Power Sources for the Galileo and Ulysses Missions

by Gary L. Bennett

The Galileo mission to Jupiter and the Ulysses mission to explore the polar regions of the Sun presented a series of technical challenges to the design, development and fabrication of spacecraft power sources. Both spacecraft were designed to fly to Jupiter. Ulysses, which was launched from the Space Shuttle Discovery (STS-41) on October 6, 1990, used the immense Jovian gravity to twist its trajectory out of the plane of the ecliptic and into a polar path around the Sun in February 1992. Launched from the Space Shuttle Atlantis (STS-34) on October 18, 1989, Galileo will arrive in December 1995 to conduct a 20-month exploration in orbit of the largest planet in the solar system.

In selecting a power source for Galileo and Ulysses, several daunting challenges had to be overcome: the solar energy flux at Jupiter is about 25 times less than it is at Earth (making solar power impractical); the temperatures are quite low ($\sim$130 K); and the radiation belts are very severe. Fortunately, the successful flights of the Pioneer 10 and 11 spacecraft and the Voyager 1 and 2 spacecraft to Jupiter and beyond had shown that radioisotope thermoelectric generators (RTGs) could easily overcome these challenges. (An RTG consists of a radioisotope heat source that provides thermal power from the natural radioactive decay of the radioisotope fuel to a converter that converts the thermal

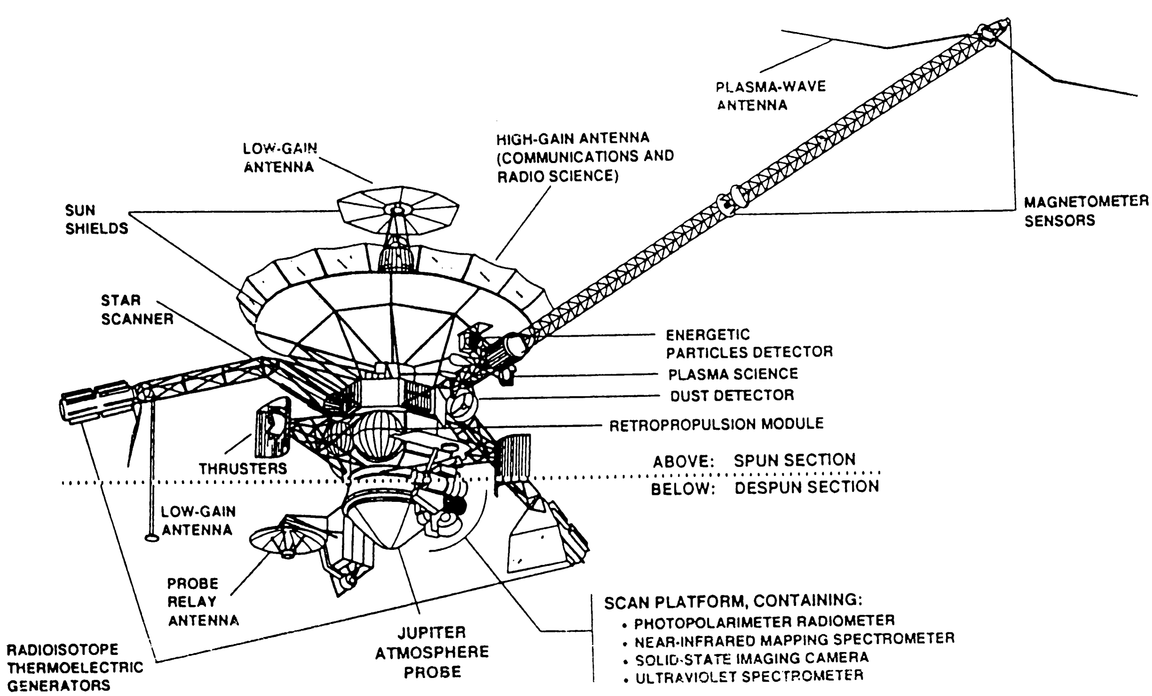

Figure 1. Diagram of the Galileo Orbiter and Probe showing the two general-purpose heat source radioisotope thermoelectric generators (GPHS-RTG) mounted on the two booms. The length of a GPHS-RTG is 113 centimeters (about 45 inches). Galileo is a NASA spacecraft mission to Jupiter, designed to study the planet's atmosphere, satellites and surrounding magnetosphere. Fully loaded with rocket fuel, the Orbiter has a mass of about 2400 kilograms (weight of about 5230 pounds). The Probe, which is designed to enter the atmosphere of Jupiter, has a mass of 340 kilograms (weight of about 750 pounds).

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After some design changes dictated by the failure of a competing thermoelectric technology and by modified user requirements, both missions settled on a common but then unbuilt power source known as the general-purpose heat source RTG or GPHS-RTG. Performance requirements for the GPHS-RTG were dictated by the spacecraft requirements and the launch vehicles (Space Shuttle originally with Centaur upper stage). The principal requirements were levied on power (at launch, at beginning of mission and at end of mission); structure (ability to withstand launch vibrations and pyrotechnic shock); magnetic field strength (low enough to avoid interfering with the science instruments); mass properties (a low mass was desired and the center of mass was tightly controlled because of spacecraft balance concerns—particularly in the case of Ulysses, which has the GPHS-RTG mounted directly on the side); pressurization (ability to hold a cover gas during ground operations); nuclear radiation (as low as practical); and great functional attributes.

In outward appearance, the GPHS-RTG is basically a cylinder of 42.2 centimeters across the fins and 114 centimeters in length with a mass of about 56 kilograms that provides about 300 watts of electrical power at the time of assembly. As such it is the largest, most powerful RTG ever flown. The Galileo spacecraft has two GPHS-RTGs and the Ulysses spacecraft has one GPHS-RTG [Bennett *et al.* 1986 and Schock *et al.* 1979].

The overall mission schedule impacted the GPHS-RTG program in a number of ways. Originally Ulysses was to be a two-spacecraft mission called the International Solar-Polar Mission; budget considerations forced NASA to drop its spacecraft, which led to the cancellation of the requirement for one of the GPHS-RTGs. Then the Galileo spacecraft switched from a Voyager-class RTG to the GPHS-RTG, requiring a net gain of one GPHS-RTG to be produced plus a common spare that had to be compatible with two spacecraft that operated at different voltages.

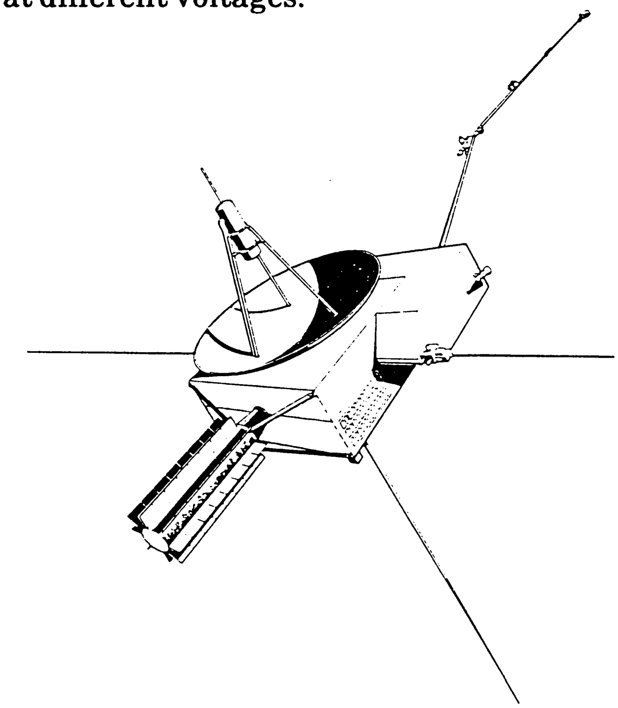

Figure 2. Diagram of the Ulysses spacecraft showing the general-purpose heat source radioisotope thermoelectric generator (GPHS-RTG) mounted on the side. Ulysses is a European Space Agency (ESA) spacecraft mission that was launched by NASA and has some U.S. experiments designed to study the polar regions of the Sun.

The biggest impacts were the launch dates and launch vehicles. Both kept shifting. While launch dates obviously drive delivery schedules, the launch vehicle drives the details of the design. All of these changes and the tight schedules (given the fixed budgets) contributed to a very tense focusing of the program. Fortunately, there was an early agreement on the basic requirements for the GPHS-RTG which allowed some stability—at least in that area!

A number of technical issues were confronted early in the program and successfully overcome through focused team efforts. The following sections describe some of these issues, followed by some personal observations on the process and lessons learned.

Technical Issues

The following subsections provide a general summary of some of the major technical issues encountered during the GPHS-RTG program.

Restarting Thermoelectric Production. The thermoelectric elements used in the GPHS-RTGs were of the same basic design as the thermoelectric elements in use on the Voyager power sources. However, during the production campaign for the Voyager program, the thermoelectric elements had been manufactured by what was then the RCA Corporation. After the completion of that program, RCA ceased its thermoelectric activities, so when the GPHS-RTG program began, the system contractor, General Electric Company (GE) [later Martin Marietta Astro Space], had to establish its own thermoelectric production line.

Small modules consisting of 18 thermoelectric elements each were manufactured and put on test to evaluate the GE product and to determine if GE had been able to duplicate the RCA product. Differences were uncovered that led to the formation of an investigative team of representatives from GE and several Department of Energy (DOE) support contractors and laboratories. The team reviewed the process and product requirements in detail and uncovered some material deficiencies that were quickly corrected.

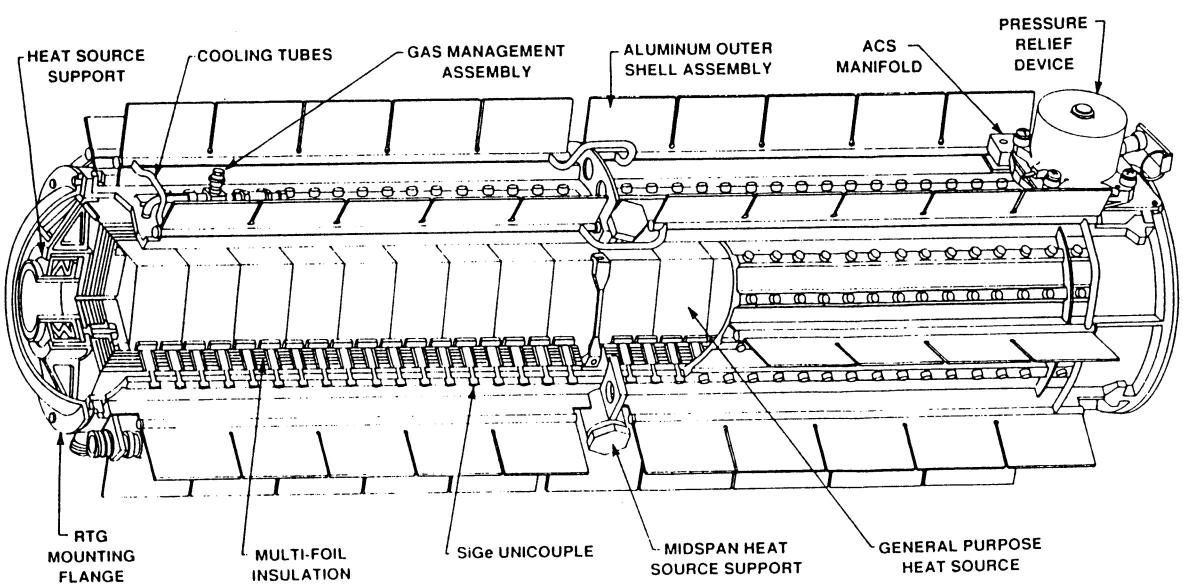

Figure 3. Cutaway drawing of the general-purpose heat source radioisotope thermoelectric generator (GPHS-RTG). The GPHS-RTG consists of two major components: the general purpose heat source (GPHS) and the converter which converts the thermal power generated in the GPHS into electrical power by means of 572 thermoelectric elements called "unicouples." The overall diameter of the GPHS-RTG with fins is 42.2 centimeters (about 16.6 inches). The mass of the GPHS-RTG is about 55.9 kilograms (weight of about 123 pounds). The GPHS-RTG produces over 300 watts of electrical power at the time of assembly. The GPHS-RTG has no moving parts and should provide power for over 20 years after launch.

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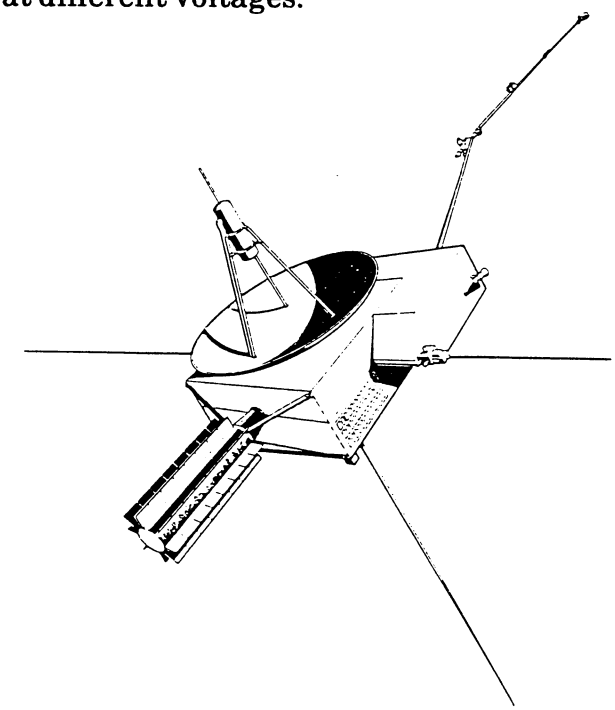

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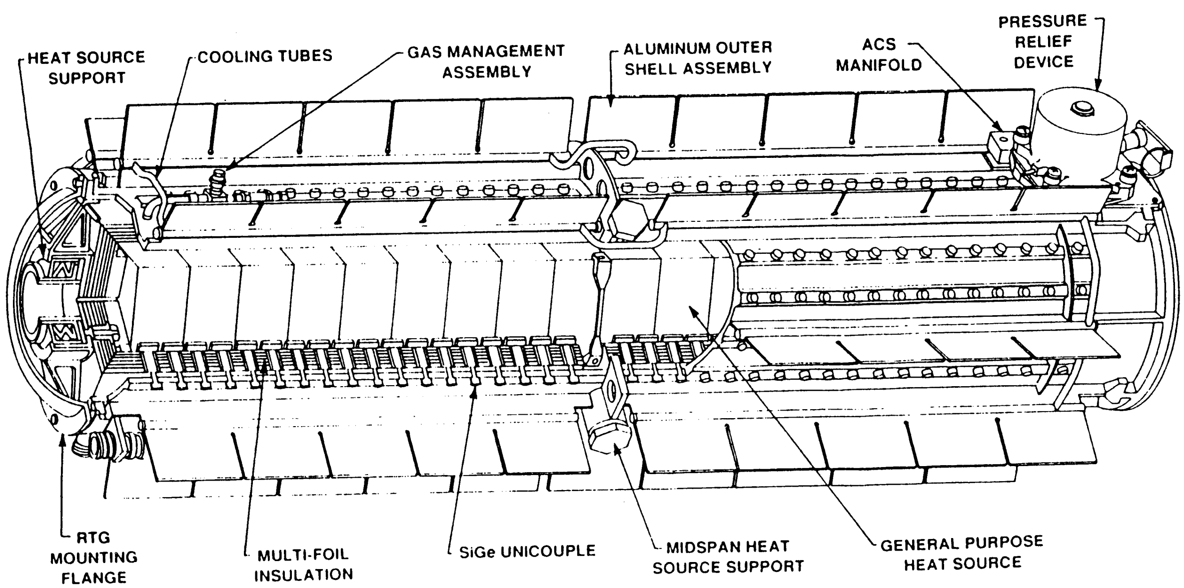

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Perhaps more important was the discovery that actual RCA practices had gone beyond documented specification and process requirements, which led to the explicit written incorporation of these practices along with more detailed instructions, tighter limits, control of more parameters and more detailed descriptions and control of the facility conditions. Facility changes and improved training were completed and a real-time trend analysis system was implemented to record and track key parameters, enabling prompt consideration of process deviations [GE 1991].

Developing a New Radioisotope Heat Source. The radioisotope heat source that powered the GPHS-RTG was a new design that had improved safety features designed to immobilize the plutonia fuel under all credible accident scenarios, including impact on Earth following a postulated atmospheric reentry from space [Snow & Zocher 1978, Snow *et al.* 1978, and Schock 1980].

Production of the radioisotope heat source components ran into a common problem: every time a component moved from the laboratory to production, defects were discovered. In each case, inter-laboratory teams were established to discover the cause of the defects.

Developing the Assembly and Testing Facility. The GPHS-RTG program was operationally conducted in a new way: a DOE laboratory instead of the system contractor had responsibility for the assembly and testing of the power sources [Amos and Goebel 1992]. In order to accomplish this transition in the shortest possible time and ensure the safety of the RTGs, a team comprised of representatives from the system contractor (GE), the heat source laboratory (DOE's Mound Plant) and other involved contractors and laboratories was employed to work the design, procedures and training in real-time. The use of practice hardware, detailed procedures, real-time check-

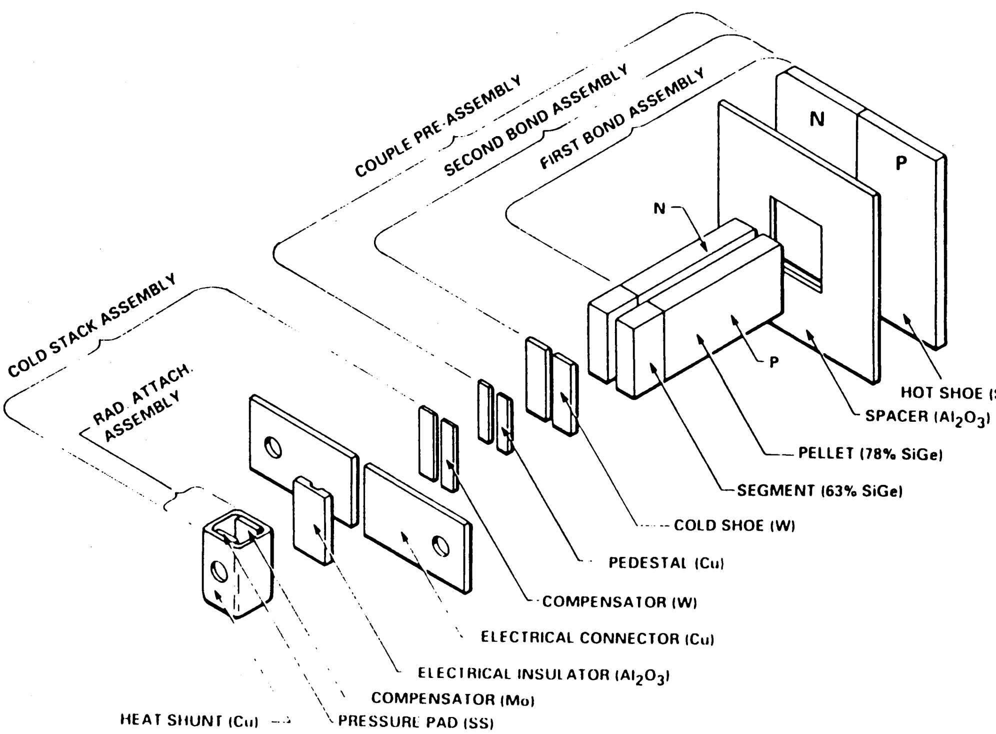

Figure 4. An exploded view of the silicon-germanium unicouple (thermoelectric element). 572 of these unicouples are used in each GPHS-RTG. The unicouple length is 3.11 centimeters and the hot shoe measures almost 2.3 centimeters by 2.3 centimeters. The hot shoe operating temperature is about 1305 K.

ing, and constant training allowed the successful completion of the Galileo and Ulysses power sources. One innovation in the assembly and testing operation was to use a team of knowledgeable people to examine the next steps in a process just before they were to be completed to ensure that nothing in the process, tooling or facilities could damage the RTG. In effect, this was a sort of "advance quality assurance."

A Unique Management Approach

The GPHS-RTG program involved a limited "production run" within a tight schedule and budget which required each power source to meet specifications—there was no extra hardware or time for mistakes. Success mainly was due to well-defined objectives with real-time problem solving and a minimum of bureaucratic interference. The GPHS-RTG program was spared the excesses of outside advice and oversight that seem to plague most government programs today. The government program office had full authority and responsibility to manage the program within the budgetary and schedular constraints.

The GPHS-RTG program was managed from a small, proactive headquarters-level government program/project office that numbered at most about 12 people, including two secretaries and several managers who had other responsibilities. This office was totally responsible for the program, including the system, heat source, safety, reliability and quality assurance, and technology, which spanned four contractors and seven government laboratories (totaling over 300 people during the different program phases). All contracting and budgeting were done through headquarters, and the laboratory program guidance was issued from headquarters. A program with as many organizations as the GPHS-RTG program had cannot delegate responsibility to the field and still expect the program to come together. In essence the GPHS-RTG program was conducted with centralized control and decentralized execution.

Some key advice from the government program office's quality assurance program requirements includes making sure that [Sommer 1982]:

- Requirements are clear and unambiguous.
- Design requirements are adequately specified.
- The design is compatible with fabrication, nondestructive testing, inspection capabilities, and that the fabrication process is adequate to yield the necessary quality hardware as defined in the contract or program guidance.
- The design lends itself to testing at various levels of assembly and the testing process is adequate to yield the required information without degradation of hardware quality.
- The design lends itself to assembly, operations, storage and shipment.
- Parts, materials and processes are selected on the basis of proven experience or qualification for the intended use.
- Cleanliness and contamination specifications for materials and processes are consistent with design requirements.
- Safety requirements are specified and procedures are established to ensure their adequate implementation.

An interagency agreement between NASA and DOE defined the roles and responsibilities for the two agencies in the GPHS-RTG program. Top-level interface specifications and drawings were jointly signed off by DOE and the NASA project office at the Jet Propulsion Laboratory (JPL). The top-level requirements were in turn translated into contractual requirements for GE and into program guidance to the national laboratories. All requirements were worked with a view toward achieving mutual agreement between the involved organizations. GE was the system contractor and DOE's Mound Plant, working under the system requirements, was responsible for all of the heat source activities.

To meet the schedule meant turning on everything at once (a technique now often referred to as "simultaneous engineering," "concurrent engineering" or "integrated product development"). Reliability, quality assurance and safety were incorporated from the beginning. This parallel approach meant constant attention to the technical and programmatic interfaces. The program office personnel met regularly with the contractors and laboratories, typically on a monthly basis and more often as the situation dictated. Program office personnel served on the major teams that were established to work the various problems. The customer (JPL) was also regularly involved in the program. In the beginning of the heat source production campaign, monthly meetings of the key organizations permitted a number of interface issues to be worked quickly between the involved parties. Throughout the program, the participants engaged in regular, informal contact and discussion. Hardware, tooling and facilities were visited on a regular basis. On-site representatives were used as needed (for example, GE had one or more representatives at Mound; DOE and its quality assurance laboratory had representatives at GE; and on occasion, Mound personnel worked directly with personnel at the other heat source laboratories). Problems were not allowed to fester. In order to meet the schedule, each problem had to be addressed as it occurred.

The program was managed with a strong focus on schedule—the overriding objective was to deliver the requisite RTGs to specification on time and within budget. There were real-time inspections, materials review boards (MRBs), failure review boards (FRBs), and process reviews. The quality control inspectors were on the line doing their work in real time. Faxes and telephone calls were used to expedite the approval process—the schedule did not permit the bureaucratic practice of letting the mail room handle the distribution of actions.

One of the outstanding resources of the GPHS-RTG program was the heritage of experienced personnel (the "RTG culture") at most of the facilities. Most of the key people knew each other and understood their capabilities and roles. These people were in the program for the "long haul" and they had a positive "can do" attitude. All of the organizations had a history of involvement in RTG programs. As a result, the various organizations were able to work as a team, forming task forces as needed to solve problems. Responsibilities, accountability and control were well defined. The government program office also maintained a check-and-balance approach as needed through the judicious use of its own people and independent organizations.

The government program office used an operations analysis to assess the facilities, procedures and training at each site before the RTG or heat source arrived there. The operations analysis team looked at the various environments to which the RTG hardware might be exposed. The team included representatives from the other organizations involved.

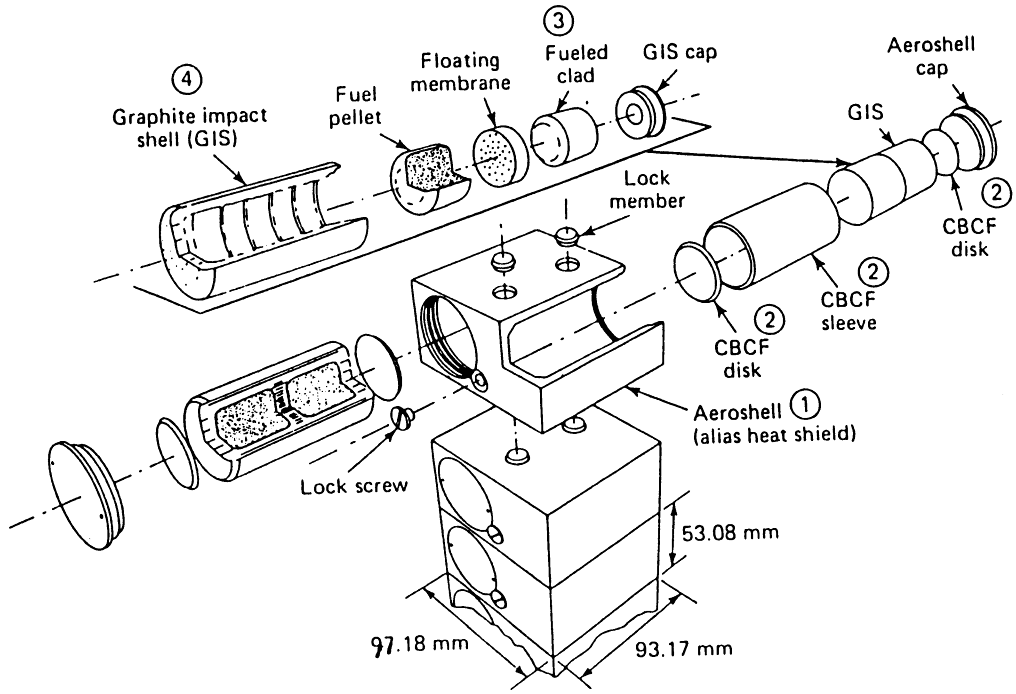

Figure 5. Cutaway view of the general-purpose heat source (GPHS) module components and assemblies. Eighteen of these modules are in each GPHS-RTG.

Readiness reviews were conducted at each step in the process to ensure that documents were complete, that the requirements and test plan were complete, that the incoming articles were as built (identification and verification of the configuration), and that the test equipment was calibrated. Tooling was under control. Data packages were prepared to document the hardware and how it was built and tested. Finally, before the GPHS-RTGs were shipped to the Kennedy Space Center (KSC), a formal flight readiness review was conducted; it covered the contractual requirements and the flight worthiness of the hardware and checked to ensure that everything was in place for the shipment.

The government program office controlled the Class I changes to specifications and procedures; that is, changes dealing with safety, performance, reliability, interchangeability, qualification status and interface characteristics ("form, fit, function, and safety"). The government had representatives on the MRBs and the FRBs.

One of the lessons from past RTG programs was the need for constant attention to detail. Everything must be documented and tracked. Full documentation is just good engineering and scientific sense because it facilitates investigations into problems that may come up. Relying on specifications is no guarantee of the quality of the final product—the processes must be under strict control, too. Like its predecessor programs, the GPHS-RTG program began with component testing and moved on to subsystem and full-up system testing before the flight hardware was built and flown. (It is worth noting that even while today's quality programs emphasize one-time inspection, the GPHS-RTG program did uncover cases where receiving inspections caught problems not identified in the sending inspection.)

To meet the schedule meant freezing the design as early as possible and sticking to that design, unless problems necessitated consideration of a change. Every program is faced with the better idea or technology that comes along after the design is frozen, but as long as the existing design meets the design requirements, changes should be avoided because they can cause enormous confusion and delays. The old adage, "better is the enemy of good enough," is true.

In addition to sticking to the frozen design, the program must also stick to the test program and avoid unnecessary tests. The GPHS-RTG program was a flight program, not a research program.

Finally, it is important to return to the matter of people. Large, complex programs cannot be run by committee or diffuse management structures. To paraphrase Charles Sheffield, large projects have been built in the past and in their day they, too, challenged the state of the art. "The problems that they ran into were often horrendous and all different, but the really successful... have had one thing in common: associated with each, obsessed by each, you will find a single individual... The Manhattan Project is a prime example of a group effort. There were dozens of scientists working on the atomic bomb whom history has judged as geniuses. But at the top, following everything at a level of detail that even his fellow workers found mind-boggling, was one man: Robert Oppenheimer. Through the 1960s, when NASA had just nine years to put a human on the Moon, a handful of staff—Wernher von Braun, George Mueller, and George Low—poked into everything and tracked everything." [Sheffield 1991.]

Fortunately for the GPHS-RTG program, there were also a handful of people who checked into and tracked everything. These people were obsessed with the success of the GPHS-RTG program and they were personally committed for the duration of the program.

Lessons Learned

From the foregoing and the author's experiences in managing the safety and nuclear operations elements of the GPHS-RTG program, the following lessons were learned:

- Dedicated, trained people working as a team are the first key to success. All of the organizations involved in the program need to understand their individual roles and responsibilities. Accountability is crucial, but with accountability must go the authority and the resources to do the job.
- The design requirements should be fixed early in the program and the principal ones should not be changed except as required by the exigency of the program and then only through a formal, disciplined process of reviews and approvals.
- A central program office should have complete authority and responsibility to manage the program. There must be a centralized decision process for the "form, fit, function, safety" of the program. Outside reviews and "help" must be minimized and the budget should match the requirements and schedule.
- Training is essential in every aspect of the program. Technicians should be formally qualified (preferably with written certificates) for each process they are asked to perform. The training must be realistic and current, and done with realistic practice hardware.
- The procedures must be sufficiently detailed to cover every step of the process. Nothing in the procedures should be left to chance or interpretation. (The author found one case in which a procedure called for a component to be "washed"

but the washing was not specified. One technician did it one way; another technician did it a different way. Needless to say, product differences were found.)

- The facilities must be clean, orderly, worker friendly and suitable for the tasks. (In checking into a problem with one metal alloy, the author found the metal pressing was being done in an old building with a hole in the roof—and the hole was above the location where the material was being worked!) It helps immensely if the facilities, equipment and tools are dedicated to the program and kept under the control of the program. If not, there must be formal reviews each time before the facilities and equipment are used to ensure that they are ready for the process. (In another program the author worked on, some technicians working on a second program borrowed a gas management console, and when it was returned, the valve settings had been changed and no one was informed. The technicians on the first program did not check this and almost destroyed a power source by admitting the wrong gas.)

- The laboratory work done to develop a process or material or component must be done with the same documented rigor as the final production work. Invariably one of the reasons that the production people found problems with a laboratory-developed product was that the laboratory people were not using the same quality control inspection techniques and tools as the production people. Also, there is a tendency in laboratory work not to document the work to the detail necessary to develop production procedures that will yield a reproducible product.

- To meet the schedule, the whole team must operate with a sense of urgency. Paperwork, reviews and approvals must not be allowed to lag. Quality control inspections and review board activities must be done in real time. However, at no time should schedule be the excuse for not producing a quality product that meets the requirements.

- A test philosophy of building and testing hardware through increasing levels of assembly should be employed. For the GPHS-RTG program, the thermoelectric elements were first built and tested, followed by the testing of 18-element modules. Then full-scale engineering units were built and tested for structural, mass properties and electrical tests. After the engineering units had proven the design, a full-scale radioisotope-heated qualification unit was built and tested to qualify the overall RTG design. Finally, the four flight RTGs were assembled and tested. Supporting this test program were engineering analyses, component testing and materials characterizations, and throughout there was a constant attention to detail.

- There must be agreement between the sender/producer and the receiver/user on the inspection procedures and the inspection tools to avoid problems where the producer sends something that passes the producer's inspection only to see it rejected by the user.

- Independent operational analyses and advanced process reviews must be conducted to ensure that personnel and facilities are ready to receive and work on the hardware. With limited hardware, the protection of the product is of paramount importance.

Four flight power sources (three flight RTGs and a common spare) were successfully assembled and tested for use on the Galileo and Ulysses spacecraft. The three GPHS-RTGs in use on the Galileo and Ulysses spacecraft have met all power performance requirements to date [Bennett *et al.* 1994]. In summary, the GPHS-RTG power sources performed as required, were delivered when required, and were completed within the cost envelope established by NASA and DOE. The GPHS-RTG program was successfully completed largely because of an experienced, dedicated team working under a small program office with focused objectives and no outside interference.

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