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CASSINI RTG ACCEPTANCE TEST RESULTS AND RTG PERFORMANCE ON GALILEO AND ULYSSES

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ABSTRACT

Flight acceptance testing has been completed for the RTGs to be used on the Cassini spacecraft which is scheduled for an October 6, 1997 launch to Saturn. The acceptance test program includes vibration tests, magnetic field measurements, mass properties (weight and c.g.) and thermal vacuum test. This paper presents the thermal vacuum test results. Three RTGs are to be used, F-2, F-6, and F-7. F-5 is the back-up RTG, as it was for the Galileo and Ulysses missions launched in 1989 and 1990, respectively. RTG performance measured during the thermal vacuum tests carried out at the Mound Laboratory facility met all specification requirements. Beginning of mission (BOM) and end of mission (EOM) power predictions have been made based on these tests results. BOM power is predicted to be 888 watts compared to the minimum requirement of 826 watts. Degradation models predict the EOM power after 16 years is to be 640 watts compared to a minimum requirement of 596 watts. Results of small scale module tests are also shown. The modules contain couples from the qualification and flight production runs. The tests have exceeded 28,000 hours (3.2 years) and are continuing to provide increased confidence in the predicted long term performance of the Cassini RTGs. All test results indicate that the power requirements of the Cassini spacecraft will be met. BOM and EOM power margins of over five percent are predicted. Power output from telemetry for the two Galileo RTGs are shown from the 1989 launch to the recent Jupiter encounter. Comparisons of predicted, measured and required performance are shown. Telemetry data are also shown for the RTG on the Ulysses spacecraft which completed its planned mission in 1995 and is now in the extended mission.

INTRODUCTION

The GPMS RTGs which were developed for the Galileo and Ulysses missions have been previously described (Hemler, 1992). The units provide a nominal 300 W(e) with a fuel loading of 4,400 W(th), utilize silicon germanium thermoelectric elements, a molybdenum multi-foil thermal insulation system, and an aluminum outer shell. They weigh 55.3 kg, are 1 meter long and have a fin envelope of approximately 0.4 meters. The RTGs (F-1, F-4) on Galileo have

continued to exceed power requirements since the October 1989 launch. Similarly, the Ulysses RTG (F-3) has met all mission power requirements since the October 1990 launch. Two new GPMS type RTGs (F-6 and F-7) have been built under the Cassini program. The third unit, F-2, was built during the Galileo program but never fueled. The backup unit F-5 was built, fueled and flight qualified under the Galileo program. All of the units have undergone the Cassini flight acceptance program and are fully qualified for the scheduled October 6, 1997 launch to Saturn. Three RTGs will provide the power for the Cassini spacecraft and are required to provide a minimum of 826 W(e) at the beginning of mission (BOM) and 596 W(e) after sixteen (16) years (EOM). If the backup unit is used the BOM and EOM requirements are 799 W(e) and 579 W(e), respectively. Small scale 18 couple module tests were used to demonstrate the initial and long term electrical performance of the thermopile as discussed in the next section.

CASSINI MODULE TEST PROGRAM

The Cassini module test program consisted of three 18 couple modules. The purpose of the testing was to demonstrate that the uncouples made for the Cassini RTGs had the same performance characteristics as those used in the Galileo and Ulysses RTGs. Two modules were operated at higher than normal temperature to obtain accelerated life data and the third was operated at normal temperature. Tests results are shown in Figures 1 through 6. Figures 1 and 2 show the power output and internal resistance trends for the Cassini modules 18-10 and 18-11 operated at the accelerated temperature of 1408 K. Also shown for comparison are the trends for modules from the Galileo/Ulysses program. Similar plots are shown in Figures 3 and 4 for module 18-12 which was operated at the normal hot shoe temperature of 1308 K. Thermopile electrical characteristics were found to be in good agreement with previous units. Figures 5 and 6 provide the isolation resistance trends between the thermoelectric circuit and foil insulation system for modules operated at 1408 K and 1308 K, respectively. These trends demonstrate that the silicon nitride coating applied to the thermoelements to suppress sublimation and insure long life has been successfully reproduced in the Cassini uncouples. The comparative performance of the

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modules provides a high degree of confidence that the Cassini uncouples will provide the same electrical performance as the Galileo and Ulysses uncouples.

CASSINI FULL SCALE CONVERTER TESTS

RTG F-5

RTG F-5, which serves as the backup RTG for the Cassini mission, completed acceptance testing in October 1995. This unit was fueled at the end of 1984 and also served as the backup RTG for Galileo and Ulysses. Thermal vacuum power measured following vibration testing is shown in Table 1. Power output was 259 W(e) with a fuel loading of 4091 W(th). This is the power at the RTG connector pins. Three watts were added to the measured power to account for the gas venting differences between the test configuration and a flight PRD (pressure relief device). Based on these test results the BOM (beginning of mission) power output is projected to be 251 We with a fuel load of 4029 W(th). EOM (end of mission) power calculated from degradation models is predicted to be 183 W(e). The specification requirements are 249 W(e) BOM and 182 W(e) EOM. This unit had the longest storage time ever experienced by an RTG. Internal resistance trends during storage clearly show the reversible nature of the dopant precipitation process. Storage condition is short circuit with hot and cold junction temperatures of 1003 K and 493 K. Prior to launch the hot junction temperature is raised to over 1173 K during an argon to xenon gas exchange process. During this process, previously precipitated dopant redissolves in certain temperature regions of the thermoelements. This results in a decrease in internal resistance when the unit is returned to storage conditions as shown in Figure 7. The net result is that RTGs can be stored in the fueled state and exhibit very little power degradation other than that associated with fuel decay. In fact, F-5 with 10 years of storage between thermal vacuum tests degraded by only two percent when normalized to a constant fuel loading.

TABLE 1. MEASURED AND PROJECTED POWER OUTPUT

	Measured Watts	BOM Fuel	Projected Watts	
<u>UNIT</u>			<u>BOM</u>	<u>EOM</u>
F-2	301.2	4378	296	213
F-6	299.2	4407	294	212
F-7	302.6	4397	298	215
F-5	261	4029	251	183
F-2, F-6, F-7		13182	888	640
F-2, F-5, F-6		12814	841	608

RTG F-2

F-2 was tested as an ETG in 1983 then put in storage at Mound Laboratory. RTG F-2 was fueled at Mound in February 1996 and completed flight acceptance testing in September 1996. At the end of the thermal vacuum test the power output at the connector pins was 301.2 W(e) with a fuel loading of 4416 W(th). Two watts were added to the measured power to account for venting differences between the test configuration

and a flight PRD (pressure relief device). Table 1 summarizes measured and predicted performance. A BOM power output of 296 W(e) is predicted with a fuel loading of 4378 W(th). The specification requirement is 274 W(e). The large margin is due to the fact that the BOM fuel loading is higher than originally planned. A BOM fuel loading as low as 4,258 W(th) had been anticipated based on fuel enrichment and packing density estimates available earlier in the program. EOM power is predicted to be 213 W(e) with a specification requirement of 198 W(e).

RTG F-6

F-6 was fueled at Mound Laboratory in November 1996. Power output at the end of the thermal vacuum test was 299.2 W(e) at the RTG pins including a 2 W(e) GMV power correction. The fuel loading at that time was 4430 W(th). Table 1 summarizes measured and predicted performance. A BOM power of 294 W(e) is predicted with a fuel loading of 4407 W(th). The specification requirement is 276 W(e). The BOM power prediction has been decreased by 2 W(e) as an allowance for power loss due to air infusion. Gas tap data analysis showed higher than normal nitrogen levels. There will be some oxidation of moly foil which will increase heat losses slightly. EOM power is predicted to be 212 W(e) with a requirement of 199 W(e).

RTG F-7

F-7 was fueled in September 1996. Thermal inventory at the time of the thermal vacuum test in November 1996 was 4428 W(th). Power output at the end of thermal vacuum testing was 302.6 W(e) at the RTG pins including a 2 W(e) GMV power correction. Measured and predicted performance are given in Table 1. 298 W(e) is predicted for B.O.M compared to the requirement of 276 W(e). EOM power is predicted to be 215 W(e).

The total Cassini spacecraft BOM power specification requirement is 799 We using RTGs F-2, F-5, and F-6. Predicted power based on thermal vacuum measurements is 841 W(e) for a 5 percent margin. Similarly, for RTGs F-2, F-6, and F-7 the specification is 826 W(e) with a predicted power of 888 We for a 7 percent margin. EOM specification and projections are 579 We and 608 We, respectively, for RTGs F-2, 5, and 6 and 596 We and 640 We, respectively, for RTGs F-2, 6 and 7. EOM margins are calculated to be 5 and 7 percent.

GALILEO RTG PERFORMANCE

The Galileo spacecraft was launched in October 1989 on a six year journey to explore Jupiter and its surrounding moons. It arrived on December 7, 1995 after a circuitous route that involved Earth flybys in 1990 and 1992. It is interesting to note that the smaller Voyager spacecraft on a direct trajectory flew by Jupiter eighteen months after launch. Telemetry data have been provided by JPL during the Galileo mission and the power profile is shown in Figure 8 up to September 1996. The power is calculated at the spacecraft bus by multiplying the measured current from each RTG by the constant bus voltage. The accuracy of the measured current is estimated to be $\pm 1.2\%$ which corresponds to ± 3 We for the power from each RTG. Initial power was reported as 577 We which was 9 We above the specification requirement. RTG power output has continued to exceed spacecraft required power throughout the mission.

ULYSSES RTG PERFORMANCE

The Ulysses spacecraft was launched in October 1990 with a single RTG, F-3. Its trajectory led it to the planet Jupiter, where in February 1992, it received a gravitational assist that sent it out of the plane of the Earth's orbit and eventually over the poles of the sun. It passed over the south pole in October 1994 and the north pole in 1995. Ulysses completed its original 4.7 year mission in August 1995 and is now in an extended mission of a second polar orbit. The power estimates for F-3 are shown in Figure 9. Unlike Galileo there is no direct measurement of RTG power output. RTG power output is estimated from an algorithm which considers (1) the main bus current, (2) an internal power dump current, and (3) nominal power consumption values for ten spacecraft components if they are operating at the time. Initial telemetry power was reported to be 289 W(e) at the RTG connector which exceeded the specification requirement of 277 W(e). (The prelaunch prediction of BOM power was in the range 282 to 287 W(e). The RTG continued to meet all spacecraft power requirements throughout the 42,000 hour (4.8 year) mission. The EOM power requirement was 245 W(e). JPL has reported that during the periods leading up to an following perihelion in March 1995, there were several spacecraft power reconfigurations in response to the large changes in solar heating as the spacecraft-Sun distance decreased and then increased. Since the algorithm used to estimate power is configuration dependent, these reconfigurations have clearly introduced artifacts into the data set.

CONCLUSIONS

Test results indicate that the BOM and EOM power requirements for the Cassini spacecraft will be met by three RTGs with a power margin of five percent. Telemetry data from the Galileo and Ulysses spacecraft show that all mission power requirements have been met.

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Hemler, R. J. et al, 1992, "Flight Performance of Galileo and Ulysses RTGs," Proceeding of the Ninth Symposium on Space Nuclear Power Systems, Albuquerque, New Mexico, 12-16 January 1992, American Institute of Physics Conference Proceedings 246, 1:171-176.

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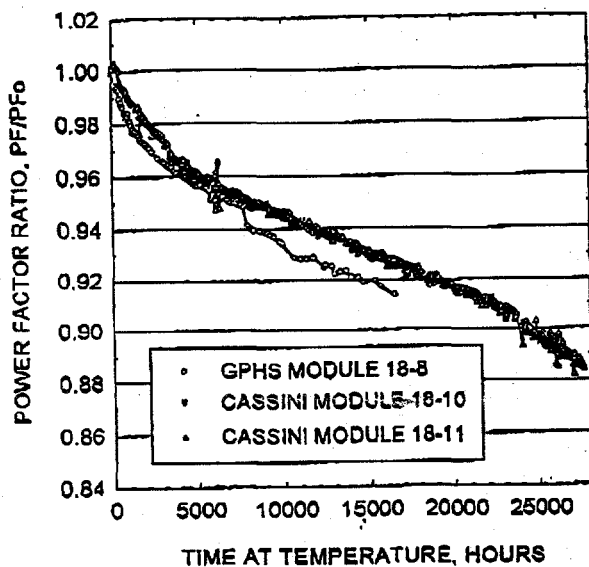


FIGURE 1. 18 COUPLE MODULE POWER FACTOR RATIO VERSUS TIME (1408 K OPERATION)

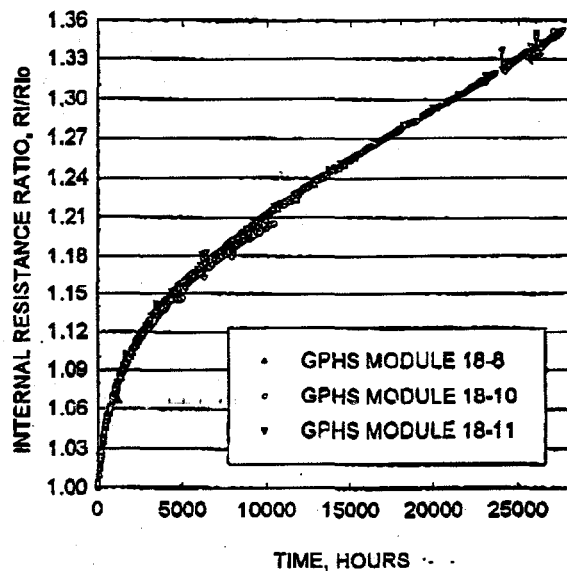


FIGURE 2. 18 COUPLE MODULE INTERNAL RESISTANCE RATIO VERSUS TIME (1408K OPERATION)

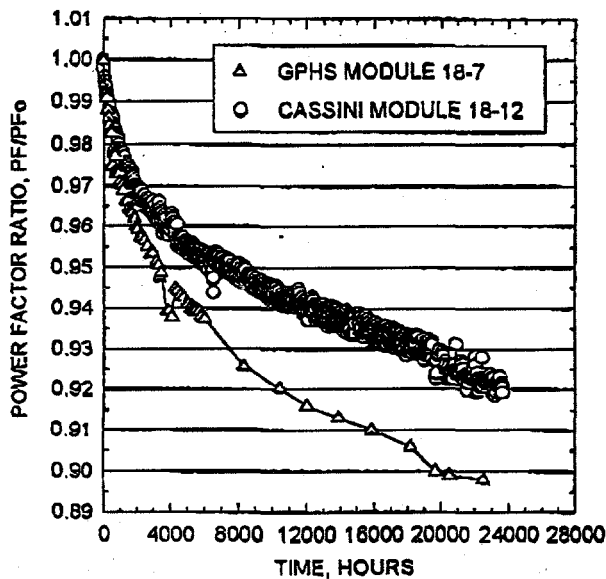


FIGURE 3. 18 COUPLE MODULE POWER FACTOR RATIO VERSUS TIME (1308 K OPERATION)

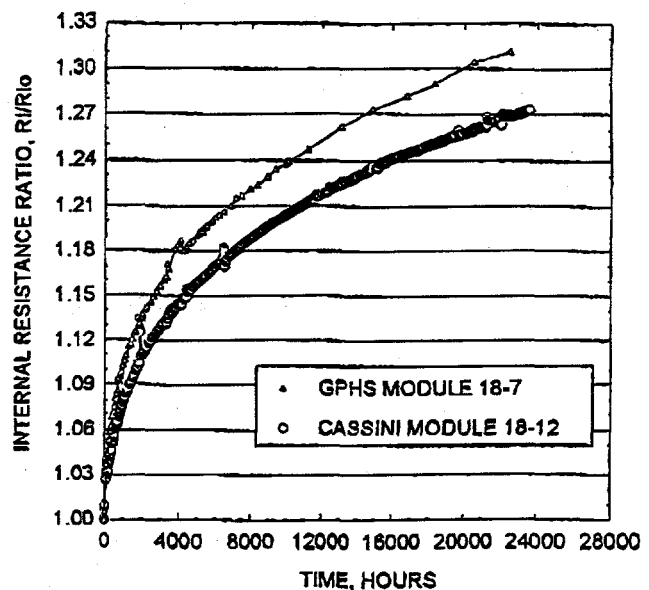


FIGURE 4. 18 COUPLE MODULE INTERNAL RESISTANCE RATIO VERSUS TIME (1308 K OPERATION)

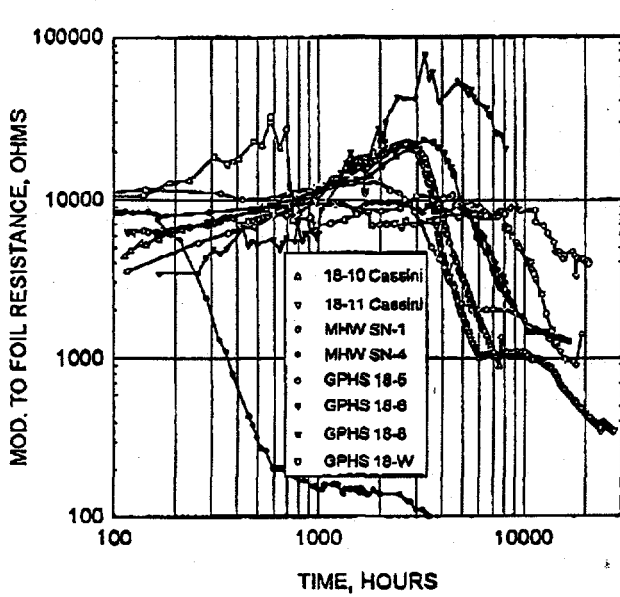


FIGURE 5. ISOLATION RESISTANCE VERSUS TIME (1408 K OPERATION)

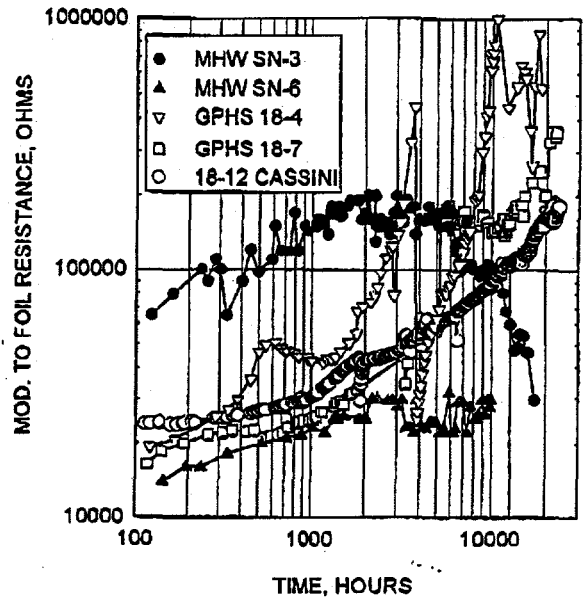


FIGURE 6. ISOLATION RESISTANCE VERSUS TIME (1308 K OPERATIONS)

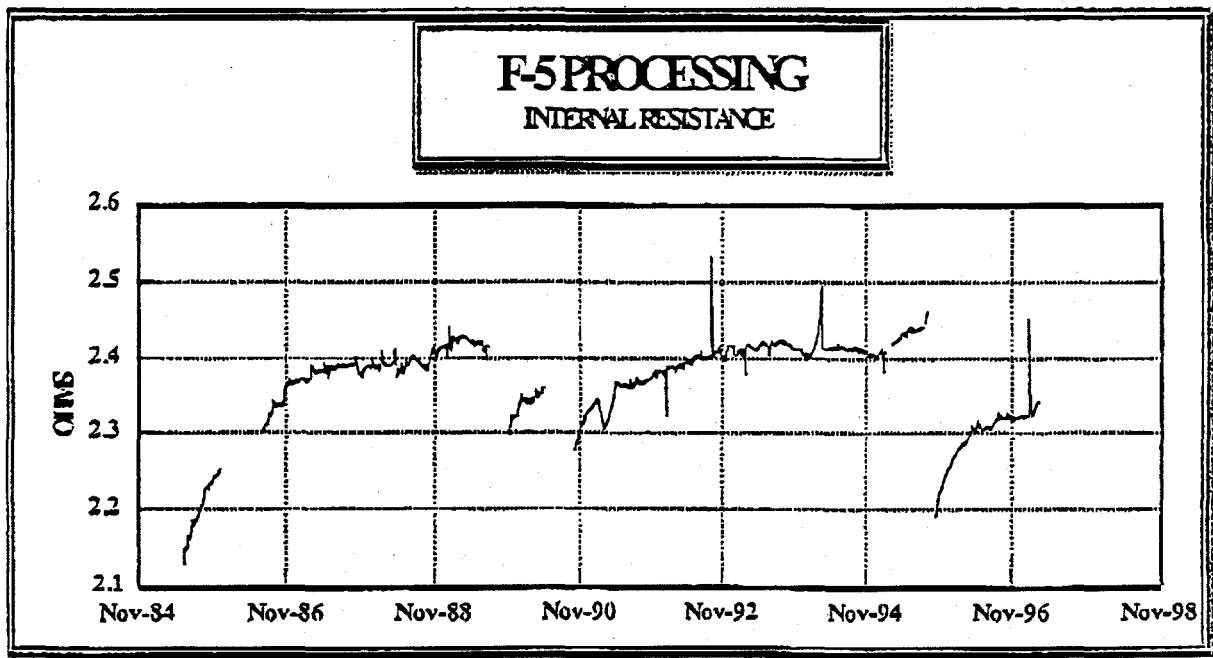


FIGURE 7. F-5 INTERNAL RESISTANCE TRENDS

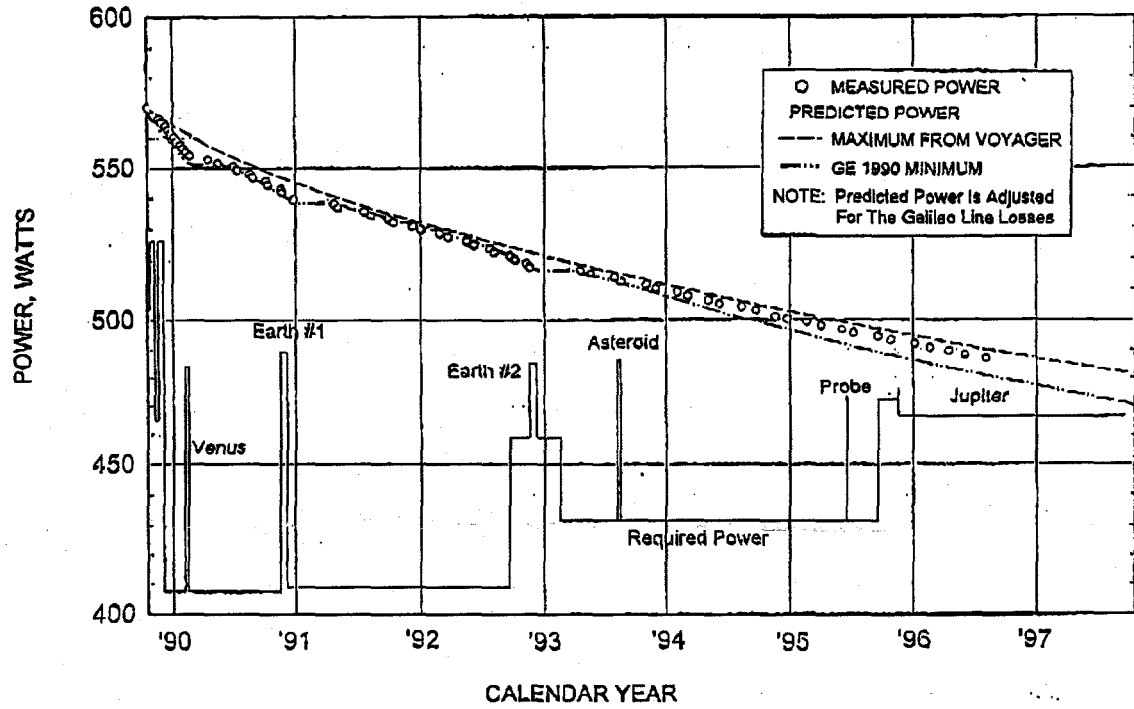


FIGURE 8. GALILEO SPACECRAFT RTG POWER VERSUS TIME (LAUNCH OCTOBER 18, 1989)

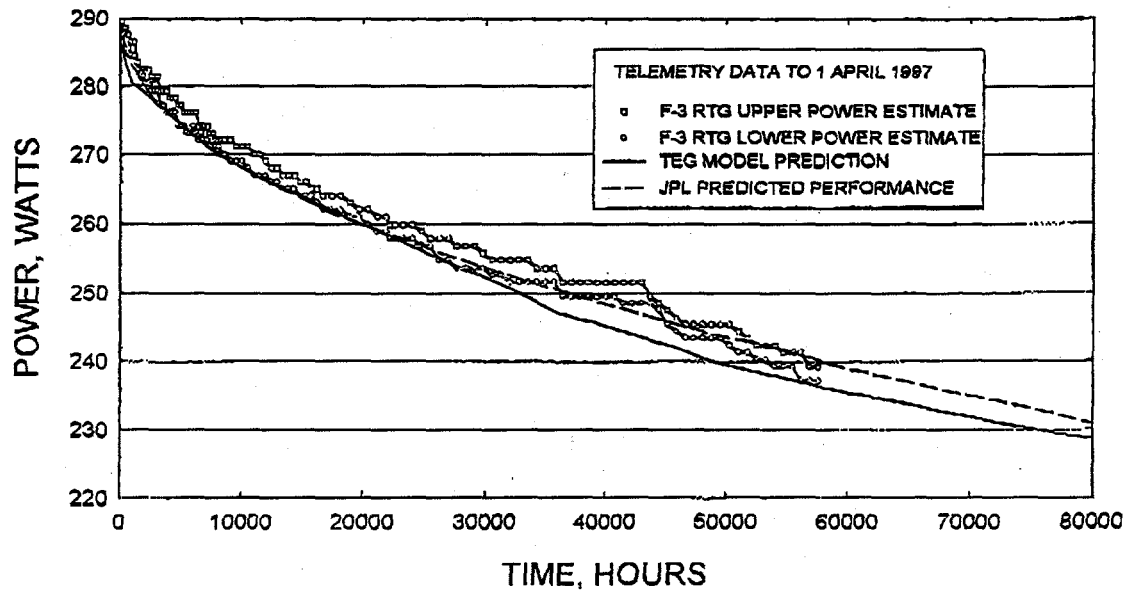


FIGURE 9. ULYSSES SPACECRAFT RTG POWER (LAUNCH OCTOBER 6, 1990)

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