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**ANALYSIS OF POSSIBLE STRATAGEMS FOR ENHANCING
THE EOM POWER OF RTGs FOR THE CRAFT MISSION**

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**For presentation at the
26th Intersociety Energy Conversion Engineering Conference
Boston, Massachusetts
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ABSTRACT

The upcoming CRAF and Cassini missions originally were each baselined to use two RTGs identical to those flown on the recent Galileo and Ulysses missions. Fairchild analyses showed that two such RTGs could meet JPL's originally specified power demands. However, JPL subsequently raised both the power demand profile and the duration for both missions, to the point where two standard RTGs could no longer provide the desired power margin. Each mission can be satisfied by adding a third RTG, and in the case of the Cassini mission the use of three RTGs appears to be unavoidable. In the case of the CRAF mission, there appeared to be a possibility that modest modifications of the RTGs' design and/or operating scheme may meet the missions' power demand (including specified contingency reserves) without the addition of a third RTG. The potential saving in cost and schedule pressure prompted Fairchild to undertake a study of various obvious and not-so-obvious power-enhancing stratagems to determine whether they could reach the desired goals, either singly or in combination. The present paper describes the various stratagems investigated by Fairchild, and discusses their drawbacks and their effectiveness. The analytical results indicated that a combination of relatively modest RTG modifications that could be implemented in time for the mission could come very close to meeting the CRAF power demand goals specified by JPL. However, since even with the modifications the two RTGs did not provide sufficient margin for possible further growth in power demand, the JPL project team ultimately decided to use three RTGs for the CRAF mission also. This had the decisive advantage of eliminating the need for load switching to reduce the power demand peaks. The purpose of this paper is to document the various power enhancement schemes analyzed and their computed effectiveness, for possible future applications.

INTRODUCTION

The Jet Propulsion Laboratory (JPL) is in the process of designing a spacecraft for NASA's upcoming CRAF and Cassini missions [1]. The CRAF (Comet Rendezvous and Asteroid Flyby) spacecraft, planned for a 1996 launch, will fly by at least one asteroid, and

rendezvous with a comet, where it will conduct scientific observations for more than two years. The Cassini spacecraft, scheduled for a late-1995 launch, will also fly by at least one asteroid, fly by Jupiter, orbit the planet Saturn, repeatedly fly by a number of Saturn's moons, and send an instrumented probe, called the Huygens probe, into the atmosphere of Saturn's moon Titan.

Both missions will be launched by unmanned Titan-4/Centaur-G' boosters, and both are part of a series which will use a new generation of cost-effective modular spacecraft (Mariner/Mark 2) that can easily be modified to accomplish a variety of missions to comets and asteroids and to the outer solar system. [2]

Because of their great distance from the sun, both missions will be powered by RTGs (Radioisotope Thermoelectric Generators). Since the planned schedules do not allow sufficient time for development and flight qualification of new RTG designs, both missions will use generators that are essentially identical to the GPHS-RTGs [3,4,5] flown on the recently launched Galileo and Ulysses missions. JPL's original plans called for two such RTGs on each mission. Their construction will be under the direction of the U.S. Department of Energy's Office of Special Applications (DOE/OSA), which commissioned Fairchild Space Company to conduct RTG design and integration studies in support of JPL's mission and spacecraft design efforts.

ANALYTICAL RESULTS

Although the RTGs for the CRAF and Cassini mission are identical to those used for Galileo and Ulysses, their placement on the spacecraft is significantly different. Each spacecraft requires two or three RTGs, which are close enough to each other to obstruct their view of space. These mutual obstructions lead to unsymmetrical distributions of temperatures, voltages, and currents of the series-parallel couple network in each RTG. Previous papers have described the special methods developed by Fairchild for analyzing the effect of unsymmetrical obstructions on RTG performance [6,7,8], and the effect of fuel decay and thermoelectric degradation on the long-term performance of the mutually obstructed RTGs [9].

JPL's original baseline design called for two RTGs per spacecraft, as illustrated in Figure 1. This configuration was analyzed for various RTG separation angles ranging from 16° to 35°. The effect of separation angle on BOM performance is illustrated in Figure 2, which shows the effect of maximum hot-junction temperature on electrical output for each of four separation angles.

RTGs used on previous space missions were designed for a maximum hot-junction temperature of 1000°C. For that temperature, the figure shows that the power loss due to the mutual obstruction between the RTGs ranges from 15.5 watts (or 5.1%) for a 16-degree separation angle to 4.0 watts (or 1.3%) for the 35-degree separation that was subsequently adopted as JPL's baseline design.

For that separation angle, the computed effect of fuel decay and thermoelectric degradation on RTG performance is illustrated by the parametric curves shown in Figure 3. For various fuel loadings, the solid curves show the variation of RTG power with time. For each solid curve, the figure shows the thermal power (in each of the 18 heat source modules) and the corresponding plutonium enrichment (for the same fuel density as that used in the Galileo RTGs). The numbers listed are for two points in time: at the chemical separation of the plutonium from the irradiated neptunium-237 targets (BOL), and three years later at launch (BOM). Thus, the figure can be employed as a useful design tool by the CRAF and Cassini mission planners.

Figure 2. Effect of Separation Angle θ Between RTGs on Power-Versus-Temperature Characteristics

Figure 1. CRAF/CASSINI Spacecraft, Initial Design

Figure 3. Effect of Fuel Loading on RTGs' Power and Temperature Histories (35° Separation, 18 Heat Source Modules, 36 Couple Rings, 3" Fins, 30 Volts/RTG)

For each solid curve in Figure 3, its intersections with the dashed curves indicate the decrease of the RTG's average hot-junction temperature with time. The bold solid curve in the figure represents the fuel loading in the Galileo RTGs, and the bold dashed curve represents the 1000°C hot-junction limit adopted in previous missions. Note that this limit is exceeded by the BOM temperatures at higher fuel loadings. But modest excesses may be allowed, since the results displayed in Figure 3 already include proper allowances for increased degradation at the higher temperatures, based on results of (accelerated) tests conducted above 1000°C.

Figure 3 shows that increasing the BOM thermal power (by increasing the fuel loading) leads to a substantial increase of the RTG's electrical power at the beginning of mission, but that this benefit diminishes towards the end of mission, particularly for long mission times. This comes about because higher thermal powers result in higher temperatures and therefore higher degradation rates. In fact, at unrealistically high hot-junction temperatures (>1100°C) increasing the thermal power can actually decrease the EOM electrical power.

PROGRAMMATIC IMPLICATIONS FOR CRAF AND CASSINI MISSIONS

Prior to September 1990, only fragmentary information about the power demand for the two missions had been issued by JPL. Preliminary analyses using the above-described Fairchild methodology indicated that JPL's initial two-RTG plan would comfortably meet the then-specified power demand for the CRAF mission, and would come close to meeting it for the Cassini mission. The then-existing status is summarized in Table 1.

Table 1. Power Margins in CRAF/CASSINI RTGs (Aug. 1990)

MISSION	CRAF				CASSINI			
Event	Rendezvous		Perihelion		Arrival		EOM	
Years After Launch	5.01		7.61		6.50		10.30	
Mission Power Requirement (watts)	458		432		524		478	
RTG #	1	2	1	2	1	2	1	2
Age of Fuel at Launch (years)	3	13	3	13	3	3	3	3
Thermal Power per H.S. Module (watts)								
At Fuel Encapsulation	252	252	252	252	252	252	252	252
At Launch (BOM)	245	227	245	227	245	245	245	245
Hot-Junction Temperature (°C)								
At Launch	1000	952	1000	952	1000	1000	1000	1000
At Event	973	924	960	910	966	966	946	946
Electrical Power (watts)								
At Launch	305	267	305	267	305	305	305	305
At Event	265	237	253	226	258	258	241	241
Total at Event	502		479		516		482	
Power Margin (watts)	44		47		-8		4	

In late September 1990, as the result of ongoing mission studies, JPL issued much more detailed (and significantly higher) power demand goals to meet the missions' engineering and science requirements. Figures 4 and 5 display these power demand goals for the CRAF and Cassini missions in the form of histograms that have been superimposed on the power supply capability curves for two RTGs. As can be seen,

for thermal powers equal to those on Galileo and Ulysses (245 watts BOM per module), the original JPL plan falls significantly short of meeting the revised power demand goals, particularly in the case of the Cassini mission.

Figure 4. Power Demand Versus Supply, for CRAF Mission (35° Separation, 18 Heat Source Modules, 36 Couple Rings, 3" Fins, 30 Volts/RTG)

Figure 5. Power Demand Versus Supply, for CASSINI Mission (35° Separation, 18 Heat Source Modules, 36 Couple Rings, 3" Fins, 30 Volts/RTG)

Subsequently, in late October 1990, the power shortfall was further exacerbated when JPL specified additional increases in power demand and mission duration, for both missions. The mission duration for CRAF was increased from 7.6 to 9.6 years, and the duration of Cassini was increased from 10.7 to 12.0 years. These time increases were introduced to allow additional gravity-assist maneuvers, in order to provide substantially higher mass margins for the spacecraft.

Because the twice-revised power demand goals for both missions significantly exceed the capability of two standard RTGs, JPL proposed the use of three instead of two RTGs for each mission. In the case of the Cassini mission, the revised power demand is so high that use of the third RTG appears to be unavoidable. But in the case of the CRAF mission, there was at least a possibility of meeting the revised power demand profile with two RTGs, by relatively modest modifications of their design and/or operating procedure. If that were possible, it would result in significant cost savings and improved schedule margins. These potential benefits prompted Fairchild to investigate a variety of stratagems, to determine whether they could meet the revised power demand for the CRAF mission.

The magnitude of the problem is illustrated in Figure 6, which compares the predicted power output of two standard GPHS RTGs (for various fuel loadings) with JPL's latest power demand goals for the CRAF mission (furnished by R. Campbell on 11/6/90).

Figure 6. Revised CRAF Power Demand (11-6-90) Versus Output of Two Standard RTGs
(35° Separation, 18 Heat Source Modules, 36 Couple Rings, 3" Fins, 30 Volts/RTG)

The CRAF power demand profile is shown in the form of a histogram which covers the cruise phase ($0 < t < 7.1$ yrs) and the comet science phase ($7.1 < t < 9.42$ yrs). As can be seen, the two standard RTGs can meet cruise power goals, but with an achievable fuel loading (240 to 245 thermal watts BOM per heat source module) they fall short of meeting the JPL-specified 524-watt goal for the comet science phase. For 245-watt heat source modules, the shortfall is seen to be about 13 watts at the beginning and 35 watts at the end of that phase. Thus, unless JPL can reduce its power requirements by that amount (e.g., by reducing the system-level and subsystem-level contingency reserves built into their estimates), the two RTGs would have to be modified to increase their power output at EOM while still meeting the cruise power demand.

OPTIONS FOR INCREASING THE POWER AT ENCOUNTER

There are several design or operational modifications that could be used singly or in combination to increase the RTG's power output:

1. "Stretch" the standard RTG, to raise the number of heat source modules from 18 to 19 or 20.
2. Increase the fuel loading by increasing its density and/or its isotopic enrichment.
3. Delay venting the RTG's cover gas, to reduce the thermoelectric degradation during the coast phase.
4. Reduce the number of thermoelectric couples and/or the leg area in each couple (to increase the temperature drop between junctions and to raise the efficiency).
5. Increase the size of the radiator fins, to decrease the RTGs' cold-junction temperatures.
6. Provide external switching to supply the desired 30-volt output with the two RTGs in series during the power-rich cruise phase and in parallel during the power-lean encounter phases. (Operating each RTG at 15 instead of 30 volts increases the couple currents and the Peltier cooling rates, which lowers the hot-junction temperatures and the thermoelectric degradation rates.)
7. Use controlled-rate venting of the helium generated by alpha decay to spoil the thermal insulation and lower the hot-junction temperatures and power output just enough to match the power demand profile. (This would minimize the thermoelectric degradation.)

The above options, used either singly or in various combinations, were subjected to detailed analyses, to assess their effectiveness in closing the gap between power supply and demand, and to determine which - if any - warrant further investigation. The computed results are presented below. In each case, the results are compared with a histogram of the power demand goals furnished by JPL on 11/6/90. It is recognized that

these goals are likely to change as the result of changed science demand and as the result of reducing the assumed multi-level contingency reserves. But it is useful to employ the same histogram as a common yardstick, to facilitate comparison of the various options.

"Stretching" the RTG length by 2 or 4 inches to allow raising the number of heat source modules from 18 to 19 or 20 would be a straight-forward method of increasing the RTG's power output. As shown in Figure 7, even the 19-module RTG would virtually meet all of JPL's power demand goals. However, such a design change would constitute a significant deviation from the standard RTG design, and would therefore require some new qualification tests. (Note that the curves for 19 and 20 heat source modules were obtained by simple scaling, which implicitly assumes the same efficiency as the 18-module case. This is conservative, since efficiency generally increases with power output, because end losses consume a smaller fraction of the thermal power in larger RTGs.)

Figure 7. Effect of "Stretching" the Standard RTG
(35° Separation, 245 Watts BOM per Heat Source Module, 36 Couple Rings, 3" Fins, 30 Volts/RTG)

Increasing the fuel loading is another obvious stratagem for raising the RTGs' output, since it would increase the electrical power by raising both the thermal power and the converter efficiency. As shown by Figure 6, increasing the BOM thermal power to ~265 watts per heat source module would raise the EOM power to the specified level. But this option may not be doable, at least within the available time.

Significantly increased fuel density, which can be achieved by using higher pressures and/or

temperatures during pellet formation, may lead to increased fuel cracking, even before impact; and would probably require additional safety tests, which can be quite costly and time consuming.

The alternative of increasing the fuel enrichment may not be possible without new fuel production, which probably will not be available in time in the required quantities. Even if higher-enrichment fuel did become available, beyond a certain enrichment the resultant higher fuel temperature could also lead to problems in pellet formation requiring costly and time-consuming new fabrication development and safety tests. In any case, until new fuel is available we are limited to the present inventory. A recent study by M. Eck [10] indicates that the present inventory, by proper selection, would yield an isotopic enrichment of 82.9% at the time of chemical separation of the plutonium. This corresponds to a BOL thermal power of 247.3 watts per heat source module, which would decay to a BOM power of 241 watts at launch, 3.25 years later.

The third stratagem for raising the encounter power, **delayed venting of the RTG's cover gas**, could be used to spoil the converter's multifoil thermal insulation until the mission's comet phase, when the maximum output power is needed. Spoiling the thermal insulation would significantly decrease the RTG's hot-junction temperatures and therefore its degradation rate during the mission's cruise phase, making more power available during the comet phase. Unfortunately, the same cover gas that increases the comet science power also diminishes the cruise power. Thus, delayed venting could be quite useful for missions in which the required ratio of cruise power to encounter power is low, but much less useful for a mission like CRAF where that ratio has quite a high value (468 w/524 w = 89%).

Figure 8 presents the results of the Fairchild analysis of two RTGs with 245-watt (BOM) heat source modules for three different cover gases: xenon, argon, and a mixture of 73% argon and 27% helium. These are the only cover gases for which RTG test data are available. This figure assumes venting of the cover gas after eight years, and confirms that delayed venting has the anticipated effect of increasing the power at EOM. The eight-year venting delay would increase the power of the two RTGs at 12 years by about 30 watts for the argon-helium mixture, almost as much for pure argon, and about 21 watts for the least conductive gas, xenon.

These EOM power increases are respectable improvements, but unfortunately all of these cover gases lead to excessive losses during the mission's cruise phase. The least excessive power loss is obtained with xenon, the inert gas with the lowest thermal conductivity. However, to be effective this would require a means of preferentially discharging the alpha-generated helium while retaining the xenon, e.g. by use of a selective vent. Selective vents made of Viton were used in the Viking RTGs, but the adequacy of those vents for the present application has not been demonstrated.

Figure 8. Effect of Delayed Venting for Various Cover Gases

Figure 9. Effect of Delayed Xenon Vent on Output of Two Standard RTGs
(35° Separation, 18 Heat Source Modules, 36 Couple Rings, 3" Fins, 30 Volts/RTG)

The effect of delayed xenon venting for two delay times is illustrated in Figure 9. Two output profiles are shown, one for venting at the beginning of the comet science phase (7.1 yrs), and one for venting just prior to the Earth flyby (4.2 yrs). As can be seen, the power demands for Earth flyby, asteroid flyby, and late cruise cannot be met if venting is delayed until comet rendezvous, but can be met if the RTG is vented just before Earth flyby. Neither option meets the power demand peak for decontamination. Both options meet the demand goal at the beginning of the comet science phase, but neither meets it at the end of that phase. The 7-year vent case misses the required EOM goal by 16 watts, and the 4.2-year vent case misses by 22 watts. Both of these power deficits are smaller than for the vent-at-launch case (35 watts), but they are still not good enough. Does that mean that the use of delayed venting is of no interest? Not necessarily. It may not be adequate when used by itself, but may be adequate in conjunction with one of the other stratagems (e.g., reduced number of couples).

The fourth stratagem investigated involves reduction of the thermoelectric area, either by reducing the number of couples in the RTG, or by reducing the leg area in each couple. The former option is easier to implement, because it avoids the need of developing a new couple. In either case, reducing the thermoelectric cross-section of the RTG increases the temperature drops between hot and cold junctions, which increases the conversion efficiency and therefore the RTG's power output for a given thermal power. The standard GPHS-RTG contains 36 rings of 16 couples. To evaluate this stratagem, we deleted some of these couple rings. The deleted couple rings were removed from the two ends of the RTG. This has the added benefit of improving the uniformity of the hot-junction temperatures, by compensating for the drop-off due to end losses.

Figure 10 compares the performance of the standard (vented-at-launch) 36-ring RTGs with those of the 34-ring and 32-ring designs; i.e., designs in which one or two rings have been deleted from each end of the RTG. As seen, these deletions lead to a substantial increase in the BOM output power. But, as shown, they do so only at the cost of substantially higher hot-junction temperatures. The consequent rise in degradation rates largely defeats the purpose of deleting the couple rings. As can be seen, for the 34-ring case increased degradation reduces the 27-watt gain in BOM power to only 4 watts by the end of mission; and for the 32-ring design the BOM power gain of 53 watts is reduced to a 13-watt power loss at EOM. All three cases fail to meet the EOM power demand goal. Thus, deletion of couple rings is not useful by itself, and would only be useful in conjunction with another method, to reduce the hot-junction temperature. Either delayed venting and/or longer fins may be used for that purpose.

Figure 11 displays the effect of delayed venting on an RTG with 32 couple rings. Results are shown for venting at launch and at 4.2, 5.0, and 7.0 years after launch. As expected, the later the venting the lower the degradation and the higher the EOM power. For

Figure 10. Effect of Deleting Unicouple Rings from Ends of 36-Ring RTGs
(35° Separation, 18 Heat Source Modules, 245-Watt BOM, 36 Couple Rings, 3" Fins, 30 Volts/RTG)

Figure 11. Effect of Delayed Xenon Vent on Output of Two 32-Ring RTGs
(18 Heat Source Modules, 245-Watt BOM, 3" Fins, 30 Volts/RTG)

venting at 7.0 years, the EOM power is increased by 45 watts, which essentially meets the EOM power demand goal. But as shown, it does not meet the power goal for Earth and asteroid flyby or for late cruise. Venting at 5.0 years meets the asteroid and late-cruise goals, but not the Earth-flyby goal. The only strategy that meets the Earth, asteroid, and late-cruise goals requires venting at 4.2 years, but this yields an EOM power gain of only 28 watts, which is 22 watts short of the EOM power goal.

Figure 12 examines the effect of varying the number of couple rings on the output of RTGs vented at 4.2 years. As can be seen, the 34-ring design results in reasonable temperatures and yields the highest EOM power (508 watts, which is still 16 watts short of the EOM goal).

Figure 12. Effect of Number of Couple Rings on Output on Two RTGs Vented at 4.2 Years
(18 Heat Source Modules, 245-Watt BOM, 3" Fins, 30 Volts/RTG)

The effect of increased fin size on performance is depicted in Figure 13. The fins have a trapezoidal cross section with a 0.015" fin tip thickness. The standard design has a 0.060" fin root thickness with a 3" root-to-tip height. This is compared with a 5" fin having a 0.100" root thickness. The larger fins lower the RTGs's housing temperatures and cold-junction temperatures. But, as shown, they also lower the hot-junction temperature by 19°C, so that there is virtually no change in ΔT or in BOM power. However, the lower hot-junction temperature does reduce the degradation rate, resulting in a 9-watt increase in EOM power. Thus, while larger fins are helpful, their benefit is not nearly enough to meet the EOM power goal. But it may be a useful design change in conjunction with other modifications.

Figure 13. Effect of Fin Size on Output of Standard RTGs
(35° Separation, 18 Heat Source Modules, 245-Watt BOM, 36 Rings, 30 Volts/RTG)

Figure 14. Voltage Switching Schematic

The next stratagem investigated is **voltage switching**. This is achieved by the addition of an external two-position switch which allows the two RTGs to be connected either in parallel or in series. The alternative circuit configurations are depicted in Figure 14. In either position, the RTGs are connected to a 30-volt load. As usual, the load voltage is regulated by a shunt dissipator. When the two RTGs are in parallel, each has an output of 30 volts. When they are in series, each has an output of 15 volts.

The resultant effects for a 34-ring RTG with 5" fins are shown by the curves of Figure 15, which were obtained by detailed analyses of the obstructed RTG at various voltages. The curve labeled "current" depicts the current-voltage characteristic of each RTG, and the other two curves show the corresponding variations of the output power and the hot-junction temperature. As can be seen, an output of 30 volts is close to the maximum-efficiency point (35 volts) while an output of 15 volts is way off-optimum. Lowering the RTG voltage to 15 volt drops the BOM power from 320 watts to 226 watts. But that would be acceptable during mission phases when the power demand is low.

As shown in Figure 15, lowering the RTG's voltage from 30 to 15 volts raises its current from 10.7 to 15.1 amps. This increases the Peltier cooling rate, and - as shown - lowers the hot-junction temperature from 1014°C to 968°C. The 46°C reduction in hot-junction temperature would greatly decrease the thermoelectric degradation rates during periods when the lower power output is sufficient to meet the demand.

Figure 15. Effect of RTG Voltage on BOM Power, Current, and Hot-Junction Temperatures
(35° Separation, 18 Heat Source Modules, 245-Watt BOM, 34 Rings, 5" Fins, 30-Volt Load)

This is illustrated in Figure 16, which shows the effect of voltage switching on the output of a 34-ring RTG with standard 3" fins, vented at launch. Voltage switching has a similar effect as delayed venting. But one of its advantages is that - unlike delayed venting - the process is reversible, and can be invoked repeatedly to meet temporary power demand peaks. Another of its advantages is that it does not require a selective vent for preferential release of the helium.

In the case illustrated by the dash-dot curve of Figure 16, the two RTGs operate in series (at 30 volts each) during the brief decontamination cycle at the beginning of the mission, during the Earth flyby, and during the asteroid flyby and the remainder of the mission. During the early cruise phases the two RTGs are in series, at 15 volts each, to reduce the thermoelectric degradation. As can be seen, this strategy meets all of the power demand goals except at the latter part of the comet science phase. Although the 505-watt EOM output for this case is seen to be 14 watts higher than what would be obtained without voltage switching, it is still 19 watts below the EOM power goal.

Figure 16. Effect of Voltage Switching on Output of 34-Ring RTGs, Vented at Launch
(35° Separation, 18 Heat Source Modules, 245-Watt BOM, 3" Fins, 15/30 Volts/RTG)

One way of further increasing the RTGs' power output is to combine voltage switching with larger radiator fins. As shown in Figure 17, this increases the EOM power by 11 watts (from 505 to 516 watts), and meets all of the power demand goals except those for the comet science phase. It exceeds that goal by 17 watts at the beginning of that phase, but falls 8 watts short of meeting it at the end of that phase.

Figure 17. Effect of Fin Size on Output of Dual-Voltage RTGs
(35° Separation, 18 Heat Source Modules, 245-Watt BOM, 34 Couple Rings)

Two more figures are shown to complete the picture for this option. Figure 18 depicts the effect of the number of couple rings on the output of the voltage-switched RTGs with 5" fins, and again shows 34 rings to be optimum. Finally, Figure 19 examines the effect of fuel loading on the output of 34-ring RTGs with voltage switching and 3" fins. It shows that if the BOM thermal power could be raised to 255 watts per heat source module, the EOM power goal could be met without changing the fins from their standard size.

Figure 18. Effect of Number of Couple Rings on Output of Dual-Voltage RTGs
(35° Separation, 18 Heat Source Modules, 245-Watt BOM, 5" Fins)

Figure 19. Effect of Fuel Loading on Output of Dual-Voltage 34-Ring RTGs with 3" Fins
(35° Separation, 18 Heat Source Modules, 15/30 Volts per RTG)

The final stratagem analyzed requires controlled-rate venting of the helium generated by the isotope's alpha decay. As indicated earlier in Figure 8, helium is such a good conductor and so effective in spoiling the thermal insulation that its retention above a continuum pressure would reduce the RTG's power output below the level required for the cruise phase. But if the helium pressure were low enough to be in the molecular-flow or transition regime, its thermal conductance could be low enough to yield the required power output. In principle, by careful control of the RTGs' helium pressure their power output could be regulated to just match the power demand histogram. Since that would minimize the hot-junction temperature history and thermoelectric degradation for the prescribed output profile, it would maximize the EOM power output.

Figure 20 shows the experimentally measured effect of helium pressure on a GPHS-RTG's power output and thermoelectric temperature drop relative to their respective vacuum values. The data plotted represent recent measurements by Mound [11] on the Galileo Qualification Unit (Q-1) after a five-year test. The measurements covered a pressure range from vacuum to 20.5 torr. As expected, the fractional decrease in power is approximately twice as great as that in ΔT .

Figure 20. Effect of Helium Pressure on RTG Power and Temperature
(Measured at Mound on Q-1 RTG)

As can be seen, at 20.5 torr the effect of increasing helium pressure on power and ΔT is greatly diminished, but has not quite leveled off yet. In other words, helium at that pressure is still somewhat below the continuum regime for this geometry. Extrapolation of the curves suggests that for this RTG geometry helium reaches a continuum at about 24 torr.

The experimental data are cross-plotted in Figure 21. The plot shows a linear relationship between temperature drop and power output. Note that the lower left terminus of the plot represents the case of a helium continuum. The plot should not be extrapolated beyond that point, since further increase of the helium pressure does not affect the RTG's temperatures or power output.

Figure 21. Effectiveness of Controlled Helium Pressure in Lowering Temperature at Partial Power

The results of applying this stratagem are illustrated in Figures 22 and 23. In both figures, the CRAF power demand profile is shown by the dotted histogram, and the power output of the two RTGs is displayed by the dashed curve. Figure 22 is for two standard RTGs, and Figure 23 is for two RTGs with 32 instead of 36 couple rings.

As can be seen, for the 36-ring RTG the power output matches the power demand for the first 8.2 years of the mission. At that time the required helium pressure drops to zero. After that time the RTGs are evacuated and their power output drops below the demand schedule. At the end of mission, the power output is 14 watts below the EOM demand.

Figure 22. Effect of Controlled-Rate Venting of Helium on Output of 36-Ring RTGs
(35° Separation, 18 Heat Source Modules, 245-Watt BOM, 3" Fins)

For the 32-ring RTG, Figure 23 shows that the power output and demand are matched throughout the mission. But the required helium pressure during the comet science phase is extremely low ($0.2 < p < 1$ torr).

Figure 23. Effect of Controlled-Rate Venting of Helium on Output of 32-Rings RTGs
(35° Separation, 18 Heat Source Modules, 245-Watt BOM, 3" Fins)

RECOMMENDATION

As can be seen, the controlled-rate helium-venting stratagem results in the lowest thermoelectric degradation, and - when coupled with reduced number of couple rings - can actually match the prescribed power demand schedule throughout the mission. Nevertheless, it was not recommended by Fairchild, because the required accurate control of the very low helium pressure shown was deemed to be impractical. The author's preference was for a combination of voltage switching, increased fin size, and 34 instead of 36 couple rings. This combination was deemed to be practical, and close enough to the previously flown Galileo and Ulysses design not to require new safety or qualification tests. Therefore, it was judged by the author that the above revisions could be implemented in time for the CRAF and Cassini missions.

The combined effectiveness of the above modifications relative to the CRAF power demand goals is displayed in Figure 24. The output of two standard GPHS RTGs is shown by the dashed curve, and the output of two modified RTGs (with voltage switching) is shown by the dotted curve.

Figure 24. Comparison of Standard and Modified RTGs
(35° Separation, 18 Heat Source Modules, 245-Watt BOM)

As can be seen, the latter, has an EOM output 26 watts above that of the standard RTGs, though still 8 watts below the EOM goal. Except for this shortfall at the end of the mission, which would have to be accommodated by a small load reduction, the modified RTGs meet all of the mission's power demand goals.

JPL DECISION AND STUDY CONCLUSIONS

Although the above two-RTG option could have resulted in substantial time and cost savings for the CRAF project, the JPL Project Office ultimately decided against its use. This was primarily because the project's science group wanted greater power margin to accommodate possible increases in power demand (above the present contingency allowances), and because the CRAF power demand schedule shown in Figure 24 assumes a good deal of load switching to reduce power demand peaks. Such load switching is undesirable, because of potential reliability problems. By using three RTGs for the CRAF mission, the need for load switching can be avoided. Also, addition of the third RTG permits elimination of the batteries.

After JPL's decision to employ three RTGs per spacecraft, the detailed thermal and electrical analysis of the obstructed RTGs had to be repeated for the three-RTG case. The mounting of the RTGs on the Mariner Mark-2 spacecraft is illustrated in Figure 25. JPL specified a separation angle of 34 degrees between neighboring RTGs. In this configuration, the middle RTG will run hottest (and degrade fastest) because it is blocked on both sides.

Figure 25. Mounting of Three RTGs on Mariner Mark-2 Spacecraft
(34° Separation Between Neighbors)

The coupled thermal and electrical analysis of the three-RTG configuration was carried out for BOM thermal powers ranging from 225 to 255 watts per heat source module. The analyses assumed a typical three-year interval between chemical separation (BOL) and

launch (BOM). The computed power histories of the three RTGs are shown parametrically in Figure 26. Each curve shows the fuel enrichment at BOL, the thermal power per heat source module and maximum hot-junction temperature at BOM, and the power output at EOM. The curves shown extend for 12 years, covering both the CRAF and Cassini mission durations.

Figure 26. Effect of BOM Thermal Power on Output History of Three Standard RTGs
(34° Between Neighboring RTGs, 18 Heat Source Modules per RTG)

As mentioned earlier, the CRAF and Cassini RTGs will be fueled entirely from existing inventory. For the earlier case of five RTGs (3 for Cassini and 2 for CRAF), selection of the highest-enrichment fuel yielded a BOM thermal power of 241 watts per heat source module. For the six-RTG case selected by JPL, it is necessary to include some lower-enrichment fuel, which drops the BOM thermal power of the freshly fueled RTGs to 238 watts per heat source module.

The corresponding power output histories for the two missions are displayed in Figures 27 and 28. Each figure shows two power output curves, representing two fueling options. The solid curve represents the preferred option, in which three freshly fueled RTGs are used for the Cassini mission while the CRAF mission employs two freshly fueled units and one aged spare (F5) left over from the Galileo/Ulysses program. This option is preferred because it favors the Cassini mission with its higher power demand. The second curve represents a back-up option, in which the lower-powered aged RTG is used for Cassini instead of CRAF. This is clearly less desirable, and would only be done if the three freshly fueled RTGs were not available in time for the Cassini launch.

Figure 27. CRAF Power Supply Versus Demand
(34° Between Neighboring RTGs)

Figure 28. CASSINI Power Supply Versus Demand
(34° Between Neighboring RTGs)

Figure 27 shows that either option satisfies the JPL-specified power demand goal for CRAF; and Figure 28 shows that the preferred option satisfies all of the Cassini goals except for some of the semi-annual 3-hour probe check-outs shortly before Saturn encounter. As can be seen, the supply falls short of meeting the demand during the last five check-outs for the preferred option, and the last eight check-outs for the back-up option. These shortfalls will have to be made up by JPL mission planners, e.g. by briefly shutting off non-essential loads during the last few probe check-outs.

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