Space Nuclear Power in Views: 50 Years Ago and Prevision for 50 Years

A.V. Zrodnikov[a], A.N. Zabud'ko[a], V.A. Linnik[a], A.A. Dubinin[a], V.I. Ionkin[a], V.I. Yarygin[a]

[a] FSUE SSC RF Institute for Physics and Power Engineering, Obninsk, Russia

Abstract. The results of scientific-technical and research-design works on the space nuclear power installations (SNPI) have been systemized. Brief description of the evolution of works on the SNPIs is presented.

Characteristics of the installations, experience of developing and operating the installations have been analyzed. The presented analysis has also included the results obtained on development works and Projects that did not reach their technical realization but made it possible to develop scientific and technical potential of the space nuclear power for the investigations showing promise for the next 50 years.

1. Background: brief history of works on the SNPIs

For about half a century the developed countries have been carrying out investigations into the area of using the nuclear power in the spacecraft. The purpose of these investigations is to design the high-efficient autonomous and compact power sources based on nuclear reactor for electricity supplying the different vehicle-borne devices and/or for providing the spacecraft propulsion.

The history reveals that the first applications of the nuclear power for the space systems relate to constructions of the nuclear rocket propulsions (NRP) in the USSR and USA.

In the USSR in the space technique area the development works on large and medium nuclear space propulsions using homogeneous and heterogeneous types of reactors were carried out. The specific impulse of that propulsion can be 2-2,5 times as much as that of propulsions using chemical fuel. Since 1956 till 1965 a lot of the variants of the reactor designs had been considered and the optimal methods and ways of solving the problems of NRPs designing had been developed.

The NRP parameters were first experimentally verified when the model fuel subassemblies (FSA) were tested in reactor IGR constructed in 1961. In 1966 the development works on the small heterogeneous reactors were launched for the purpose to construct the rocket with minimal dimensions. In the USSR the NRP works had been developed to the phase of the full-scale tests (IRGIT № 1, IRGIT № 2, IRGIT № 3). During 1961-1984 in compliance with the NRP Program ~ 10 nuclear reactors of various modifications (IGR, IVT, IRGIT and the like) were designed, fabricated and tested. In 1978-1984 they were tested [1] and the tests demonstrated sufficient operability of the reactor.

In 1980s-1990s the development works on fast reactors for the power-propulsion installations in which the NRP mode was combined with electricity generating were launched. They demonstrated that there were potentials to get small values of propulsion for the space flights at considerable increase of reactors' specific (propulsion divided by weight) characteristics for that type NRP.

The USA national Program on nuclear rockets ROVER/NERVA covered the years from 1955 to 1973. During that period over 40 nuclear reactors were tested, more than twenty reactors were subjected to the full-scale tests. The Program was recognized to be one of the most successful technical developments of the advanced technology [2].

The USSR development works adopted the scheme of the reactor with a heterogeneous core in which the neutron moderator material was located separately from fuel elements containing uranium. Fuel elements were surrounded by thermal insulation and encapsulated in the metallic case that formed a fuel elements assembly. Orientation toward the heterogeneous reactor and element-by-element development of its units was a fundamental distinction between the NSP construction Programs in the USSR and USA. As it was recognized later by the experts, among them the American specialists were also presented, this distinction was in favour of the Soviet Program [3].

In 1956 the works on studying feasibility to use the nuclear power installations (NPI) generating electricity at the spacecraft were launched. As the spacecraft's electricity supplying sources, the NPIs were considered as both the ones with machine conversion of thermal power into electricity and the ones with direct conversion of thermal power (thermoelectric and thermoemission ones) [1]. The NPI Projects with machine conversion were realized with different closed thermodynamic cycles.

In the USSR the development works on NPIs with power machine conversion reached the phases of technical proposals and feasibility studies. Abroad, in the American and French Projects, the priority was given to NPIs based on power machine conversion (Brayton and Rankine cycles). For example, in the USA the NSPs with a reactor of the S8DR type and power conversion system with a Brayton cycle (30÷50 kWe) or with a Rankine cycle (power ranged from several hundred kW to several MW).

Thermoelectric conversion in the radio-isotopic generators and in the NPIs (SNAP-10A, "BOUK") was successfully used for electricity supplying the space stations. On August 14, 1964 the world's first nuclear installation "Romashka" with thermoelectric conversion of thermal power into electricity was put in operating. SNAP-10A was the USA first vehicle-borne electric plant with nuclear reactor that was tested in space in 1965 April. Its power was ~ 0,5 kW, it operated 43 days and was shut down soon due to the fault in the voltage regulator [4]. The similar NPI operated on Earth more than 10000 hours. In 1975-1988 domestic thermoelectric NPI "BOUK" of ~ 3 kWe was operating at the man-made Earth satellites of the "Cosmos" series. Development, designing and construction of those installations took ~ 10 years (SNAP-10A (1956-1965), "BOUK" (1961-1970)).

By the year 1970 the basic R&D had been carried out, the first experimental installations had been fabricated, the ground-based delivery tests of NPI "BOUK" had been accomplished. The full-scale ground-based tests and flight-engineering development tests of the NPI had been carried out from 1970 till 1975 [1]. Altogether 33 launchings were made. The dates of their launchings, the entering and escaping orbits, the time of their flight functioning and the causes of its termination are cited in the Table in Paper [1]. Simultaneously (since 1971) the scientific and research works on finding the ways to increase the reactor power and the lifetime of installation "BOUK" were realized.

With due account of experience of designing and constructing SNAP-10A, the USA scientists developed two variants of space power unit SNAP-8, namely with thermoelectric and machine conversion as well as the more powerful thermoelectric generators for usage in space NPIs (SP-100 and others).

In the USSR the development works on constructing the thermoemission NPIs were launched in 1956-1958. They were stimulated by the USA publication that D. Grover (the USA) was going to test in reactor the diode which emitter would be heated from uranium carbide fission [1]. The total set of the expected characteristics made those power sources very promising for the spacecraft.

Since the beginning of 1960s the scientific and research works on construction of the thermoemission NPIs with small (10÷100 kWe) and large power (200÷1000 kWe) reactors-converters have been intensively carried out with different class reactors.

Detail description of designing and construction of NPI "TOPAZ" (~ 6 kW) with a slow neutrons reactor is cited in Papers [1, 5].

A physical note to the conceptual design of installation "TOPAZ" was issued in 1963 and seven years later (in 1970) the first NPI was launched and tested. Altogether, since 1970 till 1984 the ground-based power tests of the seven prototypes of thermoemission NPI “TOPAZ” were accomplished. These all enabled to begin to design the NPIs for carrying out the flight-engineering development tests on the testing area on the specially constructed technical position. Two experimental NPIs successfully passed the flight tests in 1987-1988 [1]. The great constructive contribution to designing NPIs “BOUK”, “TOPAZ” and other advanced installations was made by V.Ya. Poupko.

Along with NPI “TOPAZ”, since the second half of the 1960s design works and ground-based development of thermoemission NPI “Yenisei” with a one-element electricity generating channel (EGC) were performed.

The results obtained at constructing NPIs “BOUK”, “TOPAZ” and “Yenisei” enable validated consideration of the future NPI development on the basis of experience of “BOUK” and “TOPAZ” technologies [6].

In the USSR simultaneously with designing the “TOPAZ” type NPIs the research works on constructing the propulsion installations with reactor-converter (RC) of several hundred kW and several thousand kW were carried out.

In the USA the thermoemission NPIs were designed for three ranges of electric power: ~10 kW, ~50 kW, ~150 kW (Programs SNAP and STAR). Further this principle of conversion was applied for NPI SP-100. The highest efforts in this area were purposed to development of thermoemission EGCs. The current USA Projects on space NPIs are based on concept HPS (Heatpipe Power System) using machine conversion systems [7]. In the USA Projects the powerful turbine-generators are used for advanced NPIs of the multi-mega-watt class.

2. Nuclear space propulsions

One of the promising trends of the rocket technique is construction of the rocket with a nuclear propulsion.

The NRP includes:

- a nuclear reactor that is a heat source for heating the working medium – hydrogen;
- a turbo-pump unit that transfers liquid hydrogen from the tank into the reactor;
- a nozzle that transforms heat power received by the reactor's working medium into propulsion;
- the structures that integrate all propulsion's assembly units;
- a regulation system;
- auxiliary power sources for starting the reactor and for the pump driver at starting the propulsion.

A fuel subassembly (FSA) is a basic unit of the heterogeneous scheme propulsion reactor. In the assembly the working media is heated up to the temperature providing realization of the propulsion's necessary specific impulse.

A typical structure of the FSA includes:

- a load-bearing cooled vessel that may be ended by a nozzle;
- the FSA core itself;
- high-temperature thermal insulation;
- a support unit;
- an input unit that provides uniform over the cross section convey of the working medium to the assembly and can include a temperature compensating device;
- the elements of the end reflector and shielding.

The design of the facility's experimental reactor provided an opportunity to perform the full-scale tests of the fuel elements, FSAs and different type groups of FSAs for the NRPs of the wide power (propulsion) range.

Successfully carried out tests of FSAs in the experimental reactor made it possible to start the autonomous tests of NRP reactor IRGIT.

The tests included the stages of physical starting the reactor, cool gas-dynamical setup of the working circuits, control physical start, cool hydro-dynamical tests, power starting, “fire” tests, post-starting investigations [3].

The major goal of the “fire” tests was complex testing the operability of the reactor and its units, testing the correctness of engineering and technological solutions adopted for reactor designing.

The first reactor IRGIT passed two “fire” tests (1978). Later on, two else reactors IRGIT were subjected to the full-scale tests at facility complex “Baikal-1”.

The carried out analysis of the results revealed that the basic reactor units including the FSAs had successfully passed the full-scale tests. The fuel characteristics obtained in the USSR (in Russia) verified potential realizability of constructing the compact active zones of different power NRPs providing the specific impulse of NRP propulsion to be more than 900 s.

One of the ways to avoid restrictions imposed by materials resistance under high temperatures is to give a chance to the fission fragments to transfer their energy straight to the working medium. It means construction of the reactor with a gas phase core. As the major part of gas-phase reactor heat releases in gas, the reactor temperature might considerably exceed the temperature of the structures surrounding the core.

The propulsion specific impulse is determined by the heating temperature and molecular composition of the gases emitted from the nozzle. For that reason, an endeavour to increase the propulsion specific impulse requires to increase the heating temperature of the working medium and to use gases with low molecular mass. Use of the gas-phase reactor in which the working medium is heated by radiation from the zone filled with uranium plasma makes it possible to use hydrogen as the working medium, which can be heated to the temperature considerably increasing the structural materials' temperature. At this, heat from the reflectors and structural elements is removed to the auxiliary cooling circuits. That scheme makes it possible to increase the propulsion specific impulse up to 7000 s.

Use of the single closed circuit of heat removal makes it possible to organize heat conversion into electricity. For example, according to Program NERVA, an opportunity to use a reactor as a heat source for the system of converting 25 kWe was considered.

The gas-phase reactor enables to obtain very large power (tens of million kW). The high level of heating the working medium makes it possible to use the effective methods of heat power direct conversion into electricity.

The Projects of the space NPIs and electric power plants using gas-phase reactor are a promising trend of using the nuclear power in the future conquest of outer space.

3. NPIs with thrmoelectric power conversion

NPI “Romashka” realized as a ground-based installation [8] was the first reactor installation with thermoelectric conversion of nuclear fission heat into electricity. NPI “Romashka” successfully operated ~15000 h and generated 457…380 We. The thermoelectric generator (TEG) made from semiconductor silicon-germanium alloy was mounted on the outer surface of the fast neutron reactor's radial reflector.

In NPI “BOUK” the TEG was mounted under the cooler-irradiator (CI) beyond the radiation shielding (RS). The hot junctions of the generator were heated to 970 K by sodium-potassium coolant. The cold junctions were cooled by secondary circuit's sodium-potassium coolant, with the help of which non-transformed heat was transferred to the CI at maximal coolant's temperature at the CI inlet being at the level of 623 K.

The small-sized fast neutron reactor which core contained 37 fuel rod elements was used in NPI “BOUK”. Highly-enriched (90 %) uranium-molybdenum alloy was used as fuel. ~30 kg of uranium-235 was loaded. In the side beryllium reflector that was 100 mm in width were installed the linear-moved beryllium control rods which were ~80 mm in diameter. There were two independent sections in the TEG: the main one purposed for power supplying the spacecraft's consumers and the auxiliary one purposed for power supplying the conduction type magnetic pump, which provided coolant's circulation over both NPI circuits. Two-stage thermoelectric elements were used in the TEG: the high-temperature ones made from silicon-germanium alloy and the low-temperature ones made from lead-tellurium. ~100 kW was a limiting value for reactor heat power. In the process of operating NPI “BOUK” its lifetime was brought up to 4400 h. The NPI specific weight was 300 kg/kWe.

Radiation safety of NPI “BOUK” was provided by two systems: the main one purposed for NPI escaping to the long space disposal orbit and, in case of the main system's failure, the reserved one based on aerodynamical dispersion of the fuel composition with fission products and other materials with induced activity in the superstandard layers of the Earth atmosphere.

Installation SNAP-10A was designed for the purpose to demonstrate potential realizability for the reactor to enter the orbit and to verify reliability of TEG functioning and reliability of control devices' shielding. The reactor was the thermal neutrons reactor with 37 fuel rod elements. The fuel was uranium-zirconium hydride alloy. The coolant was sodium-potassium alloy. The regulation system consisted of the four semi-cylindrical beryllium segments, which were the part of the side reflector. The silicon-germanium TEG was a converter. The average temperature of coolant (sodium-potassium) in the area of the hot ends of the TEG module was 775 K (the maximal temperature was 818 K), the average temperature of the radiator in the area of the cold ends of the TEG module was 588 K. Lithium hydride shielding restricted radiation beyond the TEG compartment. Two parallel-connected lead-tellurium thermocouples which generated up to 700 A at 30 mV (21 W in total) supplied the electromagnetic pump with direct current. The specific weight of the installation was 810 kg/kWe [4].

Therefore, if the first experimental reactor installation “Romashka” verified the promising future for development of such (non-machine) systems, thermoelectric NPI SNAP-10A demonstrated potential realizability to use those installations as vehicle-borne power supply sources at the space vehicles. An example of successful usage of nuclear power in space was designing NPI “BOUK” and its operating that exceeded two decades.

4. NPIs with thermoemission power conversion

NPI “TOPAZ” is the first space nuclear power installation with thermoemission power conversion.

The arrangement scheme of NPI “TOPAZ” includes:

- a unit of the caesium vapour transfer system and regulation organs' drivers;
- a thermoemission reactor-converter (TRC);
- a liquid-metal circuit’s (LMC) pipeline;
- radiation shielding (RS);
- a LMC compensating tank;
- a cooler-irradiator (CI);
- a frame structure.

The core includes 79 electricity-generating channels (EGC) and four zirconium hydride moderator disks. The EGCs together with the cooling channels are installed in the holes of the moderator disks.

The five-element EGCs with a three-layer's collector package are used. The EGCs are electrically connected in the operating (60-64 EGCs) and pump (19-15 EGCs) sections. Commutation of the operating section's EGC is realized in caesium vapour from both TRC ends to provide ~32 V on its terminals, commutation of the pump section is realized to provide a necessary current (~1200 A) for electricity supplying the conduction electromagnetic pump.

The functions of heat power regulation, reactivity compensation and emergency protection are performed by the 12 rotary beryllium cylinders with carbide boron sector patches, which are installed in the side reflector and are divided into four groups with three cylinders in each. Each group is handled by its own driver.

In NPI “TOPAZ” are used: a system of caesium vapour transfer that provides circulation of vapour via the inter-electrode gap of the EGC, a one-component lithium hydride RS, a one-circuit heat removal system with sodium-potassium coolant that includes a load-bearing CI being a part of the load-bearing NPI scheme, a system of automatic handling the installation. When the flight tests were carried out, radiation safety was provided by NPI escaping to the long space disposal orbit. The specific weight of the installation was 200 (140)* kg/kWe .

When installation “TOPAZ” was designed, the basic conceptual solutions were as follows:

- a compact NPI with the following dimensions of the reactor core: 28 cm in diameter and 36 cm in width;
- zirconium hydride moderator;
- regulation organs were rotating cylinders with a boron carbide absorber;
- smoothing the radial power release field due to moderator concentration;
- series connection of the separate electricity generating elements (EGE) in the EGC (multi-element EGC);
- “geometrical” axial profiling of the EGE lengths caused by non-uniformity of power release over the reactor core width;
- forming the necessary number of the series-parallel EGC circuits, placing the pump section in the core centre;
- selection of the mode of low-voltage caesium arc as a basic power mode of thermoemission conversion;
- providing regulation of caesium vapour flow rate via the inter-electrode gap (IEG);
- particularities of designing the system of gas products removal;
- special methods of coolant's filling in and purifying;
- elimination of cavitation and local evaporation and so on.

The results of the flight tests verified the NPI reliable operation under the space conditions' factors and an opportunity to use those types of installations as the vehicle-borne power supply sources with electric power levels that several times exceeded the power levels of successfully operated NPI “BOUK”.

In the USSR together with designing NPI “TOPAZ”, the development works on the reactor-converter based on the one-element EGC of NPI “Yenisei” were carried out. The principal distinction of NPI “Yenisei” from NPI “TOPAZ” was that the design of the one-element EGC made it possible to mount the outer commutation of the EGC and electric insulation of the RC beyond caesium vapour, to test the electric circuits after assembling the reactor, to test it by using the emitter electric heaters at design power of the RC and to load fuel when the installation is completely assembled.

---

* The value in parenthesis takes into account power generating by the pump section.

Use of the one-element EGC, which outer diameter of the emitter unit was 19,6 mm, also made it possible to organize the central hole in the emitter unit, via which the gas fission products could be disposed in space. The EGCs of NPI "Yenisei" were mounted in the reactor core tubes with a small gap filled with helium. Commutation of the EGCs in the section was realized from both reactor ends in helium atmosphere.

5. The current state and advanced solutions to the space nuclear power propulsion installations in compliance with technologies "IRGIT", "BOUK", "TOPAZ" (second generation NPIs)

Having kept the certain succession to first generation's space NPIs "IRGIT", "BOUK" and "TOPAZ", the second generation's advanced space NPIs are designed for the higher levels of electric power and operating lifetime. Besides, the advanced space NPIs provide two-mode operating that is specific for the conditions of their usage as the components of the transport-power modules. Their distinctive feature is also a high level of nuclear and radiation safety meeting the current requirements to nuclear power sources usage in space.

To find the optimal solutions, the complex investigations into characteristics of the RCs and NPIs with different class reactors including reactors with hydride-zirconium and hydride-yttrium moderators (moderator's volumetric share varied in the range from 0,1 to 0,85), with beryllium and graphite moderators, fast neutron reactors, reactors using uranium-233 and plutonium-239. As it is a problem to retain hydrogen in moderator especially when the reactor lifetime is long, the reactors with less content of hydrogen were considered at simultaneous reducing moderator's volumetric share including the fast reactors. Uranium enrichment varied within 10÷90 %. Beryllium (or beryllium oxide) which albedo properties for neutrons were the best that provided maximally achieved compactness of the reactors under investigation was regarded as a reflector for all reactors. Removal of gas fission products was provided in the EGCs. Monocrystalline molybdenum or tungsten was used as emission material for the emitter and collector [9].

The computations of the NPI characteristics have revealed that reactors with $ZrH_{1,8}$ moderator and molybdenum EGCs have the least weight coefficient (kg/m^2) of the RCs in the range of common thermoemission surfaces $F_e = 0,6÷6$ m^2. The characteristics of the heterogeneous reactors with hydride-yttrium moderators are near them and the latter may be more preferable from the standpoint of thermal resistance at long lifetimes of the reactor. The RCs with beryllium and graphite moderators possess the worst weight (kg/m^2) and geometry (l/m^2) parameters. As a moderator's volumetric share of heterogeneous reactors with $ZrH_{1,8}$ moderator is being reduced at emission surface being ~10 m^2, these reactors gradually change over to the fast RCs. And for the large values of the common emission surfaces (over 10 m^2), the latter reactors are the exclusive ones among all considered RCs.

There is a principal opportunity to use sufficiently "mild" thermal heterogeneous RCs with emission surfaces being more than 10 m^2. However, the volumes of those reactors will be too large and considerably exceed the volumes of the fast neutron reactors with the same value of the emission surface.

Use of uranium-233 in fast RCs makes it possible to construct the RC in the area 5 m^2 < F_e < 10 m^2 (electric power 50÷600 kW) with an advantage in weight and geometry coefficients. At F_e < 10 m^2 those reactors have an advantage over the similar RCs using uranium-235 from the standpoint of volumetric share of charging material in the EGC cores. At F_e < 0,7 m^2 and electric power being 1-7 kW the heterogeneous reactors with uranium-233 are the exclusive ones.

The specific weight of the heterogeneous reactors using uranium-235 with $ZrH_{1,8}(YH_{1,9})$ with molybdenum EGCs varies within the range (30÷5 kg/kW), the specific weight of those reactors with tungsten EGCs varies within the range (5÷1 kg/kW) (electric power 100÷800 kW). For the power over 1 MW the fast RCs, which specific weight is ~10 kg/kW and less, have an absolute advantage.

On the basis of these investigations and knowledge gained, Projects NPI-25, NPI-50, NPI-100 and development designs "TEMBR" and "ELBRUS" are being developed in Russia now [6].

6. Large power space NPIs

The large power space NPIs are mainly the installations of megawatt and multi-megawatt power level.

The early investigations carried out in the USSR revealed that the most promising NPI of that class was the NPI with a TRC. According to the foreign reference data, the NPIs with that power level are considered for the machine conversion principles.

In the USSR the Project of the large power installation (useful electric power is 2200 kWe) was designed for the nuclear electric jet propulsion (NEJP) in 1965 [10].

The basic conceptual features:

- use of the fast neutron thermoemission RC;
- use of lithium as NPI coolant and a working medium of the electro-plazma propulsion;
- the modular principle of the NPI design;
- use of niobium alloy as the basic structural material.

In the process of works on the large power space NPIs using lithium-niobium technology, the whole number of the certain scientific tasks have been solved that enable to make a conclusion that the scientific-technical, material study and technological back-logs on that space technique trend have been developed in Russia.

In the USA the Program on multi-megawatt thermoemission space reactors is mainly aimed at development of approaches and concepts of designing the components of the EGC experimental samples.

7. Nuclear photon rocket concept

In 1998 Professor V.YA. Poupko and co-authors proposed a concept of the photon rocket based on nuclear reactor and demonstrated effectiveness of using that system for the flight to the planet Pluto [11-12].

The photon propulsion concept is based on using the conversion of nuclear reactor's heat power into the power of direct flux of electro-magnetic irradiation, namely use of “thermal” photons of the NPI CI. At this, the “thermal” photons exhausted from the photon propulsion should be shaped as parallel rays to make photon propulsion.

Meeting these purposes requires a high-temperature nuclear reactor using high-temperature materials and liquid-metal coolant with low tension of vapour.

Due to high efficiency of fission power conversion into the power of direct photon cluster, the maximal possible specific impulse of the nuclear photon propulsion is $\sim 3 \cdot 10^7$ s. Use of the “waste” heat of the space power installation's reactor does not require the auxiliary powerful spacecraft-borne sources of electricity.

Therefore, the nuclear photon propulsion operating by using CI heat which amount in the thermodynamical cycle is comparably much can be regarded as an absolutely perfect propulsion for the future space trips.

8. Use of radionuclide thermoelectric generators (RITEG) for space exploration

Expedience and showing promise of RITEG usage for space exploration are conditioned by their unique technical characteristics: high reliability, operating without failures, long functioning in the empty space conditions at keeping stability of the output parameters regardless of their orientation in space and illuminance level.

The works on designing the RITEG for the space purposes date back to the end of 1950s when works on Program SNAP (System for Nuclear Auxiliary Power) in the USA and works on Program "Orion" in the USSR were launched. The first RITEG (SNAP-3B) entered the circum-earth orbit on June 29, 1961 [13].

Electric power of RITEG SNAP-3B was 2,7 W, weight was 5,2 kg. Pu-238, which power-release is 0,55 W/g, half-life is 87,7 years and radionuclide release is low, was used as radionuclide for the RITEG.

In the USA the further works on designing the space purposed RITEG focused on increasing the electric power level, increasing the efficiency and radiation safety of the RITEG. By the end of 1960s several modified RITEGs of the SNAP series were constructed.

Next USA Space Programs (Voyager 1, Voyager 2 – 1977) used RITEGs of the MHW-RTG (multi hundred watt) series with electric power being ~170 W. Their improvement ended with construction of the latest generation RITEG: GPHS-RTG (General Purpose Heat Source-RTG) of 300 We, which were used in space expeditions "Galiley", "Kassini" and "Uliss".

Besides RITEGs, the miniature radionuclide heat units RHU (Radioisotope Heat Units) using Pu-238 which heat power was 1,0 W were widely used in the USA Space Programs. The RHU dimensions were as follows: diameter – 25,4 mm, height – 33 mm, weight – 40 g. They were used to maintain the temperature regime in the compartment with scientific devices. With due account of the obtained data (during many years) on operating the RITEGs and RHU in empty space, the NASA experts came to a conclusion in favour of their usage in the USA Space Programs at least for the nearest decade.

The USSR has less experience of RITEGs usage in space. That is explained by the chosen strategy to use in space the NPIs based on nuclear reactors with direct (thermoelectric) conversion of heat power into electricity.

In the USSR the RITEGs were first launched into space in September 1965, namely RITEG ORION-1 and RITEG ORION-2 entered the circum-earth orbit. They used Po-210 (specific power is 141 W/g, half-life is 138 days) and silicon semiconductor converters which output electric power was 20 W.

In the middle of 1970s a number of R&D on designing complex radionuclide power installation "VISIT" using Pu-238 was carried out. The RITEG with electric power 40 W, which waste heat was transferred to the 600 W heat-exchanger by using heat tubes was a component of the installation. However, due to the objective reasons, development of power installation "VISIT" ended by ground development of its structure.

At the end of 1990s in Russia within the frameworks of International Project "Mars-96" the radionuclide heat units (HU) of heat power 8,5 W using Pu-238 and the RITEG of electric power 200 mW named HU and RITEG "ANGEL" were designed [14-15].

Heat unit "ANGEL" includes a heat-shielding vessel and heat insulation made from carbon-carbon materials surrounding the capsule with plutonium-238 dioxide. The capsule contains 17 g of plutonium-238 dioxide which activity is 260 Ci. RITEG "ANGEL" was designed on the basis of HU "ANGEL". The semiconductor thermoelectric materials on the basis of bismuth-tellurion alloy were used as a converter. RITEG "ANGEL" provided electric power ~200 Mw at working voltage 15 V.

In our opinion, for the nearest decade the RITEGs using Pu-238 are, as before, the unique electric power sources of several hundred W, which reliability and operating without failures have been verified by their many-year operating in space.

REFERENCES

[1] POUPKO, V.Ya., "History of Works on Nuclear Power Flight Vehicles for Space and Aviation Installations in SSC RF-IPPE", (IPPE, Obninsk 2002).

[2] BLACK, D.L., FARBMAN, D.H., WATT, D.F., “Program NERVA: History and Technical Review”, Conference on Nuclear Power in Space, Theses of the Reports, (USSR, Obninsk 1990).

[3] KOROTEEV, A.S., PONOMARYOV-STEPNOY, N.N., ZRODNIKOV, A.V., VASIL'KOVSKY, V.S., IONKIN, V.I., ANDREEV, et al., “Experience of Development and the Major Trends of Power Development in Russia”, International Scientific and Technical NIKIET Anniversary Conference, (Moscow 2002).

[4] “Designing and testing installation SNAP-10A”, Abstract, Atomnaya Tehnika Za Rubezhom, **6** (1966), (Atomizdat, Moscow).

[5] “Designing and Construction of Thermoemission NPI “TOPAZ””, Atomnaya Energiya, **36** (1974), Issue 6, p. 450.

[6] ZRODNIKOV, A.V., IONKIN, V.I., “A.I. Leypunsky and NPIs for Space Exploration”, News of Highest Educational Institutions, Nuclear Power, **4** (2003), p. 19, Obninsk.

[7] “Space NPIs”, Review, Atomnaya Tehnika Za Rubezhom, **11** edited by Atomnaya Energiya (2002).

[8] MILLIONSCHIKOV, M.D., GVERDSTITELI, I.G., MERKIN, V.N., PONOMARYOV-STEPNOY, N.N., USOV, V.A., et al., “High-Temperature Reactor of Direct Conversion “Romashka””, Report № 873, 3rd International Conference on Nuclear Power Peaceful Usage, (Geneva 1964).

[9] DUBININ, A.A., ZABUDKO, A.N., IONKIN, V.I., LINNIK, V.A., “Review of the Scientific-Technical and Design Activities on Nuclear Power Vehicles for Space and Aviation Installations Carried out in IPPE in 1953-1999”, Analytical Review, IPPE-0301, (Moscow 2003).

[10] SUHOV, Yu.I., SINYAVSKY, V.V., “Review of Works on Large Power Space Thermoemission NPIs in RKK “Energiya” Named after S.I. Korolyov”, RCT (1995), Series XII, Issue 3-4.

[11] POUPKO, V.Ya., D'YACHENKO, P.P., GULEVICH, A.V., OVCHARENKO, M.K., “Comparable Features of the Space Vehicles Photon Propulsions of Cycling and Continuous Operating”, Preprint, IPPE-2710, (Obninsk 1998).

[12] POUPKO, V.Ya., et al., “Light Propulsion for Space Flight”, International Forum-99 on the Space Technology and Applications, (Proc. Conf. Albuquerque, NM 2003).

[13] KORLISS, W., HARVI, D., “Power Sources Using Radioactive Isotopes”, Translation from English, MIR, (1967).

[14] PUSTOVALOV, A.A., “Mini RTG on Plutonium-238: Development and Application”, 18th International Conference on Thermoelectrics (ICT-99), Report, (Proc. Conf. Baltimore, Maryland, USA, 1999).

[15] PUSTOVALOV, A.A., POLYAKOV, V., NIKULICHEV, V., “Certification of Plutonium-238 Radionuclide Power Sources for “Mars-96” International Mission Space Bulletin, **4** (1995), Vol. 2.