



## Thermal Analysis of Propulsion Components for the Europa Clipper Mission

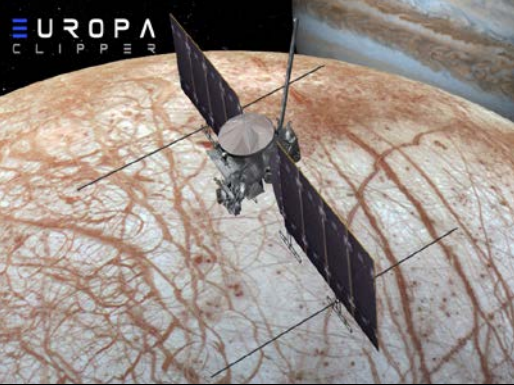
Heather Bradshaw, NASA GSFC



**TFAWS**  
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Presented By  
Heather Bradshaw

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



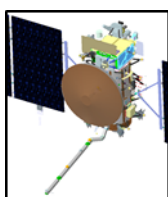
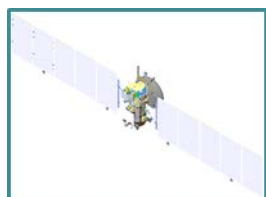
# Europa Clipper (EC)



## 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

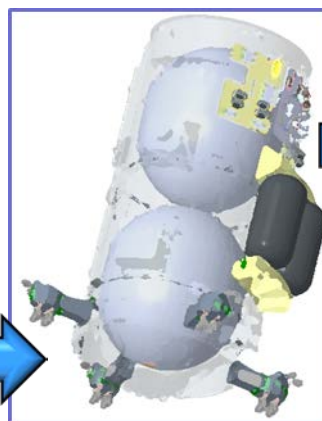
### RF Module, APL

### Propulsion Module, APL

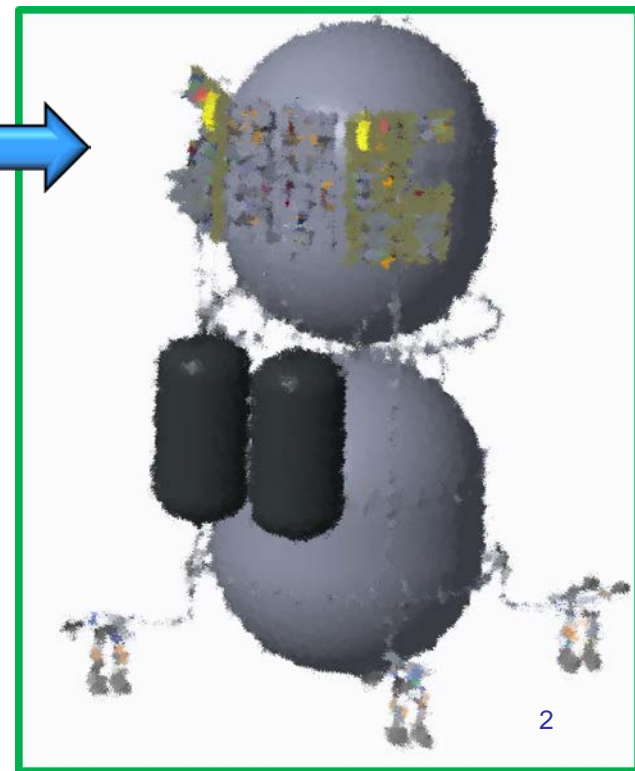
### Solar Array Wing (x2), APL

### LV Separation System & Adapter, JPL

## Propulsion Module, APL



## Propulsion Subsystem, Goddard



[details of images have been redacted]

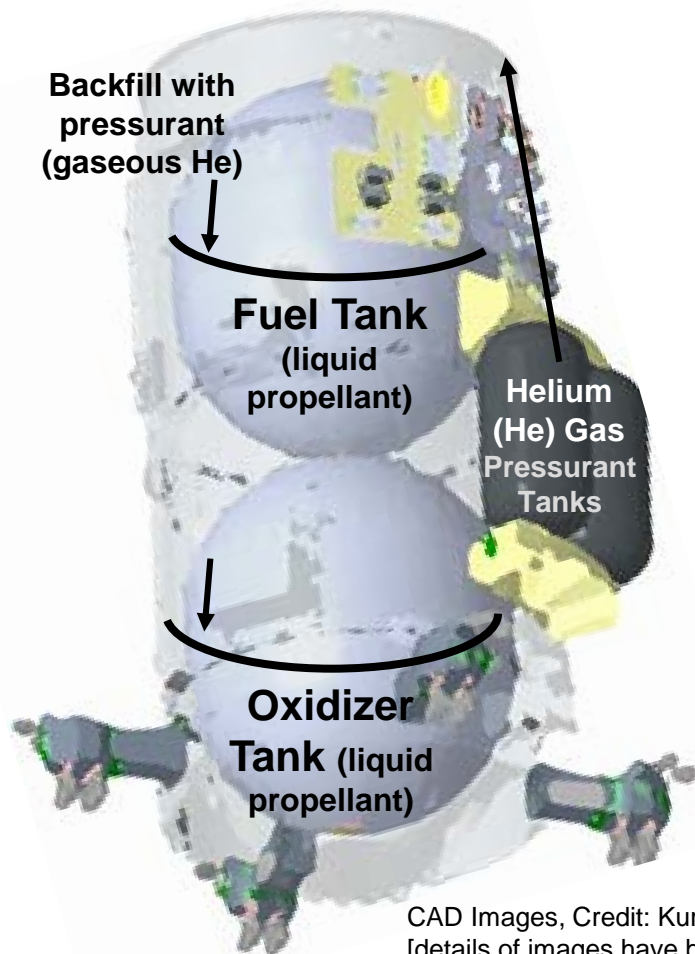
- **Liquid propellants:**

- Fuel = MMH = Monomethylhydrazine
- Oxidizer (Ox) = MON-3 (Mixed Oxides of Nitrogen)

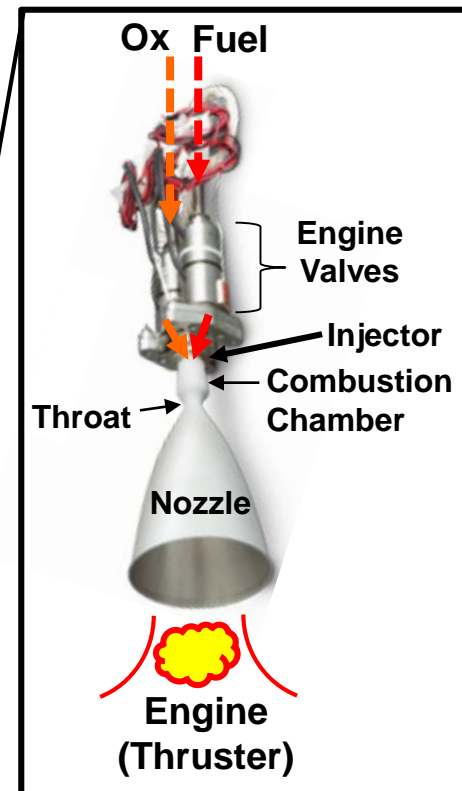
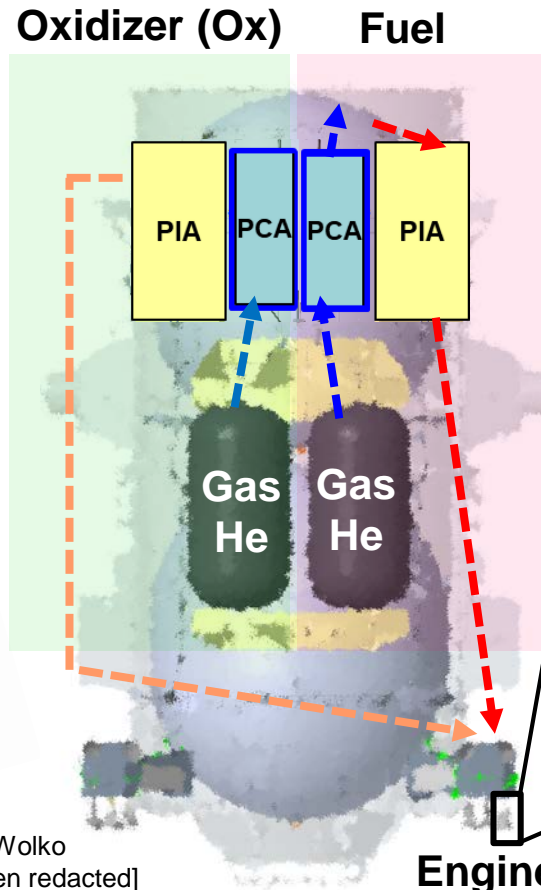
- Avoid combusting too soon (before it reaches the engine)  
= separate the paths of Oxidizer (Ox) & Fuel

- Fuel + Ox = Combustion (Thrust)

- Ensure outlet of liquid propellant remains “wetted” (avoid “slosh”) = backfill the tank using a **gas pressurant = Helium (He)** in this case
- Components mounted to plates: valves, filters, etc., (somewhat analogous to a SCUBA regulator system)
  - Adjust **gas pressurant** (He) flow = **PCA plate** = Pressurant Control Assembly
  - Adjust **liquid propellant** (fuel and oxidizer) flow = **PIA plate** = Propellant Isolation Assembly

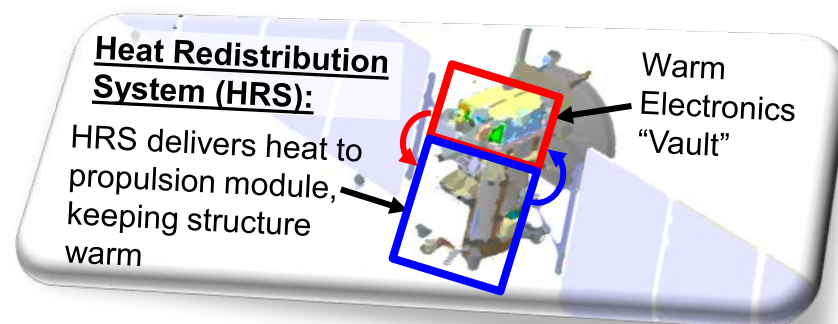


CAD Images, Credit: Kurt Wolko  
[details of images have been redacted]



Thruster Photo Credit: MOOG.  
[https://www.moog.com/content/dam/moog/literature/Space\\_Defense/spaceliterature/propulsion/bipropellant\\_thrusters\\_rev\\_0418.pdf](https://www.moog.com/content/dam/moog/literature/Space_Defense/spaceliterature/propulsion/bipropellant_thrusters_rev_0418.pdf)

	Typical	Europa Clipper ( <u>Not</u> Typical)
Approach:	<ul style="list-style-type: none"> <li><u>Isolate components</u> from structure, and <u>use heater power</u> to maintain their temperature.</li> </ul>	<ul style="list-style-type: none"> <li>Jupiter is far from sun, minimal solar power available, <u>minimize heater power</u> needed, <u>thermally couple components</u> to structure.</li> </ul>
Thermal Control:	<ul style="list-style-type: none"> <li><u>Heaters</u>, controlled by thermostats or flight software (FSW), located on: prop lines (to prevent liquid from freezing), engine valves, other components as needed.</li> </ul>	<ul style="list-style-type: none"> <li><u>Pumped fluid loop (HRS)</u> 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.</li> </ul>
Prop Lines:	<ul style="list-style-type: none"> <li>Install <u>thermostats</u>, <u>heaters</u>, <u>aluminum over-tape</u>, <u>sensors</u>, and <u>MLI</u>.</li> </ul>	<ul style="list-style-type: none"> <li><u>Bare Ti prop lines</u> and components, radiating to structure.</li> </ul>
Engine Valves:	<ul style="list-style-type: none"> <li><u>Isolate</u> from structure</li> <li>Install <u>heater</u>, <u>sensor</u> and/or <u>thermostat</u></li> <li><u>No blanket, and no over-tape</u> (need high-e to radiate during soak-back).</li> </ul>	<ul style="list-style-type: none"> <li><u>Heat-sink</u> to structure.</li> <li><u>No heater</u>. Rely on heat sink to HRS to cool valve during soak-back, and to heat valve during cold cruise.</li> <li><u>Bare</u> (no blanket or tape).</li> </ul>





	Typical	Europa Clipper ( <u>Not</u> Typical)
Propellant Tanks (liquid):	<ul style="list-style-type: none"> <li>• <u>Heaters, thermostats, sensors, aluminum tape, blanket Or</u></li> <li>• <u>Heaters on structure</u> that surrounds/holds tanks, <u>high-e surfaces inside “toasty cavity”</u>, radiative coupling.</li> </ul> <p>Note: Prop system is internal to spacecraft, <u>access is blocked</u> at later stages, so it is one of the few subsystems that is <u>critical to define Tvac Thermocouple locations and install them EARLY</u> during fabrication (not during testing phase).</p>	<ul style="list-style-type: none"> <li>• <u>Bare Ti tanks, no heaters.</u></li> <li>• Radiate to warm cylinder (prop module cylinder is irridite aluminum, heated by HRS).</li> </ul>
Pressurant Tanks (gas):	<ul style="list-style-type: none"> <li>• <u>Bare.</u> No heaters, no blankets. Tank located internal to spacecraft.</li> </ul>	<ul style="list-style-type: none"> <li>• <u>Heaters, thermostats, sensors, and blanket.</u></li> <li>• Need to maintain tank above cold limits and to pre-heat tanks before long burn.</li> </ul>
Engine Injector:	<ul style="list-style-type: none"> <li>• <u>Heater.</u></li> </ul>	<ul style="list-style-type: none"> <li>• <u>No heater.</u> Rely on conduction through valve to HRS to maintain above cold limit.</li> </ul>
Engine Nozzle:	<ul style="list-style-type: none"> <li>• <u>High-emissivity outer coating</u>, to radiate heat away when firing, to prevent engine from overheating</li> </ul>	<ul style="list-style-type: none"> <li>• Same.</li> </ul>
High-Temperature blankets:	<ul style="list-style-type: none"> <li>• <u>High-temperature blankets</u> near thrusters</li> </ul>	<ul style="list-style-type: none"> <li>• Same.</li> </ul>
Contamination Bake-out:	<ul style="list-style-type: none"> <li>• <u>Goal is to bake off volatiles</u>, and avoid having them condense on optics or sensitive hardware; meet the outgassing criteria.</li> </ul>	<ul style="list-style-type: none"> <li>• <u>Planetary Protection</u> bake-out: much <u>hotter temperatures, and longer durations</u>. Affects material selections.</li> </ul>

# 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

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

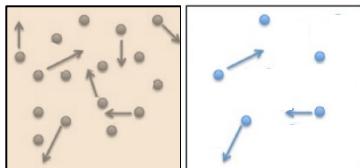
P = Pressure

V = Volume

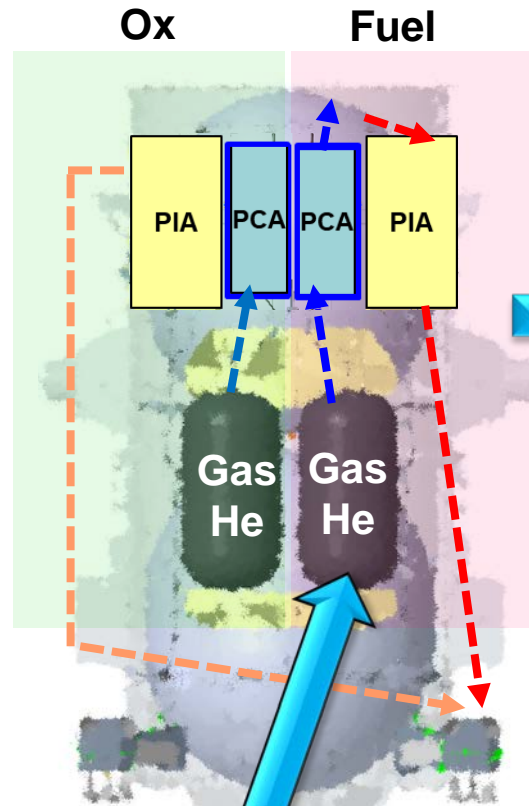
n = number of moles of gas particles

T = Temperature [K]

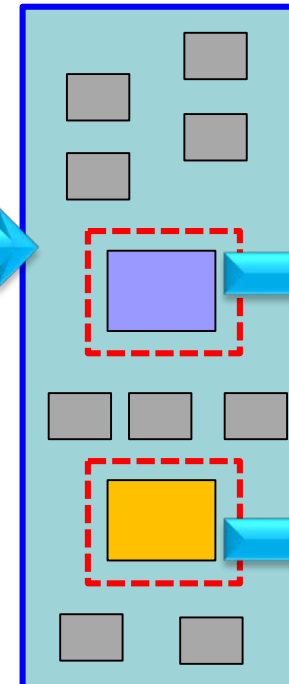
R = Gas Constant



High P&T Low P&T



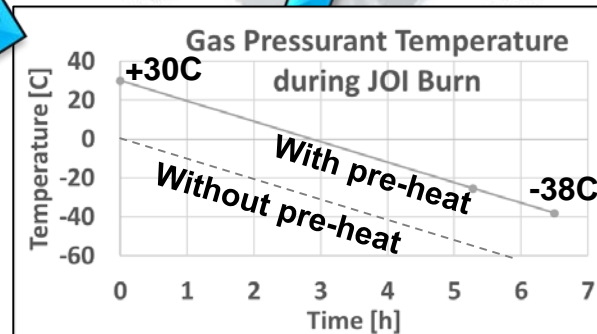
## PCA Plate



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

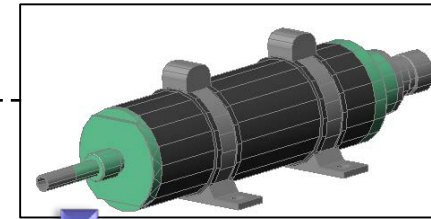
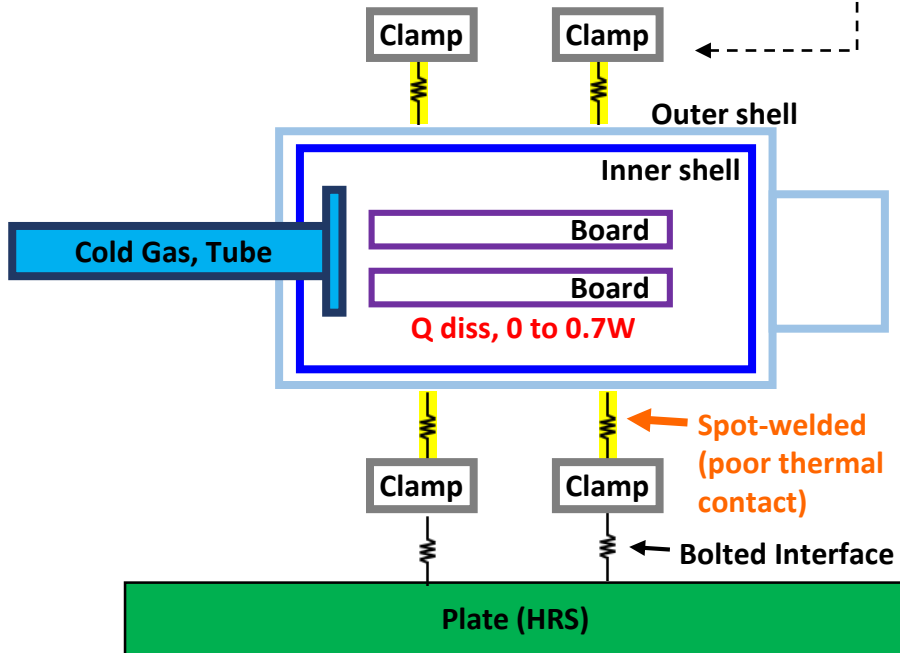
**Component 2:**  
Electronics  
inside: if too  
cold or hot,  
may not  
perform

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

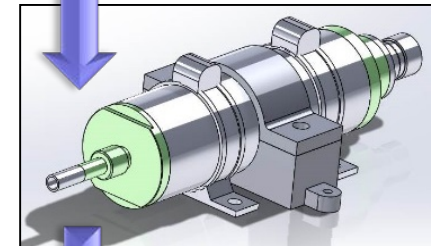


Data Credit: MSFC, Kim Holt

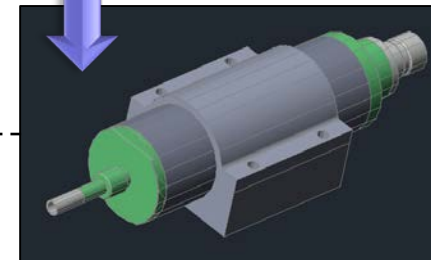
## Component #2: Design Iterations



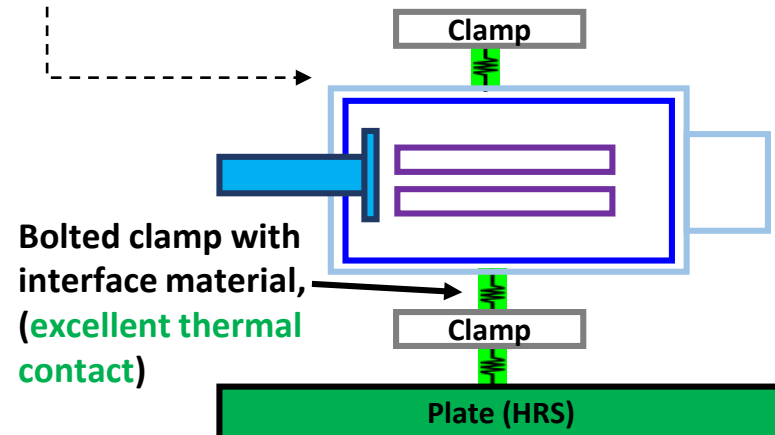
- Clamp is spot-welded to cylindrical housing (poor thermal contact)



- 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



- 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](#)

# Europa Clipper (EC) Engines (Thrusters)

- **Thermal Analyses**

- Valve & Injector: Cold cruise
- Valve & Nozzle: Hot fire
- Valve: Soak-back

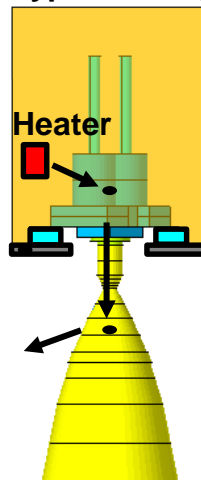
- **Minimize Heaters**

- HRS (pumped fluid) system maintains temperature
- Avoid heaters (weak sun at Jupiter, less energy from solar panels, little power available)

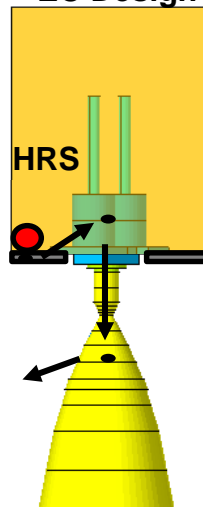
- **Hardware Considerations**

- High Temperature Blankets, near engines
- Planetary protection (PP) bake-out, (hotter than typical bake-out)

**Typical Design**



**EC Design**



**Typical Engine Design**

Valve loses heat to nozzle

Replenished by **Heater**

**Isolators** minimize heat pulled from SC

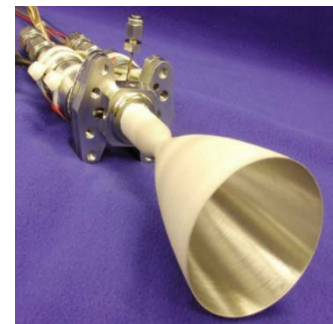
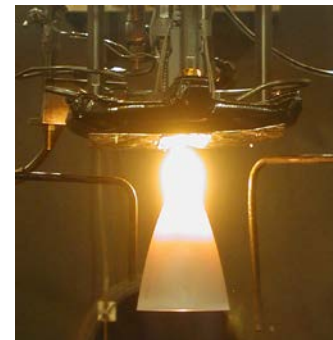
**EC Engine Design**

Valve loses heat to nozzle

Replenished by **HRS**

Heat **is** pulled from SC

Incandescence  
("glowing" temperature regime):



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

550

630

680

740

770

800

850

900

950

1000

1100

1200

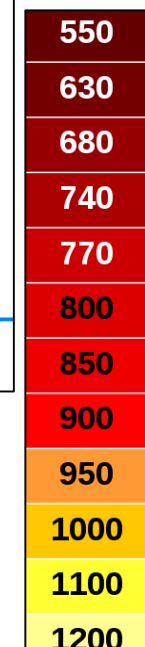
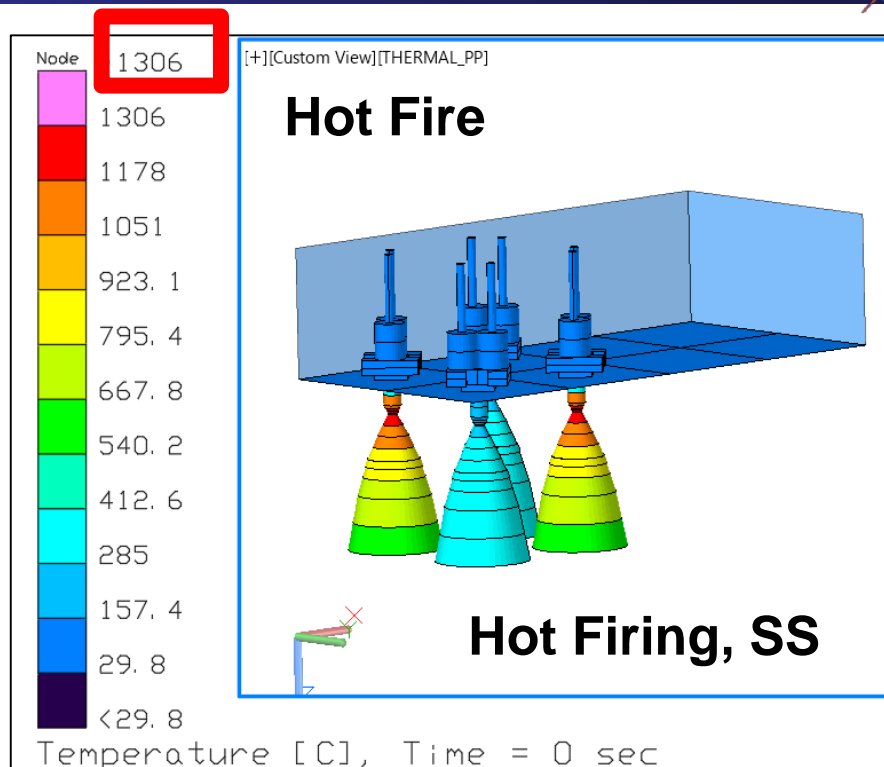
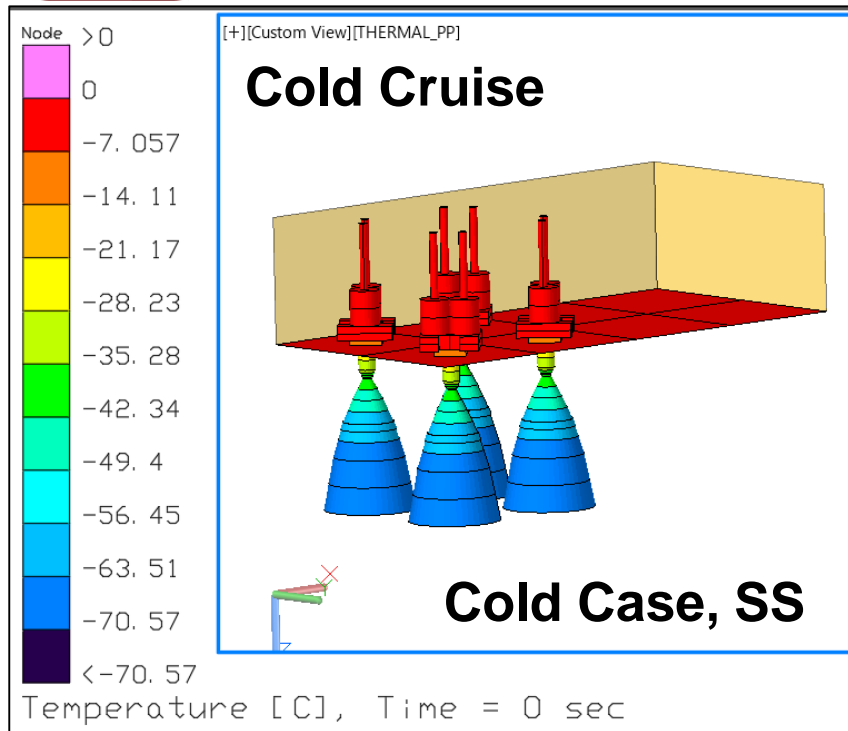
**1300**

**Temperature [C]**

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



# Engine Temperature Maps



**1300**

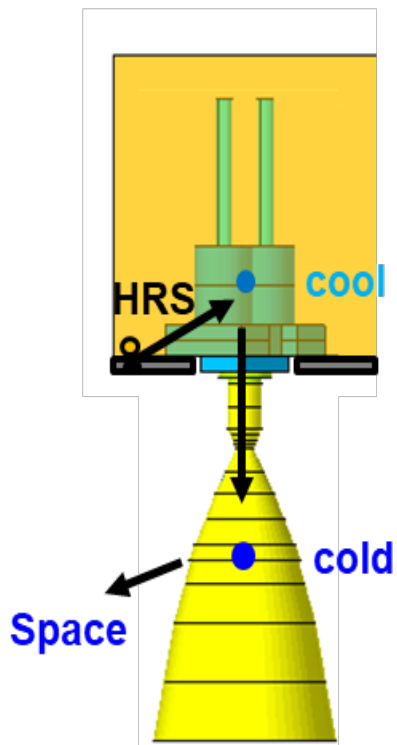
Temperature [C]



- 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)

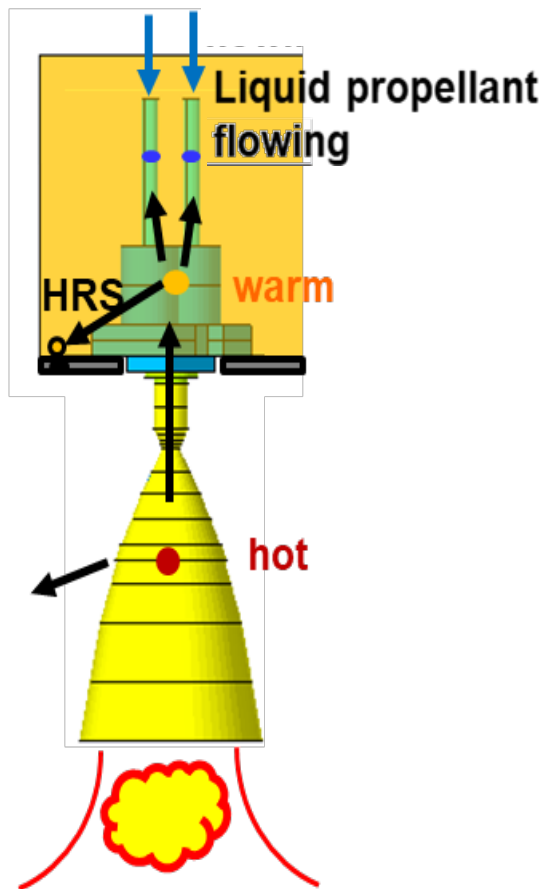
- Hot:**
- Valve hot limit: 101 C
  - Nozzle hot limit: 1371 C
  - Result: Valves and nozzles stay within this

## Before Firing:



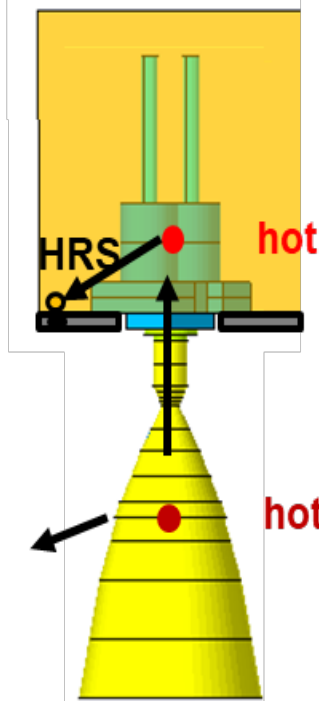
- Nozzle radiates to cold space
- Valve warmed by HRS

## During SS Firing:



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

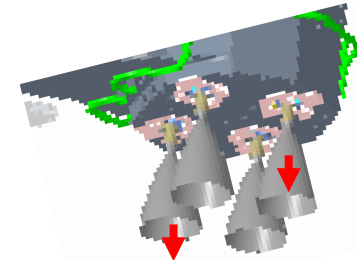
## Soak-back (Transient, right after firing):



- 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”

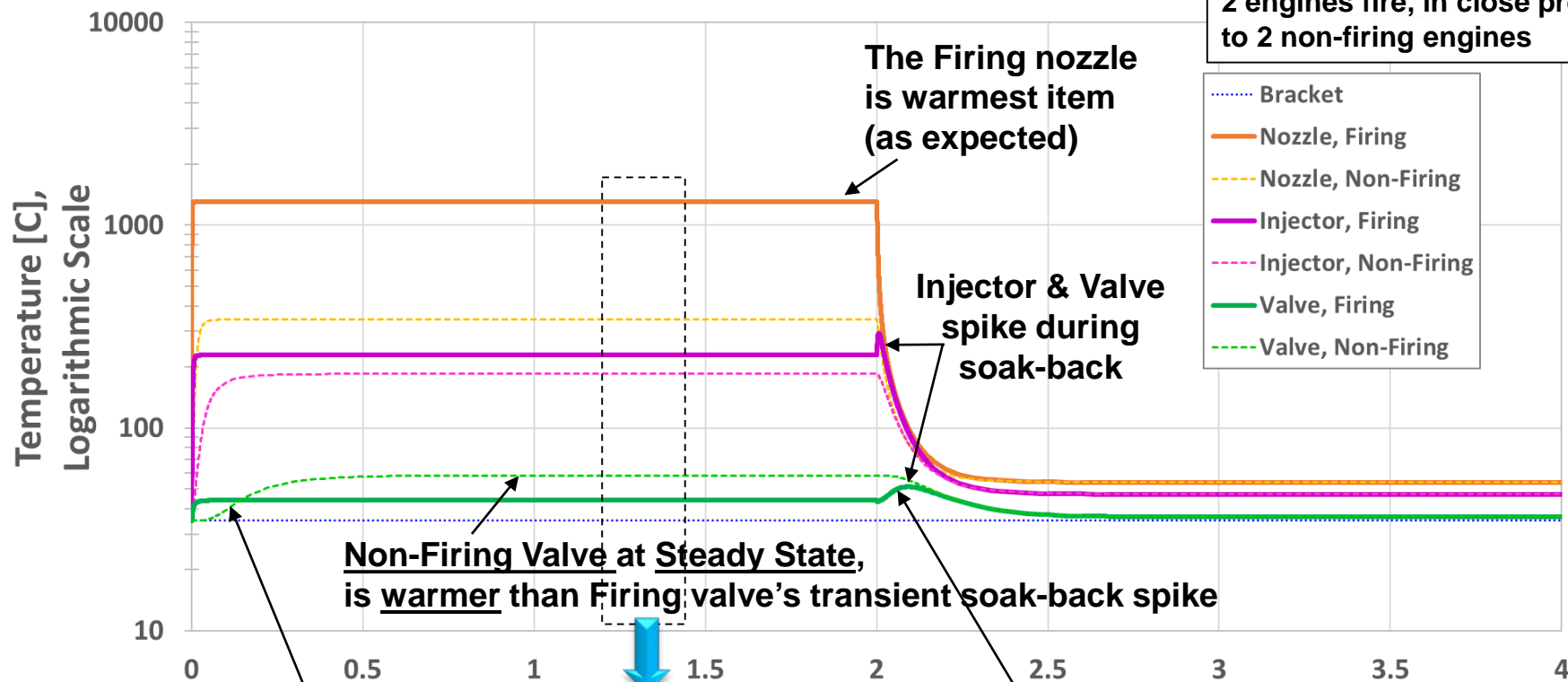
# Firing & Soak-back Temperatures

Other conclusions we can draw (specific to EC):



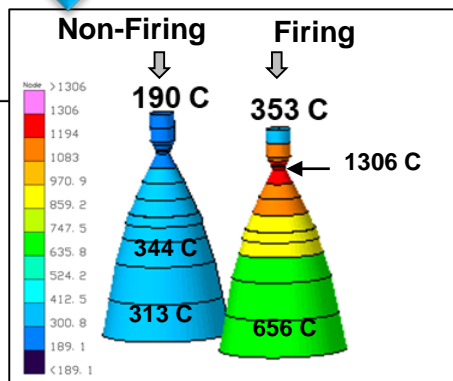
2 engines fire, in close proximity to 2 non-firing engines

Summary: Firing vs. Non-Firing Engines



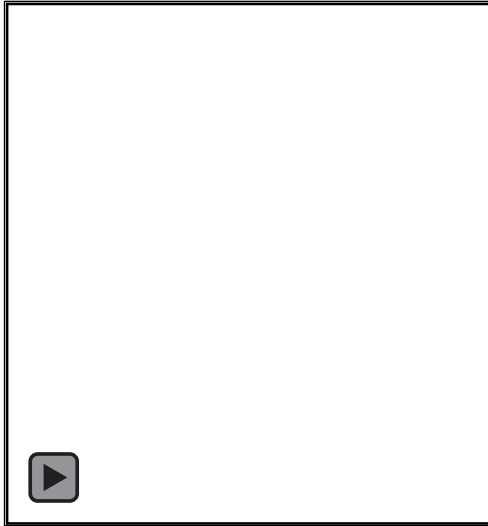
If performing a short burn, then the firing valve soak-back is hotter than non-firing valve

SS Firing Temperature Map:

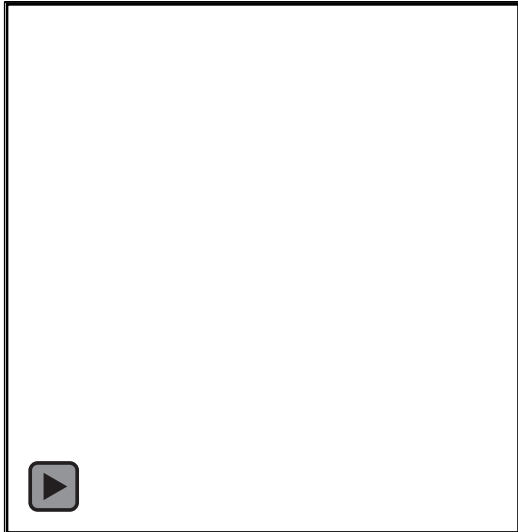


If single engine, then soak-back will be hotter than SS firing temperature

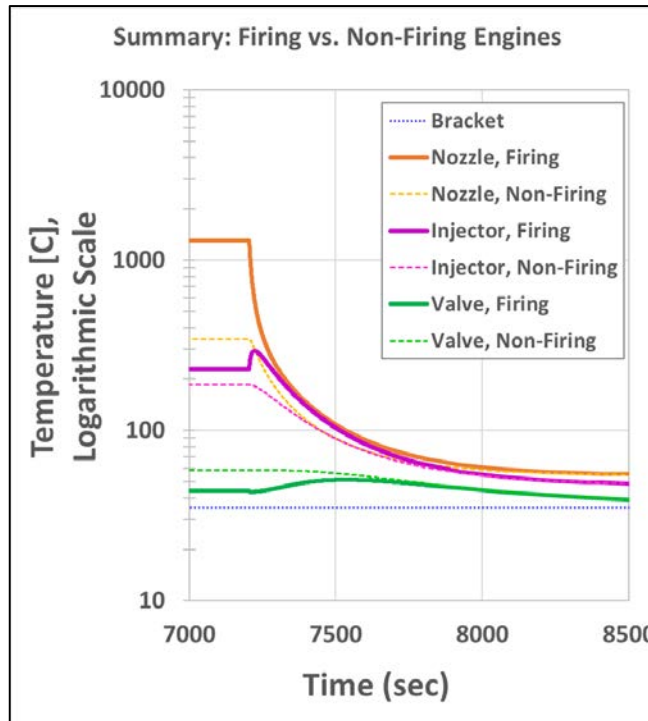
## Firing Engine:



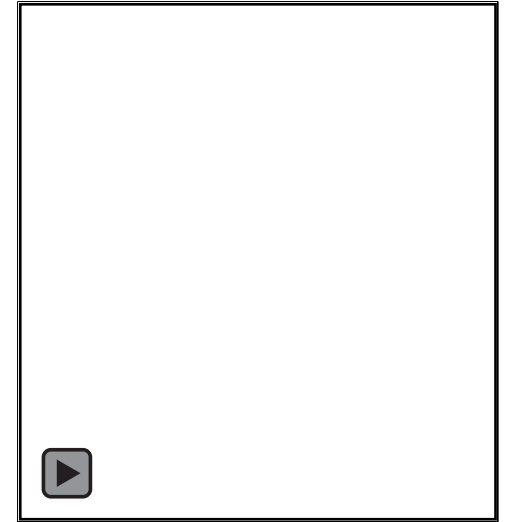
Valve warms up (soak-back), then cools



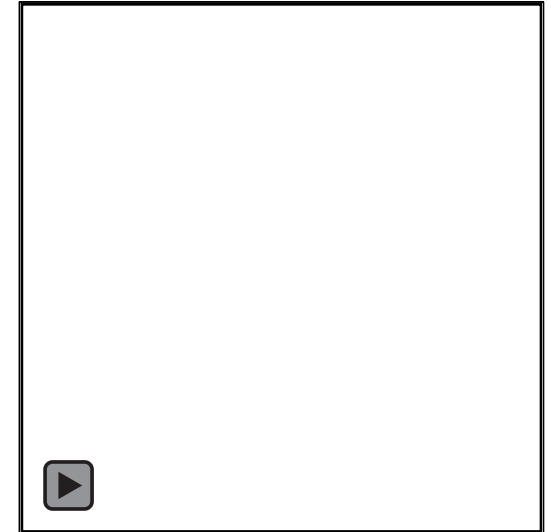
Nozzle cools



## Non-Firing Engine (Nearby):



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



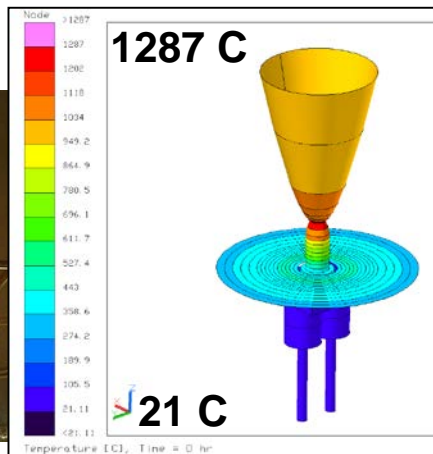
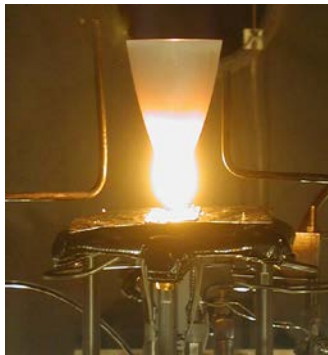
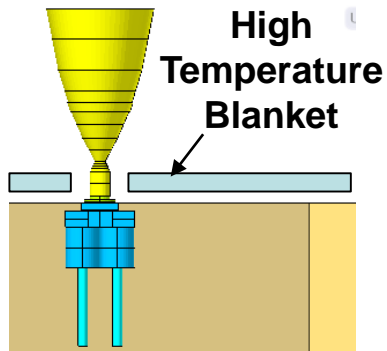
Non-Firing Nozzle cools



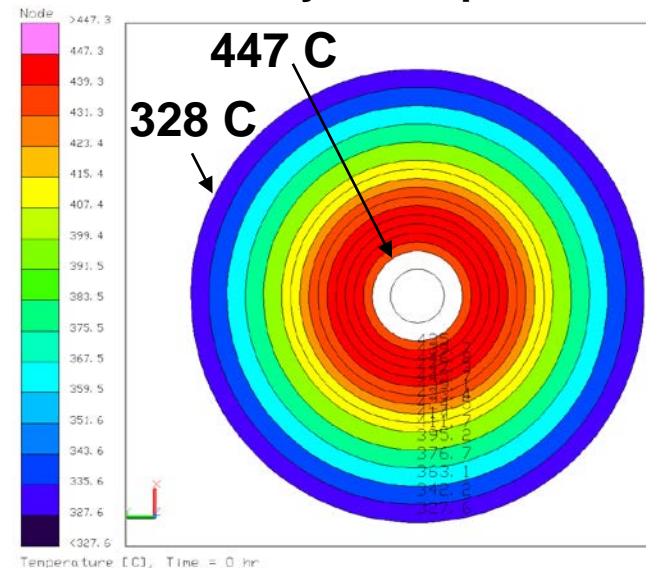
Material	Melt (°C)	Service (°C)
Mylar	250	150
Dacron	256	
Stamet		400
Kapton		400
Stainless Steel Foil (e_IR = 0.15)	>1000	
High Temp Fabric*		>1000

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

- **High temperature blankets require different materials** than normal blankets, to avoid melting during thruster burn maneuvers.
- For context:
  - EC predicted nozzle temperature = 1,306 C
  - EC predicted temperature of outermost (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.

TFAWS 2018 – August 20-24, 2018

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

## Valve:

- $Q_{\text{transient}} = m \cdot c_p \cdot dT$
- $Q_{\text{conduction}} = G \cdot dT = k \cdot A / L$

## 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:

- $Q_{\text{radiation}} = e \cdot A \cdot \sigma \cdot VF \cdot (T^4 - T_{\text{space}}^4)$

## Measured Nozzle Emissivity (e) Values in Tvac:

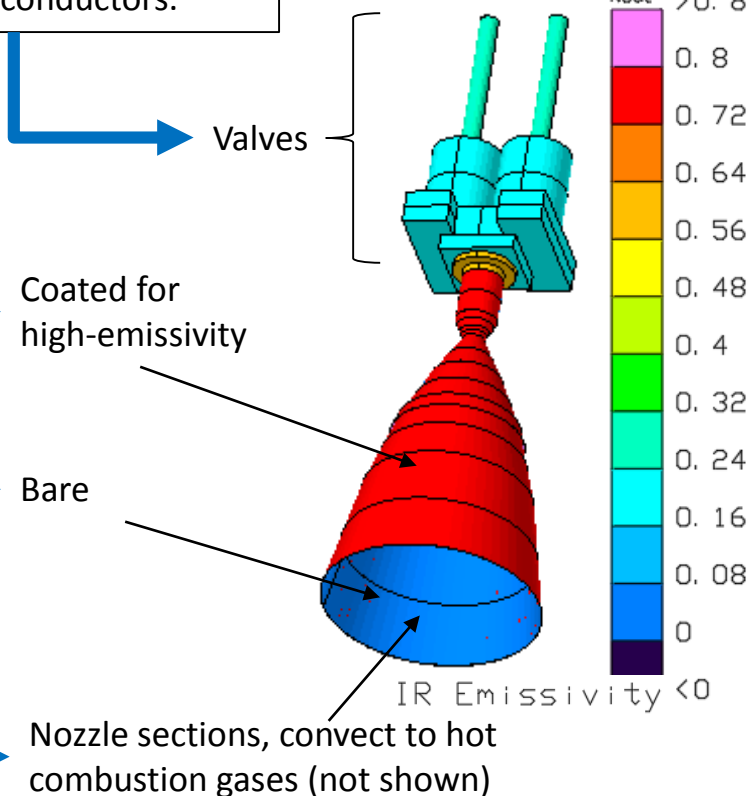
- Coated emissivity = 0.72
- Bare emissivity = 0.08

## Nozzle:

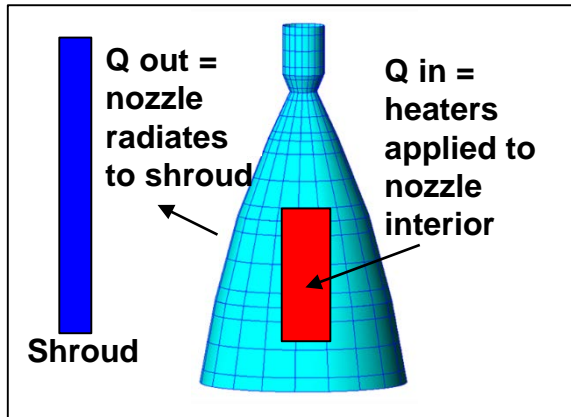
- $Q_{\text{convection}} = h \cdot A \cdot dT$

## Correlated Nozzle Convection Coefficients (h) to Combustion Gas Boundaries

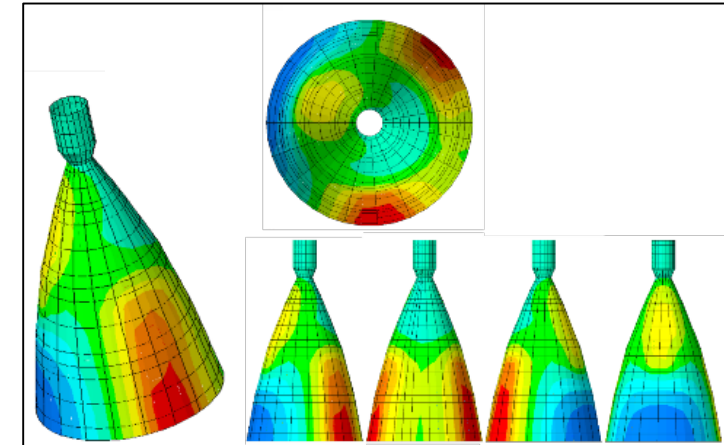
- Used previous **Hot Fire Test Data**



## Test Design & Approach:



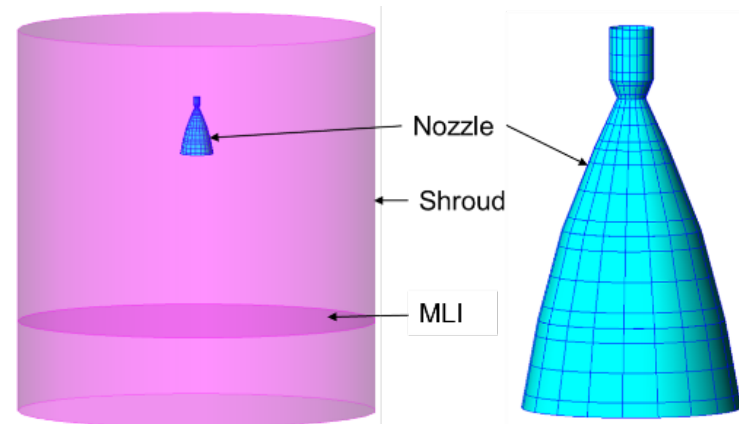
- $Q_{in} = Q_{out}$



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

$$Q_{heaters} = A \cdot e_{noz} \cdot \sigma \cdot (T_{noz}^4 - T_{shroud}^4)$$

- 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

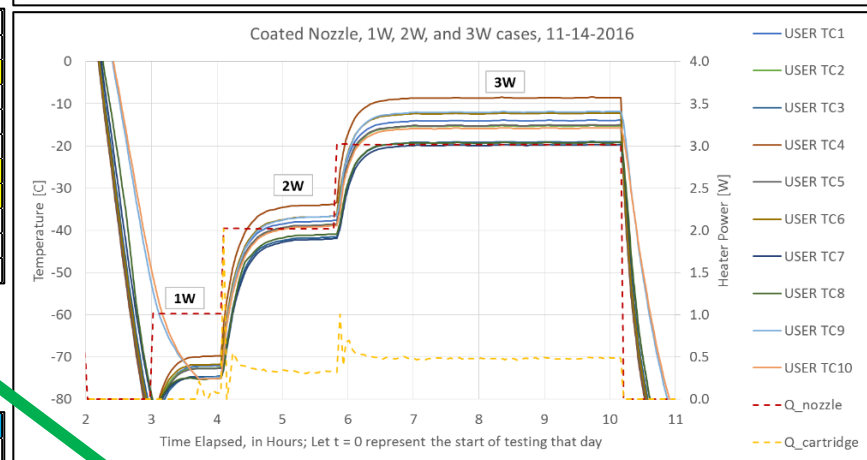
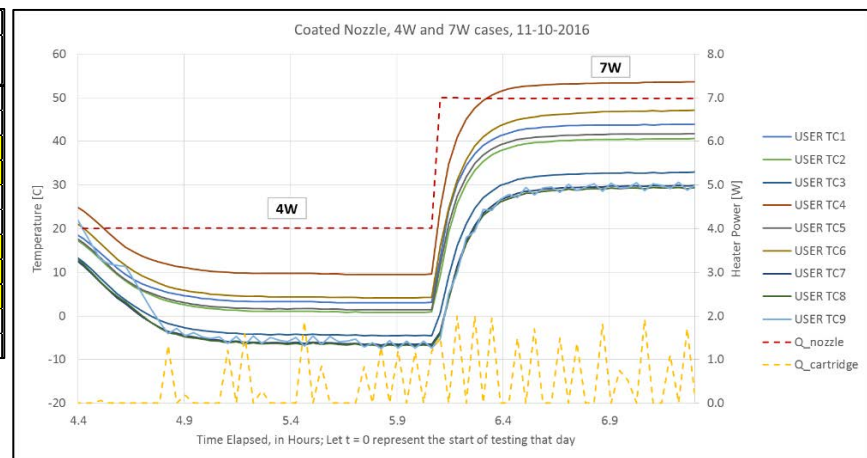
			1 W			2 W			3 W			4 W			7 W		
			Tvac Data	Model	Diff. (M-T)	Tvac Data	Model	Diff. (M-T)	Tvac Data	Model	Diff. (M-T)	Tvac Data	Model	Diff. (M-T)	Tvac Data	Model	Diff. (M-T)
Correlated Model, $e = 0.72$	TC.1	[°C]	-72.0	-74.7	-2.7	-37.8	-40.2	-2.4	-14.0	-16.6	-2.6	3.1	1.8	-1.2	43.8	41.8	-2.0
	TC.2	[°C]	-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

			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, $e + 0.01 = 0.73$	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

## Balance Points Measured:

			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
	MU	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 MU [°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												

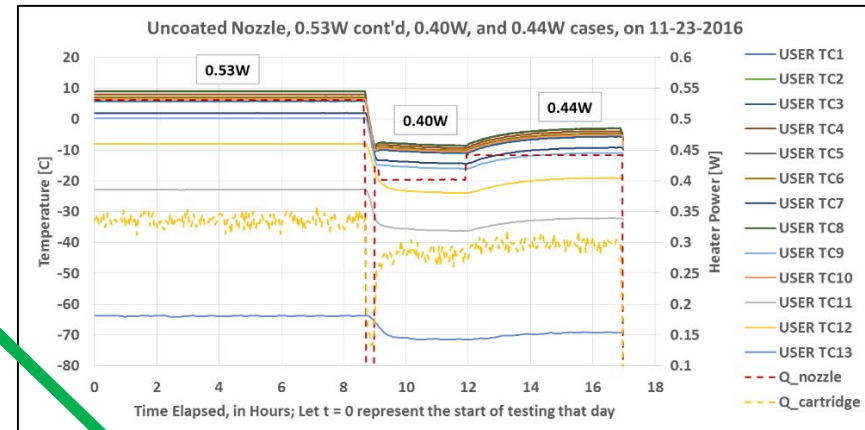
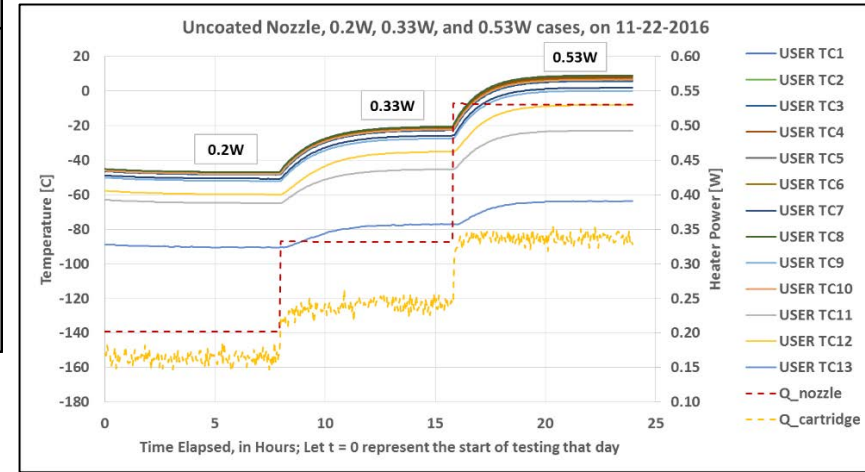
**e = 0.075, RMS error 2.5C**

			0.2 W			0.33 W			0.4 W			0.44 W			0.53 W		
			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)
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
	MU	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 MU [°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		
			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=0.005-0.085	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
	MU	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 MU [°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												

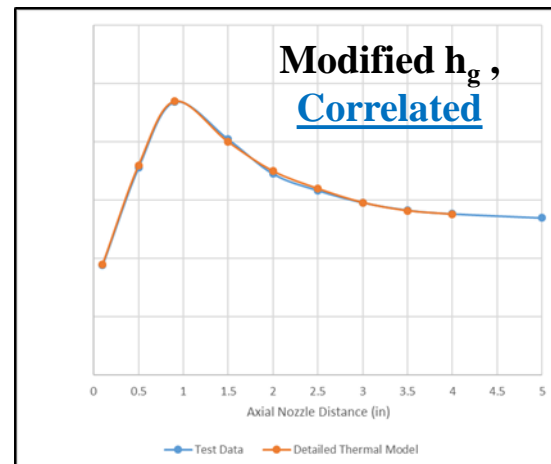
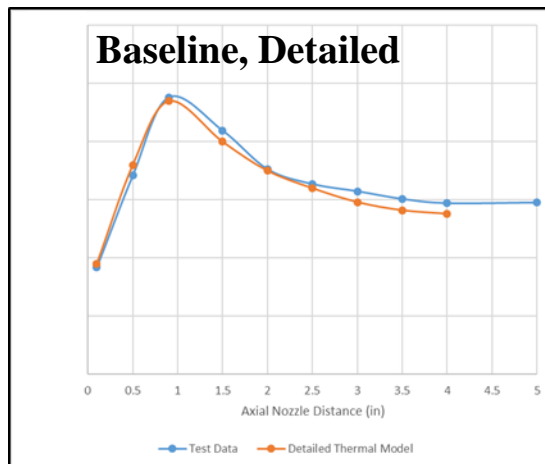
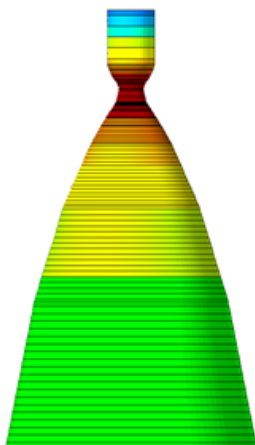
**e = 0.085, RMS error 5.4C**



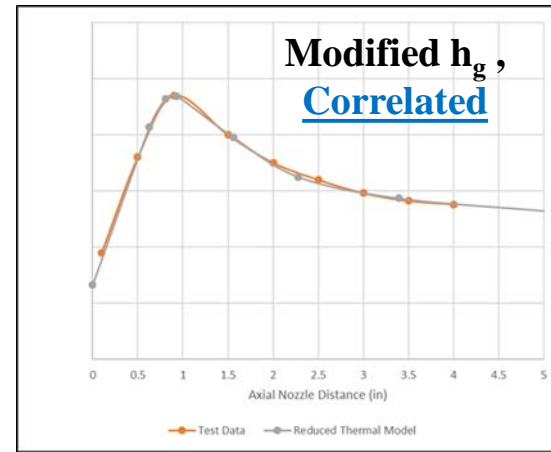
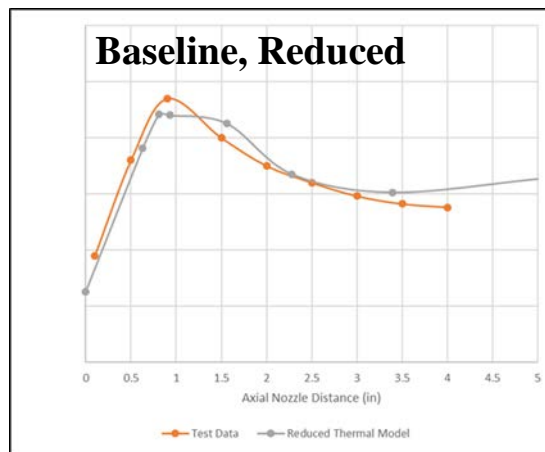
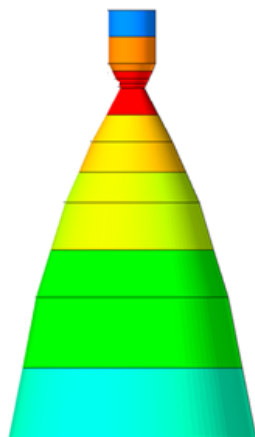
**e = 0.08**

- 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)**



## 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



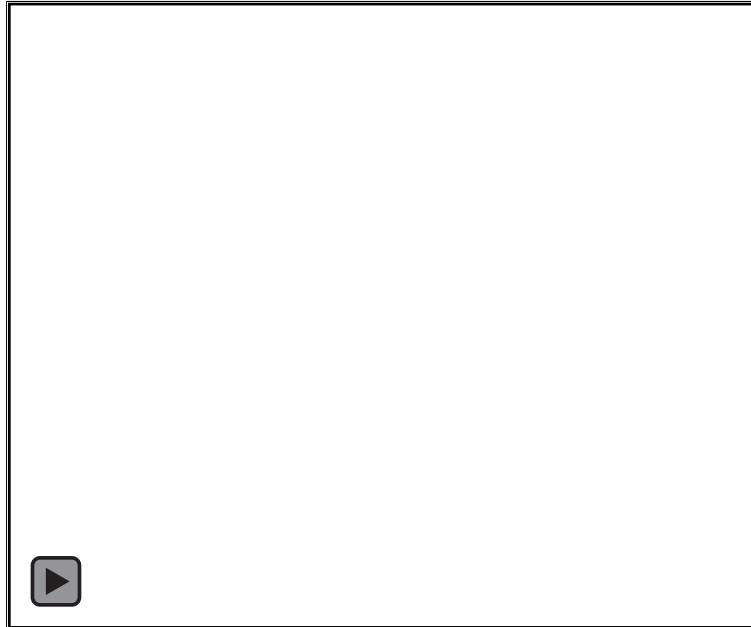
- Dan Powers
- Bruce Williams (APL)
- Kim Holt (MSFC)
- Kurt Wolko
- Steve McKim
- Dan Ramspacher
- Rich Driscoll
- MOOG, Inc.
- Mario Martins
- Brian Rice
- Cindy Beer (C&R)
- Caitlin Bacha
- David Steinfeld
- Carlton Peters
- Veronica Otero
- Daniel Nguyen
- Carl Engelbrecht (APL)
- Stuart Hill (APL)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





# Questions?





- **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.