Optimizing Composite Repair by Tailored Heat Sources

The Joint Advanced Materials and Structures Center of Excellence

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
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- Approach: An Inverse Analysis using Finite Elements, Proper Orthogonal Decomposition, Sparse Grids and Bayesian Inference
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FAA Sponsored Project Information

- A. Emery and E. Casterline
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- Curtis Davies, FAA Technical Monitor
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- Heatcon and Boeing
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Goal

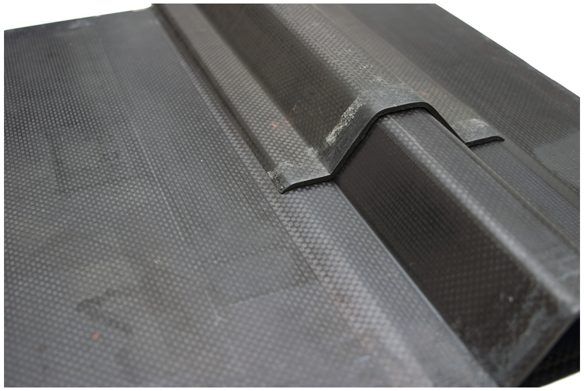
To specify the spatial distribution of heat flux from a heating source (blanket)
to produce
a specified and constant temperature throughout the cure zone

with a minimum of pre-repair testing

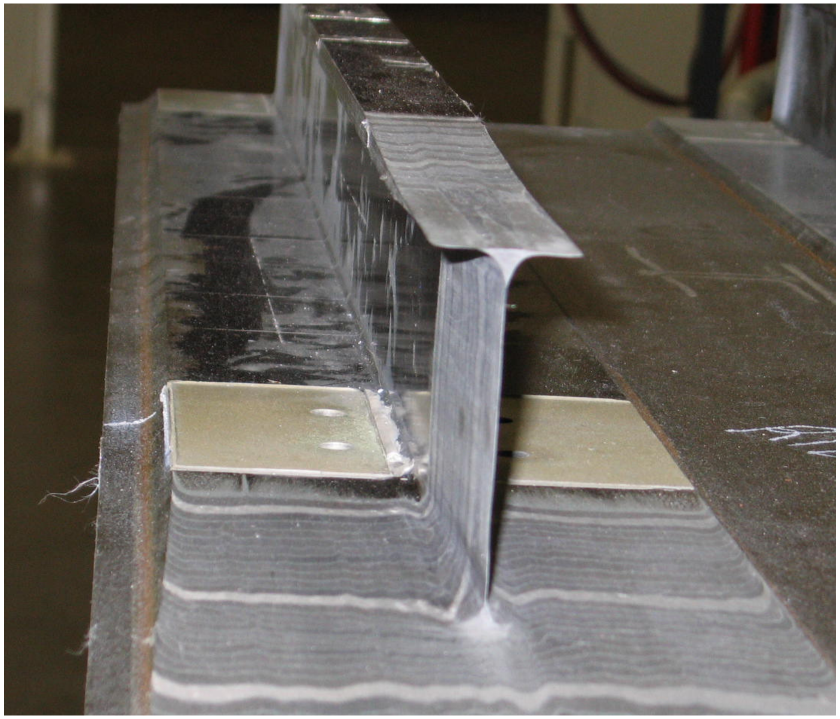
Current Process

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.

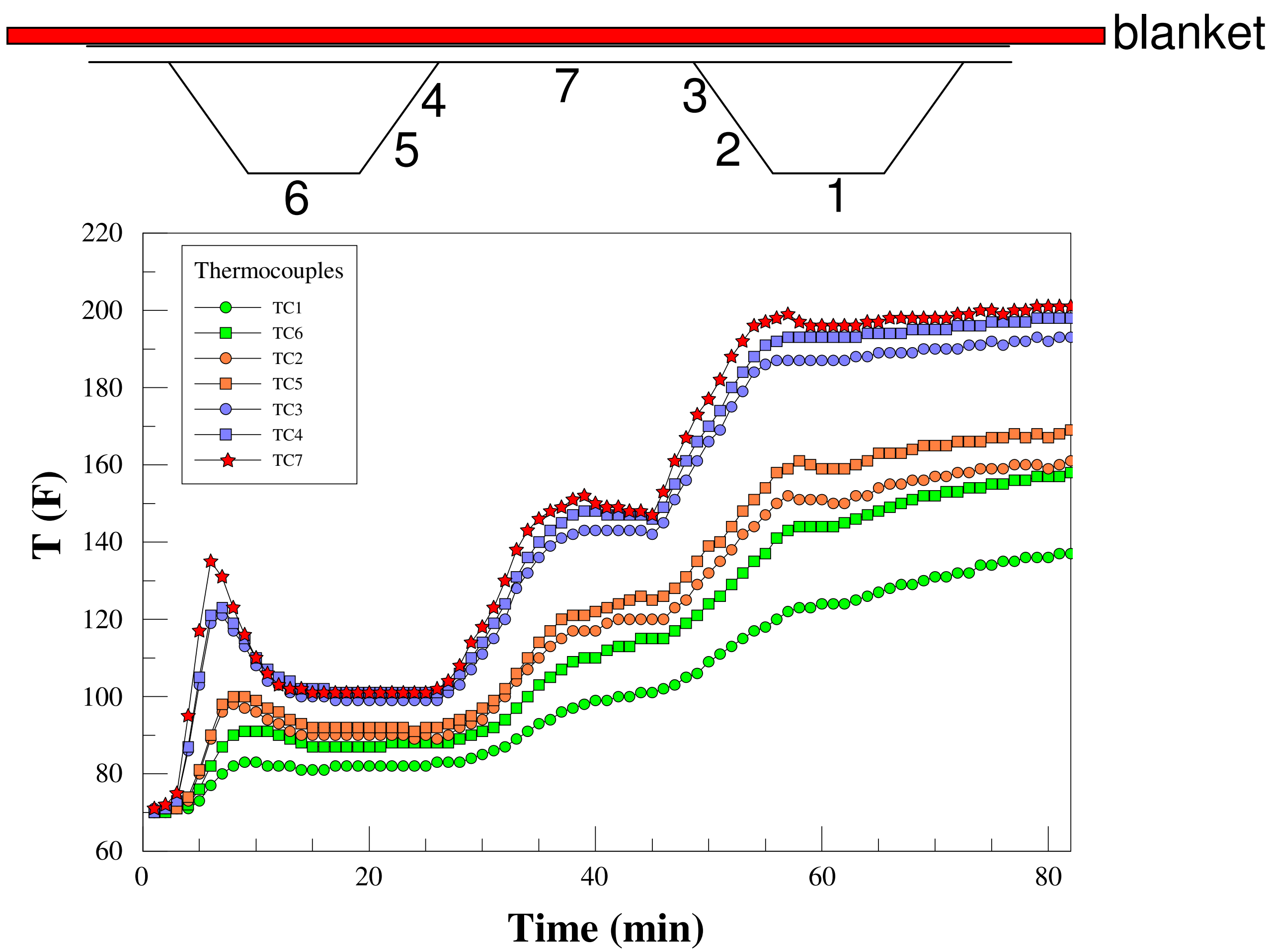
A typical configuration is



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

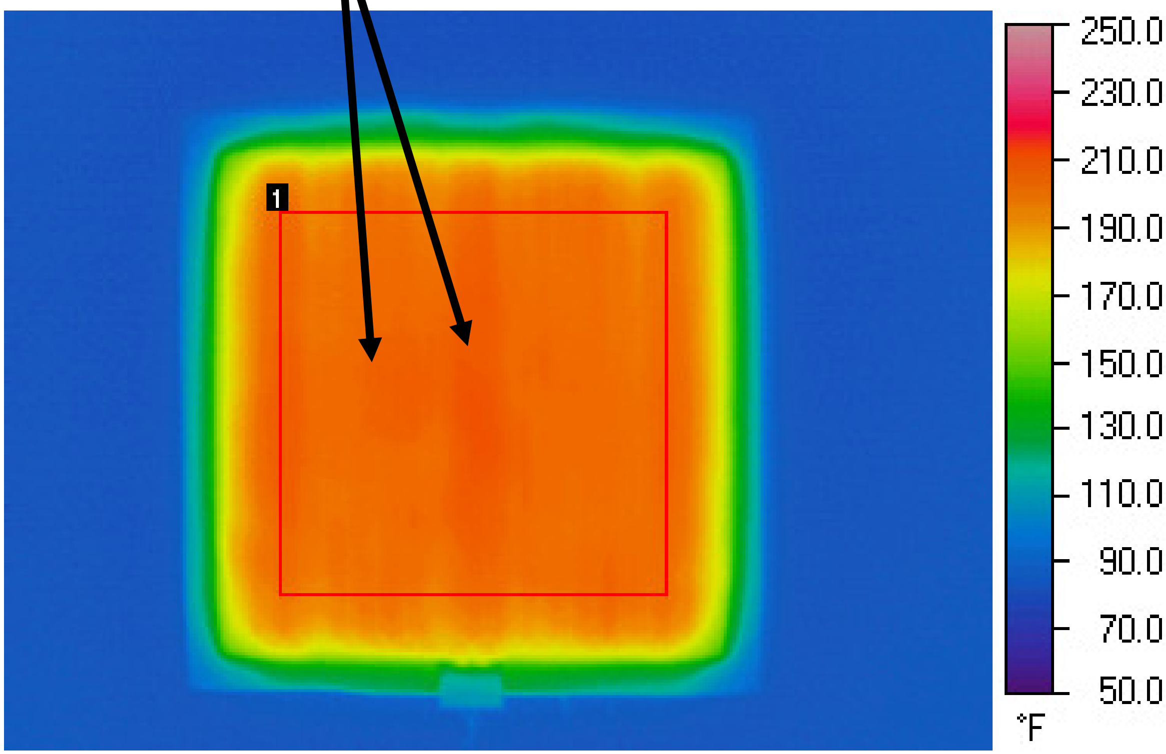


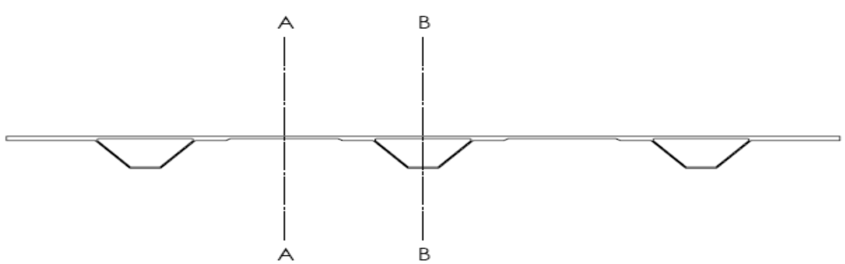
Heating history of a panel



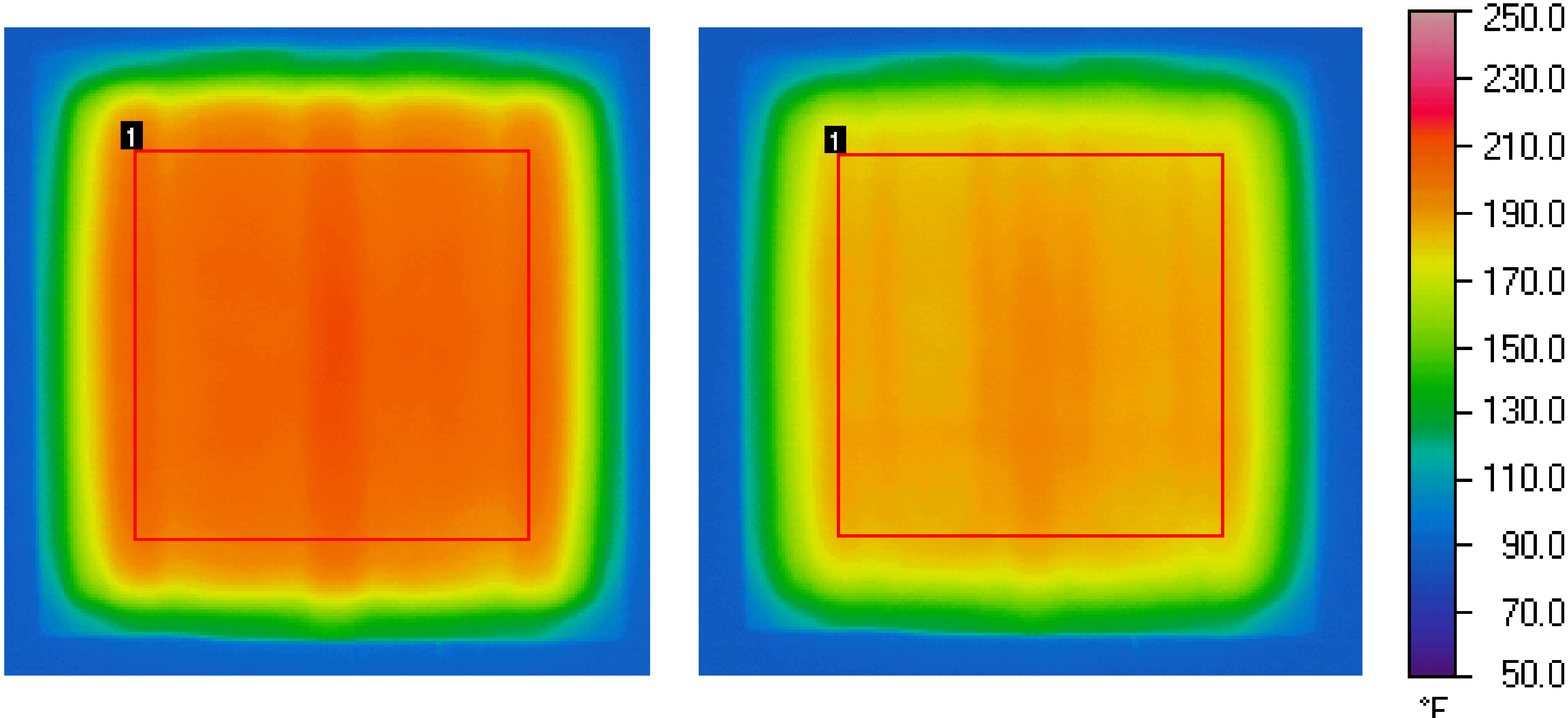
Thermogram of a panel with stringers at steady state

Note the temperature variation





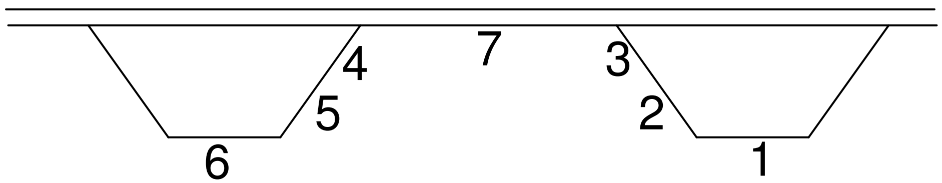
Thermogram of a panel with stringers during cool down

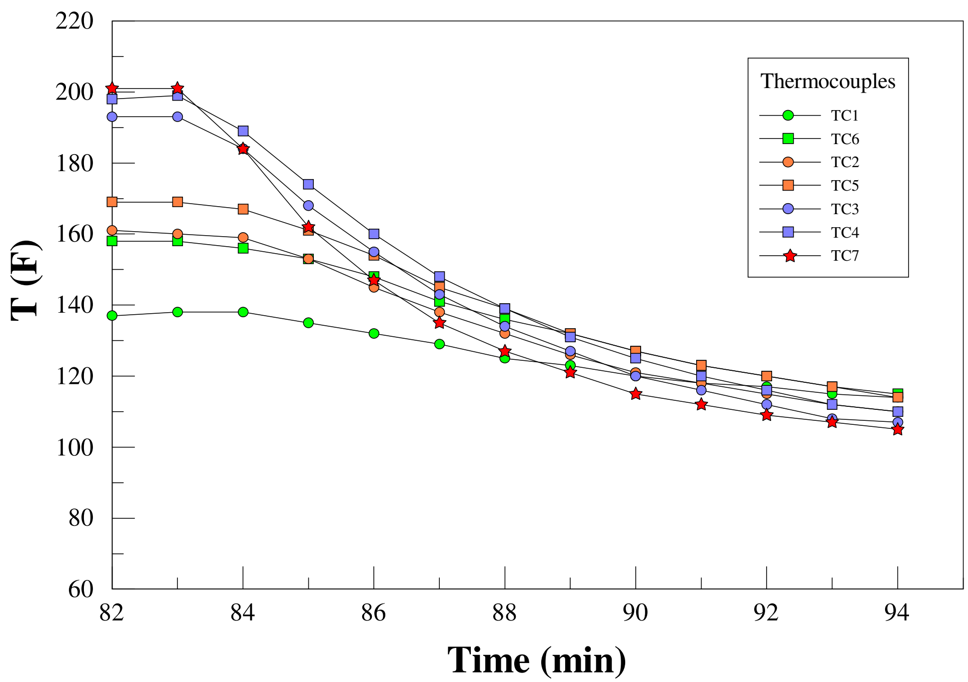


Time = 0 sec

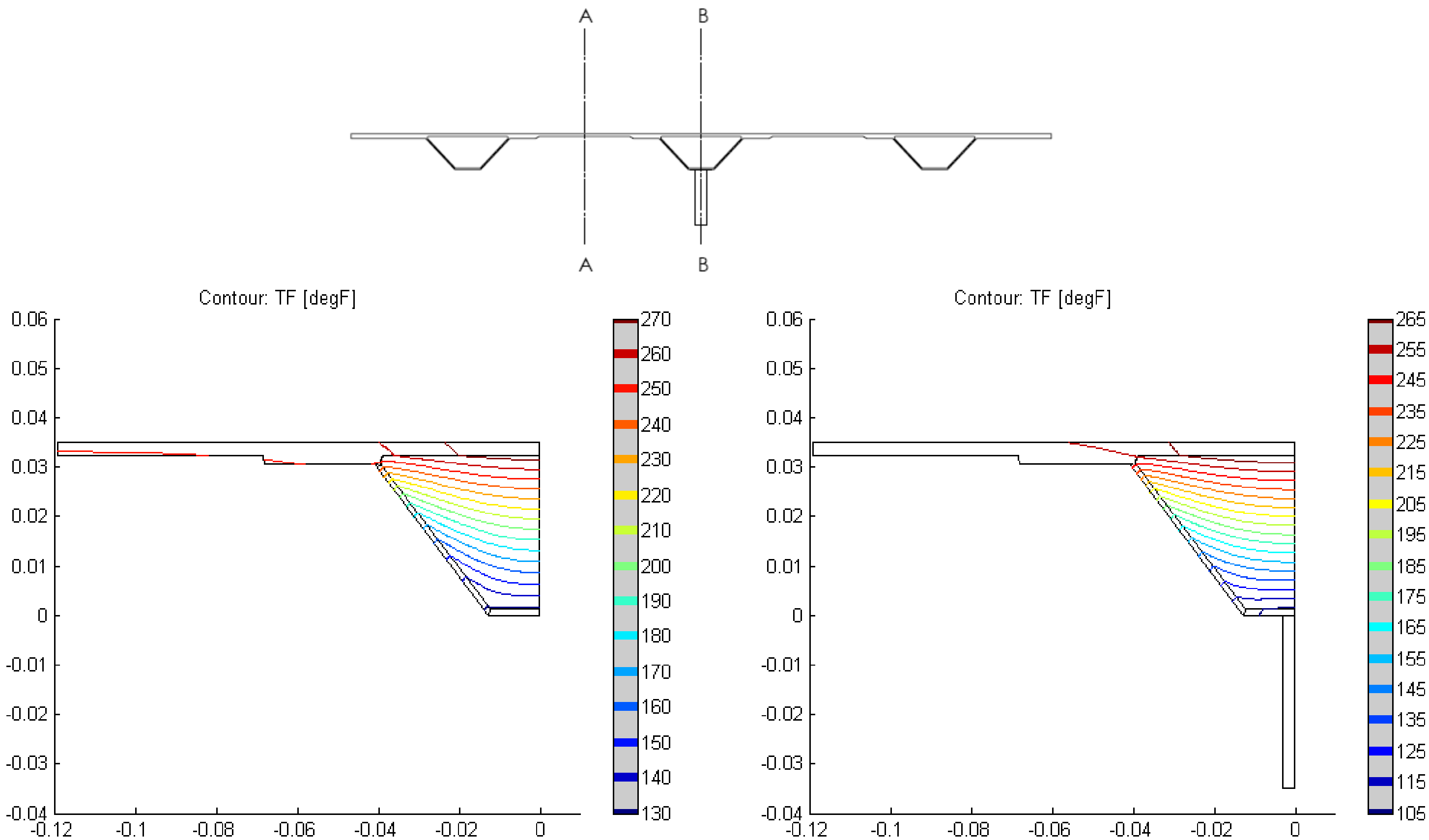
Time = 30 sec

Temperature Variation During Cooldown





Differential Cooling due to Heat Loss through the base of the stringer to an I beam



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.

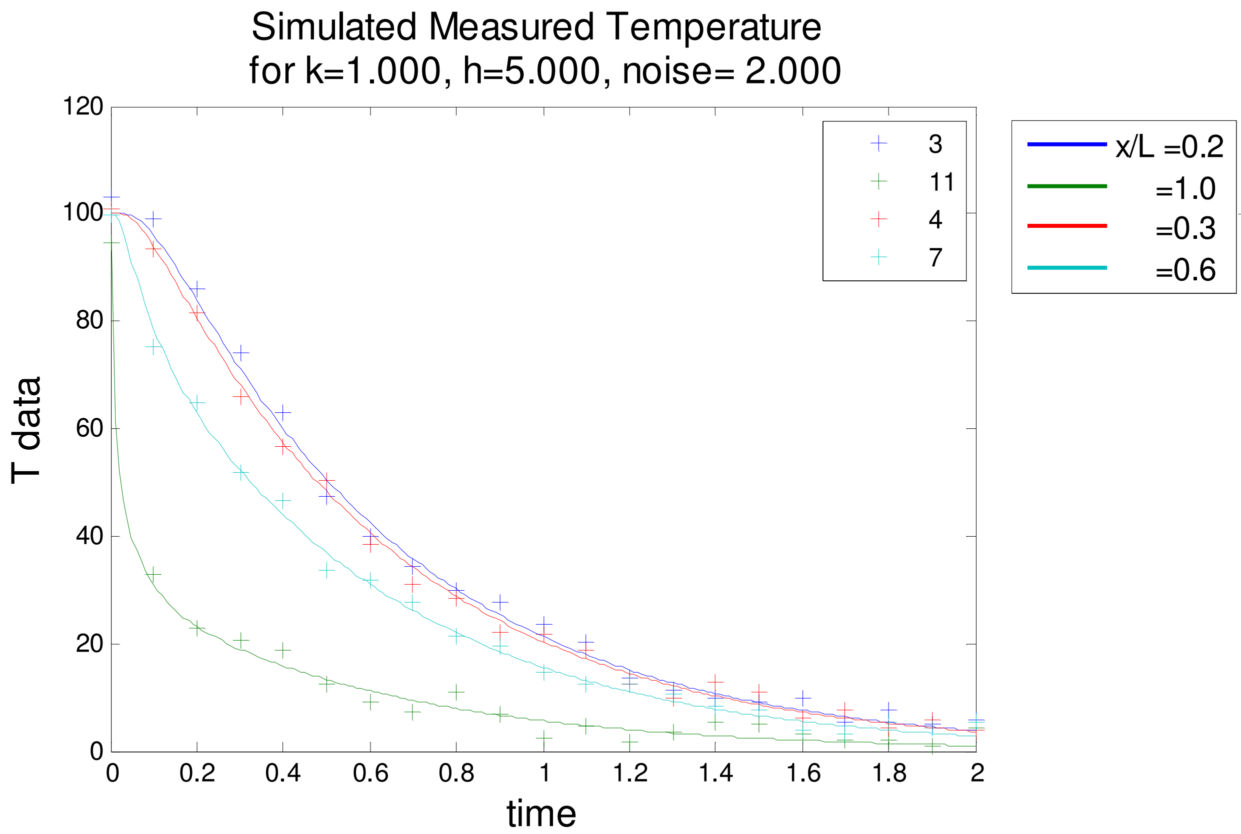
The parameters would include the heating rate and any thermal coefficients to characterize the heat transfer.

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

$$A = \begin{bmatrix} \dfrac{\partial\{M\}}{\partial P_1} & \dfrac{\partial\{M\}}{\partial P_2} & \dfrac{\partial\{M\}}{\partial P_n} \end{bmatrix}$$

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

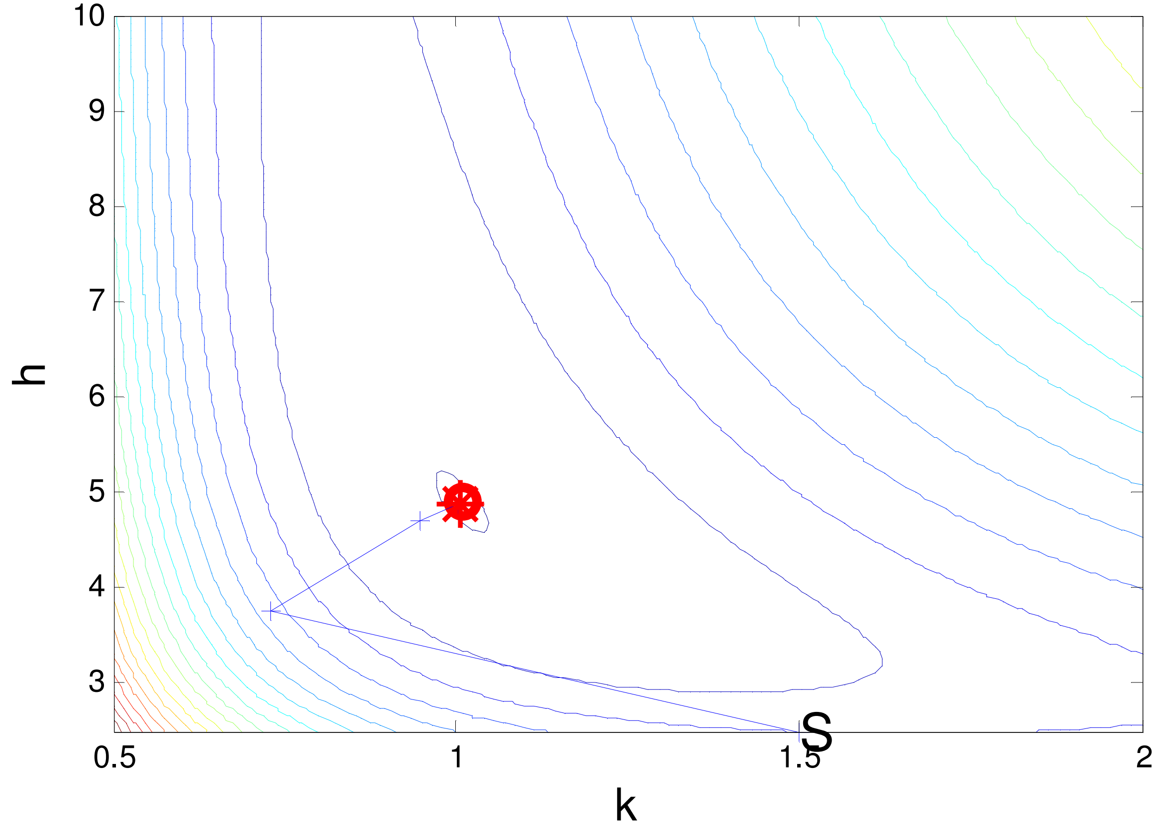
Temperatures measured in a conducting rod with uncertain thermal conductivity and surface convective heat transfer coefficient



Best parameter values are those that minimize the residual

$$\sum_i [T_i - M_i(P)]^2$$

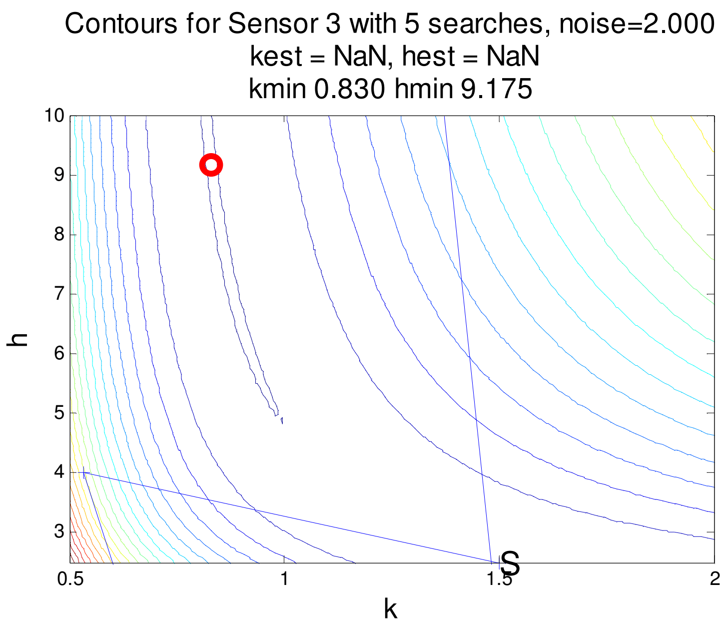
Contours for 4 Sensors with 7 searches, noise=2.000
kest = 1.007, hest = 4.888
kmin 1.010 hmin 4.900

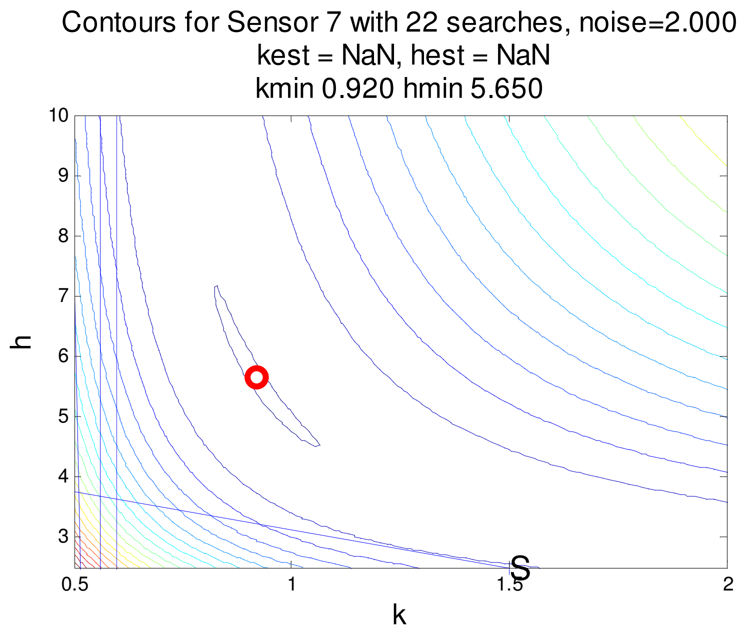


Not all searches work well

Efficiency of the search depends on the specific sensor used and the sensitivity of the model parameters to that temperature

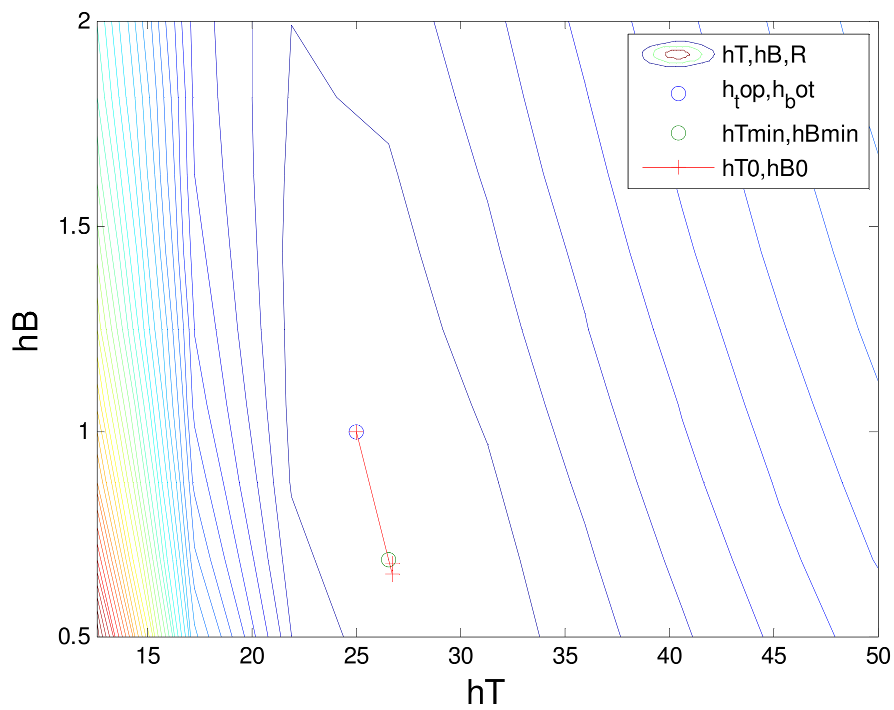
These may require much hands-on-control and heavy computer use





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.

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:

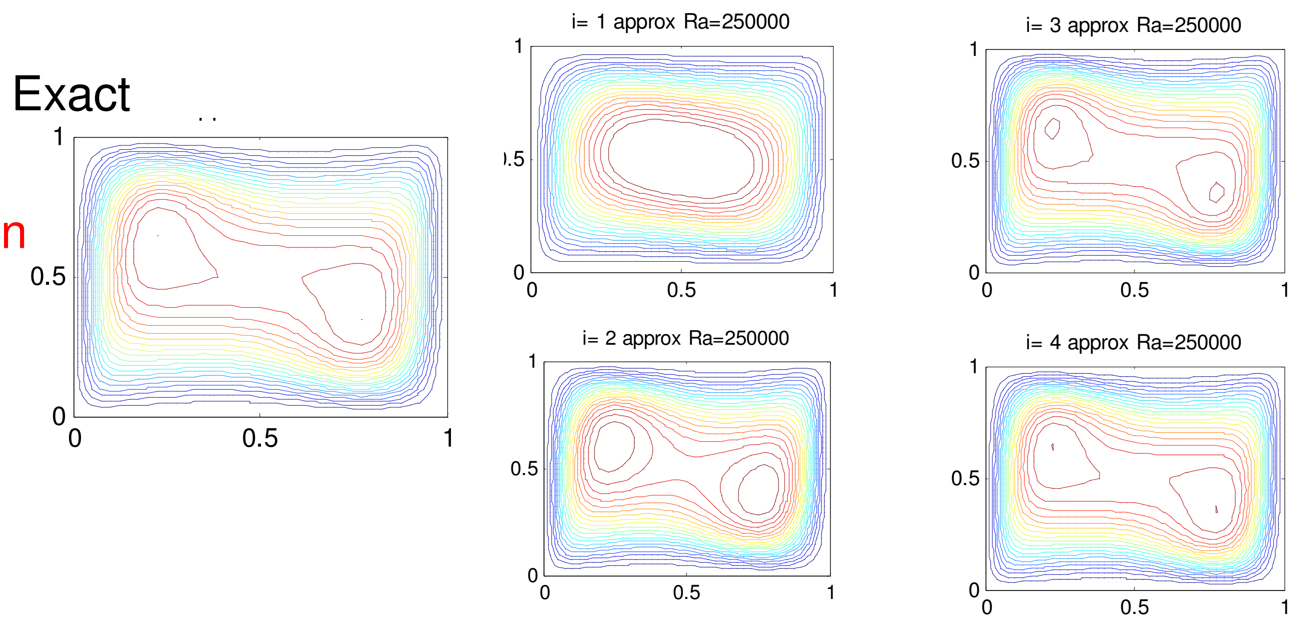
1) Reduced models using Proper Orthogonal Decomposition
2) Using sparse grids to define the parameter values

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

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

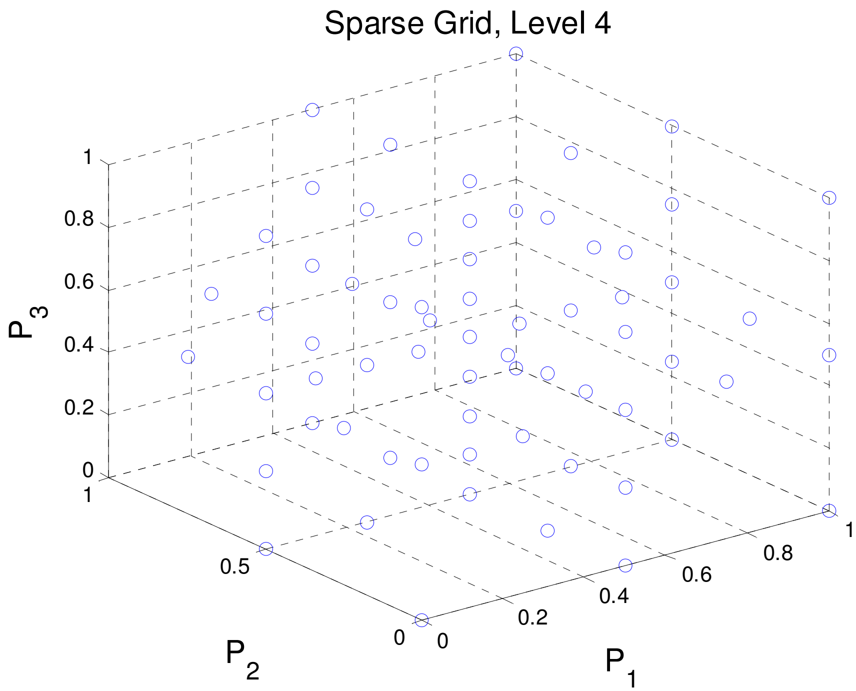
A sparse grid represents it in terms of a '*complete'* polynomial as

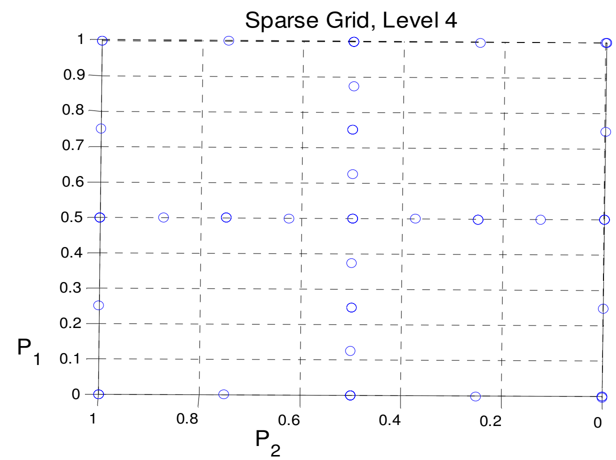
$$a_0 + a_1 x + a_2 y + a_3 x^2 + a_4 xy + a_5 y^2 + a_6 x^3 + a_7 x^2 y + a_8 xy^2 + a_9 y^3$$

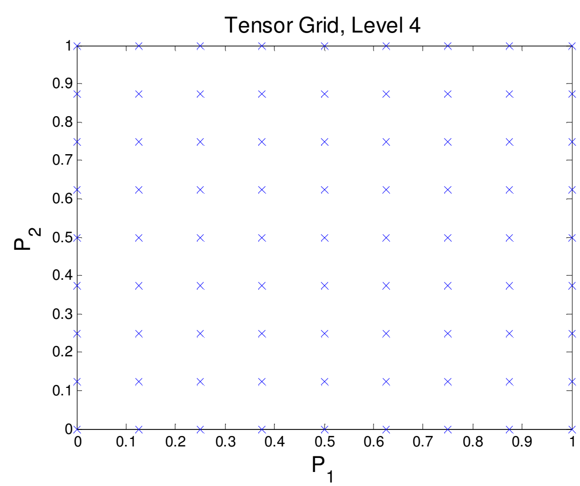
The grid points are optimized to give the best fit of the response and integrals of the response

Tensor Grid would require 729 sample points

Sparse Grid requires 177

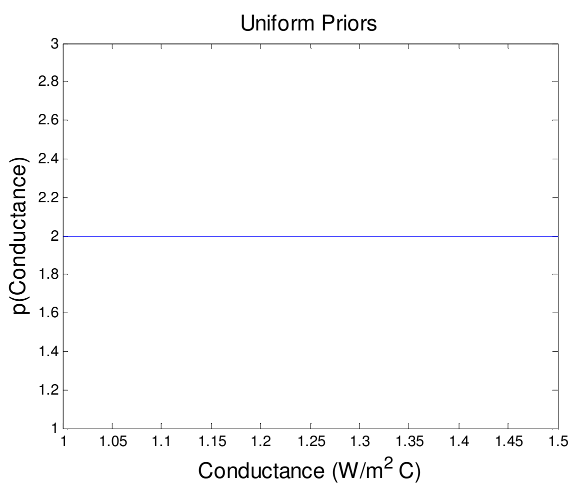


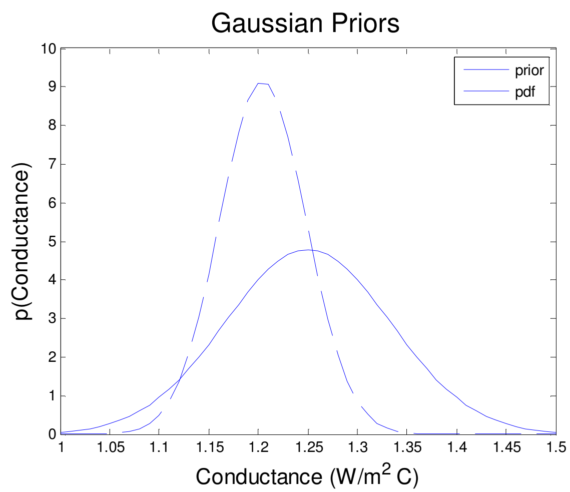




Bayesian Inference

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

Current Status

1) Testing the FEM+POD+Sparse Grid model using COMSOL
2) Determining the effect of free convection in the repair site
3) Measuring temperatures for selected repair configurations
4) Validating the FEM+POD+Sparse Grid model
5) Investigate the effect of estimates of heat losses gained from previous repairs

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.