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EMPIRICAL POWER PREDCITION FOR MMRTG F1

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Power predictions for the MMRTG are, in part, based off of early performance data for the MMRTG F1 unit, currently on Mars. Now that F1 has been in operation for over half of its design life, a detailed analysis of its performance can be obtained. In this paper, a power degradation curve was made using the F1 telemetry data. Upon analysis of the data, it was determined that the power degradation does not obey first-order kinetics, and a much higher order rate equation was derived. This empirical degradation curve and rate equation can then be used to predict the performance of F1 for the remaining 7 years of its design life. These empirical predictions indicate that at the end of design life, F1 will be producing 75.2 W_e. This is a 25% increase in power over earlier predictions. A conservative estimate for future MMRTG performance indicates that the minimum power at the end of design life is 72.8 W_e. This is a 32% increase in power over earlier predictions. Communicating this improvement in the power prediction is important so that future science missions can plan to appropriately make use of the power that MMRTG will provide. In addition, it may be useful to communicate to the community the fact that the power degradation of MMRTG is steadily decreasing with time. Using a fixed annual power degradation value will not accurately describe the behavior of the MMRTG power.

I. INTRODUCTION

The Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) is the only flight qualified Radioisotope Power System (RPS) currently available for use (Ref. 1). MMRTG may be a relatively new generator design (circa 2008), but it utilizes heritage PbTe and TAGS thermoelectric materials to convert the decay heat from $^{238}PuO_2$ into electricity. These heritage materials have a long history of robust and reliable performance during their use in the SNAP (Systems for Nuclear Auxiliary Power) program (Refs. 2 and 3). Despite the high confidence that the Department of Energy and NASA have in this heritage technology, the exact power degradation and performance characteristics of the MMRTG are not well characterized.

Power predictions are extremely important for the space power community. Mission designers rely on these power predictions when making decisions about how much science the mission can accomplish. Pre-decisional mission concepts will use these predictions to help them determine if MMRTG will be able to provide them the power they need. Accurate predictions of the MMRTG power production are therefore extremely important to the space exploration community.

As of the date of this paper, the first MMRTG flight unit ever produced (F1) is 6 years into its mission on Mars, and 10 years into its design life. A major reevaluation of the power degradation for F1 can now be performed. Using the results of this evaluation, new predictions for the End Of Design Life (EODL) of MMRTG can be made, and confidence in these predictions will be much higher.

This paper will show that the power degradation for F1 is consistently decreasing with time. A mathematical fit to the degradation curve can be made, and this will provide a high quality prediction of the power degradation for F1. This empirical prediction will show that the EODL power for MMRTG F1 is significantly higher than earlier predictions.

II. PREVIOUS MMRTG POWER PREDICTIONS

The most representative set of data that can be used to describe the power degradation for MMRTG is derived from F1, which is present in the Martian environment. Unfortunately, the space power community does not use a consistent set of power prediction numbers for the MMRTG. It therefore becomes valuable to outline what the current power prediction criteria are, and how they should be used to predict MMRTG power. Once the power prediction values are established, they can be compared to the improved power prediction presented here.

F1 was fueled in 2008 and launched on the Mars Science Laboratory mission in 2011. Early estimates for the power degradation of MMRTG indicated a degradation in power of ~4.8% per year. MMRTGs are produced to have a 17 year design life, meaning F1 will reach its EODL in 2025[1]. A constant power degradation of 4.8% per year directly implies a first-order rate degradation curve, so first-order kinetics were used in these earlier predictions. F1 was producing 115 W_e when it landed in 2012. If a 4.8% annual power degradation is then applied to F1, then the predicted power at EODL would be 59.9 W_e.

[1] It is anticipated that F1 will continue to function long past 2025. The EODL is intended to be a benchmark, not a prediction of failure.

A set of conservative criteria were then developed to help the space power community characterize and discuss the behavior of MMRTG. This criteria used a worst case of 110 W_e at the Beginning of Mission (BOM), a 4.8% annual power degradation, and a 17 year design life. This distinction is important because BOM is defined to include three years of storage and degradation, so an accurate power prediction for EODL should only include 14 years of degradation from the initial 110 W_e power value. This conservative estimate predicts MMRTG would produce 55.2 W_e at EODL.

Other power predictions do not accurately reflect the EODL power for MMRTG. A power prediction of 47.7 W_e uses the 110 W_e value as the BOL power, not the BOM power. Thus, the 47.7 W_e prediction is artificially adding an additional 3 years of degradation to the power prediction. A power prediction of 60.7 W_e is using F1 data, but it is assuming that the EODL ends exactly 13 years after landing on Mars. The actual EODL, however, occurs 13 years and 3 months after landing on Mars, so 60.7 W_e is short 3 months of power degradation.

Other EODL values have been used as well, and some members of the space power community have used power degradation numbers other than the 4.8% value. It is not worth analyzing these predictions in detail, however, since we are providing an improved power prediction here.

III. CURVE FITTING F1 POWER DEGRADATION

Figure 1 shows the power produced by F1 as a function of its time on Mars. Despite seasonal temperature fluctuations and other major environmental disturbances (e.g. dust storms), the power production for F1 appears to be following a steady curve.

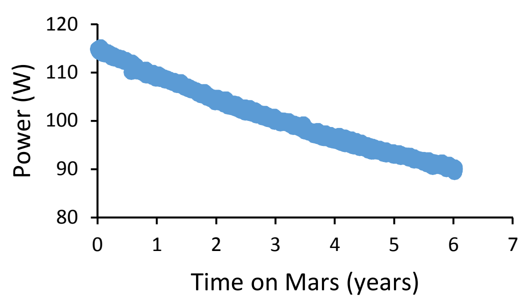

Fig. 1. Power produced by MMRTG F1 on Mars

Mathematically obtaining the power degradation curve present in Figure 1 can be accomplished by fitting the data to a classical Rate Law equation, which can be described as:

$$Rate = \frac{-\Delta P}{\Delta t} = k\,P^{x} \quad (1)$$

Where Rate is the change in power over time, P is power (W_e), t is time (years), k is the rate constant, and x is the order of the power degradation curve. x can then be obtained from the slope of a graph of ln P vs ln Rate. Figure 2 presents a plot of ln P vs ln Rate using the monthly power averages from F1. This data shows that x = 3.27.

While the data presented in Figure 2 may appear to be widely scattered, it is important to remember that changes in power each month due to degradation are fairly small, and the power produced by F1 is influenced by seasonal and meteorological changes on Mars. The combination of these two effects produces a reasonable amount of variability in apparent rate of degradation from month to month. Fortunately, the data pool present in Figure 2 is large enough that these minor disturbances in power production are easily averaged out.

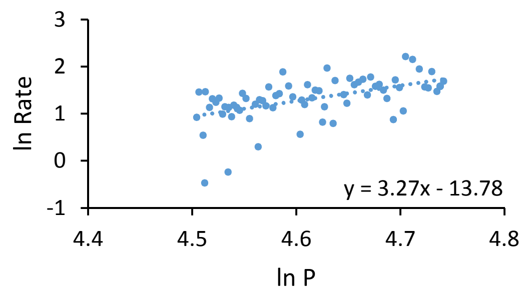

Fig. 2. Log-Log plot used to determine the order of the power degradation curve.

With the order of the power degradation established, a rate equation with an order of 3.27 can be produced.

$$\frac{1}{2.27}P_t^{-2.27} = kt + \frac{1}{2.27}P_0^{-2.27} \quad (2)$$

Which can be simplified to:

$$P_t^{-2.27} = k't + P_0^{-2.27} \quad (2.1)$$

Where k is the rate constant for the rate law (Equation 1), k′ is the adjusted rate constant that incorporates other constants for simplification purposes, and P_x is the power at time = t and time = 0, respectively. For the purposes of this paper, t = 0 will be defined as the time F1 landed on Mars. Figure 3 presents a plot of the 3.27-order rate equation with the F1 power data, and it shows an excellent fit.

Using the slope from Figure 3, it is possible to refine the rate equation further:

$$P_t^{-2.27} = 2.553x10^{-6}t + P_0^{-2.27} \quad (2.2)$$

With the rate equation established, and a good fit observed, it is possible to predict the power that will be produced by F1 over the 7 remaining years in its design life.

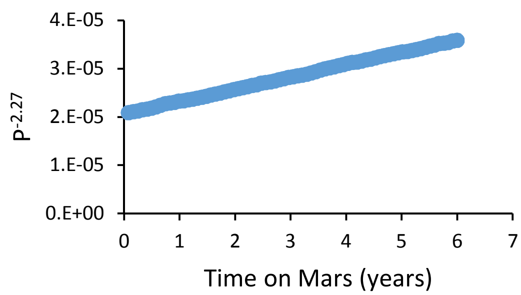

Fig. 3. 3.27-order rate plot of the power produced by F1.

IV. F1 POWER PREDICTIONS

Figure 4 presents the calculated F1 power produced using Equation 2.2. After a little over 13 years on Mars, F1 will have reached its 17 year design life, and at that point in time, F1 is predicted to produce 75.2 W_e.

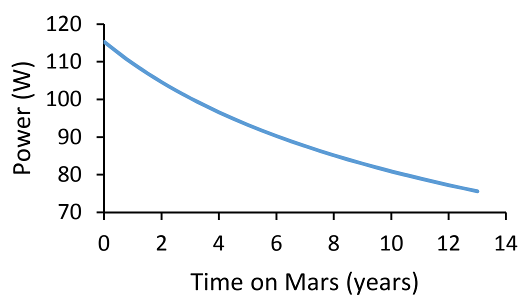

Fig. 4. Empirical power prediction for F1 using a 3.27-order rate equation.

Table 1 presents the annual power predictions in a tabular form for easier digestion.

TABLE I. Calculated power for F1.

Time on Mars (years)	Calculated Power (W_e)	1-Year Power Drop
0	115.3	
1	109.5	5.3%
2	104.6	4.7%
3	100.3	4.2%
4	96.6	3.9%
5	93.3	3.6%
6	90.3	3.3%
7	87.6	3.1%
8	85.2	2.9%
9	83.0	2.7%
10	80.9	2.5%
11	79.0	2.4%
12	77.3	2.3%
13	75.6	2.2%
EODL (13.25)	75.2	2.1%

These predicted power values were then compared to the F1 flight data. Figure 5 presents the monthly % difference between the calculated and measured power. On average, the % difference between calculated and measured power values is -0.001%. This extremely small number indicates that the various forms of Equation 2 provide an excellent fit to the F1 empirical power data.

It is interesting to note that the % difference values seem to go through a cyclic pattern that lines up approximately with the Martian year (which is 687 Earth days long). This is not surprising, as the Martian seasons are expected to have a small impact on the operational temperatures of F1. It also supports the previous conclusion that the Martian seasonal changes are one of the major contributors to the noise observed in Figure 2.

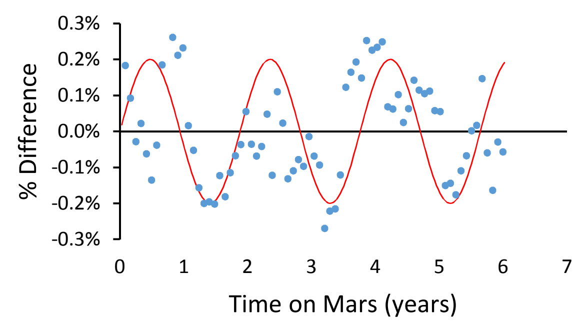

Fig. 5. Monthly difference between calculated power using a 3.27-order rate equation and F1 flight data. Solid line is a sine wave with a period equal to the Marian year. The sine wave is for reference only and is not intended to provide any detailed information regarding Martian seasons.

Figure 5 is also an important analytical tool because if there were any clear indications of Equation 2 becoming less reliable, the difference analysis should show a trend in the % difference as a function of time. Figure 5 does not show clear evidence of any trends (other than the Martian year), meaning there is no clear indication of the power prediction becoming less accurate with time. As a result, it is possible to say that Equation 2 provides an excellent fit to the F1 measured power to date.

A fundamental limitation of using a rate equation is that one of the known factors driving the power degradation is the radioactive decay of ^{238}Pu. ^{238}Pu power output decays at a rate of 0.79% per year, indicating that this is a fundamental minimum for the MMRTG power degradation. Other estimates indicate that with the fuel decay and associated Carnot efficiency losses, the thermal output of the fuel has a fundamental limit that is closer to 1.2% (Ref. 4). The 3.27-order rate equation does not account for those fundamental limits, and it will eventually reach a point where the rate equation is predicting less than 0.8 or 1.2% power degradation.

As a sanity check, the power prediction using Equation 2 was drawn out to the point where the curve failed to meet these limitations. In this extrapolation, the rate equation predicted that the annual power loss would be less than 1.2% after 29 years on Mars (33 years after fueling). It also predicted that the annual power loss would be less than 0.79% after 45 years (49 years after fueling). Clearly, the power prediction presented here will fail as we approach those timeframes. Fortunately, those timeframes are far enough out, that it is reasonable to expect that the short term (i.e. 17 year EODL) power prediction of Equation 2 will be fairly accurate.

V. DISABUSING THE ANNUAL DEGRADATION RATE FOR RTG USE

It is extremely important to note here that this data cannot be used in conjunction with standard exponential decay curves. Typically, the RTG community would take power data, like Table 1, and fit it to an exponential decay curve. This allows us to arrive at a single "annual degradation rate" value that is functionally used for easy digestion. A standard exponential decay curve is only accurate for a first-order rate law. Since the data here fits a much higher rate order (i.e. 3.27), using a first-order approximation simply *does not work*.

Using a fixed annual degradation rate for a non-first-order rate is misleading for numerous reasons. First, the annual degradation rate will only be accurate for the timeframe that it is derived from. For example, if the annual degradation rate is derived to describe a 17-year EODL, then it will be very inaccurate when describing a 5-year mission profile. Second, the annual degradation rate will underestimate the early-life degradation of the RTG. This can lead to major concerns by mission personnel when they see comparatively large power drops early in the mission. It is also misleading to mission planners as they may have a mission design that wants to make use of more power early in the mission. Third, the annual degradation rate will overestimate the later-life degradation of the RTG. This could result in mission planners assuming they will have less power during later mission phases, which could result in a mission not taking advantage of the full power production of the RTG. Fourth, trying to assign an annual degradation rate to an RTG that has not been fully characterized (e.g. MMRTG) will result in a value that is constantly evolving as the RTG is used. This constant evolution will generate significant confusion amongst the RTG user community, as has been observed with MMRTG.

Because of the misleading nature of an annual degradation rate and the confusion that it can generate, it is recommended that the annual degradation rate is no longer used to describe RTG power behavior. Power predictions, however, are very important for the mission planning community, so a replacement method for power prediction is required. It is our opinion that a team of subject matter experts should be assembled to evaluate the results that are presented in this paper, and that a new method is implemented for MMRTG power predictions based off of Equation 2.

VI. POWER PREDICTION IMPLICATIONS

The empirical power prediction presented here indicates that F1 will have an EODL power of 75.2 W_e. This is over 25% higher than the 59.9 W_e that has been used to describe the MMRTG EODL power. This is a significant increase in the available power. The mission planning and design community needs to know that MMRTG is capable of providing this power for their missions, so they can plan to take advantage of this additional power appropriately.

Table 2 presents the data for the conservative case prediction discussed previously in Section II. This would involve an MMRTG with a 110 W_e BOM power that followed the same degradation curve as F1 for a full 14 years. In this data we see that at EODL, the power output for this conservative case is 72.8 W_e, which is a 32% increase in power over the previous predictions (i.e. 55.2 W_e).

TABLE 2. Calculated power for a conservative case MMRTG.

Time on Mars (years)	Calculated Power (W_e)	Annual Power Drop
0	110.0	
1	105.0	4.7%
2	100.7	4.3%
3	96.9	3.9%
4	93.6	3.6%
5	90.6	3.3%
6	87.9	3.1%
7	85.4	2.9%
8	83.1	2.7%
9	81.1	2.5%
10	79.2	2.4%
11	77.4	2.3%
12	75.8	2.2%
13	74.2	2.1%
EODL (14)	72.8	2.0%

Results from Table 2 are believed to be a conservative case. Martian conditions are some of the most taxing that an MMRTG will experience. The very low Martian atmospheric pressure means that convective cooling is almost non-existent. In addition, Martian surface temperature is relatively high, which leads to a high radiative heat sink condition. Finally, solar radiation during the Martian day can also cause increases in system temperature. All of these factors contribute to F1 having a high fin root temperature, which results in a high thermoelectric couple hot junction temperature. High hot junction temperatures are likely to result in accelerated degradation of the thermoelectric couples, which will ultimately result in a more rapid power degradation.

Compared to other potential uses of MMRTG – like a deep space or Titan mission – the Martian case is likely to be the worst when it comes to power degradation. Thus, the results from Table 2 should present a potential worst case scenario. This allows us to conclude that as long as any future MMRTG meets the 110 W_e BOM power specification, it should produce at least 72.8 W_e at EODL.

It should be noted that the 72.8 W_e power generation value is assuming Mars-like conditions. Power production for MMRTG is dependent on the mission environment. While the specific power output will be different for a non-Mars mission, it is expected that the Martian degradation rate – as described by Equation 2 – will be the most severe, and therefore, the most conservative.

VII. F1 MMRTG CONDITIONS ON MARS

Power produced by an MMRTG is dependent on a number of different variables. In order to understand how the predicted values for F1 might compare to other scenarios, it is important to know the F1 BOL properties. Therefore, for comparison's sake, the initial conditions for F1 are presented here. BOL thermal loading = 2022 W_{th} and a BOM thermal loading of 1976 W_{th}. Operational voltage = 32.8 V. Four months after fueling, F1 was measured under thermal vacuum with a 270 K heat sink and found to have a fin root temperature = 192 ºC (Ref 5).

VIII. CONCLUSIONS

After 6 years of operation on Mars and almost 10 years after fueling, the MMRTG F1 is over half-way through its 17 year design life. Using the operational data from F1, a new power degradation curve can be established. This power degradation curve clearly shows that the degradation rate is decreasing with time, and that previous power predictions made with initial degradation rates will not be accurate. The improved power degradation curve predicts that F1 will reach EODL with a power output of 75.2 W_e, which is a 25% increase over the power predictions made previously.

Performance on Mars is considered to be one of the most rapid power degradation cases that MMRTG will experience. Since Equation 2 is derived from Martian performance data, results from this equation can be considered as a conservative power estimate. If this conservative power performance estimate is then applied to the minimum BOM power specification, then future MMRTG missions in the Martian environment should provide a minimum EODL power of 72.8 W_e.

Critical analysis of the data indicates that the improved power degradation curve matches the F1 data very well. Extrapolations for the improved power degradation curve indicate that this curve will not pass any fundamental limits until over 33 years after fueling. This strongly suggests that the short to mid-term (e.g. the 17 year EODL) predictive power of the improved degradation curve has very high confidence.

Based on the results of this analysis, some recommendations are made. First, it is recommended that the reported EODL for the MMRTG system is revisited and the data presented here is used to help revise the MMRTG performance values. Second, it is recommended that the space power community no longer advertise an MMRTG annual power degradation rate. The actual power degradation changes significantly with time, and any fixed value is likely to result in misunderstandings regarding the performance of MMRTG.

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