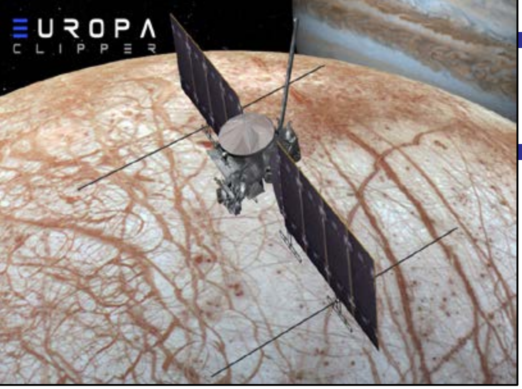
Thermal Analysis of Propulsion Components for the Europa Clipper Mission

Heather Bradshaw, NASA GSFC

Presented By
Heather Bradshaw

Thermal & Fluids Analysis Workshop
TFAWS 2018
August 20-24, 2018
NASA Johnson Space Flight Center
Houston, TX

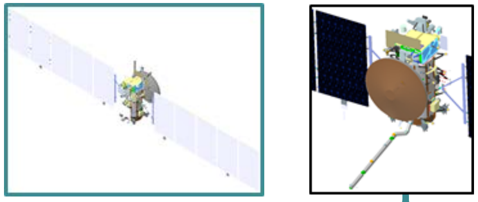
Europa Clipper (EC)

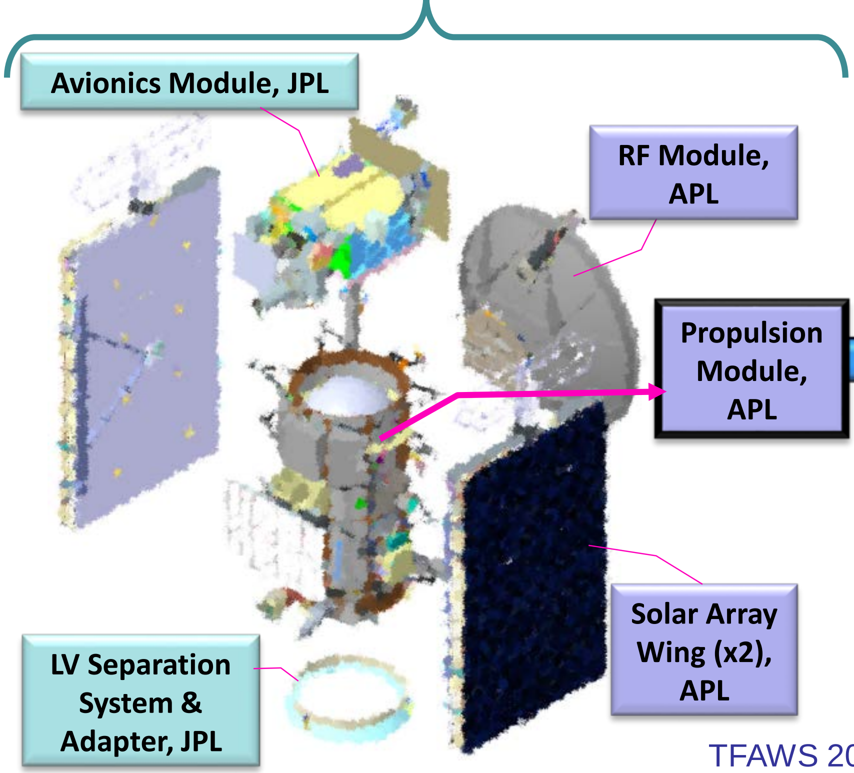


Science objectives:

- Perform flyby's to explore this icy moon of Jupiter; 9 instruments
- Determine ice thickness, search for subsurface lakes/oceans, determine the depth and salinity of these bodies of water
- Assess whether Jupiter's icy moon, Europa, may have conditions suitable for life

EC Spacecraft, JPL





Avionics Module, JPL

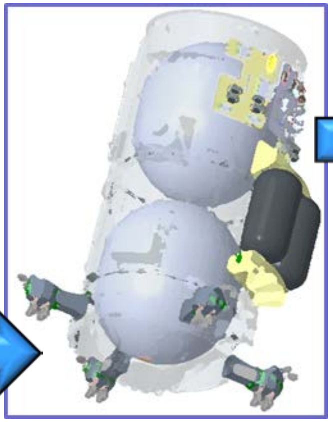
RF Module, APL

Propulsion Module, APL

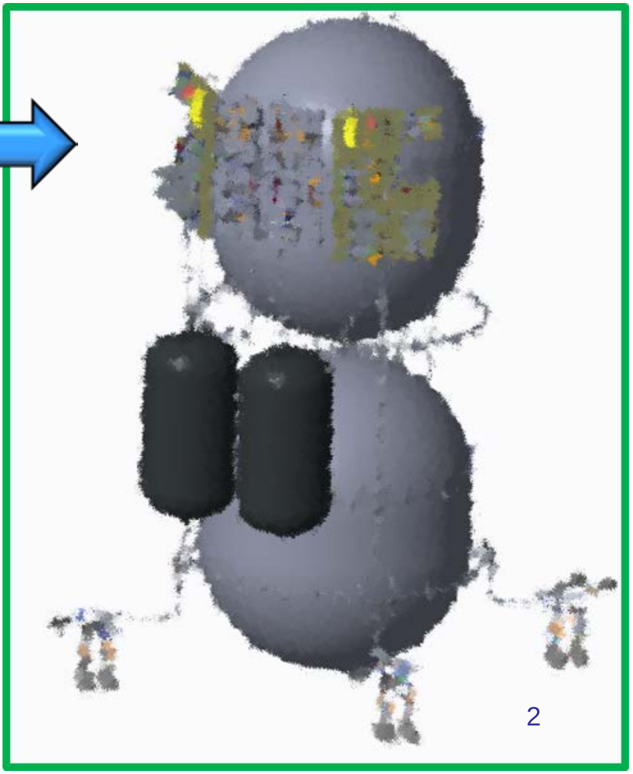
Solar Array Wing (x2), APL

LV Separation System & Adapter, JPL

Propulsion Module, APL



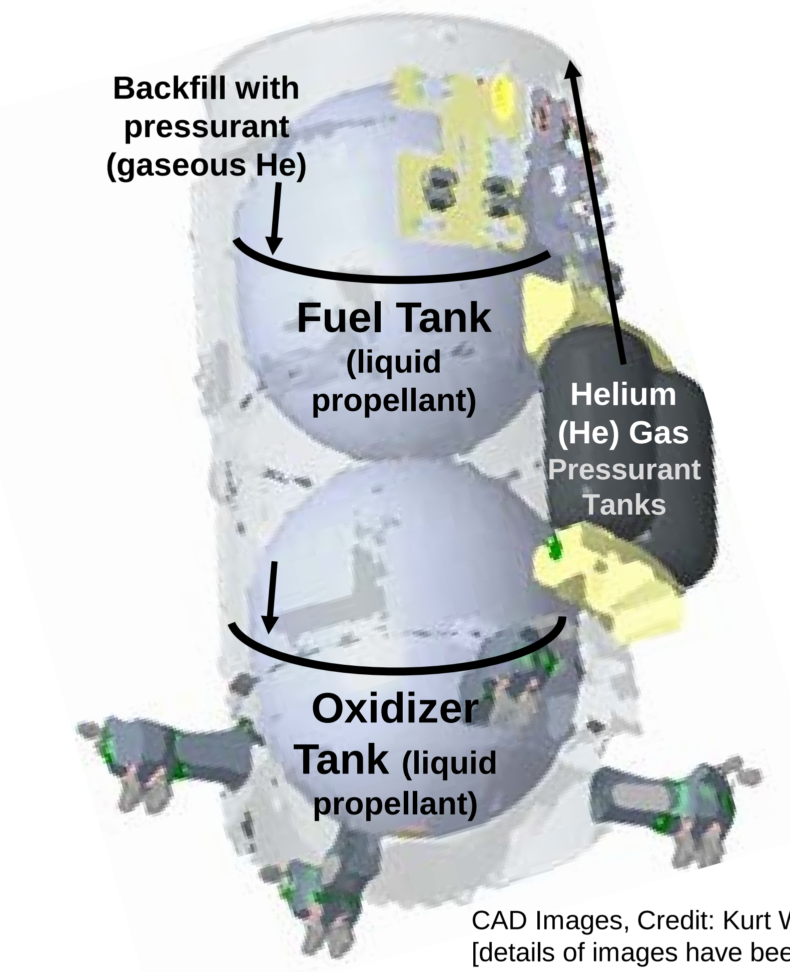
Propulsion Subsystem, Goddard

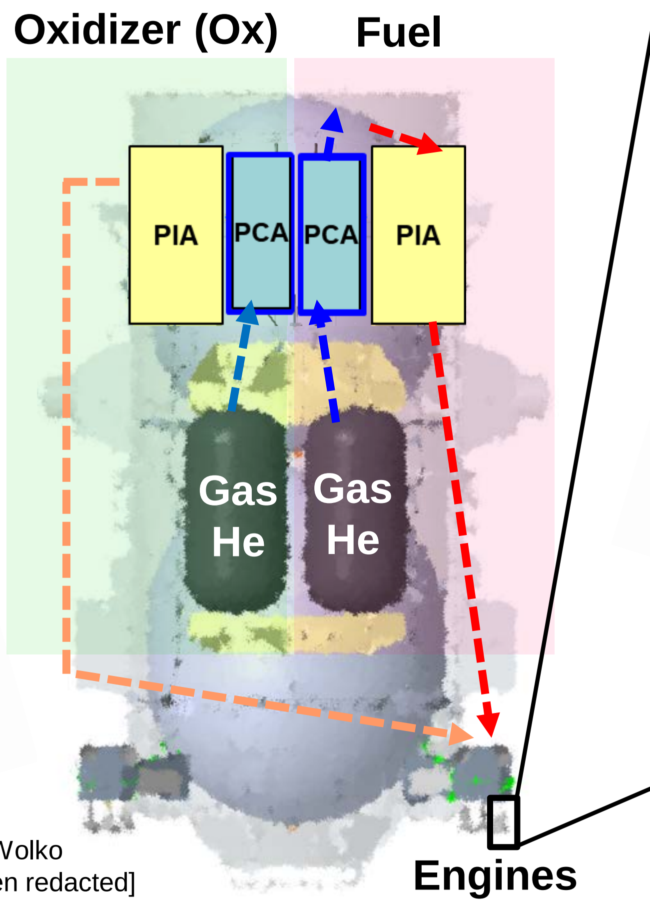


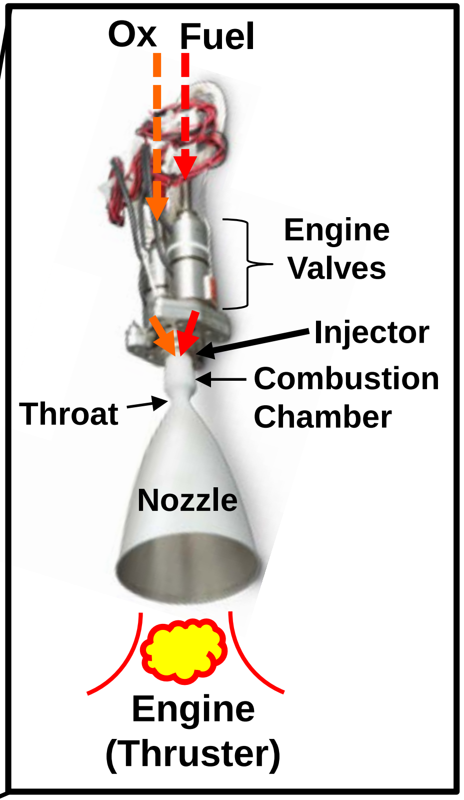
[details of images have been redacted]

Propulsion Subsystem Overview (How it Works)

- **<u>Liquid propellants</u>**:
  - Fuel = MMH = Monomethylhydrazine
  - Oxidizer (Ox) = MON-3 (Mixed Oxides of Nitrogen)
- Avoid combusting too soon (before it reaches the engine) = separate the paths of Oxidizer (Ox) & Fuel
- Fuel + Ox = Combustion (Thrust)
- Ensure outlet of liquid propellant remains “wetted” (avoid “slosh”) = backfill the tank using a **<u>gas pressurant = Helium (He)</u>** in this case
- Components mounted to plates: valves, filters, etc., (somewhat analogous to a SCUBA regulator system)
  - Adjust **<u>gas pressurant</u>** (He) flow = **<u>PCA plate</u>** = Pressurant Control Assembly
  - Adjust **<u>liquid propellant</u>** (fuel and oxidizer) flow = **<u>PIA plate</u>** = Propellant Isolation Assembly





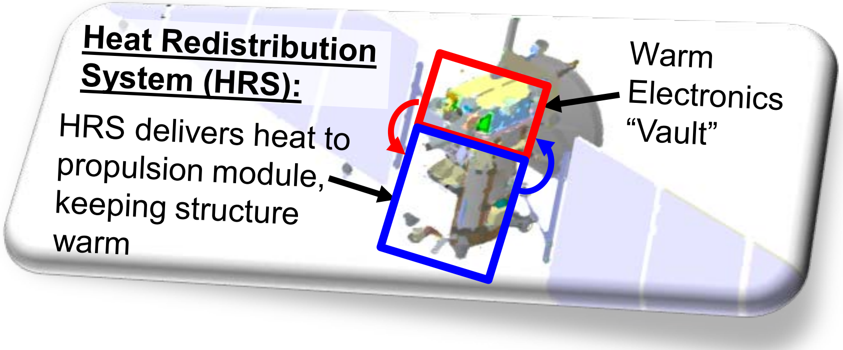


CAD Images, Credit: Kurt Wolko
[details of images have been redacted]

Thruster Photo Credit: MOOG.
https://www.moog.com/content/dam/moog/literature/Space_Defense/spaceliterature/propulsion/bipropellant_thrusters_rev_0418.pdf

Propulsion Subsystem: Thermal Overview

	Typical		Europa Clipper (Not Typical)
Approach:	- **Isolate components** from structure, and **use heater power** to maintain their temperature.		- Jupiter is far from sun, minimal solar power available, **minimize heater power** needed, **thermally couple components** to structure.
Thermal Control:	- **Heaters**, controlled by thermostats or flight software (FSW), located on: prop lines (to prevent liquid from freezing), engine valves, other components as needed.		- **Pumped fluid loop (HRS)** draws heat from the warm "Vault" of electronics, and transports it to prop module structure, PCA/PIA plates, and engine REM brackets. Goal is to avoid using heaters on prop lines or components.
Prop Lines:	- Install **thermostats**, **heaters**, **aluminum over-tape**, **sensors**, and **MLI**.		- **Bare Ti prop lines** and components, radiating to structure.
Engine Valves:	- **Isolate** from structure - Install **heater**, **sensor** and/or **thermostat** - **No blanket, and no over-tape** (need high-e to radiate during soak-back).		- **Heat-sink** to structure. - **No heater**. Rely on heat sink to HRS to cool valve during soak-back, and to heat valve during cold cruise. - **Bare** (no blanket or tape).



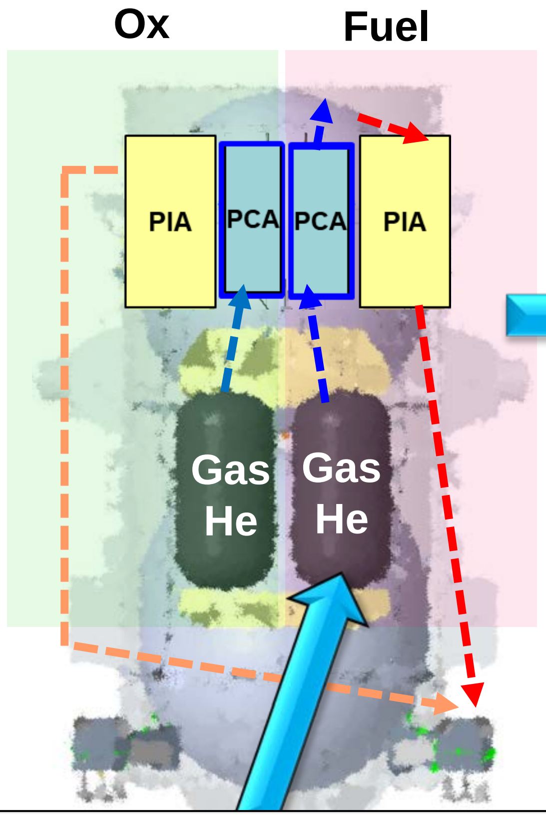
Heat Redistribution System (HRS):

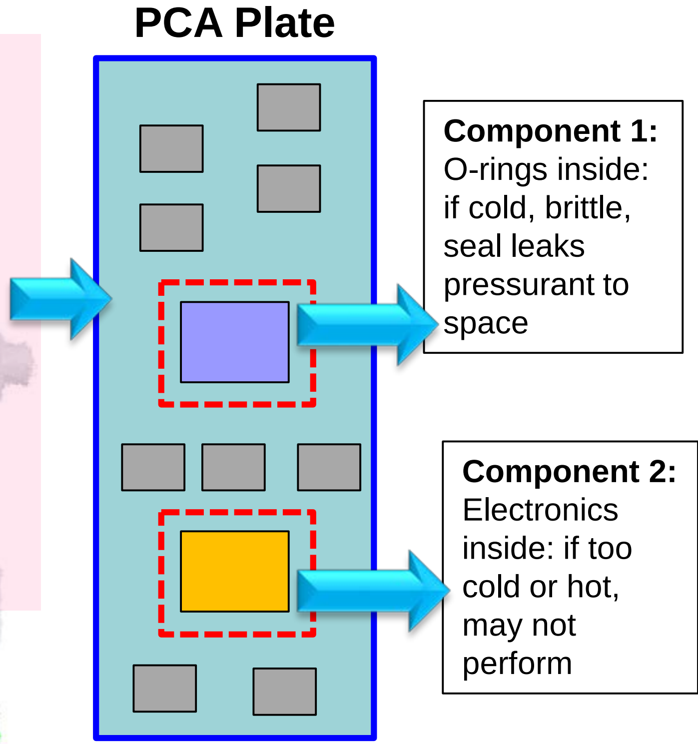
HRS delivers heat to propulsion module, keeping structure warm

	Typical		**Europa Clipper (Not Typical)**
Propellant Tanks (liquid):	• **Heaters**, **thermostats**, **sensors**, **aluminum tape**, **blanket** **Or** • **Heaters on structure** that surrounds/holds tanks, **high-e surfaces inside "toasty cavity"**, radiative coupling. Note: Prop system is internal to spacecraft, **access is blocked** at later stages, so it is one of the few subsystems that is **critical to define Tvac Thermocouple locations and install them EARLY** during fabrication (not during testing phase).		• **Bare Ti tanks**, **no heaters**. • Radiate to warm cylinder (prop module cylinder is irridite aluminum, heated by HRS).
Pressurant Tanks (gas):	• **Bare**. No heaters, no blankets. Tank located internal to spacecraft.		• **Heaters**, **thermostats**, **sensors**, and **blanket**. • Need to maintain tank above cold limits and to pre-heat tanks before long burn.
Engine Injector:	• **Heater**.		• **No heater**. Rely on conduction through valve to HRS to maintain above cold limit.
Engine Nozzle:	• **High-emissivity outer coating**, to radiate heat away when firing, to prevent engine from overheating		• Same.
High-Temperature blankets:	• **High-temperature blankets** near thrusters		• Same.
Contamination Bake-out:	• **Goal is to bake off volatiles**, and avoid having them condense on optics or sensitive hardware; meet the outgassing criteria.		• **Planetary Protection** bake-out: much **hotter temperatures, and longer durations**. Affects material selections.

Prop Subsystem: Component Thermal Considerations

- Goal:
  - Maintain components within temperature limits.
- Pressurant Tanks (gas):
  - Most burns are short, a few minutes long, small delta-P, negligible temperature change
  - Jupiter Orbit Insertion (JOI) burn:
    - lasts for several hours
    - large pressure drop
    - large temperature drop in pressurant gas
  - Use heater, to pre-heat gas before long burn
  - Analyze components: can they withstand cold transient profile?
  - Ideal gas law





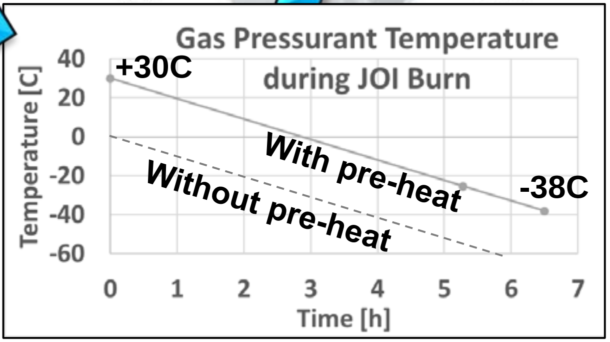
Component 1: O-rings inside: if cold, brittle, seal leaks pressurant to space

Component 2: Electronics inside: if too cold or hot, may not perform

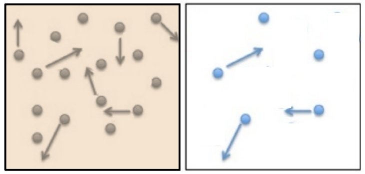
CAD Images, Credit: Kurt Wolko [details of images have been redacted]

$$P*V = n*R*T$$

P = Pressure
V = Volume
n = number of moles of gas particles
T = Temperature [K]
R = Gas Constant



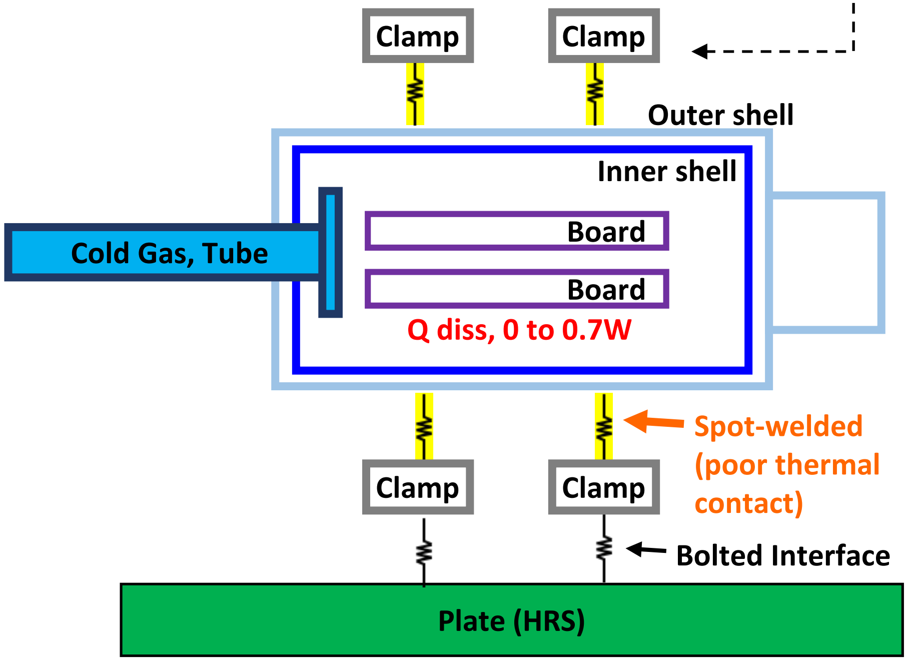
Data Credit: MSFC, Kim Holt



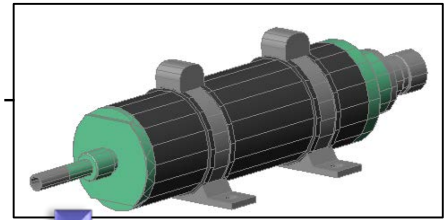
High P&T **Low P&T**

Considerations for Component #2

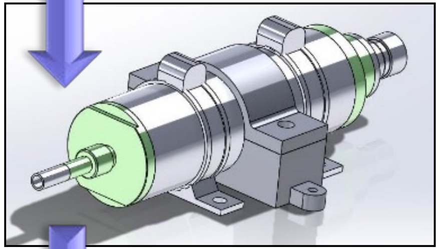
Component #2: Design Iterations



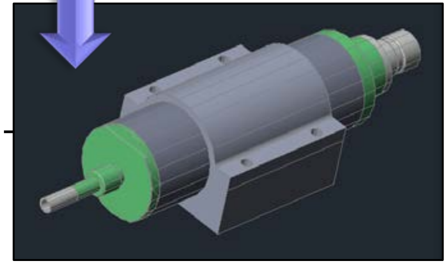
- Clamps bolted to plate, but **spot-welded** to housing (**not well coupled**).
- Cold case:
  - 0W dissipation
  - -38C cold gas
  - Heat from 0C plate, unable to reach boards, electronics became cold
- Hot case:
  - 0.7W dissipation
  - No gas flowing
  - Unable to dissipate enough heat to 35C plate, electronics became hot



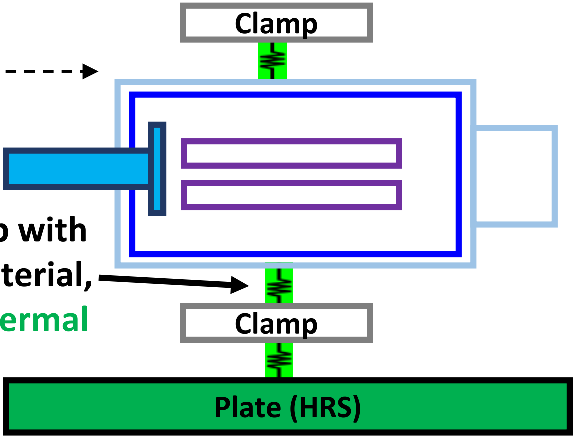
- Clamp is spot-welded to cylindrical housing (poor thermal contact)



- Added a clamp in middle, with excellent thermal contact to housing



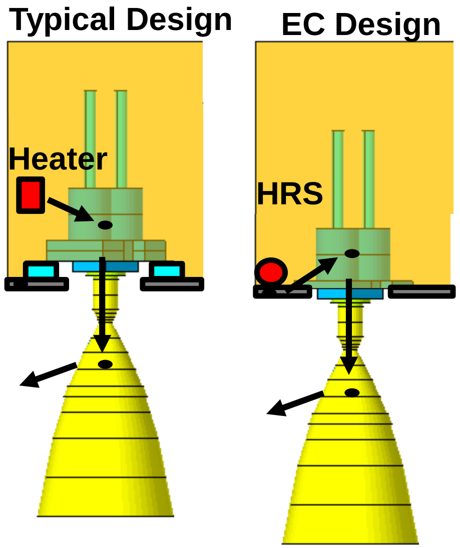
- Removed spot-welded clamps entirely
- Increased contact area of the high thermally coupling clamp



Bolted clamp with interface material, (excellent thermal contact)

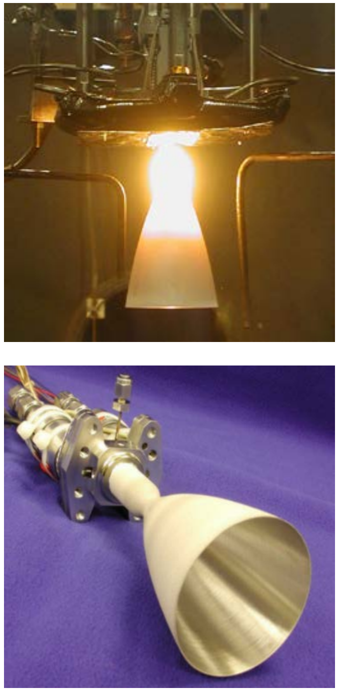
Europa Clipper (EC) Engines (Thrusters)

- Thermal Analyses
  - Valve & Injector: Cold cruise
  - Valve & Nozzle: Hot fire
  - Valve: Soak-back
- Minimize Heaters
  - HRS (pumped fluid) system maintains temperature
  - Avoid heaters (weak sun at Jupiter, less energy from solar panels, little power available)
- Hardware Considerations
  - High Temperature Blankets, near engines
  - Planetary protection (PP) bake-out, (hotter than typical bake-out)

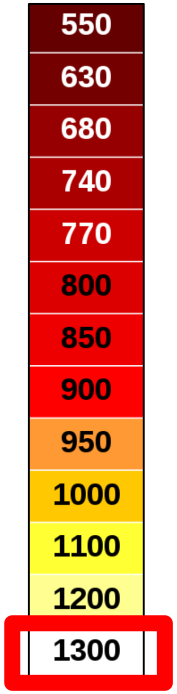


Typical Engine Design	EC Engine Design
Valve loses heat to nozzle	Valve loses heat to nozzle
Replenished by **Heater**	Replenished by **HRS**
Isolators minimize heat pulled from SC	Heat **is** pulled from SC

Incandescence (“glowing” temperature regime):



Sample photos for context. Photo Credits: MOOG & Rich Driscoll.

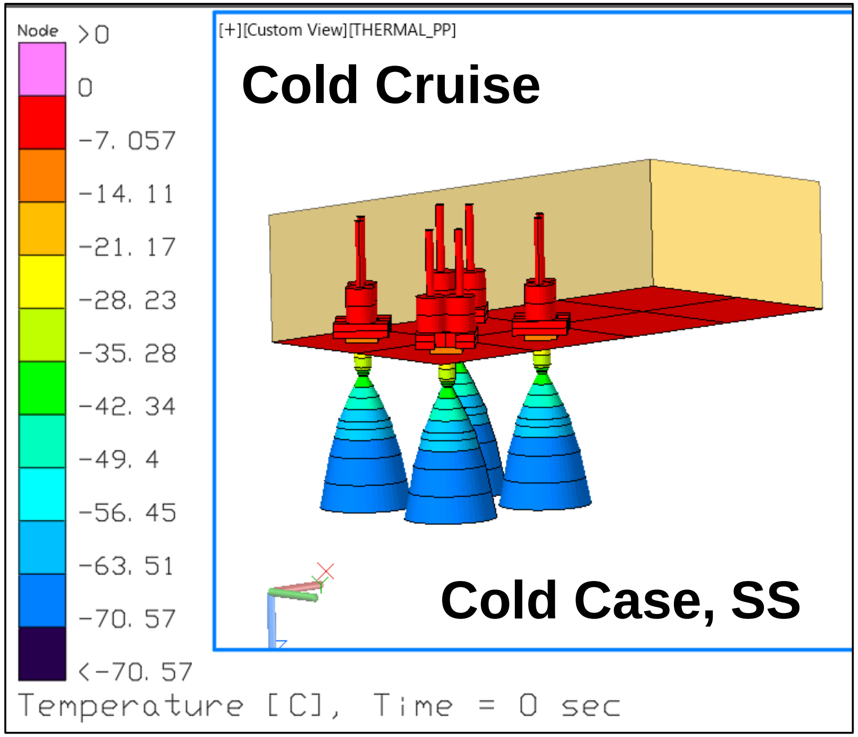


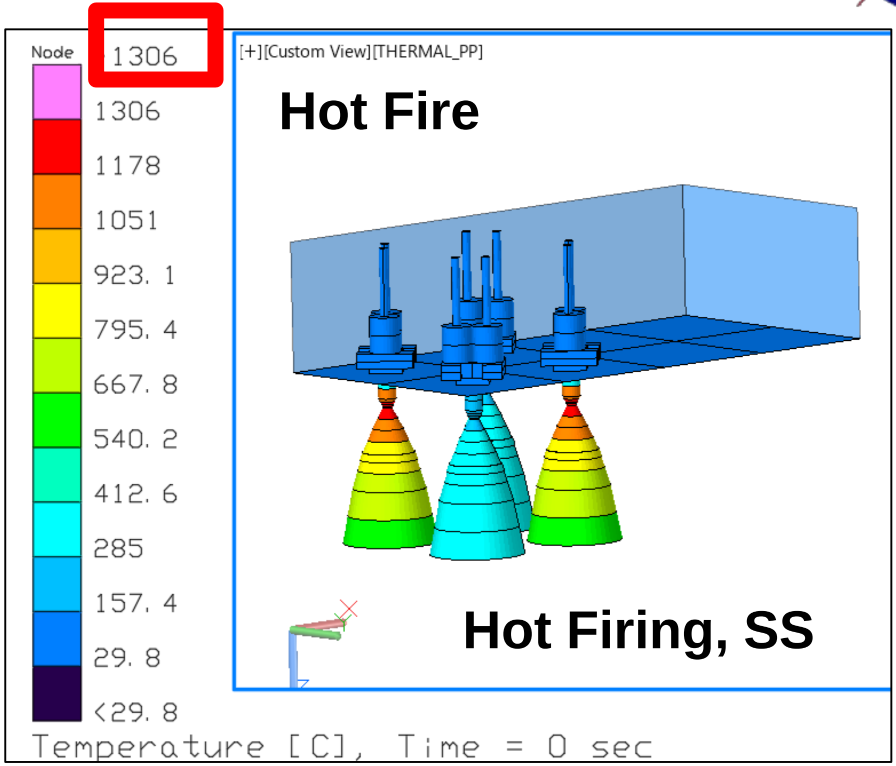
Temperature [C]

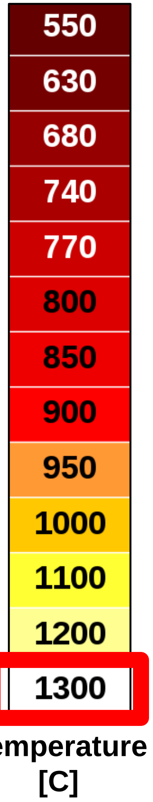
Scale Image Credit: https://en.wikipedia.org/wiki/Incandescence

Mission	Temperature	Scale [C]	Description	Orbit
ATLAS (ICESAT-2)	35 C (M55J bonded Ti inserts) (other missions ~ 55 or 60C)	**Tens**	Instrument bake-out	LEO
Europa Clipper (EC)	120 to 150 C	**Hundreds**	PP bake-out (depending on component)	Interplanetary
Engines Firing	1,306 C	**Thousands**	Nozzle temperature (need high-temp blankets)	n/a

Engine Temperature Maps





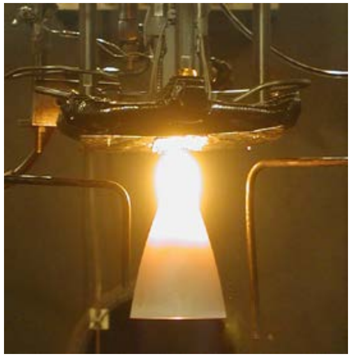


Cold:

- Liquid propellants, would freeze at:
  - Ox, MON3: -10C to -14 C
  - Fuel, MMH: -52 C
  - Result: Valves, injector, and propellant lines stay above this
  - (Some missions need heaters on valves and/or injector)

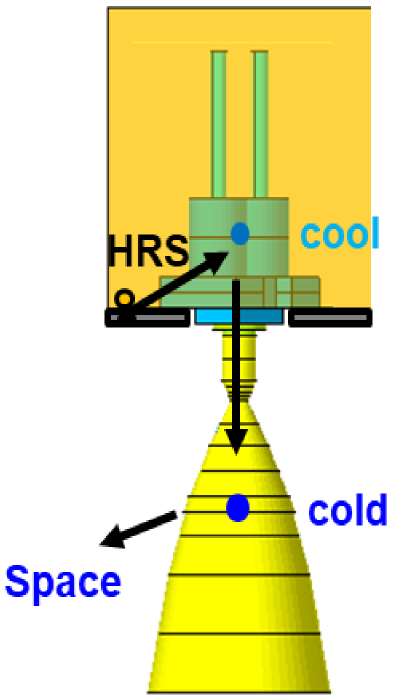
Hot:

- Valve hot limit: 101 C
- Nozzle hot limit: 1371 C
- Result: Valves and nozzles stay within this



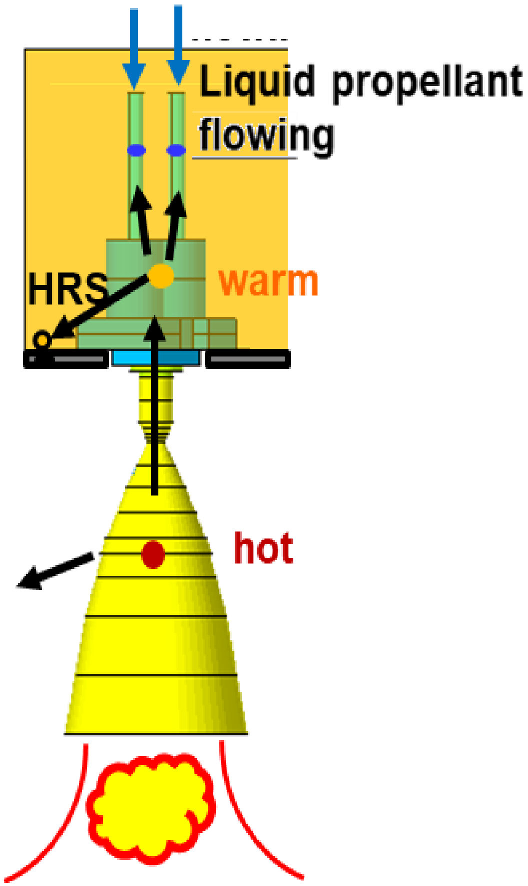
Conceptual Sketch of Heat Flows

Before Firing:



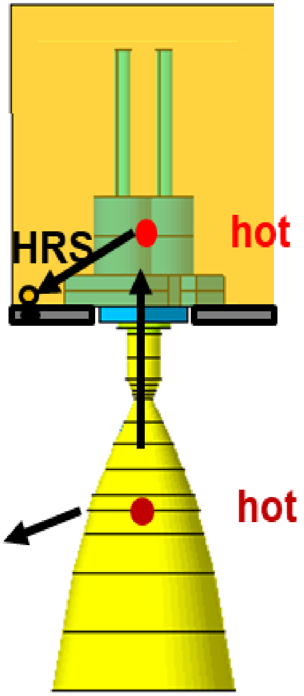
- Nozzle radiates to cold space
- Valve warmed by HRS

During SS Firing:



- Nozzle heated by combustion gases
- Valve cooled by flowing propellant

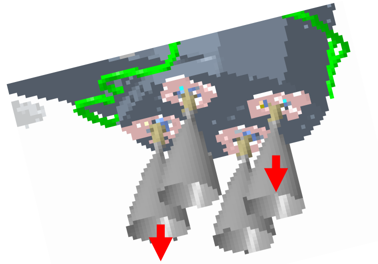
Soak-back (Transient, right after firing):



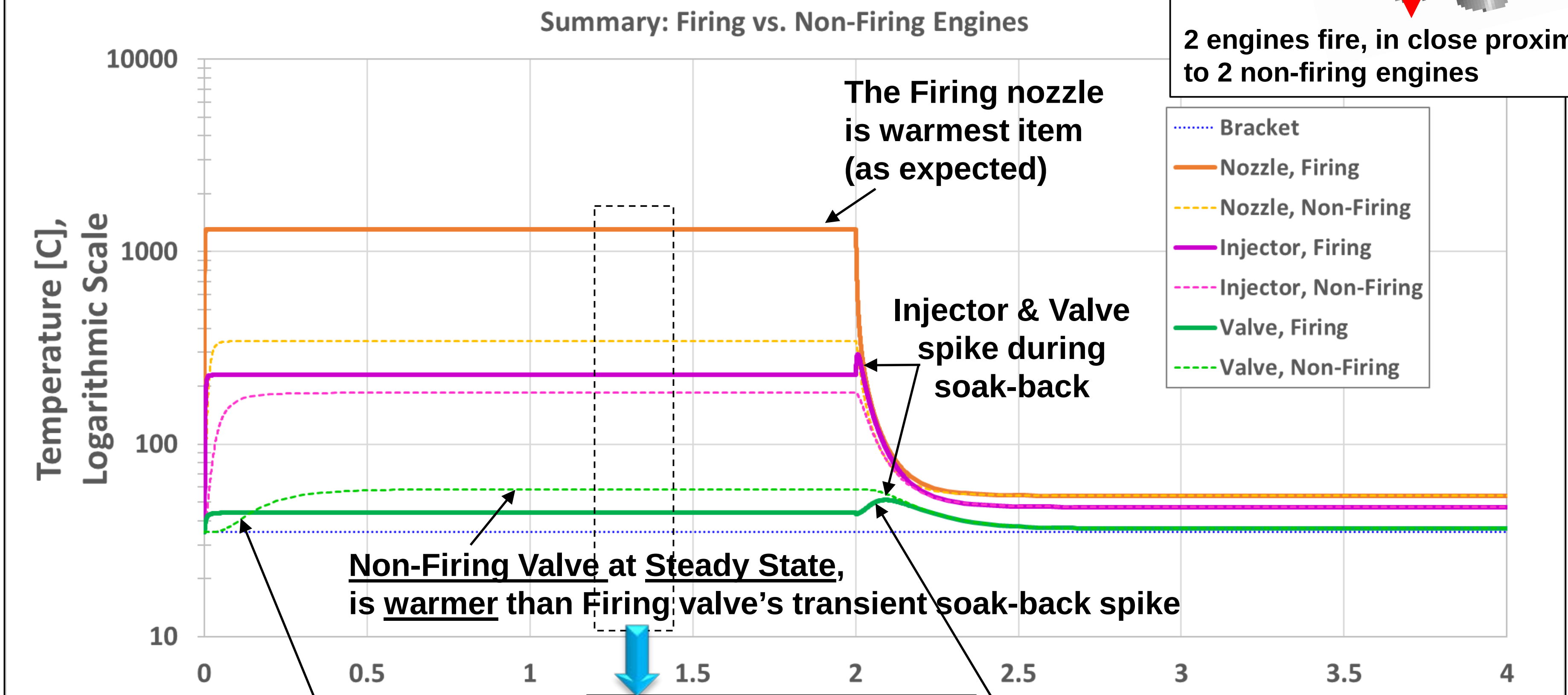
- Just after firing:
- Propellant stops flowing
- Nozzle has not fully cooled off yet
- large dT between nozzle and valve
- Q transferred to valve = “soak-back heat”

Firing & Soak-back Temperatures

Other conclusions we can draw (specific to EC):



2 engines fire, in close proximity to 2 non-firing engines



The Firing nozzle is warmest item (as expected)

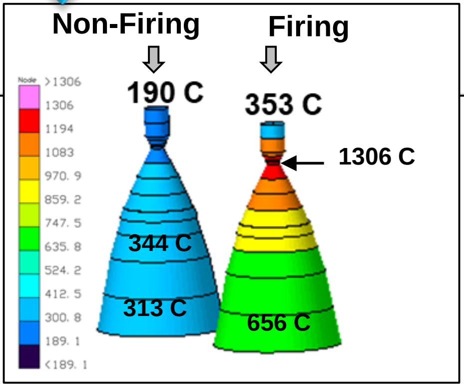
Injector & Valve spike during soak-back

<u>Non-Firing Valve</u> at <u>Steady State</u>, is <u>warmer</u> than Firing valve's transient soak-back spike

If performing a <u>short burn</u>, then the firing valve <u>soak-back is hotter</u> than non-firing valve

If single engine, then soak-back will be hotter than SS firing temperature

SS Firing Temperature Map:

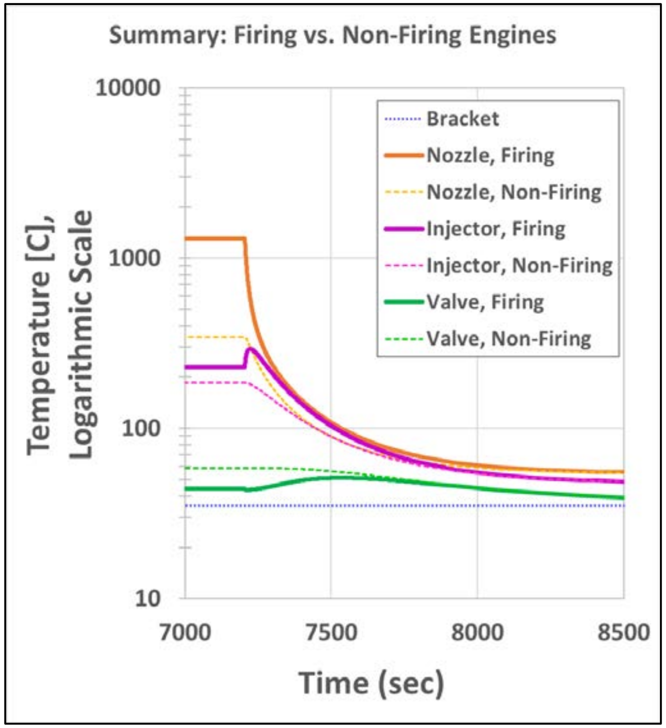


Videos: Soak-back

Firing Engine:

Valve warms up (soak-back), then cools

Nozzle cools



Non-Firing Engine (Nearby):

Valve cools (no soak-back, nozzle not hot enough)

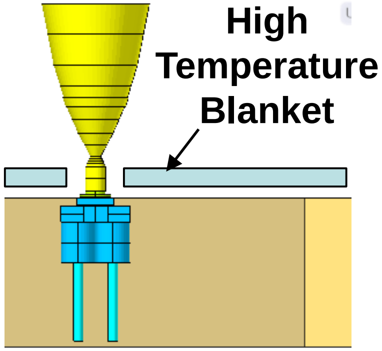
Non-Firing Nozzle cools

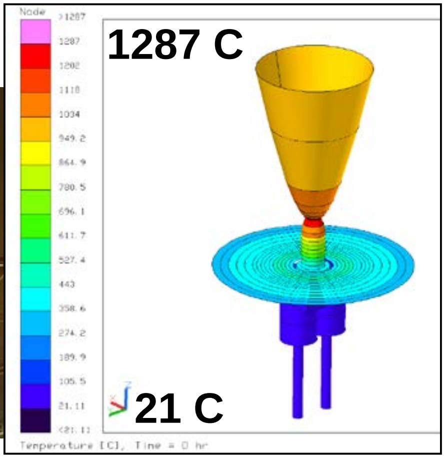
High Temperature Blankets

Material	Melt (°C)	Service (°C)
Mylar	250	150
Dacron	256	
Stamet		400
Kapton		400
Stainless Steel Foil (e_IR = 0.15)	>1000	
High Temp Fabric*		>1000

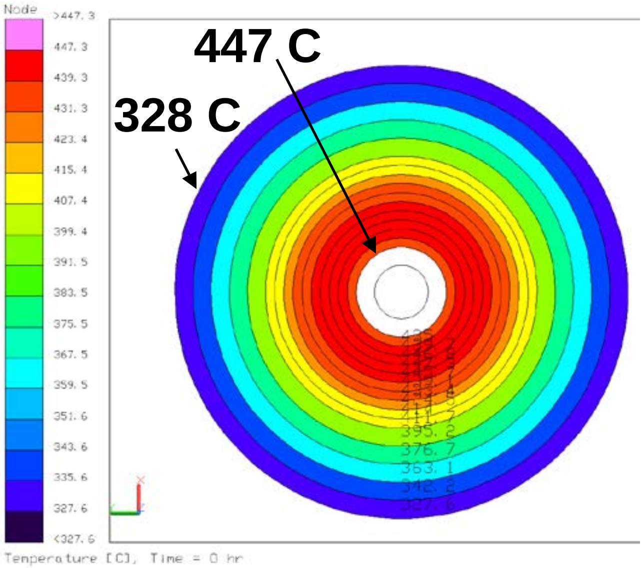
**High temperature fabric can be Astroquartz, E-glass, Nextel, etc.*

- **<u>High temperature blankets require different materials</u>** than normal blankets, to avoid melting during thruster burn maneuvers.
- For context:
    - EC predicted nozzle temperature = 1,306 C
    - EC predicted temperature of <u>outermost</u> (hottest) blanket layer = 447 C
    - Kapton’s maximum service temperature = 400 C
- Examples of materials and their melting and/or service temperature range are provided here for reference.





Outer Layer Temperature:



Credit: High temperature blanket analysis and recommendation performed by Dan Powers.

Engine Model Development (cont'd)

Key equations used in engine model, and work that went into determining G, m, e, k, & h:

Valve:
- Q_transient = m*cp*dT
- Q_conduction = G*dT = k*A/L

Used MOOG Valve Model:
- Thermal model from MOOG, for **geometry, and conductance values (G, m)**

Converted Format:
- From sinda-based text logic, to GUI-based TD control and manipulation of firing, as well as nodes and conductors.

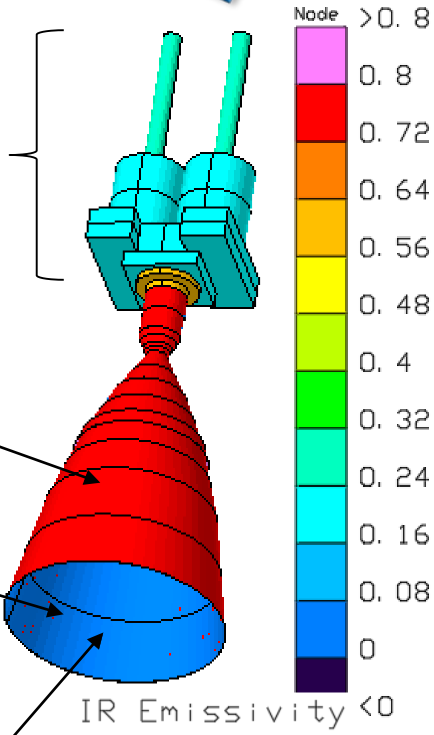
Thermal Model Delivered to APL

Nozzle:
- Q_radiation = e*A*sigma*VF*(T^4 – T_space^4)

Measured Nozzle Emissivity (e) Values in Tvac:
- Coated emissivity = 0.72
- Bare emissivity = 0.08

Nozzle:
- Q_convection = h*A*dT

Correlated Nozzle Convection Coefficients (h) to Combustion Gas Boundaries
- Used previous **Hot Fire Test Data**



Valves

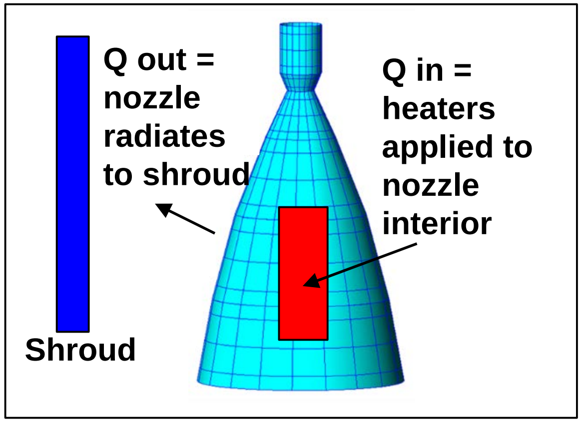
Coated for high-emissivity

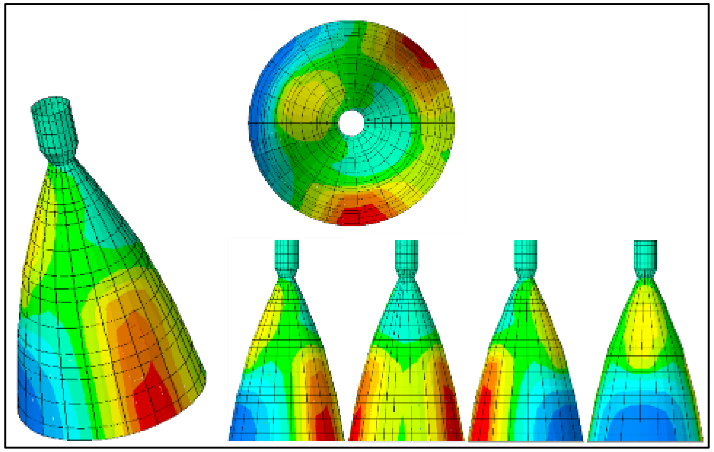
Bare

Nozzle sections, convect to hot combustion gases (not shown)

Tvac Tests: Nozzle Emissivity Measurements (Not Firing)

Test Design & Approach:



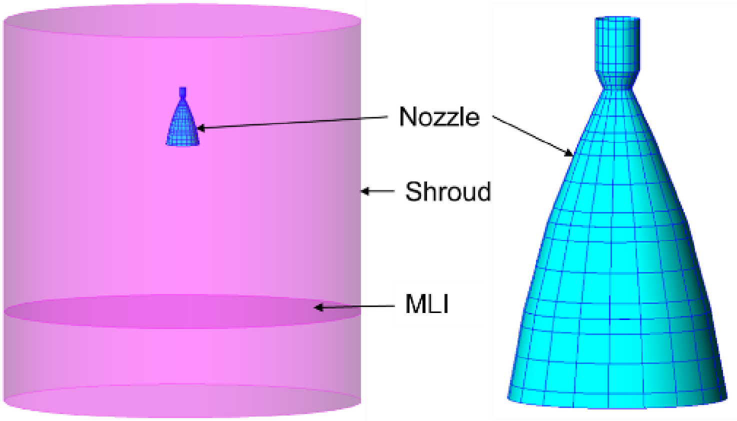


Coated Nozzle: 7W,
Thermal balance case prediction (sample)

- Qin = Qout

Q_heaters = A*e_noz*sigma*(T_noz^4 – T_shroud^4)

- Varied Q heater for multiple thermal balance points.
- Performed test for bare nozzle, and coated nozzle.
- Correlated model, derived emissivity.



Results: Coated Nozzle

Correlation Data:

			1 W			2 W			3 W			4 W			7 W		
			Tvac Data	Model	Diff. (M-T)	Tvac Data	Model	Diff. (M-T)	Tvac Data	Model	Diff. (M-T)	Tvac Data	Model	Diff. (M-T)	Tvac Data	Model	Diff. (M-T)
Sensitivity Study, e - 0.01 = 0.71	TC.1	[°C]	-72.0	-74.0	-2.0	-37.8	-39.4	-1.6	-14.0	-15.7	-1.6	3.1	2.8	-0.3	43.8	42.9	-0.9
	TC.2	[°C]	-72.5	-74.2	-1.7	-38.7	-39.7	-1.1	-15.3	-16.1	-0.8	0.9	2.3	1.4	40.5	42.3	1.8
	TC.3	[°C]	-74.5	-74.8	-0.3	-41.7	-40.9	0.8	-19.1	-17.7	1.4	-4.5	0.3	4.8	32.9	39.2	6.3
	TC.4	[°C]	-69.7	-72.2	-2.5	-33.9	-35.8	-1.8	-8.6	-10.2	-1.6	9.6	10.2	0.6	53.6	55.8	2.2
	TC.5	[°C]	-72.6	-74.5	-1.9	-38.7	-40.3	-1.6	-15.2	-16.9	-1.7	1.5	1.4	-0.1	41.7	41.0	-0.7
	TC.6	[°C]	-71.6	-73.7	-2.1	-36.7	-38.7	-2.0	-12.3	-14.5	-2.1	4.2	4.6	0.4	47.1	46.7	-0.4
	TC.7	[°C]	-75.0	-75.0	0.0	-42.1	-41.3	0.7	-19.8	-18.4	1.4	-6.5	-0.6	5.9	29.9	37.7	7.8
	TC.8	[°C]	-75.0	-75.0	0.0	-41.0	-41.3	-0.4	-19.3	-18.4	0.9	-6.9	-0.6	6.2	29.5	37.6	8.2
	Average, [C]		-72.9	-74.2	-1.3	-38.8	-39.7	-0.9	-15.5	-16.0	-0.5	0.2	2.5	2.4	39.9	42.9	3.0
	RMS of TC 1-8 errors, per case:				1.6			1.4			1.5			3.5			4.7
	Overall RMS (across all cases):				2.9												

e = 0.71, RMS error 2.9C

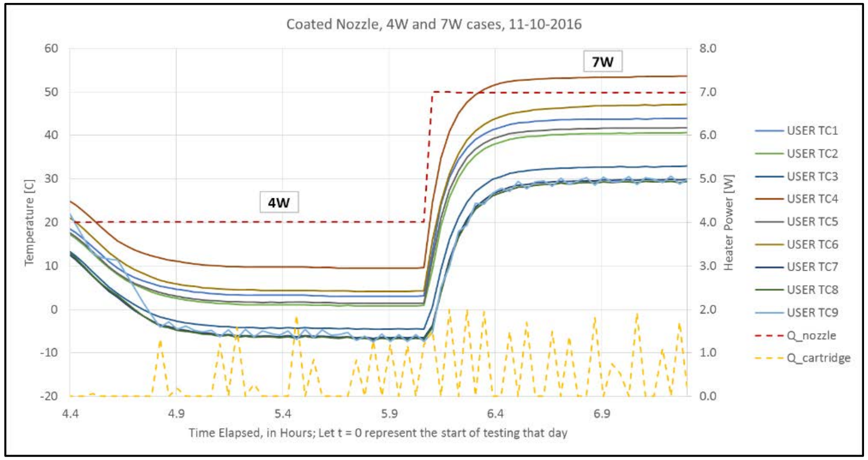
Correlated Model, e = 0.72	TC.1	[°C]	-72.0	-74.7	-2.7	-37.8	-40.2	-2.4	-14.0	-16.6	-2.6	3.1	1.8	-1.2	43.8	41.8	-2.0
	TC.2	[°C]	-72.5	-74.9	-2.4	-38.7	-40.6	-1.9	-15.3	-17.1	-1.7	0.9	1.3	0.4	40.5	41.1	0.6
	TC.3	[°C]	-74.5	-75.5	-0.9	-41.7	-41.7	0.0	-19.1	-18.6	0.5	-4.5	-0.7	3.8	32.9	38.0	5.2
	TC.4	[°C]	-69.7	-72.9	-3.2	-33.9	-36.6	-2.7	-8.6	-11.1	-2.5	9.6	9.1	-0.4	53.6	54.6	1.0
	TC.5	[°C]	-72.6	-75.2	-2.6	-38.7	-41.1	-2.4	-15.2	-17.8	-2.6	1.5	0.4	-1.1	41.7	39.8	-1.9
	TC.6	[°C]	-71.6	-74.4	-2.7	-36.7	-39.5	-2.8	-12.3	-15.4	-3.1	4.2	3.6	-0.6	47.1	45.5	-1.6
	TC.7	[°C]	-75.0	-75.7	-0.7	-42.1	-42.2	-0.1	-19.8	-19.3	0.5	-6.5	-1.6	4.8	29.9	36.5	6.6
	TC.8	[°C]	-75.0	-75.7	-0.7	-41.0	-42.2	-1.2	-19.3	-19.4	-0.1	-6.9	-1.7	5.2	29.5	36.5	7.0
	Average, [C]		-72.9	-74.9	-2.0	-38.8	-40.5	-1.7	-15.5	-16.9	-1.5	0.2	1.5	1.4	39.9	41.7	1.9
	RMS of TC 1-8 errors, per case:				2.2			2.0			2.0			2.9			4.0
	Overall RMS (across all cases):				2.7												

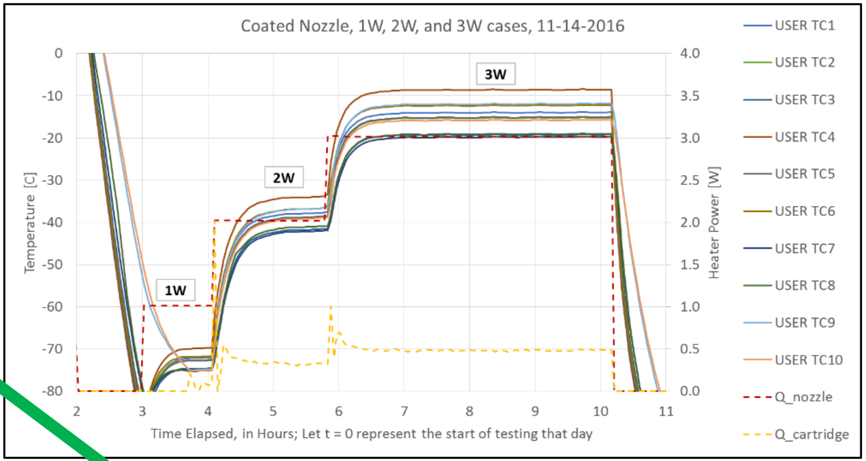
e = 0.72, RMS error 2.7C = lowest error = sweet spot

Sensitivity Study, e + 0.01 = 0.73	TC.1	[°C]	-72.0	-75.3	-3.3	-37.8	-41.0	-3.2	-14.0	-17.4	-3.4	3.1	0.9	-2.2	43.8	40.7	-3.0
	TC.2	[°C]	-72.5	-75.5	-3.0	-38.7	-41.3	-2.7	-15.3	-17.9	-2.6	0.9	0.4	-0.5	40.5	40.0	-0.5
	TC.3	[°C]	-74.5	-76.1	-1.5	-41.7	-42.4	-0.8	-19.1	-19.5	-0.4	-4.5	-1.6	2.9	32.9	37.0	4.1
	TC.4	[°C]	-69.7	-73.5	-3.8	-33.9	-37.4	-3.4	-8.6	-12.0	-3.4	9.6	8.2	-1.4	53.6	53.5	-0.1
	TC.5	[°C]	-72.6	-75.8	-3.2	-38.7	-41.9	-3.2	-15.2	-18.7	-3.5	1.5	-0.6	-2.0	41.7	38.7	-3.0
	TC.6	[°C]	-71.6	-75.0	-3.3	-36.7	-40.3	-3.5	-12.3	-16.2	-3.9	4.2	2.7	-1.5	47.1	44.5	-2.6
	TC.7	[°C]	-75.0	-76.3	-1.3	-42.1	-42.9	-0.8	-19.8	-20.2	-0.3	-6.5	-2.5	3.9	29.9	35.5	5.6
	TC.8	[°C]	-75.0	-76.3	-1.3	-41.0	-42.9	-1.9	-19.3	-20.2	-0.9	-6.9	-2.5	4.3	29.5	35.4	6.0
	Average, [C]		-72.9	-75.5	-2.6	-38.8	-41.3	-2.4	-15.5	-17.8	-2.3	0.2	0.6	0.4	39.9	40.7	0.8
	RMS of TC 1-8 errors, per case:				2.8			2.7			2.7			2.6			3.7
	Overall RMS (across all cases):				2.9												

e = 0.73, RMS error 2.9C

Balance Points Measured:





e = 0.72

Results: Bare/Uncoated Nozzle

				0.2 W			0.33 W			0.4 W			0.44 W			0.53 W		
				Tvac Data	Model	Diff. (M-T)	Tvac Data	Model	Diff. (M-T)	Tvac Data	Model	Diff. (M-T)	Tvac Data	Model	Diff. (M-T)	Tvac Data	Model	Diff. (M-T)
Sensitivity Study, e-0.005=0.075	Nozzle	TC.1	[°C]	-48.0	-49.0	-1.0	-22.2	-20.8	1.4	-10.6	-8.9	1.7	-5.2	-2.8	2.5	6.5	9.7	3.2
		TC.2	[°C]	-47.8	-48.8	-1.0	-21.9	-20.6	1.3	-10.3	-8.6	1.7	-4.8	-2.4	2.4	6.9	10.1	3.1
		TC.3	[°C]	-48.4	-49.1	-0.7	-22.7	-21.0	1.7	-11.1	-9.1	2.0	-5.8	-3.0	2.8	5.9	9.4	3.6
		TC.4	[°C]	-47.5	-48.6	-1.1	-21.2	-20.2	1.0	-9.4	-8.2	1.2	-3.9	-2.0	1.9	8.0	10.6	2.6
		TC.5	[°C]	-47.0	-48.2	-1.2	-20.5	-19.6	0.9	-8.6	-7.4	1.1	-3.0	-1.1	1.9	9.1	11.6	2.5
		TC.6	[°C]	-47.8	-49.0	-1.2	-21.8	-20.8	1.0	-10.1	-8.9	1.2	-4.7	-2.8	1.9	7.2	9.6	2.5
		TC.7	[°C]	-50.7	-49.3	1.5	-25.7	-21.3	4.4	-14.4	-9.5	4.9	-9.3	-3.4	5.8	2.0	8.9	6.9
		TC.8	[°C]	-47.0	-48.3	-1.3	-20.6	-19.7	0.9	-8.7	-7.6	1.1	-3.1	-1.3	1.8	8.9	11.4	2.5
	MLI	TC.12	[°C]	-59.9	-56.5	3.4	-35.0	-29.5	5.6	-24.0	-18.0	6.0	-19.0	-12.1	7.0	-8.1	0.0	8.0
		TC.13	[°C]	-90.5	-100.3	-9.8	-76.9	-80.9	-4.0	-71.5	-72.5	-1.0	-69.3	-68.1	1.2	-63.8	-59.2	4.6
	dT Thru MLI		[°C]	30.5	43.7	13.2	41.9	51.4	9.5	47.5	54.5	7.0	50.3	56.1	5.8	55.7	59.2	3.4
		Avg Nozzle [C]		-48.0	-48.8	-0.8	-22.1	-20.5	1.6	-10.4	-8.5	1.9	-5.0	-2.3	2.6	6.8	10.2	3.4
		RMS of TC 1-8 errors, per case:				1.1			1.9			2.2			2.9			3.6
		Overall RMS (across all cases):				2.5												

e = 0.075, RMS error 2.5C

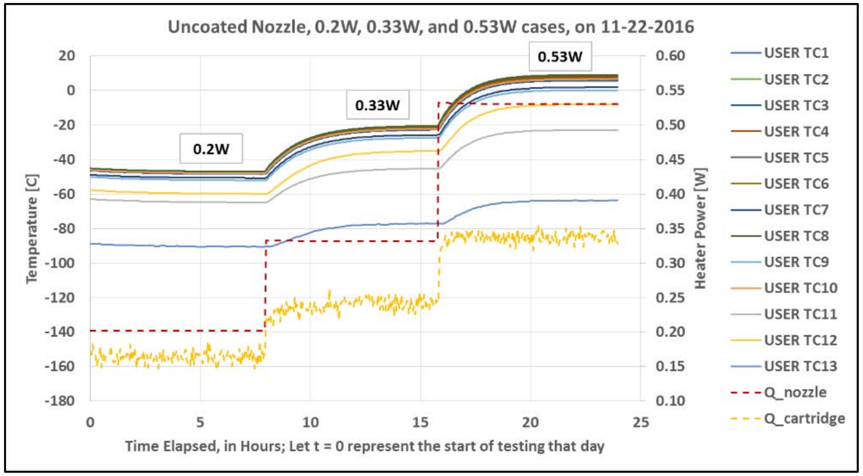
				0.2 W			0.33 W			0.4 W			0.44 W			0.53 W		
Correlated Model, e = 0.080	Nozzle	TC.1	[°C]	-48.0	-52.0	-4.0	-22.2	-24.3	-2.1	-10.6	-12.6	-2.0	-5.2	-6.6	-1.3	6.5	5.7	-0.8
		TC.2	[°C]	-47.8	-51.9	-4.0	-21.9	-24.1	-2.2	-10.3	-12.3	-2.0	-4.8	-6.2	-1.4	6.9	6.1	-0.8
		TC.3	[°C]	-48.4	-52.1	-3.7	-22.7	-24.5	-1.8	-11.1	-12.8	-1.7	-5.8	-6.8	-1.0	5.9	5.4	-0.4
		TC.4	[°C]	-47.5	-51.6	-4.2	-21.2	-23.7	-2.5	-9.4	-11.9	-2.4	-3.9	-5.8	-1.8	8.0	6.6	-1.4
		TC.5	[°C]	-47.0	-51.3	-4.3	-20.5	-23.1	-2.6	-8.6	-11.1	-2.5	-3.0	-4.9	-1.9	9.1	7.6	-1.5
		TC.6	[°C]	-47.8	-52.0	-4.2	-21.8	-24.3	-2.5	-10.1	-12.6	-2.5	-4.7	-6.6	-1.9	7.2	5.7	-1.5
		TC.7	[°C]	-50.7	-52.3	-1.6	-25.7	-24.8	0.9	-14.4	-13.2	1.2	-9.3	-7.2	2.0	2.0	4.9	2.9
		TC.8	[°C]	-47.0	-51.3	-4.3	-20.6	-23.2	-2.6	-8.7	-11.3	-2.6	-3.1	-5.1	-2.0	8.9	7.4	-1.5
	MLI	TC.12	[°C]	-59.9	-59.1	0.9	-35.0	-32.4	2.7	-24.0	-21.1	2.9	-19.0	-15.2	3.8	-8.1	-3.4	4.7
		TC.13	[°C]	-90.5	-102.0	-11.6	-76.9	-83.0	-6.1	-71.5	-74.7	-3.2	-69.3	-70.5	-1.2	-63.8	-61.7	2.1
	dT Thru MLI		[°C]	30.5	43.0	12.4	41.9	50.6	8.8	47.5	53.7	6.1	50.3	55.2	5.0	55.7	58.3	2.6
		Avg Nozzle [C]		-48.0	-51.8	-3.8	-22.1	-24.0	-1.9	-10.4	-12.2	-1.8	-5.0	-6.1	-1.2	6.8	6.2	-0.6
		RMS of TC 1-8 errors, per case:				3.9			2.2			2.2			1.7			1.5
		Overall RMS (across all cases):				2.4												

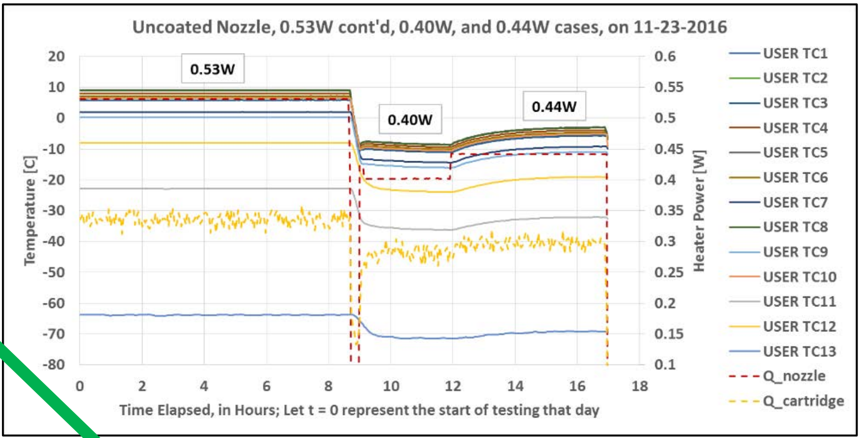
e = 0.080, RMS error 2.4C = lowest error = sweet spot

				0.2 W			0.33 W			0.4 W			0.44 W			0.53 W		
Sensitivity Study, e+0.005=0.085	Nozzle	TC.1	[°C]	-48.0	-54.8	-6.8	-22.2	-27.5	-5.3	-10.6	-16.0	-5.4	-5.2	-10.0	-4.8	6.5	2.0	-4.4
		TC.2	[°C]	-47.8	-54.6	-6.8	-21.9	-27.3	-5.4	-10.3	-15.7	-5.4	-4.8	-9.7	-4.9	6.9	2.4	-4.5
		TC.3	[°C]	-48.4	-54.9	-6.5	-22.7	-27.7	-5.0	-11.1	-16.2	-5.1	-5.8	-10.3	-4.5	5.9	1.8	-4.1
		TC.4	[°C]	-47.5	-54.4	-7.0	-21.2	-26.9	-5.7	-9.4	-15.3	-5.8	-3.9	-9.3	-5.3	8.0	3.0	-5.1
		TC.5	[°C]	-47.0	-54.0	-7.0	-20.5	-26.3	-5.8	-8.6	-14.5	-5.9	-3.0	-8.4	-5.4	9.1	4.0	-5.1
		TC.6	[°C]	-47.8	-54.8	-7.0	-21.8	-27.5	-5.7	-10.1	-16.0	-5.9	-4.7	-10.1	-5.4	7.2	2.0	-5.2
		TC.7	[°C]	-50.7	-55.1	-4.4	-25.7	-28.0	-2.3	-14.4	-16.6	-2.2	-9.3	-10.7	-1.5	2.0	1.2	-0.8
		TC.8	[°C]	-47.0	-54.1	-7.1	-20.6	-26.4	-5.8	-8.7	-14.7	-5.9	-3.1	-8.6	-5.4	8.9	3.8	-5.2
	MLI	TC.12	[°C]	-59.9	-61.4	-1.5	-35.0	-35.1	-0.1	-24.0	-23.9	0.0	-19.0	-18.2	0.9	-8.1	-6.4	1.6
		TC.13	[°C]	-90.5	-103.7	-13.2	-76.9	-85.0	-8.1	-71.5	-76.8	-5.3	-69.3	-72.6	-3.3	-63.8	-64.0	-0.2
	dT Thru MLI		[°C]	30.5	42.3	11.7	41.9	49.9	8.0	47.5	52.9	5.4	50.3	54.5	4.2	55.7	57.5	1.8
		Avg Nozzle [C]		-48.0	-54.6	-6.6	-22.1	-27.2	-5.1	-10.4	-15.6	-5.2	-5.0	-9.6	-4.7	6.8	2.5	-4.3
		RMS of TC 1-8 errors, per case:				6.6			5.2			5.4			4.8			4.5
		Overall RMS (across all cases):				5.4												

e = 0.085, RMS error 5.4C

Balance Points Measured:





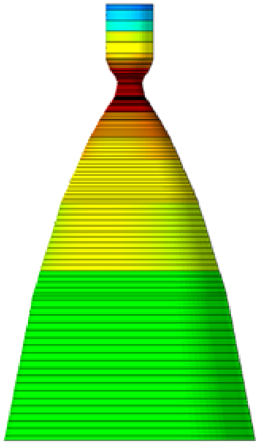
e = 0.08

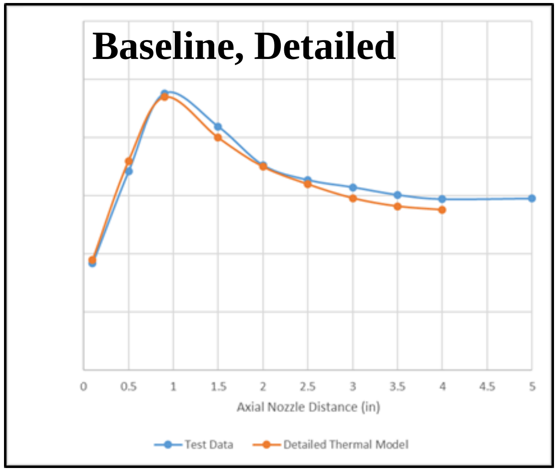
Nozzle Model: Correlation to Hot Fire Test Data

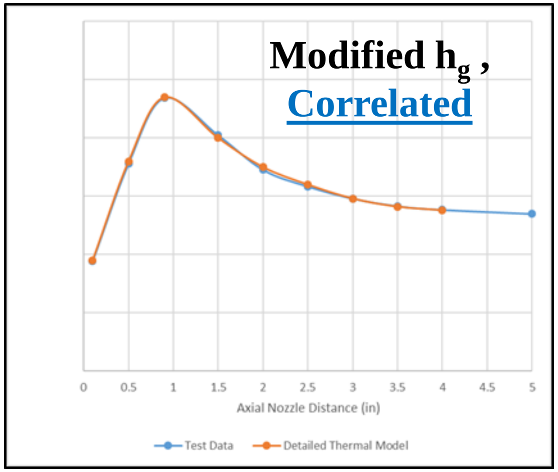
- Hot firing test data consisted of:
  - Discretized gas temperatures
  - Corresponding convection coefficients along the length of the nozzle.
  - Nozzle temperatures along the length
  - Nozzle dimensions and thicknesses

- Created detailed and reduced thermal models from this data, and modified convection coefficients (h_g) to match nozzle temperature data, especially the peak temperature
- **Correlations matched well**, within 17C (out of thousands of degrees C)

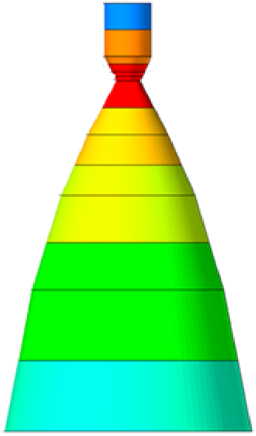
Detailed:
(111 nodes)

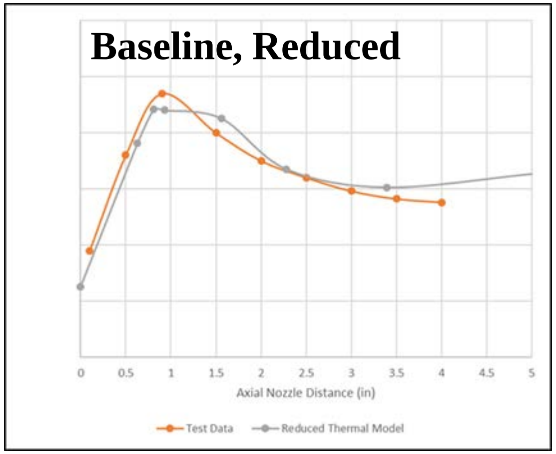


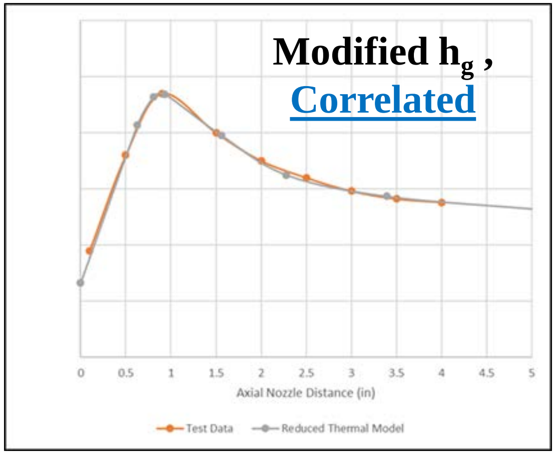




Reduced:
(8 nodes)







Conclusions

Lessons Learned & Thermal Considerations for Propulsion Systems

- Propellants
  - Will the **liquid propellants freeze** in the prop lines, or anywhere else along the system?
- Components
  - Will the components used to regulate flow, whether on the pressurant gas or liquid propellant side, stay within their hot and cold limits, in all cases?
- Engines (thrusters), 3 cases:
  - Will **valves** or **injector** freeze during cold case?
  - Will **valves** overheat during SS firing, and/or transient soak-back?
  - Will **nozzle** overheat when firing?
- Environmental Hot/Cold cases:
  - Hot case: close to sun (Venus flyby)
  - Cold case: deep space, near Jupiter (weak sun), and/or eclipse (no sun)
- Evaluate the coldest gas case:
  - What is the longest burn during the mission?
  - How cold will the pressurant gas become?
  - Will exposure to this cold gas cause components, or the pressurant tank, or gas lines, to exceed limits? (if so, may need to add heaters)
- *Caveat:*
  - *This is not a complete list of propulsion thermal considerations.*
  - *It contains highlights related to EC and what I've learned so far.*

Acknowledgements

- Dan Powers
- Bruce Williams (APL)
- Kim Holt (MSFC)
- Kurt Wolko
- Steve McKim
- Dan Ramspacher
- Rich Driscoll
- MOOG, Inc.
- Mario Martins
- Brian Rice
- Cindy Beer (C&R)
- Caitlin Bacha
- David Steinfeld
- Carlton Peters
- Veronica Otero
- Daniel Nguyen
- Carl Engelbrecht (APL)
- Stuart Hill (APL)
- Brenna Freeman

Questions?

Backup

- Bracket is held at constant boundary temperature (HRS).
- MLI inner layer sees a slight spike due to valve soak-back as well.

Abstract

This presentation describes the thermal analysis and model development that occurred for selected components on the propulsion module subsystem of the Europa Clipper mission, which will fly to Jupiter’s icy moon Europa and collect science data from orbit. An overview of a bipropellant system is given, as well as a description of a typical thermal propulsion design. A comparison is also provided, describing the unique Europa Clipper thermal design, which is atypical in many respects. The engine thermal model development is also discussed, including hot-firing tests with nozzle convection correlation, as well as thermal vacuum tests to measure and correlate the emissivity of critical nozzle surfaces. A description of engine firing, as well as valve soak-back, is also provided, including temperature maps and results of engine cases. A summary is also provided, of lessons learned regarding thermal propulsion considerations.