# Overview of the Mars Science Laboratory Entry, Descent, and Landing Instrumentation (MEDLI) Project with an Emphasis on Thermal Analysis and Testing


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**Thermal and Fluids Analysis Workshop (TFAWS)**
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# Outline

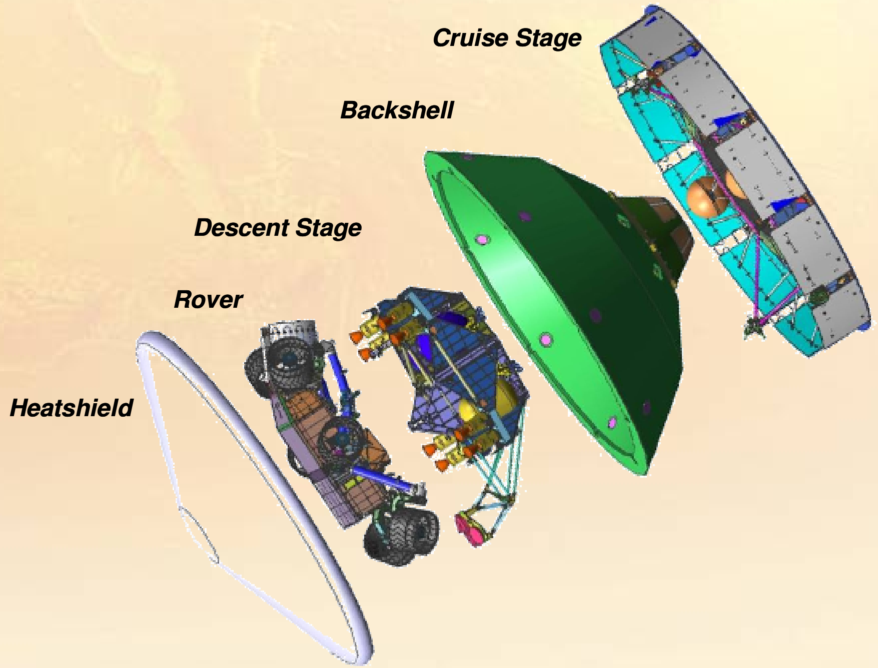
- Overview of MEDLI
- Summary of MEADS Developmental Arc-Jet Testing to Date
- Thermal Analysis, MEADS and SSE
  - Summary of MEADS Thermal Analysis
  - SSE Thermal Analysis
    - Pre-Launch Case
    - Cold Cruise Case
    - Hot Operating Case (Entry)
    - Current Challenges
- Open Issues and Future Work

# What is MEDLI and Why is it Important?

- Instrumentation suite to be installed on the heatshield of the Mars Science Laboratory (MSL) entry vehicle, scheduled to launch in 2009
  - To measure aerothermal environments, sub-surface heatshield material response, vehicle orientation, and atmospheric density
  - Current aeroheating uncertainties are greater than 50% on the MSL heatshield, primarily due to a lack of relevant flight data
- Main objective is to obtain valuable atmospheric entry measurements that will benefit future Mars missions
  - Validation of aerothermal, aerodynamic, atmospheric, and TPS response models
  - Help to quantify design uncertainties and identify driving risks for future missions
- The MEDLI suite consists of three main subsystems
  - MEDLI Integrated Sensor Plug (MISP)
  - Mars Entry Atmospheric Data System (MEADS)
  - Sensor Support Electronics (SSE)

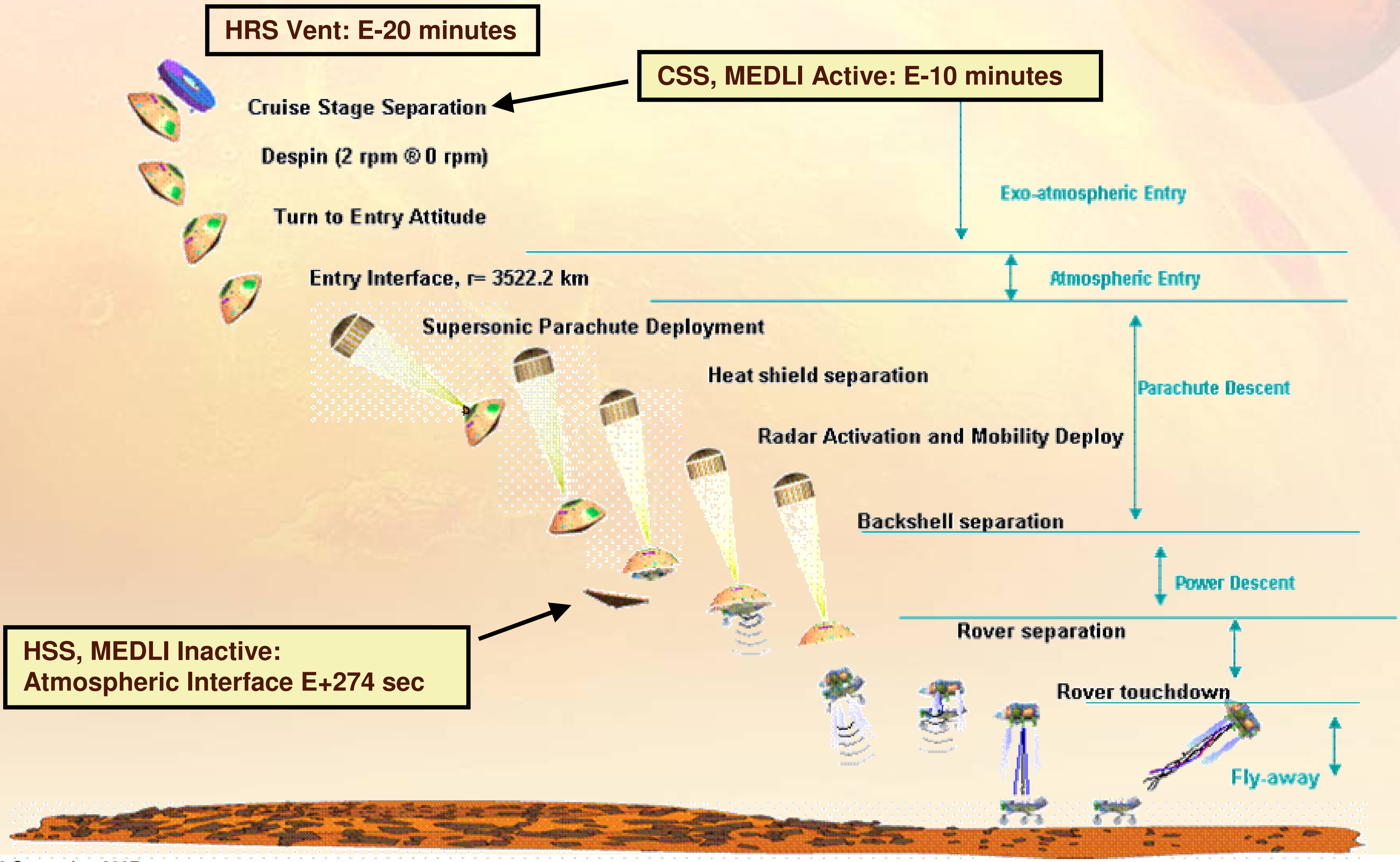
# Overview of the MSL Entry Vehicle

- The MSL EDL system is a new architecture based on Viking heritage technologies, but designed to meet the challenges of landing a greater entry mass than any previous Mars entry vehicle to within 10km of the desired landing site
- MSL will fly the largest aeroshell, generate the highest hypersonic lift-to-drag ratio, and deploy the largest Disk-Gap-Band supersonic parachute of any previous Mars mission



# MSL Entry, Descent, and Landing (EDL) Timeline

- **Transient analysis begins at Cruise Stage Separation (CSS) & ends at Heat Shield Separation (HSS)**



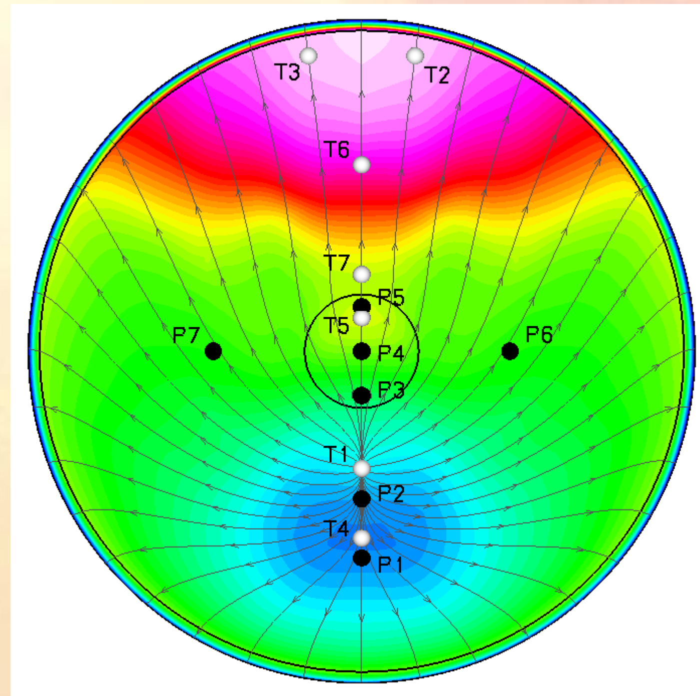
# MEDLI Science Objectives

## Aerothermal / TPS

– Verify transition to turbulence
– Determine turbulent heating levels
– Determine recession rates and subsurface material response of ablative heatshield at Mars conditions

| Technical Objectives | Location | | | | | | |
|---|---|---|---|---|---|---|---|
| | T1 | T2 | T3 | T4 | T5 | T6 | T7 |
| Basic Aeroheating | x | x | x | x | x | x | x |
| Stagnation Point Heating | x | | | x | | | |
| Turbulent Leeside Heating | | x | x | | x | x | x |
| TPS Recession Rate | | x | x | | x | x | x |
| Windside Heating Augmention | x | | | x | | | |
| TPS Total Recession | | x | x | | x | x | x |
| Subsurface Material Resp. | x | x | x | x | x | x | x |
| Turbulent Transition | | x | x | | | x | x |

**7 Integrated Sensor Plugs (T#)**
**7 Pressure Ports (P#)**




## Aerodynamics / Atmosphere

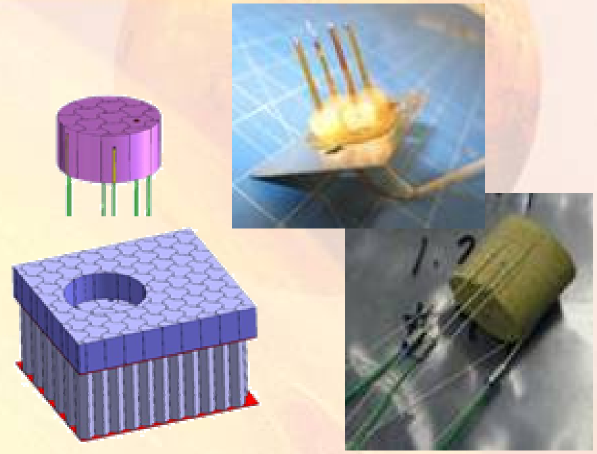
– Separate aero from atmosphere
– Determine density profile (vertical and gravity waves) over large horizontal distance
– Isolate wind component
– Confirm aero at high angles of attack

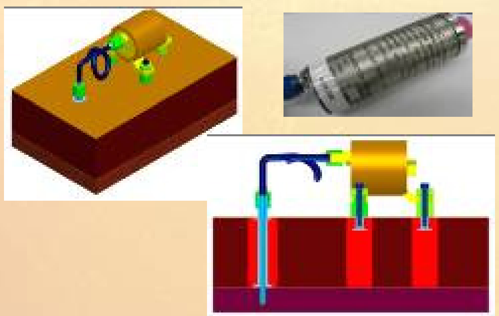
| Technical Objectives | Location | | | | | | |
|---|---|---|---|---|---|---|---|
| | P1 | P2 | P3 | P4 | P5 | P6 | P7 |
| Basic Pressure Dist. | x | x | x | x | x | x | x |
| Angle of Attack | x | x | x | x | x | | |
| Angle of Sideslip | | | | x | | x | x |
| Dynamic Pressure | x | x | | | | | |
| Mach Number | x | x | | | | | |

# MEDLI Subsystems

**MEDLI Integrated Sensor Plug (MISP)**

- Instrumented plug made from heatshield TPS material
- Includes four embedded thermocouples and one Hollow aErothermal Ablation and Temperature (HEAT) recession sensor



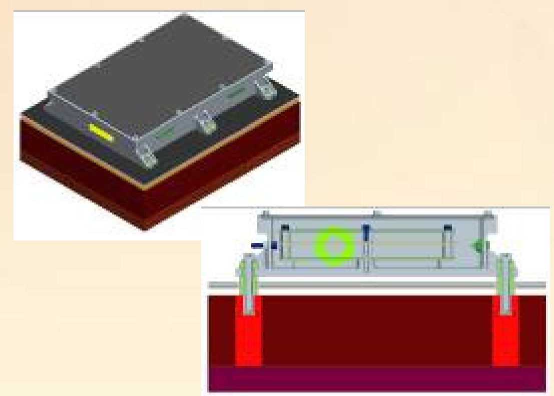


**Mars Entry Atmospheric Data System (MEADS)**

- Series of through-holes, or ports, that connect via tubing to pressure transducers mounted on the heatshield interior

**Sensor Support Electronics (SSE)**

- Electronics that condition sensor signals, provide power to MISP and MEADS, and interface to the MSL data acquisition system



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# MEADS Developmental Arc-Jet Testing: Overview

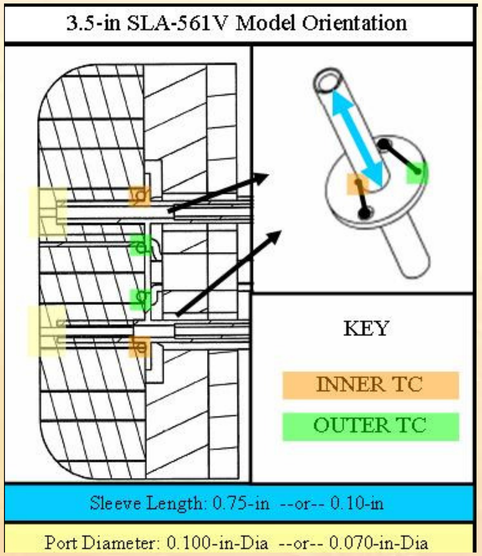
- Objectives
  - Determine an acceptable pressure port diameter for through-hole in SLA-561V TPS material
  - Demonstrate pressure measurement capability
  - Quantify possible effects of through-hole on bondline temperature
  - Quantify possible effects of pyrolysis gases on pressure readings
    - Determine whether or not a sleeve to line the through-hole in the TPS is necessary (and validate sleeve material, if necessary)
- Two 2-week test entries were completed at Boeing's Large Core Arc Tunnel (LCAT) facility in St. Louis, MO
  - Phases I & II combined: 22 runs, 38 models tested
  - Huels-type arc heater facility, 4-inch exit diameter nozzle
  - Flow-field probes verified test conditions (heat flux and stagnation pressure)

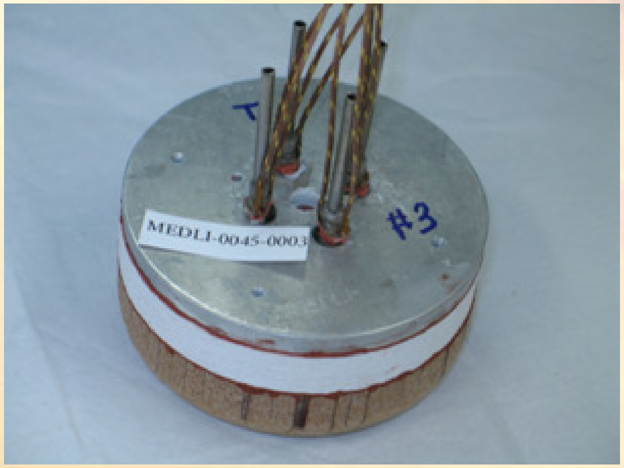
**Overall View**

**Test Chamber**

# MEADS Developmental Arc-Jet Testing: Model Design and Test Conditions

- Models were designed and built in a collaborative effort between NASA LaRC and NASA Ames

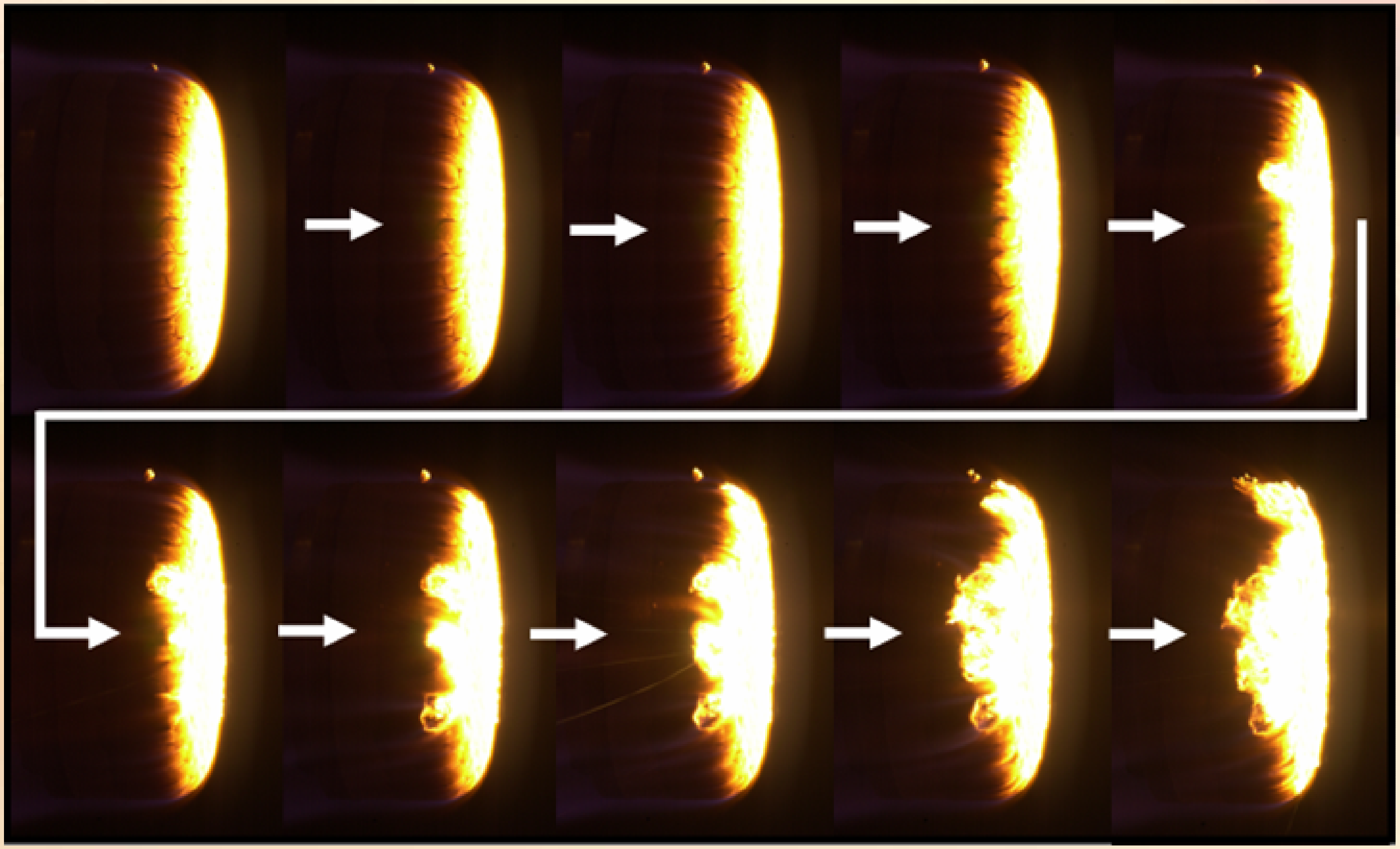



- Test conditions were designed to encompass all potential environments to which MEADS will be exposed, including margin

| Summary of Target Test Conditions | |
|---|---|
| Hot Wall Heat Flux (W/cm$^2$) | Stagnation Pressure (atm) |
| 60 | 0.15 |
| 60 | 0.25 |
| 100 | 0.15 |
| 100 | 0.25 |
| 115 | 0.15 |
| 115 | 0.25 |
| 130 | 0.2 |
| 140 | 0.15 |

# MEADS Developmental Arc-Jet Testing: In-Test Photo Sequence

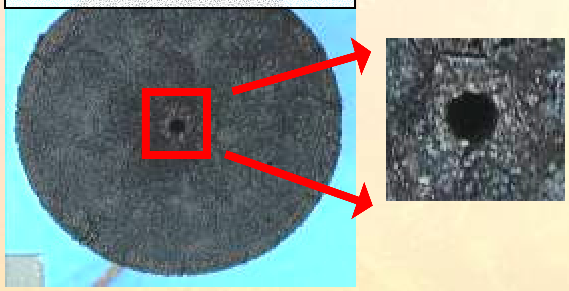


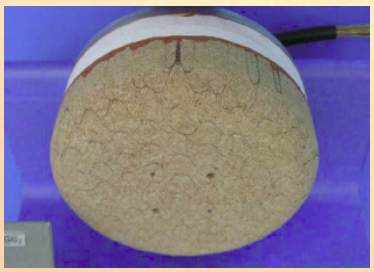
**Images shown are representative, and are not intended to reflect results of a particular test run**

# MEADS Developmental Arc-Jet Testing: Model Evaluation

## Visual Inspection

Note: Phase 1 model



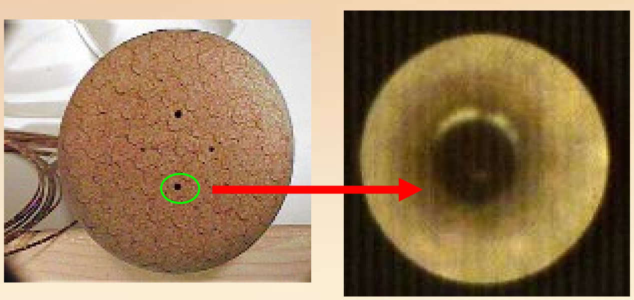


Pre-test

Post-test

## Boroscopy

Note: Still images shown at ~ 8mm depth



Pre-test

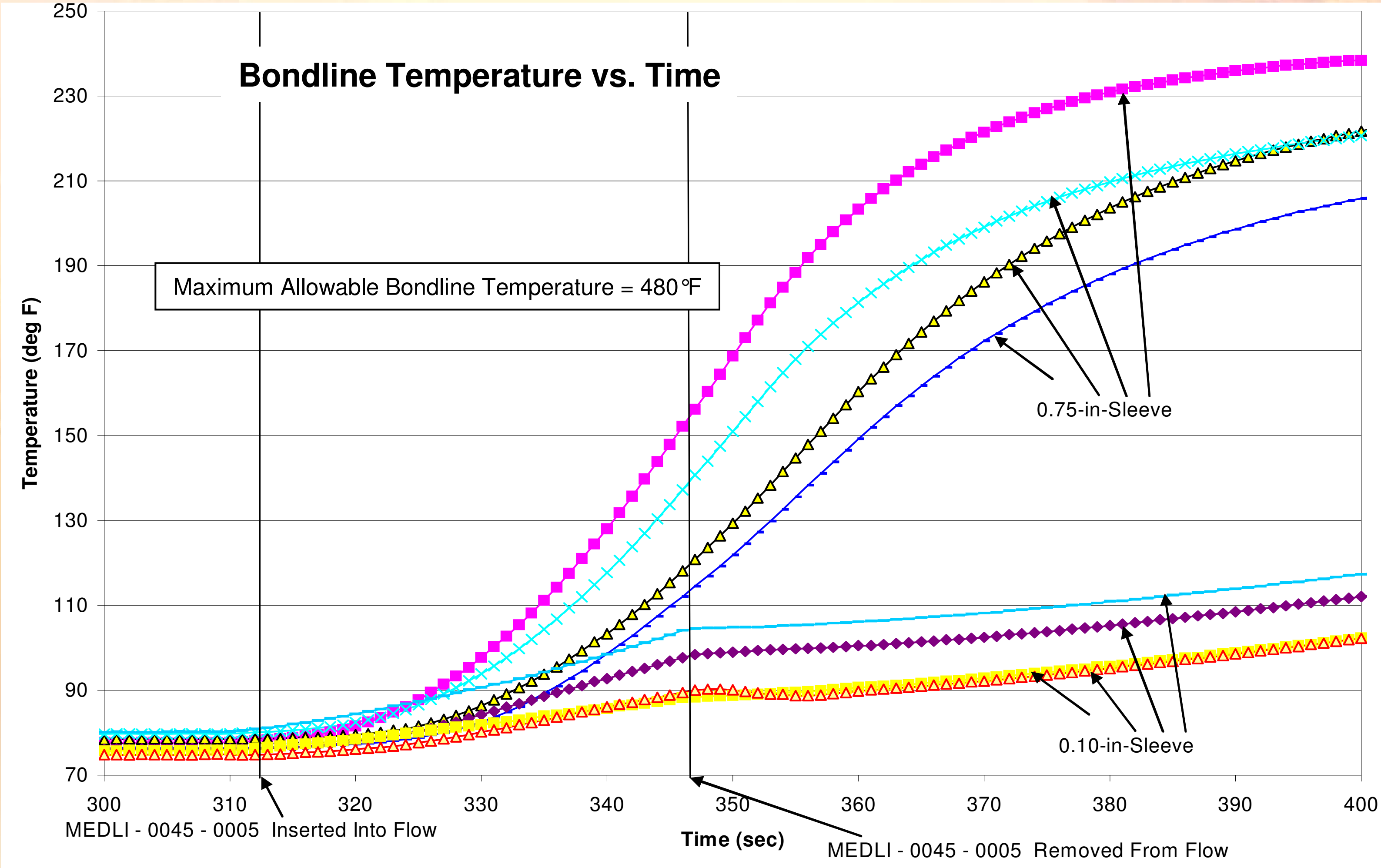
Post-test

## Sectioning

Note: Measurements of centerline recession, char depth, pyrolysis depth, and final curvature were taken from sectioned samples

Images shown are representative, and are not intended to reflect results of a particular test run

# MEADS Developmental Arc-Jet Testing: Test Data



# MEADS Developmental Arc-Jet Testing: Conclusions

- All primary objectives were met
  - No discernable degradation of port shape at SLA interface for each diameter
  - Demonstrated ability to measure pressure in SLA-561V
  - The amount of surface recession observed was minimal and will not invalidate pressure measurements
  - The bondline temperature for any model never exceeded the maximum allowable temperature
  - Presence and/or difference in length of the sleeve lining the ports did not contribute to the integrity of the pressure measurements made in-test
    - Pyrolysis did not show a measurable effect on the measurements at tested conditions

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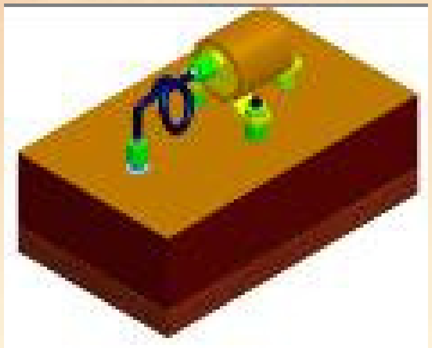
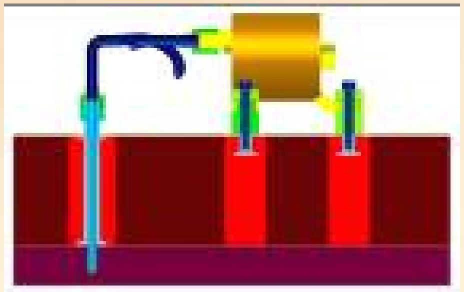
# MEDLI Thermal Analysis: Overview

- Initial concern: Can MEDLI survive the cruise phase of the mission without the use of survival heaters?
  - Several MEADS transducers are located in the colder regions of the aeroshell; these regions will get much too cold for the electronics to survive
    - This prompted a design change: All signal conditioning electronics move to the SSE; only non-temperature sensitive components are left in the transducer heads
    - Thermal analysis focus shifted to the SSE
  - When placed at the nominal location, the SSE reached steady-state temperatures that were too cold to allow electronics survival
    - No heater power is available due to MSL power budget constraints; SSE relocated and coated in black anodize to take advantage of radiative heating from the Radioisotope Thermoelectric Generator (RTG)
  - In new location, there was a concern that the SSE may exceed maximum allowable temperatures either on the launch pad or during EDL
- Design changes that affected thermal analysis (other than those imposed by it)
  - SSE-to-aeroshell interface mounting scheme (still TBD due to structural concerns)
  - Cable harnessing
- One of the largest uncertainties/biggest changes throughout was the constant updating of thermal boundary conditions as MSL completed various phases of their work

# MEADS Thermal Analysis: Overview

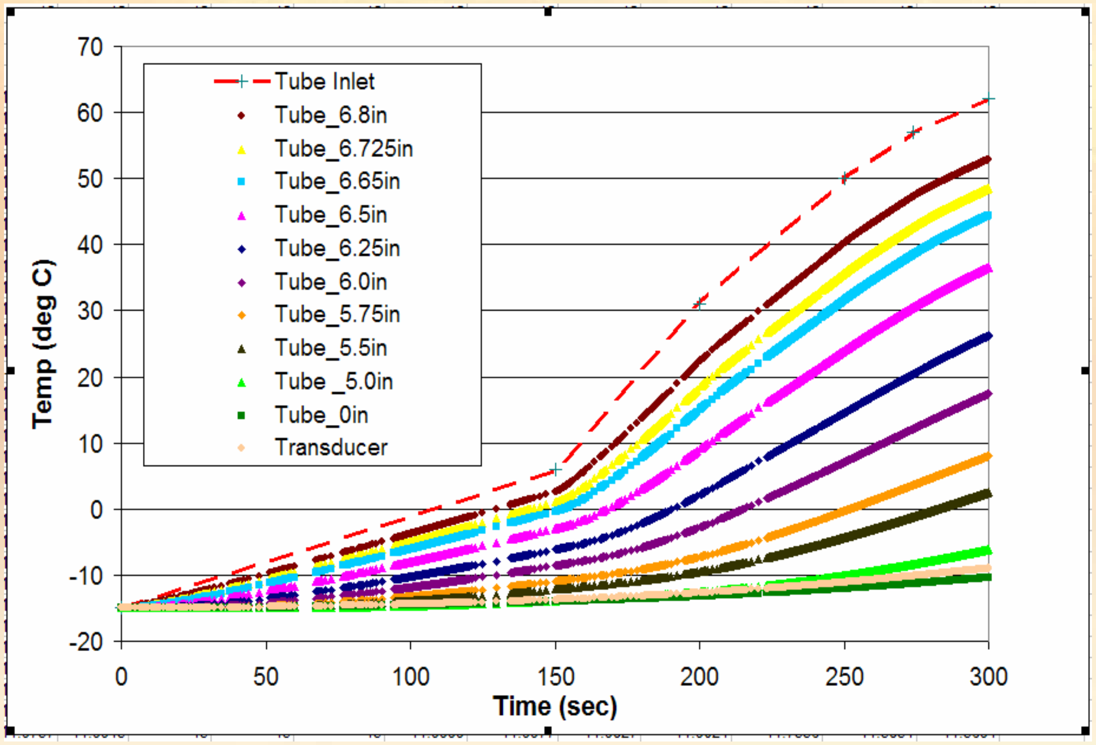
- Manufacturer specified temperature range is -300℃ to 200℃
  - Transducer heads assumed to reach steady-state heatshield temperature during cruise; coldest prediction is -120℃ including margin
- Preliminary analyses have been completed; detailed analyses are not required at this time
  - Before completion of arc-jet testing, there was a concern that tube inserted into TPS may adversely affect MSL bondline temperature
  - Analysis to predict the temperature profile through the tube during EDL as well as the temperature change of the transducer heads for calibration purposes completed for one MEADS location
- Boundary Conditions
  - Conductive heating from heatshield through G10 standoffs, stainless steel A-286 bolts, stainless steel 304 pressure tube, and electrical wires
  - Radiative heating from estimated ambient node (estimated high emissivity for conservatism)
  - Assumes good thermal contact at fastened locations

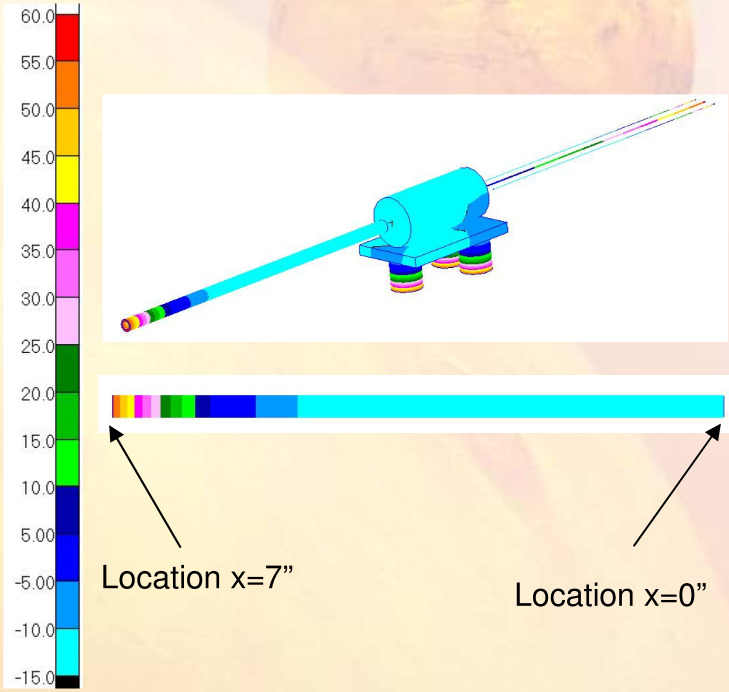




# MEADS Thermal Analysis: Results Summary

- Approximate worst-case hot location (P4)
- Tube inlet temperature profile provided by Roger Giellis (LM)
  - Heat flux profile scaled for nose location (peak=130W/cm$^2$)
- Initial transducer temp based on predicted steady-state worst case hot temperature of the heatshield at the P4 location

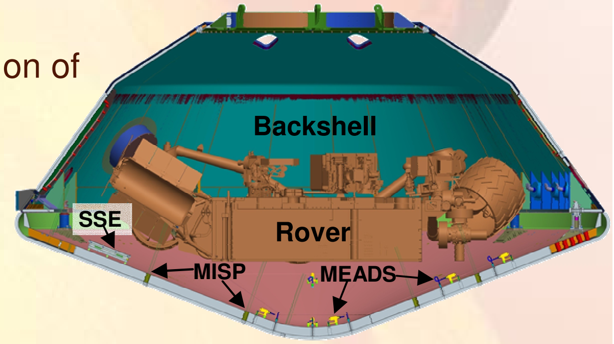



- Transducer temperature rise of ~5℃
  - Max temp of ~-10℃ for these conditions
  - Max temperature change through pressure tube of ~70℃

# SSE Thermal Analysis: General Modeling & Assumptions

- **The purpose of this analysis is not to predict exact temperatures the system will reach; rather it is to determine the bounds of the system (i.e., temperatures it will not fall below or exceed)**
- Rover not included in model due to significant distance from SSE
  - Sensitivity studies performed with the cruise model showed that the inclusion of the Rover in the model made no significant difference in the results




- Operational Limits (specified by manufacturer): -55℃ to 125℃
- Cabling
  - All cabling is tied down every 6” along the heatshield under MLI blanket
- Emissivities
  - External Single-Layer Insulation (SLI), ε =0.10-0.02 (varies for worst-case hot vs. worst-case cold)
  - Internal Multi-Layer Insulation (MLI), ε * = 0.02-0.05 (varies for worst-case hot vs. worst-case cold)
  - SSE ε = 0.8-0.95 (anodized aluminum finish, varies for worst-case hot vs. worst-case cold)
  - MMRTG ε = 0.85, Internal MLI top surface ε = 0.7 (IOM-3547/T&SE 001-2006, 2/15/07)
- Temperature dependant material properties were used (except for thermocouple materials)

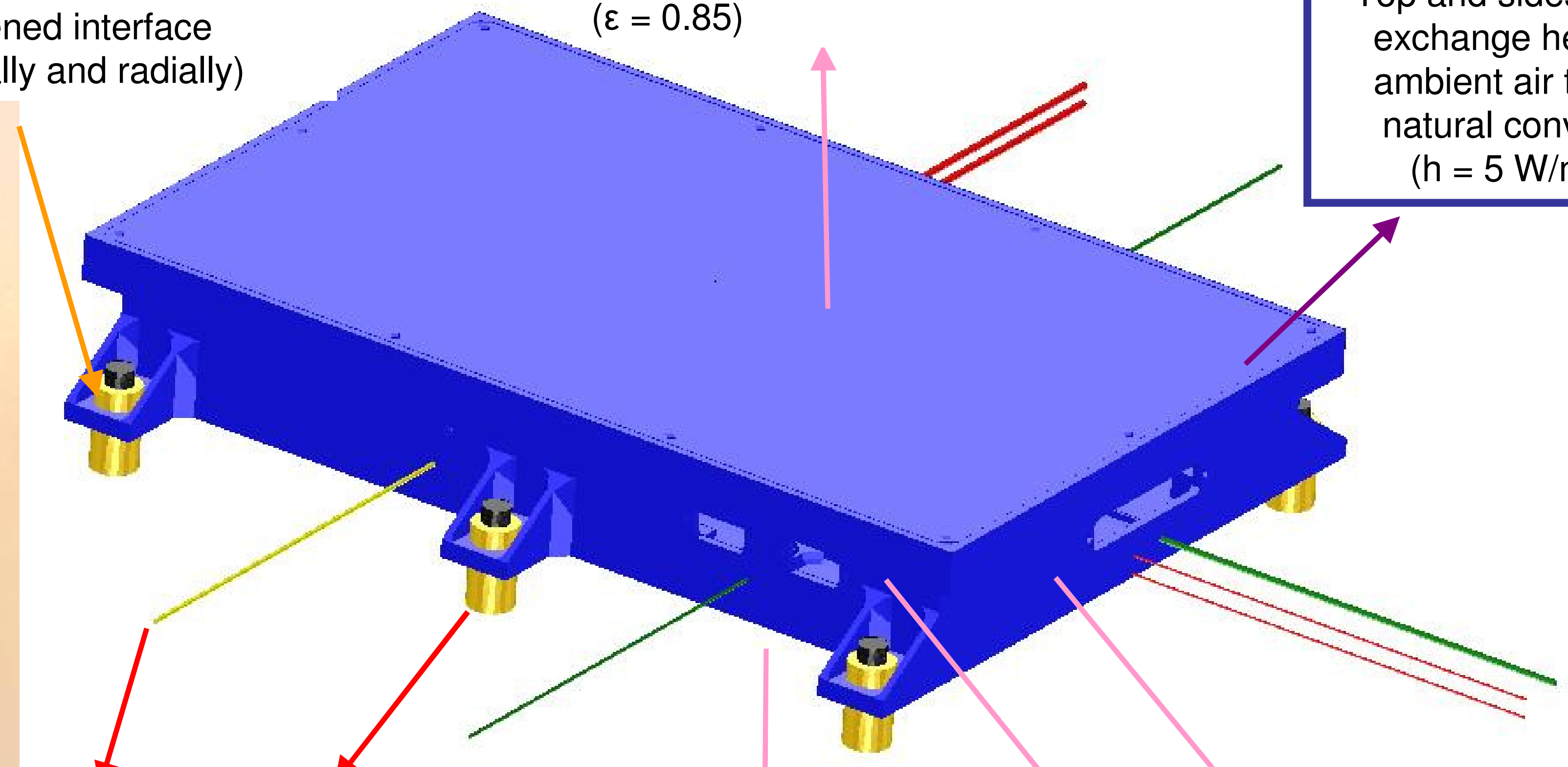
| Component | Material | Source |
|---|---|---|
| SSE case | Al 6061-T6 | Windchill Database |
| Screws | SS A286 | Knovel, Mil Handbook 5H |
| Electronics Fasteners | SS HS 188 | Knovel, Mil Handbook 5H |
| Standoffs & Washers | G10 | NIST |
| TSPs | Copper | Patran Library |
| Thermocouples | Chromel | Matweb |
| | Alumel | Matweb |

# SSE Thermal Analysis: Thermal Model in MSC/Patran

Contact resistance at fastened interface (axially and radially)

Top surface radiates to ambient temperature and MMRTG surface (ε = 0.85)

*Pre-Launch Only:*
Top and sides of SSE exchange heat with ambient air through natural convection ($h = 5\ W/m^2\text{-}K$)



Bolts, standoffs, TSPs, TCs, and grounding strap conduct to heatshield

Bottom surface radiates to MLI temperature (ε = 0.7)

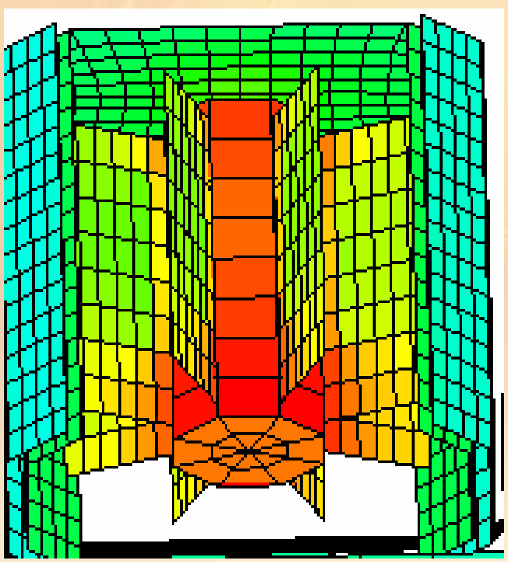
Side surfaces radiate to ambient temperature and MLI temperature (ε = 0.7)

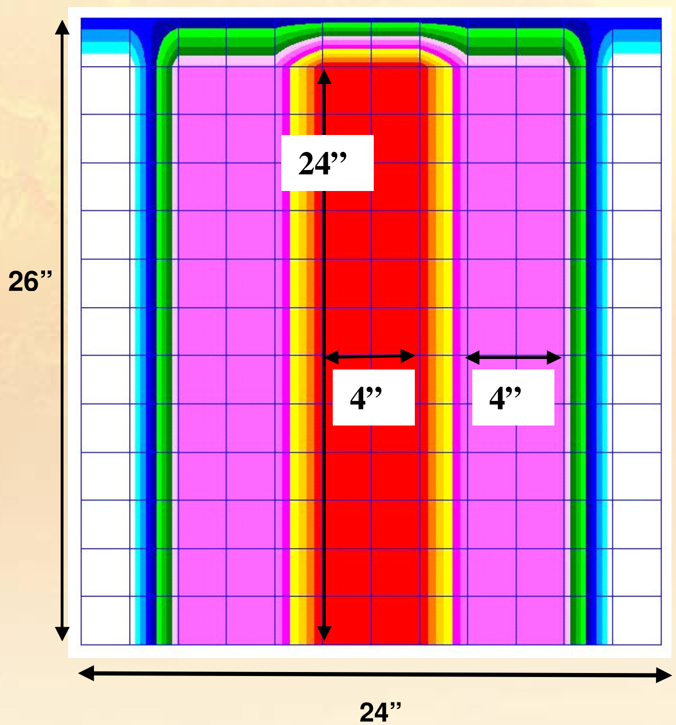
# SSE Thermal Analysis: Thermal Model in MSC/Patran, MMRTG

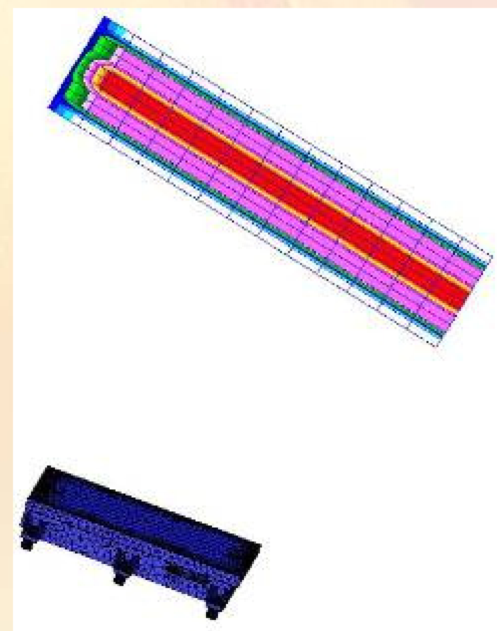
- MMRTG is modeled as a simple surface for the purpose of a radiation view-factor analysis
- JPL provided temperature profiles and physical dimensions

Actual Dimensions:

Cylinder Height = 24”
Cylinder Diameter = 12”
Fin Length = 6”



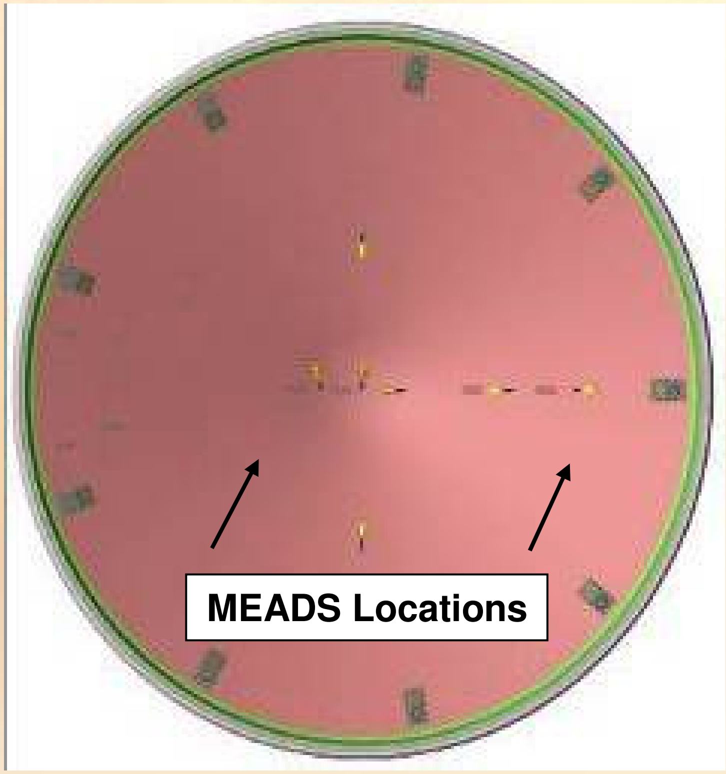


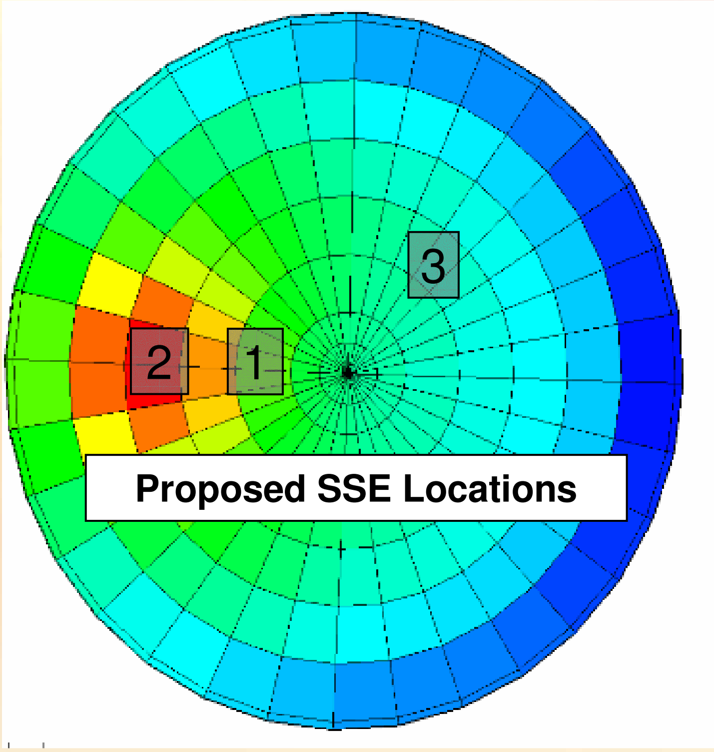



# SSE Thermal Analysis: Initial Trade on Location

- After accounting for model uncertainty and adding margin, the only acceptable SSE location was found to be underneath the RTG

*Note:* Scale not shown; temperature magnitudes do not reflect current MSL predictions



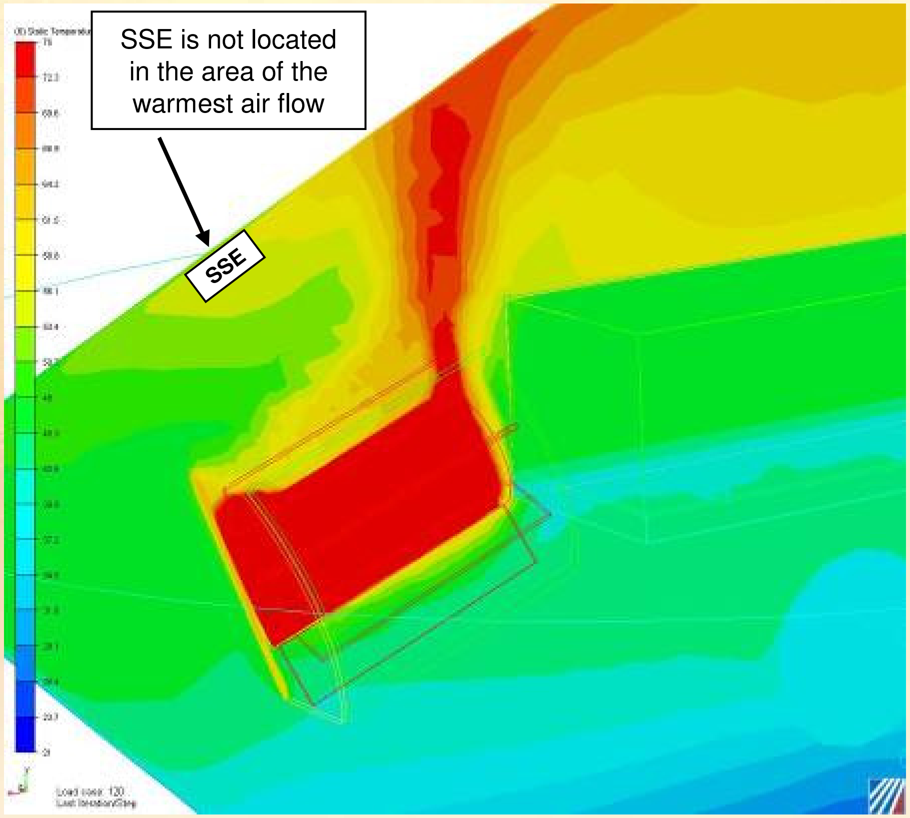

| Minimum SSE Temperature w/o Survival Heater (°C) | | |
|---|---|---|
| Location 1 | Location 2 | Location 3 |
| Initial Baseline | Current Baseline | Away from RTG |
| -50 | -25 | -63 |

# SSE Thermal Analysis: Temperature Boundary Condition Sources

- JPL CFD analysis provided predictions for ambient environment in the vicinity of the SSE while on the launch pad
- JPL System Level Thermal Model (Tony Paris & Frank Kelly)
  - Provided temperature maps for MMRTG, internal MLI blanket, and SSE surroundings
  - Results generated were intended for use as inputs for LM's detailed aeroshell model, and were biased to be the worst-cold and worst-hot case for the aeroshell
- LM Aeroshell Thermal Model (Roger Giellis & Mike Connelly)
  - Provided temperature predictions for the heatshield (at SSE insert) based on inputs from JPL's system level thermal model

# SSE Thermal Analysis: Environments, Pre-Launch

- JPL's CFD analysis provided predictions of the temperature of the convecting air in the vicinity of the SSE
- *Given current baseline design and no failures*, recommended model uncertainty is 20°C worst-case




**Predictions provided by Pradeep Bhandari, JPL**

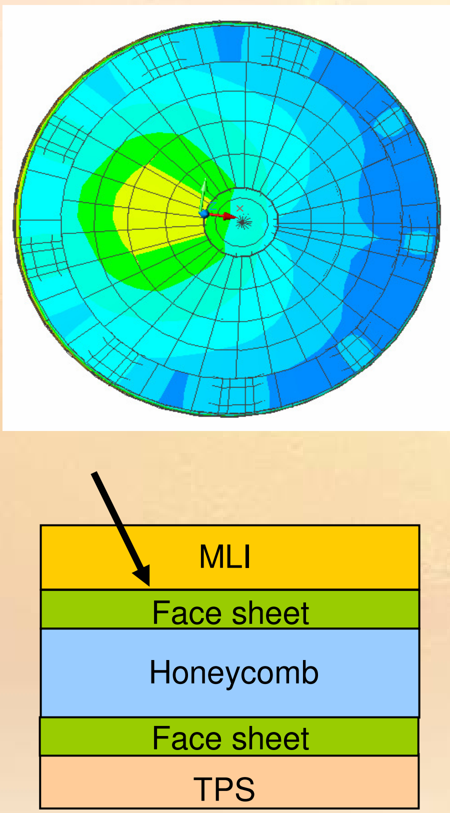
# SSE Thermal Analysis: Summary of Pre-Launch Case

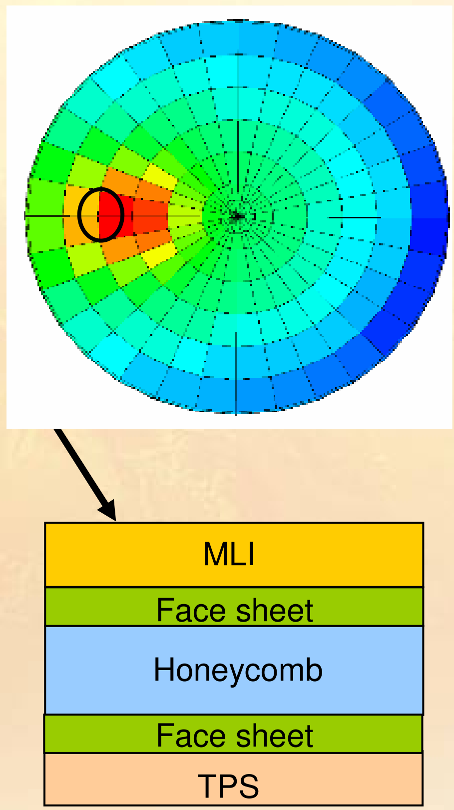
- Steady-state analysis to show that the SSE will not exceed its maximum allowable temperature if left on the launch pad for an extended period of time
- Does not include internal SSE components (non-operational)
- Inputs to SSE model include JPL recommended uncertainty
- Entire MMRTG is assumed to be at the fin root temperature
- Heatshield temperature is assumed to be equal to that of the circulating air
- Heat transfer coefficient assumed is on the low end of the range of accepted natural convection coefficients (h = 5 W/m2-K)
- SSE ε = 0.95 in order to maximize heating from RTG
- Radial contact resistance at bolted interface is infinite (energy is only transferred vertically through bolt/washer/standoff stack-up), to minimize amount of energy loss from the SSE to the heatshield


| JPL Predictions (°C) Including +20°C for Uncertainty | | | | | SSE Predictions (°C) | | | |
|---|---|---|---|---|---|---|---|---|
| Heat Shield | RTG | Ambient Radiation | Ambient Convection | MLI | MEDLI Model Predict | MEDLI Uncertainty | Allowable Flight Temp. | Qualification Temp. |
| 75 | 135 | 70 | 75 | 80 | 80 | 5 | 85 | 105 |

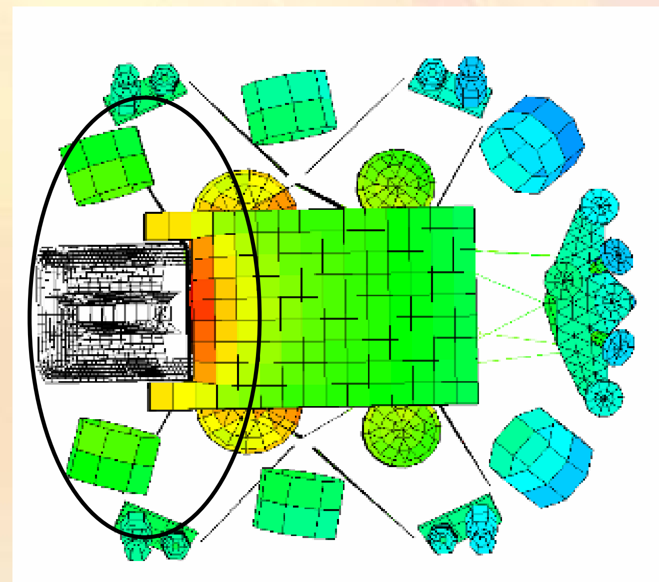
# SSE Thermal Analysis: Environments, Cruise Hot & Cold

- Images shown are representative of thermal environments provided by MSL for use as boundary conditions for the SSE thermal model




**Ambient node temperature for radiative energy exchange estimated based on predictions in the vicinity of the SSE**

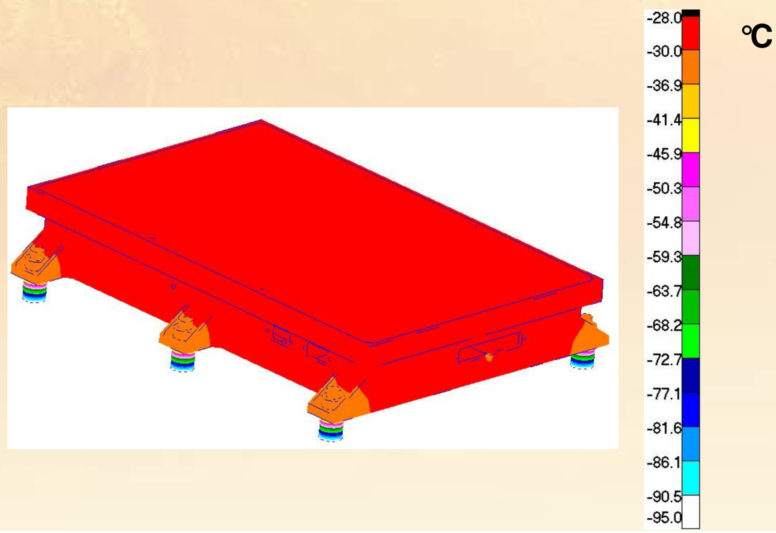


**Predictions provided by Roger Giellis & Mike Connelly (LMSSC), Tony Paris & Frank Kelly (JPL)**

# SSE Thermal Analysis: Summary of Cold Cruise Case

- Steady-state analysis to show that the SSE will not fall below its minimum allowable temperature during cruise, without the use of survival heaters
- Does not include internal SSE components (non-operational)
- Inputs to SSE model include JPL and LM recommended uncertainty
- SSE $\varepsilon$ = 0.8 in order to minimize heating from RTG
- Radial contact resistance at bolted interface is low to maximize amount of energy loss from the SSE to the heatshield

| JPL Predictions (°C) Including -10°C for Uncertainty | | | | | | | SSE Predictions (°C) | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Heat Shield | RTG (mapped) | | | | Ambient | | MEDLI | MEDLI | Allowable | Qualification |
| (LM) | Fin Root | Fins | Side Cover | Top Cover | Radiation | MLI | Model Predict | Uncertainty | Flight Temp. | Temp. |
| -95 | 90 | 45 | -25 | 5 | -30 | 0 | -30 | -5 | -35 | -50 |



# SSE Thermal Analysis: Summary of Entry Case

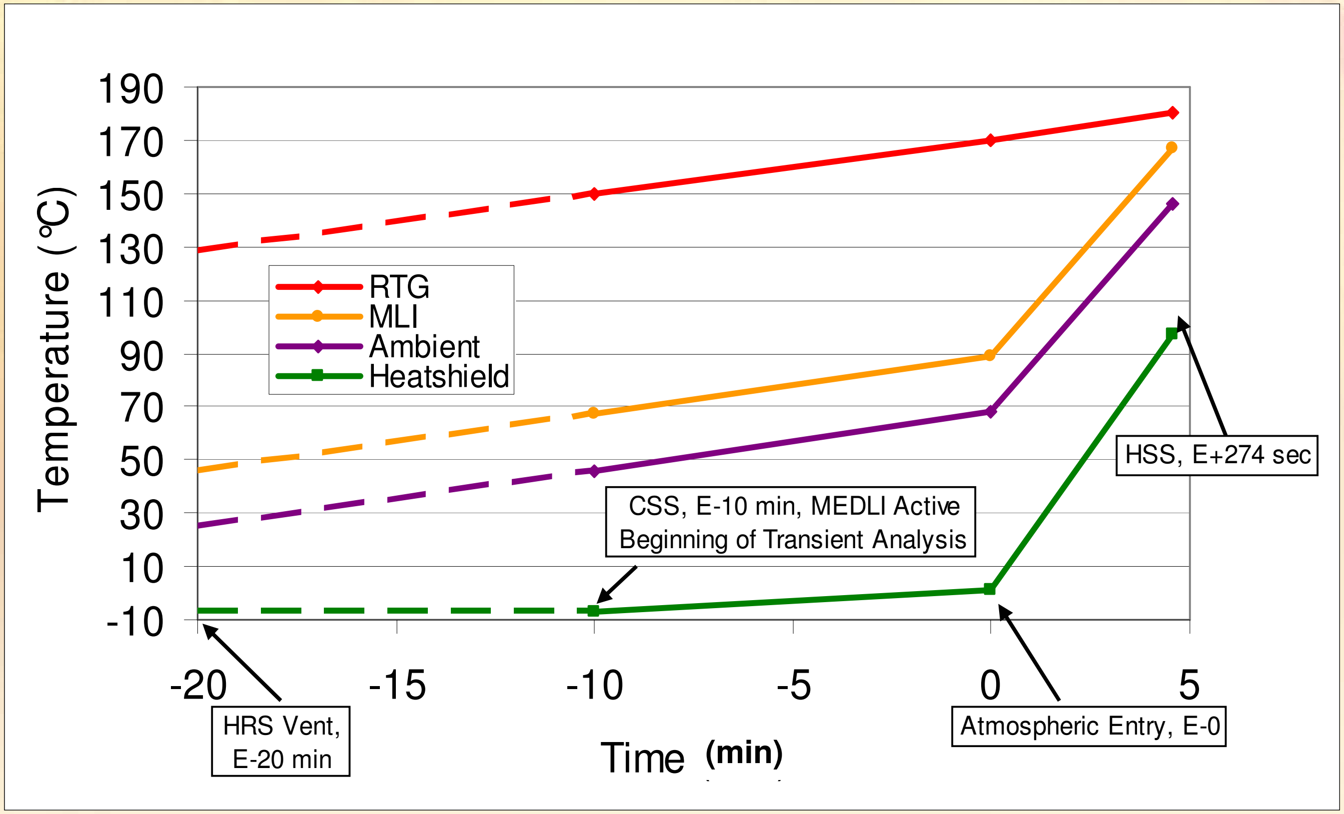
- EDL Analysis is comprised of two parts
  - **Mars Approach:** Steady-state analysis to determine the worst-case hot temperature of the SSE at the start of EDL
    - Used as a conservative start temperature for EDL analysis
    - Modeling approach the same as cruise cold case
  - **EDL:** Transient analysis to determine whether or not the SSE will exceed maximum allowable temperatures during EDL
    - Includes a representation of the internal SSE components (powered on during EDL)
    - Entire MMRTG is assumed to be at the fin root temperature
    - Radiative cooling inside the chassis is neglected
- Inputs to SSE model include JPL and LM recommended uncertainty
- SSE $\varepsilon = 0.95$ in order to maximize heating from RTG
- Radial contact resistance at bolted interfaces is infinite (energy is only transferred vertically through bolt/washer/standoff stack-up), to minimize amount of energy loss from the SSE to the heatshield

**Summary of Part 1: Mars Approach Hot Case, Steady-State**

| JPL Predictions (°C) Including -10°C for Uncertainty | | | | | | | SSE Prediction (°C) |
|---|---|---|---|---|---|---|---|
| Heat Shield | RTG (mapped) | | | | Ambient | | MEDLI |
| (LM) | Fin Root | Fins | Side Cover | Top Cover | Radiation | MLI | Model Predict |
| -7 | 138 | 90 | 35 | 55 | 25 | 46 | 39 |

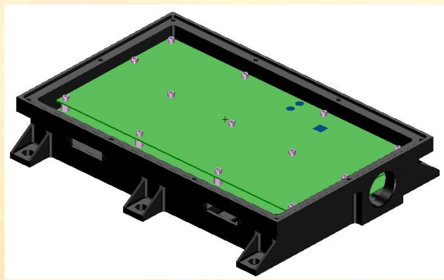
# SSE Thermal Analysis: Environments

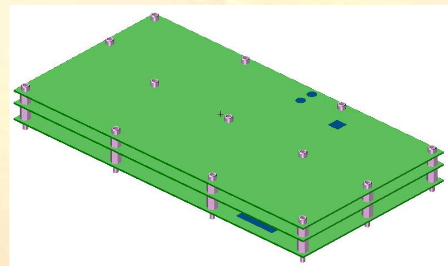
- MMRTG begins to heat up at HRS vent
- Heatshield temperature profile at SSE insert was provided by LM detailed aeroshell model
- Temperatures are conservatively assumed to increase linearly
  - MLI & Ambient assumed to increase by a total of 100℃ from worst-case hot initial temperatures before HRS vent

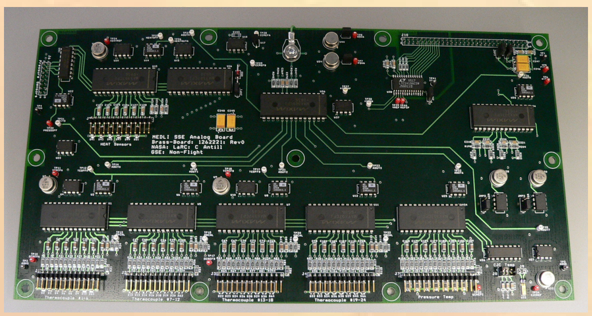


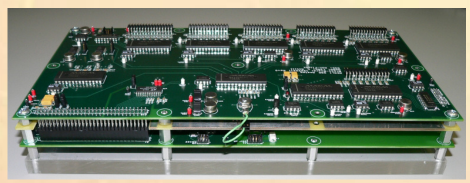
# SSE Thermal Analysis: Thermal Model in MSC/Patran, Electronics

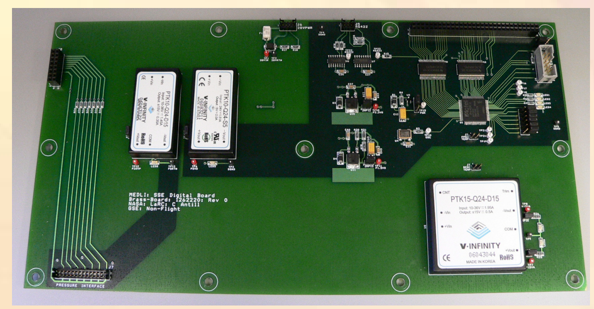
- Chassis, MMRTG, and surroundings are modeled the same as in steady-state cases
- Components that dissipate significant amounts of power were modeled at the board level
- Conduction through components and to boards was modeled as a resistive network

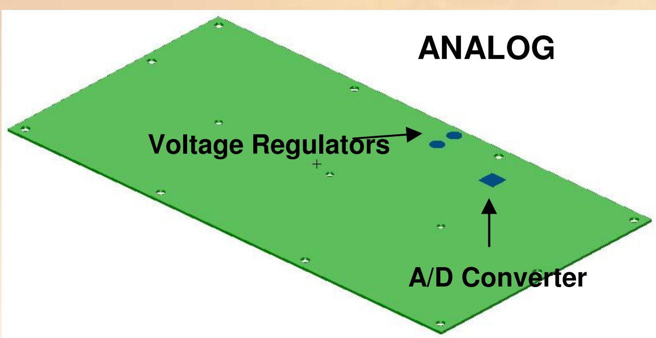




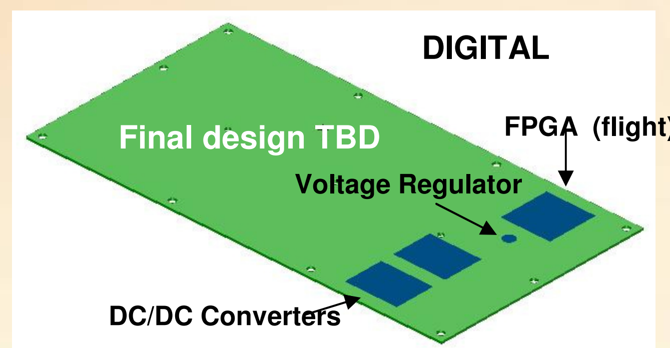






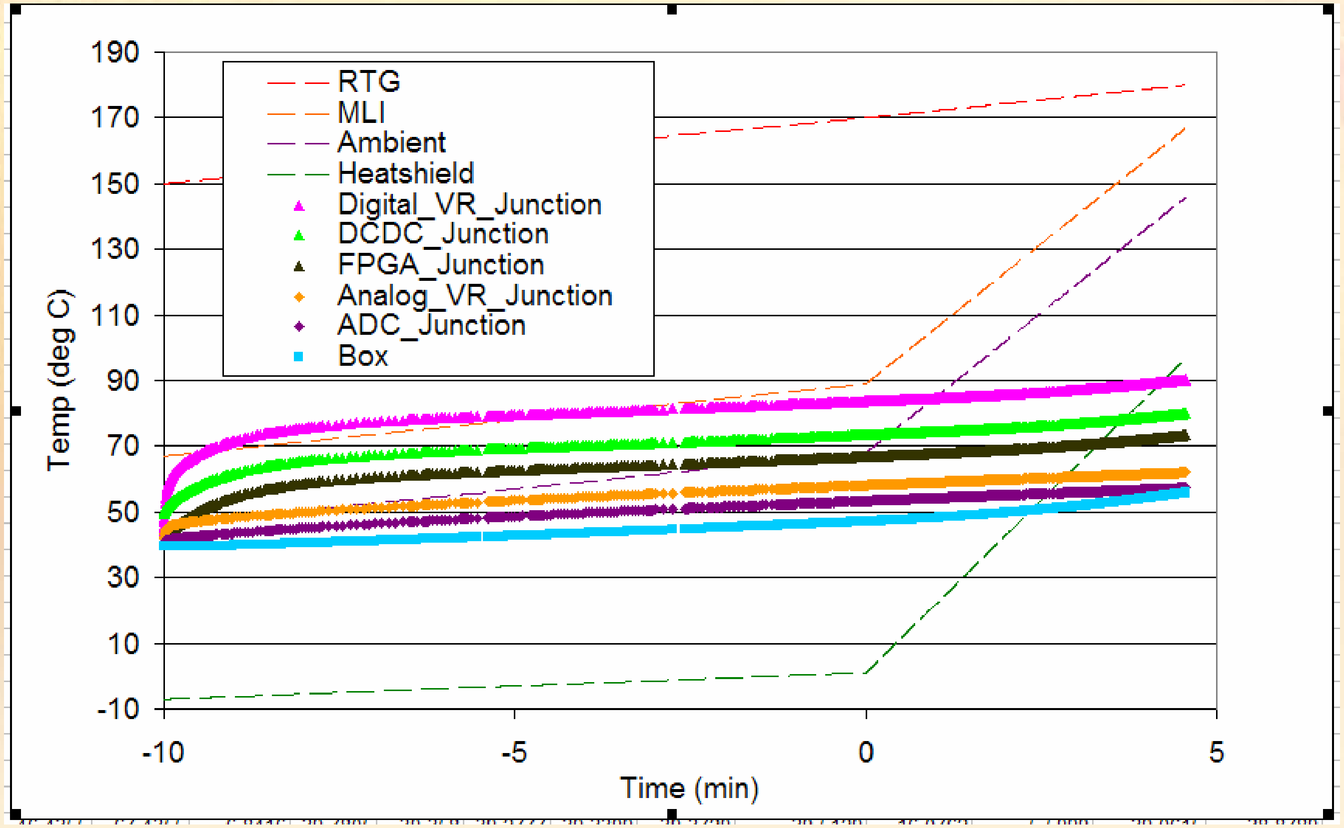



**Engineering boards are shown. Layout differs slightly from flight board design (in thermal model).**



# SSE Thermal Analysis: Entry Results

- Hottest component is the voltage regulator on the digital board
  - Results shown are for nominal power and component size
  - Trades have been performed on power dissipation and component size
- Boundary temperatures are shown for reference



# SSE Thermal Analysis: Results Summary

- Below is a summary of the predicted SSE temperatures for the 2 steady-state analysis cases

| Analysis Case | SSE Predictions (°C) | | | |
|---|---|---|---|---|
| | MEDLI Model Predict | MEDLI Uncertainty | Allowable Flight Temp. | Qualification Temp. |
| Pre-Launch | 80 | 5 | 85 | 105 |
| Cold Cruise | -30 | -5 | -35 | -50 |

**Operational Limits: -55C to 125C**

- Maximum predicted component temperature during atmospheric entry operation *with nominal power dissipation and component size* = ~90℃ (95℃ AFT, 100℃ FA, 115℃ Qual/PF)
- **With the given assumptions, MEDLI's electronics will perform as expected during all phases of the MSL mission**

# Open Issues & Future Work

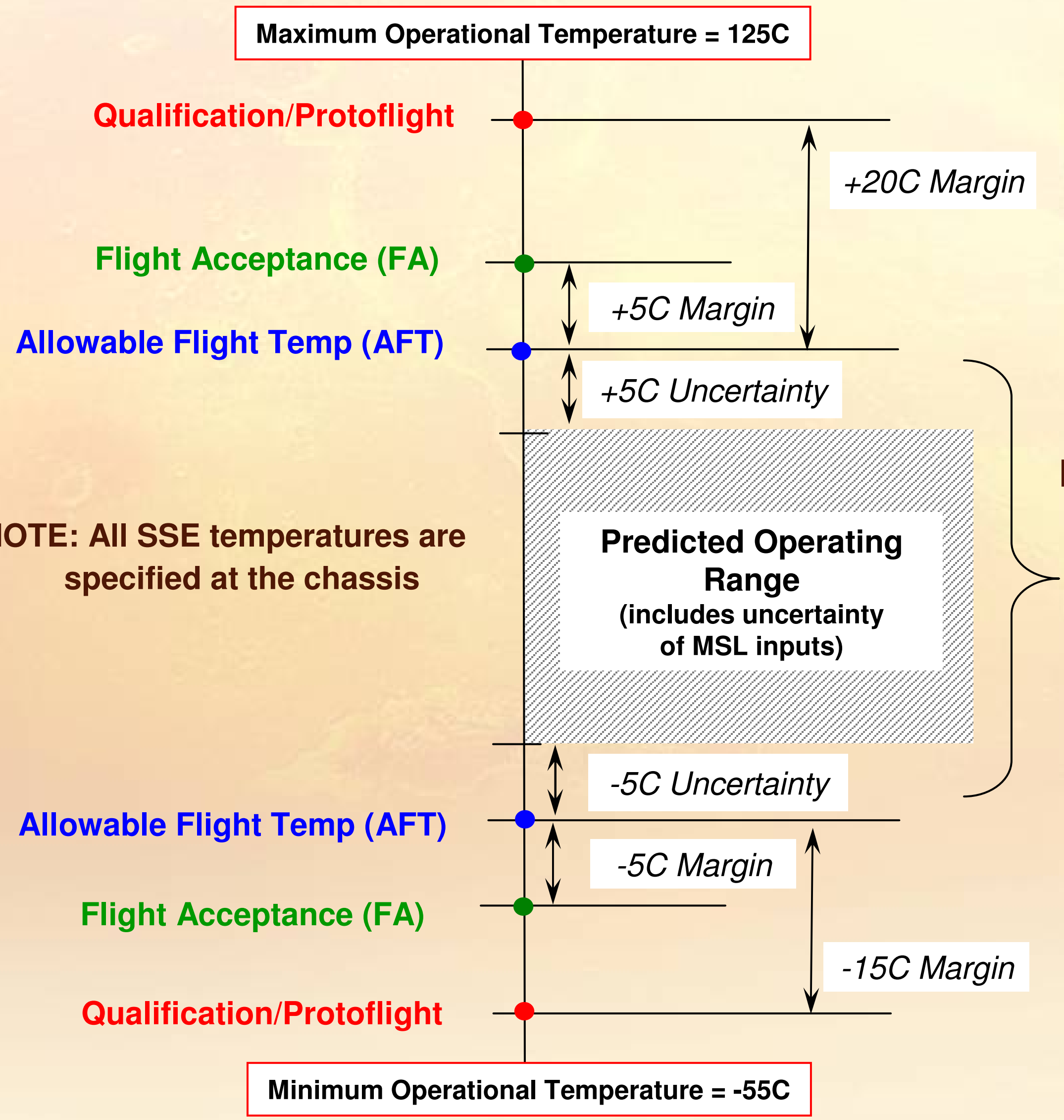
- Open Issues
  - Finalization of design for digital board to get better definition of voltage regulator power dissipation
  - Possible change to SSE/heatshield interface due to structural concerns
  - Possible TPS change
  - Possible switch to alternate trajectory
- Future Work
  - Potential arc-jet shear testing of SLA-561V
  - Continue to refine thermal model; remain current as prediction updates and/or design changes occur
  - Perform small-scale thermal vacuum testing (bell jar) to verify SSE predictions
    - Cold start-up
    - Hot operation
  - Provide formal definition of SSE and MEADS temperature limits to MSL

# Acknowledgements


- Thanks to:
  - MSL Analysts
    - Frank Kelly & Tony Paris (JPL), MSL system-level thermal model
    - Roger Giellis & Mike Connelly (Lockheed Martin), MSL detailed aeroshell thermal model
    - Pradeep Bhandari (JPL), MSL pre-launch CFD calculations
  - Christine Szalai & Arbi Karpatian (JPL), MSL-MEDLI interface
  - Tory Scola (NASA LaRC), assistance with modeling of electronics
  - MEDLI Project
    - Neil Cheatwood, Alan Little, Michael Gazarik, Michael Wright, Helen Hwang, Jeff Herath, Henry Wright, Frank Novak, John Teter, Wade May, Chuck Antill
  - Boeing LCAT and NASA LaRC Staff
    - Matt Kardell, John Simms, Greg Bass, John Bomar
    - John Pandolf, Jim Baughman, Harold Claytor

# BACKUP

# Calculation of Flight Acceptance and Qualification/Protoflight Temperatures



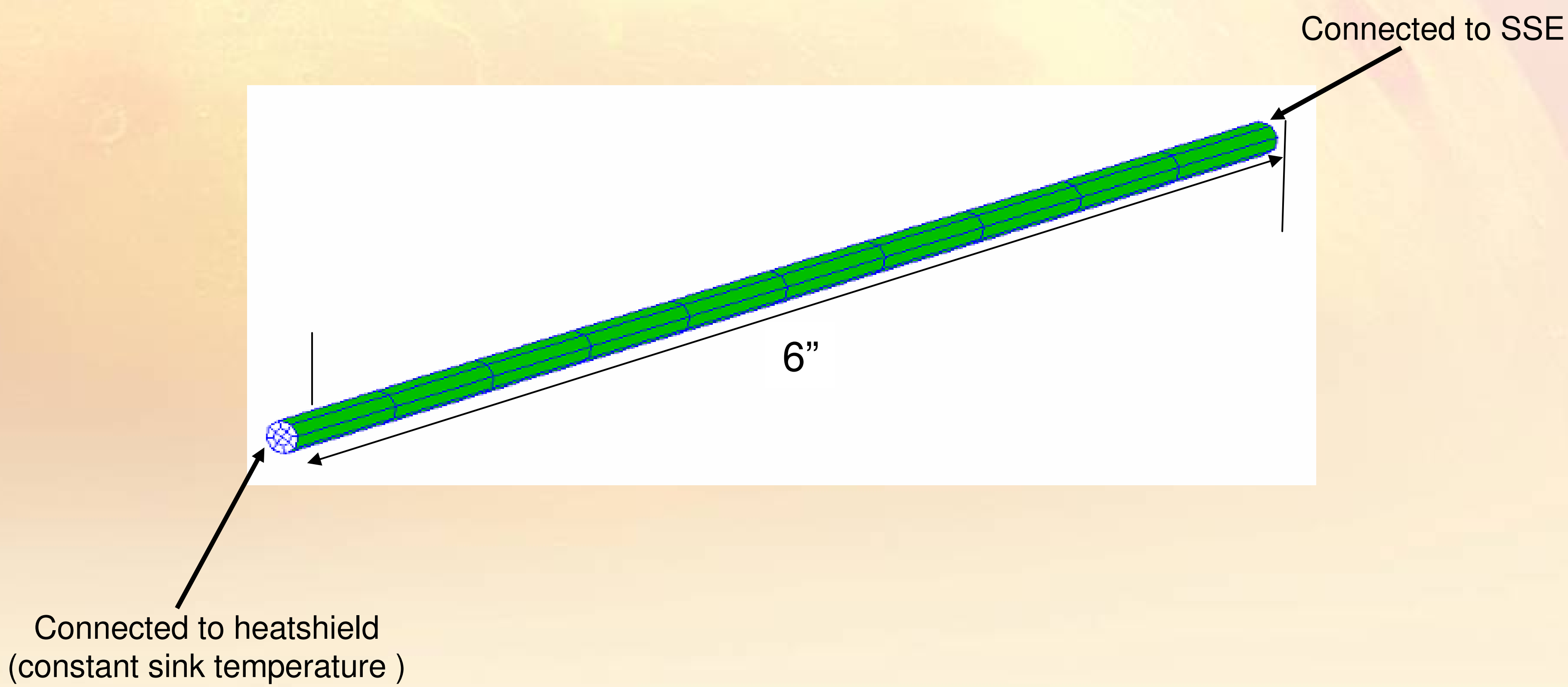

**NOTE: All SSE temperatures are specified at the chassis**

MEDLI SSE model uncertainty of +/-5C is sufficient because each modeling decision was made conservatively, and studies were performed to determine model sensitivity to various parameters (emissivities, contact resistance, boundary temperatures, etc.)

**Chart adapted from Henry Wright**

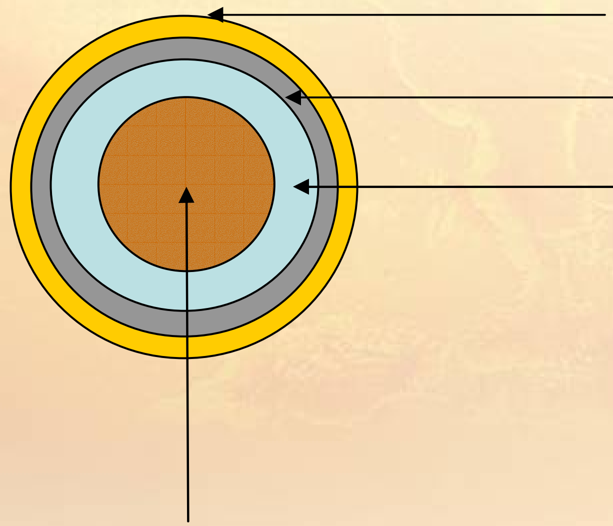
# SSE Thermal Analysis: Thermal Model in MSC/Patran, Cabling

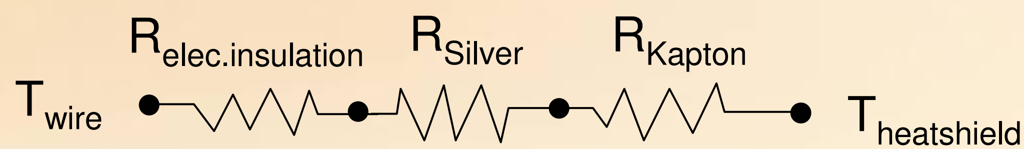
- All electrical wires are modeled as perfectly insulated 6” wires, with the end of the wires held to a constant temperature to simulate the wire being tied down securely to the heatshield
  - The only heat transfer is conduction through the copper wire from the SSE to the heatshield
  - Radiation losses are not modeled (studies showed the effects to be minimal)



# SSE Thermal Analysis: Thermal Model in MSC/Patran, Cabling

- Due to concern that this model was too conservative (did not account for electrical insulation and its potential thermally insulating benefits), a study was performed to determine the effectiveness of the electrical insulation as a thermal insulator
- A total thermal resistance value was calculated based on the assumed electrical insulation design shown below. An analogy to electrical resistance helps to clarify the methodology used.

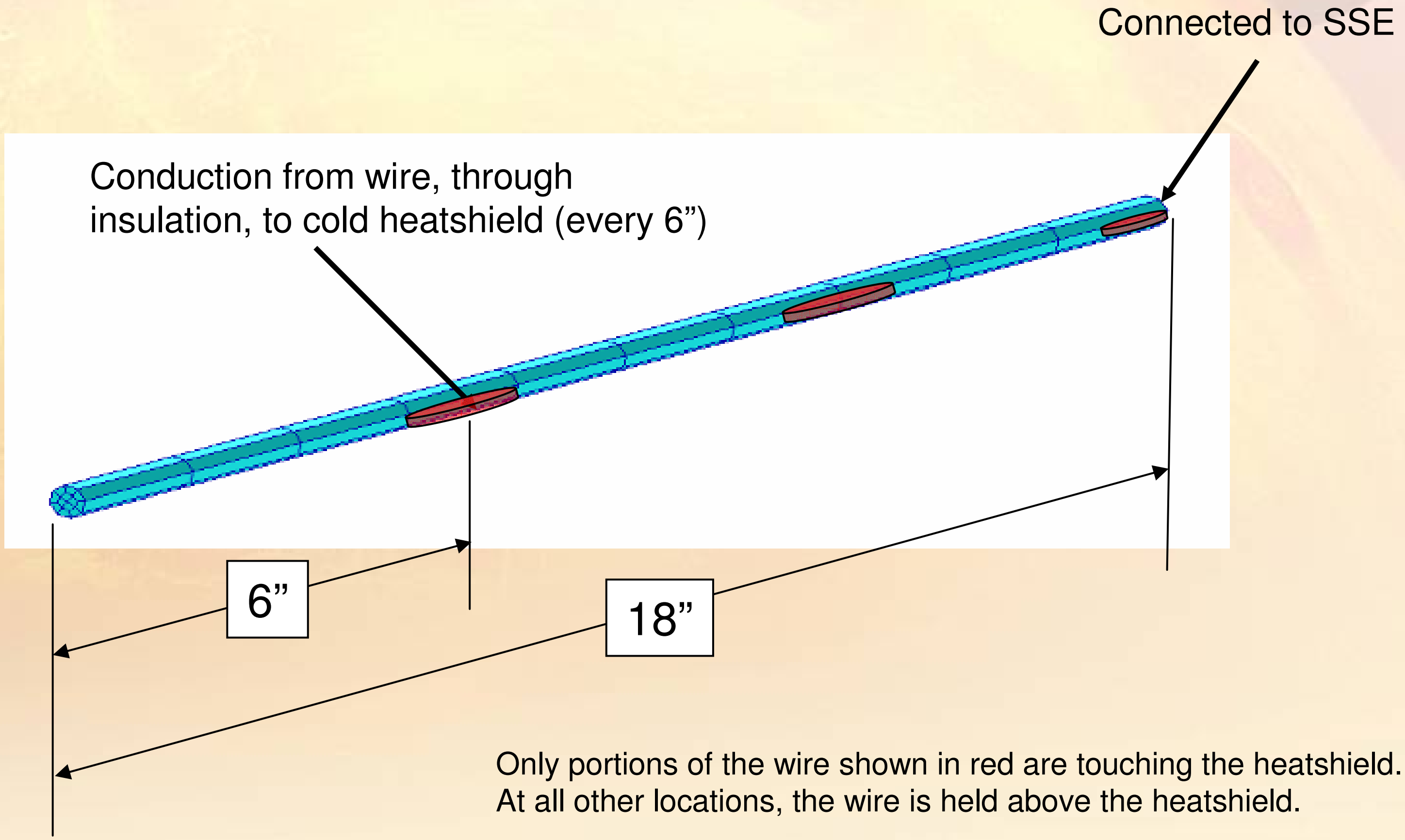



$R = \frac{L}{k}$  L = thickness, k = thermal conductivity

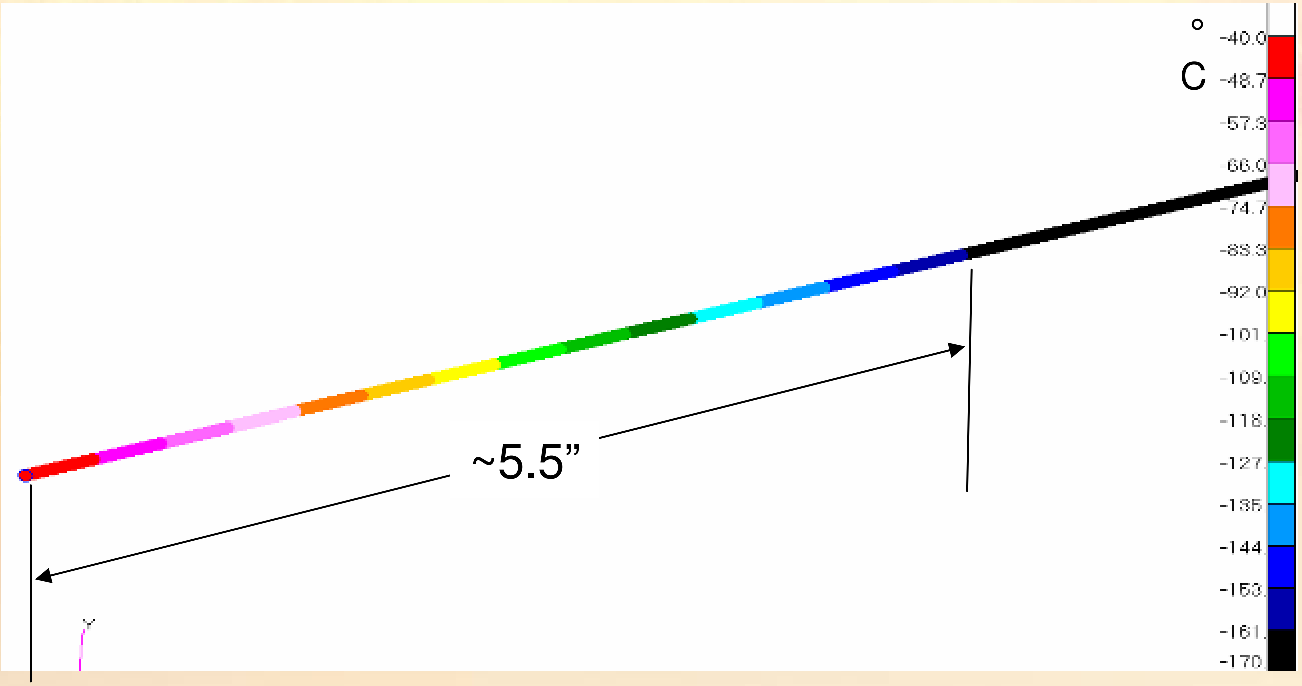
# SSE Thermal Analysis: Thermal Model in MSC/Patran, Cabling

- A model was created to simulate an 18” wire that is tied securely to the heatshield every 6”
  - At every other point, the wire is perfectly insulated



# SSE Thermal Analysis: Thermal Model in MSC/Patran, Cabling

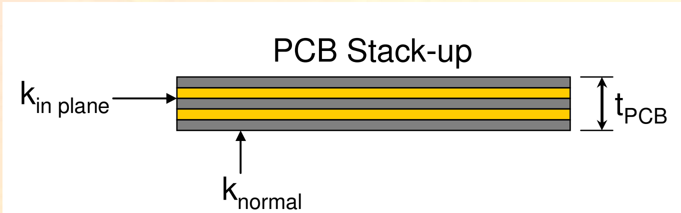
- **Wire reaches heatshield temperature after about 5.5” of length**
  - Original model provided a reasonable representation of the heat loss through the electrical wiring
- This approach simplifies the model and helps to avoid longer run times due to complex meshing of very small wires, since groups of wires can be modeled as a bundle.

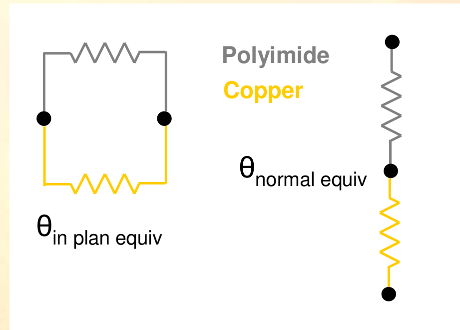



- A sensitivity study showed that adding an extra layer of thermal insulation (0.25” thick pyrogel blanket) at one tie-down provides nearly a 50% decrease in the heat loss through the wire
  - Thermal insulation is not included in the nominal design; but was analyzed as an option if needed

# SSE Thermal Analysis: Thermal Model in MSC/Patran, Electronics

- Calculation of circuit board material properties




$t_{polyimide}$ = total polyimide thickness in the normal direction
$t_{Cu}$ = total copper thickness in the normal direction
$m_{cu}$ = total copper mass
$m_{polyimide}$ = total polyimide mass
$M_{total}$ = total board mass
$C_{equiv}$ = equivalent board heat capacity

**Illustrations from Tory Scola, NASA LaRC**

$$\theta_{in\ plane\ equiv} = \frac{1}{k_{polyimide} \cdot t_{polyimide} + k_{Cu} \cdot t_{Cu}}$$

$$\theta_{normal\ equiv} = \frac{t_{polyimide}}{k_{polyimide}} + \frac{t_{Cu}}{k_{Cu}}$$

$$k_{in\ plane\ equiv} = \frac{1}{\theta_{in\ plane\ equiv} \cdot t_{PCB}}$$

$$k_{normal\ equiv} = \frac{t_{PCB}}{\theta_{normal\ equiv}}$$

$$C_{equiv} = \frac{m_{Cu} \cdot C_{Cu} + m_{polyimide} \cdot C_{polyimide}}{m_{Cu} + m_{polyimide}}$$

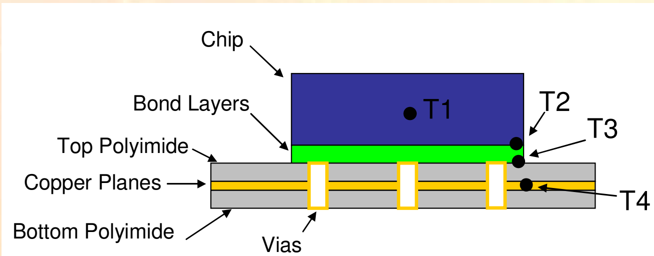
$$M_{total} = m_{Cu} + m_{polyimide}$$

Note that thermal conductivity calculations are independent of board length and width

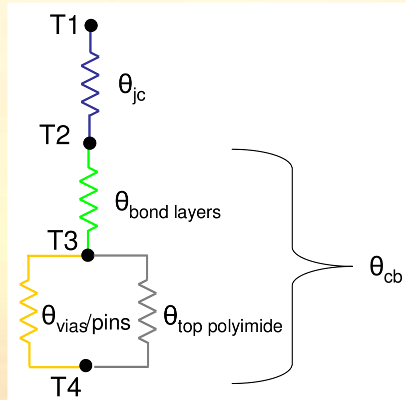
| Stackup (4 layer PCBs) Total thickness = 62 mil | $k_{in\text{-}plane\ equiv}$ (W/m-K) | $k_{normal\ equiv}$ (W/m-K) | $Cp_{equiv}$ (J/kg-K) | Mass (gm) |
|---|---|---|---|---|
| 3-oz copper Rest of thickness is FR4 | 27.4 | 0.32 | 673 | 160 |

# SSE Thermal Analysis: Thermal Model in MSC/Patran, Electronics

- Calculation of chip to board thermal resistance




**Illustrations from Tory Scola, NASA LaRC**




$t_{polyimide}$ = top polyimide thickness
$t_{viaCu}$ = thickness of via plating
$n_{vias}$ = number of vias
$A_{via}$ = area of 1 via
$A_{polyimide}$ = Area of polyimide under chip

$L_{pin}$ = length of pin

n = number of pins

$A_{pin}$ = cross sectional area of 1 pin

$$A_{via} = \frac{\pi}{4}\left[d_{via}^{\ 2} - (d_{via} - 2 \cdot t_{via\,Cu})^2\right] \qquad A_{polyimide} = A_{chip} - n_{vias}\frac{\pi}{4}d_{via}^{\ 2}$$

$$\theta_{1via} = \frac{t_{top\ polyimide}}{k_{Cu} * A_{via}} \qquad \theta_{pins} = \frac{L_{pin}}{n * k_{pin} * A_{pin}} \qquad \theta_{top\ polyimide} = \frac{t_{top\ polyimide}}{k_{polyimide} * A_{polyimide}}$$

$$\theta_{cb} = \theta_{bondlayers} + \left[\frac{1}{\theta_{toppolyimide}} + \frac{n_{vias}}{\theta_{1via}} + \frac{1}{\theta_{pins}}\right]^{-1}$$

| | Component | Power (W) | Mass (kg) | $\theta_{jc}$ (°C/W) | $\theta_{cb}$ (°C/W) |
|---|---|---|---|---|---|
| Analog Board | A/D Converter | 0.095 | 0.0031* | 2.44 | 8.8 |
| | (+) Voltage Regulator, TO-39 case | 0.06 | 0.0031* | 21 | 18.93 |
| | (-) Voltage Regulator, TO-39 case | 0.13 | 0.0031* | 12 | 18.93 |
| Digital Board | FPGA | 2 | 0.0202 | 0.5 | 0.647 |
| | Voltage Regulator, TO-39 case | 0.5/1.1 | 0.0031 | 15 | 18.93 |
| | DC/DC Converters | 1.2 | 0.03 | 8.33 | 0.922 |

***Assumption**