RTG Degradation Primer and Application to MMRTG

Nuclear and Emerging Technology for Space (NETS) 2015
February 23-26, 2015
Abstract 5107

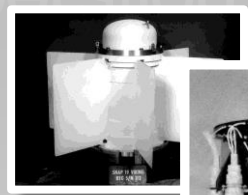
Presenting Author: Tom Hammel, Teledyne Energy Systems

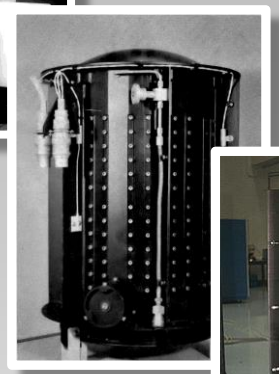
Co-Authors: Russell Bennett, Teledyne Energy Systems
Robert Sievers, Teledyne Energy Systems
Bill Otting, Aerojet Rocketdyne

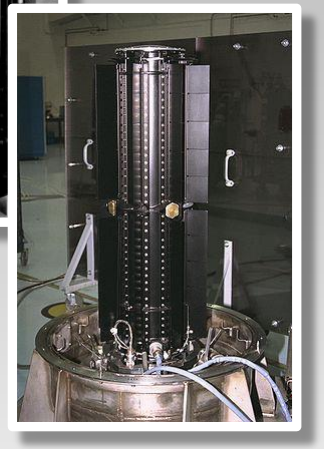
RTG - History of Reliable Operation

Previous RTG's

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



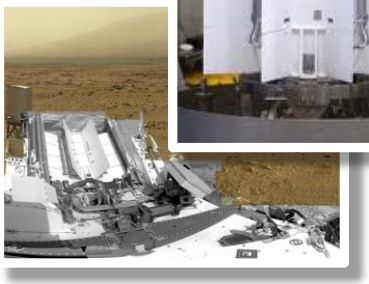




Needed a multi-environment, low risk technology for future missions

MMRTG (110 W)

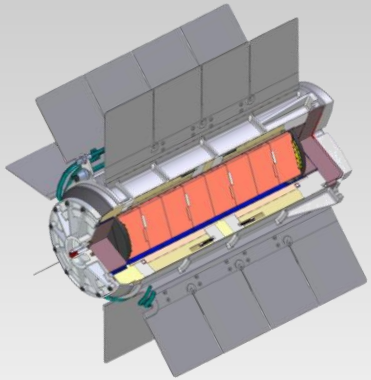
- Robust solution designed for broader range of missions
  - Planetary surfaces and deep space
- Based on TAGS and PbTe materials, with mature system architecture
- From concept to flight unit ready for fuel in 5 years
- 1st unit on MSL, 2nd unit getting prepared for Mars 2020



* 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

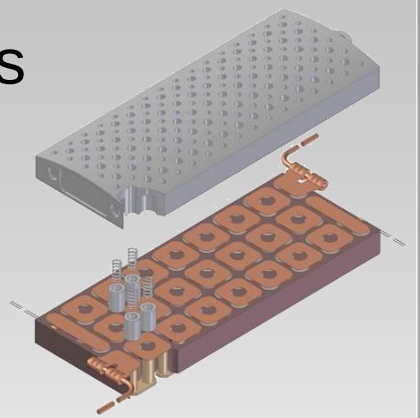


TE Degradation Causes

- 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

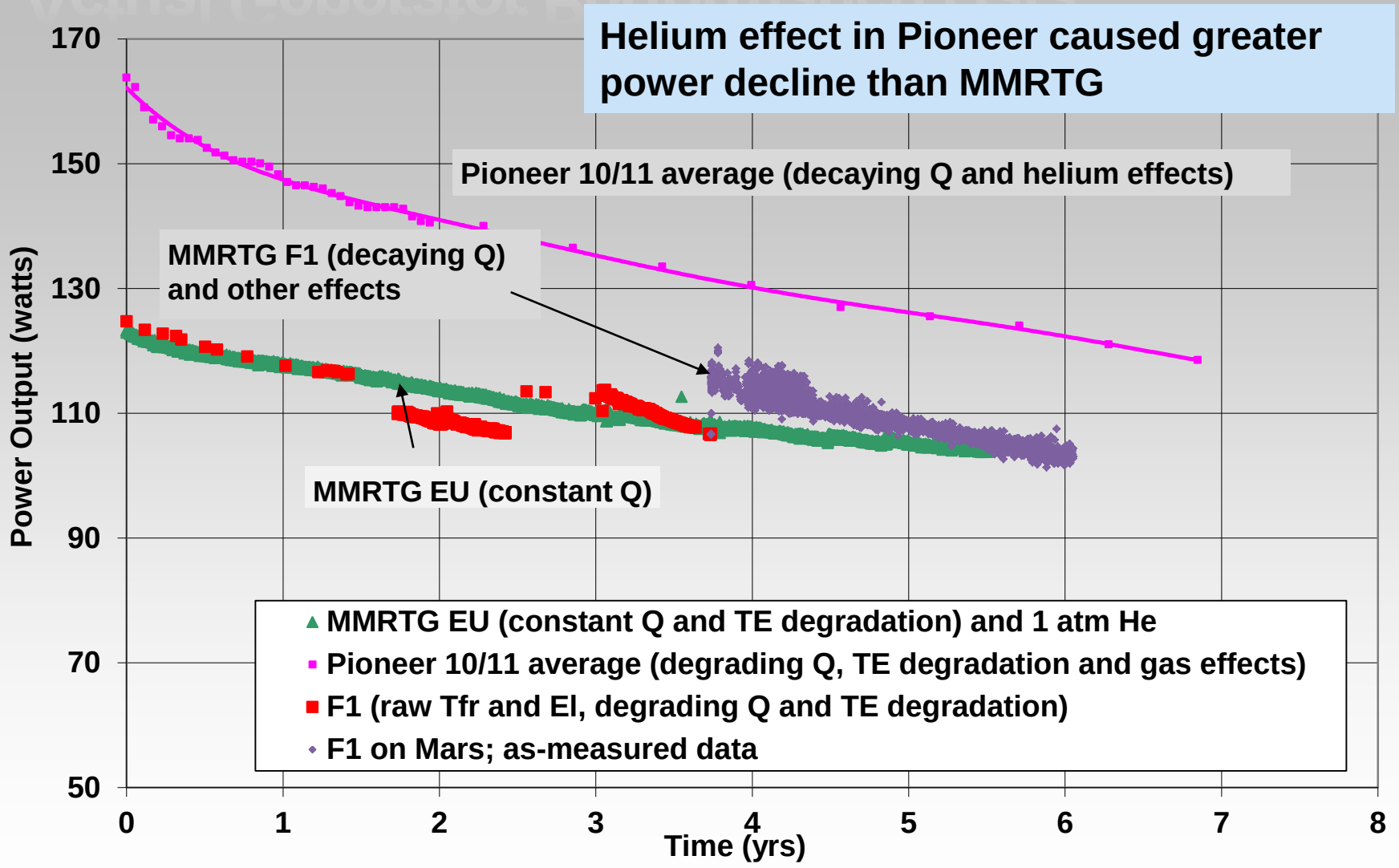
More Causes of TE Degradation

- 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!

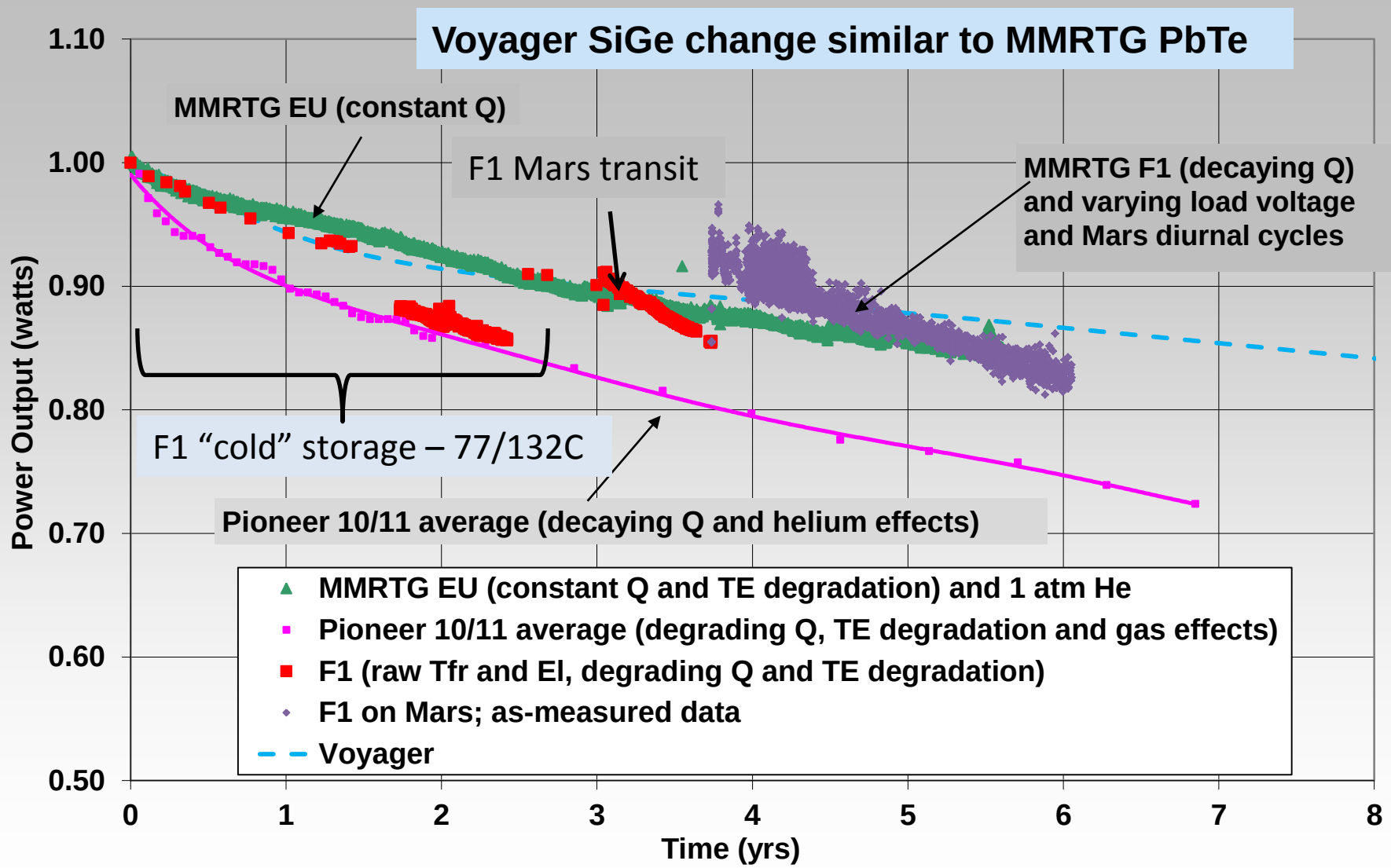


- Changes to inherent TE properties (alpha, rho, k)
  - Grain growth increases k
  - Dopant precipitation
  - Diffusion of species due to both temperature and potential gradients
  - Oxidation

Actual Generator Performance Data



Actual Performance Data Normalized to BOL (1.0)



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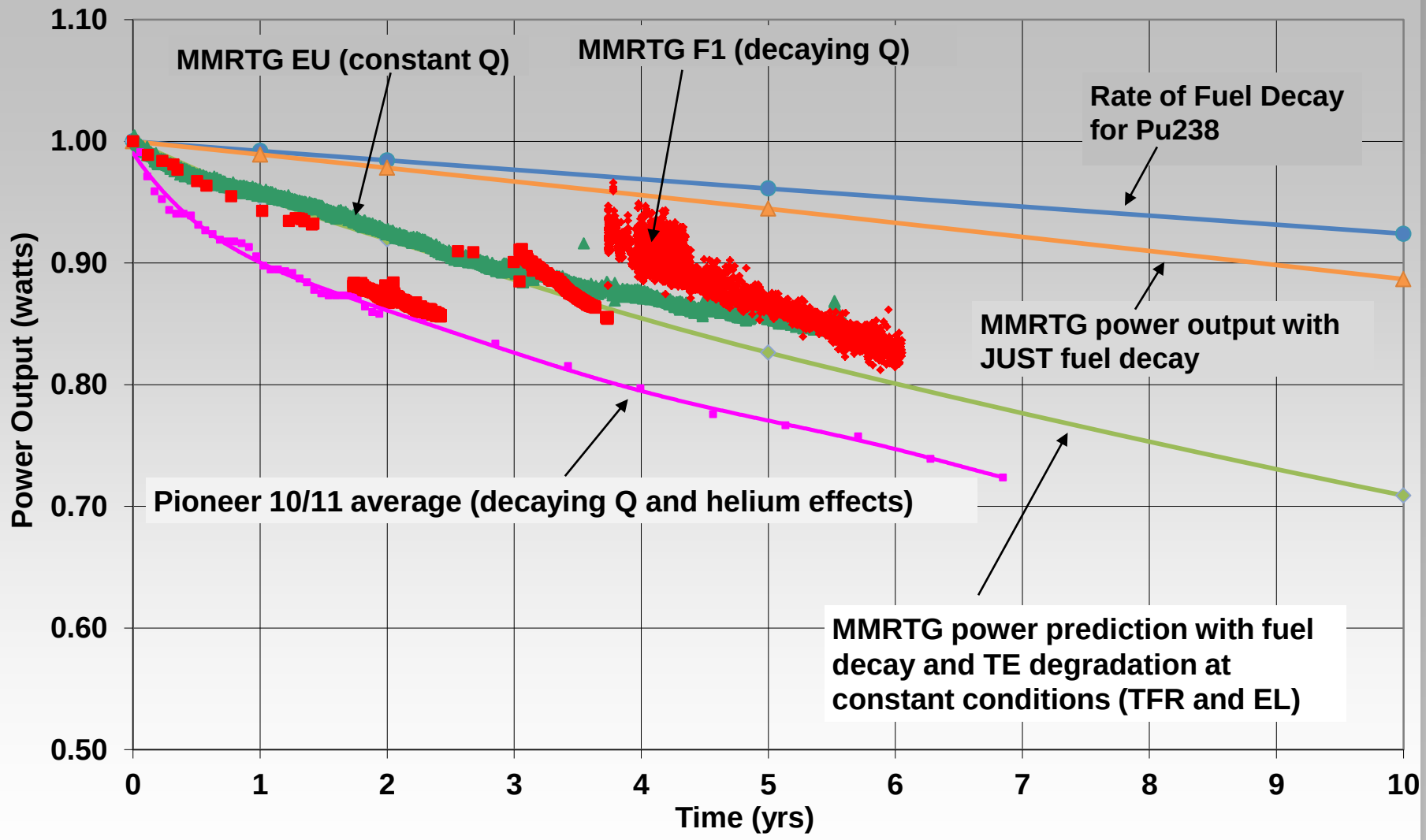

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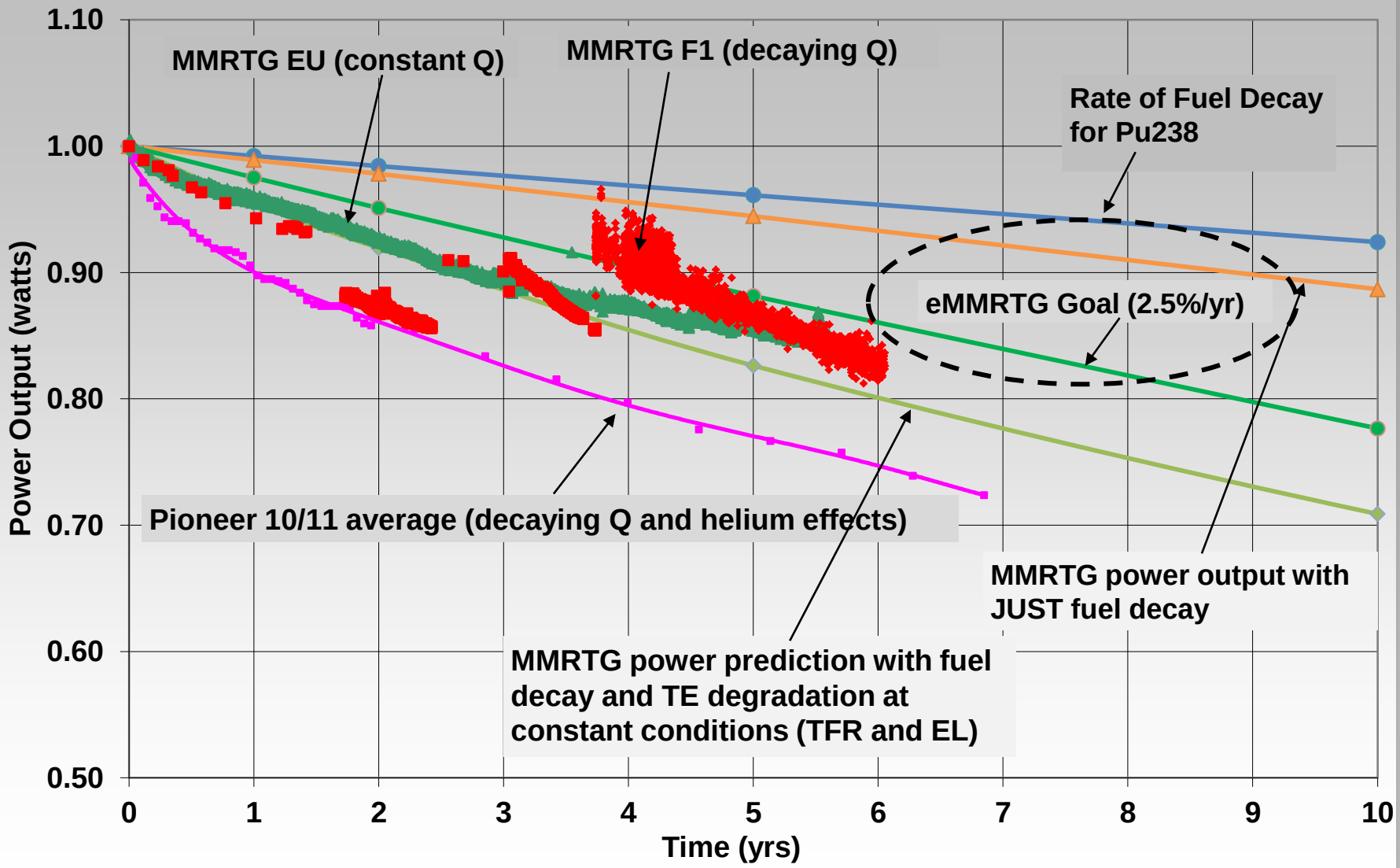


Power Change Effects Averaged Over 10 Years

- 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

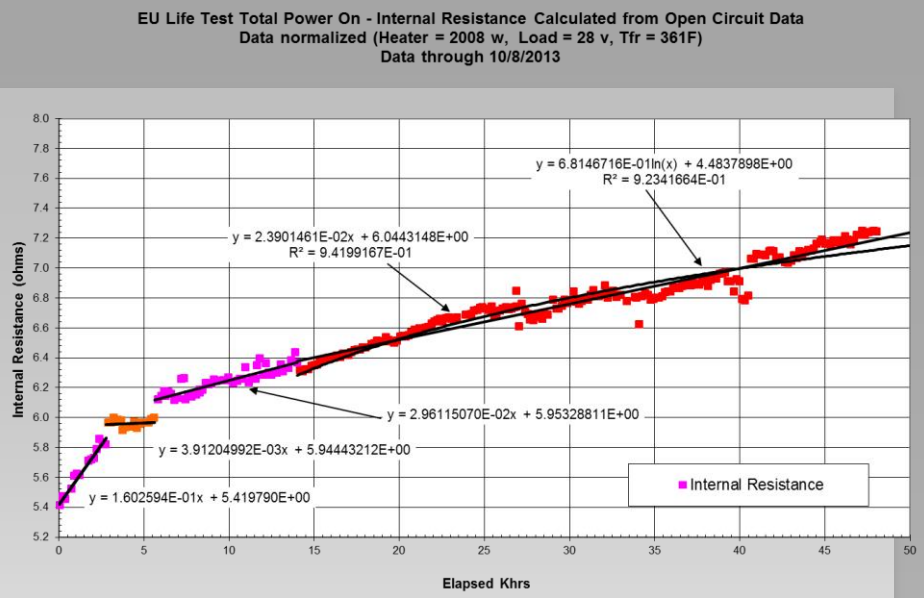
Basis of MMRTG System Performance Model

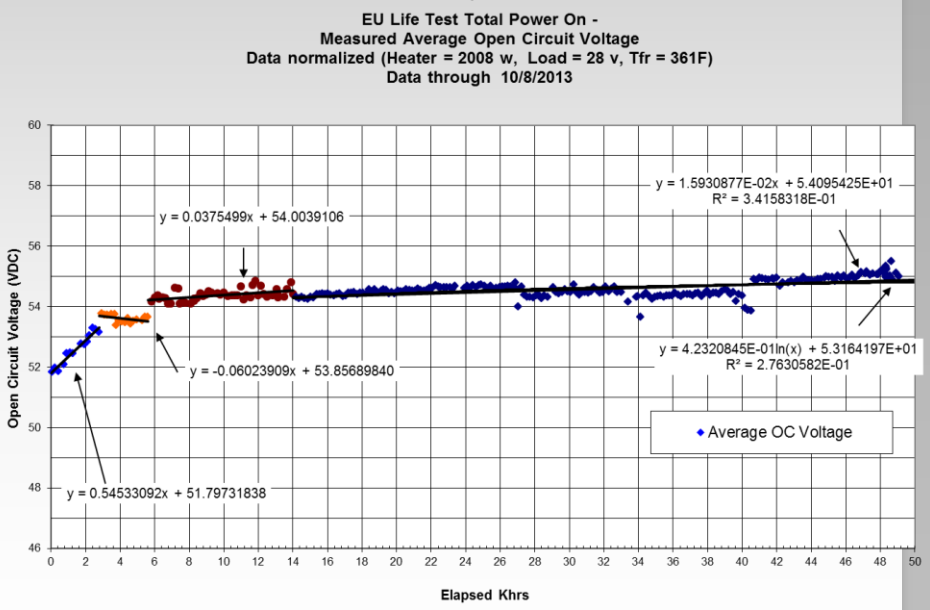
- **System performance model performs Beginning of Life (BOL) analysis**
  - Heat balance of heat losses and thermoelectric heat flow to determine TE hot junction temperature
  - From this and TE data/model, power output is determined

- **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
      - <u>Will be updated when module life data is available</u>

EU Test Data for Performance Model

- Both E_{OC} and R_I 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

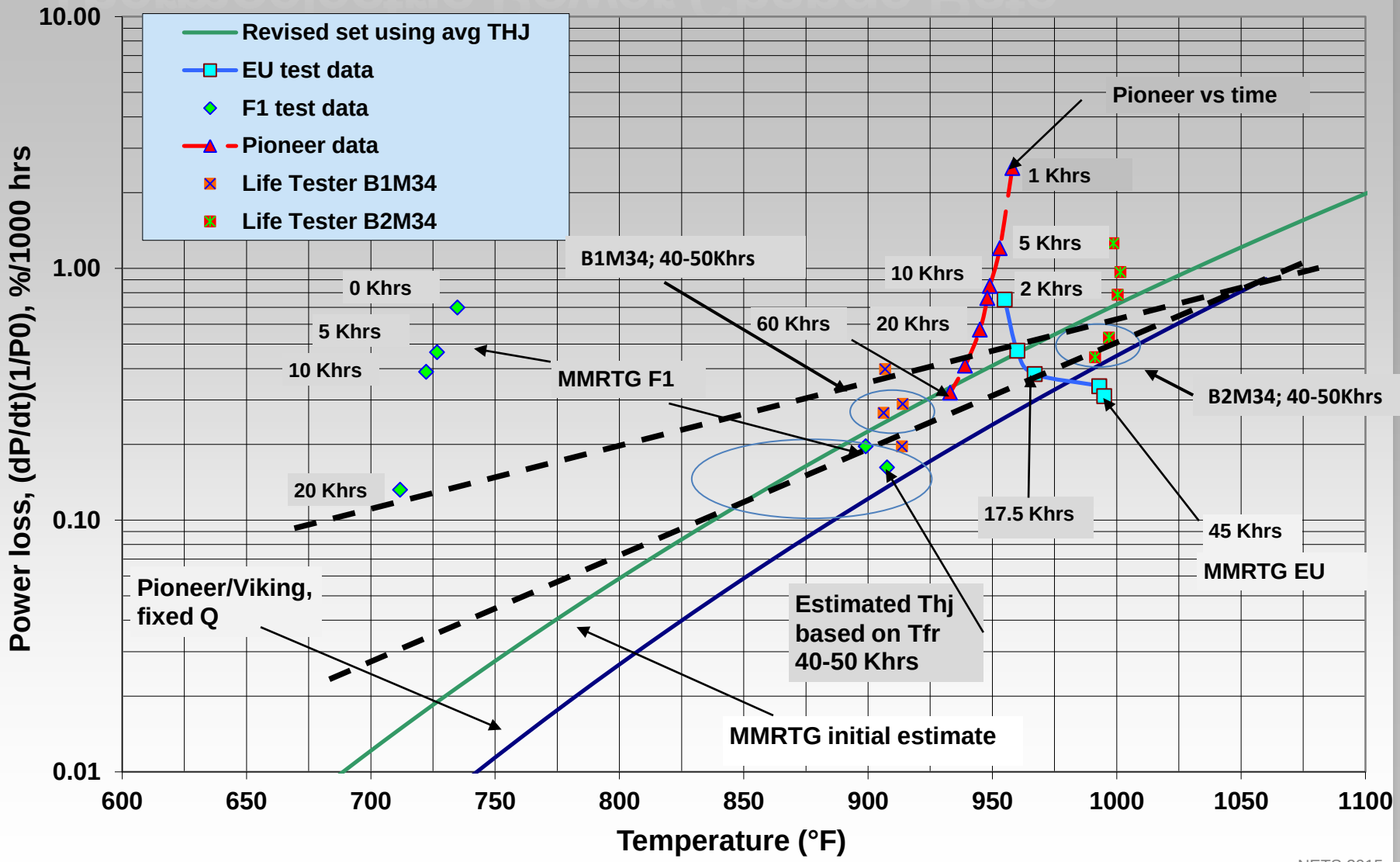
- **Tests**
  - Couple tests
  - Module tests
  - ETG tests
  - Long term Module life tests

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



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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 ½ to 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

The authors would like to acknowledge the support of DOE, JPL and NASA.