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The Soviet Space Nuclear Power Program

A Research Paper

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Directorate of Intelligence

The Soviet Space Nuclear Power Program

A Research Paper

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The Soviet Space Nuclear Power Program

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 [ ].

If the need arose, the USSR has the capability to use low-power reactors in space at any time. [ ].

Efforts to develop higher power output space reactor systems [ ] have 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

Within 10 years the Soviets could produce a thermionic reactor with [ ] Research is under way that could lead to fast reactors using in-core multicell thermionic converters and gas-cooled reactors coupled to turbines [ ].

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

Contents

	Page
Summary	iii
Introduction	1
Space Electrical Power Generation	1
Thermoelectric Energy Conversion	1
Romashka	1
RORSAT	2
Radioisotope Thermoelectric Generators	6
Thermionic Energy Conversion	6
TOPAZ	6
Cosmos 1818 and Cosmos 1867	7
[ ] (TOPAZ-II)	9
Brayton-Cycle Conversion	10
Space Nuclear Propulsion Technology	13
Nuclear Electric Propulsion	13
Nuclear Rockets	13
Solid-Core Nuclear Rocket Development	13
[ ]	17
Gas-Core Nuclear Rockets	17
Prospects and Missions for Soviet Space Nuclear Power	18
Near-Term, Low-Power Missions	18
High-Power Missions and Nuclear Rockets	18
Mars Mission	18
Other Potential Missions	21

Appendix	
Rocket Propulsion Technology—A Primer	23

Insets	
Thermoelectric Conversion	1
Thermionic Conversion	3
Space Nuclear Propulsion Technology	13

Tables

1.		5
2.	Soviet RTGs Developed for Use on Satellites of the Regatta Program	7

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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 [ ] 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) [ ] 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

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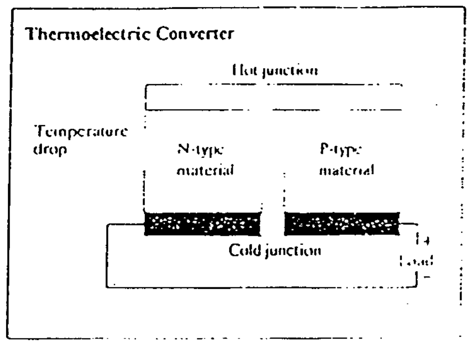
Thermoelectric Conversion



*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 * 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 application.*

** 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).*

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.

the first Romashka never reached criticality because the materials reacted so poorly when the reactor was heated to operating temperature.

the Romashka that began operating in 1964 was actually the second Romashka.

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).

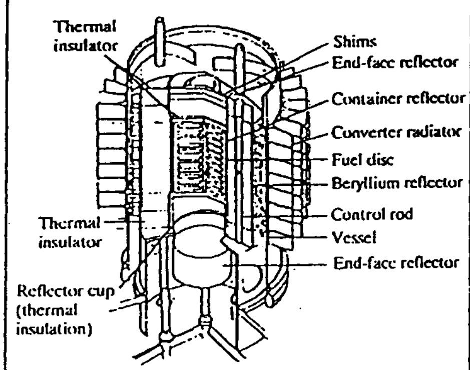
In the early 1970s, I. D. Morokhov published a paper describing a Romashka with a thermionic converter (see inset). The idea of a thermionic Romashka reappeared in a 1990 paper presented at the Seventh Symposium on Space Nuclear Power Systems, but this was nothing more than a revisit of the earlier 1970s concept.

RORSAT.

. 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

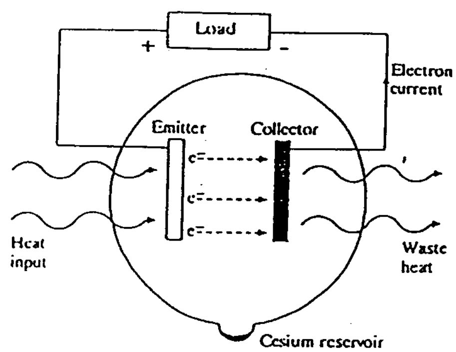
Romashka Reactor



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

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 mas

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 operate

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

The RORSAT used a fast reactor

Heat was dissipated by a radiator covering much of the forward portion of the satellite

At the end of the mission, the reactor was shut down

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

[1] RORSAT missions were not limited by the reactor's lifespan. The reactor on the malfunctioning Cosmos 1900 was still operating after 204 days, when the emergency backup system finally activated.

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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). [redacted]

[redacted] 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]

[redacted] 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]

[redacted] Characteristics of these RTGs are listed in table 2.

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]

[redacted] 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 [illegible] preobrazovanie v aktivnoy zone*.") [redacted]

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 1,500 hours. A third TOPAZ prototype became operational in March 1973 and generated electricity for 2,760 hours. [redacted]

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]

[redacted] early TOPAZ reactor performance was satisfactory [redacted]

The TOPAZ prototypes were followed by a fourth reactor installed in the TOPAZ facility at the FEI. [redacted]. 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

[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 [redacted].

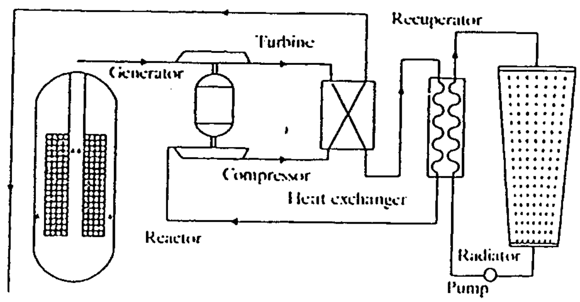
Beginning in 1989, the Soviets revealed a number of details about the flight tests of the two reactors. The reactor is now referred to as TOPAZ-I. [redacted] The lifespan of both reactors was limited by the amount of cesium carried (2.5 kg). [redacted] No attempt was made to recycle cesium, which passed 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. [redacted]

Soviet scientists claim that Cosmos 1818 and Cosmos 1867 were primarily reactor tests

Flight tests of TOPAZ-I were successful.

The TOPAZ-I production program was terminated, and two space reactors that had been completed are for sale.

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.

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 sinc

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.

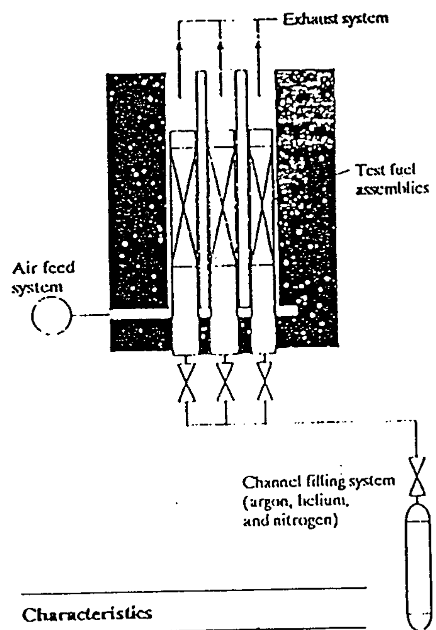
Brayton-Cycle Conversion

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).

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.

Figure 6
RA Reactor and Characteristics

RA Reactor



Characteristics

Startup	1985
Reactor thermal power	Up to 400 kW
Number of fuel assemblies	37
Power per assembly	Up to 10 kW
Exit gas temperature	Up to 2,000 K

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.

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

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.

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

Nuclear Rockets

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

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

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

[redacted]

[redacted]

[redacted]

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 [redacted] 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 model

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. [redacted]

There are no obvious missions, however, for reactors of this power class. [redacted] 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.

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 [redacted]

[redacted] 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

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]

Recent concept papers envision the earliest mission to be in the year 2018, when the relative positions of Earth and Mars minimize travel time [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

Potential military uses of nuclear rockets might include direct-ascent antisatellite (ASAT) systems and antiballistic missile (ABM) defense interceptors.

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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 second