RTG Degradation Primer and Application to MMRTG

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Previous RTG’s

- SNAP19 (40 W)
  - Pioneer and Viking
- MHW RTG* (160 W)
  - Voyager
- GPHS RTG* (300 W)
  - Galileo, Cassini, Ulysses, New Horizons

MMRTG (110 W)

- Robust solution designed for broader range of missions
  - Planetary surfaces and deep space
- Based on TAGS and PbTe materials, with mature system architecture
- From concept to flight unit ready for fuel in 5 years
- 1\textsuperscript{st} unit on MSL, 2\textsuperscript{nd} unit getting prepared for Mars 2020

Needed a multi-environment, low risk technology for future missions

* Deep space only
Causes of RTG Power Decline with Time

• Fuel decay
  - Less Q to be converted to electricity with time
  - Delta T reduction across TE
  - Pu238 half life of 87.7 years

• Helium gas effects if Pu238 heat source
  - Sealed vs. vented heat source
  - Vented
    • Separated TE converter like MMRTG
    • Helium gas management like Viking

• Thermoelectric degradation
  - Any changes to TE or bonds that cause power decline with time
  - Function of time and temperature
  - Many causes
TE Degradation Causes

• Sublimation
  - Geometry changes
  - Porosity effects on TE properties
  - Preferential sublimates causing TE property changes
  - Effect of deposited sublimates on other materials and/or insulation thermal conductivity
- Suppression techniques
  • Argon gas fill
  • Tightly packed insulation
  • Poured aerogel insulation
  • Ceramic paints
  • Segmenting to reduce hot side temperature of sublimation sensitive segments
More Causes of TE Degradation

• Bond changes; increasing bond resistance (thermal and electrical) vs time
  - Spring pressure to minimize effect of changes
  - Diffusion barrier to prevent bond degradation and poisoning of TE material from bond
  - Better bonds!

• Changes to inherent TE properties (alpha, rho, k)
  - Grain growth increases k
  - Dopant precipitation
  - Diffusion of species due to both temperature and potential gradients
  - Oxidation
Actual Generator Performance Data

Helium effect in Pioneer caused greater power decline than MMRTG

- Pioneer 10/11 average (decaying Q and helium effects)
- MMRTG F1 (decaying Q) and other effects
- MMRTG EU (constant Q)

- MMRTG EU (constant Q and TE degradation) and 1 atm He
- Pioneer 10/11 average (degrading Q, TE degradation and gas effects)
- F1 (raw Tfr and EI, degrading Q and TE degradation)
- F1 on Mars; as-measured data
Voyager SiGe change similar to MMRTG PbTe

MMRTG EU (constant Q)

F1 Mars transit

MMRTG F1 (decaying Q) and varying load voltage and Mars diurnal cycles

F1 “cold” storage – 77/132°C

Pioneer 10/11 average (decaying Q and helium effects)

- MMRTG EU (constant Q and TE degradation) and 1 atm He
- Pioneer 10/11 average (degrading Q, TE degradation and gas effects)
- F1 (raw Tfr and El, degrading Q and TE degradation)
- F1 on Mars; as-measured data
- Voyager
Actual Performance Data Normalized to BOL (1.0)

Power Output (watts) vs. Time (yrs)

- MMRTG EU (constant Q)
- MMRTG F1 (decaying Q)
- Rate of Fuel Decay for Pu238
- MMRTG power output with JUST fuel decay
- Pioneer 10/11 average (decaying Q and helium effects)
- MMRTG power prediction with fuel decay and TE degradation at constant conditions (TFR and EL)
Actual Performance Data Normalized to BOL (1.0)

- MMRTG EU (constant Q)
- MMRTG F1 (decaying Q)
- Rate of Fuel Decay for Pu238
- eMMRTG Goal (2.5%/yr)
- Pioneer 10/11 average (decaying Q and helium effects)
- MMRTG power output with JUST fuel decay
- MMRTG power prediction with fuel decay and TE degradation at constant conditions (TFR and EL)
Power Change Effects Averaged Over 10 Years

- Fuel decays 0.8%/year
- Power drops 1.1%/year due to fuel decay alone
- MMRTG power reduces 2.9%/year due to fuel decay and TE degradation
  - TE degradation adds 1.8%/year to fuel decay effect
- eMMRTG goal is 2.5%/yr (on an each-year basis)
  - Over 10 years this averages to 2.24%/year
  - TE degradation would be about equal to fuel decay effect
Basis of MMRTG System Performance Model

• **System performance model performs Beginning of Life (BOL) analysis**
  - Heat balance of heat losses and thermoelectric heat flow to determine TE hot junction temperature
  - From this and TE data/model, power output is determined

• **TE Life model is additional analysis which solely adds TE changes with time**
  - This model includes two components
    • Magnitude and change with time from EU test data
      - Uses Eoc and Ri vs time, extrapolated
      - EU test data taken at one set of temperature conditions
    • Uses “heritage” model from Pioneer and Viking data to adjust the EU results for hot side temperature changes determined from system model
      - Will be updated when module life data is available
EU Test Data for Performance Model

- Both $E_{OC}$ and $R_l$ for EU are normalized and plotted vs time.
- Currently, data are broken into four time periods:
  - 0 to 2800 hours
  - 2800 to 5600 hours
  - 5600 to 14000 hours
  - Greater than 14000 hours
- Linear data fits enable reasonable and well-behaved extrapolation.
- Approach easily modified to more groups and other type of fits as warranted.
Testing to Characterize TE Degradation

• **Test Challenges**
  - Constant vs Degrading Q
  - Hot and Cold junction temperatures; constant vs vary with Q
  - Load current (load)
  - Environment considerations

• **Tests**
  - Couple tests
  - Module tests
  - ETG tests
  - Long term Module life tests

  Testing Goal: Simulate actual use conditions in an RTG as closely as possible!
Putting Some Test Results Together.....

- Showing some various test results from
  - MMRTG life test boxes
  - MMRTG EU, and
  - MMRTG F1
- % change/1000 hours shown as a function of TE hot junction temperature and time
Thermoelectric Power Change Rate

Power loss, \( \frac{dP}{dt}(1/P_0) \), %/1000 hrs

Temperature (°F)

- Revised set using avg THJ
- EU test data
- F1 test data
- Pioneer data
- Life Tester B1M34
- Life Tester B2M34

Pioneer vs time

MMRTG F1
B1M34; 40-50Khrs
B2M34; 40-50Khrs

MMRTG EU

Estimated Thj based on Tfr 40-50 Khrs

MMRTG initial estimate

Pioneer/Viking, fixed Q

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TE Degradation Trends

• Conclusions:
  - MMRTG degradation rate is likely flatter vs. temperature than prior Pioneer and Viking generators
  - Difficult to use F1 data due to varying conditions
  - Reduced TE hot junction temperature gives less degradation reduction than with heritage (Pioneer/Viking units)
• Makes sense as TAGS segment is much shorter than prior units
Conclusions

• Characterizing TE degradation is important: it is roughly $\frac{1}{2}$ to $\frac{2}{3}$ of the power loss in an RTG with time
• Long term testing needs to planned well in advance
• Understanding basic physical effects in TE couples and modules is important
• Consider testing MMRTG QU with Mars diurnal cycling
• Next generation eMMRTG using Skutterudite couples should see reduced degradation: stable materials, no segmentation and testing is underway

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