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A STATUS UPDATE ON THE eMMRTG PROJECT

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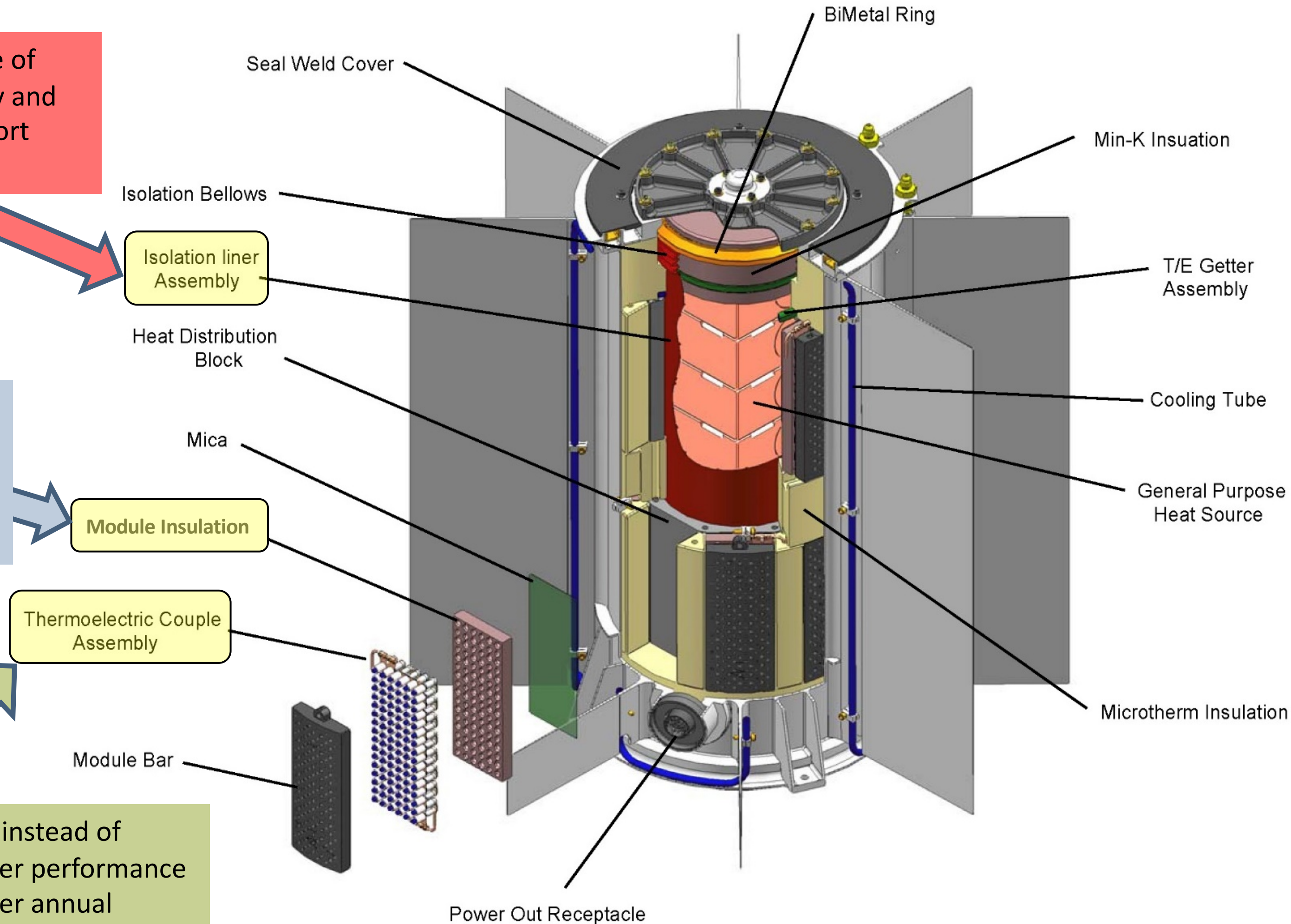
Agenda

- Background
- Project Status
  - Project organization
  - Systems Engineering activities
- Design Criteria
  - Requirements
- Systems Engineering Studies
- Roadmap & Summary

What is being enhanced in the eMMRTG?

Oxide layer added to inner surface of liner to increase surface emissivity and lower temperature of Min-K support system

Insulation changed from Promalight to aerogel-based insulation to provide adequate sublimation suppression for skutterudite (SKD) materials and easier integration with couples

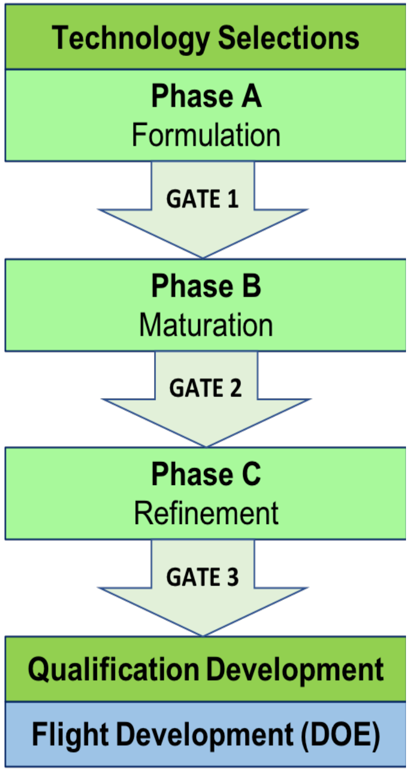


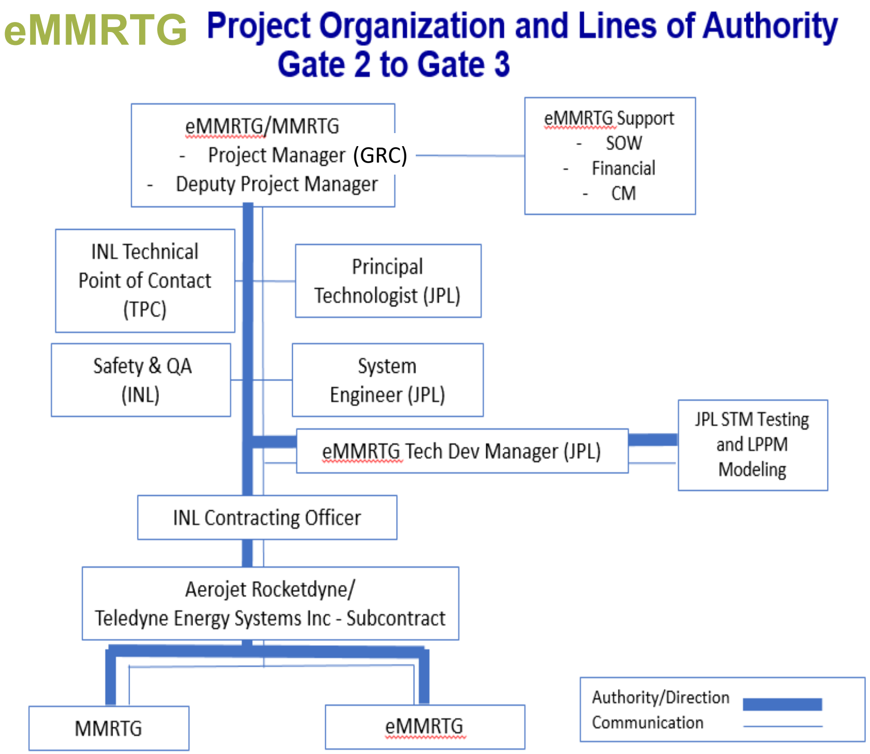
Using skutterudite (SKD) couples instead of PbTe/TAGS couples provides better performance (better ZT and larger ΔT) and lower annual power degradation rates are projected (~ 2.5%/year target)

The MMRTG thermoelectric converter (composed of sixteen 48-couple modules packaged in fibrous insulation) operates under inert gas in an hermetically sealed environment that contains O_2 and H_2 getters

eMMRTG Project Lifecycle and Organization

- The eMMRTG Project is managed out of **NASA Glenn Research Center** with technical support from **NASA JPL**
- System development will by supported by a contract through **DOE Idaho National Laboratory** with **Aerojet Rocketdyne** and **Teledyne Energy Systems, Inc.**





* Direction to Systems Vendor is through Project Manager to Contracting Officer

Timeline of eMMRTG Systems Engineering Activities

Pre – Gate 1
- Accounted for skutterudite-based TE couples in performance assessments
- Identified module insulation and liner changes for design
- Evaluated performance and design for hot junction temperature options

2016
- Advanced Thermoelectric Prediction Model (ATPM) development began
- BOL Monte Carlo sensitivity studies & temperature analysis

2017
- Liner fabrication and testing
- Min-K Uniform Temperature Testing

2018
- Min-K In-Gradient Temperature Testing
- ATPM peer review and began comparisons against LPPM

2019
- Complete LPPM/ATPM model comparisons
- System-level requirements V&V tasks
- Conduct lifetime performance prediction trade studies to size the couples

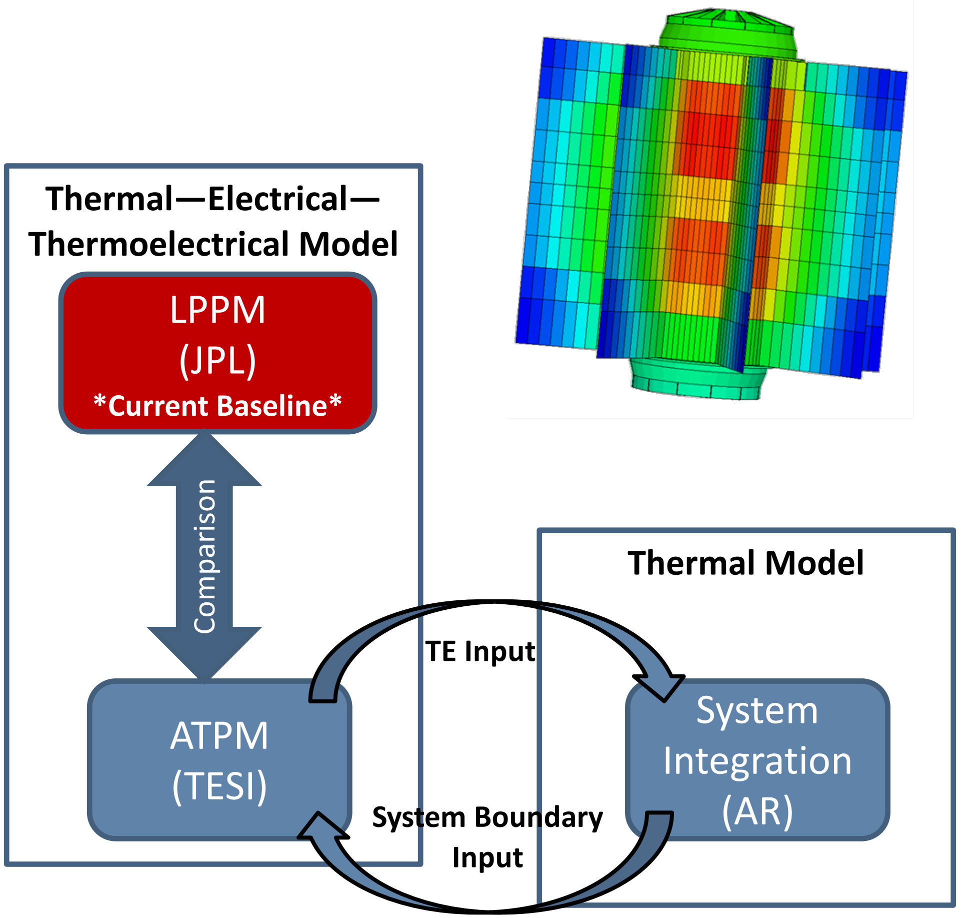
Requirements Development & Management

Systems Engineering tasks are critical to improving an understanding of the eMMRTG system, reducing risk, determining design point temperature and associated couple sizing, obtaining performance predictions.

Modeling

Three System Models:

1. **Lifetime Performance Prediction Model (LPPM) – Baseline at Gate 2**
2. Advanced Thermoelectric Prediction Model (ATPM) – EODL requirements verification
   - High fidelity generator model
3. System Integration – mission planning
   - Low fidelity thermal model



Why do we need System Modeling?

- Certain system requirements occur at end of design life (17 years)
- Define requirements
- System trade studies
- Power predictions for mission planning.

To eliminate the need for 17 years of test data, the IRCD EODL Requirement is verified by analysis using lifetime performance prediction tools, anchored by test data.

Allowable Flight Envelope (AFE)

Moderate effect on hot junction temperatures

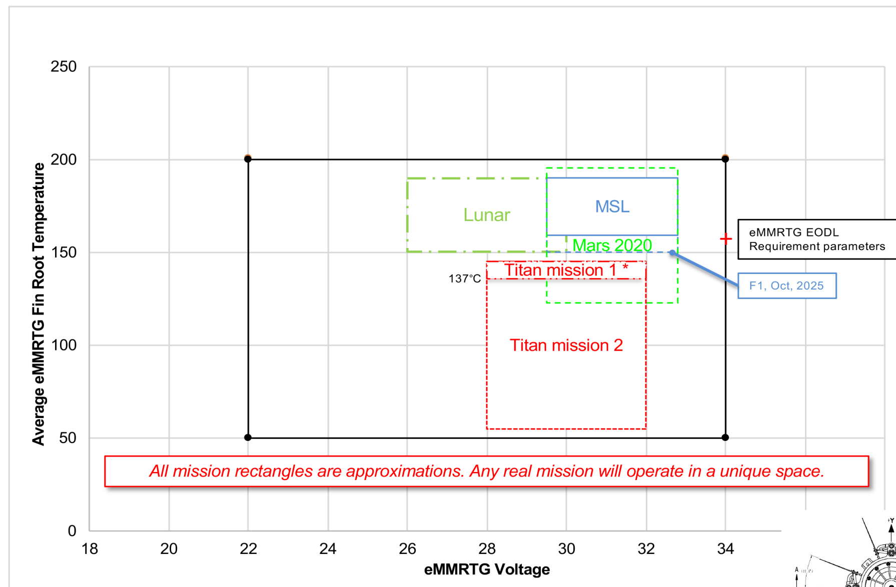
Small effect on hot junction temperature

Tfr	Q in	1952	2000	2048	1952	2000	2048	1952	2000	2048
	Voltage	22	22	22	28	28	28	34	34	34
157°C	**Power**	**136.1**	**140.6**	**145.1**	**141.9**	**147.7**	**153.3**	**135.9**	**142.7**	**149.5**
	Thj	518.2	524.4	530.6	536.1	542.2	548.3	554.9	560.9	566.9
	Tcj	177.5	178.0	178.4	177.3	177.8	178.2	177.3	177.7	178.2
190°C	**Power**	**130.5**	**134.9**	**139.2**	**135.9**	**141.4**	**146.8**	**129.6**	**136.1**	**142.5**
	Thj	545.7	551.8	557.9	563.7	569.8	575.8	582.7	588.6	594.5
	Tcj	210.5	211.0	211.5	210.4	210.8	211.3	210.3	210.8	211.2
200°C	**Power**	**128.8**	**133.1**	**137.3**	**134.0**	**139.4**	**144.7**	**127.5**	**133.9**	**140.2**
	Thj	554.1	560.2	566.3	572.2	578.2	584.2	591.2	597.1	603.0
	Tcj	220.6	221.0	221.5	220.4	220.8	221.3	220.3	220.8	221.2

Relatively large effect on hot junction temperature

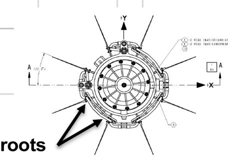
- T_{HJ} is affected by T_{FR}, operating voltage, and thermal inventory
- If T_{HJ} is driven higher by operating conditions, it will have an effect on degradation
- 77W EODL Requirement @ T_{FR} =157°C, Q_{TH}=1952 W_{TH}, V_{load}=34 V

The SRD requires the eMMRTG to operate within the Allowable Flight Envelope (AFE), but EODL power will vary according to the specific mission profile.

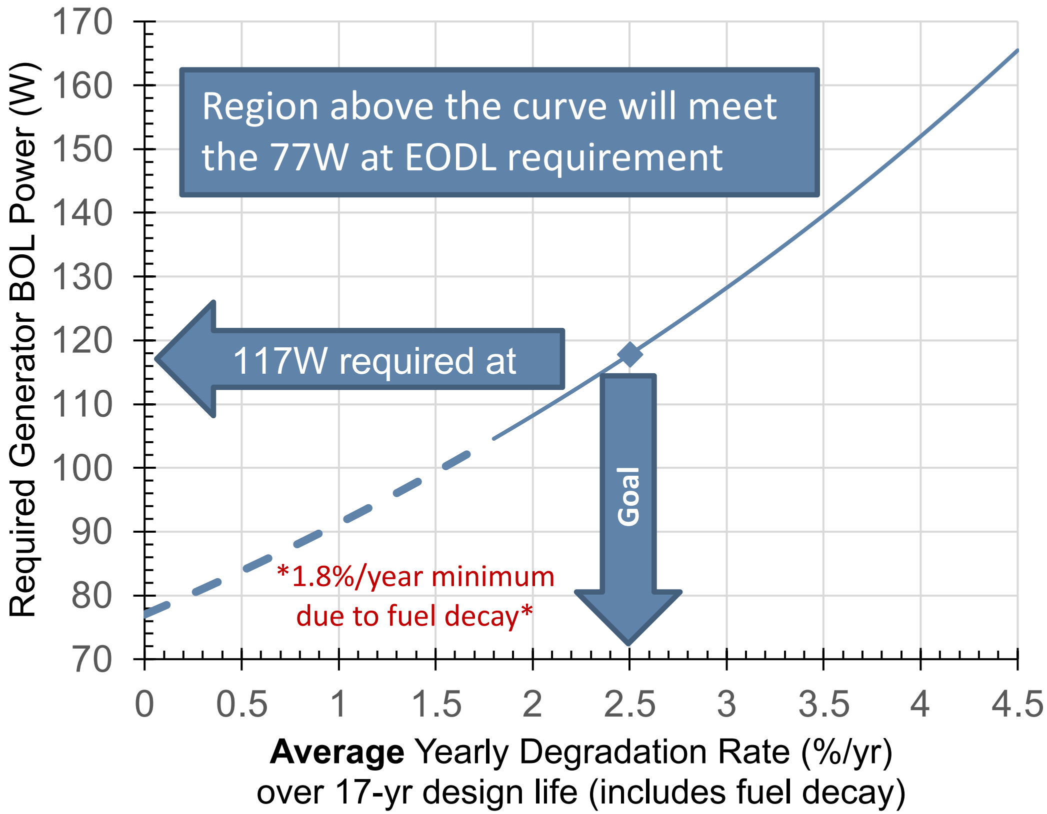


* Region of EODL parameters for MMRTG on Titan lander

Lunar mission scenario assumes eMMRTG protected from temperatures over 190C and load centered at 28V +/-2V



EODL Optimization



- The **derived BOL power requirement** is determined based on an allowable annual degradation rate to meet 77W EODL
- Higher **hot junction temperatures** give more BOL power, but also more **degradation**, meaning EODL power may not be higher.
- T_{hj} is controlled by slightly resizing couple **cross section** as needed
- As more data is collected at different temperatures, the **couple will be sized** to achieve acceptable degradation with maximum EODL power
- Higher BOL power provides **margin** on the allowable yearly degradation to meet EODL power requirement

Success criteria for verifying technology performance is defined as shown using the system-level requirement

eMMRTG Liner Segment Fabrication Process

- Fabrication of liner segments with oxide layer on both the inside and outside surfaces was successfully developed and demonstrated
- Liner emissivity testing indicated a stable emissive layer was formed
- Liner emissivity testing also indicated the liner emissivity was 0.77 not the assumed 0.8
  - The impact is a small increase in heat source temperatures

Sample	Emissivity
Sample 1	0.77
Sample 2	0.76
Sample 3	0.77
Sample 4	0.78

Results are at the temperature of interest and average to 0.77

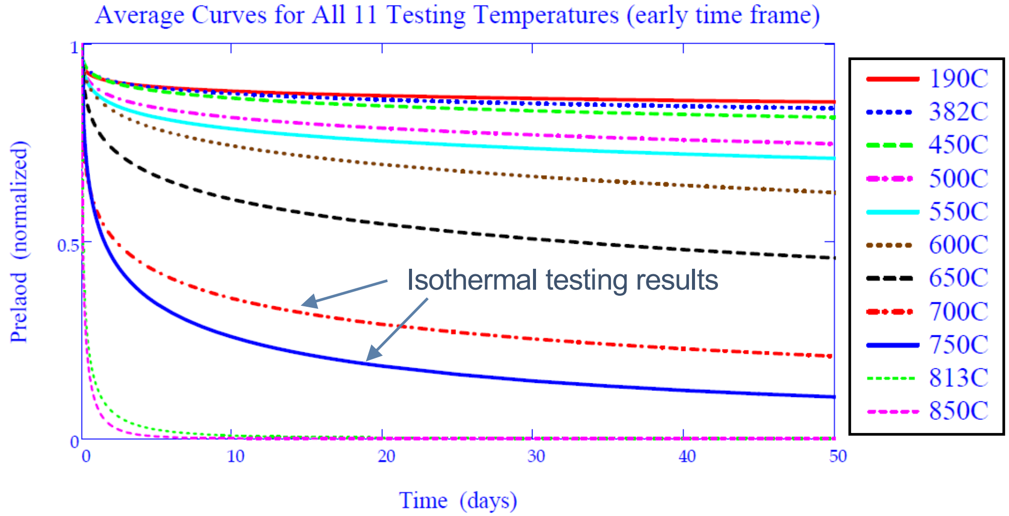
Upgraded liner fabrication process has been successfully demonstrated and shown to minimize heat source temperature.

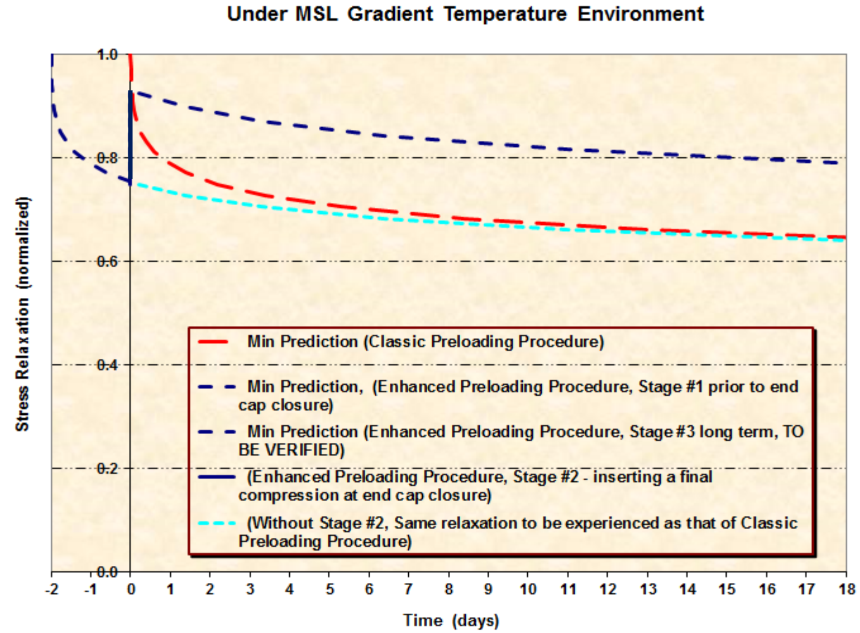
Grit Blasting

Oxidizing

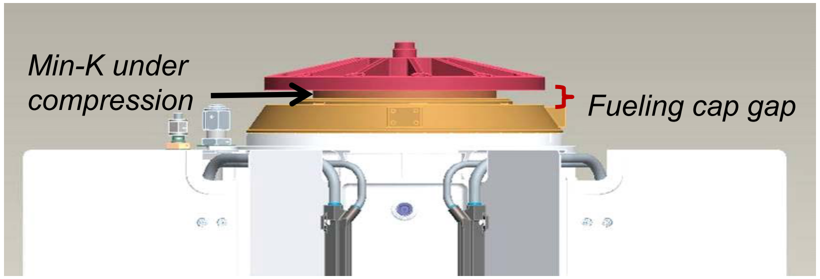
Min-K Testing to assess stress relaxation

Increased temperatures in eMMRTG result in higher stress relaxation of end-support insulation. A pre-loading approach has been developed to accommodate the higher temperatures while preserving the MMRTG design heritage.





- The eMMRTG (Thj=600C BOL) operates at a higher temperature than MMRTG (Thj=530C BOL)
- Min-K end-support insulation will experience higher relaxation at these elevated temperatures
- With 2-days of preconditioning prior to closing the end cap, a 15% preload gain is potentially achievable
- The preload reduces stress relaxation following end cap installation to maintain structural integrity of the Min-K

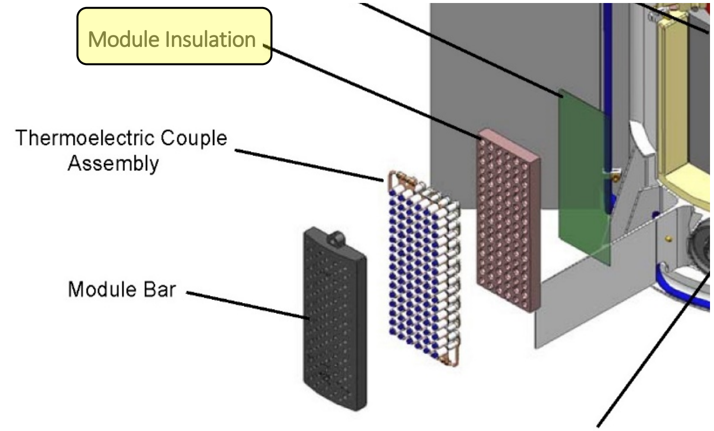


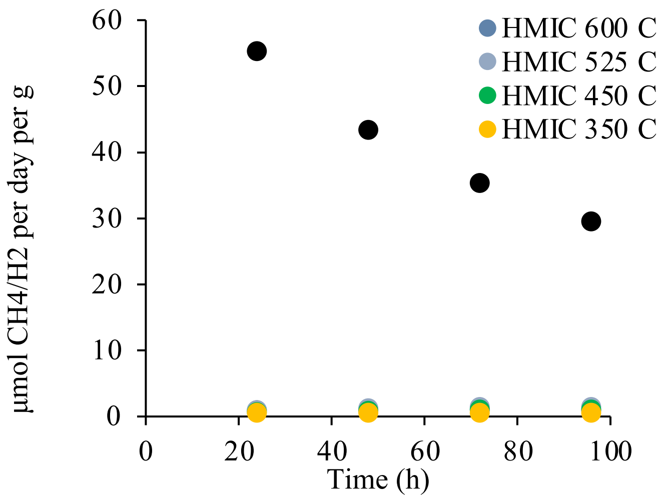
Size Min-K length to provide desired strain/gap for last compression increment after 1-2 days of relaxation

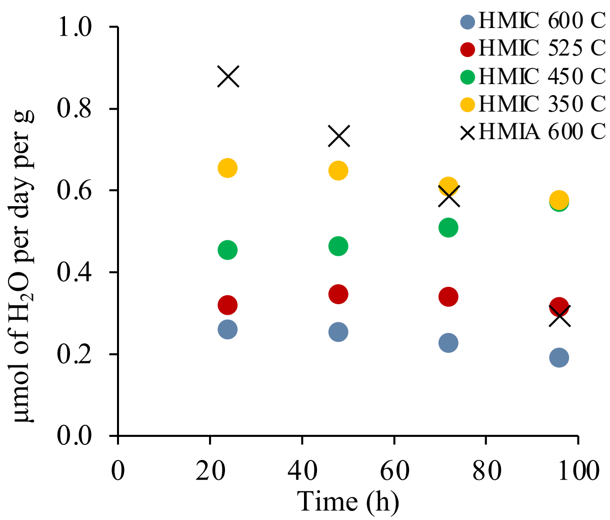
This preloading method ensures structural integrity of the end-support system at the higher operational temperatures of the eMMRTG

HMIC Outgassing Assessment

- Module insulation is planned to be changed from Promalight in MMRTG to aerogel-based insulation in eMMRTG
- Early testing utilized ambient-dried aerogel (HMIA), however this was replaced with critically point-dried aerogel (HMIC)
- Dr. Chris Whiting of University of Dayton Research Institute (UDRI) performed experiments to understand the outgassing behavior of HMIC relative to HMIA







- Aerogel outgassing products, including CH_4 and H_2 shown above, were found to be 98% lower in HMIC compared to HMIA, lowering the risk of chemical interactions at the system-level
- Outgassing of H_2O in HMIC was shown to be more consistent over time, with a lower rate overall than HMIA, lowering the risk of oxidation at the system-level

Summary & Path Forward

- The eMMRTG Project has made considerable progress in advancing SKD couple technology, and will be presenting progress at the upcoming Gate 2 review (March 13-14, 2019)
- System studies continue to enable a greater understanding of proposed design changes and risk mitigation
  - Modeling capabilities have been significantly advanced
  - Manufacturing and design changes have been established and better understood for the next stages of the project
- 48-couple module development and testing is planned to begin upon completion of Gate 2
- A successful Gate 3 review would initiate qualification unit build for a potential 2024 delivery

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