Thermal Analysis of Propulsion Components for the Europa Clipper Mission

Heather Bradshaw, NASA GSFC

Presented By
Heather Bradshaw

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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
**Propulsion Subsystem Overview (How it Works)**

- **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

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**Backfill with pressurant (gaseous He)**

**Fuel Tank** (liquid propellant)

**Oxidizer Tank** (liquid propellant)

**Helium (He) Gas Pressurant Tanks**

**PIA**

**PCA**

**Fuel**

**Oxidizer (Ox)**

**Gas He**

**Gas He**

**Engine Valves**

**Injector**

**Combustion Chamber**

**Nozzle**

**Engine (Thruster)**

**Thruster Photo Credit: MOOG.**


**Liquid propellants:**

- **Fuel** = MMH = Monomethylhydrazine
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**CAD Images, Credit: Kurt Wolko** [details of images have been redacted]
## Propulsion Subsystem: Thermal Overview

<table>
<thead>
<tr>
<th>Typical</th>
<th>Europa Clipper (Not Typical)</th>
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<tbody>
<tr>
<td><strong>Approach:</strong></td>
<td>• Jupiter is far from sun, minimal solar power available, <strong>minimize heater power</strong> needed, <strong>thermally couple components</strong> to structure.</td>
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<td>• Isolate components from structure, and <strong>use heater power</strong> to maintain their temperature.</td>
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<td><strong>Thermal Control:</strong></td>
<td>• <strong>Pumped fluid loop (HRS)</strong> 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.</td>
</tr>
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<td>• Heaters, controlled by thermostats or flight software (FSW), located on: prop lines (to prevent liquid from freezing), engine valves, other components as needed.</td>
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<td><strong>Prop Lines:</strong></td>
<td>• <strong>Bare Ti prop lines</strong> and components, radiating to structure.</td>
</tr>
<tr>
<td>• Install <strong>thermostats, heaters, aluminum over-tape, sensors</strong>, and MLI.</td>
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</tr>
</tbody>
</table>
| **Engine Valves:** | • **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). |
| • Isolate from structure  
• Install **heater, sensor** and/or **thermostat**  
• **No blanket, and no over-tape** (need high-e to radiate during soak-back). | |

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**Heat Redistribution System (HRS):**

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

\[ P \cdot V = n \cdot R \cdot T \]

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

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]
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*

**Considerations for Component #2**

- 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

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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)

**Incandescence** ("glowing" temperature regime):

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

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

Cold:
- Liquid propellants, would freeze at:
  - Ox, MON3: -10°C 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”
Other conclusions we can draw (specific to EC):

- **Firing & Soak-back Temperatures**

**Summary: Firing vs. Non-Firing Engines**

- The Firing nozzle is warmest item (as expected)
- Injector & Valve spike during soak-back
- Non-Firing Valve at Steady State, is warmer than Firing valve’s transient soak-back spike
- If performing a short burn, then the firing valve soak-back is hotter than non-firing valve
- If single engine, then soak-back will be hotter than SS firing temperature

SS Firing Temperature Map:

- 2 engines fire, in close proximity to 2 non-firing engines
Videos: Soak-back

Firing Engine:
Valve warms up (soak-back), then cools

Non-Firing Engine (Nearby):
Valve cools (no soak-back, nozzle not hot enough)

Summary: Firing vs. Non-Firing Engines

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High Temperature Blankets

- **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.

<table>
<thead>
<tr>
<th>Material</th>
<th>Melt (°C)</th>
<th>Service (°C)</th>
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<tbody>
<tr>
<td>Mylar</td>
<td>250</td>
<td>150</td>
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<tr>
<td>Dacron</td>
<td>256</td>
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<tr>
<td>Stamet</td>
<td>400</td>
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<tr>
<td>Kapton</td>
<td>400</td>
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<tr>
<td>Stainless Steel Foil (e_IR = 0.15)</td>
<td>&gt;1000</td>
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<tr>
<td>High Temp Fabric*</td>
<td>&gt;1000</td>
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</table>

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

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

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Engine Model Development (cont’d)

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

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

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.

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

Measured Nozzle Emissivity ($e$) Values in $T_{\text{vac}}$:
- 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

Thermal Model Delivered to APL

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:

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

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

- \( Q_{\text{in}} = Q_{\text{out}} \)

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

Correlation Data:

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<th>2 W</th>
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<th>3 W</th>
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<th>4 W</th>
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<th>7 W</th>
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<td>-74.7</td>
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<td>RMS of TC 1-8 errors, per case:</td>
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<td>1.4</td>
<td>1.5</td>
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<td>3.5</td>
<td>4.7</td>
<td>2.9</td>
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Overall RMS (across all cases): 2.9

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<td>2.8</td>
<td>2.7</td>
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<td>2.6</td>
<td>3.7</td>
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</table>

Overall RMS (across all cases): 2.9

e = 0.71, RMS error 2.9°C

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

Balance Points Measured:

e = 0.73, RMS error 2.9°C
### Sensitivity Study, $e^{-0.005} = 0.075$

<table>
<thead>
<tr>
<th>Case</th>
<th>$\Delta T$ (M-T)</th>
<th>Overall RMS (across all cases: 2.5)</th>
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<td>TC.1</td>
<td>-4.80</td>
<td>0.075</td>
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<td>Avg Nozzle</td>
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<td>2.2</td>
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<td>TC.3</td>
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<tr>
<td>TC.4</td>
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</tr>
<tr>
<td>TC.5</td>
<td>0.0</td>
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</tr>
<tr>
<td>TC.6</td>
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<td>2.2</td>
</tr>
<tr>
<td>TC.7</td>
<td>0.0</td>
<td>2.2</td>
</tr>
<tr>
<td>TC.8</td>
<td>0.0</td>
<td>2.2</td>
</tr>
<tr>
<td>TC.12</td>
<td>0.0</td>
<td>2.2</td>
</tr>
<tr>
<td>TC.13</td>
<td>0.0</td>
<td>2.2</td>
</tr>
<tr>
<td>Avg Nozzle</td>
<td>-48.0</td>
<td>0.075</td>
</tr>
<tr>
<td>Overall RMS (across all cases):</td>
<td>2.5</td>
<td></td>
</tr>
</tbody>
</table>

### Results: Bare/Uncoated Nozzle

- **e = 0.075,** RMS error 2.5C
- **e = 0.080,** RMS error 2.4C = lowest error = sweet spot
- **e = 0.085,** RMS error 5.4C

---

**Balance PointsMeasured:**

<table>
<thead>
<tr>
<th>Case</th>
<th>$\Delta T$ (M-T)</th>
<th>Overall RMS (across all cases: 2.5)</th>
</tr>
</thead>
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<td>TC.8</td>
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<tr>
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<td>Avg Nozzle</td>
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<td>0.075</td>
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<tr>
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<tr>
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<td>0.075</td>
</tr>
<tr>
<td>Overall RMS (across all cases):</td>
<td>2.5</td>
<td></td>
</tr>
</tbody>
</table>

---

**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 17°C (out of thousands of degrees C)

Detailed: (111 nodes)

Baseline, Detailed

Baseline, Reduced

Modified $h_g$, Correlated

Modified $h_g$, Correlated
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

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- Bruce Williams (APL)
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- 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.