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Robust Thermal Control of Propulsion Lines for Space Missions

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- Typical Configurations & Designs for Thermal Control of Propulsion Lines for Space Missions
- Historical Context of Problem Statement
- Numerical Examples to Illustrate Magnitude of Potential Problems
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- Potential Solution Approaches
- Applicability & Limitations of Various Approaches
- Conclusions
- Acknowledgements

Introduction

- Typical propulsion lines in Spacecraft have narrow allowable temp. range
  - +15/+50 C (Hydrazine)
  - Required to be maintained at every location on them
- Thermal environment varies along the entire length
- Electrical heaters bonded to supply survival power
- Covered with cylindrically wound MLI blankets
- PRTs or Mech. Thermostats sense temps. & trigger heater duty cycles
- Heat balance at each location is very small (~10 mW/cm) & varies from location to location
  - Supports, cables, MLI, conduction

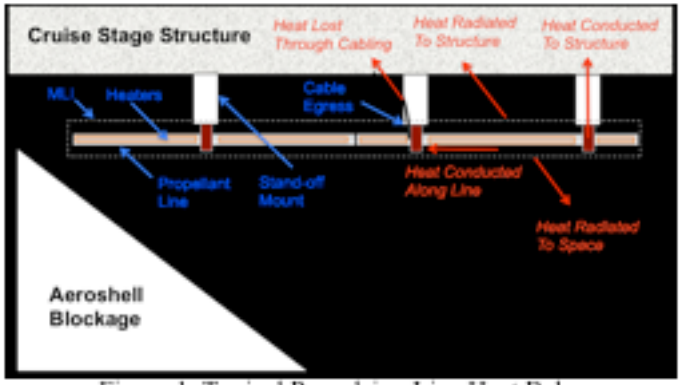
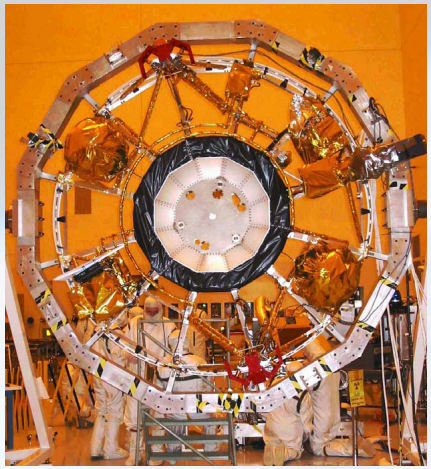


Figure 1. Typical Propulsion Line Heat Balance



Problem Statement

- ***MLI*** **is typically the largest contributor of heat balance & has significant** ***variability*** **in e* (effective emissivity of blanket) –** ***random and unpredictable***
  - ***Workmanship related***
- ***Heat conduction along length (spreading) is very small due to poor thermal conductivity of lines (Titanium)***
- **Temp. sensor at single location controls power over as much as 1 m of length**
- ***So this inevitably leads to significant unpredictability of the propulsion line temperatures***
  - **Can sometimes lead to the same controlled zone having simultaneously a overheated location and a frozen location**

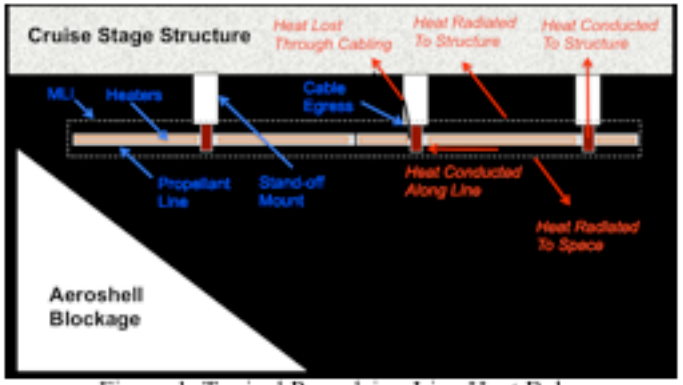
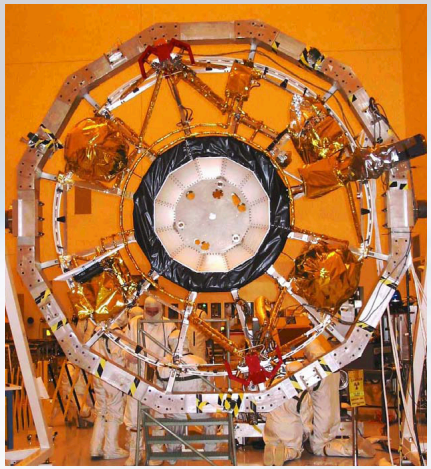
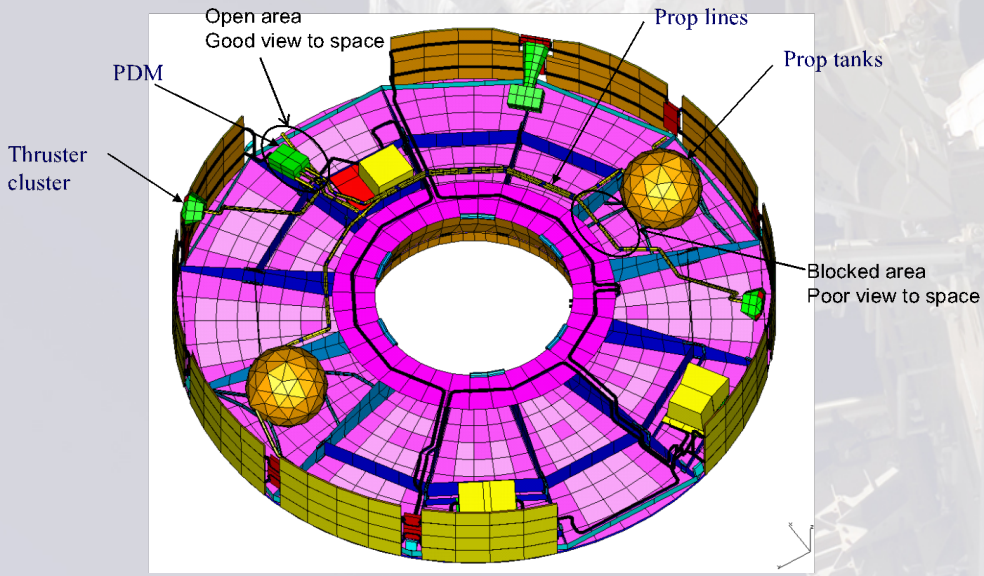


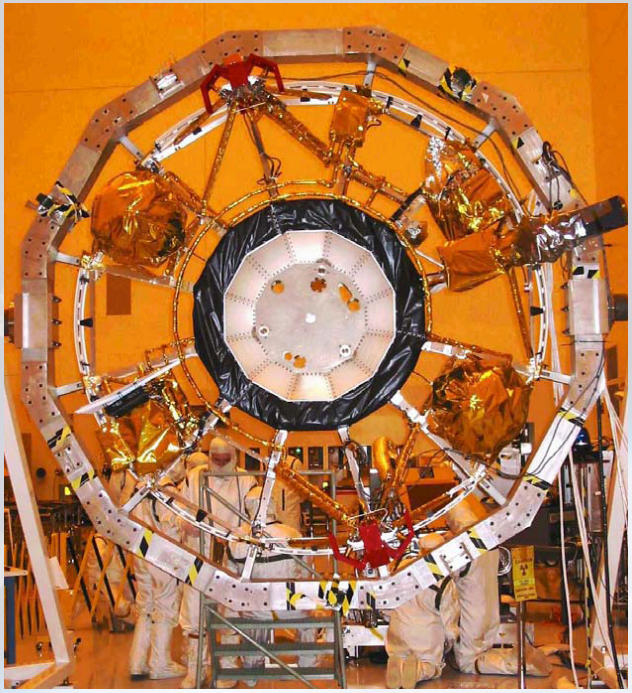
Figure 1. Typical Propulsion Line Heat Balance



Typical Configurations & Designs for Thermal Control of Propulsion Lines for Space Missions

MSL Cruise Stage Propulsion Line Layout & Thermal Model

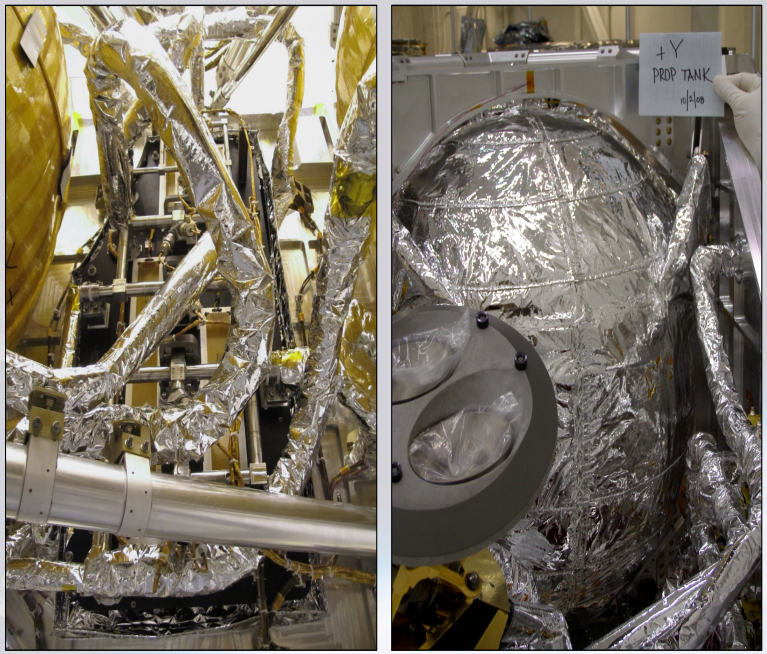




- Note how the thermal environment varies along the length of propulsion lines

Historical Context of Problem Statement

- Recurring problem over several missions in the past couple of decades
  - Mars Pathfinder, Mars Exploration Rovers, Mars Science Laboratory, DAWN, etc.
- Lack of predictability & robustness experienced in tests as well as flight
- Constant battle between overheating & freezing concerns
  - Simultaneous violations of max and min temp limits within same section!
- Hence the need for robust thermal designs to reduce or avoid these problems



MSL Descent Stage Propulsion Line Layout

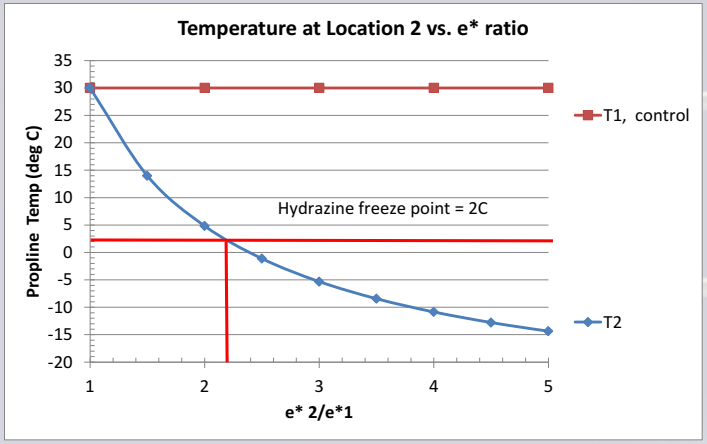
Numerical Examples to Illustrate Magnitude of Potential Problems

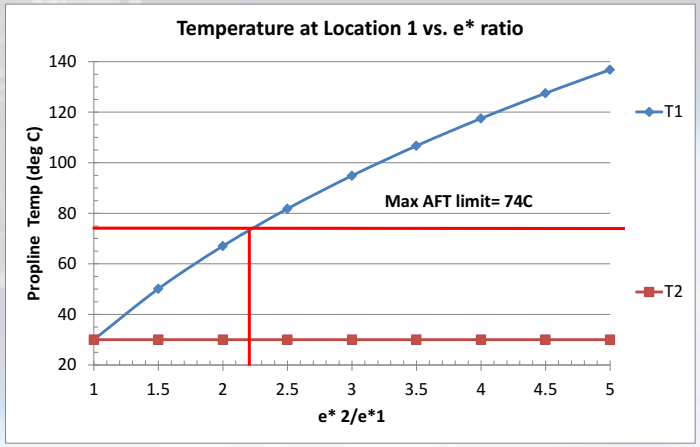
Category	Low ε*	High ε*	Ratio
Straight lines	0.022	0.11	5
Bent lines	0.049	0.245	5
Stand-offs	0.033	0.165	5

- MLI e* varies by as much as 5x even for similar sections
- Could be as much as 10:1 over different kinds of sections

$$Q_{heater} = \varepsilon^* \sigma A (T_{prop}^4 - T_{sink}^4)$$

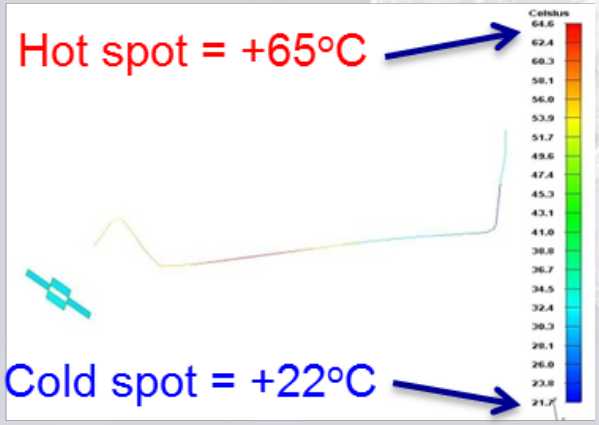
Basic Heat Balance

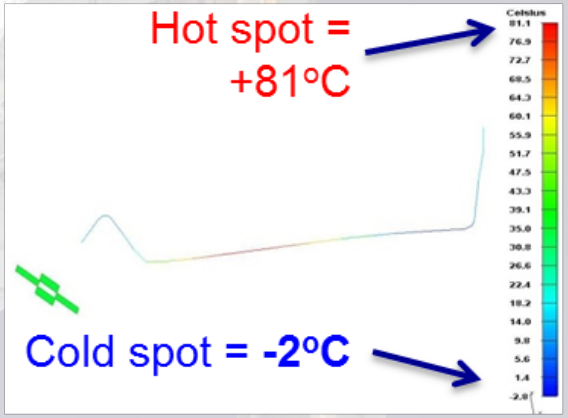


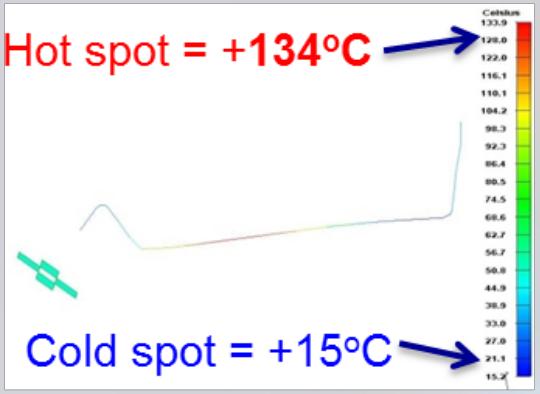


Freezing (left) and overheating (right) concerns due to variations in MLI e*

Effect Of Variation of MLI e* Even with Realistic Analyses







Reference Case:
Nominal e* values from MSL test/flight data

Case 1:
- High e* values at cold spots
- Allow min AFT violations
- No change in heater duty cycles

Case 2:
- High e* values at cold spots
- Increase heater duty cycles to ensure that all locations > 15C

Example of computer model simulation of MSL lines with realistic configuration & environments including any conduction along lines

Typical Analytical means to accommodate effect of MLI e* Variation to Predict their Temperatures

- MLI e* variation essentially due to workmanship differences – so is a range of possible values
- Thermal model use worst case combinations of e* value to assess range of possible temperatures
- Temp. control points tuned with emphasis on ensuring that no locations go below freezing point and even allow resultant hot spots to exceed max allowable limits

Development Tests

- Since MLI e* is essentially workmanship related and random, the development tests are not very useful to pin down the exact values
- At best they serve to provide a range of possible values
- Also the workmanship is very related to the exact configuration, and is very hard to mimic flight configuration in these tests

Solar Thermal Vacuum Testing & Impact on Mission Operations

- Solar Thermal Vacuum (STV) tests are the 1st instance of actually measuring the temps. of flight article lines
  - Predictions have large error bars
- Adequate number of temp sensors provide a map of temperature distributions along the lines
- This then anchors thermal models to allow for tuning of flight set points as well as tools for adjusting them during flight
- Since are some inevitable differences between flight operating conditions and environments, mission operations requires constant vigilance to ensure temps are within allowable limits

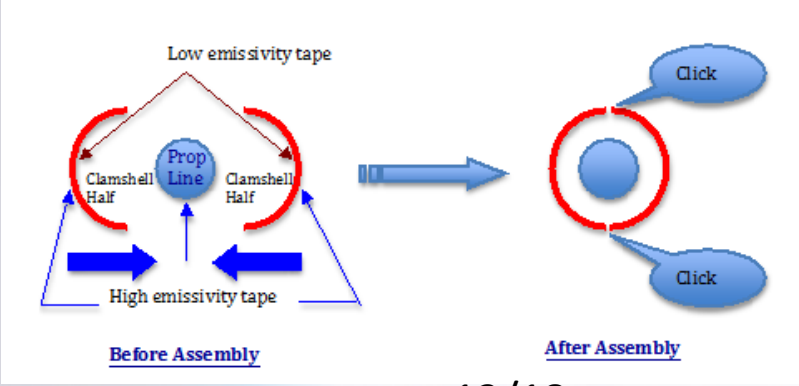
Potential Solution Approaches (I)

- **Black Tape on Prop Lines (instead of MLI blankets)**
  - Black tape emissivity is very deterministic & would lead to very predictable temps.
  - But emissivity is so high that it would lead to prohibitively high power use (10 – 20 X larger than MLI)

- **Low emissivity tape (instead of MLI)**
  - Very prone to large localized and unpredictable emissivity change due contamination during installation and handling

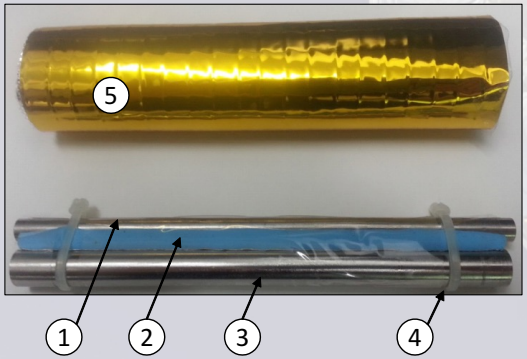
Potential Solution Approaches (II)

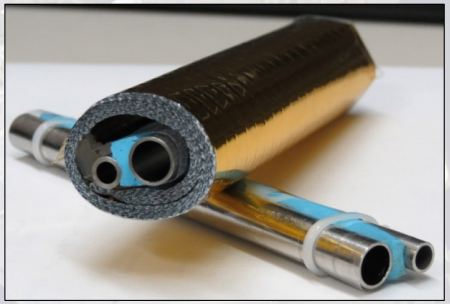
- **Clamshell around Prop Lines**
  - Internal surface of clamshell have low emissivity coating
  - Not subject to handling contamination (protected until all hardware installed on prop lines)
  - Not subject to outgassing contamination (internal surface)
  - Low emissivity ensure low heater power requirement
  - Details of local thermal shorting at clamshell supports and implementation need to be thought through

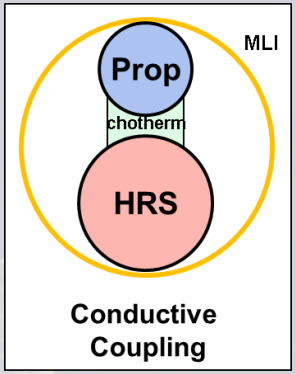


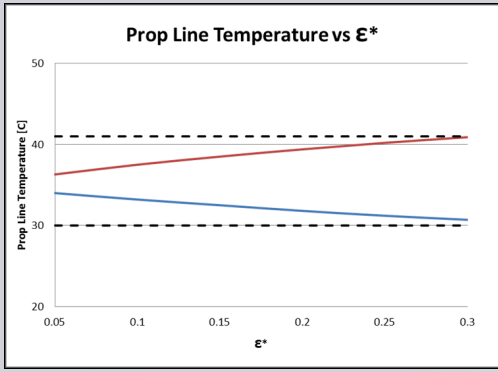
Potential Solution Approaches (III)

- **Thermally Couple Fluid Loop to Prop Lines**







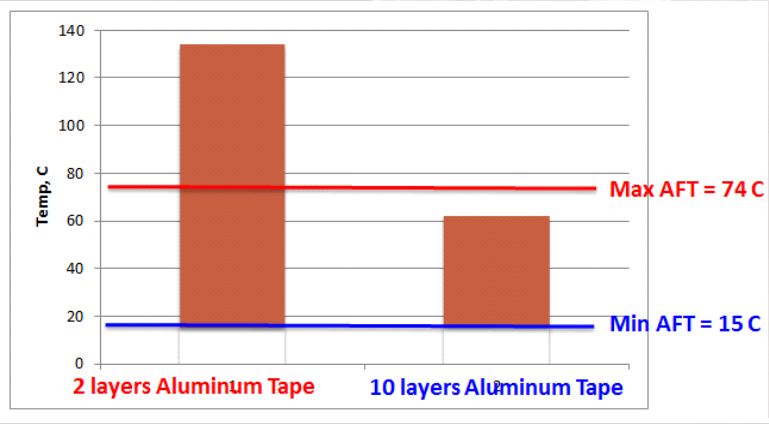


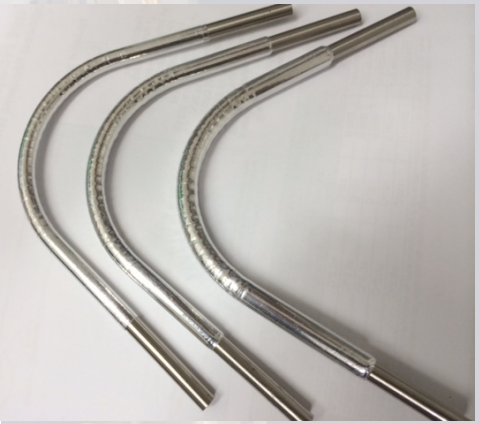
Fluid Loop to Propulsion Line Thermal Coupling Concept. 1) ¼" Propulsion Line, 2) Thermal Interface (CHO-THERM®), 3) 3/8" HRS Line, 4) "Straps," and 5) MLI.

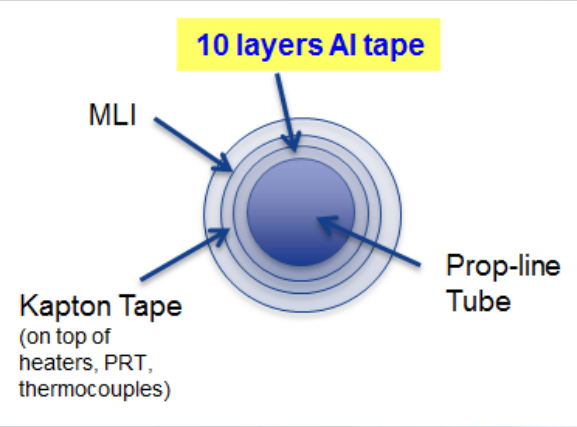
- **Fluid Loop for thermal control of s/c provides a nearly isothermal and constant temperature boundary**
- **Thermally coupling prop lines to loop would slave them to a stable, robust and highly predictable temperature boundary**
- **If fluid loop is also harvesting waste heat from electronics, it could also eliminate needed heater power**
- **Chotherm or similar interface filler or local thermal straps (spaced periodically) could achieve coupling**

Potential Solution Approaches (IV)

- **Heat Spreader Tape on Prop Lines**







- **Lack of heat spreading in bare Titanium prop line leads to large temp variations along length**
  - **Which cannot overcome the effect of workmanship based variation in MLI e***
- **Aluminum (or Copper) foil tape glued on prop lines would significantly increase heat spreading and nearly eliminate large gradients**
- **Reduction in propulsion line temperature gradients**
  - With ten layers Aluminum Tape (left)
  - Sample tubing covered with increasing numbers of tape layers (center)
  - Complete thermal hardware stack-up (right)

Applicability & Limitations of Various Approaches

Category	Thermal Mitigation Scheme				
	Black Tape on lines	Low emissivity Tape on lines	Clamshell around lines	Fluid Loop connected to lines	High conductivity Tape on Lines
Relative robustness	Very robust	Not robust due to contamination sensitivity	Robust	Extremely robust	Robust
Thermal control power required	Extremely large, probably not affordable for most missions, 10x to 20x larger than typical	Smaller than typical MLI designs	Small, comparable to typical MLI designs	Small, comparable to typical MLI designs; if fluid loop pre-exists then could be zero if waste heat is harvested from other thermally controlled	Same as for typical MLI designs
Sensitivity to contamination	Not sensitive	Very sensitive	Not sensitive	Very insensitive	Not sensitive
Mass	Small	Small	Small	Small: for mass of extra fluid lines (if fluid loop pre-exists) Medium: for fluid loop if it does not pre-exist	Small
Impact on rest of the spacecraft system	Neglible, except for thermal power	Negligible	Small, comparable to typical MLI designs	Medium: due to analysis required to confirm integrity of mechanically coupling propulsion lines with fluid loop	Negligible
Thermal modeling complexity	Small	Significant due to lack of robustness (contamination	Small	Much simpler due to extreme robustness	Small
Ease of implementation	Relatively easy	Relatively easy	Harder than typical MLI designs, but still realtively easy	Harder than other concepts	Very labor intensive due to several (10) layers that need to be individually installeed on every
Mission operations	Simpler due to thermal robustness	Very complex due to lack of thermal robustness	Simpler due to thermal robustness	Much simpler due to thermal robustness	Similar but simpler than typical MLI designs
Cost	Relatively small impact	Relatively small impact	Relatively small impact	Medium: due to implementation reasons	Relatively small impact
Schedule	Small impact	Small impact	Small impact	Medium: due to implementation reasons	intensive nature of tape installation

Conclusions

- Current designs of propulsion lines for space missions are not robust and lead to highly unpredictable temperatures of these lines
- Large variation in workmanship related e* of MLI blankets used to insulate lines along with poor lateral conduction along the lines are the primary culprits
- Alternative designs exist in concept and practice that can be employed for future space missions to overcome these concerns

Acknowledgements

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