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ABSTRACT

The Soviet Union has been flying nuclear power sources in space since about 1965. For the most part these nuclear power sources have been low-power nuclear reactors using a thermoelectric conversion principle. Recently the Soviet Union has flown two satellites using a higher power reactor that employs a thermionic conversion system. Reentry of two of the earlier reactors on board Cosmos 954 and Cosmos 1402 plus the recent potential accident involving Cosmos 1900 have focused world attention on Soviet usage of space nuclear power. Despite these problems the evidence points toward a continued Soviet usage of nuclear power sources in space.

INTRODUCTION

The reentry over Canada of the Soviet radar ocean reconnaissance satellite (RORSAT) known as Cosmos 954 on 24 January 1978 focused world attention on the Soviet Union's use of nuclear power in space. While Soviet specialists had publicly admitted in the 1960s that they were working on space nuclear reactors, little was known of their actual use. In view of the paucity of Soviet information it is appropriate to assemble what little information is publicly available on the Soviet space nuclear power program.

The Soviet Union has been a steady user of nuclear power in space beginning with their first publicly identified launch in 1965 (four years after the first U. S. launch of a nuclear power source). Whereas the U. S. has tended toward the use of nuclear power on civilian missions, especially on space systems operating on the Moon or beyond Earth orbit, the Soviets have primarily confined their activities to military missions operating in low Earth orbit (LEO). With one exception, the U. S. has used radioisotope thermoelectric generators (RTGs) on its nuclear-powered spacecraft. (The one exception was the SNAP-10A reactor flown in 1965.)[1] It must be emphasized again that very little is publicly known about the Soviet space nuclear power program because, unlike the U. S., they do not publish in the open literature information on the space nuclear power sources they are flying. Thus, what follows on the Soviet program is based largely on speculation.

This paper summarizes the open literature information on the soviet space nuclear power program, including the "Romashka", "Topaz", the new reactor based on the Topaz program, and the RORSAT reactor experience. A more extensive summary has been prepared for later publication.

SOVIET SPACE REACTOR PROGRAM

The following sections provide an overview of the Soviet space reactor program, beginning with the known reactor programs (Romashka and Topaz) and then discussing what can be inferred from the RORSATs.

Romashka

Figure 1 is a cutaway drawing of Romashka (Camomile), which was unveiled in 1964 at the Third U. N. Conference on the Peaceful Uses of Atomic Energy. Figure 2 depicts one of the UC_2 fuel disks. In many respects Romashka looks like a reactor analog of an RTG in that the heat generated in the core is converted directly to electricity without flowing coolant or rotating machinery. In this respect Romashka resembled the U. S. SNAP 10 reactor which was abandoned in favor of SNAP-10A in order to remove the thermoelectric elements from the vicinity of the core and to provide the ability to deal with planned future temperature increases needed to improve performance.[2,3] Table 1 compares the design features of SNAP-10A and Romashka.

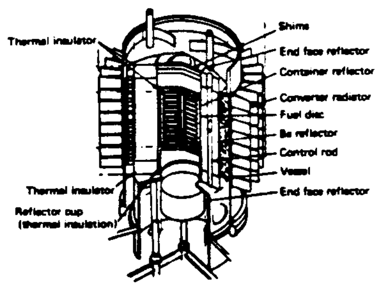

Figure 1. Cutaway view of an early ground-based Romashka reactor showing 11 fuel disks.

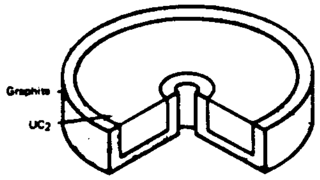

Figure 2. Cutaway view of a Romashka fuel disk.

TABLE 1

COMPARATIVE DESIGN FEATURES OF SNAP-10A AND ROMASHKA[2,7,15]

FEATURES	SNAP-10A	ROMASHKA
Thermal Power	34 - 45.5 kWt	40 kWt
Thermal Energy Produced	44,000 kWt-h (SNAPSHOT) 382,944 kWt-h (FS-3)	~600 kWt-h
Electrical Power	0.54-0.65 kWe	0.5-0.8 kWe
Fuel Material	U-ZrHx	UC_2
Core Loading of ^{235}U	4.3 kg	49 kg
Mass	435 kg (shielded)	455 kg (unshielded)
Enrichment of Fuel	>90% ^{235}U	90% ^{235}U
Reflector Material	Be	Be
Coolant	NaK	(Conduction)
Temperatures		
Core, maximum	858 K	2173 K
Hot Junction	774 K	1253 K
Base of Radiator, average	588 K	823 K
Differential across converter	152 K	~315 K
Neutron Spectrum	Thermal	Fast
Average Flux	1.7×10^{11} n/cm^2-s	~9×10^{12} n/cm^2-s
Converter Characteristics		
Material	SiGe	SiGe
Figure of Merit	0.58×10^{-3}/K	N/A
Material Efficiency	9.4%	N/A
Overall Efficiency	~1.3%	~1.5%
Working Voltage	~30V	1.6V/section

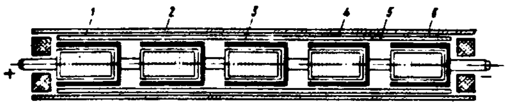

Figure 3. Basic arrangement of the TOPAZ thermionic fuel element (TFE): 1) fuel pellet; 2) emitter; 3) collector; 4) interelectrode gap; 5) collector insulation; 6) sheath.

Topaz

In several papers and press releases dating from 1971, Soviet authorities cited the existence of a thermionic reactor program known as "Topaz" (signifying thermionic, experimental, conversion in the active zone). At least three versions of Topaz were tested. The first reactor tests on a single thermionic converter were reportedly carried out even earlier in April 1961.[4,5,6]

Like Romashka, Topaz was a direct conversion nuclear power source with no moving parts. The thermionic converter was combined with the fuel element as shown in Figure 3 to produce a single power-generating channel ("power channel"). The power channels included urania fuel, cathodes made from a tungsten alloy or the molybdenum alloy VM-1, anodes made from the niobium alloy VN-2, beryllia insulators, stainless steel outer casings and cesium vapor in the interelectrode gap. Figure 4 shows a cutaway of the Topaz reactor showing the principal subsystems and design features.[4,7]

Referring to Figure 4, Soviet specialists have described Topaz as comprising ". . . a set of channel converters (8) arranged in a moderator (3) and defining the reactor core. The reactor control is effected by means of rotatable cylinders (7) of boron carbide arranged in a beryllium reflector (4). The profiling of fuel and moderator helps attain a high radial uniformity of energy generation. The plant is provided with caesium delivery (1) and removal (5) devices, coolant (2), commutation chamber (11) and current leadouts (10). All this is housed in a single body (9) and results in an adequately compact arrangement . . ."[7]

Table 2 lists the publicly known design features of the Topaz thermionic reactor system.

The Soviets have recently announced that they have flown two 5-Mg Cosmos satellites powered by 10-kWe reactors based on the Topaz design albeit with a reported two-fold improvement over Topaz.[6,8,9,10] Reportedly one of the reactors ". . . successfully functioned in orbit for six months and the second one for a year".[8] It is widely believed that these satellites were Cosmos 1818 and Cosmos 1867, which were launched on 1 February 1987 and 10 July 1987 respectively and are rumored to be a new generation of ocean surveillance satellite.[9,10,11,12] Additional information reported by the Soviets may be found in Table 3.[6,10]

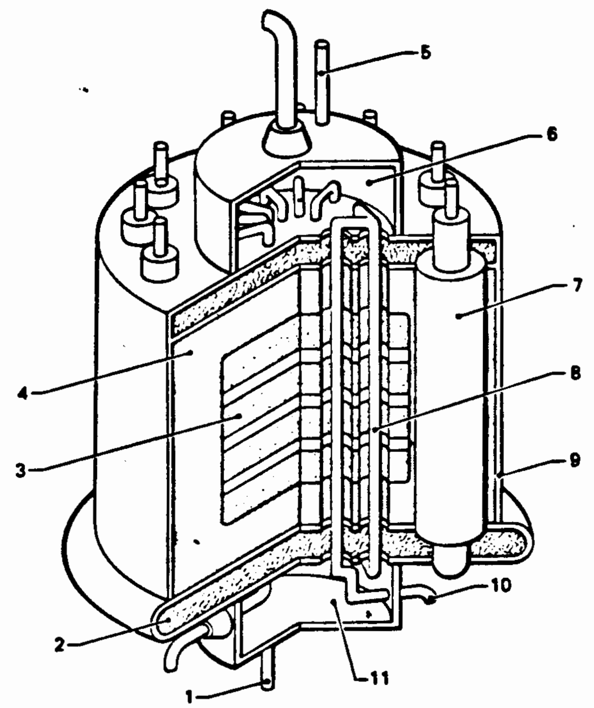

Figure 4. Configuration of the TOPAZ reactor.

TABLE 2

DESIGN FEATURES OF THE TOPAZ THERMIONIC REACTOR SYSTEM[4,5,6]

Parameter	Value
Thermal Power	130 - 150 kWt
Electrical Power (maximum)	5 -10 kWe
Fuel Material	UO_2
Fuel Loading (^{235}U)	12 kg
Enrichment of Fuel	~90% ^{235}U
Moderator	ZrH
Neutron Spectrum	Thermal
Reflector	Be
Reactor Mass	320 kg
Core Diameter	0.3 m
Core Length	0.4 m
Reflector Thickness	0.08 m
Control Drums	12 Rotary, Be with B_4C backing
Coolant	NaK
Converter Characteristics	
Efficiency	4 - 7 %
Number of Converters	5 (of variable length) per TFE, totaling 395
Emitters	Mo or W (may be W-coated Mo)
Collectors	Nb
Emitter Temperature	~1725 K
Collector Temperature	~ 925 K

TABLE 3
SUMMARY OF CHARACTERISTICS OF TOPAZ-TYPE REACTORS FLOWN ON COSMOS 1818 AND COSMOS 1867[6,8,10]

Electrical Power	~10 kWe
Conversion System	~80 in-core thermionic fuel elements (TFEs)
Emitter Temperature	~1875 K
Collector Temperature	~800-875 K
Efficiency	5 - 10%
Fuel Material	Urania (hollow geometry)
Uranium-235 Enrichment	90%
Uranium-235 Loading	~12 kg
Moderator	Zirconium Hydride
Cooling System	Pumped loop radiator (EM pump) with fins (all stainless steel loop)
Outlet Temperature	875 K
Inlet Temperature	790 K
Core Arrangement	0.3-m D x 0.3-m L single stainless steel calandria can
Reflector Material	Beryllium
Reflector Thickness	~8 cm
Neutron Spectrum	Thermal
Shield	Gamma: borated stainless steel Neutron: lithium hydride
Control Elements	Rotating drums (no central control rod)
Overall Reactor Mass	~1000 kg

RORSATs

The Soviet Union has been launching RORSAT-related spacecraft since 1967. Table 4, which is based on the extensive studies of N. L. Johnson and others, provides a listing of publicly identified launches.[13] The Soviets have recently confirmed Western speculation that the RORSATs are fast reactors using a thermoelectric conversion system and that they are of a different design from Romashka.[10]

Based on an analysis of the RORSATs flown through Cosmos 954, G. E. Perry concluded that "The Russian ocean surveillance satellite probably consists of three parts -- the final stage of the rocket which carries the slot antenna for the SLR [side-looking radar] along its length, an attitude stabilisation platform, and a nuclear power source with its own rocket engine. Normally, at the end of the mission, the three parts separate. The nuclear power plant is raised to a higher circular orbit where it will remain for up to 500 years or more and the other two parts decay rapidly from the lower orbit. It seems probable that it proved impossible to separate the components of Cosmos 954 during November and that it remained in one piece until the end."[14] Following the reentry of Cosmos 954, the RORSATs reportedly displayed a new sequence of operations and events. Upon completion of its operational life the RORSAT was split into three parts:

TABLE 4
SOVIET ORBITAL REACTOR PROGRAM HISTORY*

Number	Name	Launch Date	Termination Date	Lifetime
1	Cosmos 198	27 Dec 67	28 Dec 67	1 da
2	Cosmos 209	22 Mar 68	23 Mar 68	1 da
3	Cosmos 367	3 Oct 70	3 Oct 70	< 3 h
4	Cosmos 402	1 Apr 71	1 Apr 71	< 3 h
5	Cosmos 469	25 Dec 71	3 Jan 72	9 da
6	Cosmos 516	21 Aug 72	22 Sep 72	32 da
7	Cosmos 626	27 Dec 73	9 Feb 74	45 da
8	Cosmos 651	15 May 74	25 Jul 74	71 da
9	Cosmos 654	17 May 74	30 Jul 74	74 da
10	Cosmos 723	2 Apr 75	15 May 75	43 da
11	Cosmos 724	7 Apr 75	11 Jun 75	65 da
12	Cosmos 785	12 Dec 75	12 Dec 75	< 3 h
13	Cosmos 860	17 Oct 76	10 Nov 76	24 da
14	Cosmos 861	21 Oct 76	20 Dec 76	60 da
15	Cosmos 952	16 Sep 77	7 Oct 77	21 da
16	Cosmos 954	18 Sep 77	~31 Oct 77	~43 da
17	Cosmos 1176	29 Apr 80	10 Sep 80	134 da
18	Cosmos 1249	5 Mar 81	18 Jun 81	105 da
19	Cosmos 1266	21 Apr 81	28 Apr 81	8 da
20	Cosmos 1299	24 Aug 81	5 Sep 81	12 da
21	Cosmos 1365	14 May 82	26 Sep 82	135 da
22	Cosmos 1372	1 Jun 82	10 Aug 82	70 da
23	Cosmos 1402	30 Aug 82	28 Dec 82	120 da
24	Cosmos 1412	2 Oct 82	10 Nov 82	39 da
25	Cosmos 1579	29 Jun 84	26 Sep 84	90 da
26	Cosmos 1607	31 Oct 84	1 Feb 85	93 da
27	Cosmos 1670	1 Aug 85	22 Oct 85	83 da
28	Cosmos 1677	23 Aug 85	23 Oct 85	60 da
29	Cosmos 1736	21 Mar 86	21 Jun 86	92 da
30	Cosmos 1771	20 Aug 86	15 Oct 86	56 da
31	Cosmos 1818	1 Feb 87	~ Jul 87	~6 mo
32	Cosmos 1860	18 Jun 87	28 Jul 87	40 da
33	Cosmos 1867	10 Jul 87	~ Jul 88	~1 yr
34	Cosmos 1900	12 Dec 87	~14 Apr 87	~124 da**
35	Cosmos 1932	14 Mar 88	19 May 88	66 da

* Sources include references 10, 11, 12, 13, and 14.
**Note: The Cosmos 1900 reactor continued to operate past the 124-day mission lifetime.

- Object A - reactor plus small kick stage;

- Object B - expended Scarp-11 second stage of the launch vehicle plus instrument section; and

- Object C - radar antenna.

The reactor was boosted into a higher orbit and the reactor core was then ejected (Object D) to prevent reentry for some 500 years.[17,18,19]

In the non-technical summary of the U. S. participation in "Operation Morning Light" (as the U.S. participation in the Cosmos 954 reentry was named), the Cosmos series of satellites were pictured as shown in Figure 5 and described as being cylindrical with a mass of approximately 4000 kg. The reactor was described as producing 100 kWt or less and containing ". . . on the order of 50 kg of highly enriched uranium-235".[15] The Soviets have recently reported the satellite to be 1.3-m in diameter and 10-m long.[16]

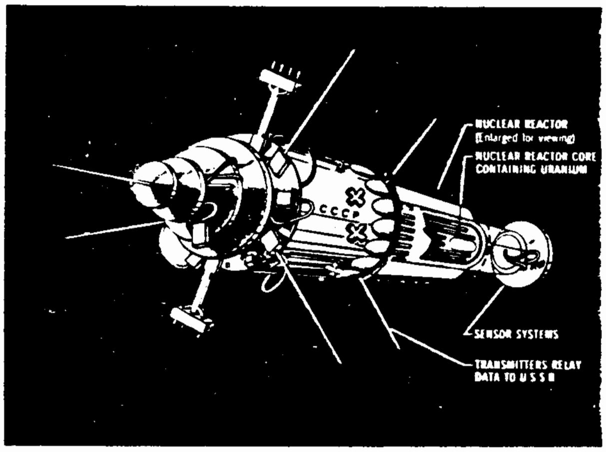

Figure 5. Artist's early conception of one of the RORSATs (courtesy DOE).

Given that the RORSAT reactors use a thermoelectric conversion system allows some estimates to be made of the electric power output. For example, Romashka was about 1.5% efficient (although values from 1.25% to 2% have also been cited) and the SNAP-10A flight reactor was about 1.3% efficient. While current U. S. RTGs are 6.8% efficient, the SP-100 reactor is estimated to be only about 4% efficient. These efficiencies when coupled to a 100-kWt reactor would yield electrical power outputs in the range of 1.3 kWe to 4 kWe.

<u>RORSAT Reactor</u>

From References 10, 15, 16, 20, 21, 22, and 23, it is possible to construct the following table of estimated RORSAT reactor parameters:

Thermal Power	≤100 kWt
Conversion System	Thermoelectric
Electrical Power Output	≤5kWe (~1.3-2 kWe)
Fuel Material	U-Mo(≥3wt% Mo)
Uranium-235 Enrichment	90%
Uranium-235 Mass	≤ 31 kg (~20-25 kg)
Burnup	$\leq 2\times10^{18}$ fiss/g of U
Specific Power	~ 5 Wt/g of U
Core Arrangement	37 cylindrical elements (probably 2-cm dia)
Cladding	Possibly Nb or SS
Coolant	NaK
Coolant Temperature	≥ 970 K (outlet)
Core Structural Material	Steel
Reflector Material	Be (6 cylindrical rods)
Reflector Thickness	0.1 m
Neutron Spectrum	Fast (~ 1 MeV)
Shield	LiH (+ W & depleted U)
Core Diameter	≤ 0.24 m
Core Length	≤ 0.64 m
Control Elements	6 in/out control rods composed of BC_2 with LiH inserts to prevent neutron streaming and Be followers to serve as the radial reflector
Overall Reactor Mass	< 390 kg

Figure 6 is an artist's concept of Cosmos 954. Figure 7 is an engineering sketch of the general features of the Cosmos 954 reactor. While public attention has focused on Cosmos 954, Cosmos 1402, and Cosmos 1900, the DOE and other observers have noted that the Soviets have had other accidents involving space nuclear power sources (see Table 5).

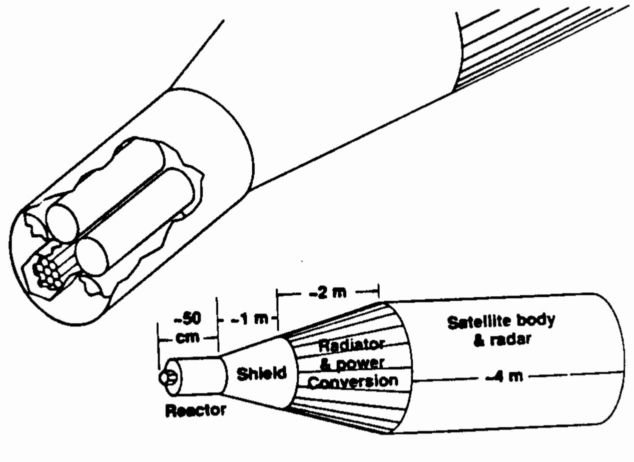

Figure 6. Artist's concept of Cosmos 954 showing the reactor (courtesy LLNL).

TABLE 5
REENTRIES OF SOVIET SPACE NUCLEAR POWER SOURCES[13]

Name	Launch Date	Reentry Date	Type of Power Source	Comments
-	25 Jan 1969	25 Jan 1969	Reactor	Possible launch failure of RORSAT.
Cosmos 300	23 Sep 1969	27 Sep 1969	Radioisotope	One or both of these payloads may have been a Lunokhod and carrying a ^{210}Po heat source. Upper stage malfunction prevented payloads from leaving Earth orbit.
Cosmos 305	22 Oct 1969	24 Oct 1969		
-	25 Apr 1973	25 Apr 1973	Reactor	Probable launch failure of RORSAT.
Cosmos 954	18 Sep 1977	24 Jan 1978	Reactor	Payload malfunction caused reentry near Great Slave Lake in Canada.
Cosmos 1402	30 Aug 1982	23 Jan 1983 (spacecraft) 7 Feb 1983 (reactor core)	Reactor	Payload failed to boost to storage orbit on 28 Dec 1982. Spacecraft structure reentered at 25°S, 84°E. Fuel core reentered at 19°S, 22°W.

TABLE 6
SUMMARY OF RADIOISOTOPE POWER SOURCES REPORTED TO HAVE BEEN LAUNCHED BY THE U.S.S.R.[13]

Power Source	Spacecraft	Mission Type	Launch Date	Status
RTG (?)	Cosmos 84	Navigation (?)	3 Sep 65	In orbit
RTG (?)	Cosmos 90	Navigation (?)	18 Sep 65	In orbit
RHU	Luna 17 (Lunokhod-I)	Lunar rover	10 Nov 70	Shutdown
RHU	Luna 21 (Lunokhod-II)	Lunar rover	8 Jan 73	Shutdown

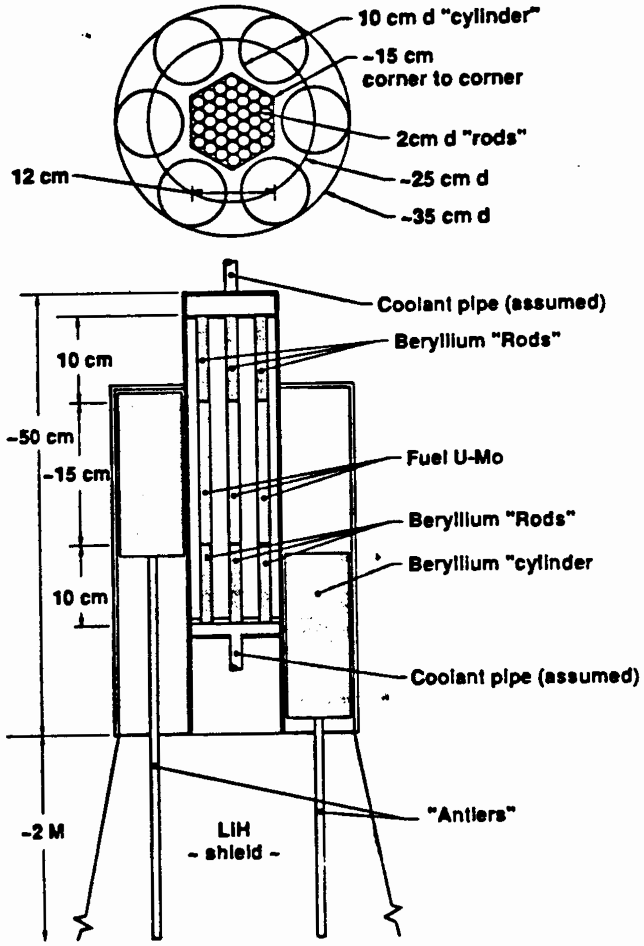

Figure 7. Engineer's sketch of Cosmos 954 reactor (courtesy LLNL).

SOVIET SPACE RADIOISOTOPE PROGRAM

The Soviets have reported using only a few radioisotope power sources -- including their first radioisotope generator, Orion 1, on Cosmos 84 and Cosmos 90.[24] For Lunokhod-I ("Moonwalker I") and Lunokhod-II, the Soviets used an isotopic heat source to maintain the desired temperatures in the Lunokhod compartment during the lunar night.[25] Table 6 summarizes what has been publicly reported on the successful flights of Soviet radioisotope power sources.[13]

FUTURE USES OF SPACE NUCLEAR POWER

The Soviets have consistently stated that they intend to continue using nuclear power in space. Less than a month after the reentry of Cosmos 954, Soviet Academician Yevgeni Federov ". . . made it clear that the Soviets will continue launching satellites with nuclear power plants aboard. In fact, Federov suggested that at least two new types of atomic powered satellites are under development". Federov was indirectly quoted as saying one of the satellites would be a television relay and the other would be a meteorology satellite with a radar to map storms.[26]

Following the Cosmos 1900 incident, Izvestia reported that "The operation of nuclear power plants in radiation-safe orbits opens up broad scope for the introduction of nuclear power on spacecraft with a national economic purpose". The article went on to note that "Nuclear power plants can play an important role on interplanetary flights. According to the assessments of Soviet specialists, a multimegawatt nuclear plant can create the necessary jet thrust for a spacecraft on a flight to Mars".[27]

There have been several recent quotes from the Soviets that they plan to use nuclear reactors for power on a manned mission to Mars, including the possible use of nuclear electric propulsion (NEP or NEJ in Soviet parlance).[28,29,30] One concept calls for a hybrid system -- a direct nuclear thermal rocket that would eventually be used as a closed Brayton cycle power converter for a NEP system.[30]

The Soviets have also shown illustrations of a Mars rover with an RTG and they have spoken of planning unmanned missions to the outer planets, which would clearly require RTGs.

Looking to the future, it is clear that the Soviets intend to continue using nuclear power in space.

CONCLUSION

By Western practices, the Soviet Union has a vigorous, ongoing program to develop and employ space nuclear power sources, especially reactors. The two types of reactors that have been flown appear to have been used or are planned to be used for ocean reconnaissance satellites. The Soviets have made it clear that the continued use of space nuclear power is important to their national goals.

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