ON THE DEVELOPMENT OF THE POWER SOURCES FOR THE ULYSSES AND GALILEO MISSIONS

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ABSTRACT

The technically challenging European Space Agency *Ulysses* mission to explore the polar regions of the Sun and the NASA *Galileo* mission to explore Jupiter have prompted the development of the most powerful radioisotope thermoelectric generator (RTG) yet built for space use. This RTG, which was designed to provide a minimum of 285 We at beginning of mission builds upon the successful thermoelectric technology developed for the RTGs now in operation on the Voyager 1 and 2 spacecraft. A total of four flight RTGs, one ground qualification RTG, and one Engineering Unit have been built and tested for the *Galileo* and *Ulysses* missions. The tests have included measurements of functional performance, vibration response, magnetic signature, mass properties, nuclear radiation, and vacuum performance. The RTGs are fully flight qualified for both missions and are ready for launch.

Keywords:Ulysses, Galileo, General-Purpose Heat Source Radioisotope Thermoelectric Generator, GPHS-RTG, Thermoelectrics.

1. INTRODUCTION

The European Space Agency's *Ulysses* mission to explore the polar regions of the Sun (Ref. 1) and the NASA *Galileo* mission to explore the Jovian system (Ref. 2) present challenges to spacecraft power system designers. Both spacecraft will travel to Jupiter; *Ulysses* to take advantage of Jupiter's tremendous gravity to bend its trajectory out of the plane of the ecliptic and *Galileo* to conduct a 20-month exploration in orbit around the largest planet in the solar system. The *Ulysses* and *Galileo* spacecraft are shown in Figures 1 and 2 respectively. In deciding on a power source the designer is faced with several serious challenges: the solar energy flux at Jupiter is about 25 times less than it is at Earth, the temperatures are quite low (~130 K), and the radiation belts are very severe.

Under a memorandum of understanding, NASA is responsible for providing the power source for *Ulysses* and for launching the spacecraft. Given the continuing successful flights of Pioneers 10 and 11 and Voyagers 1 and 2, each fully powered by radioisotope thermoelectric generators (RTGs), the natural choices to power *Ulysses* and *Galileo* were also RTGs. As the *Galileo* and *Ulysses* programs evolved both missions settled on a common RTG design with launches planned for May 1986. The loss of the *Challenger* led to delays in both launches and the long-term storage of the RTGs.

The original power requirement for the *Ulysses* mission was to provide at least 250 We with one RTG at 4.7 years (41,200 h) after beginning-of-mission (BOM). The

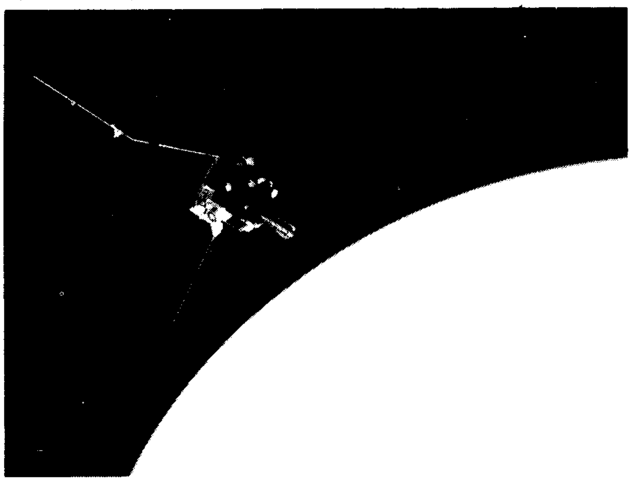

Figure 1. Ulysses spacecraft with GPHS-RTG mounted on the right side

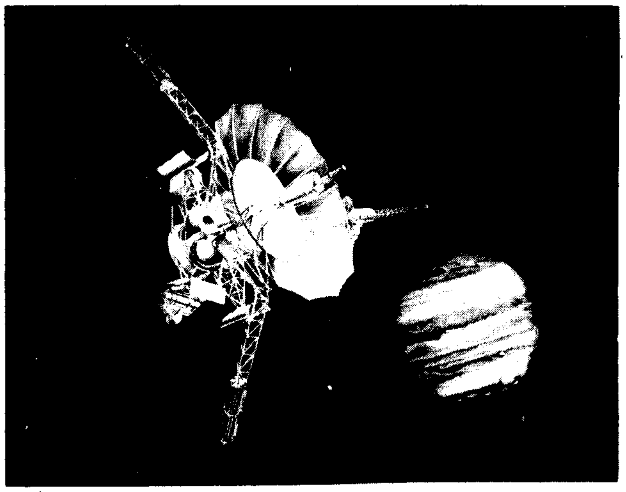

Figure 2. Galileo spacecraft orbiter with two GPHS-RTGs mounted on the two booms

original requirement for the *Galileo* mission was to provide at least 510 We with two RTGs at 4.2 years (36,800 h) after BOM. These requirements were higher than those imposed on the Voyager RTGs which produced about 155 We each at BOM (for a total of 465 We per spacecraft) and were the most powerful then flown.

The result was the design, development and fabrication of a new RTG, known as the general-purpose heat source (GPHS) RTG, capable of producing at least 300 We at the time of fueling. Four flight-qualified GPHS-RTGs were fabricated with one to be used on *Ulysses*, two to be used on *Galileo* and one to be a common spare. In addition an Engineering Unit and a Qualification Unit were fabricated to qualify the design for space (Refs. 3-9).

Under the test program a series of test hardware was assembled and tested culminating in the successful qualification of the flight GPHS-RTGs for the *Ulysses* and *Galileo* missions (Refs. 7-9, 13).

2. GPHS-RTG

The GPHS-RTG, which is based on the ongoing successful thermoelectric technology of the RTGs carried on the Voyager 1 and 2 spacecraft and two Air Force satellites (LES 8 and LES 9), consists of two major components as shown in the cutaway in Figure 3: the general-purpose heat source (GPHS) and the converter. The GPHS-RTG converts over 4.4 kWt from the GPHS into 300 We at beginning-of-life (BOL) and at least 285 We at BOM. The RTG external envelope is based on a cylindrical geometry with overall diameter of 0.42 m across the fins and length of 1.14 m. The average mass of a flight RTG is 55.90 kg. The principal design requirements governed power (at launch, BOM, end-of-mission or EOM), structural (ability to withstand launch vibrations and pyrotechnic shock), magnetic field strength, mass properties (mass, center of mass, moments of inertia, products of inertia), pressurization, nuclear radiation, and general functional attributes (insulation resistance, internal resistance, pressure decay, nonsusceptibility to electrostatic discharging). The GPHS-RTG case allows for attachment to the spacecraft. The GPHS-RTG is configured for Space Shuttle launches and is designed to withstand the launch and ascent environment. The radioisotope heat source, which was designed and tested for improved safety and power performance, represents a major step forward in RTG technology. It consists of a stacked column of 18 individual modules each providing about 245 Wt from the decay of encapsulated plutonium-238 oxide, which has a half-life of 87.8 years. Information on the design and testing of the heat source may be found in Refs. 10-13.

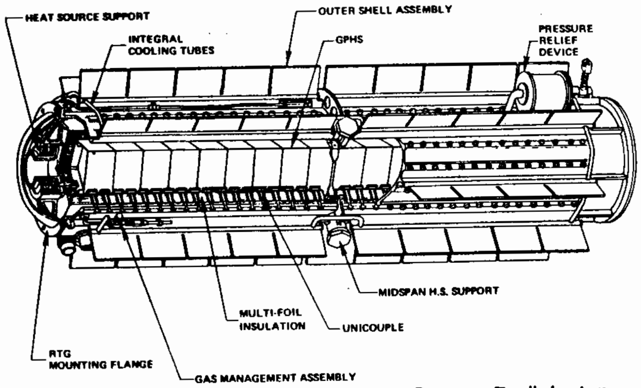

Figure 3. The General-Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS-RTG)

2.1 GPHS-RTG converter

The basic components of the GPHS-RTG converter are: (1) the thermopile which converts the radioisotope-generated heat into electrical power; (2) support assemblies at the ends and middle for the GPHS; and (3) a housing that encloses the rest of the RTG and acts as a heat rejection radiator. The thermopile consists of 572 thermoelectric elements and the layered molybdenum and astroquartz multifoil insulation assemblies. The housing consists of an aluminum alloy outer case (nominal thickness 1.5 mm) with aluminum alloy pressure domes and an active cooling system. A gas management assembly mounted externally to the outer case is provided for charging the RTG with inert gas for ground operation. A pressure relief device (PRD) is designed to vent the gas once the spacecraft is deployed.

2.2 GPHS-RTG thermoelectric elements

The GPHS-RTG thermoelectric elements, which are called "unicouples", are of the same design as those used on the Voyager 1/2 and LES 8/9 spacecraft. Each GPHS-RTG has 572 unicouples individually bolted to the outer case and arranged in 16 longitudinal columns. The unicouples are supported in a cantilever fashion from the aluminum outer case and, in turn, the unicouples support the insulation packet. The GPHS-RTG uses two series-parallel electric wiring circuits in parallel to enhance reliability and to provide the required output voltage (28 V for *Ulysses* and 30 V for *Galileo*). The circuit will continue to operate even if a unicouple fails in either the open or short circuit mode. The circuit loops are also arranged to minimize the net magnetic field of the RTG.

Figure 4 shows a cutaway of the unicouple which basically consists of a P leg (doped with boron), an N leg (doped with phosphorous) and a heat collector and electrical connector called the hot shoe which consists of a P shoe and a N shoe. Two compositions of a silicon germanium (SiGe) alloy are used in the legs and a silicon molybdenum (SiMo) alloy is used in the hot shoe. The nominal hot shoe operating temperature is 1308 K at BOM. The hot junction averages 1273 K at BOM and the cold junction averages about 566 K.

The N and P legs are equal in size, 2.74 mm x 6.50 mm in cross section, with a total length of 20.3 mm. The overall unicouple length is 31.1 mm and the hot shoe measures 22.9 mm x 22.9 mm and is 1.9 mm thick.

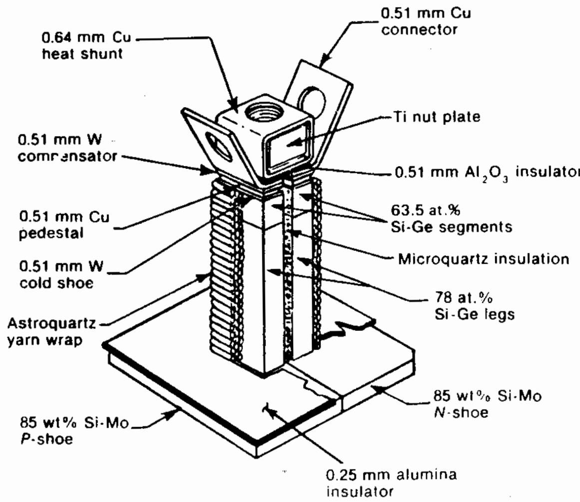

Figure 4. GPHS-RTG silicon-germanium thermoelectric element ("unicouple")

3. PERFORMANCE TESTS

The test philosophy was to build and test hardware through increasing levels of assembly. First unicouples were built and tested, followed by testing of six 18-couple modules. Next full-scale Component Engineering Test (CET) units were built and tested for structural, thermal, and material properties. With this information the electrically heated Engineering Unit was built and tested with the result that the design was proven. The assembly and testing of the nuclear-heated Qualification Unit qualified the overall RTG design. Finally the four flight RTGs were assembled and tested. Parallel engineering analyses, component tests and materials characterizations supported this test program (Refs 5-9, 13).

The general sequence of tests performed is shown in Figure 5. A cover of argon gas was used to protect the inside of the RTGs when they were tested in air. The functional tests, which were performed to assess the RTG at key points in the test sequence, generally included measurements of power output, load voltage, open circuit voltage, internal resistance, isolation ("insulation") resistance, and pressure decay. All of the RTGs satisfactorily completed these functional tests thereby giving added assurance of electrical and structural integrity of the RTGs.

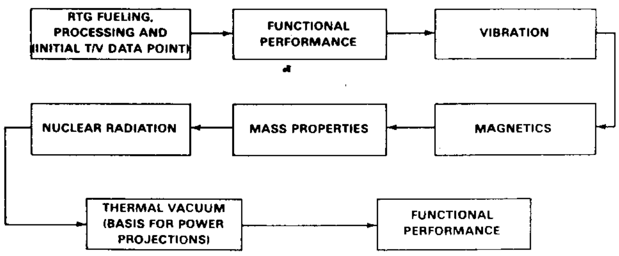

Figure 5. Performance sequence for GPHS-RTG assembly and testing

The Engineering Unit and the Qualification Unit were subjected to flight acceptance (FA) and type acceptance (TA) vibrations. (The flight RTGs were subjected to FA vibrations.) The dynamic environments during the TA vibrations were 50% more severe in amplitude and longer in duration than the expected launch vibration environment. The successful completion of the TA vibration tests demonstrated that the GPHS-RTG design has more than sufficient structural strength margin. The active cooling system was also successfully tested during both the vibration testing and the thermal vacuum testing. In addition, the Engineering Unit successfully passed acoustic testing and pyrotechnic shock testing (Ref. 8).

The magnetics testing showed the need to use compensation magnets on the *Ulysses* RTG. All of the RTGs met the mass properties and nuclear radiation requirements (Ref. 8).

The thermal vacuum test, which was designed to simulate space conditions, provided the basis for the power projections, both BOM and EOM, for each RTG. During the thermal vacuum test each RTG was placed in a thermal vacuum chamber and provided electrical power for test times ranging from 6 h to over 40 h at a pressure of 0.1 mPa or less and an average sink temperature of 308.9 K (Ref. 7).

All of the tests were successfully completed in 1985 in sufficient time to support the then planned 1986 launches of *Galileo* and *Ulysses.*

4. POWER PROJECTIONS

Power projections were originally made from the results of the thermal vacuum tests using the process diagramed in Figure 6. The decay of the fuel causes a reduction in heat input which, in turn, causes a loss in electrical power (about 0.12 We/Wt). Dopant precipitation, which causes a power loss, occurs when the unicouples are at temperatures below the temperature at which the boron and phosphorous dopants were added to the solubility limit. Since the dopants were added at the same temperature as the operating temperature the precipitation is expected during storage. The use of the less effective gas management valve (GMV) (compared to the PRD) during the thermal vacuum tests resulted in having some residual gases within the converter which caused some power loss. This situation would not occur in space.

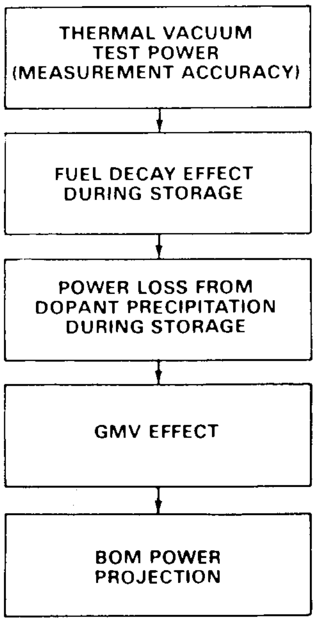

Figure 6. Basis for BOM power projections

For the rescheduled launch dates and the new *Galileo* trajectory new power projections, as shown in Figures 7 and 8, have been calculated using a computer model that includes the effects of fuel decay, dopant precipitation, changes in the thermal conductivity of the unicouple alloys, sublimation of the unicouple materials, sink temperatures, and the effects of carbon monoxide (which can degrade the silicon nitride coating on the unicouples). Based on the experience gained from the performance of the unicouples on Voyagers 1 and 2 and the LES 8/9 satellites, two non-unique combinations of an "effective age" (T_0 age) for dopant precipitation effects and an "effective age" (k-function) for thermal conductivity changes have been selected to bound the projections. The continuing successful prediction of the long-term vacuum test of the Qualification Unit as shown in Figure 9 provides additional assurance of the correctness of the projections.

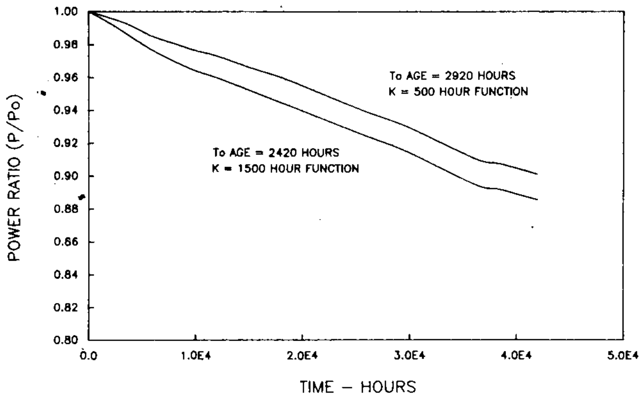

Figure 7. Projected power ratios for the Ulysses GPHS-RTGs

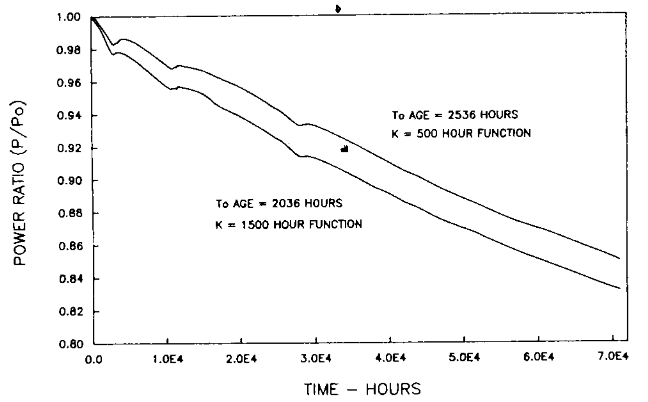

Figure 8. Projected power ratios for the Galileo GPHS-RTGs

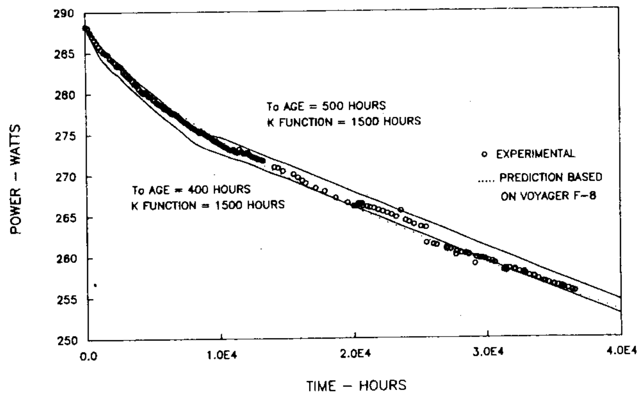

Figure 9. Power output of the GPHS-RTG Qualification Unit during life testing

5. CONCLUSION

Based on the extensive testing program and the excellent correlation between the predicted and actual performance of the Voyager 1/2 and LES 8/9 RTGs as well as the GPHS-RTG Qualification Unit, it is concluded that the GPHS-RTGs will meet or exceed the performance requirements of the *Galileo* and *Ulysses* missions.

6. ACKNOWLEDGMENTS

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