Inverse/Optimal Repair of Composites

Goal: To minimize set up time and assure temperature control of repair site

Objective: To design heat sources that achieve an isothermal state in the repair zone

Approach: An inverse analysis using finite elements, proper orthogonal decomposition, sparse grids and Bayesian Inference

FAA-Sponsored Project

A. Emery and E. Casterline

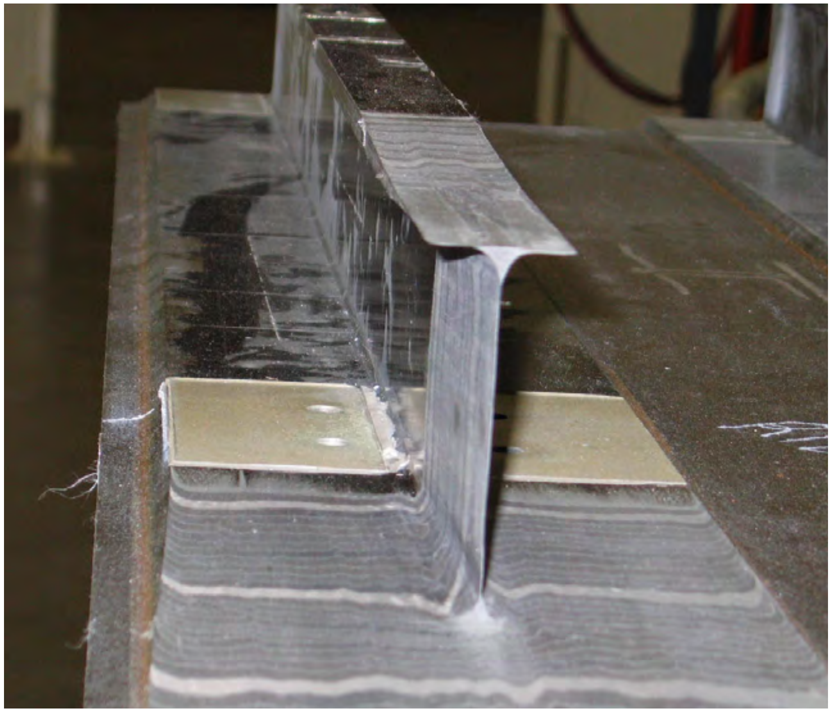
Heatcon and Boeing

Current Process

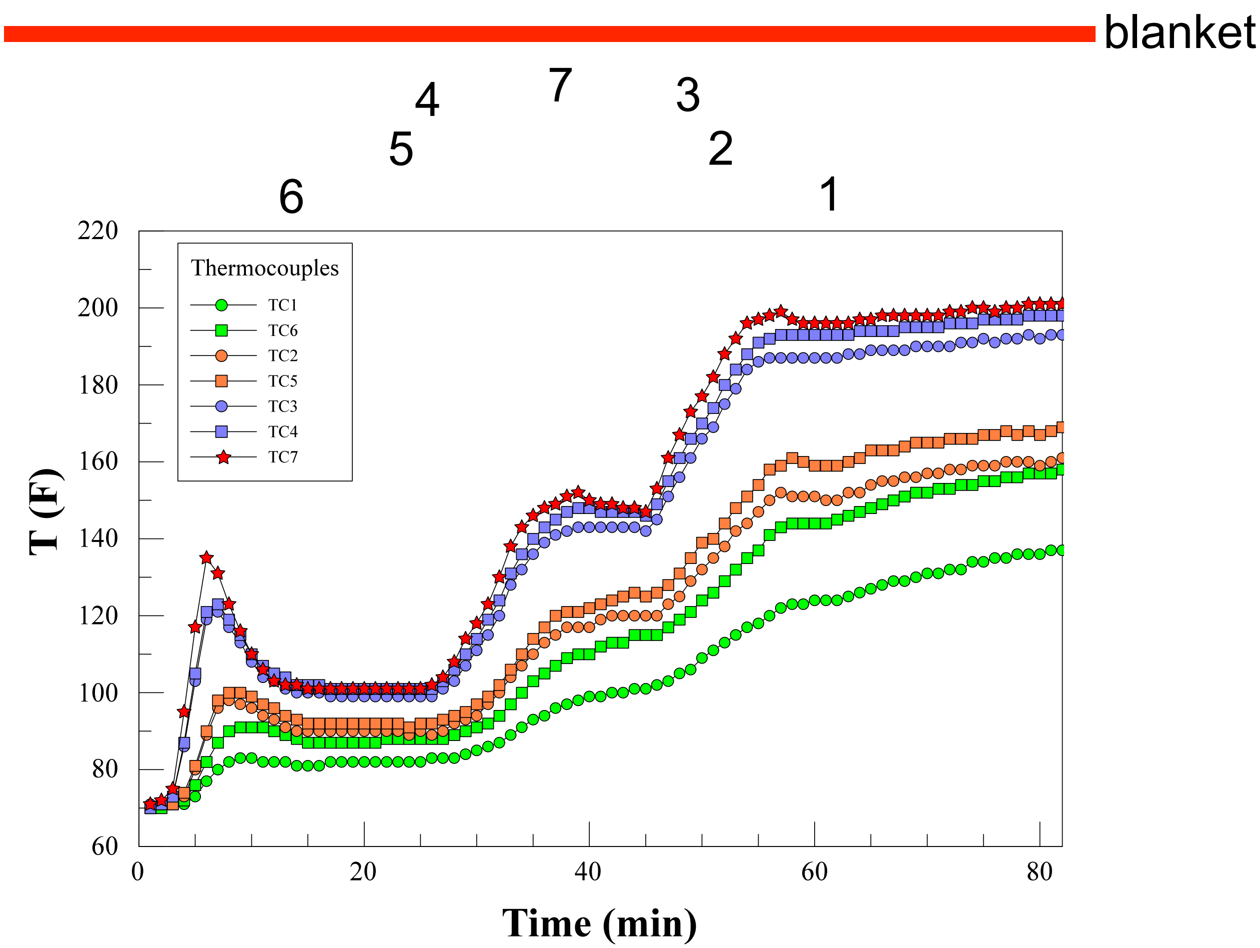
1. install any necessary structural forms
2. emplace a surrogate repair patch
3. instrument the repair zone with thermocouples
4. Install the blanket and heat and measure thermocouple temperatures and take thermograms of the blanket surface temperature
5. determine which areas are over or underheated
6. estimate what additional local heating and/or insulation are needed
7. Repeat steps 4-6 until the desired performance is achieved.

A typical configuration is

Any structural device under the composite will permit heat to escape, leading to cool spots.



Heating history of a panel



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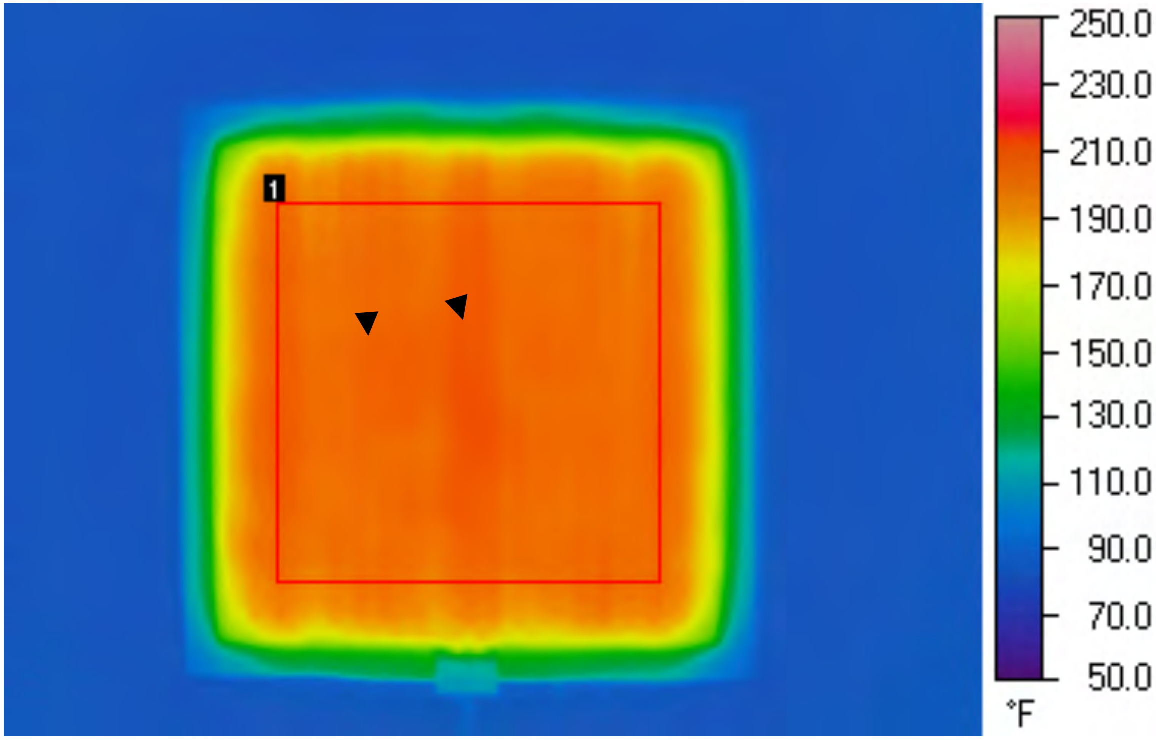
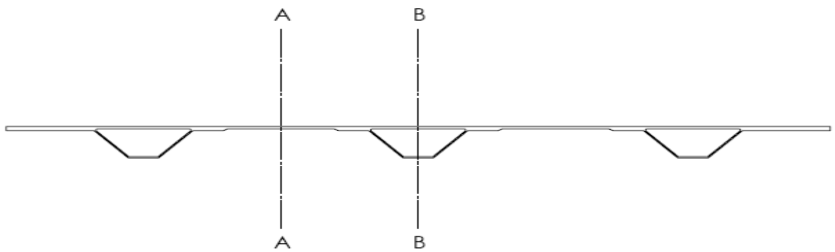
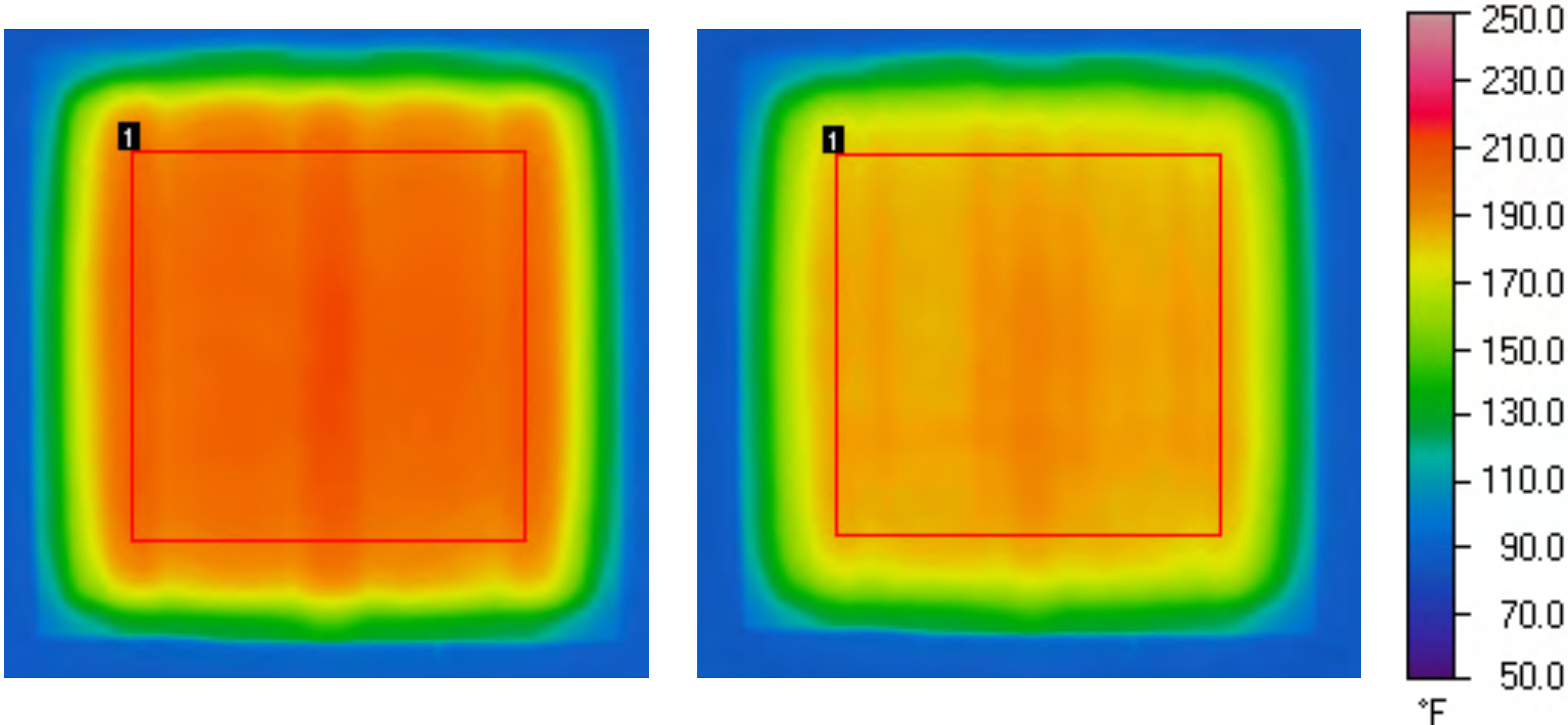
Thermogram of a panel with stringers at steady state

Note the temperature variation





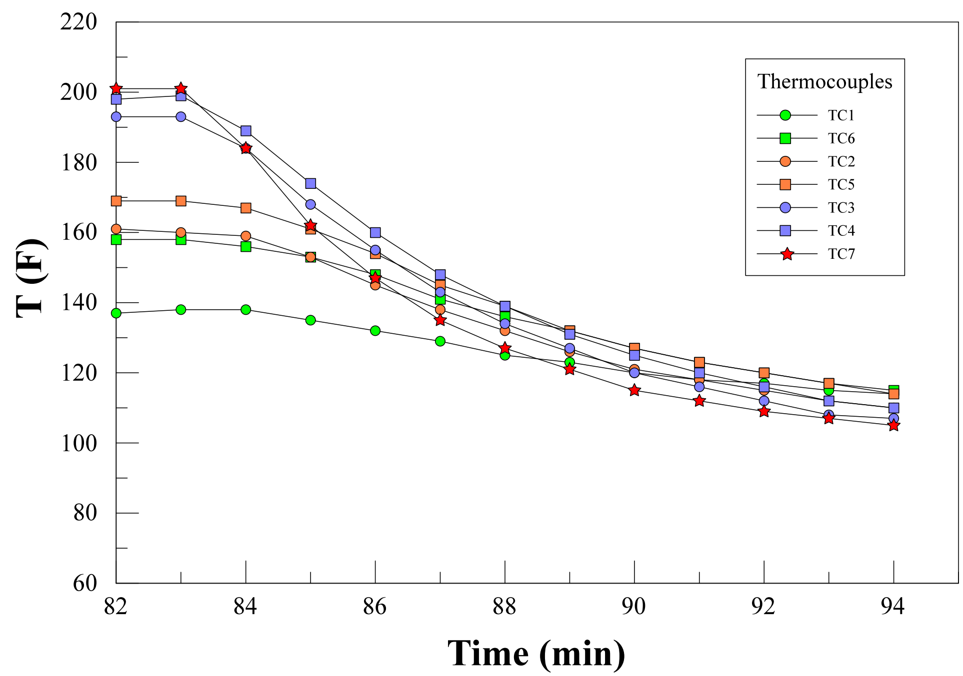
Thermogram of a panel with stringers during cool down



Time = 0 sec

Time = 30 sec

Temperature Variation During Cooldown



How to estimate the heat loss from the temperature measurements

Construct a finite element model with uncertain parameters, P, and adjust the values of P until the model agrees with the measurements.

The parameters would include the heating rate and any thermal coefficients to characterize the heat transfer.

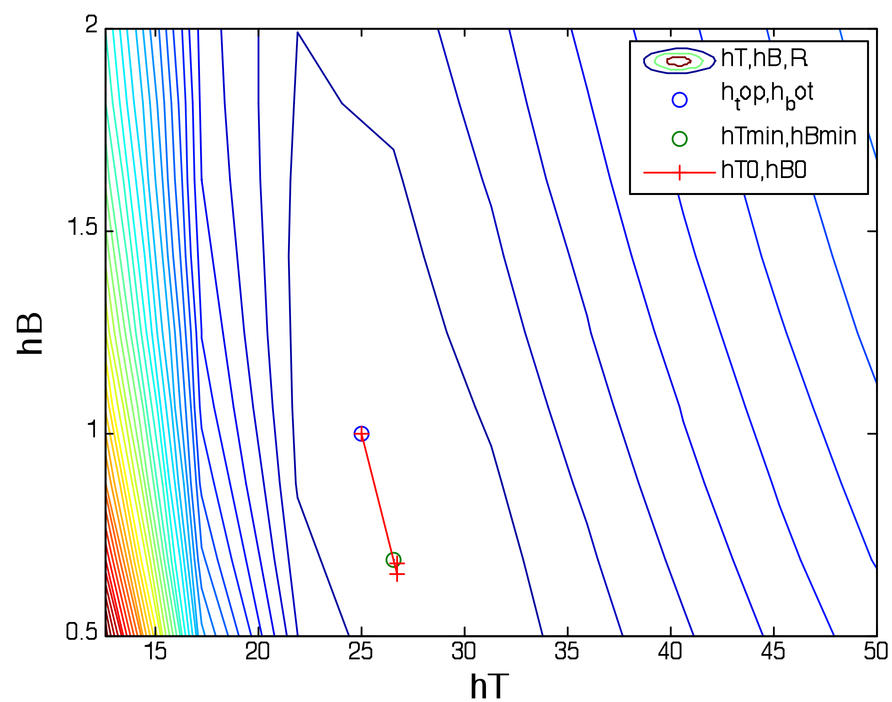
Let M(P) be the finite element model, guess initial values of P calculate the sensitivity of the model to each P, use the least squares method to correct the values of P

$$A = \left[\frac{\partial \{M\}}{\partial P_1} \quad \frac{\partial \{M\}}{\partial P_2} \quad \frac{\partial \{M\}}{\partial P_n} \right]$$

$$\begin{Bmatrix} \Delta P_1 \\ \Delta P_2 \\ \Delta P_n \end{Bmatrix} = (A^T A)^{-1} A^T \{T - M(P_0)\}$$

For the Panel Test

Estimating the convective heat transfer coefficients and heat losses



The flat valley means that it is hard to find the minimum point with precision and a large number of computations will be needed.

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Minimizing computer use is critical because 3D models are expensive in terms of execution time and memory.

This is particularly important for the non-linear problems that have temperature dependent properties and particularly when air currents must be considered.

Two approaches are suggested:

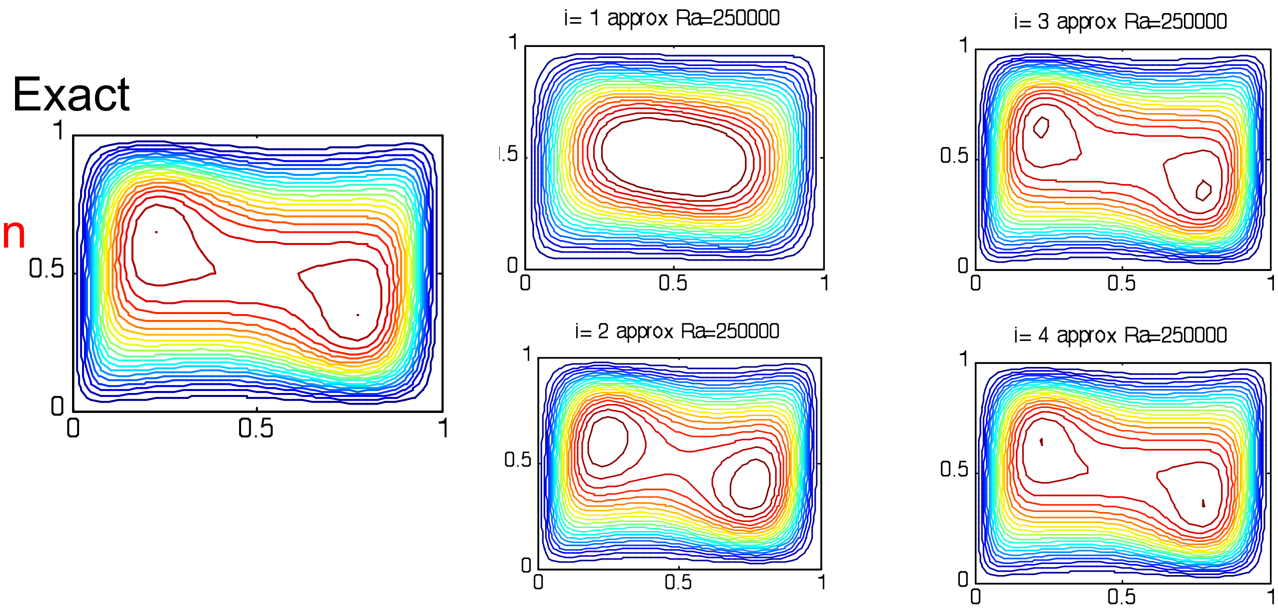
1) Reduced models using Proper Orthogonal Decomposition
2) Using sparse grids to define the parameter values

Proper Orthogonal Decomposition

The method examines snapshots of the computed response to extract information about the basic patterns contained in the response.

Using only the fundamental patterns reduces the computational expense

Example:
Free Convection
In a Cell



Sparse Grid

In addition to using a reduced model (POD) we also make use of the sparse grid algorithm *spinterp*

Example:

assume that the response in terms of two parameters, x and y is to be represented by a third order polynomial tensor grid

then we have

$$M(x,y) = (a_0 + a_1 x + a_2 x^2 + a_3 x^3)(b_0 + b_1 y + b_2 y^2 + b_3 y^3)$$

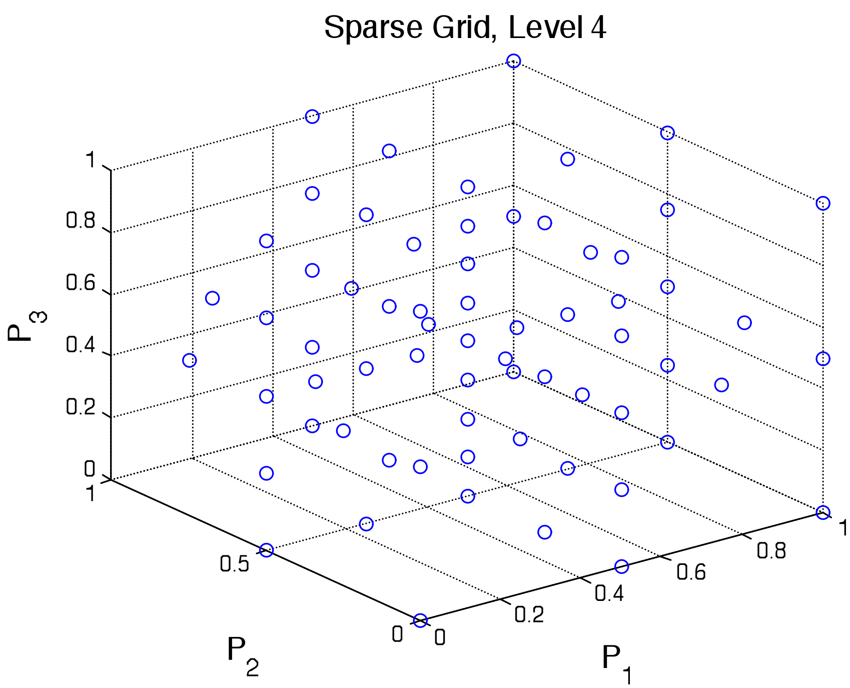
A sparse grid represents it in terms of a '*complete'* polynomial as

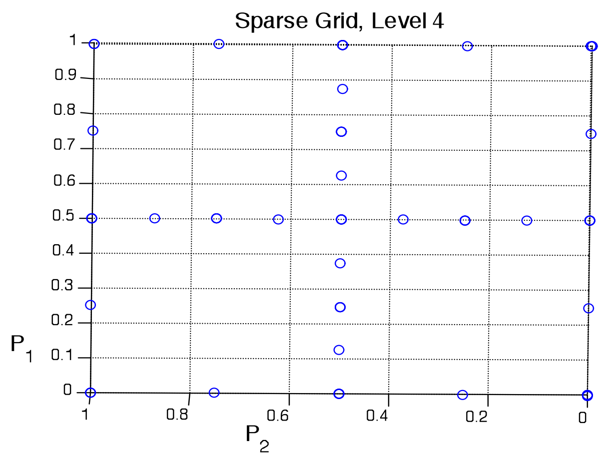
$$a_0 + a_1 x + a_2 y + a_3 x^2 + a_4 xy + a_5 y^2 + a_6 x^3 + a_7 x^2 y + a_8 xy^2 + a_9 y^3$$

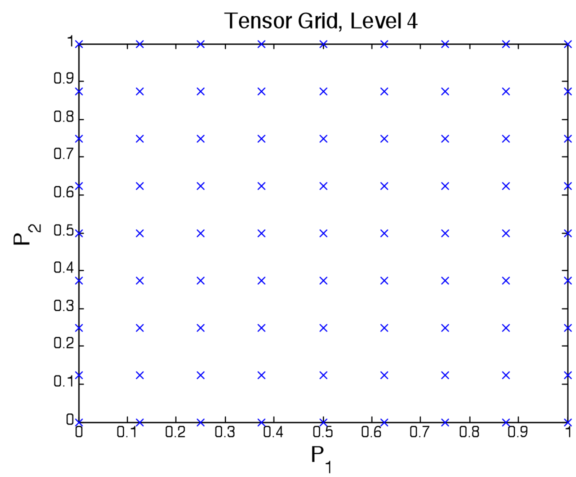
The grid points are optimized to give the best fit of the response and integrals of the response

Tensor Grid would require 729 sample points

Sparse Grid requires 177

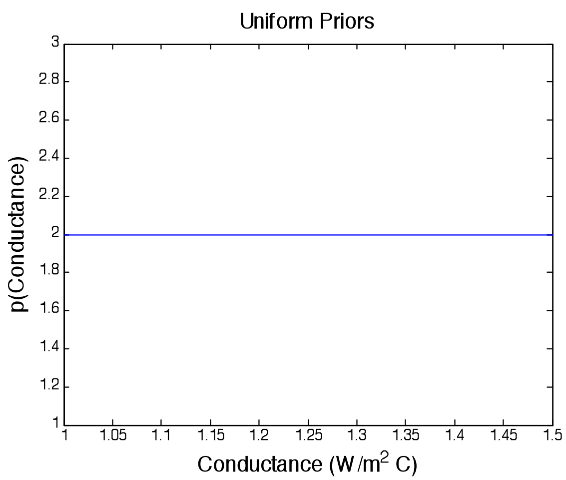


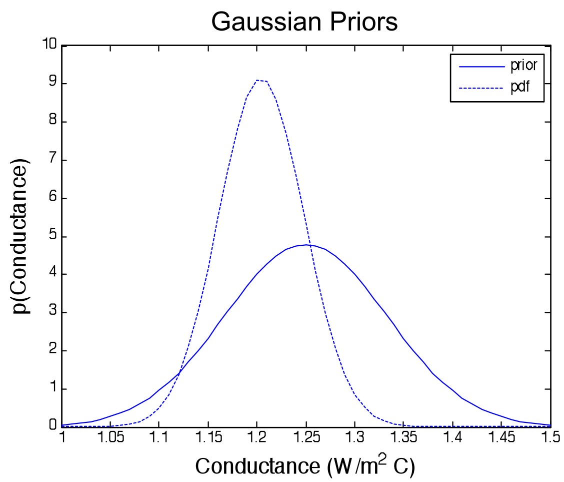




Bayesian Inference

From the cool down tests we find an effective conductance from the stringer through the insulating pad





Note the range which is of the order of 30% for either prior

A Look Forward

Benefit to Aviation:

Repair/Repair design can take days through weeks. Using this method the temperature measurements from one pre-repair blanket test can be used to design and construct a blanket overnight that we are confident will produce the desired repair site temperature distribution without further testing and with a high degree of confidence.

A Look Forward

Needed:

Once the procedure for determining the heat losses has been validated, an algorithm for optimizing the spatial distribution of heat will be developed.

Experimental validation of the entire process will then be done using typical repair configurations chosen by Heatcon, Boeing, and other aviation sources.

Status of Experiments and Modeling 11-03-2009

1) Test 4: first well defined experiment. Analyzed using several different models: a) two heat transfer coefficients, top and bottom
b) three coefficients, top, bottom, and stringer
Analysis predicts temperatures with reasonable accuracy.
Uncertainty in h about 20%

2) Test 5: aluminum heat sink attached to stringer. Analysis just begun

3) Instrumenting panel with more thermocouples

4) Questions about thermocouple placement and tape emissivity need to be resolved.

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Current TC Placement

10 (107)

9 (146)

8 (185)

7 (107)

3 (87)

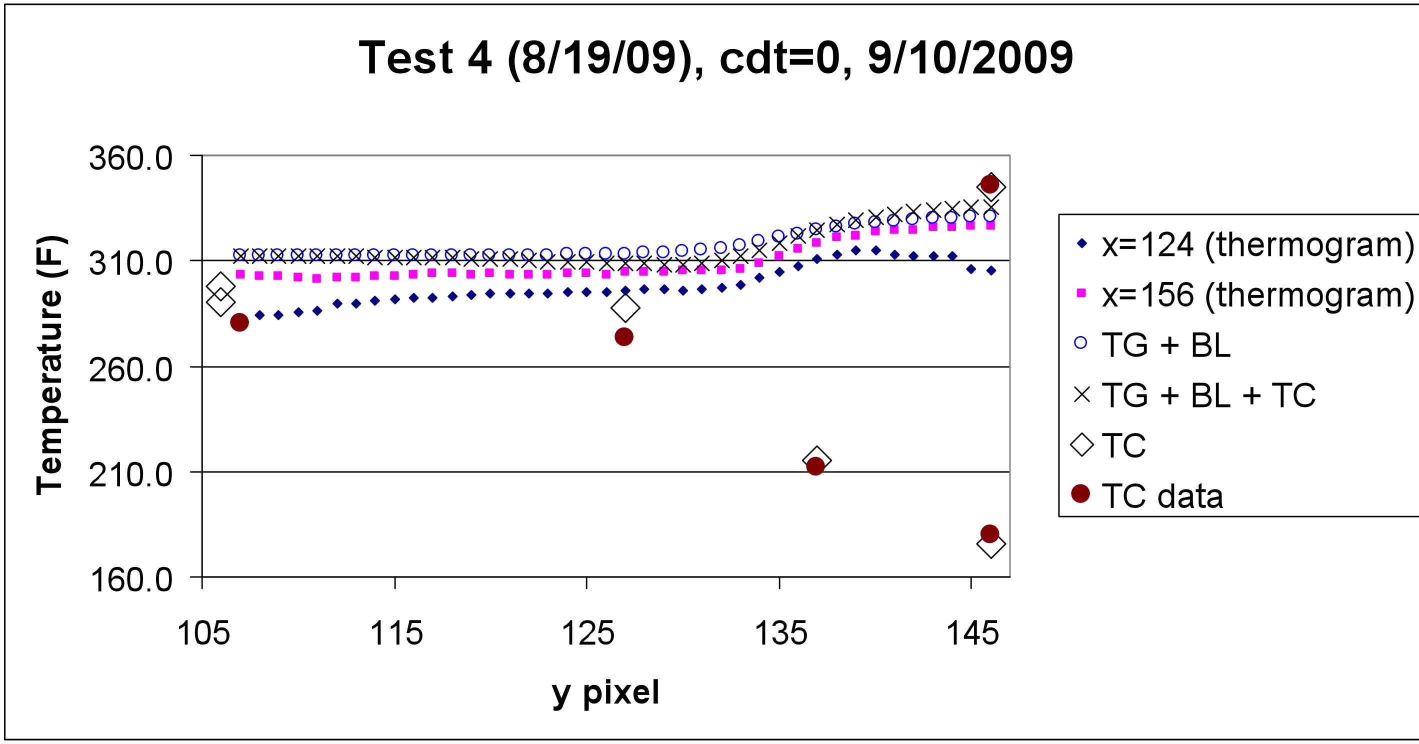
4 (127)

5 (137)

2 (77)

1 (68)

6 (146)



Showing the agreement between different FEM models and the data

Estimation of Model Parameters:

TG+BL+TC: thermogram and thermocouple data used with the blanket deployed.

TG+BL : only thermogram data used with the blanket deployed

TC : only thermocouple data used

X: x location of the pixel line of thermogram data 124=over the TCs
156=away from TCs

Questions

1. What kind of data are we likely to get in a real on-site preliminary test?
   Thermogram? Thermocouple?
2. Where are the TCs likely to be placed?
3. Can we get data from a Boeing Hot Air test? What kind and how many sensors?

10
(107)

9
(146)

8
(185)

7
(107)

3
(87)

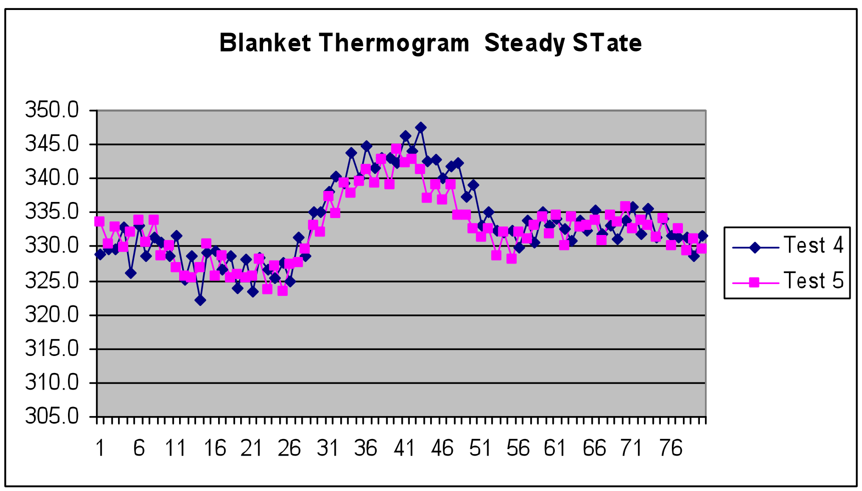
4
(127)

5
(137)

2
(77)

1
(68)

Aluminum
Heat Sink



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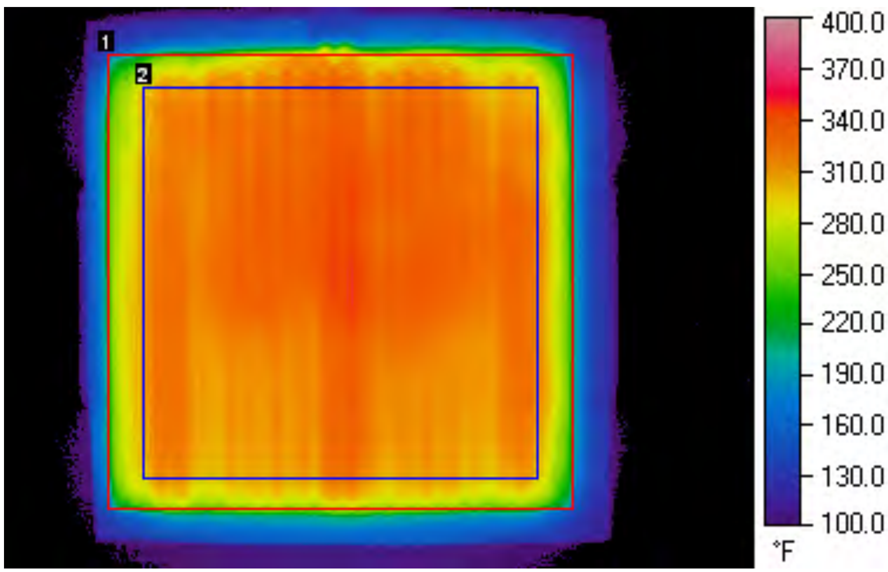
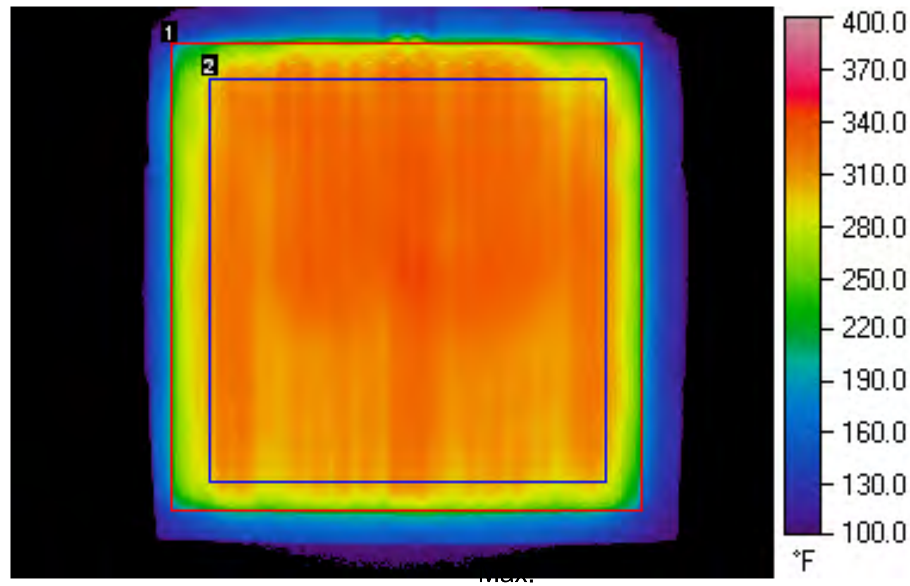
Test 4



	Min. °F	Max. °F	Avg. °F	Range °F
Rotated Rect 1	146.8	348.5	309.5	201.7
Rotated Rect 2	287.9	348.5	320.9	60.6

Test 5



	Min. °F	Max. °F	Avg. °F	Range °F
Rotated Rect 1	134.7	344.2	307.6	209.5
Rotated Rect 2	284.8	344.2	319.9	59.4

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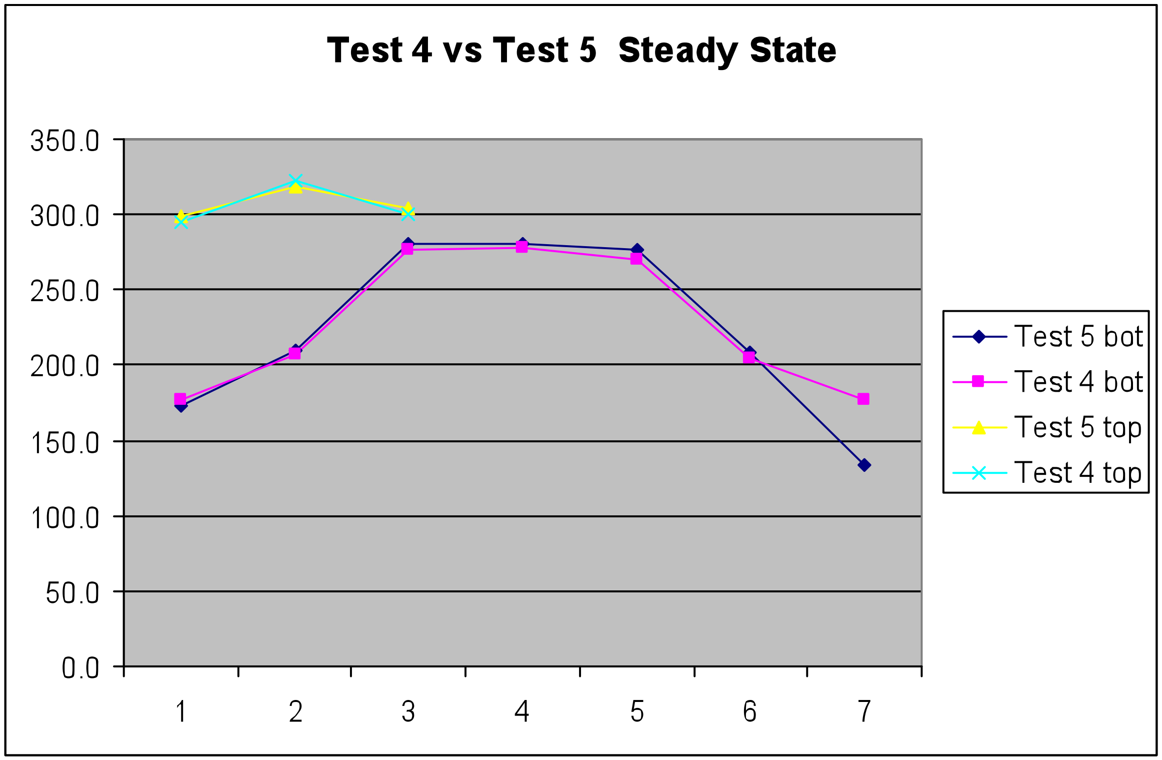
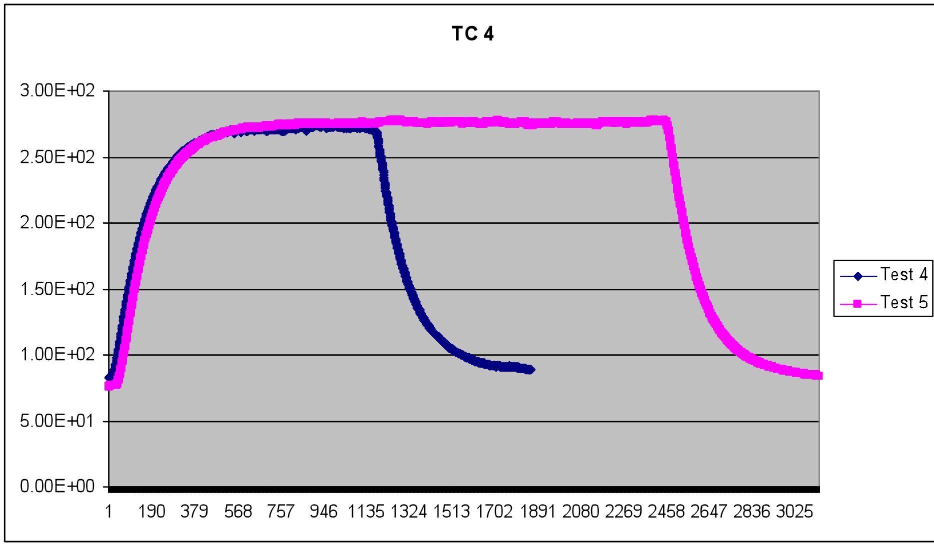
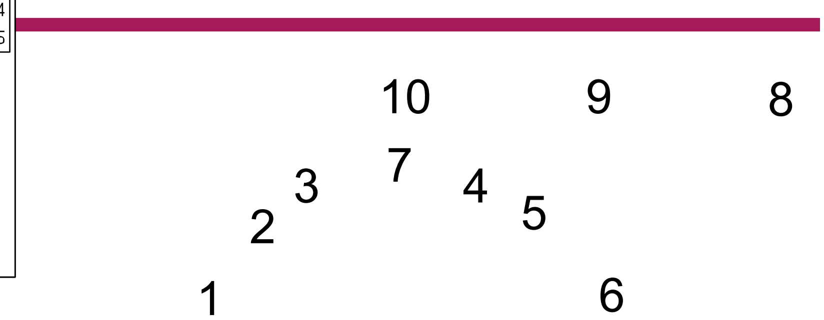



TC 4
3.00E+02
2.50E+02
2.00E+02
1.50E+02
1.00E+02
5.00E+01
0.00E+00
1 190 379 568 757 946 1135 1324 1513 1702 1891 2080 2269 2458 2647 2836 3025
Test 4
Test 5


10
9
8
7
3
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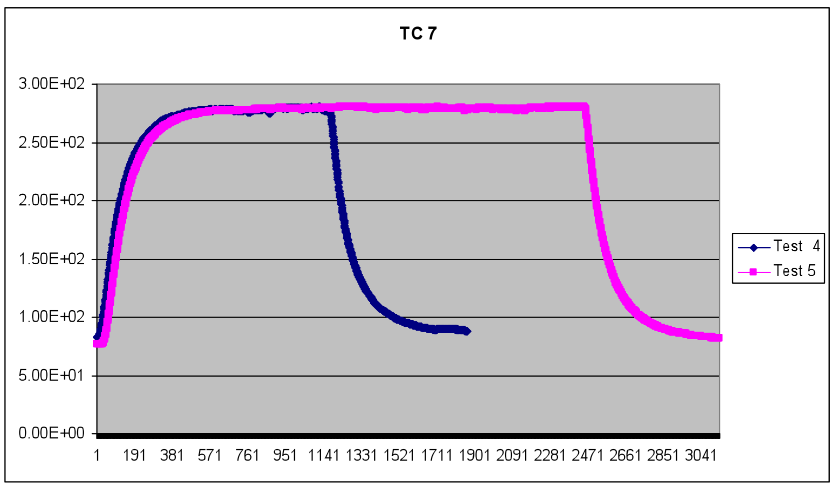
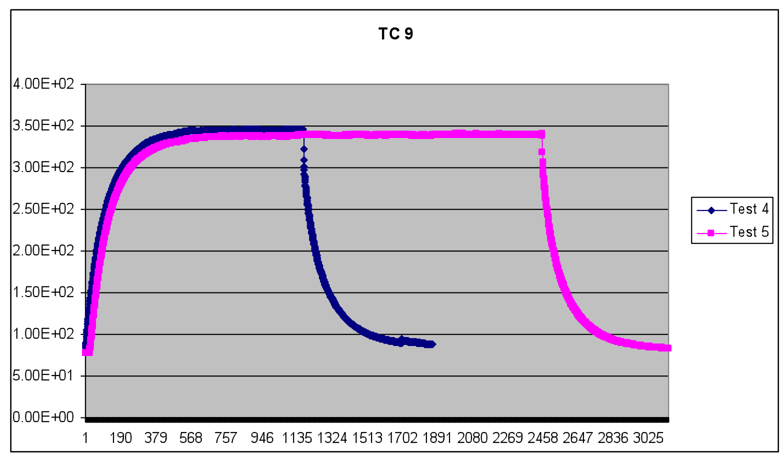
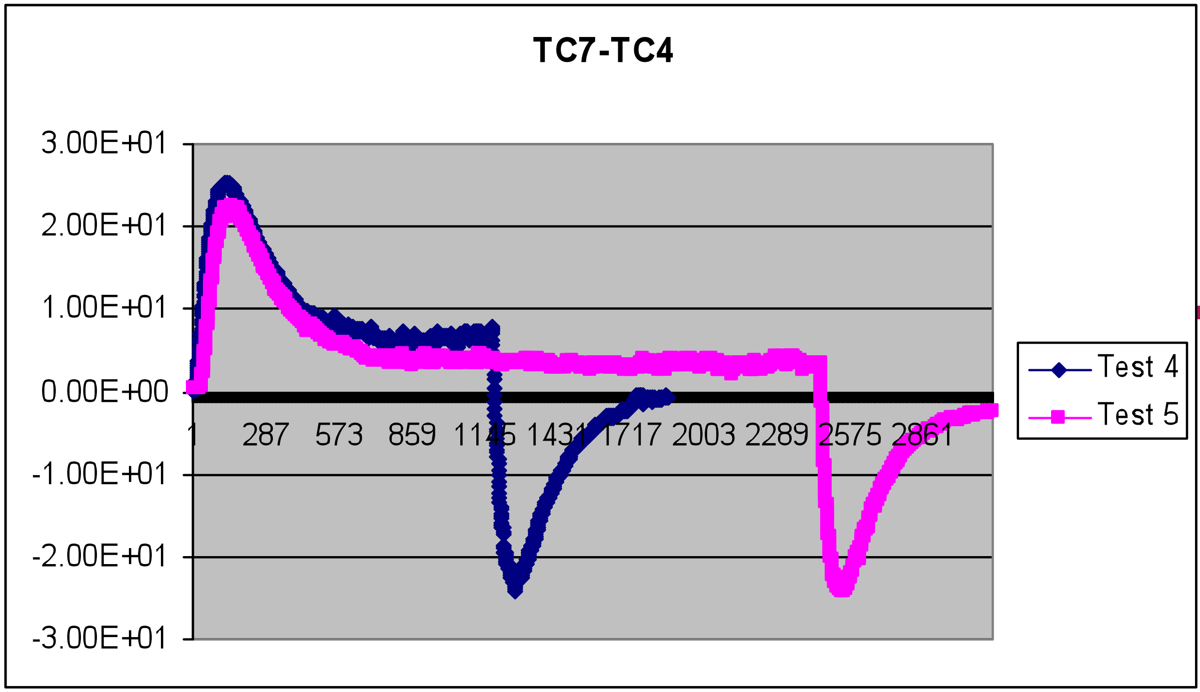
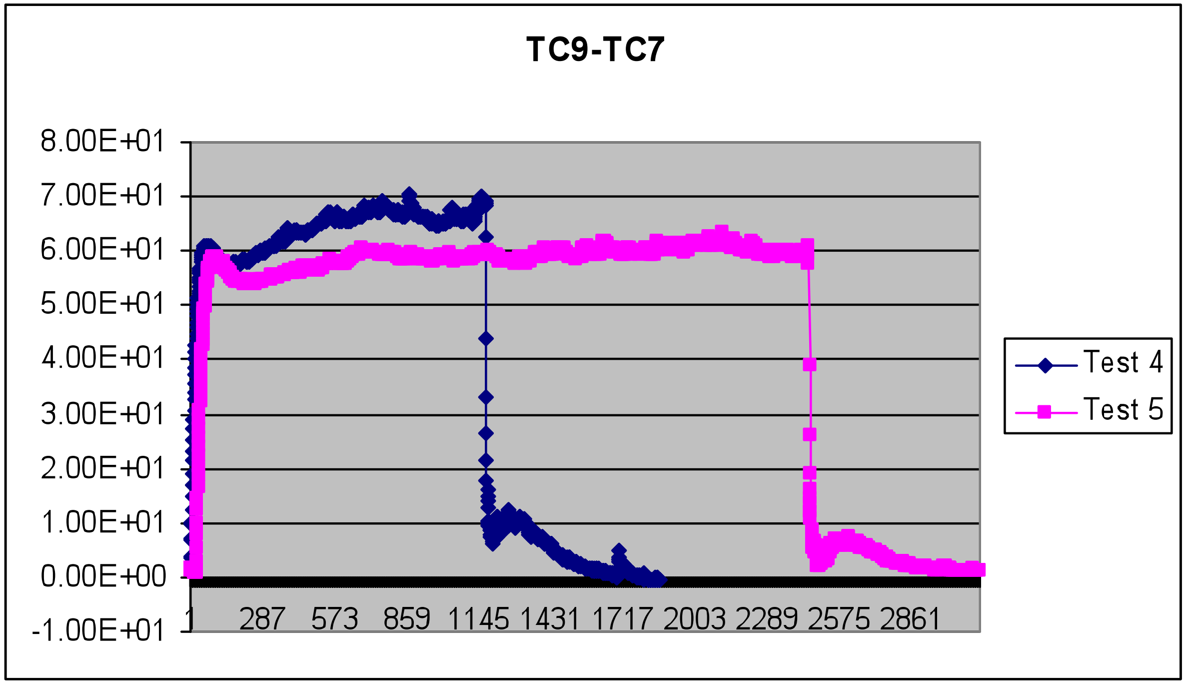
2
5
1
6


TC 7
3.00E+02
2.50E+02
2.00E+02
1.50E+02
1.00E+02
5.00E+01
0.00E+00
1 191 381 571 761 951 1141 1331 1521 1711 1901 2091 2281 2471 2661 2851 3041
Test 4
Test 5


TC 9
4.00E+02
3.50E+02
3.00E+02
2.50E+02
2.00E+02
1.50E+02
1.00E+02
5.00E+01
0.00E+00
1 190 379 568 757 946 1135 1324 1513 1702 1891 2080 2269 2458 2647 2836 3025
Test 4
Test 5



TC7-TC4
3.00E+01
2.00E+01
1.00E+01
0.00E+00
-1.00E+01
-2.00E+01
-3.00E+01
1 287 573 859 1145 1431 1717 2003 2289 2575 2861
Test 4
Test 5



TC9-TC7
8.00E+01
7.00E+01
6.00E+01
5.00E+01
4.00E+01
3.00E+01
2.00E+01
1.00E+01
0.00E+00
-1.00E+01
1 287 573 859 1145 1431 1717 2003 2289 2575 2861
Test 4
Test 5

Heating