A Survey of Current Russian RTG Capabilities

by

Arthur B. Chmielewski, Alexander Borshchevsky
Jet Propulsion Laboratory
California Institute of Technology
Robert Lange, Beverly Cook
Department of Energy

Abstract

Supplying radioisotope thermoelectric generators (RTGs) to American space missions became very complex. The process is marred by many obstacles: high cost, lack of new developments, difficult launch approval-and NEPA compliance. At the same time there are many ambitious space missions for which an RTG would indisputably be the lightest, smallest and most robust power source.

An American delegation investigated status of RTG production in Russia to decide if our product line could be supplemented by the Russian designs. The delegation consisted of members of the Department of Energy representing the body responsible for RTG production and safety process and JPL representing the potential users of the Russian RTGs. The emphasis of the survey was on small RTGs that can produce powers from a fraction of a watt to several watts. The customers for such RTGs could be the missions to Pluto or Mars landers. The delegation visited several Russian installations chartered with design and production of RTGs.

The paper provides a compendium of Russian RTG capabilities. Different RTG installations and their products arc described. The RTGs under development arc characterized by their thermal power, electrical power produced, weight, size and environmental capabilities. The current state of development of each RTG is also stated.

Terrestrial RTGs

The premier capability in developing RTGs lies with a small firm, BIAPOS , that works within the Russian Academy of Sciences Institute of Earth Physics, Special Design Bureau, The Institute designed many terrestrial power supplies for long term operation under water. These power supplies were to operate seismic stations for monitoring nuclear weapon testing. Similar stations were used to measure earthquakes. They were designed to be placed at a depth of 1200 meters and had the coverage of 600 km. The RTGs for these stations were developed in the nineteen eighties. The late systems were deployed with batteries instead of the radioisotope. The Institute has designs of RTGs for monitoring and sensing equipment in nuclear waste storage sites. There are many RTG based systems that have been deployed in the Arctic regions. These generators have strontium based heat sources. The RTGs were always tested with the electrical heat sources at the Institute in Moscow and then field tested in Siberia,

The highest efficiency RTGs ever built by the Russians arc for the sea bottom applications. The thermopiles were cascaded PbTe/BiTe heated by a 42 W source. The generators that arc being designed and produced now arc for such applications as powering Arctic surface stations. They can be fueled by kerosene, natural gas or just about any other source of heat.

The sensors that were designed to operate with the RTGs have many uses. For example, they were installed in the Kremlin as motion detectors. The most recent application of sensors initially developed to bc operated by RTGs includes studying high frequency industrial noise and its effect on workers.

The Intraindustrial State Amalgamation, Pravidenski, near Moscow, was responsible for manufacture of many of the thermopiles used on terrestrial and space missions. Pravidenski currently makes thermoelectric generators in the range of 10-150 W, that ean be heated by gas or liquid fuel, The Institute also fabricates Si solar arrays for spacecraft. A completed array installed on the customer's support structure including all the tests and fabrication of the substrate, cells, connectors, cover glass and iridium coating costs approximately $20/We(!) A similar product in the United States would cost about $2000/We.

The Tensor Electronics instrument Works in Dubna, 200 km from Moscow, was responsible for design and manufacture of pacemaker RTGs. The standard pacemakers used RTGs that delivered 1 mW at 5 V. The thermopiles used BiTe thermoelectric material. The Pu was shipped to the factory from Cheliabinsk. The largest RTG ever made by Tensor delivered 50 mW and was 60 mm in diameter and 90 mm high. After the Chernobyl accident 95 % of demand for radioisotope products have disappeared. All new pacemakers were converted to use lithium batteries instead of RTGs. The factory is testing currently thin film thermoelectrics deposited through evaporation,

Space RTGs

The Russian space history of RTGs is not very extensive. This is due to the fact that Russians depended on thermionic reactors for powering their satellites. The first space RTGs were launched in 1964. They supplied 20 W_e and were fueled with Po 210. In 1969, two lunar rovers - Lunoehod were launched powered by 800 W_{th} Po 210 RTGs. In 1978, Po 210 RTGs that supplied 40 We, 600 W_{th}, were built, tested and never launched.

RTG Fuel Choices

The Russian National Technical Physics and Automation Research Institute has worked on many different fuels for RTGs, Sr90, Cs137, Pu238, tritium, americium, Co60, Ir192. Most of the RTGs built for space as well as terrestrial applications used strontium as fuel. For terrestrial uses strontium is preferred due to its lower price. Pu larger specific power and longer half life make it more attractive for space applications. Terrestrial RTGs used strontium heat sources that supplied power .5 to 100 W. Several hundred of RTGs fueled with strontium are still in operation, The only Pu sources made were for pacemakers. These sources were for microwatt applications.

Mars 96 Mission

The next space mission that will have RTGs on board is the Mars 96 project. The Institute of Space Research (IKI) is the leader for this mission. The mission will involve four small lander stations. Two Proton launch vehicles will carry two stations each. Each lander will also carry two penetrators. Penetrators will also be launched with the rovers on the Mars 98 mission. It will take 305 days from launch to reach Mars. The stations will use parachutes and air bags to cushion the landing. The stations will make a contact with the surface at 5-6 km/s. It was initially estimated that the RTGs will have to withstand ,500-700 g's. This estimate has now been down rated to 270-300 g's. Each station will have two RTGs and two Russian radioisotope heater units (RHUs) on board. The RHUS and RTGs will be integrated into the spacecraft just before the launch from Bajkonur launch site. Four RTGs will be built for flight and two for spares. Each lander will also have a set of two Ni-Cd batteries. The batteries will provide 1.2 Ah, at 1,2 V each cell for the total bus voltage of 15V. The batteries are produced by a French company SAFT.

Mars 96 RHU/RTG Heat Source

The code name for the Mars 96 heat source is "Angel". It was developed by what is now a small company called BIAPOS. The heat source for the RTG doubles as a heater unit. The development of the RTG and the heat source is financed by the Red Star company. BIAPOS is working for Red Star under, what Russians call written task request, and what we would probably call a contract. BIAPOS subcontracts the development of the capsule to a company in Petersburg. That company also contributes to studying the heat source performance under normal conditions, The Scientific Institute of Graphite is studying the RTG behavior under different accident scenarios. There are also several experts that perform short term tasks for Biapos. The fuel is supplied by a company from Arzemas. The actual fabrication of the RTGs took place outside of BIAPOS in the designated factories. 13 heat source capsules have been made so far. There will be five more made to complete the program for the total of 18. The Russian Pu has a high cerium content that interacts with iridium, That is why a limit on cerium was put at 50 ppm to prevent embrittlement of Ir in the clad, The heat sources are designed to operate at low temperatures around 250°C. There is also a lower limit to the heat source temperature because of iridium becoming more brittle as the temperature is dropped. Plutonium is produced in Suchum in Georgia, The Russian RHU heat source is shown on figure 1,

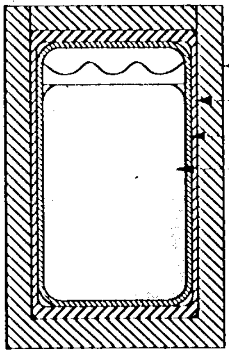

Figure 1
Russian RHU/heat source (8.5W$_t$)

'I'he heat source capsule is designed for integrity under all normal conditions, accidents, and launch pad fire of fuel during flight or reentry. The heat source has a one-time vent to release the helium pressure build-up in an accident, The heat source was tested for surviving a simulated reentry and the subsequent heat up, followed by an impact on granite. Other cases, such as launch pad fires where the RTG is considered to be at the epicenter of the fire were also considered. The integrit y of the RTG was predicted analytically and verified by tests. There arc two reentry trajectories that arc considered worst thermally. The first one is the reentry into the atmosphere under O.1°. This trajectory is the longest and results in the greatest heating and the consequent large loss of mass. The second trajectory is under 90° and results in the greatest heat flux. The most probable reentry is under 30-35°. Multiple effects were also considered in the heat source design. One of the challenging cases involved the RTG falling into a cryo pool, then into a fire followed by an impact.

The radiation from this RHU is estimated to be about 2 mrads at 1 meter from the block. This estimate was obtained using the same plutonium fuel as will be used for the flight units but in a different capsule built for a pacemaker. The Ministry for Atomic Energy is responsible for delivering the heat source. The heat source will be tested using both Pu and U02. The specific power of the heat source is 23 W/kg. It is designed to withstand an impact at 80 m/s on granite, 1000 atm under water and impact shock of 500 g. The heat source "Angel" is designed to provide integrity of the fuel capsule at any normal regime conditions and accidents.

Mars 96 RTG

The development of the RTGs for Mars 96 mission was a complex task involving several companies lead by the firm BIAPOS. The design power of the RTG was 100 mW, but the electrically heated unit achieved 150 mW at 15 V in testing. It was unofficially estimated that the RTG without Pu would cost $15-20k. A schematic of the Mars 96 RTG is shown in figure 2.

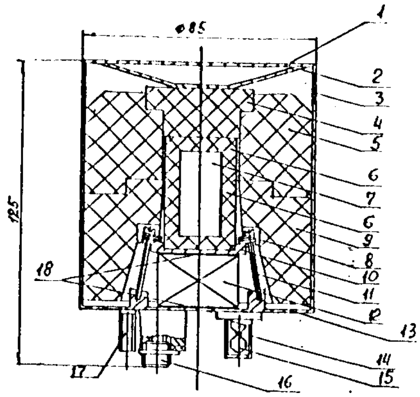

Figure 2
Mars 96 RTG

Penetrators

The Russian National Technical Physics and Automation Research Institute is designing power sources for penetrators. These RTGs are to produce 400mW at 15V. The thermal power supplied to the RTG is 18 W$_t$h. The design has passed a test for withstanding an impact at 500g for 2 to 10 milliseconds. This RTG will work in conjunction with a 13 cell, 1.3 Ah, 15 V Ni-Cd battery.

Rover RTGs

The Red Star company started working 3-4 years ago on the development of RTGs for the Mars rover. Initially two different designs were considered. The first design used cascaded thermionics (TI) and thermoelectrics (TE). The thermoelectrics were the bottom stage using PbTe material operating at approximately 460°C hot side temperature and 320°C cold junction temperature. The thermionic hot side operated between 950°C and 460°C. This design proved to be very difficult to manufacture although had superior efficiency. Two different approaches were tried in construction of the TI stage. The first onc manufactured the emitter and collector in contact and then achieved about 5 microns of separation duc to different thermal expansion coefficients of the emitter and collector.

However, it was difficult to prevent buckling of the matcrial that caused electrical shorts. The second approach dcpcndcd on a 200 micron gap which was wide enough to prevent shorts but required development of ncw materials for collector and emitter. Because of the difficulties in the development of the TI/TE RTG, it was decided to select an all TE option. This RTG is based on PbTe and provides 5 We. There are three such RTGs on Mars Rover. All RTGs arc located in the vehicle wheels. The thermal model of this RTG is shown on figure 3.

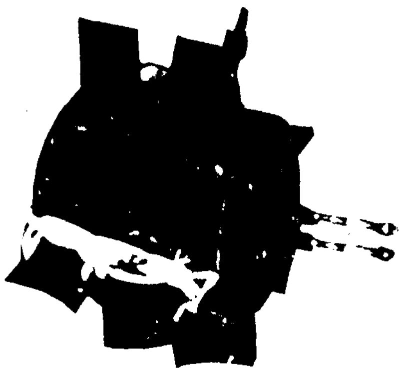

Figure 3
Thermal Model of Mars Rover RTG

The RTGs weigh 4.2 kg each, provide 6 V and use 100 Wth of Pu fuel. The RTG has an aluminum case filled with fibrous insulation. The heat source was designed at Red Star. Currently three units are undergoing tests. Eventually six units will be built for two rovers and two for spares. There will also be five test models built. Three models will bc electrically heated and two fueled with radioisotope. The test models will undergo accelerated life tests, fire tests, and impact tests at up to 100 m/s. The Russian engineers estimated that the RTGs cost about $300k to develop for onc rover. The radiation environment is estimated to be about 35 mrcm/h at 1 meter,
Red Star has also designed a higher power RTG. This RTG would deliver 60 We at 27 V from 1100 Wth. The diameter of the RTG corpus is 0.3 meters (0.37 m with the radiator fins) and the height is 0.5 meters.

RTG afcty

The Russian designs are based on the same philosophy as the U.S. RTGs that the reentry of the capsule should be intact. The safety approval process is similar to the American launch approval and NEPA compliance. More details of the process will become available this year as the Russians will complete the approval process for their Mars 96 RTGs.

Russians have design principles that fall under the UN Principle 3, The Russians feel that any combination of Russian-American generator-spacecraft-launch vehicle would require satisfying the safety proccsscs of both sides. This is why it is important that both sides communicate very well to establish a common process for approval and safety of the radioisotope sources. Mars 96 RTG has a heat source that will be tested for containment using Pu and simulant materials. The specific power of the heat source is 23 W/kg. It is designed to withstand an impact at 80 m/s on granite and 1000 atm pressure in the ocean and shock of 500 g, The heat source was tested for resilience against fires. A three minute 1700°C test was performed. The heat source was also exposed to shorter duration 3000 -3500°C fires. The fire tests and impact tests were conducted in the city of Arzemas 16, near Novogrod.

Russians also perform safety analyses to launch a nuclear systcm, including the probability of launch accidents, the conscqucnccs of release of material, potential health effects, ground contamination, and overall risk. The reviews arc conducted by three different organi zations within Russia, and the decision to launch is made at the highest government level on a risk/benefit basis.

Conclusion

There are several companies in Russia that develop RTGs. There are *three* models of RTGs that arc most advanced in the development. The first is the Mars 96 RTG developed by the firm BIAPOS in Moscow. This RTG and its heat source "Angel" is currently in the final stages of the launch approval process. The RTG will deliver 150 mW at the beginning of the mission. The second RTG is developed by the company Red Star for the Mars 98 rover. This is a 5 electrical W RTG. Its development is somewhat behind the Mars 96 RTG. The third RTG is being developed by the Russian National Technical Physics and Automation Research Institute for an application in pcnct.raters. It is difficult to assess progress made on its development although an electrically heated engineering model was available in 1993.

All Russian companies arc very willing to work under contract to develop space hardware or sell the existing RTGs. Such hardware could bc orders of magnitude cheaper than pursuing a similar development in the U.S. At the same time it must bc noted that the Russian RIGs although very robust in construction have not been designed with great attention to weight and specific power. The heat sources for all of the above RTGs appear to bc designed to meet the same stringent fuel containment requirements as their American counterparts. It will bc possible to learn more about the Russian launch approval process this summer as the Mars 96 RTG will complete certification.

Acknowledgement

The work described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.