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TECHNOLOGY-BASED DESIGN AND SCALING LAWS FOR RTGS FOR SPACE EXPLORATION IN THE 100 W RANGE

Leopold Summerer*, Jean Pierre Roux+, Alexey Pustovalov×, Viacheslav Gusev×, Nikolai Rybkin×

* ESA-ACT, Keplerlaan 1, NL-2201 Noordwijk, The Netherlands
+ Areva TA - Energy Systems, CS50497 – 13593 Aix en Provence, France
× BIAPOS, Leninsky pr. 38, bld. 1, 119334 Moscow, Russia
contact author: Leopold.Summerer@esa.int

ABSTRACT

This paper presents the results of a study on design considerations for a 100 W radioisotope thermo-electric generator (RTG). Special emphasis has been put on designing a modular, multi-purpose system with high overall TRL levels and making full use of the extensive Russian heritage in the design of radioisotope power systems. The modular approach taken allowed the derivation of robust scaling laws covering the electric power range from 50 to 200 electric Watt (EoL). The retained concept is based on a modular thermal block structure, a radiative inner-RTG heat transfer and using a two-stage thermo-electric conversion system.

INTRODUCTION

From the first steps into space, nuclear power sources have been developed and used in space alongside solar-based power sources. In parallel to nuclear reactor for space, radioisotope-based power sources have been developed by the Soviet Union/Russia and the US for their use in Earth orbit, on the moon as well as on planetary landers and deep space missions, e.g. into the outer solar system.

While some early attempts in designing and developing European radioisotope thermoelectric generators (RTG) were made during the 1960s in Germany, these projects never came to fruition, leaving Europe with no independent access to all those type of space missions for which solar energy is impossible or unpractical.

Scope and objectives

This paper reports the results of a joint study on a new RTG design for deep space and Martian surface missions. The study has been conducted in a spirit of mutually beneficial cooperation involving the chief designer of the latest Russian "Angel"-type RHU and RTGs BIAPOS, the European Space Agency ESA, the French Space Agency CNES and the European energy engineering company Areva.

The study was driven by basic considerations on foreseeable European needs for space exploration and the requirement to better understand the different RTG design options.

The main study objectives were to design a reference RTG system and to derive technically sound scaling laws while benefiting from the Russian expertise and taking advantage of past technology developments.

Technically, the study focused on a modular RTG design in the 50 to 200 W_e range, with 100 W_e (EoL) as baseline, a minimum lifetime of ten years and the ability to operate in all foreseeable environments (e.g. deep space as well as lunar and Martian surface environments). Furthermore, the chosen technology should be readily available and at high TRL levels either in Russia or Europe and thorough safety considerations should play a pervasive role at each design step.

METHODOLOGY

While taking advantage of existing Russian experience and expertise, the study reconsidered the elementary options for the full design and development process, including its safety, technical, administrative and legal parameters.

Administrative and Legal Design Requirements

The study first reviewed applicable requirements to the design of RPS stemming from international agreements, principles and conventions, from federal Russian law, from other normative Russian documents as well as from international recommendations and bilateral international agreements.

Applicable international documents relevant for the design phase were identified as being those listed in the UN Document A/AC.105/781 "*A review of international documents and national processes potentially relevant to the peaceful uses of nuclear power sources in outer space*" from 2002.

In the meantime, in 2009 the *International Framework for the Safety of Nuclear Power Source Applications in Outer Space*, has been adopted by the Scientific and Technical Subcommittee of UN COPUOS as well as the IAEA and would constitute a further applicable document to such a design process.

In case of the assumed, at least partial, development of the RTG in Russia, the Russian federal documents applicable at the date of the study are

- Law on Space Activities No. 5663-1 of the Russian Federation, dated August 20, 1993 (with amendments dated November 29, 1996 and January 10, 2003)
- Federal Law on the Use of Nuclear Power No. 170-FZ dated November 21, 1995 (with amendments dated February 10, 1997, July 10, 2001, December 30, 2001, and March 28, 2002)

Furthermore, the study took into account several applicable Russian and French normative documents:

- Norms of Radiation Safety (NRB-99) SP 2.6.1.758-99, Official publication, Ministry of Health and Social Development of the Russian Federation, 1999 (Appendix A).
- Basic sanitary regulations of radiation safety (OSPORB-99) SP 2.6.1.799-99, Official publication, Ministry of Health and Social Development of the Russian Federation, 2000 (Appendix B).
- Rules for notification of executive authorities about launching a spacecraft with a nuclear power source and notification of local authorities and providing necessary assistance for population in the case of emergency reentry of such a vehicle to the Earth, adopted by the Resolution No. 1039 of the Government of the Russian Federation on August 15, 1997.
- System Safety. Nuclear Safety Requirements, adopted by the *Centre National d'Etudes Spatiales* (CNES, France), No. RNC-CNTS-R-15, Issue 1 dated July 17, 2002.

The law of the Russian Federation on space activities does not contain the notion of space nuclear power sources as an object of the law. Space nuclear power sources are however indirectly included in Clause 4, which deals with the inadmissibility of space activity prohibited by international treaties of the Russian Federation.

The federal law on the use of nuclear power is directly related to space NPS (Clause 43) and does not restrict the use of NPSs as long as "a necessary level of safety is ensured".

Physical Design Requirements

The key element of any RPS design is the choice of the radioisotope that provides the elementary heat source for the device. The key technical parameters for this choice are

- specific energy
- half-life
- ionizing radiation environment
- production capacities
- chemical state and physical form

PHYSICAL DESIGN CHOICES

Radioisotope Selection

The comparison included the following main radioisotopes that could be produced at large enough quantities: e.g. strontium-90, cesium-137, polonium-210, cerium-144

Choice of PuO_2

A comparative analysis of radiative and physical properties of various radionuclides showed that plutonium-238 is better in terms of the above-mentioned set of requirements than all other radiunuclides that can be produced at an industrial scale (strontium-90, cesium-137, polonium-210, etc.).

Plutonium-238 is an alpha emitter with a half-life of 87.74 years. The specific activity of metallic isotope-pure plutonium-238 is $6.33 \cdot 10^{11}$ Bq/g, and the specific heat release is 0.568 W/g.

Alpha-particles with two levels of energy (5499.21 keV (71.5%) and 5456.5 keV (28.4%)) prevail in the energy spectrum of alpha-radiation from Pu-238. Spontaneous disintegration of Pu-238 is accompanied by gamma-radiation in the range of energy from 43.48 keV (0.038%) to 1085.4 keV ($2.2.10^{-7}$ %).

Plutonium would in principle be available in several chemical forms. In addition to the stability of the compounds, the following additional parameters have been taken into account: melting temperature, volumetric energy release, specific energy and the associated neutron radiation mainly due to (α,n) reactions. The following Plutonium compounds have been considered: mononitride, monophosphide, monosulfide, dioxide, sesquioxide, sesquicarbide, metallic plutonium under the parameters: Melting Temperature, material density, concentration of Pu, its volumetric mass fraction, the volumetric energy release, the specific energy release, the intensity of neutron radiation, oxidability in air, solubility in water and compatibility with other structural materials.

Plutonium mononitride has the best characteristics in terms of volume energy release and compatibility with structural materials. However, it is unstable in air and water. Plutonium sesquicarbide has worse parameters than plutonium mononitride in terms of volume energy release and much worse parameters in terms of the melting temperature. Plutonium sesquicarbide is much worse than plutonium mononitride in terms of its compatibility with structural materials, and it is absolutely unsatisfactory in terms of interaction with air and water. Taking all parameters thoroughly into account, we conclude that plutonium-238 dioxide is potentially rather stable in contact with the ambient medium and, despite its somewhat lower energy and radiative properties, represents the most suitable choice.

Dioxide of plutonium-238 has a crystalline structure of fluorite (face-centered cube) with a lattice parameter a = 5.3960 Å. The x-ray density of plutonium-238 dioxide is 11.46 g/cm^3, and its specific heat release is approximately 0.5 W/g. The presence of other plutonium radionuclides in the real fuel, with allowance for bulk density or pressing density, decreases specific heat release to about 0.4 W/g.

Plutonium dioxide annealed at temperatures above 1000°C is almost insoluble even in hot concentrated acids, which is associated with the growth of crystallites and drastic decrease in specific area of the substance during annealing.

TECHNICAL DESIGN CHOICES

Based on the above listed design requirements and basic physical choices, the approach adopted for the design of the reference RTG-100 system consisted of an iterative process taking into account the operating environments as well as potential accidental situations combined with radiation safety analysis and recursively optimising the sizing of the heater and conversion subsystems.

The finally retained concept is based on Pu-238 in form of high-temperature sintered PuO_2 pellets assembled into heater units delivering each 58.7 thermal Watts. Four of these symmetric cylindrical heat sources of 29.4x29.4 mm and a mass of 256 g as assembled into a basic heater unit, delivering 234.8 thermal Watt with a heater unit system mass of 1.900 kg (123.6 W/kg).

Based on Martian surface operation assumptions and cold well temperatures of 80 or 250°C, an RTG that could deliver approximately 100 electric Watt at end of life after 10 years would require six basic heater units, generating about 1409 thermal Watt.

Radioisotope Fuel Considerations

Several Pu-238 forms and treatments were considered. Microsphere fuel with a bulk density of 5.5-6.0 g/cm^3 is worse than the pressed ceramic fuel in terms of volumetric heat release. At the same time, microsphere fuel has some advantages related to elimination of the finely dispersed fuel particles during the production process and subsequent utilization. It is possible to produce microspheres from 50 to 1200 μm in diameter with subsequent application of a protective iridium coating via a gas-phase technique. These processes are however rather expensive, which restricts their extensive use in traditional nuclear fuel cycles.

The pressed ceramic fuel from pure plutonium-238 dioxide has the highest volumetric heat release. Pressed into spherical or cylindrical pellets, a density of about 9.7 g/cm^3 (approximately 85% of the theoretical density of plutonium dioxide) can be obtained, which was found to be optimal from the viewpoint of mechanical strength of the pellet. A further increase leads to closed porosity and failure of the pellet by radiogenic helium during its heating.

The compact shape of the fuel ensures the lowest degree of radiation hazard both in working with the fuel and in its contact with the ambient medium.

An industrial technology of hot pressing of ceramic fuel pellets from plutonium-238 dioxide powder cladded with iridium foil up to 0.1 mm thick was developed in Russia. The density of the obtained pellets varies between 8.5-9.5 g/cm.[3]

Modular Approach

The RTG-100 project was developed on the basis of the modular principle of the RHU structure, which decomposes into identical elements in the case of severe accidents. Each modular element satisfies radiation safety requirements. Such a modular approach is also applicable in design of a single heater module. In such a case, a larger radioisotope heater source or several small sources with an identical total fuel load are put inside a single protective casing made of carbon-graphite materials. At first glance, the variant with one large RHS seems to be simpler and more rational. Nevertheless, it has several essential drawbacks. First, there are some technological constraints on the size of pressed fuel pellets. Second, a larger heat source experiences higher mechanical loads in emergency situations and thus requires a stronger structure.

One of the most essential constraints in the design of the fuel assembly and its elements comes from radiation safety[1] (maximum temperatures during various emergency situations). For the variant with several small RHS, the equivalent fuel density (and specific thermal power) inside the RHU module is lower because individual RHS are separated from each other. As a result, the RHU size is greater, but the temperature of the force shell of the RHS is lower both for both, the nominal RTG operation mode and emergency situations (e.g., incidence of the RHU into soil with low thermal conductivity).

He-vented RHS

During normal operations and especially during abnormal heating, radiogenic helium is building up inside the PuO_2 lattice, leading to pressure build-up with lifetime. In the general case, the RHS can be designed vented or non-vented. Non-vented sealed RHS ampoules are normally used in low-temperature RHUs with fuel temperatures lower than 700°C. The possibility of using the non-vented RHS structure with a sufficiently low temperature is explained by the fact that a significant part of radiogenic helium up to a temperature of approximately 600°C is in the bound state in the crystalline lattice of the fuel, and, for a standard period of exploitation within 10 years, the pressure of helium accumulated in the RHS ampoule (if there is a certain free expansion volume inside the ampoule) does not exceed the critical value in terms of the strength properties of the shell.

During its exploitation, the RHS force shell is exposed to the pressure of radiogenic helium increasing with time. For high-temperature RHS at above 1000°C, almost all the released helium is in the gaseous state and the higher the temperature, the higher the helium pressure. The strength properties of the RHS ampoule casing material become significantly worse with increasing temperature, and even free expansion volumes inside the capsule would not solve the problem of retaining the ampoule leak-proof up to the end of a long lifetime and especially in the case of accidents (fire at the launch pad or aerodynamic heating during atmospheric re-entry). In this case, it would be necessary to significantly increase the free volume for helium accumulation to reach the sufficient strength of the force shell, which would substantially increase the RHS size. Therefore, bleeding devices for helium are introduced in high-temperature RHS. The radiogenic helium is exhausted directly into the RTG casing in the case of a vented vacuum RTG or is removed to a gas tank located in the cold zone, and/or is released outside the RTG by means of special devices (valves, tubes etc.).

Choice of Structural Material for RHS shells

The requirements for the structural material for the RHS are essentially radiation safety driven:

1) high temperature strength and high heat resistance during normal operation (1100-1150°C) and emergency temperatures (in case of fire and of accidental atmospheric re-entry);

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[1] The term “radiation safety” is used in the frame of this paper as including radiation protection and nuclear safety.

2) high mechanical properties under the action of dynamic loads (impact on a solid surface);
3) compatibility with PuO_2 fuel and structural materials of other RHU and RTG elements (with graphite, TEC materials, etc.);
4) sufficient own heat resistance
5) high corrosion resistance in all types of natural environment (fresh and salt water, various soils, etc.).

Since there is currently no material satisfying all these requirements, all radioisotope designs use a multi-layered approach.

Since the RTG-100 design aimed at relying as much as possible on space qualified (TRL-9) materials and components, the list of suitable materials is rather small. Two alloys were developed and examined in Russia especially for the high-temperature RHS: five-species platinum-based alloy K-1 and the Tantalum based alloy TaW-10.

The K-1 alloy is extremely stable in all types of natural environment, compatible with the PuO_2 fuel (no interaction up to 1200-1250°C), insignificant interactions with graphite up to temperatures of 1000°C, and offers the possibility to add barrier coatings (e.g. Hafnium dioxide) to further decrease interactions at even higher temperatures. The RTG-100 RHS was has therefore been designed with a K-1 structural material with Hafnium-dioxide coating.

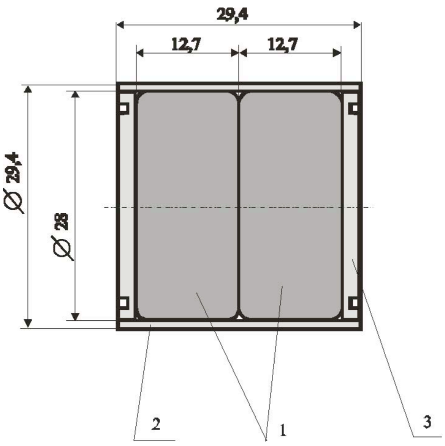

Figure 1: RHS design (1:fuel pellets, 2:K-1 fuel capsule casing, 3:K-1 structural casing)

The RHS structure is shown in Fig. 1. Two identical fuel pellets (1) from hot-pressed plutonium dioxide clad by iridium are located inside the capsule casing (2) made of the K-1 alloy. Based on the chosen PuO_2 pellet density of 9.5 g/cm^3, the specific heat release of the fuel is 0.4 W/g.

In addition to radiation safety contributions, the use of iridium as a cladding material improves compatibility of the capsule material with the fuel since iridium does not interact with plutonium dioxide up to a temperature of 1350°C.

For the He vent, a helically wound 0.1 mm thick band of K-1 foil is used around the fuel cylinder and electron-beam welded. A special technology of band winding provides extended gaps formed by microscopic roughness of the surface of the contacting layers of the shell, which ensures helium exhaust from the RHS while preventing fuel particles to pass or the inflow of atmospheric oxygen.

RHU design

Four RHS, each delivering 58.7 thermal Watt are assembled into one RHU unit, delivering 134.8 thermal Watt as shown in Fig. 2. The RHU has an external and internal protective graphite shells. The external carbon-graphite shell (2) is a parallelepiped (100x100x57.5 mm) and made of composite three-dimensional material, while the internal shells of the RHS consist of a multi-layered wrapper and multi-layered plate inserts. Four protected cylindrical ampoules RHS are closed in one RHU by covers glued to the RHU body by a special high-temperature glue. One RHU delivers 234.8 thermal Watt. Six independent RHU form the heat source for one RTG-100.

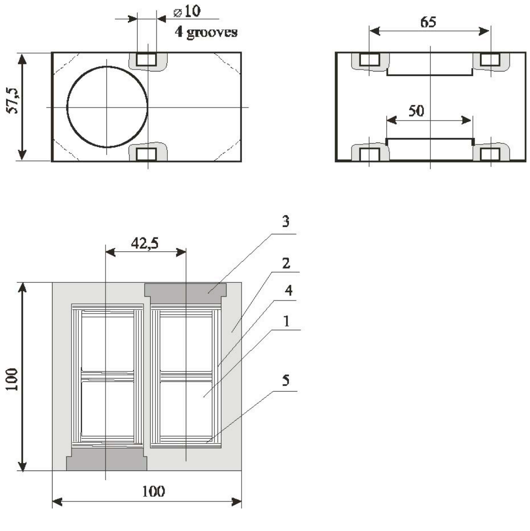

Figure 2: Four RHS assembled into one RHU delivering 235 thermal Watt

Thermal to Electric Conversion System

For RTG designed for space applications, the conversion efficiency and electric current stability, fuel load and the service life, are important. The larger the temperature difference between the hot and the cold side, the higher the conversion efficiency. The maximal operation temperature of the converter in RTGs is determined by the capabilities of the converter and limits of the RHU materials.

Russian expertise and available technology restricts the maximal operation temperature of the thermoelectric converter (TEC) to 950-980°C (based on SiGe alloys; no reliable evidence available for lifetimes of 10-15 years for higher temperatures). Thus, the maximum temperature of the hot side of the thermoelectric converter is limited to 950°C. Since the device needs to be designed for multiple types of missions, the temperature of cold junctions had to be assumed in a realistic range. The two reference cold side temperatures were 250°C and 80°C: At a casing temperature of about 240°C, the conditions of natural heat removal in space and on the Martian surface do not substantially affect RTG operation, and the expected RTG surface area is close to the calculated area of the radiator necessary to ensure this thermal regime of the RTG. The temperature of 80°C represents the case where the RTG heat is transferred efficiently to the structure of the spacecraft or lander.

The large total area of the heat-removing surface of the RHU dictates the conditions for the TEC structure. The TEC needs to be a set of identical single thermoelectric units uniformly distributed over the RHU surface and commutated into a single electric circuit.

Based on the general conditions taken for the design concept, only Seebeck-effect based thermoelectric conversion was considered. The trade-off of state-of-the-art reliable and long-life thermoelectric materials with emphasis on existing technology and reliability lead to the choice of a two-cascade thermoelectric stack: with its high-temperature part based on SiGe alloys and the medium-temperature on the basis of PbTe/GeTe alloys.

Thermal insulation

The chosen range of operation temperatures, namely, 240-980°C (for RTG), dictates the choice of thermal insulation. While maximum insulation efficiency can be obtained via vacuum insulation, other options, e.g. high-temperature gas insulation with the generator cavity filled by Xenon might be preferable for operations in deep space and in atmospheres. Furthermore, gas insulation allows for a better resource stability of the TEC (antisublimation medium, which is particularly important for the medium-temperature PbTe/GeTe cascade). Since Xenon is the inert gas with the lowers thermal conductivity, it is traditionally used to fill RTGs. The excess pressure of Xenon over the Martian atmospheric pressure will prevent penetration of carbonic acid and other gases into the RTG through potential micro-leaks, which might arise during long-time RTG operation and which would decrease the thermal efficiency of the RTG.

RTG Outer Casing Choices

Requirements for the outer casing of the RTG are: lightweight, strength, tight sealing, high thermal conductivity and ease of operations. For the RTG-100, a suitable aluminium alloy was chosen as casing material.

Correlation of RHU and TEC structures within the RTG

Another important issue that had to be resolved at the preliminary stage of design is the correlation and heat transfer between RHU and TEC. The RHU and TEC can be included into a single mechanical (and thermal) circuit or separated by using a radiative heat transfer. The contact method of heat transfer by heat conduction is much more efficient than radiation in the range of low and medium temperatures up to 600-700°C. Since the efficiency of the radiative transfer scales with the fourth power of the temperature, it requires temperatures above roughly 1000°C to be competitive with conduction. Simplicity in design and ease in the RHU mounting process play another substantial role in the design trade-off.

Direct thermal contact would provide the most efficient heat transfer from RHU to TEC at the chosen temperatures but significantly complicate the structure of the RTG. It would require powerful damping pressing of each TEC element between the RHU surface and the RTG casing to compensate for thermal expansion (stress loads can lead to TEC failures under vibration). In the case of heat transfer by radiation through an optically transparent gap in the temperature range of 950-980°C, no more than 15-25°C will be lost on the temperature difference between the RHU surface and the heat-accepting board of the TEC.

Meanwhile, mechanically separating RHU and TEC, allows for a simple technology of RTG assembling and avoids mechanical loads, which would act on the thermoelectric units clamped between the massive RHU and the casing.

Taking all parameters into account, a radiative contactless heat transfer from RHU to TEC through a transparent technological clearance has been chosen.

Final RTG-100W design

According to the assumptions and preliminary estimates of the analysis, a 100 W RTG, based on a cold well (casing) temperature of 240°C would be able to achieve roughly 7.8 % conversion efficiency and specific power of roughly 5.2 W/kg with overall system dimensions 240 x 240 x 580 mm and a system mass of about 21 kg.

Numerical investigations have been performed to determine the approximate expected equivalent dose levels of such an RTG in order to take these into account due to their impact on storage, operations and especially AIV processes and procedures. For 100 W RTGs based on the described design, the equivalent dose has been calculated to reach the maximum value in the central part of the side surface of the cylinder of about 27 mSv/h, with the values on the axial directions being roughly 30% lower.

Table 1: RTG-100 characteristic design parameters

Thermal power BoL, [W]	1408.8 W_{th}
Electric power BoL, [W]	110.4 W_e
Voltage, [V]	31.6 V
Electric current, [A]	3.5 A
Temperature of hot junctions of TEC, [°C]	950°C
Temperature of cold junctions of TEC, [°C]	240°C
Mass PuO_2, [g]	3522 g
Efficiency at BoL, %	7.8%
Service life [years]	10 years
Total Mass, [kg]	20.950 kg
Power of the equivalent dose of neutron emission (distance of 1 m), [Sv/h]	$5 \cdot 10^{-4}$ Sv/h
Dimension, [mm]	240 x 240 580 mm
Specific power, [W/kg]	5.2 W/kg

Table 2: Mass distribution among the major RTG-100 subsystems

Thermal Unit (6 RHU)	11.4 kg (1.9 kg)
TEC (16 TE modules)	4.092 kg (0.256 kg)
Heat insulation + Xenon	1.108 kg
Ti frame for Thermal Unit	0.720 kg
Housing	3.630 kg
TOTAL:	20.950 kg

A preliminary drawing of the RTG-100 design is shown in Fig. 3. The numbers in the following paragraphs are referring to the numbers in Fig. 3.

The thermal assembly RHU consisting of six heat blocks (1) is located in the gas collector (6) made of a high-temperature titanium-based alloy BT. The gas collector is designed for collecting radiogenic helium released by radionuclide heat sources with its subsequent exhaust through the gas bleeder (9) outside of the RTG. The gas-bleeder base rests on four tubular supports located on the lower base (5) of the generator.

The upper cover of the gas collector contains four bellows with blind holes in four corners of the cover, which can move in the axial direction and serve to transfer the tightening force to the thermal assembly, thus, providing leak-proofness of the inner cavity of the gas collector. Tightening is ensured by four upper supports (11) with a predetermined force ensured by springs, which compensate for temperature expansions and ensure reliable fixation of the thermal assembly at all stages of RTG exploitation. Radial slipping of the RHU composing the thermal assembly is eliminated with the use of stoppers (10) and also lugs at the lower base of the gas collector. Each stopper (10) is fixed in grooves of two contacting RHU.

Thus, the thermal assembly located in the gas collector is reliably fixed to avoid displacements in all directions, whereas the tightening mechanism ensures resistance to external loads during the entire period of RTG exploitation.

The RTG-100 structure uses 16 high-temperature thermoelectric modules (2), each consisting of 10 elementary TEC.

Each thermoelectric module in the thermoelectric unit has a heat-removing base, which is fixed with a certain tightening force on the inner side of the lateral casing of the RTG, which allows effective heat removal.

The RTG casing (3), cover (4), and base (5) are made of a high-strength aluminum alloy AMg6. The RTG casing (3) has a square cross section with cooling ribs in the corners of the casing on the outer side. The lower base (5) of the RTG has an electric terminal (8) and RTG attachment points to the lander or spacecraft.

The thermal insulation material is the gas-screen thermal insulation made out of 10 µm thick molybdenum foil with spacers of quartz fog between the layers.

The inner cavity of RTG (where components of TEC are placed) is filled by an inert gas (xenon) through a tube system (7).

SCALING LAWS

Numerical analysis of a 50, 100, 150 and 200 electric Watt RTG has shown that this power range could be covered with the same modular technology and structure. Tentative dimensions, masses, and materials have been calculated and are shown in Table 5.

The modular design allows for simple adaptations of the 110 W (BoL) RTG with a system mass of 21 kg to lower (50 W) and higher (up to 200 W) power levels, which would increase the specific power to 5.74 W/kg.

CONCLUSIONS

Based on solid engineering and decades of Russian expertise in designing and manufacturing radioisotope power sources, a modular design for a 100 W_e (EoL) RTG has been developed, taking into account constraints coming from safety and legal requirements as well as considerations related to technology readiness levels, assembly and manufacturing ease, typical mission requirements (e.g. cold well temperature ranges, operations in vacuum and on planetary surfaces with atmospheres).

ABBREVIATIONS

BoL	Beginning of (service) Life
EoF	End of (service) Life
NPS	Nuclear Power Source
RHS	Radioisotope heat source
RHU	Radioisotope heater unit (made of several radioisotope heat sources)
RTG	Radioisotope Thermo-Electric Generator
TEC	Thermo-Electric Converter

Table 3: Scaling laws for modular designed RTGs from 50 to 200 W

	RTG Power Levels			
	RTG-50 W	RTG-100 W	RTG-150 W	RTG-200 W
Dimensions of RTG: section, [mm x mm] height, [mm]	240 x 240 407	240 x 240 580	240 x 240 752	240 x 240 925
Number of GRHU	3	6	9	12
Number of thermo-electric modules	8	16	24	32
Thermal power, BoL [W_{th}]	704.4	1408.8	2113.2	2817.6
Power Output BoL [W_e]	55.20	110.40	165.60	220.80
Mass of RTG, [kg]	12.2	20.95	29.72	38.5
Specific Power [W/kg]	4.52	5.27	5.57	5.74

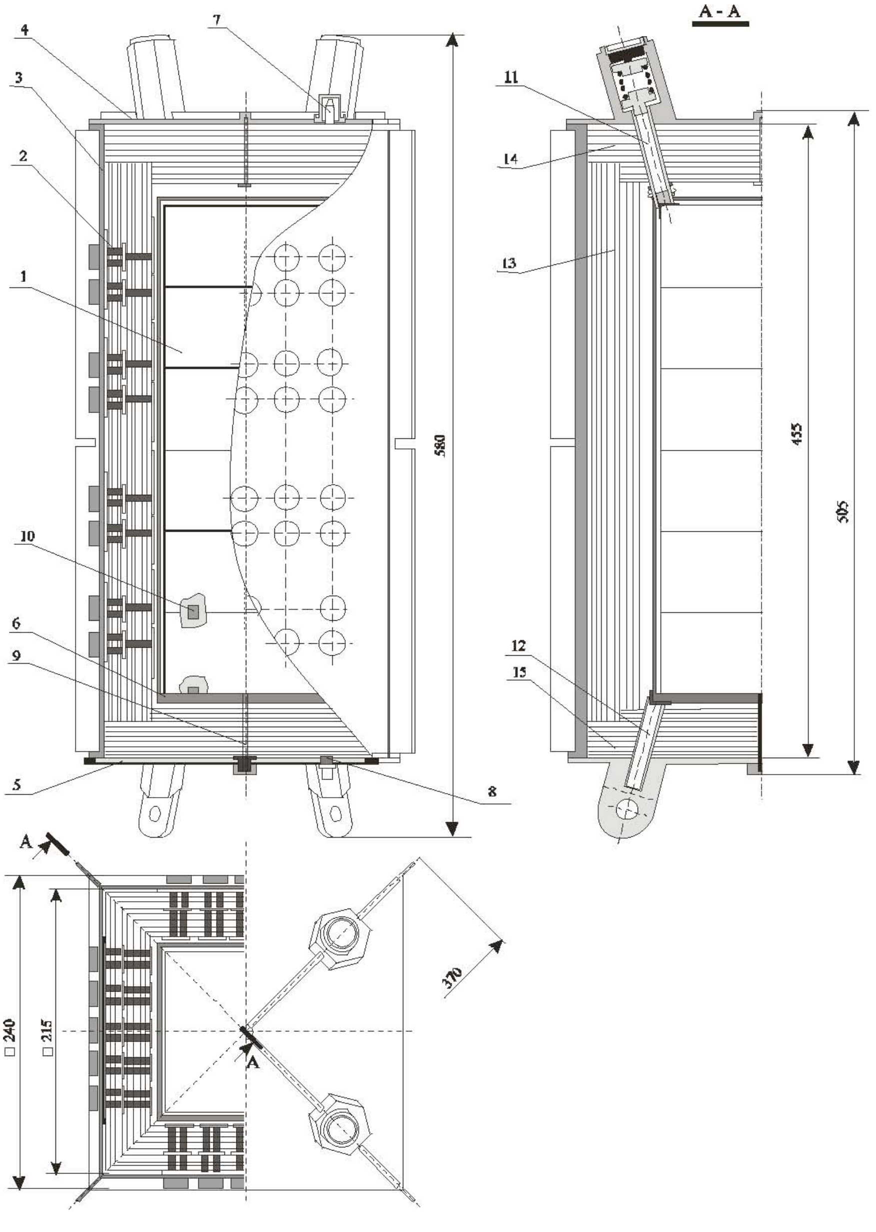

Figure 3: Preliminary drawing of RTG-100

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