Role and Prospects of Application of RTG on Base of Plutonium-238 for Planetary Exploration

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Abstract

Brief review of the practical applications of radionuclide thermoelectric generators (RTG) for research of planets and Deep Space in conditions, where use of solar batteries because of the big remoteness from the Sun is inefficient, is surveyed.

More than 40-years experience of RTG use in Space has shown their obvious advantages: high reliability and long service life, compactness, stability of parameters irrespective of external conditions and from a level of light exposure.

Basic characteristics of RTG "Angel" developed earlier within the framework of the International project "Mars - 96" for spacecraft "Mars - 96" are listed.

The importance of RTG application for space missions of 21 century is emphasized, especially in structure of probes, landed on surface of planets of Solar system (rovers, autonomous stations etc.).

Introduction

Beginning of application of RTG in the space dates from middle of the last century. In USA these works were keeping under the SNAP program (System for Nuclear Auxiliary Power). In USSR such type activity was conducting under «Orion» program and then under "BUK" and "Topaz" programs concerning reactor energy plants [1-3].

Advisability and perspectivity of RTG application for space research is dictated by their unique characteristics: high reliability, non-failure operation, a long functioning in conditions of outer space at maintenance of stability of output parameters irrespective of orientation in space and of an illumination level. The last factor should be especially taken into account at a planning the space expeditions for exploration of the planets distant from the Sun (Jupiter, Saturn, Neptune, Pluto).

As a radionuclide for the present-day space application RTG Pu-238 is used, which possesses a high specific energy-release (0,57 W/g), a long half-life period (87,7 years), a low radiation emission (equivalent dose rate from neutron and gamma rays), that allows to refuse the use of additional radiation protection in the RTG on base of Pu-238 and to develop rather a compact RTG with a small weight and a long service life.

The first RTG on the basis of Pu-238 (SNAP-3B) was launched by USA «Transit-4A». That RTG electric power was 2,7 W and mass was 2,1 kg [1].

Till the end of 1960-th in USA a number of RTG of SNAP series (SNAP-9A, SNAP-19, SNAP-27, MHW, CPHS) was developed, which have found a wide application for Deep space exploration.

In USSR strategy of use of nuclear power plants (NPP) in Space was focused, mainly, on the reactor-type NPP with direct (thermoelectric and thermoemission) conversion. Till middle of 1960-th thermoelectric NPP «BUK» of 3 kW electric power was developed and in the beginning of 1970-th thermoelectric NPP «Topaz» of 6,0 kW_{el} was designed. From 1970 to 1988 31 NPP «BUK» were launched in structure of satellites of the "Kosmos" series. NPP «Topaz» were launched in 1987-1988 in structure of spacecrafts «Kosmos-1818» and «Kosmos-1867. Launchings of Polonium-210 based RTG in USSR took place in 1965 in structure of satellites «Kosmos-84» [2].

Besides RTG the compact radionuclide heat units (RHU) equipped with a small amount of plutonium fuel (several grams) have found an application in the space. Such units are used only for heating scientific apparatus and the other equipment with the purpose of maintenance of the necessary heat mode during its operation on the planets surface.

1. History and state of the works in the field of RTG development in USA and Russia

RTG developed in USA have found wide application in research of planets of Solar system and Deep Space. Thus RTG-SNAP-27 were used for realization of seven lunar expeditions under the program "Apollo" in the period from 1969 till 1972 and they have worked in structure of the scientific equipment placed on the Moon surface from 5 up to 7 years.

RTG SNAP-19 were put in spacecrafts Pioneer-10 and Pioneer-11 (1972-1973) and have worked in conditions of deep space for about 30 years at a distance more than 80 A.U. (10^{10} km) from the Earth. RTG SNAP-19 was used in the landing Martian modules (1977) - the program "Viking".

In structure of spacecrafts "Voyager-1" and "Voyager-2" (1977) RTGs of MHW-RTG series with 170 W electric power were used. During more than 20-years voyage in the space spacecrafts «Voyager-1,2» studied from the transit orbit and took the fist photographs of Jupiter, Saturn, Uranus, Neptune. Communication with the Earth was keeping continually as long as the spacecrafts had left the Solar system.

The most significant space missions with use of RTG of GPHS-RTG series (fig. 1) were the following:

- Galileo – exploration of Jupiter and its satellites (launch in 1989)
- Ulisses – investigation of polar areas of the Sun (launch in 1980);
- Cassini – exploration Saturn and its satellite Titan (launch in 1997);
- mission New Horizons – exploration of Pluto planet (launch in 2006).

Table 1 presents the general parameters of RTG on base of Pu-238, developed in USA.

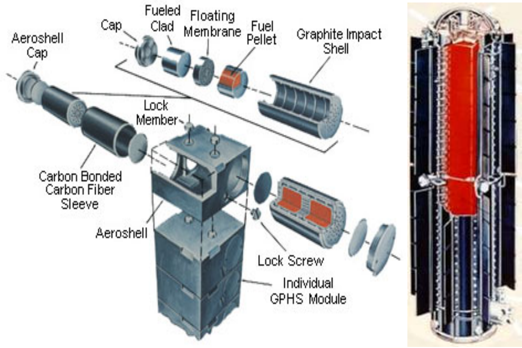

Fig. 1 Radionuclide Heat Assembly design GPHS and RTG GPHS-RTG

Table 1

Parameter	SNAP-3B	SNAP-19	MHW	GPHS-RTG
Electric power, W	2,7	40	170	300
Output voltage, V	5,6	30,0	30,0	30,0
Heat power, W	53	610	2400	4500
Mass of PuO_2, kg	0,12	1,230	4,8	9,0
Efficiency, %	4,5	6,5	6,7	6,7
Mass, kg	2,1	15,0	36,0	60,0
Specific power, W/kg	1,3	2,7	4,7	5,0
Service lifetime, years	5	10	10	15

In addition to RTGs the RHUs of 1 $W_{el.}$ were used in structure of spacecrafts Galileo, Cassini, of Mars rovers Pathfinder, Opportunity, Spirit. At that there were 3…8 heat units in the Mars rovers, whereas for spacecrafts Galileo and Cassini amount of RHU rose up to 120 units.

Fig. 2 Radionuclide Heat Unit LW RHU

Since in USSR strategy of nuclear energy sources development was based on designing reactor plants on kilowatt energy level, therefore development of the space application RTG was carrying out on a limited scale. Nevertheless to the middle of 80-th of the last century a complex energy plant on base of plutonium-238 named as "Visit" (fig. 3) was developed under program of the long-term exploration of Mars planet. There was applied in structure of that plant RTG of 40 $W_{el.}$, heat power from which (near 600 W) was transmitted to a heat exchanger.

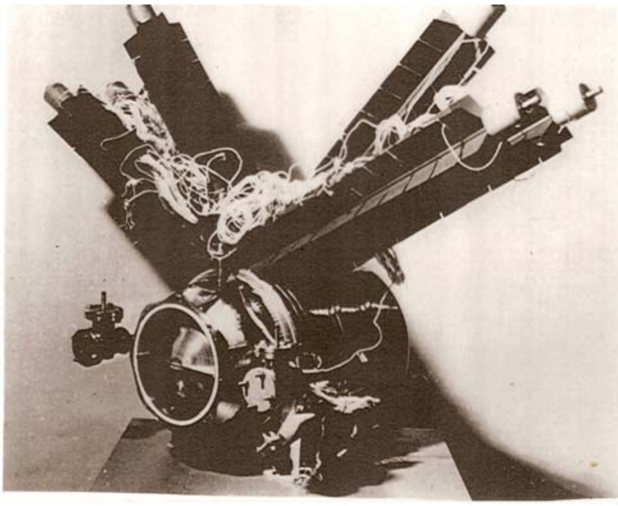

Fig. 3 Complex energy plant on base of plutonium-238 «Visit»

To that time in USSR a number of the key problems of development of space application TRG was solved, i.e. manufacturing capabilities on industrial production of plutonium-238 and of structural materials, as well as technology of fabrication of the cascade-type thermoelectric converters on base of high-temperature (Si-Ge) and middle-temperature (PbTe-GeTe) semiconductor materials were elaborated.

Later on in USSR development of the plutonium-238 RTG was carrying out only for the ground application, including for electric supply of the implantable electric cardiostimulators [4].

Fig. 4 Radionuclide Energy Sources for electric cardiostimulator: RECS-D, Gemma-2.

A new urgency of RTG use in the space had emerged in Russia in frame of International project «Mars-96», when need of a long-time energy feeding small autonomous stations (SAS) landed on Mars appeared. For this purpose RTG of 0,2 W electric power and heat unit of 8,5 W_{heat} were developed. These RTG and RHU for use in structure of SAS of spacecraft «Mars-96» were named as RTG and RHU «Angel» [5].

In Europe at the present time development of RTG and RHU is not performing though European Space Agency (ESA) examines possibility of use of RHU "Angel" in framework of "Exomars" program and later on, maybe, use of RTG on 4…5 W electric power level.

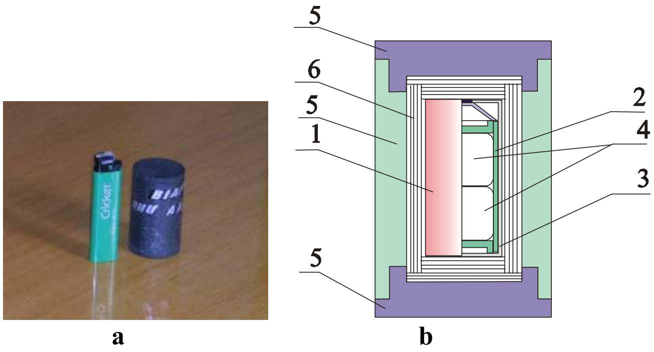

Fig. 5 Appearance (a) and design of RHU «Angel» (b): 1- radionuclide heat source (RHS); 2 – anticorrosive shell; 3 – protective shell; 4 - PuO_2 pellet; 5 – heat-protective casing; 6 – heat-insulation insert

2. RTG and its basic component parts

RTG consists of a number of basic components which secure its long operation regardless of environmental conditions: radionuclide heat unit (RHU), thermoelectric converter (TEC), heat insulation, attachment fittings of RHU and TEC inside RTG casing, heat-rejection system etc. One of the main RTG members is radionuclide heat unit (RHU), containing the certain amount of plutonium-238 based fuel, radioactive decay of which produces a heat flux onto thermoelectric converter.

2.1. Radionuclide heat unit (RHU) represent a complex high-technology product, as it imposed by a number of severe requirements on integrity securing for any kinds of external actions at a nominal operation mode and in case of probable emergencies. These requirements are stated in Resolution № 14/68 dated 14.12.1992, approved by General Assembly of the United Nations and related to "Principles relevant to use of nuclear power sources in outer space" which must be taken into account at a designing of RTG.

Fig. 1 shows design of a heat assembly and GPHS-RTG. Basis of the heat assembly is a module containing four capsules of 62.5 W heat power each. The total assembly is placed inside heat-protection and shockproof body made of carbon-carbonic materials, which are capable of ensuring the body integrity in case of emergency impacts.

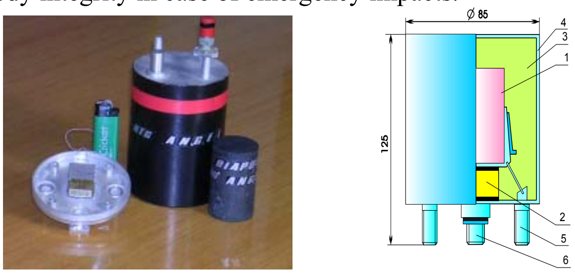

Fig. 6. Photo of RTG «Angel» with the basic accessories (RHU «Angel» and thermoelectric battery) (a) and its design (b): 1 – RHU; 2 – thermoelectric battery; 3 – heat insulation; 4 – casing; 5 – fastening members; 6 – electric connector

On base of such the single modules it is feasibly to build up the aggregate assemblies on heat power from 250 W up to 5.0 kW. RTG of GPHS-RTG series with use of such heat aggregate assemblies and efficient thermoelectric converters generated practically about 300 $W_{el.}$. This design of heat unit is the basic one.

RHU of 1,0 W_{heat} represents a multilayer capsule, inside which the pellet of plutonium-238 dioxide is placed and this capsule is enclosed into heat-protection body made of carbon-carbonic materials (fig. 2).

The information exists that on the basis of 1,0 W RHU is conducting project engineering RTG on electric power of about 40 mW (Powerstick) [6].

Design of RHU «Angel» is presented in fig. 5. Fig. 6 demonstrates structural layout and photo of RTG «Angel».

Plutonium-238 dioxide pellets are placed in the two-shell pressurized capsule which is in turn closed in multilayer heat insulation and housed in heat-protective casing made of composite carbon-carbonic materials.

RHU «Angel» had passed the planned tests and was certificated in accordance with International requirements on a safety use in structure of spacecraft «Mars-96» [9].

RHU «Angel» is an unified product ant it can be used both independently and as part of RTG.

2.2. Thermoelectric converter

In the RTGs developed under program SNAP there were used thermoelectric converters on base of bismuth telluride, lead telluride, materials of TAGS-type (tellurium, antimonide, germanium and argentum). Thermoelectric converters on base of silicon-germanium alloys were used in RTG MHW and GPHS-RTG, Pluto-Kuper.

Fig. 7 exemplifies the dependences for figure of Merit of some thermoelectric materials and skutterudites as a function of temperature.

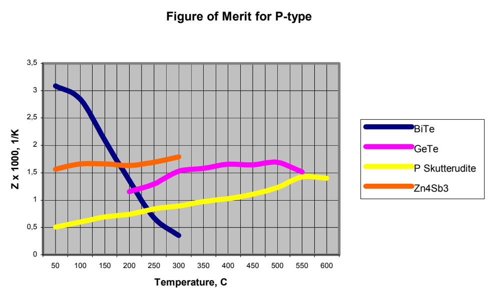

Fig. 7 Figure of Merit Z for P-type materials as a function of Temperature

In RTG «Angel» the thermoelectric materials on base of bismuth telluride were applied.

Fig. 8 demonstrates dependences of parameter Z as a function of temperature for such materials.

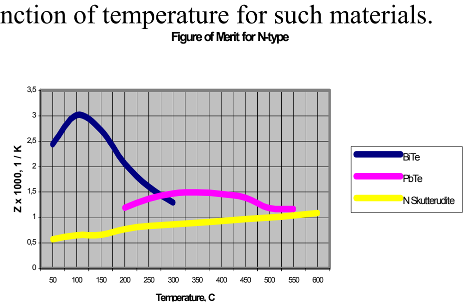

Fig. 8 Figure of Merit Z for N-type materials as a function of temperature

In the Russian projects on the space application RTG of watt range electric power (from 4 up to 30 W) a possibility of application of a middle-temperature (PbTe-GeTe) materials together with low-temperature materials (Bi_2Te_3) is considered with purpose to arrange the cascaded or segmented thermoelectric converters for operation temperature range of 20-480^{0}C.

3. Prospects of RTG application for planet investigations

By now RTG are still unique, the most reliable energy sources for a long-time activity in outer space. The elaborations by USA on designing the standard plutonium-238 heat assemblies GPHS based new autonomous electric energy sources AMTEC-type and thermo-photo-voltaic generators (with efficiency at a level of 16-18% according predicted estimations) are meanwhile at a stage of R&D project and they are inferior drastically in reliability and service life in comparison with RTG.

In this connection, in framework of the space programs USA plan to use a new RTG named as MM RTG (multi-mission RTG) on base of 8 heat assemblies GPHS-type (of heat power about 2,0 kW) and thermoelectric converter PbTe/TAGS-type.

According to developers' assessments this RTG will generate 125 $W_{el.}$ at an efficiency of 6,2% and its mass will be 45 kg. These RTGs are planned to be used in course of the Martian exploration under program Mars Science Laboratory (MCL) and for mission Solar Probe.

Russian experts think expedient to develop RTGs of electric power up to 2,0 W with adaptation of heat assemblies based on a few RHU «Angel» and with appliance of thermoelectric converter on the basis of bismuth tellurides. Design parameters for a few such type RTG are resulted in Table 2.

Table 2

Parameter	RTG «Angel»	RTG A-1	RTG A-2	RTG A-3
Electric power, W	0,2	0,30	0,70	1,1
Voltage, V	15	5	5	5
Heat power, W	8,6	8,6	17,2	25,8
Efficiency of RTG, %	2,6	3,4	4,1	4,3
Mass of RTG, kg	0,5	0,5	1,0	1,5
Specific power, W/kg	0,4	0,6	0,7	0,7
Amount of RHU	1	1	2	3
Dimensions of RHU, mm				
diameter	40	40	40	90
height	60	60	122	60
Dimensions of RTG, mm				
diameter	85	85	85	160
height	120	120	185	140
Service lifetime, years	10	15	15	15

For RTG on electric power level more than 3 W it is necessary to fulfill a new elaboration of a basic heat unit with heat power 50-60 W, as well as of a new cascaded (segmented) thermoelectric converter and RTG design. As an example, fig. 9 shows one of the possible unified designs for RTG module on 30 $W_{el.}$ with efficiency of about 9,5% [8].

Such RTG can find application in the future Russian space programs, ESA missions on exploration of Mars, Jupiter and its satellite Europe as well as in frame of the programs related with detailed and prolonged research of the Moon.

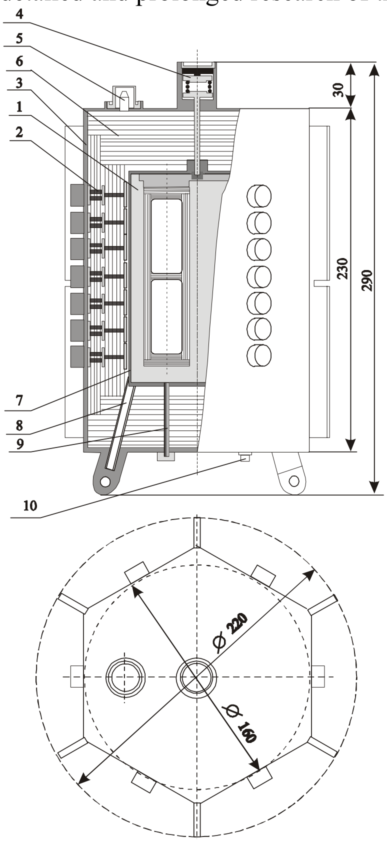

Fig. 9 Principle design of RTG on 30 W_{el}.
1 – Radioactive nuclide thermal block
2 – Thermoelectric battery (42 pieces)
3 - Base
4 - Tightening device
5 - Exhaust tube
6 - Gas-screen thermal insulation
7 - Helium gas collector
8 - Support (4 pieces)
9 - Helium gas outlet
10 - Socket

In our opinion, RTG on base of plutonium-238 are the unique energy sources with which use it is possible for the planetary exploring both to support a nominal heat operation mode at the negative low temperatures and to provide electric supply for various transducers during 20 and more years.

Conclusions

1. During last 40 years plutonium-238 based RTG have been founding a wide application in framework of the USA planetary exploration programs and they showing themselves as a high reliable energy sources efficient for a work in conditions of Deep space for more than 20 years.
2. At the present time for appliance in the space RTG for two basic electric power ranges are developed: from tens up to a few hundreds W and compact mini-RTG less than of 1 W.

3. Besides RTG in the planetary researches the compact radionuclide sources containing a small amount of plutonium-238 (grams) are used as the heaters.
4. In Russia for spacecraft «Mars-96» RTG and RHU were developed, which were named as RHU/RTG "Angel". For the future space programs in Russia projection of watt-power RTG is conducting now.
5. In Europe there is no project engineering on RHU and RTG for space programs of ESA and CNES. For the time being ESA examines possibility of appliance of RHU "Angel" in frame of Exomars program and later on, evidently, of RTG on electric power level of 4-5 W.
6.The urgency of application of RTG for planetary exploration does not raise doubts owing to prospects to support a long-time (for more than 20 years) functioning the scientific equipment on the planets surface and in Deep space.

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