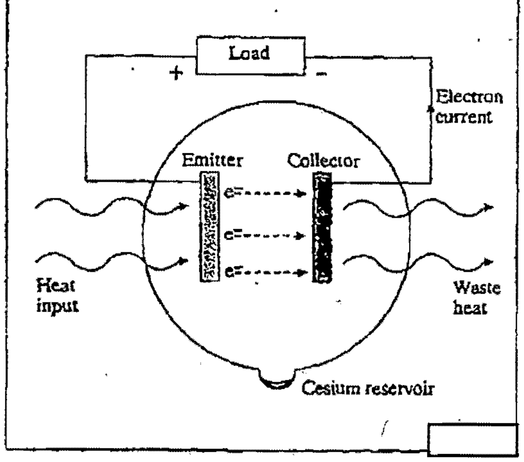
Thermionic Conversion

Thermionic Converter



Thomas Edison first observed the emission of electrons from a heated lamp filament. Heating metal increases the kinetic energy of conduction electrons. Electrons with kinetic energies greater than a value known as the work function may escape the surface of the metal. If a cooler metal surface is placed close to the hot surface, electrons "boiling off" the hot surface will condense on the cooler surface. The hot surface that emits the electrons is called the emitter, and the cooler surface that collects the electrons is called the collector. If a conducting path is provided between the emitter and collector, a current will flow. Filling gases are used in thermionic converters to neutralize the space charge that would otherwise build up around the emitter and retard the passage of electrons. Cesium vapor is the most common filling gas (see figure).

Thermionic converters are relatively inefficient devices (about 5 to 10 percent of the energy is converted to electricity), but they are more effective than thermoelectric converters and retain much of their ruggedness and simplicity. Thermionic converters can operate at a high-heat rejection temperature, which is particularly important in space applications, because the size of the radiator is inversely proportional to the fourth power of the temperature. Thus, thermionic reactors offer the possibility of comparatively high-conversion efficiency and a compact radiator, reducing overall system mass.

The technical challenge of a thermionic reactor using in-core converters is in the converter design and materials. The fuel elements are complex, and the emitter-collector spacing is typically about 0.5 millimeter. Properties of the emitters, collectors, and insulators must be maintained, despite having to operate at high temperatures in a high-radiation environment. Further, the emitter material must resist the tendency of the nuclear fuel to expand as the reactor operates.

power would have been so large that drag would have severely affected satellite stabilization and its lifespan.

The RORSAT used a fast reactor with liquid metal (sodium-potassium eutectic alloy) coolant and thermoelectric converters. Heat was dissipated by a radiator covering much of the forward portion of the satellite.

of Cosmos 626, 651, and 654 suggested a reactor thermal power of about 50 kilowatts thermal (kWt). However, analysis of debris from Cosmos 954 indicated the power was about 100 kWt. Other characteristics are given in figure 2.

The RORSAT's missions typically lasted about 65 days, although missions as short as eight days and as

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long as 136 days were observed (see table 1).[1] At the end of the mission, the reactor was shut down by ground command or by a preprogrammed automatic sequence, separated from the satellite, and boosted into a high orbit (about 800 km). If the boost was successful, the reactor would remain in orbit for about 300 years, allowing its radioactivity to decay to a safe level before reentry. If the boost did not occur, however, the highly radioactive reactor would reenter the atmosphere within a year or less. Because the Soviets recognized that if the boost was not successful the RORSAT reactor would reenter the atmosphere, they designed the reactor to break up on reentry, thereby dispersing the fuel by aerodynamic heating. Theoretical and experimental studies of RORSAT reactor breakup were described in a paper presented in 1991 at the Eighth Symposium on Space Nuclear Power Systems.

But when the RORSAT Cosmos 954 failed to boost itself into high orbit and reentered the atmosphere over Canada on 24 January 1978, radioactive debris—a few pieces with activities as high as 200 roentgens per hour—were spread over a large area. The contaminated area was uninhabited, but, if reentry had occurred over a populated area, radiation injuries, and possibly a few deaths, would have occurred. As a result, the Soviets added a backup safety system to the RORSAT. 25X1, E.O.13526 this backup system is automatically activated by the loss of radio contact or loss of satellite stability or by atmospheric heating when the satellite reaches an altitude of about 100 km. In addition, the reactor was modified so that the core was ejected about 50 minutes after the activation of either the primary or backup safety systems, whether or not the reactor had reached high orbit. Ejection of the core was intended to guarantee that the highly radioactive fuel was dispersed in the upper atmosphere by separating the reactor from structural and reflector material that might protect the fuel during reentry.

[1] RORSAT missions were not limited by the reactor's lifespan. The reactor on the malfunctioning Cosmos 1900 was still operating after 294 days, when the emergency backup system finally activated.

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Table 1
RORSAT Launch History

Mission	Cosmos	Launch Date	Launch Time (*Zulu*)	Days of Radar Operation
Propulsion tests	102	27 Dec 1965	2225	
	125	20 Jul 1966	0858	
Transfer maneuver tests	198	27 Dec 1967	1129	
	209	22 Mar 1968	0930	
	Failure [a]	25 Jan 1969	1114	
	Failure [a]	1 Nov 1969	1059	
	367	3 Oct 1970	1026	
	402	1 Apr 1971	1130	
Operational satellites	469	25 Dec 1971	1130	10
	516	21 Aug 1972	1036	32
	Failure [a]	25 Apr 1973	0910	
	626	27 Dec 1973	2020	46
Dual-system tests	651	15 May 1974	0730	72
	654	17 May 1974	0653	75
	723	2 Apr 1975	1100	3
	724	7 Apr 1975	1100	66
	785	12 Dec 1975	1245	
	860	17 Oct 1976	1807	24
	861	21 Oct 1976	1653	62
	952	16 Sep 1977	1425	21
	954 [b]	18 Sep 1977	1348	40
Post–Cosmos 954 missions	1176	29 Apr 1980	1140	134
	1249	5 Mar 1981	1809	106
	1266	21 Apr 1981	0345	8
	1299	24 Aug 1981	1637	12
	1365	14 May 1982	1928	136
	1372	1 Jun 1982	1358	71
	1402 [c]	30 Aug 1982	1006	121
	1412	2 Oct 1982	0002	40
	1579	29 Jun 1984	0028	90
	1607	31 Oct 1984	1229	93
	1670	1 Aug 1985	0536	83
	1677	23 Aug 1985	2234	61
	1736	21 Mar 1986	1005	92
	1771	20 Aug 1986	1258	55
	1860	18 Jun 1987	2133	40
	1900 [d]	12 Dec 1987	1421	120
	1932	14 Mar 1988	1421	66

[a] Spacecraft did not achieve orbit; therefore, it is not given Cosmos designation.
[b] Cosmos 954 reentered over Canada on 24 January 1978.
[c] Cosmos 1402 reentered over the Indian Ocean on 23 January 1983.
[d] Cosmos 1900 backup safety system activated on 1 October 1988.

This table is .

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The core successfully separated from Cosmos 1402 after it failed to boost itself into high orbit and reentered the atmosphere on 23 January 1983. The last RORSAT safety system failure was in 1988: this time the backup system of Cosmos 1900, triggered by atmospheric heating, successfully boosted the reactor to high orbit. There have been no RORSAT launches since Cosmos 1900 malfunctioned. Considerable international concern over the malfunctioning of Cosmos 1900, and subsequent statements by Soviet scientists, suggest Soviet safety requirements have been changed to preclude the operation of reactors in low Earth orbit. [redacted]

Radioisotope Thermoelectric Generators

Radioisotope thermoelectric generators (RTG) are composed of a nuclear heat source and thermoelectric power conversion equipment. Unlike a reactor, where fissioning uranium is the heat source, the heat source for an RTG is radioactive decay of an artificially produced unstable isotope. In 1964 the Soviets launched an "Orion" RTG on Cosmos 84. A second RTG followed on Cosmos 90. The "Orion" was a short-lived RTG using a polonium-210 heat source (138-day half-life). These technology demonstration flights are the only known use of RTGs in space by the Soviets. The Soviets did use radioisotope heat sources to warm critical equipment on the Lunokhod moon rovers in 1969 and 1973, but the RTG program was basically dormant for 25 years. [redacted]

In 1990, Soviet scientists blamed their lack of progress in RTG development for space applications on inadequate funding. Recently, the Soviets decided to again use RTGs in space. Small RTGs are being developed for use on two satellites of the Regatta program, which will study the affect of solar activity on the environment, scheduled for launch in about 1995. The RTG will provide an autonomous power source for the satellite data and control unit. Small RTGs may also be used on the "small space laboratory" satellites planned for about the year 2000. Work on larger RTGs is faltering. [redacted]

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[redacted]

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Thermionic Energy Conversion

Steps leading to the development of thermionic reactors began in 1958 at the Institute of Physics and Power Engineering (FEI), Obninsk. In-reactor tests of thermionic converters began in 1961. [redacted] 25X1, E.O.13526 competing programs to build thermionic space reactors began in 1965. The TOPAZ design, which originated in Obninsk, featured a reactor using multicell thermionic fuel elements (TFE). (TOPAZ is the Russian acronym for "thermionic conversion in the reactor core" or "*termoemissionnyy opytnyy preobrazovanie v aktivnoy zone*.") The Yenisey design, which originated in the Central Design Bureau for Machine Building in Leningrad (now St. Petersburg), featured single-cell TFEs. Initially, these were alternate versions of the same project, but the programs quickly became separate. Initial work on the TOPAZ was funded by the Soviet Navy, possibly for eventual use in submarine detection. The Yenisey reactor was originally to power a geostationary civilian communications satellite. Later, [redacted] the military took over the Yenisey reactor. Potential military missions for the Yenisey included powering an aircraft surveillance radar satellite and a military communications satellite. A lifespan of 10,000 hours at a power of at least 5 kWe was required. Unlike TOPAZ, Yenisey was a highly classified program. [redacted]

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TOPAZ. In 1970 the first prototype TOPAZ reactor became operational at the FEI in Obninsk. This reactor was shut down in 1971, after 1,300 hours of operation at power levels up to 7.2 kWe. A second TOPAZ prototype became operational in 1972 at Obninsk. This reactor operated for 5,000 hours but reportedly produced electricity for only 1,600 hours. A third TOPAZ prototype became operational in March 1973 and generated electricity for 2,760 hours. [redacted]

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Table 2
Soviet RTGs Developed for Use on Satellites of the Regatta Program

	Electrical Power (*watts*)	Weight (*kilograms*)	Specific Power (*watts/ kilograms*)
RTG-238-0.02/12	0.02	0.5	0.04
RTG-238-0.3/7	0.3	2.0	0.15
RTG-238-3/7	3.0	5.0	0.6

[redacted]

The prototype TOPAZ reactors were zirconium hydride moderated, liquid metal cooled, and fueled with uranium dioxide enriched to 90 percent uranium-235. The reactors used 79 TFEs, each containing five converters. The TFEs were connected in a series-parallel arrangement with six circuits in the outer section and an auxiliary section of 19-parallel, connected TFEs in the center dedicated to the electromagnetic coolant pump. Reactor control was accomplished by using rotating drums with absorber sections in the reflector. [redacted]

Although early TOPAZ reactor performance was satisfactory, TFE performance was, at best, marginal. Efficiency levels were lower than expected. Poisoning of emitter surfaces by trace impurities caused electrical power to decrease with time. Mass transfer of emitter material to the insulators and fuel swelling decreased internal resistance of the interelectrode gap, causing short circuits. Clearly, materials problems severely limited the lifespan and thus the potential utility of the TOPAZ prototypes. [redacted]

The TOPAZ prototypes were followed by a fourth reactor installed in the TOPAZ facility at the FEI. Two types of emitters were tested: tungsten-coated single-crystal molybdenum and uncoated single-crystal molybdenum. According to a paper presented in May 1990 at the Obninsk conference on nuclear power engineering in space, the reactor operated for 5,000 hours and produced up to 9 kWe. Tests were completed in 1978, but the results have never been published, and the existence of this reactor was not revealed until 1990. [redacted]

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[redacted] as of July 1977 the TOPAZ program was complete, and the Soviets were capable of "flying" a nuclear thermionic converter. However, automatic startup of a prototype TOPAZ reactor was not achieved until 1979. This was followed in the period 1982-84 by two tests of flight-system prototypes. The first prototype, which used single-crystal molybdenum emitters covered with single-crystal tungsten, was tested for 4,500 hours. The second prototype, which used single-crystal molybdenum emitters, operated for 7,000 hours. These tests were followed by orbital tests of two thermionic reactors. [redacted]

Cosmos 1818 and Cosmos 1867. On 1 February 1987 the Soviets launched the first thermionic reactor into space on Cosmos 1818. This was followed on 10 July 1987 by a second reactor on Cosmos 1867. Unlike the RORSAT, these reactors operated in the 800-kilometers orbit, and so no end-of-life orbital transfer maneuver was required. Cosmos 1818 operated for 143 days, and Cosmos 1867 operated for 342 days. [redacted]

Beginning in 1989, the Soviets revealed a number of details about the flight tests of the two reactors. The reactor is now referred to as TOPAZ-I. It used the TOPAZ multicell TFE design. The reactor on Cosmos 1818 used single-crystal molybdenum emitters, and the reactor on Cosmos 1867 used an emitter of single-crystal molybdenum coated with a layer of single-crystal tungsten. The lifespan of both reactors was limited by the amount of cesium carried (2.5 kg). Cosmos 1867 operated longer because the optimum cesium pressure for tungsten emitters is lower. No attempt was made to recycle cesium, which passed through the reactor and was vented to space through a zero-thrust nozzle. According to Soviet statements, there was no design requirement for a long life for the TOPAZ-I system. Had the supply of cesium not been limiting, loss of hydrogen from the zirconium hydride moderator would have limited life to about two years. Characteristics of the TOPAZ-I reactor are given in figure 3. [redacted]

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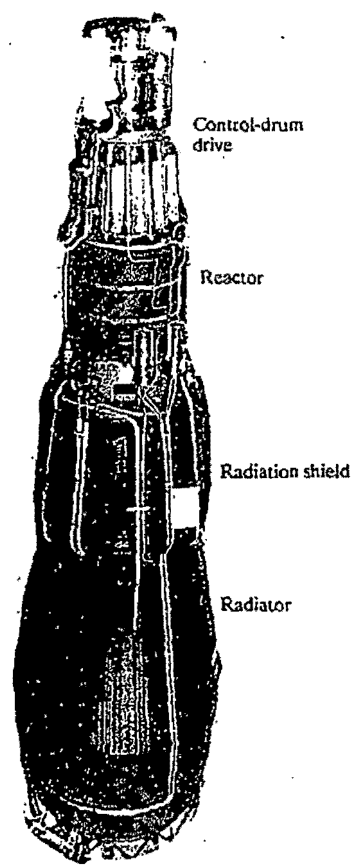
Figure 3
Design Parameters of TOPAZ-I Reactor

TOPAZ-I Reactor



Characteristics	
Power level	
Thermal	About 150 kW
Electrical	About 5 kW
Reactor	
Moderator	Zirconium hydride
Reflector	Beryllium
Coolant	Sodium potassium alloy
Control	12 beryllium control drums with boron insert
Fuel	
Composition	Uranium dioxide
Enrichment	90-percent uranium-235
Uranium mass	12 kg
Thermionic fuel	
Element	
Number	79
Emitter	
Cosmos 1818	Single-crystal molybdenum
Cosmos 1867	Single-crystal molybdenum coated with single-crystal tungsten
Collector	Niobium
Insulator	Beryllium oxide
Number of converters	Five per TFE
Gas	Cesium
Coolant	Sodium potassium eutectic
Pump	Conduction-type electromagnetic
Power required	1,200 amps at 1.1 V
Pump efficiency	About 11 percent
Radiator area	7 sq m
Weight	1,200 kg
Specific mass	About 240 kg/kWe

[redacted]

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Soviet scientists claim that Cosmos 1818 and Cosmos 1867 were primarily reactor tests. [redacted] 25X1, E.O.13526 [redacted] the TOPAZ-I flights were intended to verify reactor suitability for use as a power source for satellites designed to monitor US submarines. Flight tests of TOPAZ-I were successful, but the Yenisey (TOPAZ-II, see figure 4) reactor won the competition. The TOPAZ-I production program was terminated, and two space reactors that had been completed are for sale. [redacted]

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Yenisey (TOPAZ-II) 25X1, E.O.13526 the first complete test of the Yenisey reactor occurred in 1973. Unlike TOPAZ-I, the Yenisey can be fully tested in a nonnuclear mode by inserting tungsten heaters into the TFEs in place of the nuclear fuel pellets. Nonnuclear tests continued up to 1982 in

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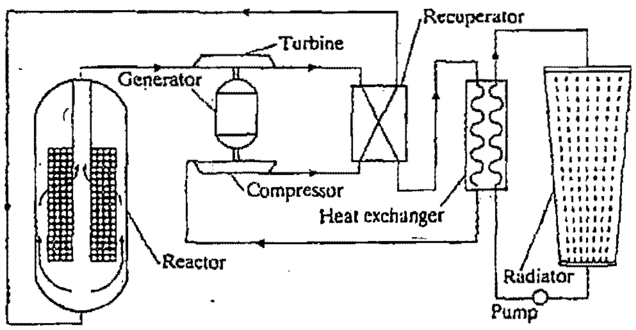
Figure 5
Brayton-Cycle System



A Brayton-cycle system is simply a closed-cycle gas turbine with a nuclear heat source and a gaseous working fluid, typically helium or xenon. Most such systems utilize a heat exchanger called a recuperator to increase efficiency.

The motive for switching to a dynamic power conversion system is to increase efficiency over static conversion systems. A Brayton-cycle system would typically have an efficiency of 20 to 30 percent.

vacuum test stands in Leningrad (now St. Petersburg). The total number of tests is unknown, but the engineer claims that between 1975 and 1980 at least seven test reactors were produced and that by 1982 three or four test reactors were built each year. The existence of the Yenisey reactor was revealed in 1990 at the Seventh Symposium on Space Nuclear Power Systems. During the presentation, Ponomarev-Stepnoy, apparently not having approval to reveal the classified name, stumbled over what to call the reactor. A US scientist volunteered the name TOPAZ-II, which the Soviets have used ever since.

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The cesium supply still limits ultimate life to about three years, but the Soviets have designs for a circulating cesium system and estimate that the ultimate limit on the operating lifespan of the TOPAZ-II is in the five- to seven-year range.

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Brayton-Cycle Conversion

the bulk of Soviet work on electric power production in space has focused on thermionic energy production. However, work on closed-cycle Brayton systems for higher power applications is also being conducted (see figure 5).

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The principal fuel-element test facility is the 400-kilowatt RA reactor. Key technical characteristics of the reactor are shown in figure 6. Sketches shown in 1990 at Obninsk and in 1991 at Los Alamos, New Mexico, indicate the reactor is air-cooled; the cooling air mixes with heated inert gas from the test channels and then exhausts directly to the atmosphere. This design precludes the use of the reactor for turbine tests, consistent with Soviet statements that complete Brayton-cycle systems have not been run in a nuclear mode.

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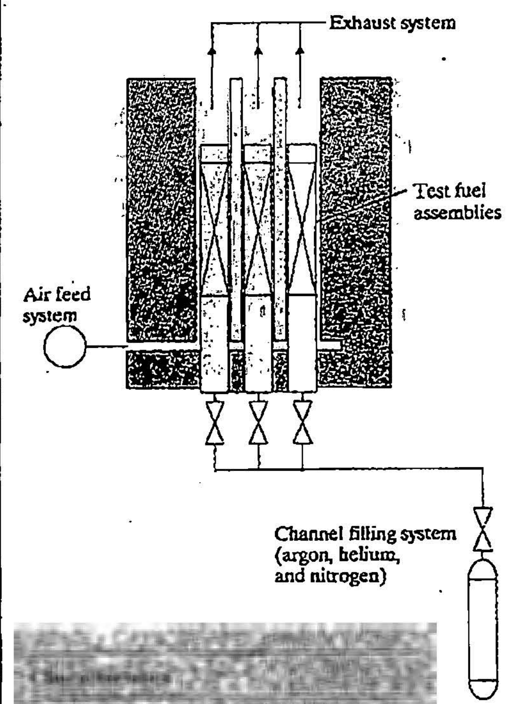
Figure 6
RA Reactor and Characteristics

RA Reactor



[redacted]

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Figure 7
Brayton-Cycle Developments

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Space Nuclear Propulsion Technology

Nuclear Electric Propulsion

The USSR first used electric propulsion in 1962 on Zond-2, which used pulsed magnetoplasmadynamic (MPD) thrusters for satellite orientation. This was followed in 1971 by tests of a steady state MPD thruster on a Meteor satellite.

25X1, E.O.13526

Today, the Soviets claim to routinely use xenon propellant MPD thrusters on satellites.

25X1, E.O.13526

Nuclear energy is the only practical source of power for large thrusters. The Soviets have discussed using nuclear-powered electric propulsion systems, requiring from tens of kilowatts for orbital maneuvering to tens of megawatts for both manned and unmanned spaceflights to Mars.

25X1, E.O.13526

However, work on space propulsion is focusing on the more sophisticated MPD technology.

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Nuclear Rockets

Soviet research on nuclear rockets began in the late 1950s.

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Space Nuclear Propulsion Technology

Electric Thrusters

Electric thrusters are low-thrust, very-high-specific-impulse (I_{sp}) engines. Types of thrusters include:

- *Arcjet-propellant gas flows through and is heated by an electrical arc. I_{sp} is generally greater than 1,000.*
- *Magnetoplasmadynamic current flowing through ionized propellant gas in a coaxial thrust chamber interacts with a magnetic field to produce thrust. I_{sp} is greater than 1,500.*
- *Ion engine-propellant atoms are ionized, and the resultant ions are accelerated to high velocities by an electrostatic field. The exhaust beam is neutralized by electron injection. I_{sp} is greater than 3,000.*

Nuclear Rockets

Nuclear rockets use energy from fission to heat up a low-molecular-weight propellant, usually hydrogen, which is expanded through a nozzle to produce thrust. A nuclear rocket with solid fuel can attain an I_{sp} of between 850 and about 1,000. If fissioning plasma could be used as a heat source in a nuclear rocket, an I_{sp} of roughly 2,500 is attainable.

Solid-Core Nuclear Rocket Development. Testing of developmental fuel for solid-core nuclear rockets began in 1962.

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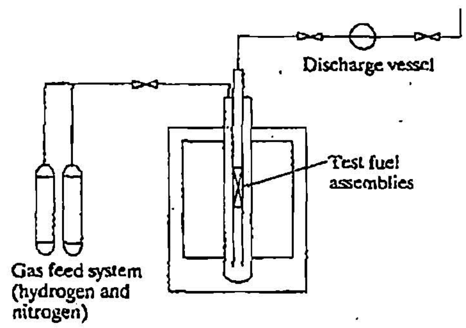
Figure 8
Pulse Graphite Reactor



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The Soviets have focused their efforts on developing and testing nuclear rocket fuel.

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Gas-Core Nuclear Rockets. The Soviets have been discussing gas-core reactor concepts since the 1950s, but the effort has remained at the concept stage. The principal proponent in recent years was V. M. Iyevlev, who headed the Division for Nuclear Rocket Engines at the NIITP until his death in 1990. The scheme favored since the inception of the program is a cavity-type reactor using a magnetic field to confine the fissioning plasma. Heat is transferred to the hydrogen by radiation—a process enhanced by alkali metals seeded in the coolant to increase optical density. Over the years, numerous experiments have been performed on the mixing of gas jets, the effect of acoustic vibrations on criticality, and the stability of uranium hexafloride (UF_6) in a reactor. Except for an experiment years ago demonstrating that a UF_4-fueled reactor was practical, all known work has involved surrogate materials, such as Freon and liquid metals, rather than fissile material. In 1983 the program was reportedly canceled because the projected development cost and risk outweighed the potential benefit. However, it is now clear that Iyevlev and other proponents kept a small research effort alive. According to a paper presented at Obninsk in May 1990, the NIITP in 1991, in cooperation with the IAE, will attempt to create a uranium plasma in the center of a stream of flowing hydrogen in the IGR reactor. Researchers hope to briefly achieve a plasma temperature of 8,000 to 9,000 K and obtain, for the first time, data to validate theoretical models.

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Prospects and Missions for Soviet Space Nuclear Power

Near-Term, Low-Power Missions

The Soviets have the capability to launch low-power space reactors at any time. Soviet scientists have stated that there are two TOPAZ-I and six TOPAZ-II reactors available. These almost certainly include the TOPAZ-II reactor exhibited in Albuquerque, New Mexico, in 1991 at the Eighth Symposium on Space Nuclear Power Systems. There is also an unknown number of RORSAT reactors available. [redacted]

There are no obvious missions, however, for reactors of this power class. Although there are probably RORSATs available for use should a crisis arise, there have been no launches since Cosmos 1900 malfunctioned in 1988. Within the last year, Vyacheslav Balebanov, a Deputy Director of the USSR's Space Research Institute, and Ponomarev-Stepnoy have both stated that there are no plans to orbit another nuclear-powered spacecraft until after the year 2000. Production of TOPAZ-I reactors has ceased. TOPAZ-II components continue in production, but Soviet Government funding has become erratic, and a major portion of funding for the TOPAZ program has come from the IAE's budget, rather than being funded directly. Soviet scientists hope to sell at least one TOPAZ-II reactor to the United States, believing that a sale would provide impetus for further Soviet funding of the program. [redacted].

It is not surprising that the Soviets have been hard pressed to suggest missions for TOPAZ-II. The low power and short design life limit and provide little, if any, advantage over solar arrays. Instead, the Soviets emphasize the potential for TOPAZ variants with much higher power, power that only a nuclear system could provide. Soviet concept papers have discussed TOPAZ variants with powers of 50 to 80 kWe. While such a system might be possible, size and mass considerations probably limit TOPAZ-type thermal reactors to 20 kWe or possibly 30 kWe. Fast reactors are much more attractive for higher power systems. Soviet concept papers discuss lithium-cooled multicell TFE fast reactors producing 100 kWe to 2.5 MWe. But the Soviets have yet to test the multicell TFE designs being developed for use in a fast reactor. When considering system size and mass, Brayton-cycle systems would also be very competitive at higher powers. It is unlikely that a thermionic fast reactor or a Brayton-cycle system would be ready for space use in this decade, even if the Soviets were not having funding problems. [redacted]

High-Power Missions and Nuclear Rockets

Mars Mission. Providing propulsive power for manned and unmanned missions to Mars has been the focus of Soviet public efforts to develop both nuclear rockets and large nuclear-electric propulsion systems. In the late 1980s, the Soviets selected manned flight to Mars as one of the new S&T programs to be funded during the 13th Five-Year Plan (1991-95). [redacted] **25X1, E.O.13526** [redacted]

Recent concept papers envision the earliest mission to be in the year 2018, when the relative positions of Earth and Mars minimize travel time. Because of their reported success in developing and testing nuclear fuel elements, this is a realistic goal for a well-funded, organized program. For the last few years, however, Soviet scientists have complained that they had not received the financial resources necessary to proceed from technology development to integrated system development. Rather, they claimed, support for space programs is diminishing. Environmental concerns have precluded fuel-development testing at Semipalatinsk since 1985. According to Ye. O. Adamov, Director of the NIKIET, a new space-reactor test facility is being considered on Novaya Zemlya, but construction of such a facility well north of the Arctic Circle would be difficult and expensive. Further, [redacted] **25X1, E.O.13526** [redacted] Adamov had decided to deemphasize space nuclear propulsion in order to use the funds for research on next-generation power reactors. Smetannikov added that the consensus among NIKIET scientists was that the space nuclear propulsion program would eventually be canceled unless it received Western investment. [redacted] **25X1, E.O.13526**

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[redacted] 25X1, E.O.13526 [redacted] that funding for development of a large nuclear rocket engine was approved in mid-1991. The scientist claimed that the effort would receive 3-8 billion rubles per year. [redacted]

Other Potential Missions. One potential application for a nuclear rocket is a reusable orbital tug, a role the Soviets currently are promoting for an upgraded TOPAZ reactor coupled to an electric propulsion unit. Although a nuclear rocket requires more propellant than a nuclear-electric system, its much higher thrust provides a time advantage—a few hours from low Earth orbit to geostationary orbit rather than the year or so required for a nuclear-electric propulsion system. Time is important, not only in getting the satellite into use but also in reducing the time spent in the Earth's radiation belts. The Soviets, however, will have to weigh the cost advantages of a reusable tug against concerns about the possible reentry of a reactor from low Earth orbit. The Soviets apparently are not very serious about orbital tugs using existing TOPAZ technology, unless another country volunteers to fund the project. Thus, it is most unlikely that they are looking seriously at nuclear rockets for this application. [redacted]

Potential military uses of nuclear rockets might include direct-ascent antisatellite (ASAT) systems and antiballistic missile (ABM) defense interceptors. [redacted] the Soviets were unlikely to pursue these applications, as the combination of nuclear safety issues and daunting development costs outweighed any advantages offered by nuclear propulsion. A key part of this evaluation was based on the fact that the Soviets already have ASAT systems and an ABM system. Thus, nuclear propulsion would improve only incrementally an existing capability, rather than creating a capability. [redacted]

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Appendix

Rocket Propulsion Technology—A Primer

The thrust produced by any rocket is determined to a large extent by the exhaust velocity, which is proportional to the square root of the ratio of the exhaust gas temperature at the entry to the nozzle and the molecular weight of the exhaust gases. In a conventional bipropellant chemical rocket, fuel and oxidizer are burned in a combustion chamber and expelled through a nozzle. The best available fuel-oxidizer combination is hydrogen-oxygen, which burns, producing water with a molecular weight of 18. A nuclear rocket is potentially capable of reaching higher operating temperatures and uses hydrogen, with a molecular weight of 2, as a propellant. This difference in molecular weight means that for the same exhaust temperature a nuclear rocket will have three times the exhaust velocity of a hydrogen oxygen rocket engine.

The simple fact that the operating temperature of the fuel and structural components of a solid-core rocket cannot exceed the material's melting point limits the maximum propellant temperature to a little over 3,000 Kelvin (K). This inherent limit led scientists to look at designs in which the fuel was a plasma. Adding incentive to this effort is that as hydrogen temperatures exceed about 4,000 K the molecules begin to dissociate. At the gas temperatures suggested for plasma-core nuclear rockets, the propellant is fully dissociated hydrogen with a molecular weight of 1—yielding a potential performance more than four times greater than a hydrogen oxygen engine. However, a key difficulty of any plasma-core scheme is finding an effective means of keeping the plasma and propellant separate. Despite years of research, a suitable containment scheme has not been developed, and, for theoretical reasons, the prospects are poor.

Rocket engine performance is often characterized by a parameter called the specific impulse (I_{sp}), defined as the ratio of the thrust generated per unit flow rate of propellant. A hydrogen oxygen chemical rocket—theoretically the most efficient chemical engine—typically has an I_{sp} of about 425 seconds. In contrast, a solid-core nuclear rocket could have an I_{sp} of 1,000 seconds, and a plasma-core nuclear rocket an I_{sp} of 2,500 seconds. Electric thrusters produce an I_{sp} in the range of 1,500 to over 10,000 seconds.