Design and Thermal-Structural Analysis of PICA Coupons for Solar-Tower Test

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Outline

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- Motivation & objective
- Thermal analysis of single PICA tile
- Parametric optimization
- Final coupon design
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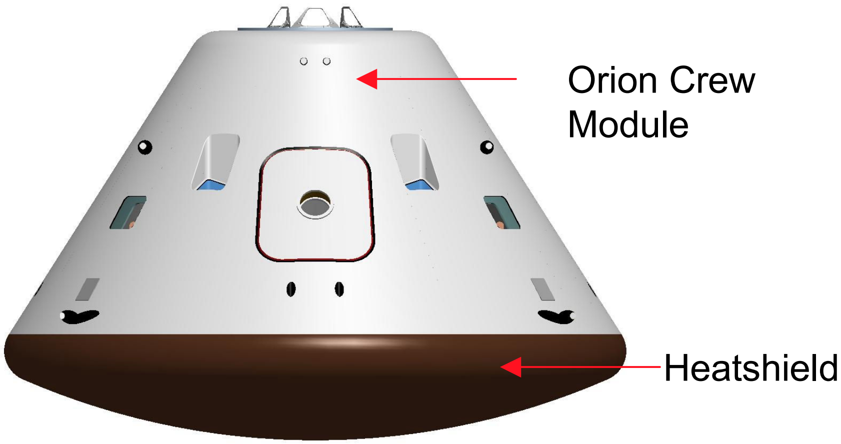
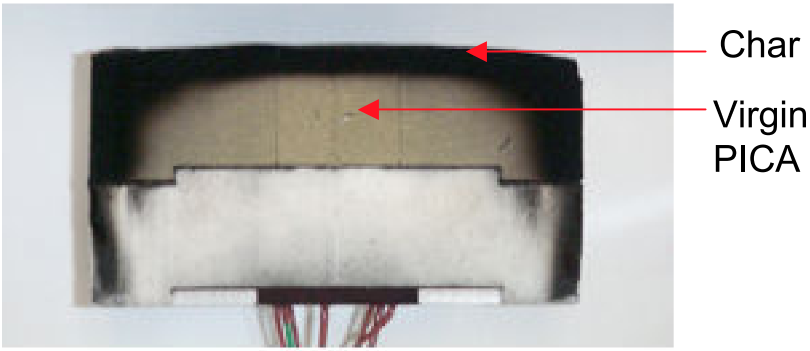
  - Temperature history from thermocouples
  - Strain data
- Conclusions
- Future test design and analysis

Background

- PICA (phenolic impregnated carbon ablator) is the candidate material for Orion and Mars Science Lab (MSL) heatshield
- It is a porous pyrolyzing ablator material made by impregnating phenolic resin inside the carbon preform.
- It is structurally weak material. It forms a char layer when subjected to high temperature.
- The re-entry conditions impose a very high thermal gradients on PICA tiles. The positive coefficient of thermal expansion cause the upper layer to expand significantly.
- The lower cool virgin material imposes compressive stress on the upper layer.



Orion Capsule for re-entry



Cross section of PICA coupon after high temperature test

Motivation and Objectives

- Preliminary thermal analysis of PICA tiles for CEV re-entry showed the presence of very large in-plane compressive stresses at the top char layer.

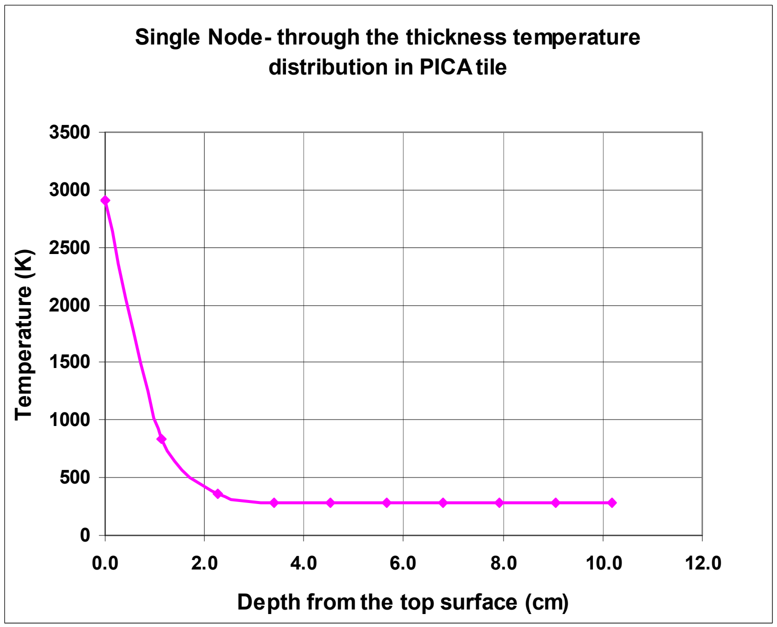
  In some cases, the magnitude of in-plane compressive stresses exceeded the allowable compressive stress for PICA and char.
- We decided to conduct solar-tower tests at Sandia National Labs to:
  - Investigate failure mechanisms in PICA tiles.
  - Validate the FEM predictions.
  - Evaluate char layer integrity.
  - Test large PICA tiles representative of sizes currently being analyzed.
- Analysis and tests were performed under the following loads:
  - Large temperature gradients due to high heat flux.
  - High heat flux load combined with mechanical loads to represent the worst conditions.

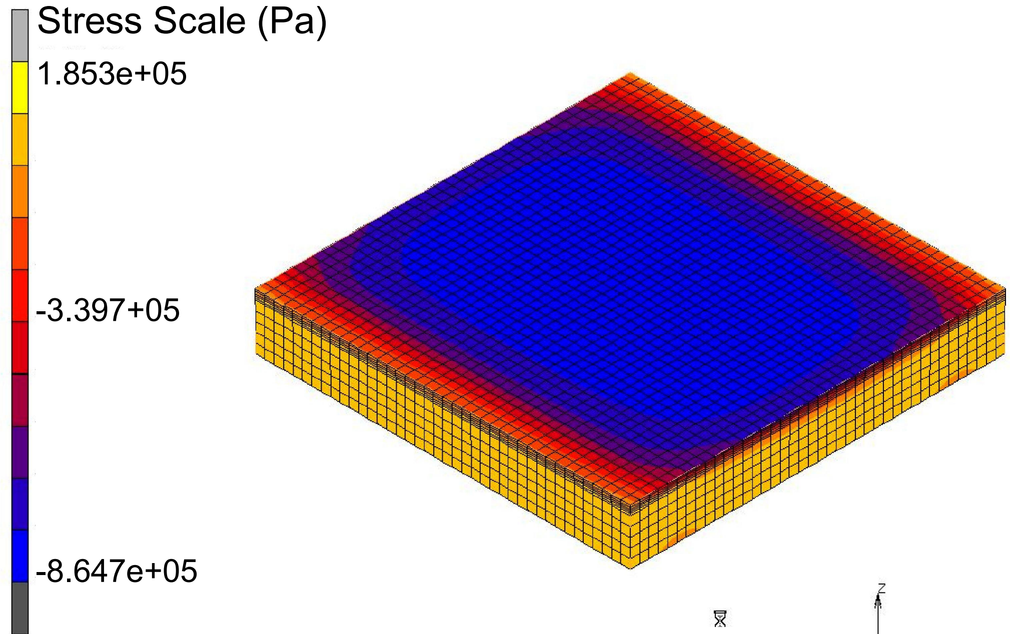
Sandia Test Facility

Solar Tower Test Facility

PICA Coupon during Test

Thermal Stress Analysis During Re-Entry





In-plane Stress Distribution

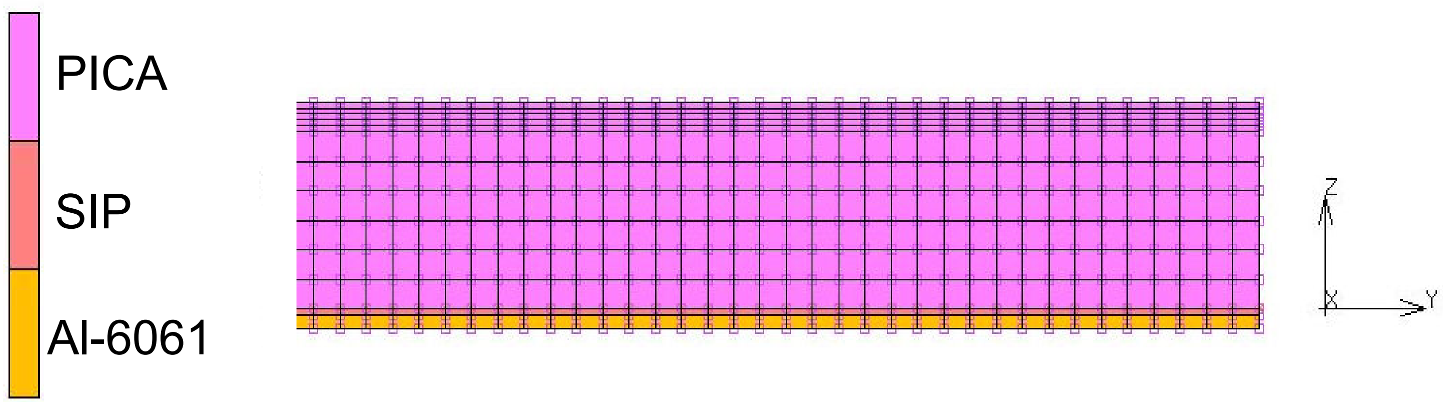
- Stress analysis on single PICA tile for above temperature distribution showed very large in-plane compressive stress at the top layer.
- The maximum in-plane compressive stress at the top layer was very close to the listed in-plane yield stress value for PICA.

Pathfinder Coupon Design

- Analysis objective: Obtain stress-strains caused by thermal and mechanical loads at various heat fluxes:
  - During the heat pulse period
  - During cool-down period
- Preliminary design inputs from modeling:
  - Heat flux magnitude
  - Duration of heat pulse
  - Cooling requirements
  - Tile thickness
  - SIP vs. Direct Bonding
  - Panel configuration and instrumentation

FEM Model: Design & Assumptions

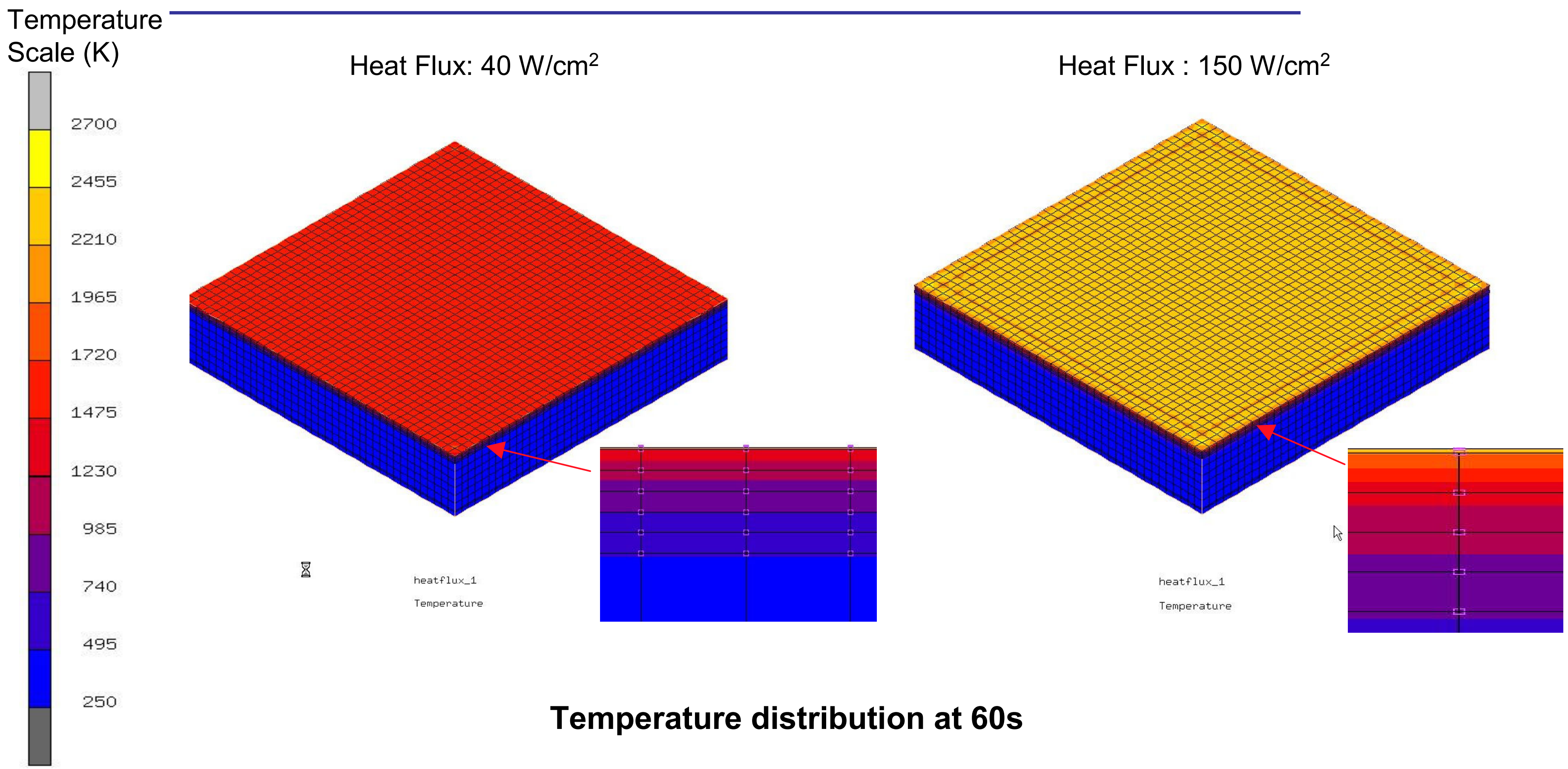
- Used MSC.Marc commercial finite element solver.
- Used Mentat integrated user interface with Marc as pre- and post-processor.
- Quasi-static, coupled thermal/mechanical FE analyses.
- Assumed radiation equilibrium.
- Did *not* model ablation.
- Assumed the different layers were to be fully bonded and shared the same nodes.
- Assumed following temperature-dependent material properties for all materials:
  - Assumed PICA “virgin” until (550 °F) and fully charred at 1,033 K (1400 °F).
  - For thermal properties, assumed FIAT input properties for virgin PICA until 1,033 K (1400 °F) and then char for 1,033 K (1400 °F) and above temperature range.
- Used solid Hex-8 elements.
- Used refined mesh at the top to accommodate steep thermal gradients.



Design Matrix

Case Objective	Material Stack	Cooling	Flux (W/cm^2)	Duration (seconds)	Tile Thickness (inches)	Tile Length & Width (inches)	Bottom Nodes	Results
Flux Amplitude	**PICA-SIP-AL**	Cooling at back	40	60s	3.5"	20 x 20	Fully Constrained	150 W/cm^2 heat flux was selected
		Cooling at back	150	60s				Cooling at the back plate not required
Cooling Conditions		Cooling at back	150	60s				120 sec heat pulse chosen to utilize block more efficiently.
		No Cooling		60s				
Flux Duration		**No Cooling**		60s			Fully Constrained	Corner constraints chosen to obtain the strains at the metal base plate
				240s				
Tile Thickness				60s	3.5"		Corners Only	
Bottom Constraints					2.5"		Fully Constrained	Both types were used in final test matrix
SIP vs. Direct Bonding	PICA-SIP-AL				2.5"		Corners Only	
	PICA-AL						Corners Only	Results not very different. 12"x12" chosen to allow more coupon fabrication
Tile Length & Width	PICA-SIP-AL			120s		12x12	Corners Only	
	PICA-SIP-AL			120s				

Effect of Heat Flux Intensity — Temperature

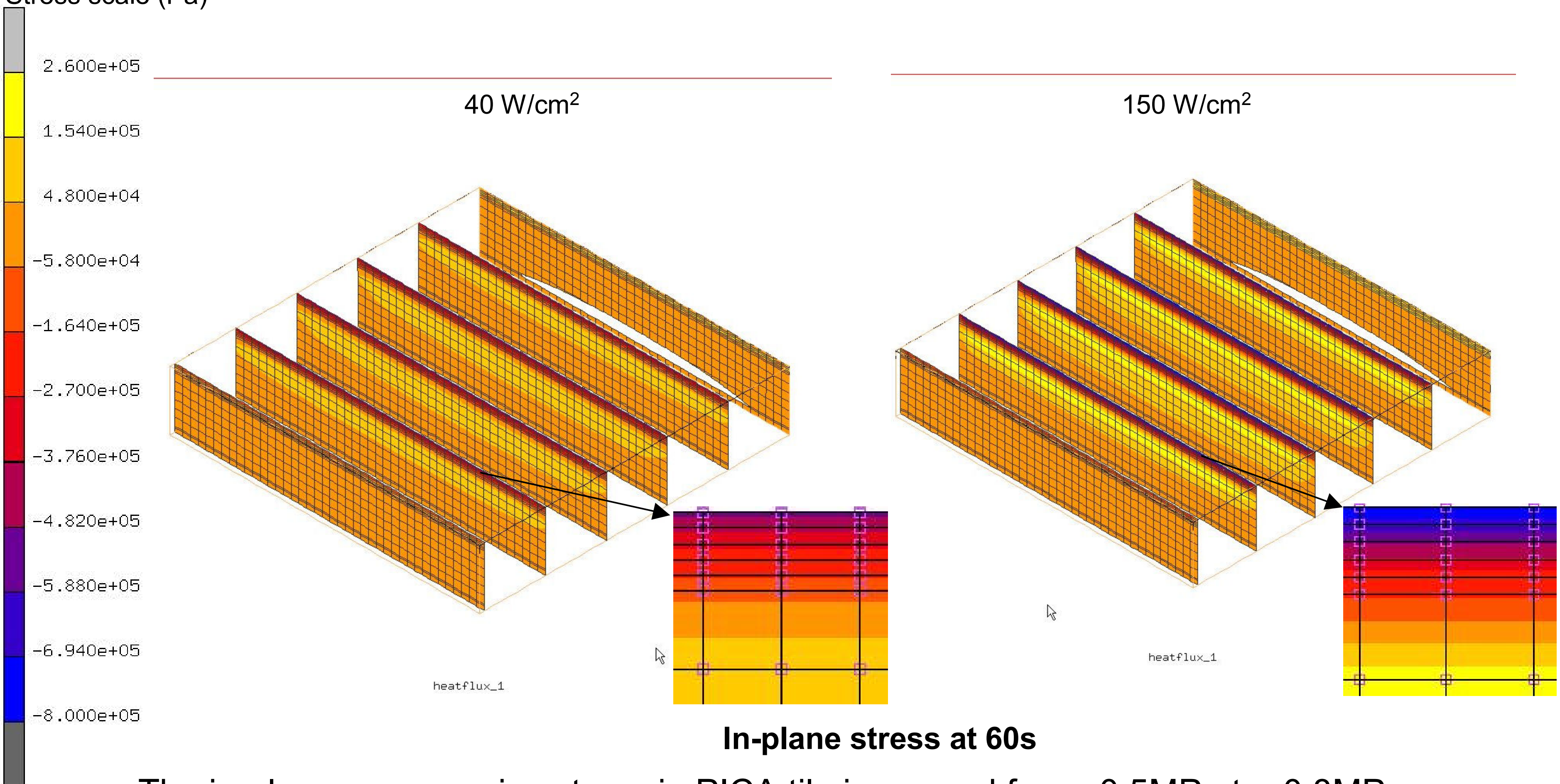


Temperature distribution at 60s

- Maximum surface temperature changes from 1400 K to 2200 K when heat flux is increased from 40 W/cm^2 to 150 W/cm^2.
- In both cases, the high temperature gradient stays only at the top 1.27cm (0.5") layer.

Effect of Heat Flux Intensity — Stress

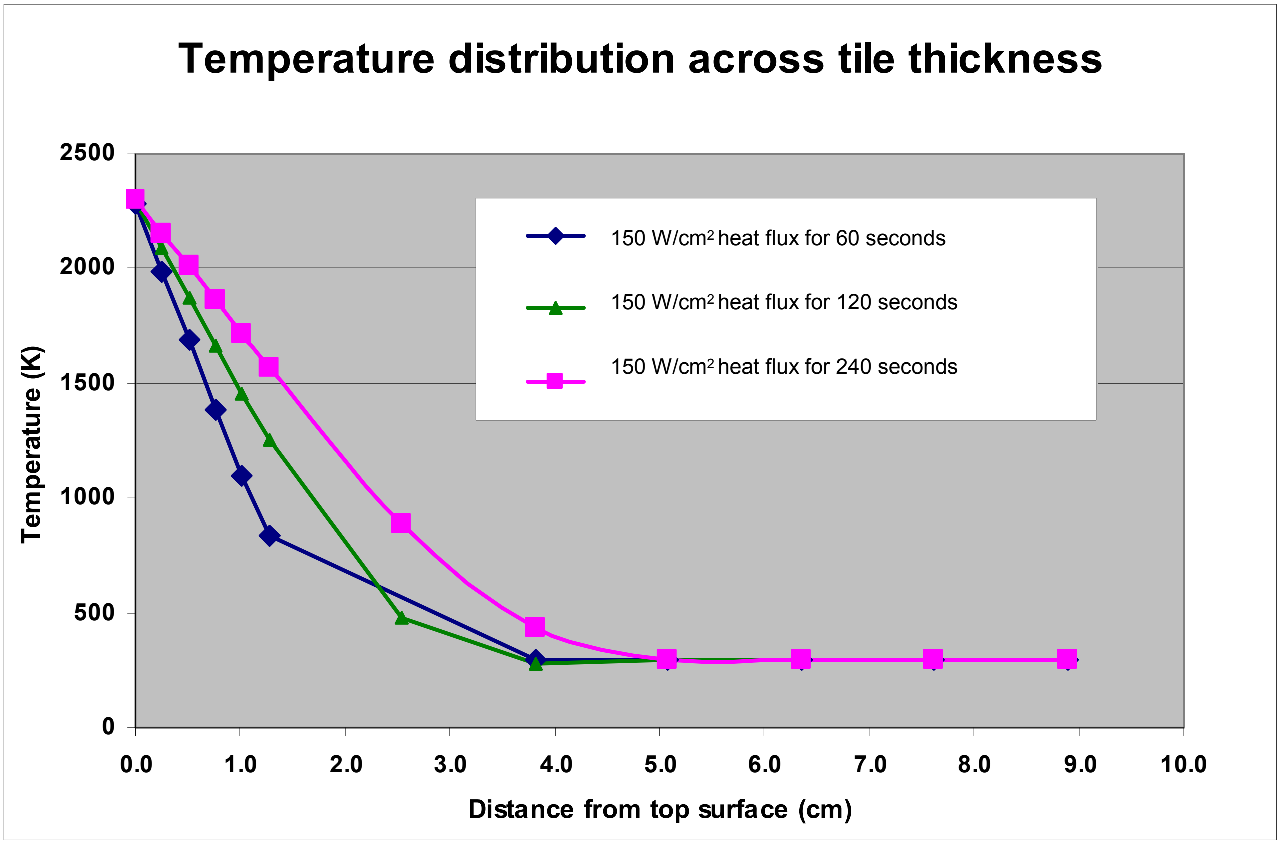
Stress scale (Pa)



In-plane stress at 60s

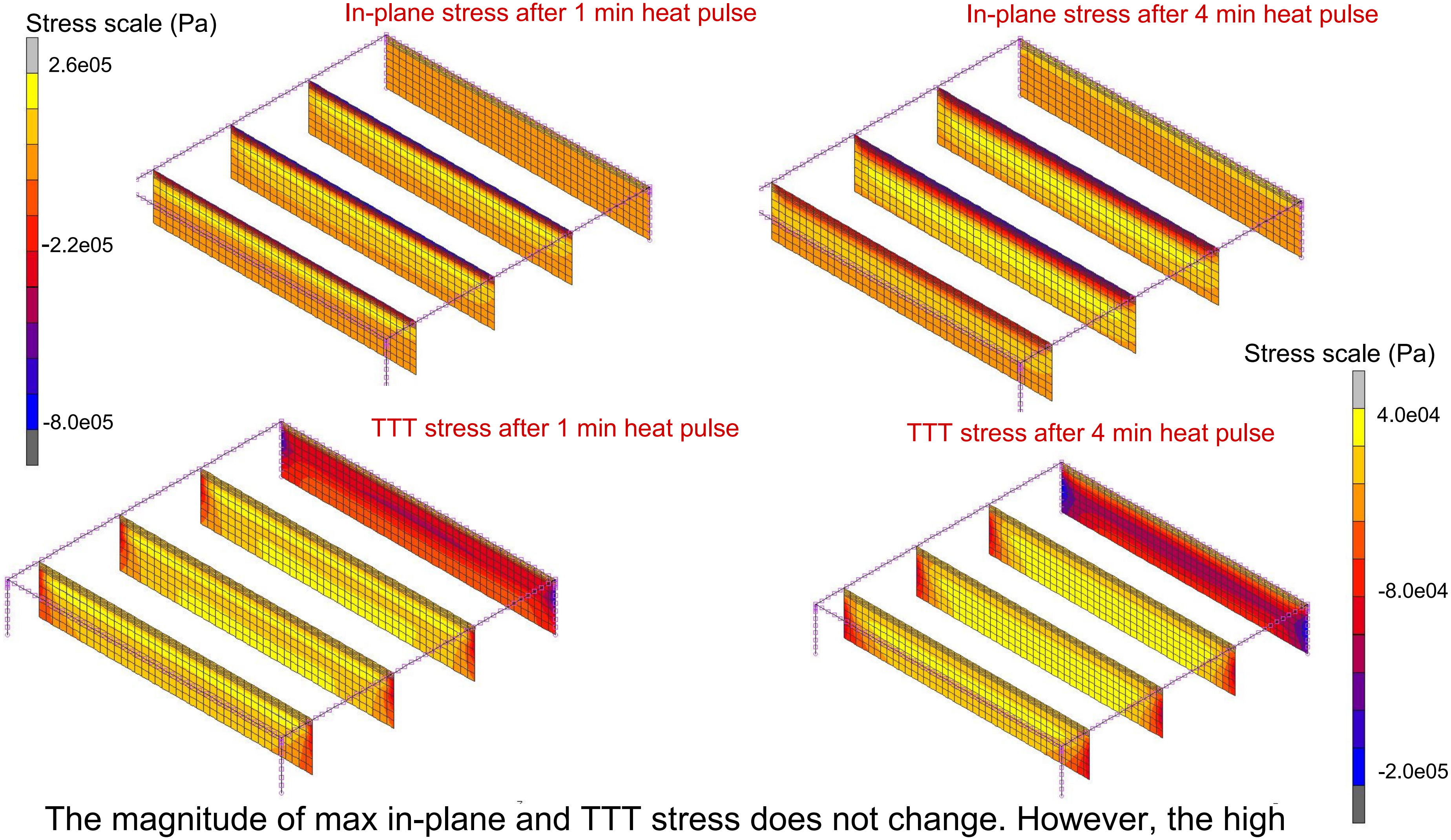
- The in-plane compressive stress in PICA tile increased from -0.5MPa to -0.8MPa.
- The tension zone right below the compression zone also increased significantly.
- Through-the thickness (TTT) tensile and compressive stress also increased significantly when heat flux increased.

Effect of Increased Duration —Temperature



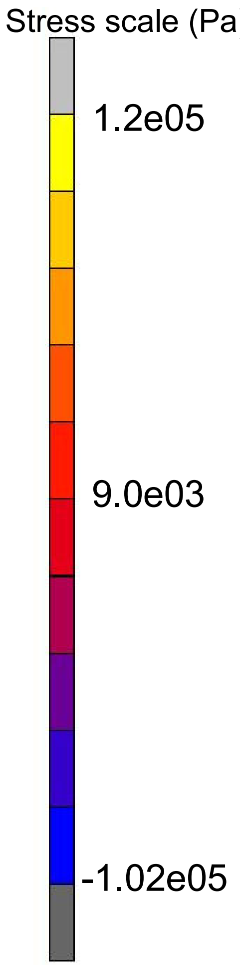
- As flux duration increases from 1 to 4 minutes, more heat penetrates through the depth, and temperature rises, even at 4.0 cm below the surface.
- Peak surface temperature remains the same, at about 2477 K (4000 °F).

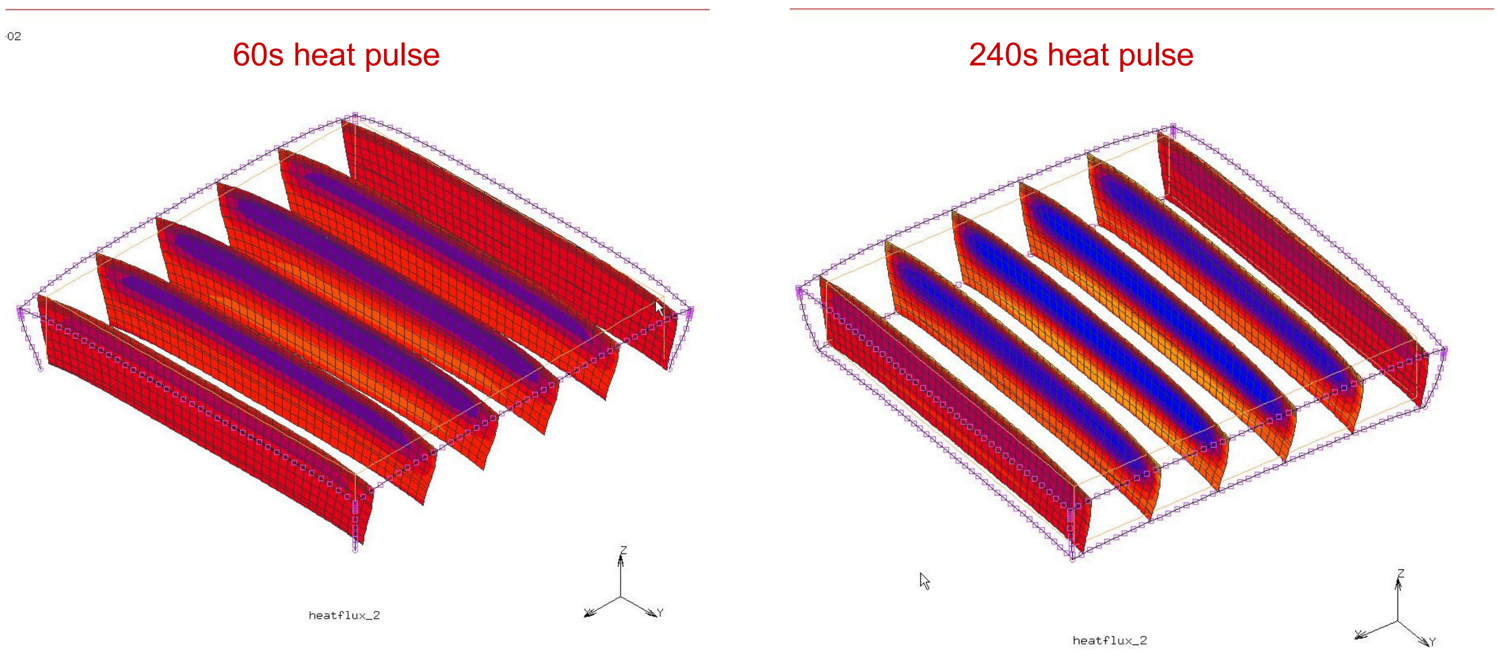
Effect of Increased Duration — Stress



The magnitude of max in-plane and TTT stress does not change. However, the high compressive stress, as well as tensile stresses, are distributed through a significantly larger region when duration is increased.

Effect of Increased Duration — Stress After Cool-Down Cycle





In-plane stress after 500 sec of cool down

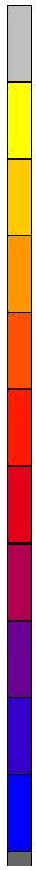
For longer heat pulse, both compressive and tensile magnitudes and distribution zones are significantly larger.

Effect of Cooling At Back Plate

- For 1 minute of heat pulse at 150 W/cm^2, there was no significant rise of temperature at the back metal plate.
- For 4 minutes of heat pulse, the back metal plate temperature starts to rise. After 500 seconds of cooldown, the temperature rises to 316.5 K (110°F), and the upward curve suggests that it would likely rise more.
- However, since the sample is exposed to open atmosphere with sufficient wind, we assumed that the temperature would not rise significantly above 316.5 K (110 °F) during the cool-down period.

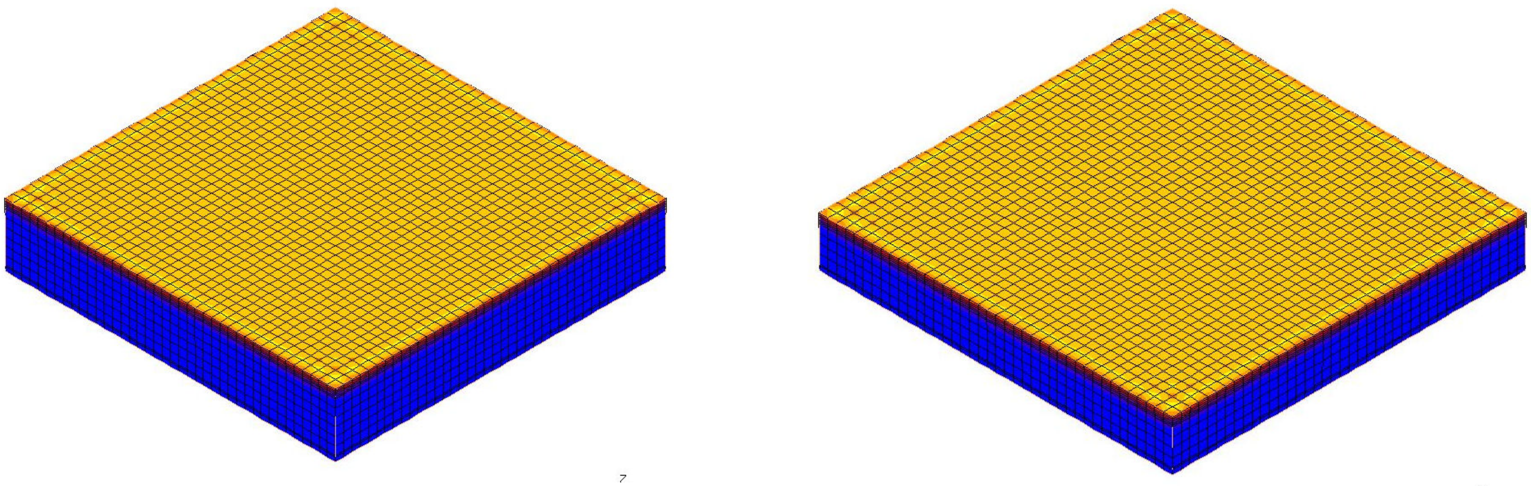
Effect of Tile Thickness — 3.5" vs 2.5"

Temperature Scale (K)



3.5 inch thickness

2.5 inch thickness



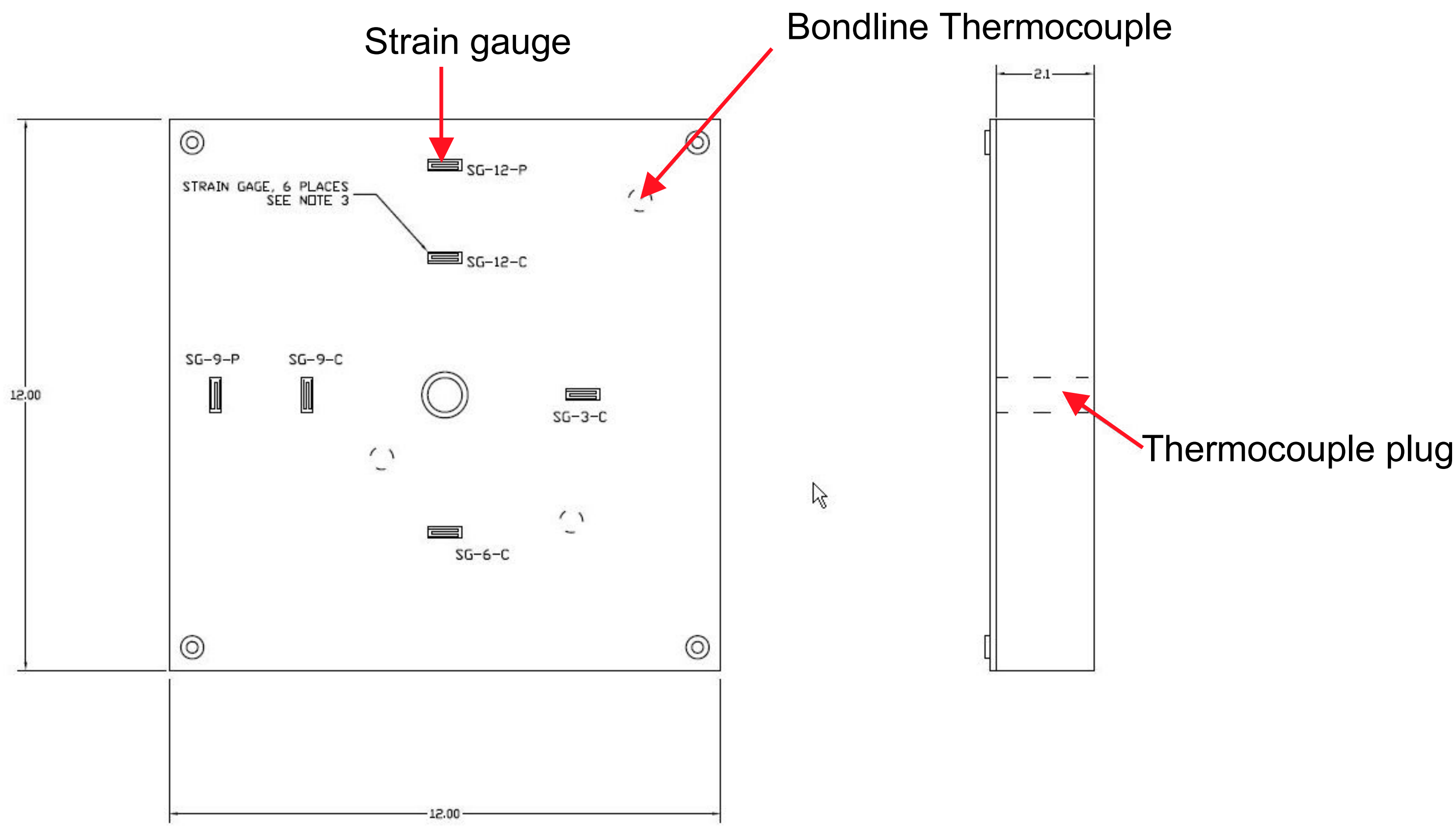
Temperature distribution after 60 Seconds

- Reduction of tile thickness from 8.9 cm (3.5") to 6.35 cm (2.5") does not impact the surface temperature or stress distribution.
- Peak still is in the range of 2600 K (4,220°F). So 6.35 cm (2.5") thick coupons could be used for experiments.

SIP vs. Direct Metal Plate Bonding to PICA

- For CEV heatshield, a layer of SIP (strain isolation pad) is used between the PICA tiles and metal carrier structure.
- However, direct bond between tiles and metal gives rise to higher strains, making the measurement errors smaller.
- Both options were used in modeling and test coupon design.
  - For direct bonding, a thin layer of RTV was included between the metal and PICA tile. (It acted as a buffer and avoided very high stress concentrations.)
  - Direct bonding did not change the maximum in-plane tensile and compressive stresses in PICA. They were still in the top layer, driven by the high thermal gradient.
  - However, the strains in the metal sheet were higher, due to direct bonding.

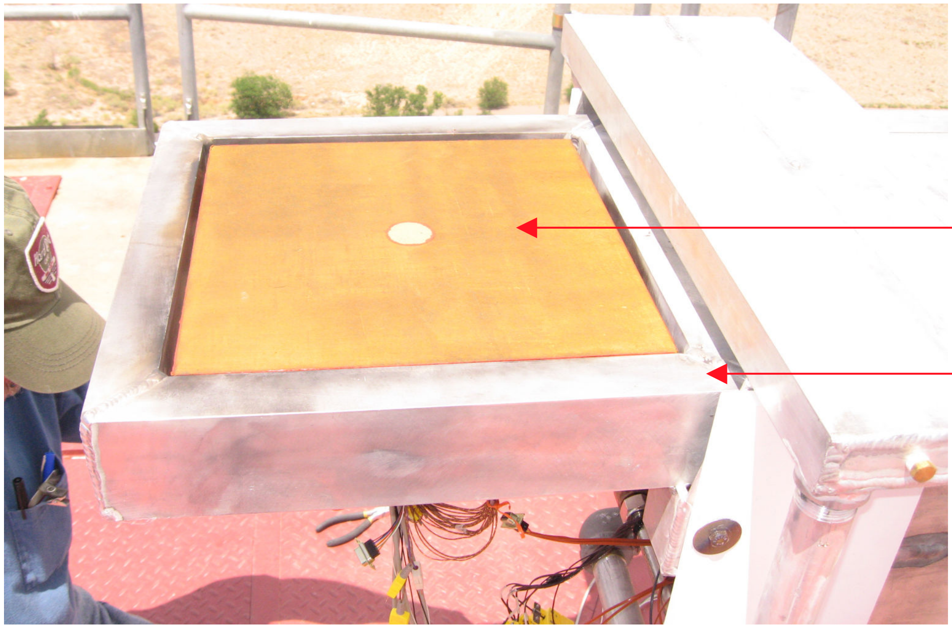
Final Coupon Design



- All the test coupons were coated with RTV on the side.
- N_2 flow was used to prevent PICA burning from atmospheric oxygen.

Test Matrix & Conditions

Test Coupon #	Heat Flux	Duration	Thermocouples	Strain Gauges at the Back Plate	SIP at Interface	Test Sequence
STE-04	150 W/cm^2	120 sec	TC plug 0.10", 0.20", 0.45", 0.70" from top surface, 3 TC at the bondline	No	Yes	Coupon 1
STE-03			TC plug 0.10", 0.20", 0.45", 0.70Ó from top surface, 3 TC at the bondline	Yes	No	Coupon 2
STE-02			No plug, Bondline TC	Yes	Yes	Coupon 3
STE-01			No plug, Bondline TC	No	No	Not tested



Pathfinder Coupon

Test Frame

Sandia Test Facility

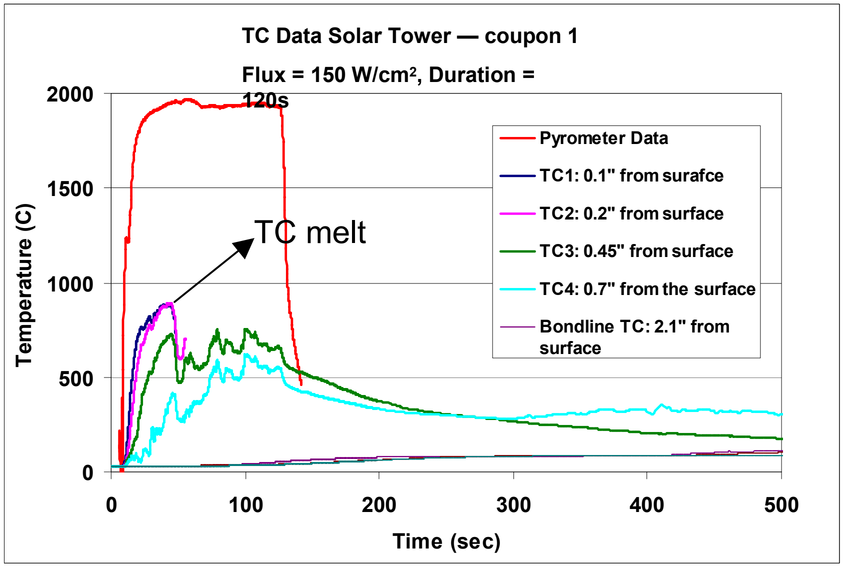
Solar Tower Test Facility

PICA Coupon during Test

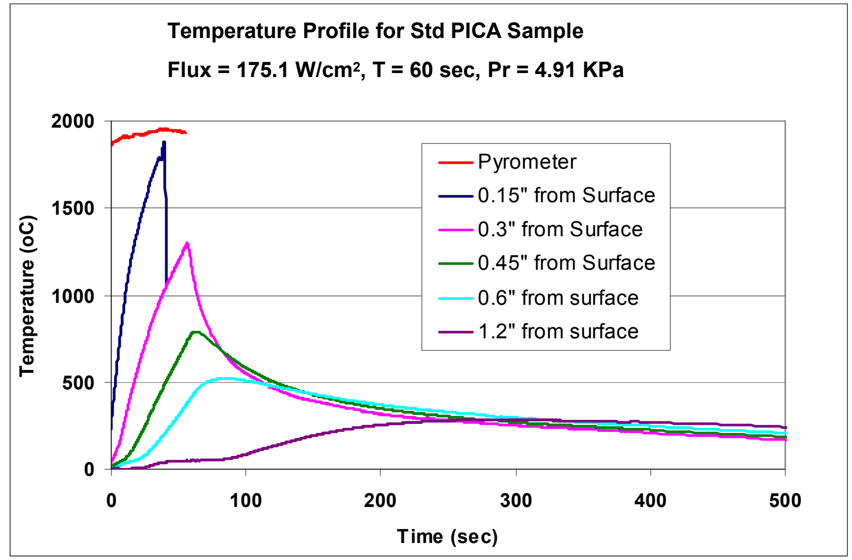
Video of Test #2

Post-test X-ray analysis of coupons showed surface cracks at regular intervals in the char layer.

Temperature History



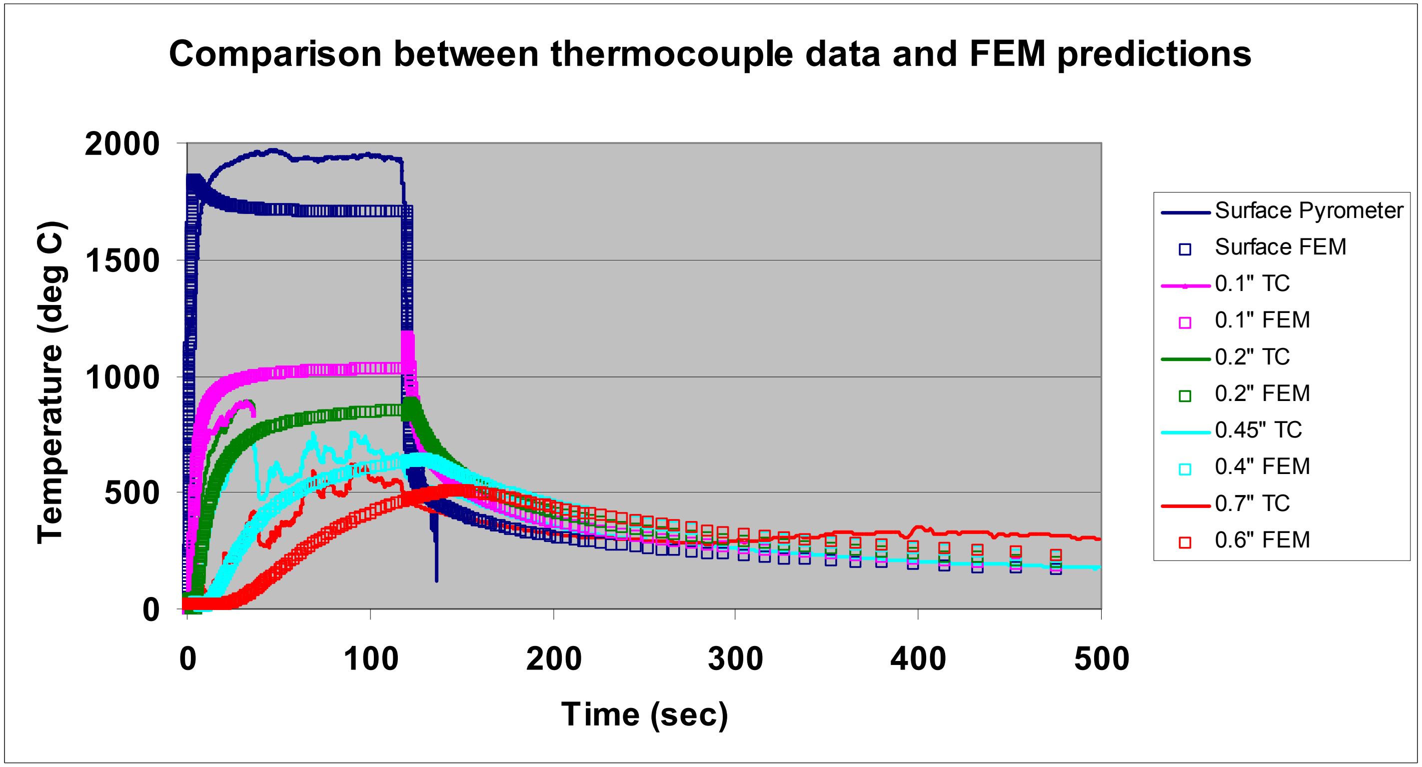
Solar Tower Test



Arcjet Test

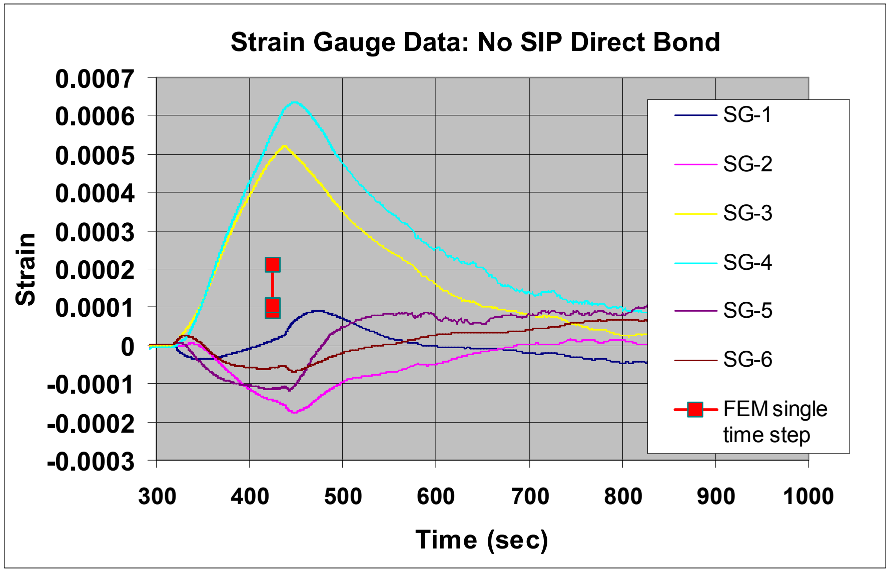
- X-ray analysis showed that the first two thermocouples (TC) melted during the solar tower test; authors could not obtain reliable data.
- The 0.1" spacing between TC1 and TC2 was not sufficient to distinguish the measurements.
- The magnitude of TC3 and TC4 was comparable to arcjet test data.
- In general, there is substantial noise in thermocouple data from solar tower tests.
- Bondline thermocouple show consistent data.

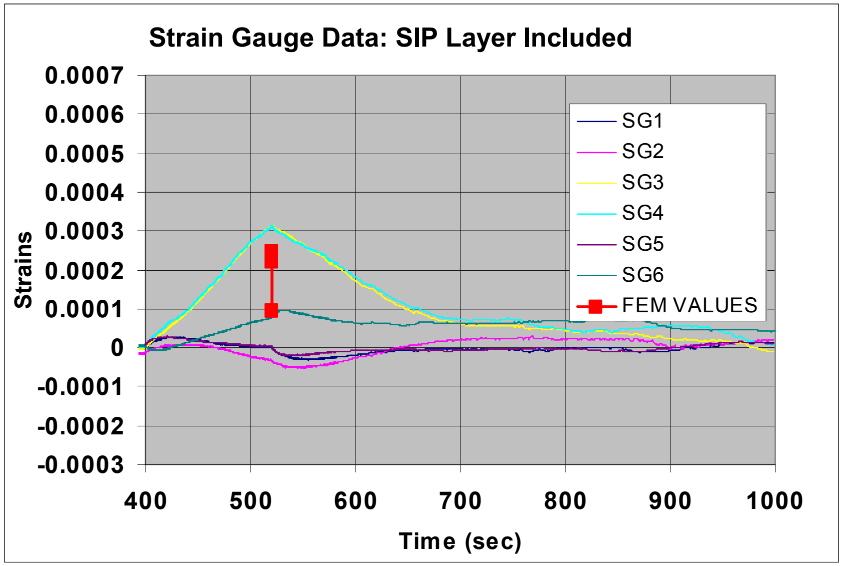
Temperature Profile – Comparison with FEM model



- It was difficult to compare the test data with FEM values due to significant noise.
- The surface temperature was about 250 °C lower compared to pyrometer data. In the next test series, authors plan to mount a surface TC on a coupon.
- In general, the FEM predictions were slightly lower than experimentally obtained values at similar location.

Strain Comparison — Test Data vs FEM





- FEM values from single-temperature profile are comparable in magnitude with the test data, but signs are always positive. This makes intuitive sense, as the overall block is expanding in the in-plane direction, except for the corner constraint points.
- The team is still investigating the reason for inconsistency.

Conclusions and Future Work

- We were able to optimize the final design of pathfinder coupons and test conditions for solar tower tests.
- The tests were successfully conducted at Sandia National Laboratory.
  - N_2 flow helped avoid burning of PICA and aided completion of test.
  - Small surface cracks were observed in the char layer.
  - Post-test analysis of char layer and instrumentation is in progress.
- Lessons learned for future testing:
  - Use type R or type C thermocouples for higher temperature measurements.
  - Use surface TC and IR camera to obtain accurate surface temperature values.
  - Control N_2 flow to eliminate its effect on surface char.
- Design and analysis of multi-arrayed PICA tile system is in process.
  - Coupled thermal-mechanical loads will be used to study the material behavior at elevated temperature and cool down process.
  - Different gap filler options will be studied under these test conditions.