TFAWS Interdisciplinary Paper Session

Thermal Analysis and testing of the 12.5 kW HERMeS Hall Thruster

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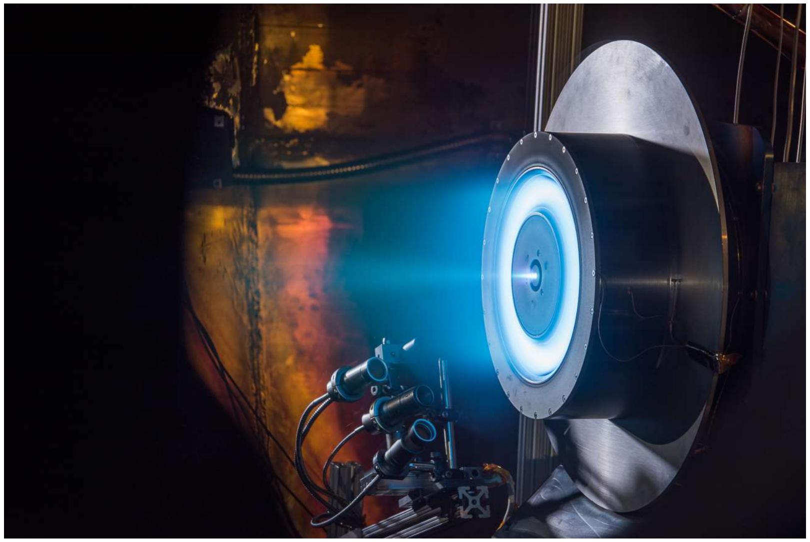
Questions

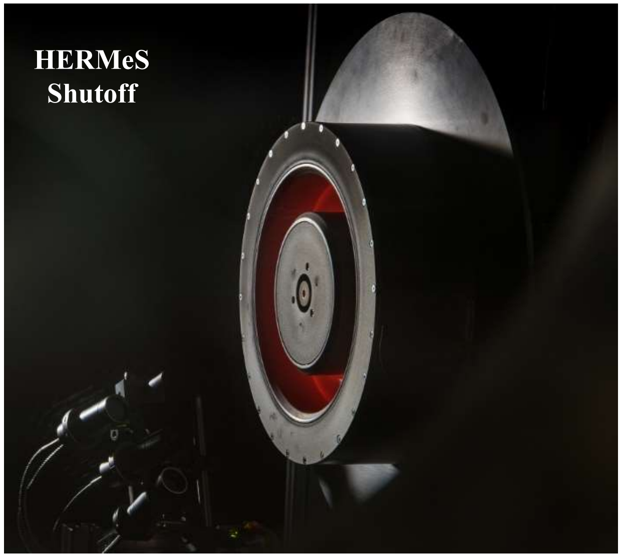
- Thermal Model Overview
- Boundary Conditions
  - Lamps, Shroud
- Plasma Loads
  - Channels, Front Pole, Anode
  - Outer Front Pole Load
- Thermal Results
  - Images
  - IR
- Thermal Model Validation
- Outer Front Pole Load
- Conclusions

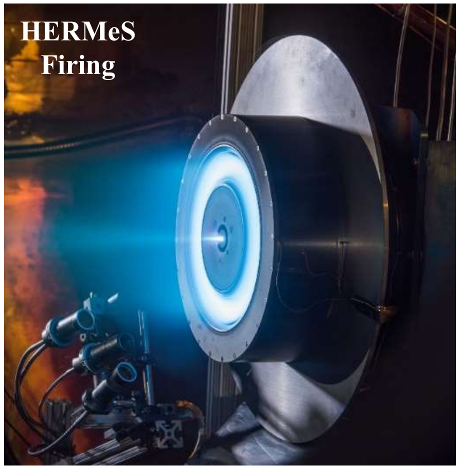
Goals of HERMeS Environmental testing

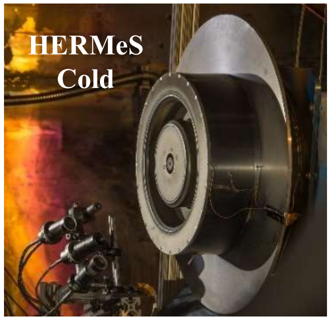
- HERMeS (Hall Effect Rocket-Magnetically Shielded) is a 12.5 kW electric thruster designed for a myriad of applications for future space transport
- Goal of testing was to demonstrate the thruster could operate in elevated temperature environments roughly equivalent to the solar loading experienced at Venus
- Thruster was run to steady state at high temperature, hot started, then cooled to low temperature and cold started
  - Cycle completed three times
- Many thermal modeling challenges
  - Lamps
  - Plasma modeling
  - Temperature dependent properties
  - Loss of pre-load in fasteners



- Large plasma loads (~10-20% of total discharge power deposited as heat load) on thruster during typical firing condition

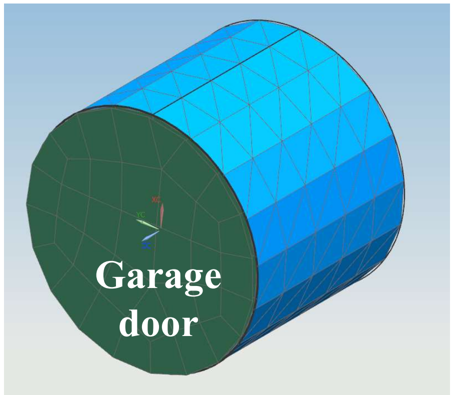


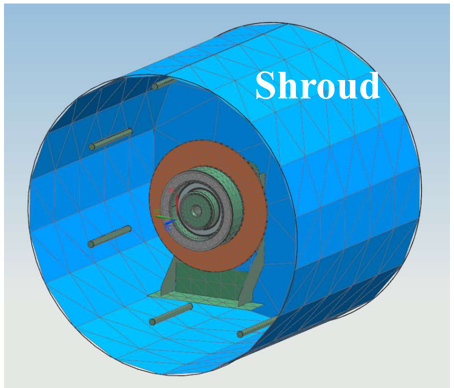


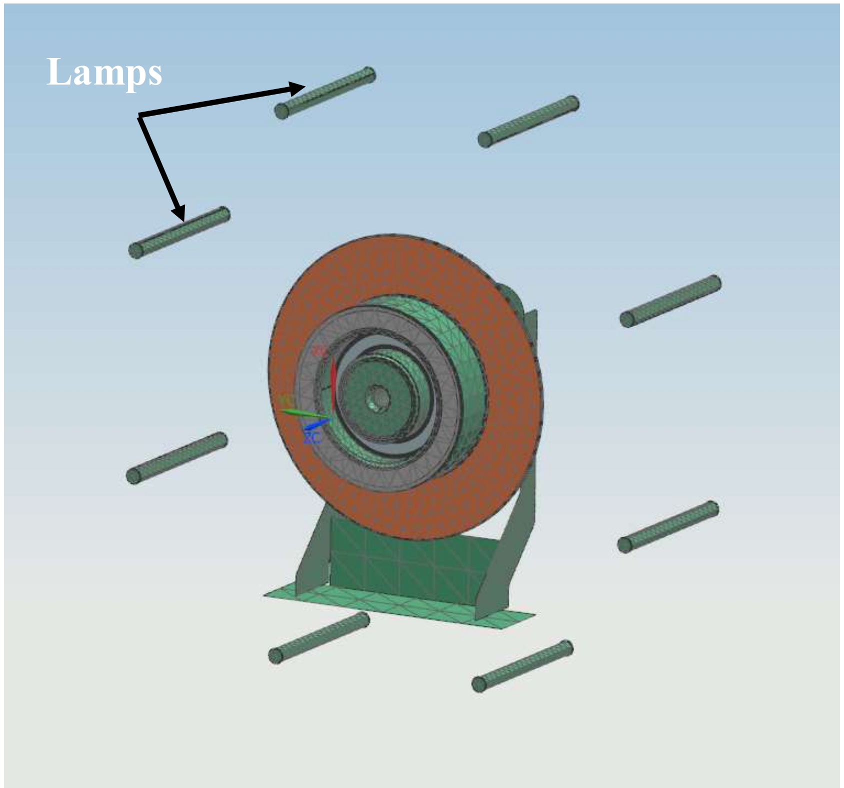


Thermal Model Overview - Configuration

- Thermal Model configurations (CCW from top left)
  - Shroud with garage door closed
  - Shroud open, showing thruster, lamps and mounting assembly
  - Shroud removed, showing all lamps







Boundary Conditions

- Steady State Heatup
  - Lamps: assumed to be 700 K, correlates roughly with the average black body emissive power coming from the lamps in order to maintain steady state thruster operation at the elevated temperature condition
  - Shroud: allowed to float
- Plasma Loading
  - Taken from Mikellides' 2-14-17 (Jan 26 2FLD - 600V 250G) Plasma loads
  - Modulated by 0.96 for all except outer front pole
  - More discussion on this topic later in presentation
- Coil Loads
  - Taken from experimental data
  - Seen in table to the right
  - Temperature dependence accounted for in transient model
  - All analysis conducted for 250 G, even though test conditions were slightly different magnetic field (add temperature)

Coil Loading (taken from experiment)	Coil Power [W]	Coil Current [A]	Coil Volatage [V]
Inner Coil	83	4.45	18.4
Outer Coil	86	4.74	18.2

Plasma Loading

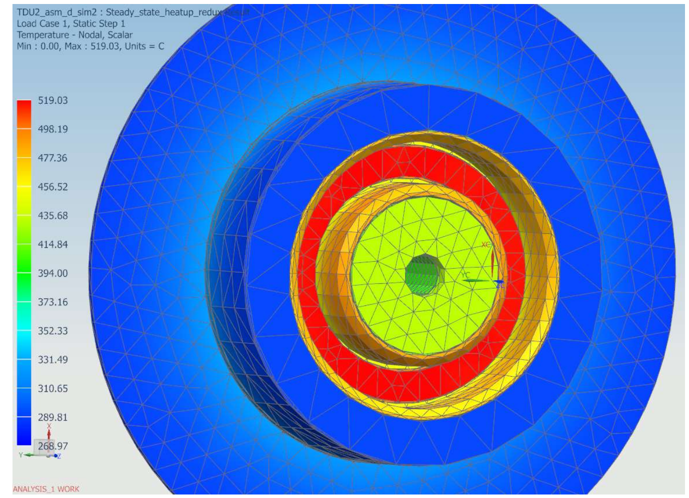
- Plasma loading was tuned in order to validate model
  - Started with 2.14.17 values and used multiplier consistently across Inner Channel, Outer Channel, Anode, and Inner front pole
  - 0.96 yielded best results
  - However, gradients on outer front pole and outer guide indicate that there is plasma loading present on outer front pole
  - Application of 149 W to outer front pole was necessary in order to validate thermal model
- Lamp loading
  - Lamps were assumed to be blackbody emitters at an equivalent 700 K
  - This corresponds to roughly 675 W per lamp, ~34% of the max lamp power (lamps are rated to 2kW)
- Outer Front Pole load
  - Not present as part of 2-14-17 800V 2FLD 250 G, added to aid validation
  - Discussed later

Thruster component, 800 V 250 G	Plasma Loading [W]	Plasma Model Predictions (2.14.17, 12.5kW 600 V 2 FLD, Jan 26) [W]	Fraction of Thermal Model Power to Plasma Model Power
Inner Channel	422	440	0.96
Outer Channel	591	616	0.96
Anode	476	496	0.96
Inner Front Pole Load	174	181	0.96
Cathode load imposed on inner core	14	N/A	N/A
Outer Front Pole load	**149**	**N/A**	**N/A**

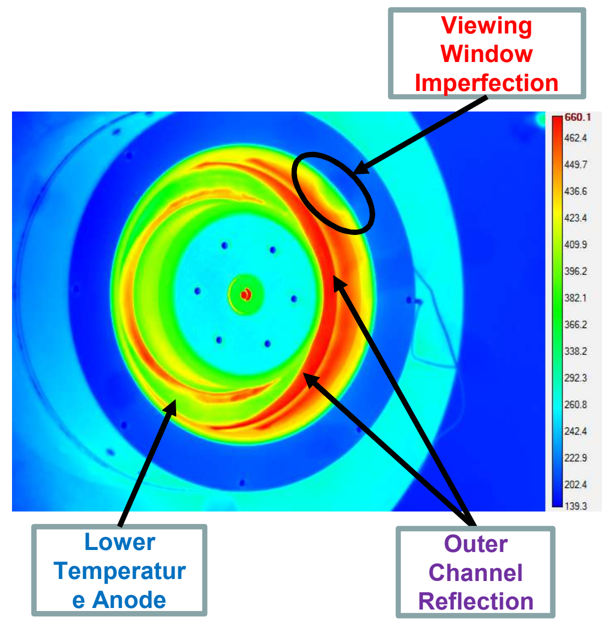
Results -IR Image Comparison

- Note: IR image assumes ε = 0.95 for all surfaces and picks up reflections from surfaces and imperfections in viewing window that Thermal Model does not account for
  - Outer Channel reflection on anode (right side of anode)
  - Anode appears lower temperature but it's optical properties in the thermal model are assumed to be a lower emissivity, however it is difficult to quantify carbon deposition on anode surface
  - "Spots" on downstream face of outer channel wall are imperfections in viewing window to chamber
- Overall IR image matches very well with thermal predictions and deviations are deterministic and known
  - OFP/IFP likely somewhat reflective

Thermal Model

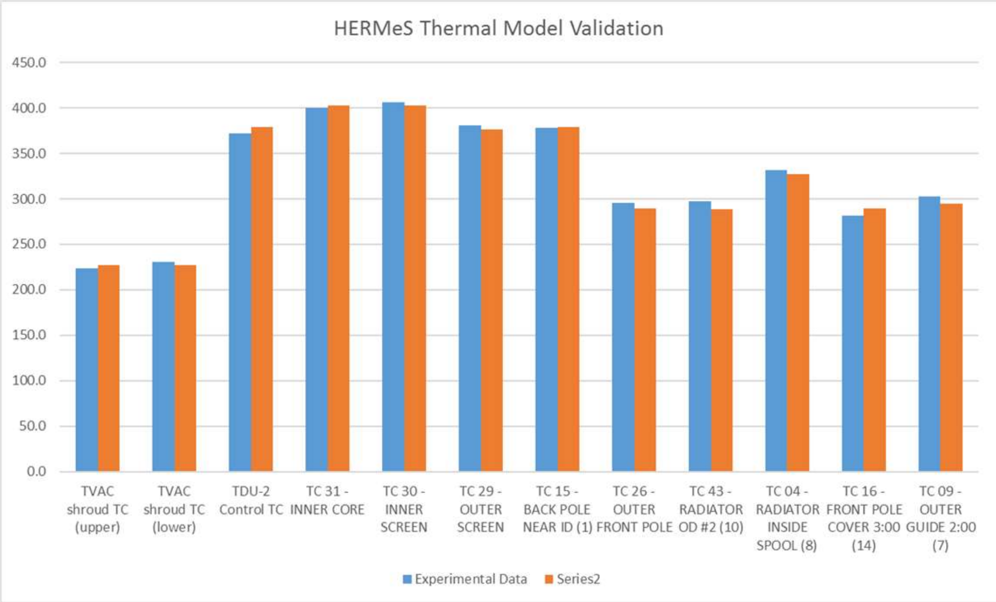


Experiment



Thermal Model Validation - Results

TC location	Error [°C]	Experimental Data [°C]	Thermal Model Predictions [°C]
TVAC shroud TC (upper)	4.1	223.4	227.4
TVAC shroud TC (lower)	-3.6	230.5	227.0
TDU-2 Control TC	6.5	372.1	378.6
TC 31 - INNER CORE	2.9	400.2	403.0
TC 30 - INNER SCREEN	-3.4	406.5	403.0
TC 29 - OUTER SCREEN	-4.4	380.8	376.4
TC 15 - BACK POLE NEAR ID (1)	1.0	377.7	378.6
TC 26 - OUTER FRONT POLE	-5.6	295.4	289.8
TC 43 - RADIATOR OD #2 (10)	-8.6	241.7	288.8
TC 04 - RADIATOR INSIDE SPOOL (8)	-4.7	297.4	326.9
TC 16 - FRONT POLE COVER 3:00 (14)	8.4	331.6	289.7
TC 09 - OUTER GUIDE 2:00 (7)	-7.1	281.2	295.1



Thermal Model Validation

- Accounting for TC's that delaminated during testing, all test TC's were able to be validated with error <±10°C using reasonable variance in optical properties, contact conductance, and plasma loads
  - Optical properties and contact conductances in backup
  - Table values for optical properties used as starting point, some variance but generally consistent with bare metal (exception for radiator, where carbon deposition assumed)
  - Table values for bolted joint contact conductances were used as a starting point when possible, but it is speculated that as the thruster warms up, the contact conductance can change somewhat beyond room temperature, isothermal, bolted joint estimates
  - Since we have good agreement between model and data across thermal interfaces (backpole/outer guide, backpole/outer screen, backpole/inner screen, backpole/inner core, outer front pole/outer front pole cover), there is confidence that listed conductance values are accurate at thermal steady state
- Running the thruster to steady state allowed for a good reference point by which to validate the thermal model
- There will be some variance in the fact that the lamp loads were not entirely constant but the thruster temperatures did reach steady state during the hot dwell duration of the thermal test

TC location	Error [°C]	Thermal Model Predictions [°C]
TVAC shroud TC (upper)	4.1	227.4
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Outer Front Pole Loading

- Outer Front Pole Plasma Loading
  - Without outer front pole load (lamps on power on other surfaces) it is not possible to match the gradients across the backpole/outer guide and especially outer guide/outer front pole without overheating the rest of the thruster
    - Note the significant drop in **outer front pole**, **front pole cover**, and **outer guide** temperatures (all >20° C)
    - Note: No OFP load and No lamp load shown for comparison, to understand **absorbed lamp power** on outer surfaces (Control TC temp w/o lamps ~ 353 ° C)
  - OFP load has little effect on control TC
  - Uncertainty is higher at outer front pole, with respect to plasma loading
  - Most gradients driven by bolted joints

TC location	Experimental Data [°C]	Thermal Model Predictions W/ OFP LOAD [°C]	Thermal Model Predictions W/ LAMPS, NO OFP LOAD [°C]	Thermal Model Predictions W/ NO OFP LOAD AND NO LAMPS [°C]
TVAC shroud TC (upper)	223.4	227.4	225.9	90.9
TVAC shroud TC (lower)	230.5	227.0	225.5	88.6
TDU-2 Control TC	372.1	**378.6**	**373.5**	344.4
TC 31 - INNER CORE	400.2	403.0	399.0	375.9
TC 30 - INNER SCREEN	406.5	403.0	397.9	369.1
TC 29 - OUTER SCREEN	380.8	376.4	369.7	339.2
TC 15 - BACK POLE NEAR ID (1)	377.7	378.6	373.5	344.4
TC 26 - OUTER FRONT POLE	295.4	**289.8**	**250.1**	219.3
TC 43 - RADIATOR OD #2 (10)	241.7	288.8	284.3	250.7
TC 04 - RADIATOR INSIDE SPOOL (8)	297.4	326.9	321.2	289.4
TC 16 - FRONT POLE COVER 3:00 (14)	331.6	**289.7**	**237.8**	208.4
TC 09 - OUTER GUIDE 2:00 (7)	281.2	**295.1**	**276.3**	240.6

Outer Front Pole Loading

- GRC does not use outer front pole loading in his thermal model and has validated his model
- Why does JPL think it is necessary?
  - Outer Coil covers are possible culprit for JPL model needing OFP load
    - No telemetry so hard to tell
  - It might be possible validate the JPL thermal model without outer front pole loading
    - This would likely involve using contact conductances that are unrealistically high in order to get enough energy into outer guide and outer front Pole
  - Additionally, model appears to demonstrate effect of lamps on outer surfaces, indicating that outer front pole loading is not an effect caused by lamps
- Outer Front pole loading is <10% of total thermal load on thruster and heat flux is about 1/3 of IFP thermal flux (0.45 W/cm^2 vs 1.4 W/cm^2)

TC location	Experimental Data [°C]	Thermal Model Predictions W/ OFP LOAD [°C]	Thermal Model Predictions W/ NO OFP LOAD [°C]	Thermal Model Predictions W/ NO OFP LOAD AND NO LAMPS [°C]
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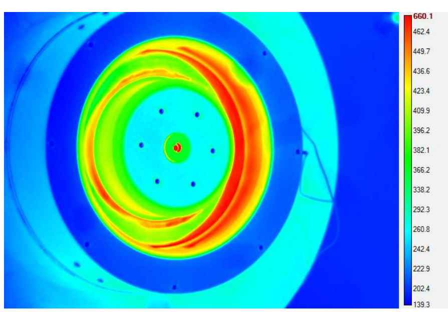
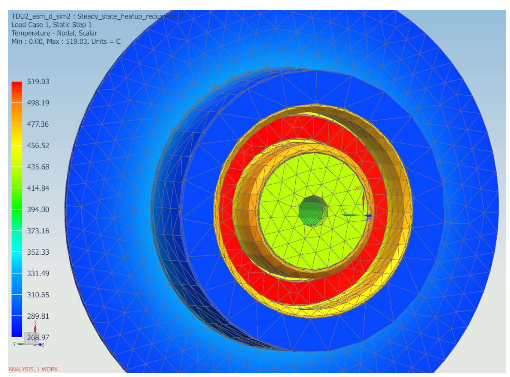
Conclusion

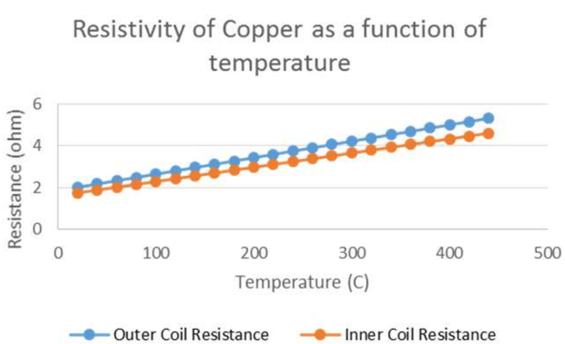
- A thermal model of TDU2 was validated against experimental data collected during environmental testing at JPL
  - Model validated predictions with thermocouple data to within <10° C
  - Used Mikellides' 2-14-17 plasma loading file, specific loads were Jan26 12.5kW 600 V 2FLD loads
  - Multiplier was 0.96
- Additionally 149 W were applied to outer front pole in order to match Outer Front Pole and Outer guide temperatures
  - Without this additional load, validation would be very difficult
  - Outer components thermal contact conductance deemed to be relatively deterministic since driven by bolted joints
  - Optical properties are within reasonable bounds

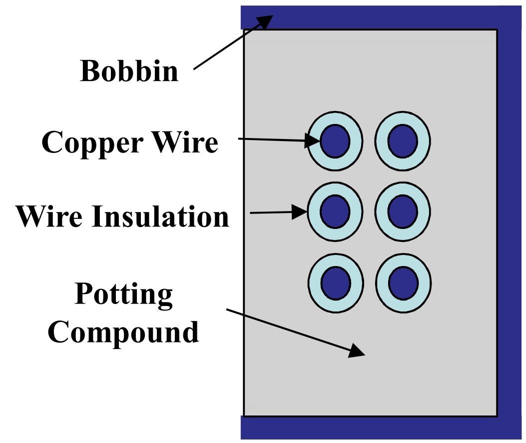




Thermal Issues - Magnetic Coils

- Magnetic coils have unique high temperature issues
  - Wires with high temp insulation, doped in a compound to keep them from contacting each other
  - Hard to determine thermal conductivity of coils
  - Emissivity is not well understood



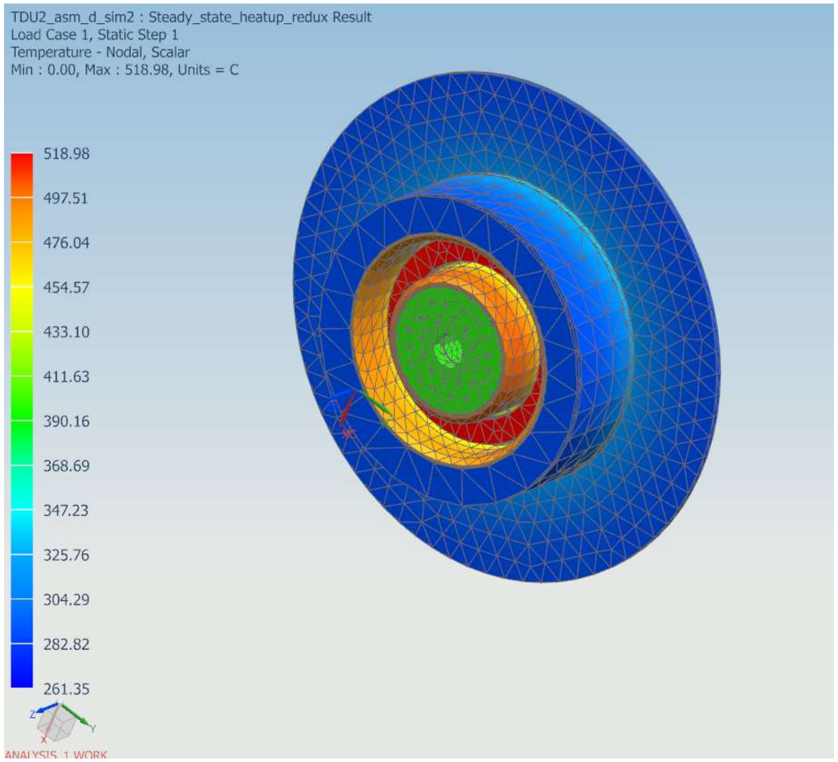


Schematic of coils
Note: not to scale, many more wires, less space

Backup

Results

Control TC Location



Optical and Material Properties JPL TDU-2 env Test

	Component	Desired Material	Emissivity
1	Backpole	Hiperco	0.3
2	Inner Core	Hiperco	0.2
3	Inner Front Pole	Hiperco	0.2
4	Outer Screen	Iron	0.33
5	Inner Screen	Iron	0.25
6	Outer Core	Hiperco	0.9/0.35
7	Outer Bobbin	Al	0.65
8	Outer Coil Cover	Steel	0.7
9	Inner Coils	Copper Coil Potting Compound	0.85
10	Inner Bobbin	Copper	0.1
11	Inner Coil Cover	Steel	0.7
12	Inner Coils	Copper Coil Potting Compound	0.85
13	Isolators	Alumina	0.8
14	IFP cover	Graphite	0.98
15	OFP Cover	Graphite	0.95
16	OFP	Iron	0.25
17	Discharge Channel	BN	0.9
18	Anode Top Plate	Stainless Steel	0.7
19	Anode Orifice Plate	Stainless Steel	0.7
20	Anode Base	Stainless Steel	0.7
21	Mt. Spool	Steel	0.95/0.9
22	Radiator Plate	Aluminum 6061	0.9/0.6
23	Mt Angle	Aluminum	0.65
24	Quartz Lamp	Quartz	0.8
25	Shroud	Aluminum	0.05/0.9
26	Support Arm	Aluminum 6061	0.65
27	Mount Cover plate	Aluminum 6061	0.9/0.55
28	Mount Plate	Aluminum 6061	0.65
29	Garage Door	MLI	0.05

Discharge Channel Temperature Trend vs. Plasma Trend

- For 12.5 kW 800 V case, Mikellides' plasma predictions track the test data GRC collected at 12.5 kW 800 V

12.5 kW	600 V 150 G (Jan. 26)	600 V 200 G (Feb 2017)	600 V 250 G (Jan. 26)	800 V 130 G	800 V 250 G	800 V 300 G
Inner Channel	398.392	377.017	439.5	417.745	569.181	557.348
Outer Channel						
Total Load	1615.62	1393.11	1732.373	1622.73	2134.57	2093.395

	800 V 130 G	800 V 250 G	800 V 300 G
May 2015 Data, from HERMes Final Report	455.6	551	533.44

Thermal Connections (1 of 2) JPL TDU-2 env Test

	Face 1	Face 2	Nominal	Model
1	Outer Core	Backpole	24 x 6-32 fasteners ((0.42-0.176 W/k per fastener) 10.24 - 4.224 W/K	10.08 w/k
2	outer core	outer front pole	24 x 6-32 fasteners ((0.42-0.176 W/k per fastener) 10.24 - 4.224 W/K	10.08 w/k
3	Inner Core	Backpole	3 x 6-32 fasteners ((0.42-0.176 W/k per fastener) 1.26 - 0.528 W/K	1.26 W/K
4	Inner Core	Inner Front pole	3 x 6-32 fasteners ((0.42-0.176 W/k per fastener) 1.26 - 0.528 W/K	1.26 W/K
5	Inner Front Pole	IFP cover	3 x 6-32 fasteners ((0.42-0.176 W/k per fastener) 1.26 - 0.528 W/K	1.26 W/K
6	Outer Screen	Backpole	18 x 6-32 fasteners ((0.42-0.176 W/k per fastener) 7.56 - 3.168 W/K	7.56 W/K
7	Inner Screen	Backpole	12 x 6-32 fasteners ((0.42-0.176 W/k per fastener) 5.04 - 2.112 W/K	5.04 W/K
8	Inner Bobbin	Backpole	6 x 6-32 fasteners ((0.42-0.176 W/k per fastener) 2.52 - 1.056 W/K	2.52 W/K
9	Discharge Channel	Backpole		900 W/m^2/K
10	Anode Base	Discharge Channel		500 W/m^2/K
11	Anode Base	Anode Orifice		10000 W/m^2/K
12	Anode Orifice	Anode Top		10.08 w/k

Thermal Connections (2 of 2) JPL TDU-2 env Test

	Face 1	Face 2	Nominal	Model
13	Outer Bobbin	Backpole	12 x 6-32 fasteners ((0.42-0.176 W/k per fastener) 5.04 - 2.112 W/K	10000 W/m^2/K
14	outer front pole	OFP Cover	24 x 6-32 fasteners ((0.42-0.176 W/k per fastener) 10.24 - 4.224 W/K	5.04 W/K
15	Radiator	Backpole	~60 x 6-32 fasteners ((0.42-0.176 W/k per fastener) 25.2 - 10.56 W/K	10.24 W/K
16	Outer Coils	Outer Bobbin		2000 W/m^2/K
17	Inner Coils	Inner Bobbin		500 W/m^2/K
18	Inner Bobbin	Inner Core		perfect
19	Isolators	DC		120 W/m^2/K
20	Isolators	Radiator		1000 W/m^2/K
21	Radiator	Spool	18 x 6-32 fasteners ((0.42-0.176 W/k per fastener) 7.56 - 3.168 W/K	0.6 W/m^2/K
22	Spool	Mount Plate	12 x 6-32 fasteners ((0.42-0.176 W/k per fastener) 5.04 - 2.112 W/K	3.168 W/K
23	Inner Coil Cover	Inner Bobbin		5.04 W/K
24	Outer Coil Cover	Outer Bobbin		1000 W/m^2/K

Power and Lamp Settings JPL TDU-2 JPL env Test

Coil Loading	Coil Power [W]	Coil Current [A]	Coil Volatage [V]
Inner Coil	83	4.45	18.4
Outer Coil	86	4.74	18.2

Lamp Effective temperature	Number of active lamps
700 k (675 W, blackbody emission per lamp)	8

Thruster component, 800 V 250 G	Plasma Loading [W]	Plasma Model Predictions (2.14.17, 12.5kW 600 V 2 FLD, Jan 26) [W]	Fraction of Thermal Model Power to Plasma Model Power
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