Hall Thruster Thermal Modeling and Test Data Correlation

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Outline

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- Hall Effect Thrusters – Thermal Characteristics
- Thermal Design
- Thermal Model Development
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- Thermal Model Correlation
- Model Correlation Results
- Conclusions

Introduction

- HERMeS - Hall Effect Rocket with Magnetic Shielding
- Developed through a joint effort by NASA/GRC and the Jet Propulsion Laboratory (JPL).
- Design goals: High power (12.5 kW) high Isp (3000 sec), high efficiency (> 60%), high throughput (10,000 kg), reduced plasma erosion and increased life (5 yrs) to support Asteroid Redirect Robotic Mission (ARRM).
- Further details see “Performance, Facility Pressure Effects and Stability Characterization Tests of NASA’s HERMeS Thruster” by H. Kamhawi and team.

Hall Effect Thrusters – Thermal Characteristics

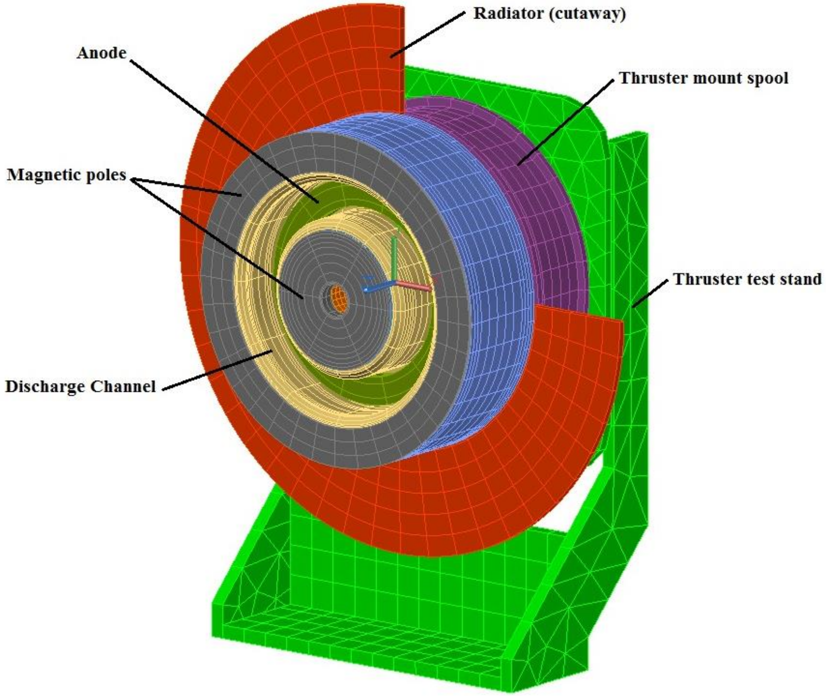
- Hall Thrusters (HT) inherently operate at elevated temperatures ~ 600 C (or more).
  - Due to electric & magnetic (E x B) fields used to ionize and accelerate propellant gas particles (i.e., plasma).
  - Cooling is largely limited to radiation in vacuum environment.
- Thus the hardware/components must withstand large start-up delta-T's.
- HT's are constructed of multiple materials; assorted metals, non-metals and ceramics for their required electrical, magnetic and erosion resistant properties.

Thermal Design

- To mitigate thermal stresses HT design must accommodate the differential thermal growth from a wide range of material Coef of Thermal Expansion (CTE's).
  - Prohibiting the use of some bolted/torqued interfaces.
  - Spring loaded interfaces are commonly used, particularly at the metal-to-ceramic interfaces to allow for slippage.
- However most component interfaces must also effectively conduct heat to the external surfaces for dissipation by radiation.
  - Thus contact pressure and area are important.

Thermal Model Development - Overview

- To aid the mechanical design a thermal model was developed concurrent with the evolution of the hardware configuration.
  - Model results were used to optimize materials, interfaces, contact areas, bolt patterns, surface finishes and coatings to achieve effective heat transfer and minimize component operating temperatures.



Thermal Model Development – Component Fidelity

- The model contains ~ 9600 nodes over 19 submodels.
  - Cathode was modeled separately with heat load impressed on thruster model.
- The table illustrates the moderately high fidelity used to accurately define all conduction pathways internal to each component.

Component	Submodel(s)	# of Nodes
Anode	Anode	174
Backpole	Backpole	936
Discharge Channel (DC)	Dischamber	636
DC Mount Ring	DCRing	1077
Thruster Mount	GimbalMnt	252
Inner Coil Bobbin	InCoilBob	258
Inner Magnet Coil	InMagCoil L1 to L12	2097
Mid-stem	InnerCore	702
Inner Front Pole	InnerFrtPole	153
Inner Magnet Shield	InnerShield	540
Outer Coil Bobbin	OutCoilBob	300
Outer Magnet Coil	OutMagCoil L1 to L6	540
Outer Magnet Shield	OuterShield	540
Outer Front Pole	OutFrtPole	108
Outer Magnet Guide	OutSupRing	324
Radiator	Radiator	360
Rear Cover	RearScreen	1
Thruster Test Stand	ThrustStand	528
Vacuum Tank	VacTank	82
	Total =	9608

Thermal Model Development – Heat Loads

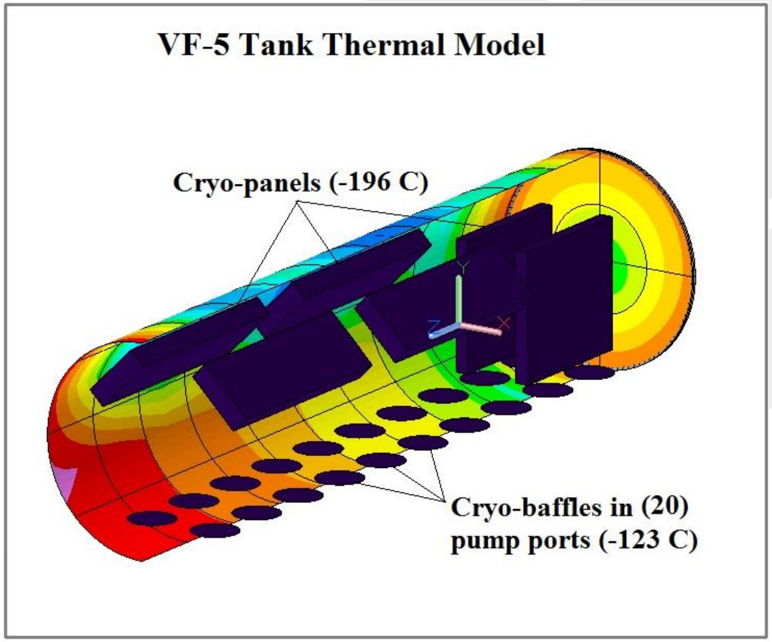
- Magnet coils and cathode heat loads determined by test.
- Plasma heat loads (anode, discharge channel walls and front pole) were predicted by JPL's plasma physics model.
- Scale factors were applied to the plasma heat loads during model correlation to match test temperatures.

Component	Predicted Heat (W)	DC_Factor†	Pole_Factor†	Total Heat Loads (W)
Inner Magnet Coil	44.1	-	-	44.1
Outer Magnet Coil	48.1	-	-	48.1
Anode	496	0.52	-	257.9
Cathode	41	-	-	41.0
DC Walls	1056	0.52	-	549.1
Inner Front Pole	181	-	0.23	41.6
	1866.2			**981.9**

† DC_Factor and Pole_Factor determined by iterative analysis to match test temps.

Thermal Model Development - Environment

- With the vacuum tank being the ultimate/final heat sink, due diligence was placed on modeling the tank geometry, surface emittances and cryo-pumping surface temperatures.
- Model predicts dormant HT temperature to within 1 C.



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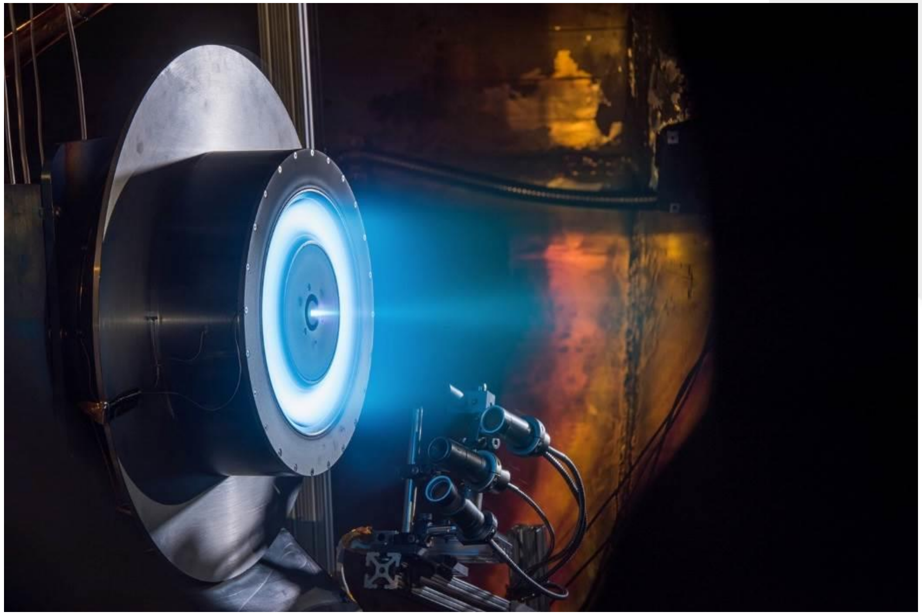
HT Test Data

- Test temperatures and coil currents were collected for all components at max thermal op's. (12.5 kW, 600 V)
- Temps showed large thermal margins.



Component	Data File Column	12.5kW 600V Test Temps (C)	Avg Test Temps (C)	Thermal Margin (C)
DC outer wall Dwnstrm 3 Oc	BI	404		
DC outer wall Upstrm 3 Oc	CI	343		
DC inner wall Upstrm 3 Oc	BJ	341		
DC inner wall Dwnstrm 3 Oc	CH	364	363	296
DC Base 6 Oclock	BK	328		
DC Base 12 Oclock	CK	357	343	343
Outer Coil - Dwnstrm	BH	271		
Outer Coil - Upstrm	CA	272	272	253
Inner Coil - Upstrm	BX	393		
Inner Coil - Dwnstrm	CE	380	387	132
DC Mount Ring OD	BL	308		
DC Mount Ring-ID	CJ	319	314	181
Radiator OD 12 Oc	BO	86		
Radiator OD 6 Oc	BP	178		
Radiator ID	CB	260	219	140
Back Pole Near OD	BZ	267		
Backpole Near DC	BR	278		
Backpole Near ID	CC	299	281	151
Spool Mount Front Flange	BQ	186		
Spool Mount Rear Flange	BN	106	146	164
Inner Front Pole 6 Oc	BU	309		
Inner Front Pole 12 Oc	CG	306	308	191
Outer Screen	BF	285		65
Inner Screen	CD	322		228
Outer Front Pole-Inside	BG	216		134
Outer Guide - Middle	BM	221		129
Thrust Stand Base	BV	42		-
Thrust Stand Arm	BY	73		-
Midstem	BS	323		202
Back Cover Plate	BT	113		-
Inner Magnet Current (A)	V	3.38		
Outer Magnet Current (A)	N	2.82		
Values in red are suspect.				

Thermal Model Correlation – The Process

- During model construction parameters are calculated, estimated or even assumed leading to varying degrees of uncertainty.
  - Therefore inaccuracies exist in any uncorrelated model.
- For the HT model these ‘tuning’ parameters were identified as;
  - Interface contact thermal conductance
  - Surface emittance
  - Plasma heating
- The correlation process is systematic adjustments to these parameters to achieve a balanced temperature profile in good agreement with test temperatures.

Thermal Model Correlation – The Process con’t

- Each of these parameters has its own effect on component temperatures of the thruster. The predominant effects of each are as follows:
  - Interface conductance controls the component-to-component delta T’s thereby setting the temperature profile or gradients in the assembly.
  - Emittance of the external surfaces and plasma heating controls the magnitude of the temperature profile.
- However these parameters do have their interdependencies affecting the conduction and radiative heat dissipation paths, and so the model ‘tuning’ process can be highly iterative.

Correlation Parameter – Contact Conductance

- Interface contact conductance primarily depends on the ***effective contact area***. Many factors can adversely affect this area.
  - Materials, thicknesses, surface finish, hardness, bearing pressure, etc.
  - Elevated temps precluded the use of most thermal interface materials.
  - Heat transfer thru bare bolted interfaces typically occur in the immediate vicinity of the holes. Resulting in the effective contact area << the interface area, producing higher delta T's.
  - Thus calculating the heat transfer (in this manner) thru a dry/bare interface is prone to inaccuracy (especially in vacuum service).
- Fortunately having measured most of the delta T's (from thruster test data) facilitates the direct calculation of thermal conductance.

Correlation Parameter – Contact Conductance con't

- Through iterative model solutions these contact conductance values produced the best overall agreement with the test ΔT's.

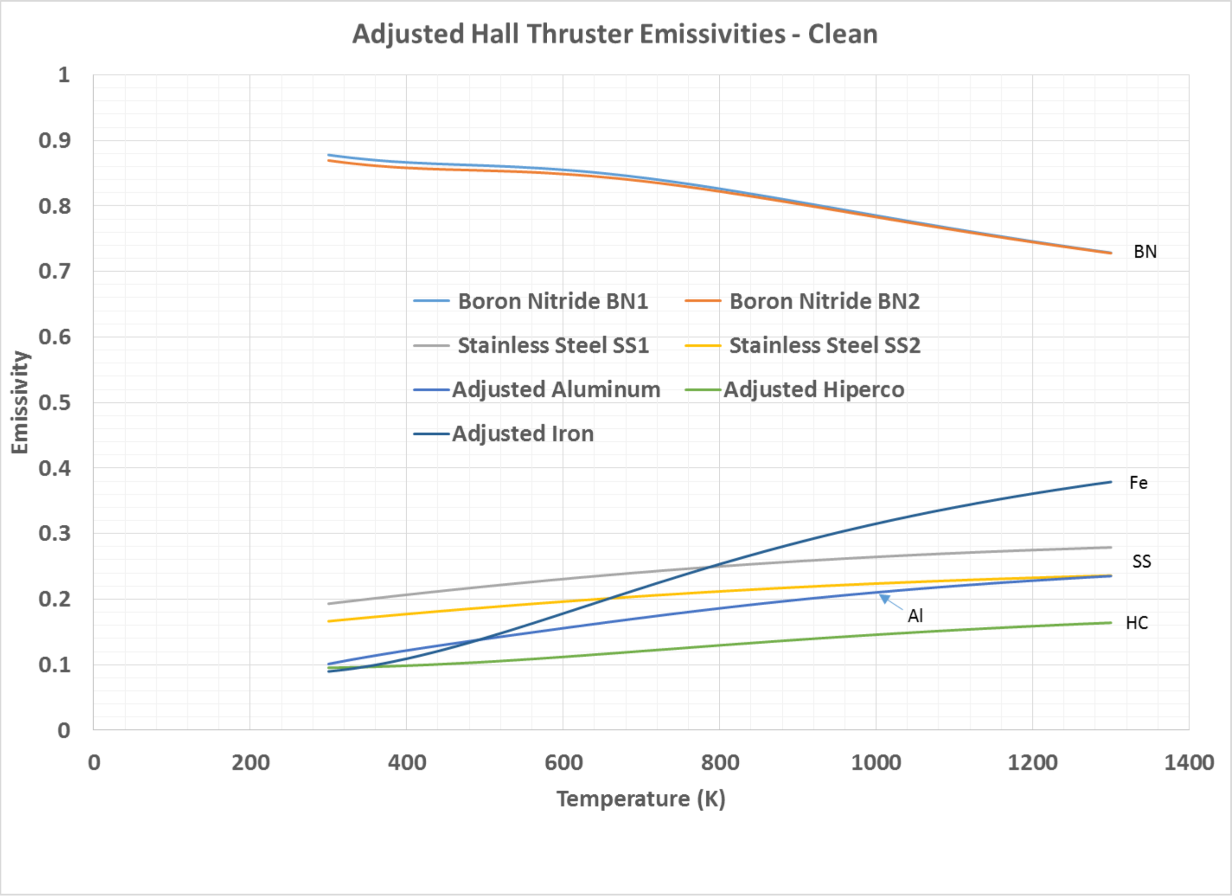
HERMeS TDU-1 Thruster Thermal Contact Conductance Values derived from 12.5 kW 600 V Test Data (May 18, 2016)		
Interface	Conductance (W/m2-K)	Comments
DC to Mount Ring	1160	Bearing force maintained with Belleville washers.
Mount Ring to Backpole	1240	Slightly more then other side due to backpole fasteners.
Mid-stem to Backpole	3100	
Inner Front Pole to Mid-stem	155	
Radiator to Backpole	266	Broad area contact over 3 bolt circles
Inner Shield to Backpole	620	
Outer Shield to Backpole	310	
Inner Coil Bobbin to Backpole	3100	Applied on 6 circular contact areas at the bolts (OD=.15", ID=0.05")
Outer Coil Bobbin to Backpole	3100	Applied on 12 circular contact areas at the bolts (OD=.15", ID=0.05")
Inner Coil Layers to Bobbin Flanges	388	
Outer Coil Layers to Bobbin Flanges	465	
Gimbal Mount Spool to Radiator	155	
Gimbal Mount Spool to Thrust Stand Plate	155	
Outer Guide to Backpole	3100	
Outer Front Pole to Outer Guide	3100	
Anode to DC	15500	Applied on 6 circular contact areas at the bolts (OD=.80", ID=0.50")
Thrust Stand Plate to Arms	6 W/K	1.0 W/K for each of 6 bolts
All other thruster stand interfaces	1550	

Correlation Parameter – Surface Emittance ε

- Published values of surface emittance can range widely for many common materials depending on many variables;
  - Surface finish, oxidation, temperature, info source, IR range, etc.
- Therefore the emittance of nearly all materials in the thruster were measured over 2 to 25 μm (most common IR range).
- During thruster testing graphite deposition occurs (from beam target sputtering) producing varying degrees of *dirty* surfaces that increased emittance of low value surfaces (metals). The emittance of some dirty materials were also measured.
- Some adjustments to ε of exterior surfaces used during tuning.

Correlation Parameter – Surface Emittance ε con't

- Measured ambient emittance projected to ~ 1000 C.



Correlation Parameter – Plasma Heating

- In support of HT development JPL has performed much research in the area of gas/plasma modeling.
- The physics associated with plasma simulations in a HT are highly complex, leading to some elements of uncertainty in the predicted heat loads.
- Having achieved a good level of confidence in contact conductance and surface emittance thru thruster test data and optical measurements the 3 correlation parameters have been reduced (to a large extent) to one, plasma heat loads.
- Again through iterative model solutions scale factors were applied to these heat loads to match the test temperatures.

Correlation Parameter – Plasma Heating con't

- This process not only produced a correlated thermal model but also provided feedback for refinement of the plasma model.
- Although the thermal model was used along with the test temperatures to determine the magnitude of the plasma heating, the distribution of these heat loads was (and must be) predicted by the plasma model.

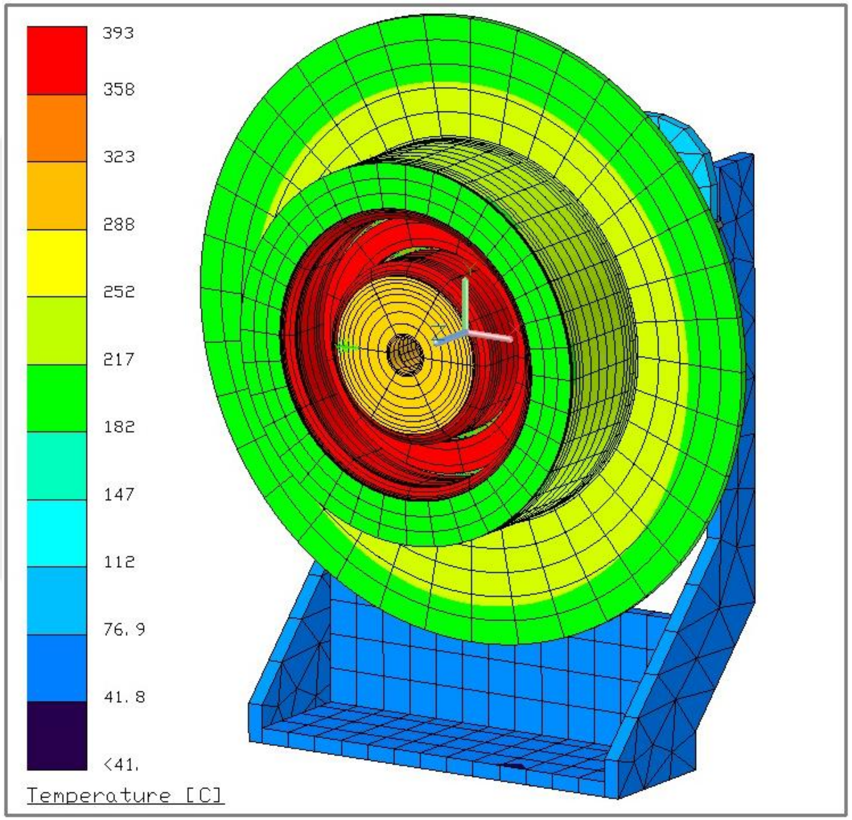
Model Correlation Results

- At the conclusion of the correlation process all model temperatures were within 10 C of thruster test data.
- This is within the tolerance (+/- 5 C) of the thermocouples and the data acquisition system.

Component	Data File Column	12.5kW 600V Test Temps (C)	Avg Test Temps (C)	Thermal Margin (C)	12.5kW 600V 250G (DC = 0.55, Pole = 0.25) Model Temps (C)	Avg Model Temps (C)	Test to Model ΔT (C)
DC outer wall Dwnstrm 3 Oc	BI	404			383		
DC outer wall Upstrm 3 Oc	CI	343			353		
DC inner wall Upstrm 3 Oc	BJ	341			353		
DC inner wall Dwnstrm 3 Oc	CH	364	363	296	389	370	-7
DC Base 6 Oclock	BK	328			344		
DC Base 12 Oclock	CK	357	343	343	344	344	-1
Outer Coil - Dwnstrm	BH	271			274		
Outer Coil - Upstrm	CA	272	272	253	273	274	-2
Inner Coil - Upstrm	BX	393			384		
Inner Coil - Dwnstrm	CE	380	387	132	390	387	0
DC Mount Ring OD	BL	308			314		
DC Mount Ring-ID	CJ	319	314	181	318	316	-2
Radiator OD 12 Oc	BO	86			213		
Radiator OD 6 Oc	BP	178			213		
Radiator ID	CB	260	219	140	243	223	-4
Back Pole Near OD	BZ	267			246		
Backpole Near DC	BR	278			295		
Backpole Near ID	CC	299	281	151	307	283	-2
Spool Mount Front Flange	BQ	186			183		
Spool Mount Rear Flange	BN	106	146	164	109	146	0
Inner Front Pole 6 Oc	BU	309			310		
Inner Front Pole 12 Oc	CG	306	308	191	310	310	-2
Outer Screen	BF	285		65	284		1
Inner Screen	CD	322		228	322		0
Outer Front Pole-Inside	BG	216		134	212		4
Outer Guide - Middle	BM	221		129	228		-7
Thrust Stand Base	BV	42		-	42		N/A
Thrust Stand Arm	BY	73		-	68		5
Midstem	BS	323		202	321		2
Back Cover Plate	BT	113		-	114		-1
Inner Magnet Current (A)	V	3.38			3.38		
Outer Magnet Current (A)	N	2.82			2.82		

Conclusions

- The HERMeS HT has achieved its performance goals with large thermal margins.
- Having completed an extensive test campaign successfully demonstrating thruster performance, the development team has high expectations proceeding into the final testing to assess the durability of the HERMeS design.



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