Predicting Heat Transfer Rates For Industrial Scale Quench Tanks

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Motivation

Surface heat flux is a key input parameter for quenching simulations using DANTE or another FEA program.

Accuracy is important as surface heat fluxes have a strong influence on microstructure, residual stress, and distortion.

Without a good definition of surface heat fluxes, the chain of analysis is broken

Existing Method

The current standard is to perform a thermocouple quench trial followed by inverse analysis to extract the heat transfer coefficients

- Time-consuming
- Subject to non-unique solutions
- Costly
- Limited applicability

. . . . or other approximations are made

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The Ultimate Goal

The Holy Grail of surface heat flux specification is a direct numerical simulation of the boiling phenomena

- Avoids the issues with quench trials
- Fits directly into ICME framework
- Can address any quench situation

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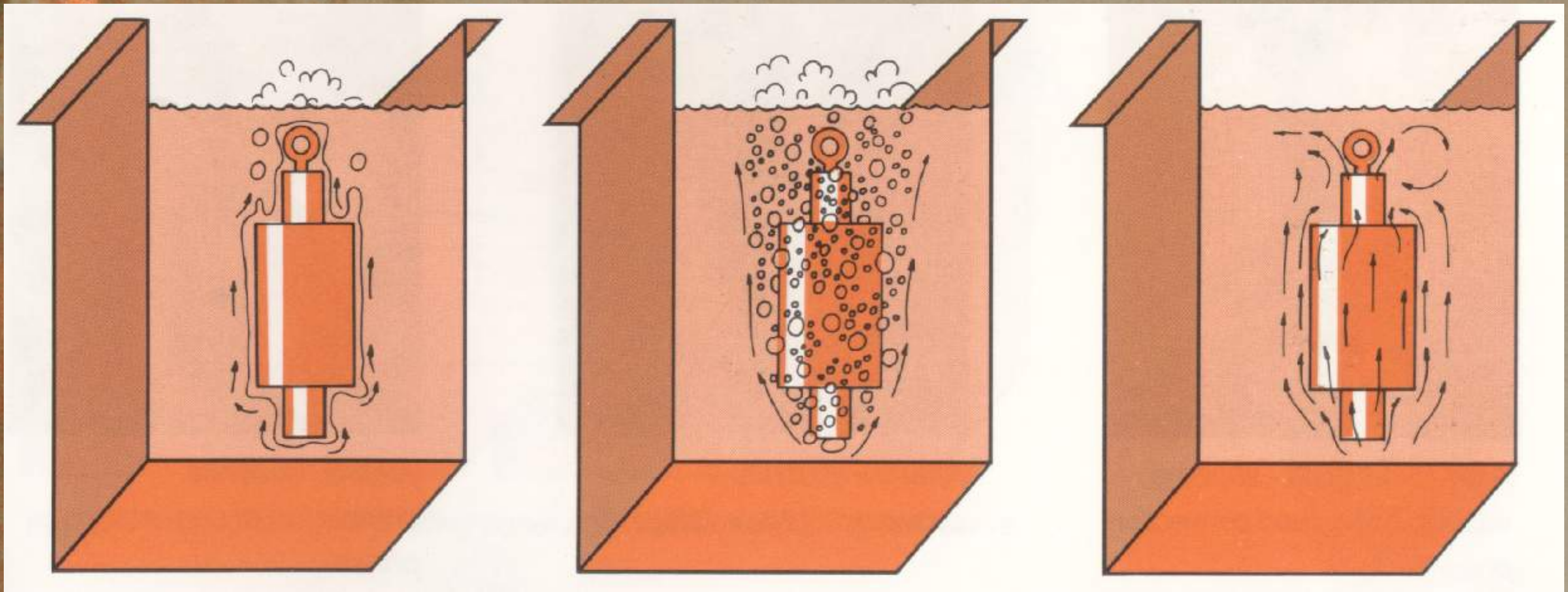
Boiling Basics

Boiling heat transfer is a highly complex process with physical phenomena that occur at small length scales and very small time scales.



Film Boiling Nucleate Boiling Convection

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What's the way forward?

- ✓ First principles simulation of boiling is impractical due to length and time scales
- ✓ Current mechanistic simulation methods may rely on tunable parameters
- ✓ Further development is hampered by the lack of flow boiling heat flux data in the literature
  - Water at significant subcooling
  - Quench oil under any conditions
  - Polymer solutions under any conditions
- ✓ Development of a flow boiling database can:
  - Aid in the development of improved mechanistic models
  - Be used directly for quenching simulations

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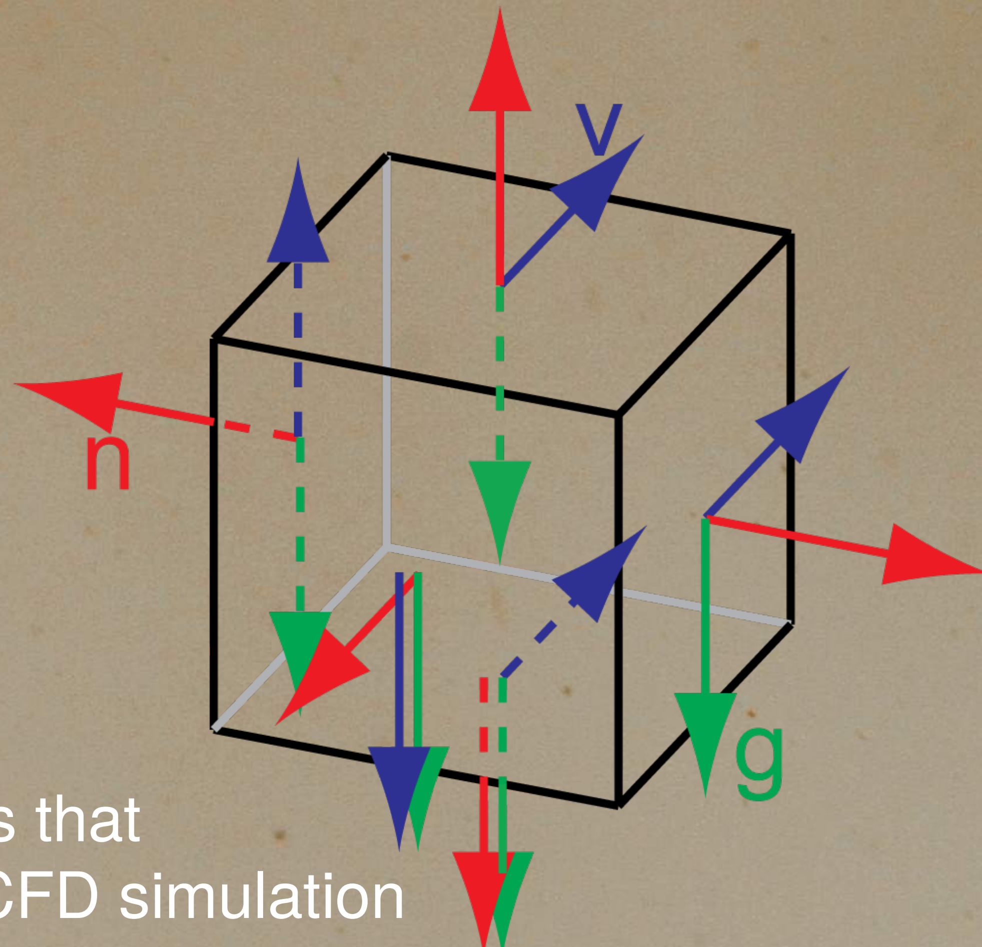
Factors Affecting Surface Heat Flux

Surface heat flux during quenching operations will be most affected by:

- Surface temperature
- Surface orientation
- Quenchant velocity
- Flow direction
- Quenchant temperature
- Type of quenchant



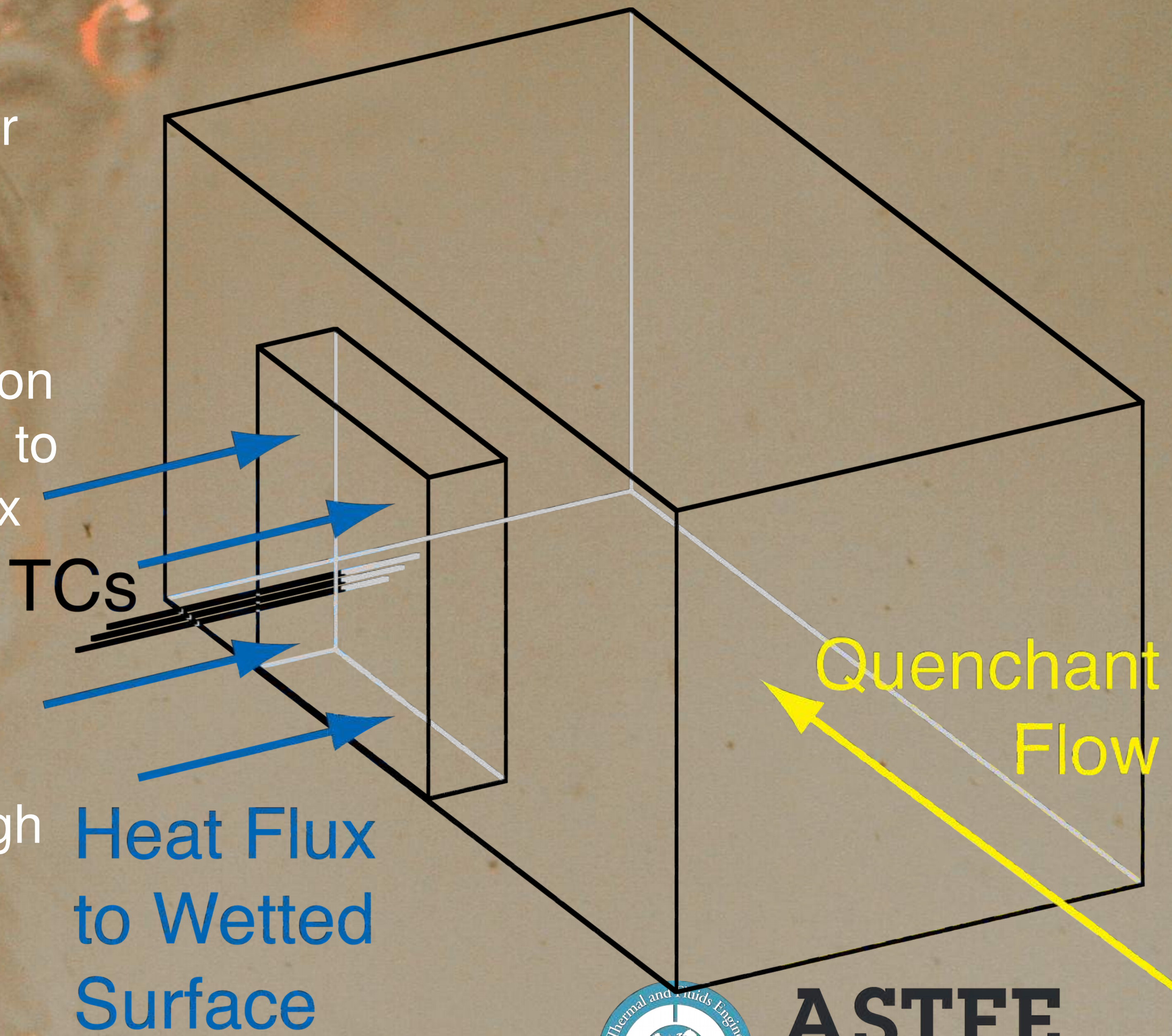
These are also the variables that are available in a practical CFD simulation

Experimental Method

Pass quenchant at known velocity over heated coupon

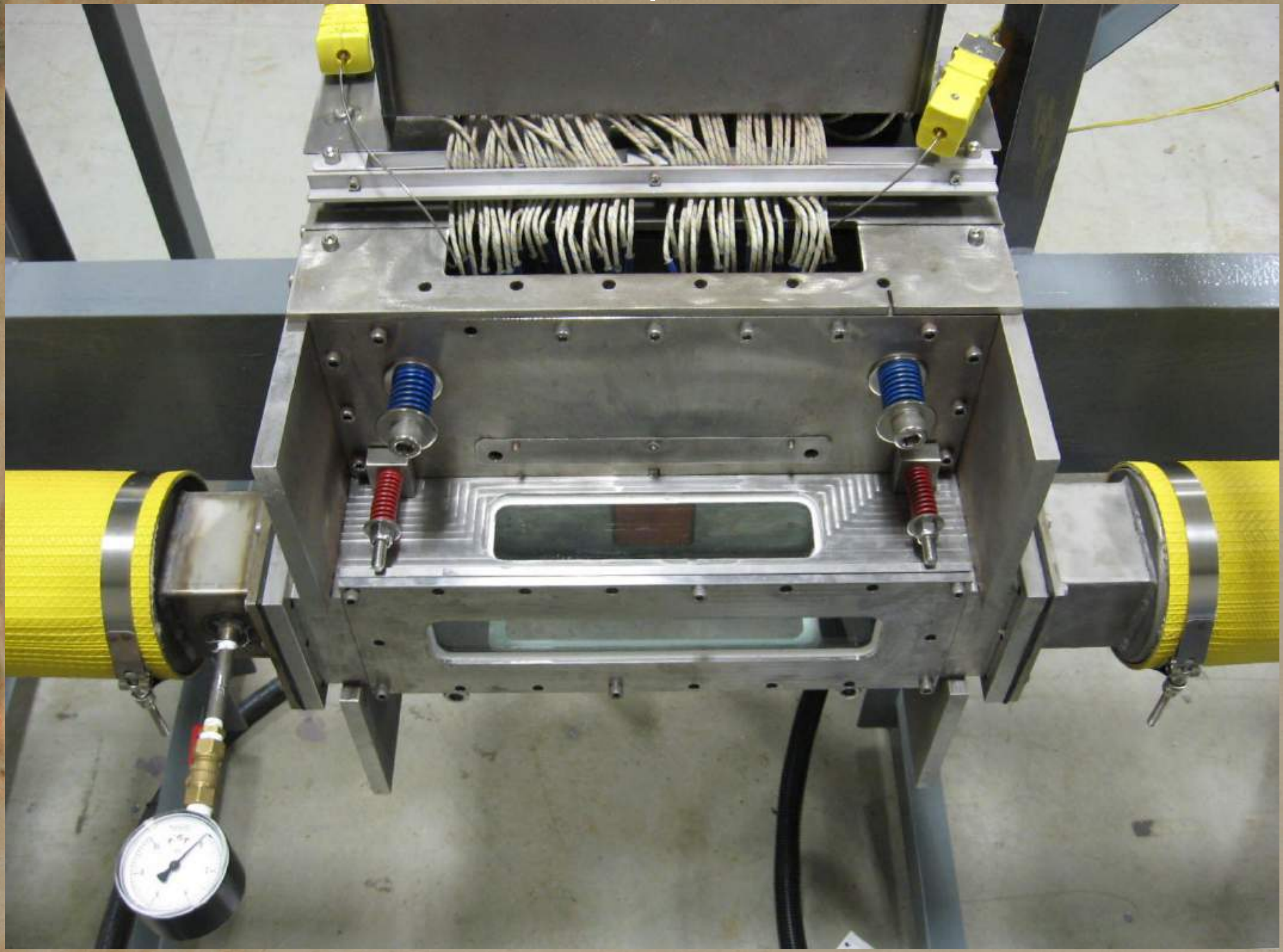
Thermocouples embedded in coupon allow for projection to the face of heat flux and surface temperature

Quasi steady-state testing provides high quality data



Test System

Implementation of the test concept



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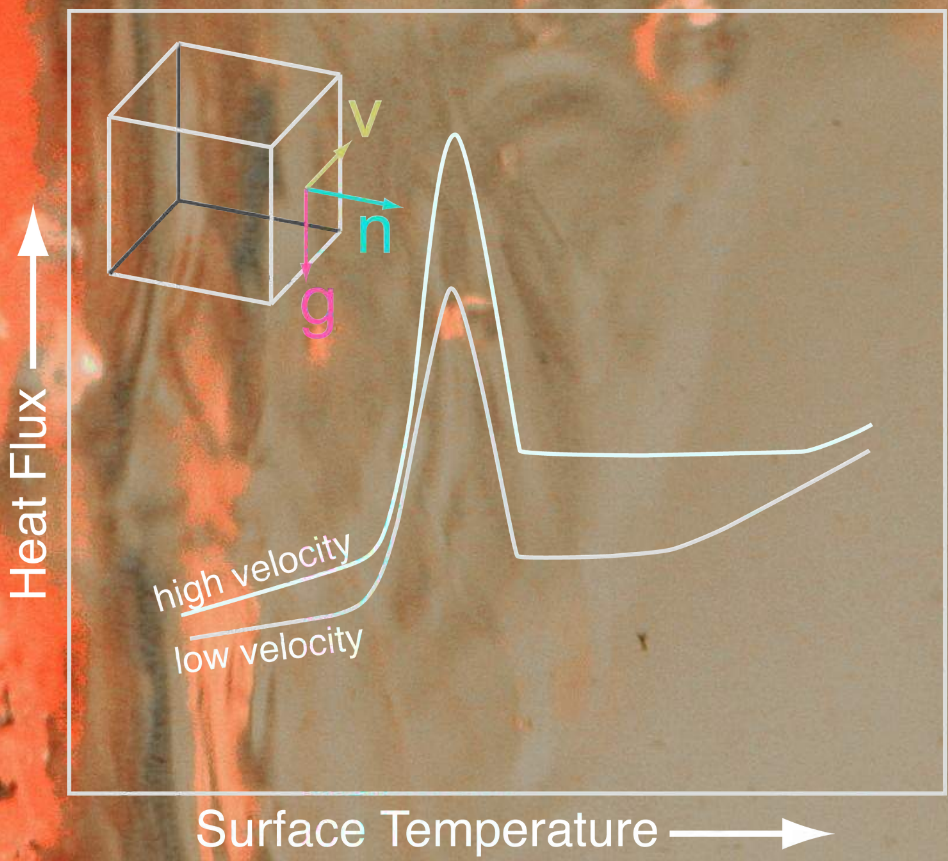
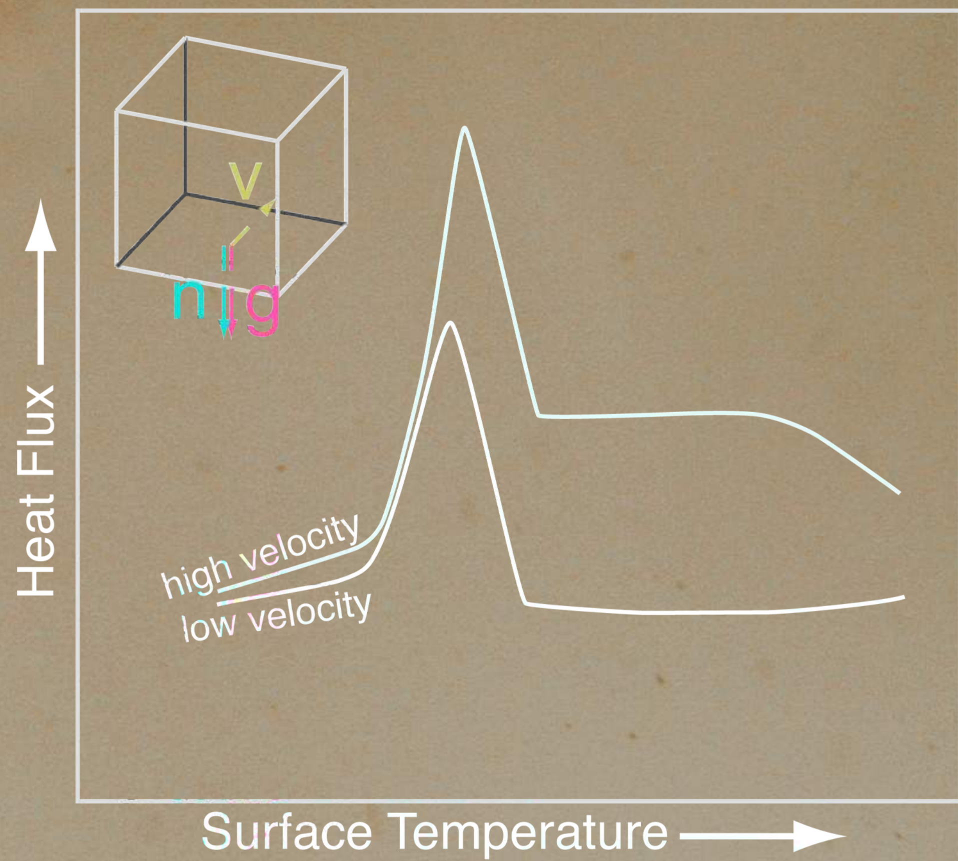
Sample Data





For side surface film boiling, heat flux rate increases for increasing temperature above a certain threshold – that threshold is higher for higher velocities. For underside film boiling at high velocity, heat flux rate falls for increasing surface temperature above a certain threshold.

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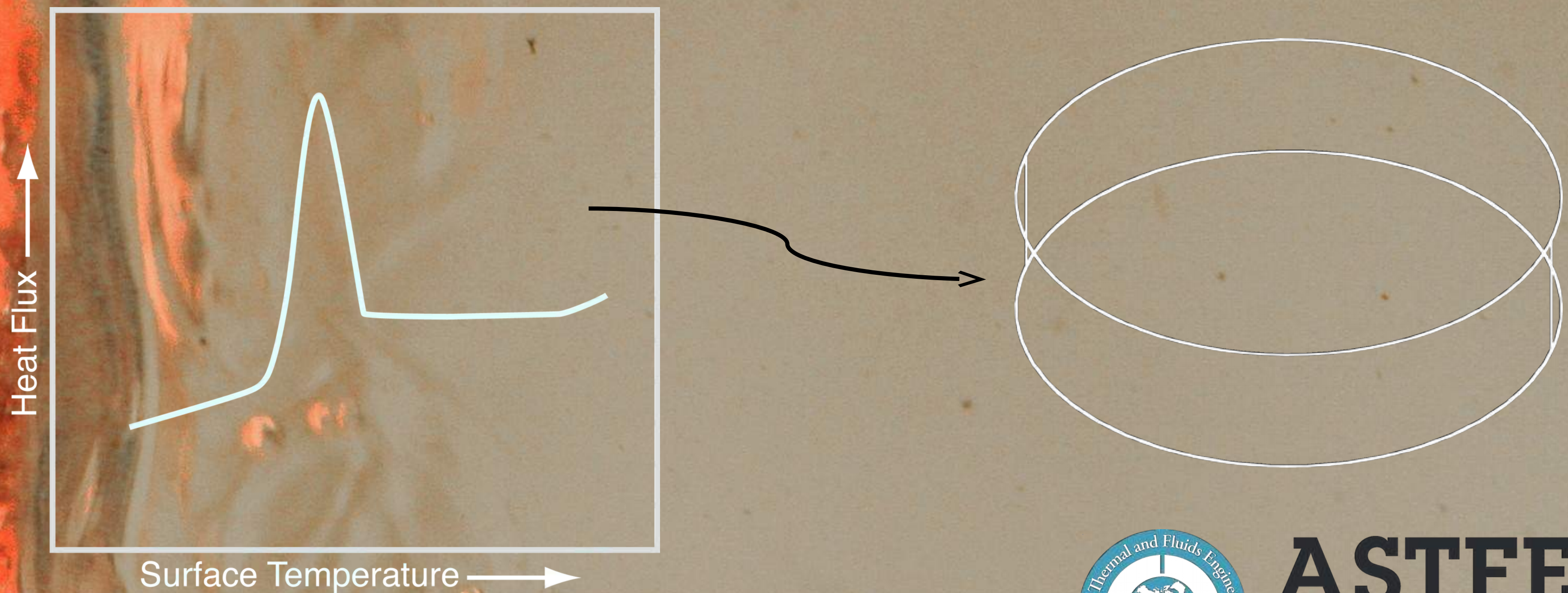
Simulation Method

While the collected data may be used to refine boiling model theory, any mathematical abstraction of the data will necessarily deviate from that data.

As a first test of the validity of the data, measured heat fluxes were directly applied to part surfaces in a CFD simulation.



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Test Cases

Two geometries were simulated and compared to quench tank test data, both for still and agitated oil

Generic turbine disk

Simple pancake disk

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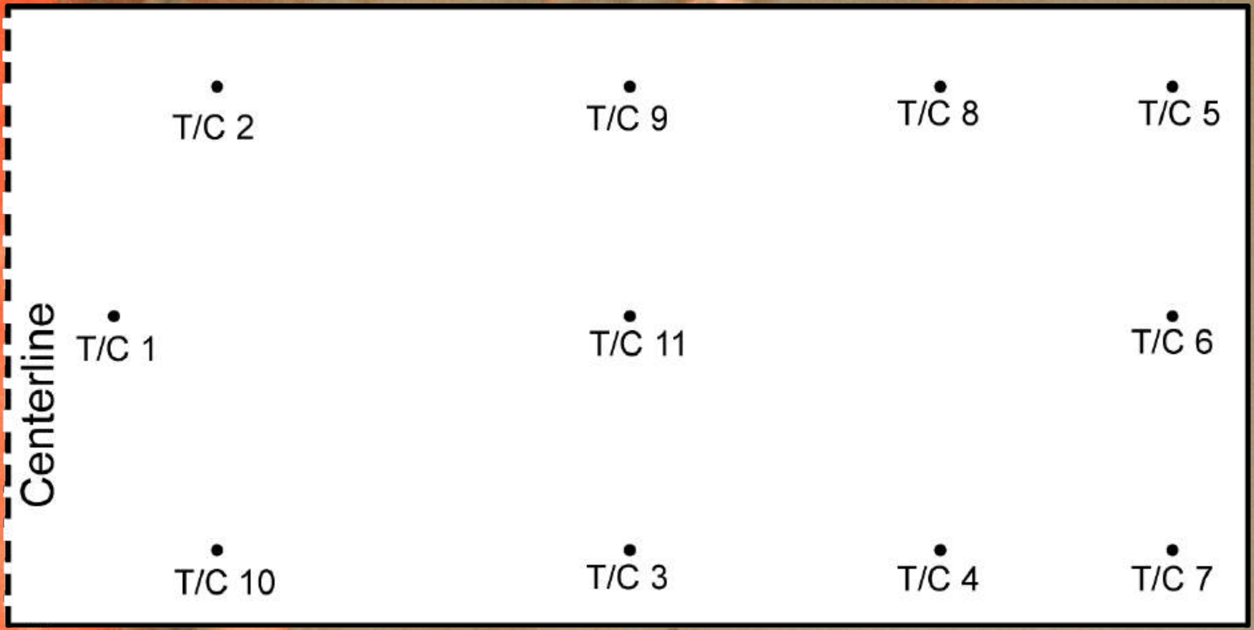
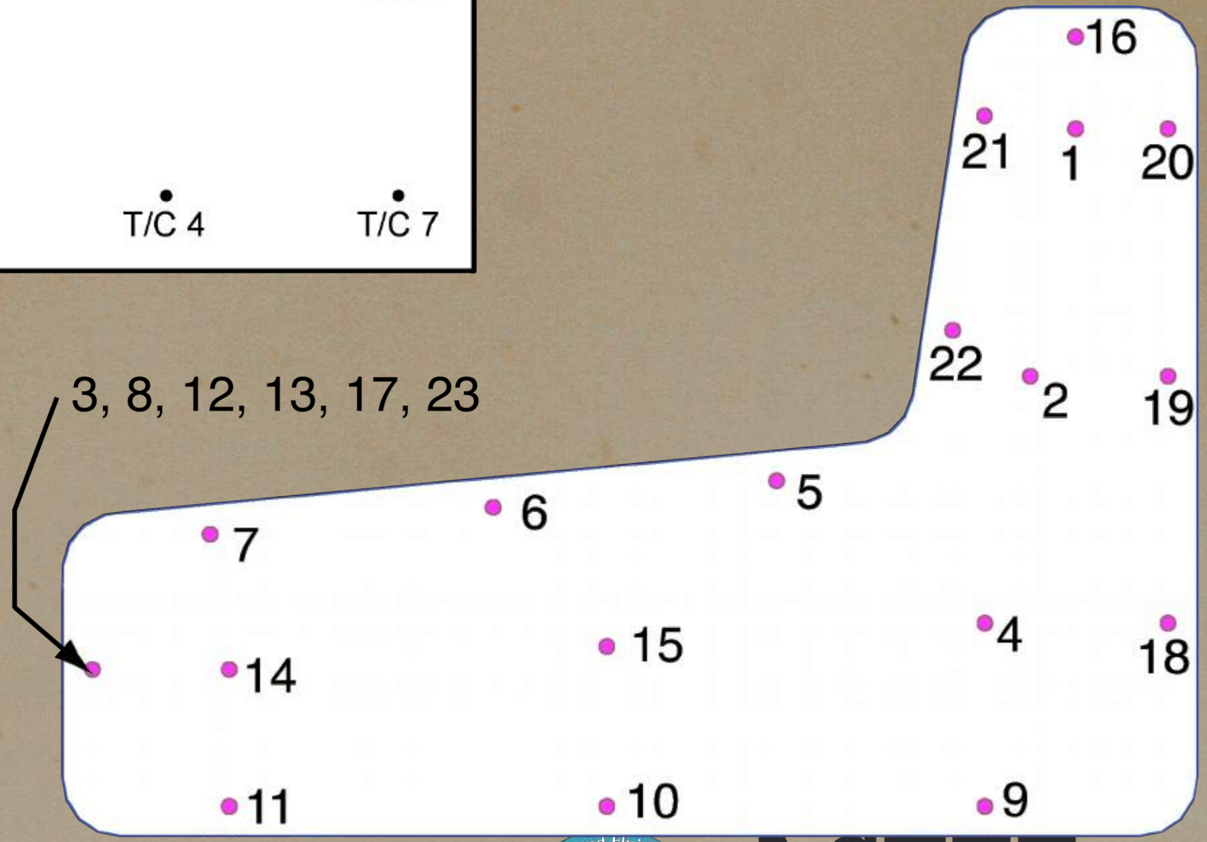
Instrumentation



Pancake disk had 11 TCs in a single plane. 1/8” Type K with Swagelok fittings

Turbine disk had 23 total TCs divided into 6 planes. 1/16” Type K press fit into part.
TC near edge of disk was included in each of the 6 planes to assess variation in test method.



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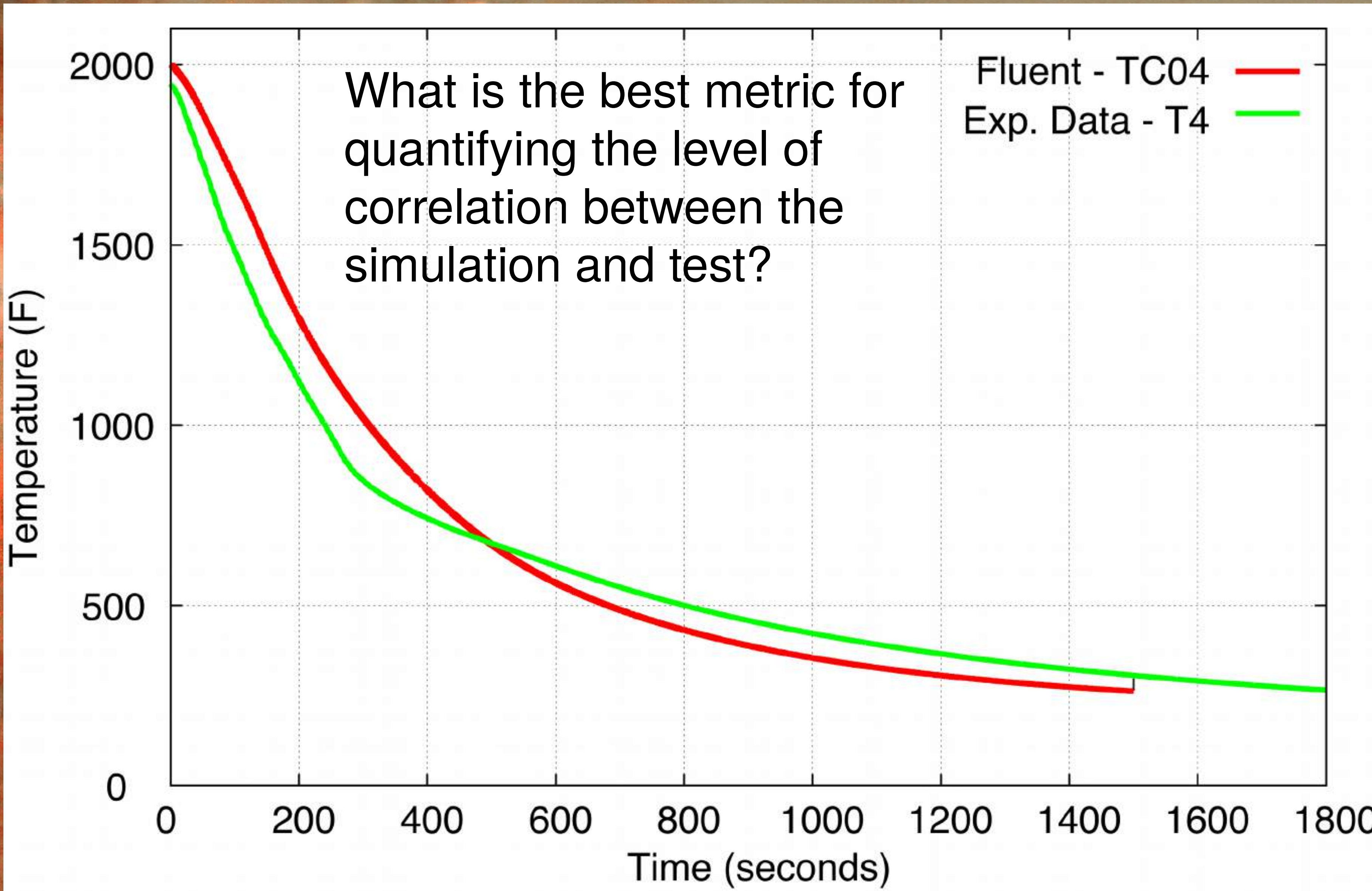
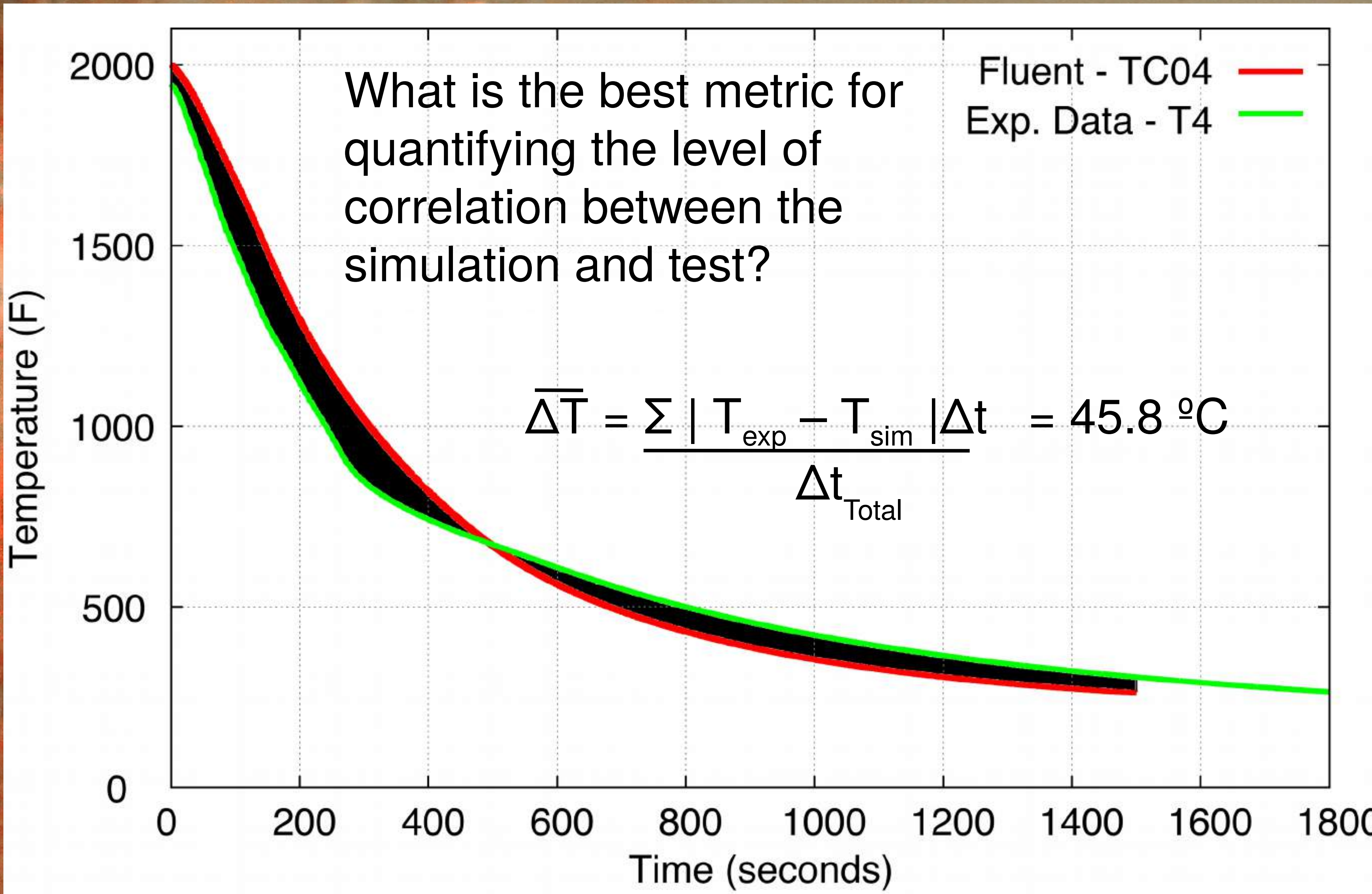
Correlation Metric



Correlation Metric



$$\overline{\Delta T} = \frac{\Sigma \mid T_{exp} - T_{sim} \mid \Delta t}{\Delta t_{Total}} = 45.8\ ^{o}C$$

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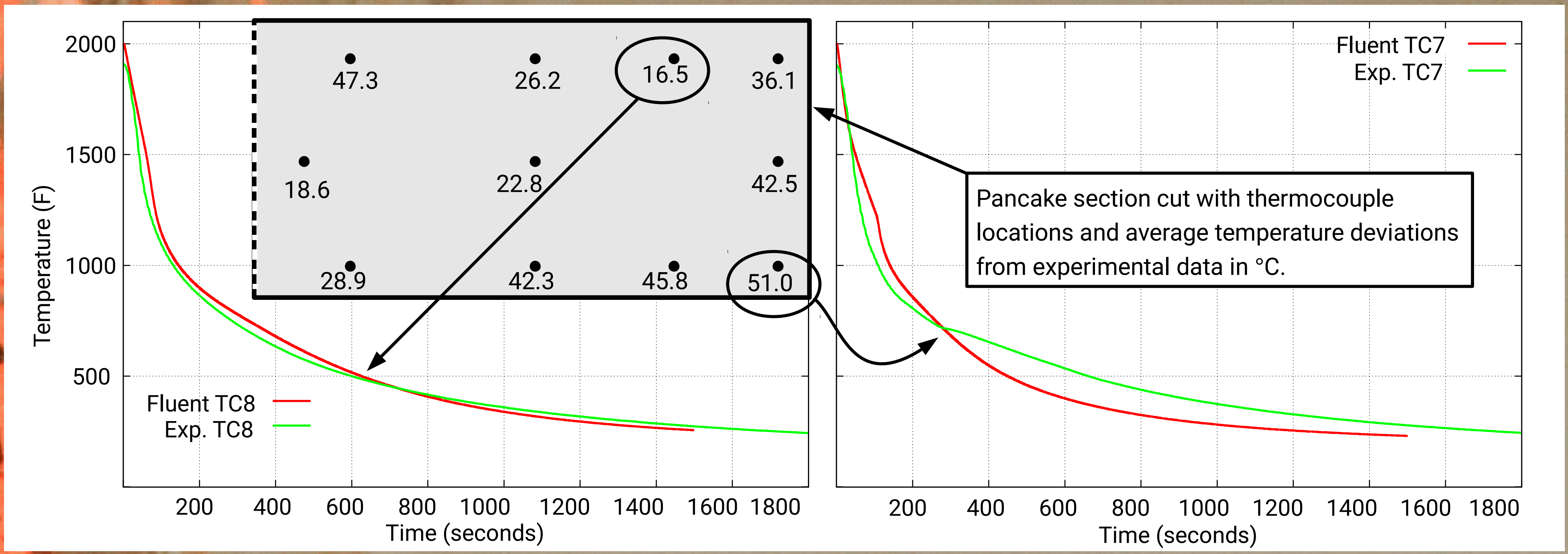
Cooldown Comparisons – Pancake Disk

Smallest and largest deviations from experimental data



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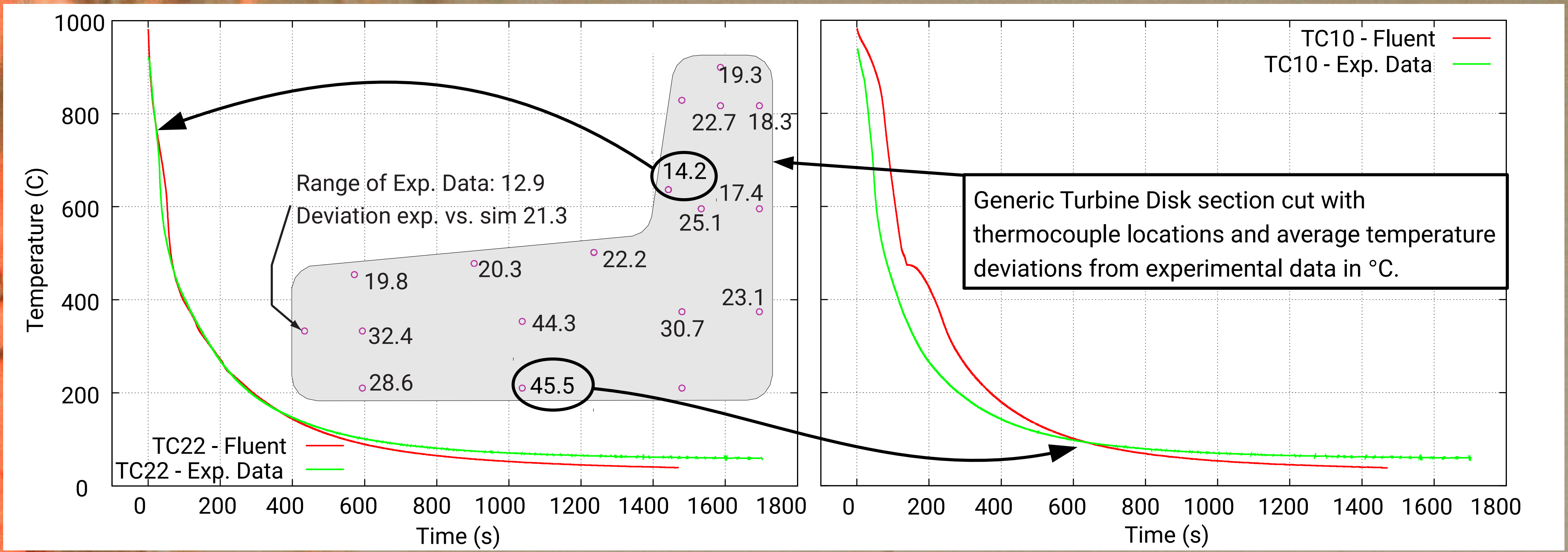
Cooldown Comparisons – Turbine Disk

Smallest and largest deviations from experimental data



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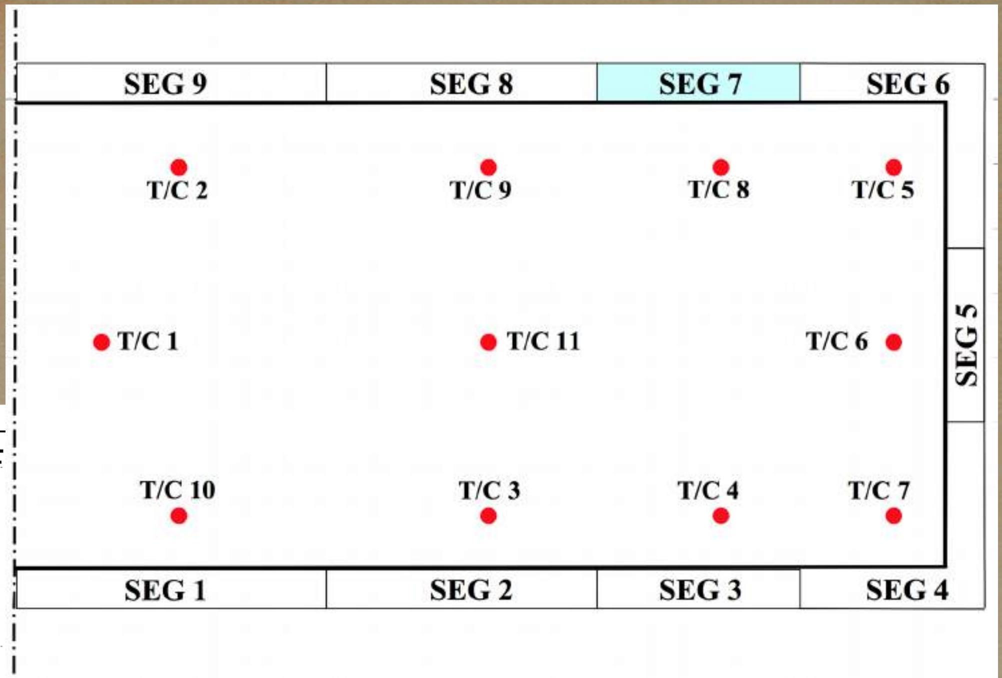
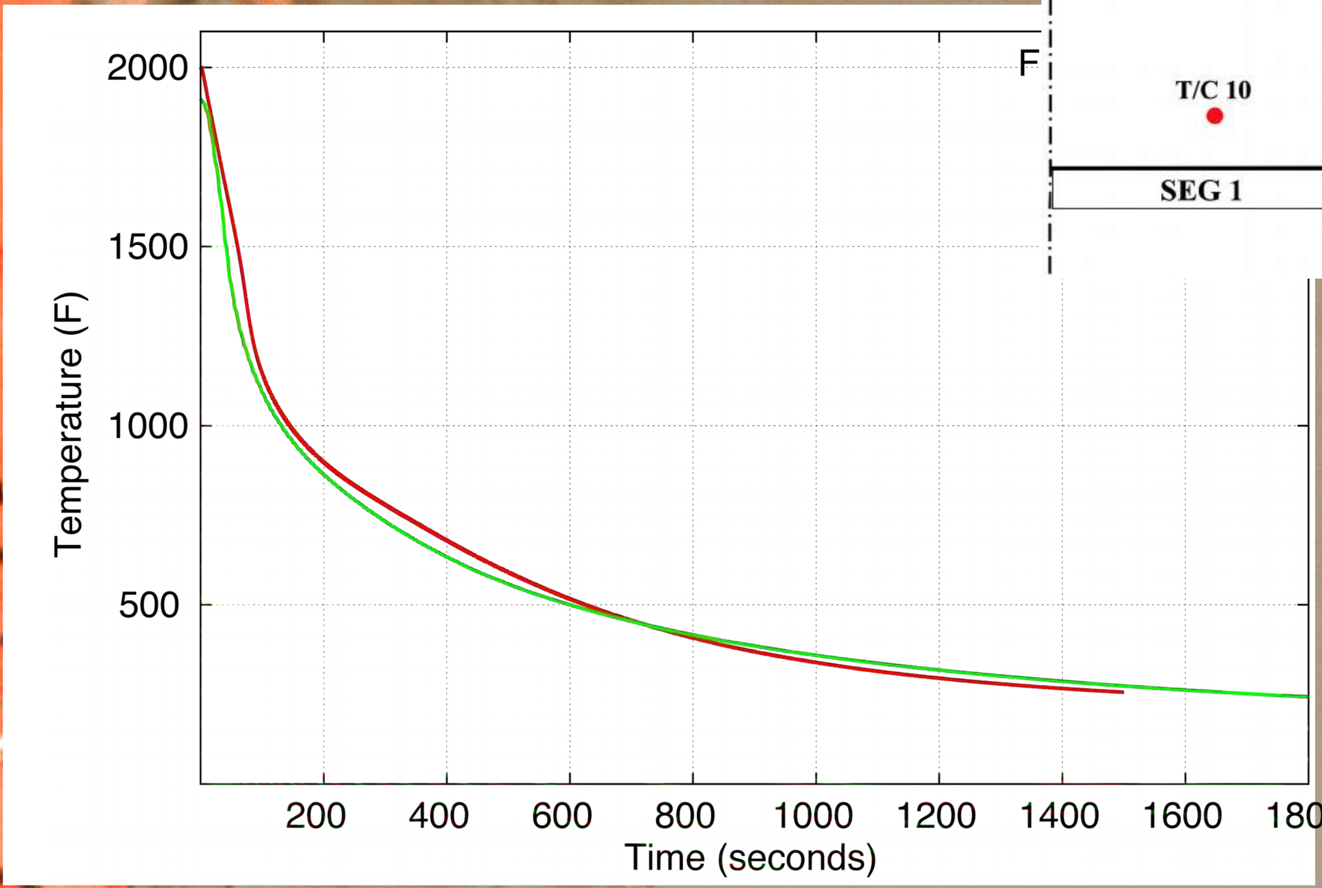
Implications for Surface Heat Transfer Coefficients

Comparison between inverse HTC and database HTC for indicted segment





Pancake disk still oil case with best TC match (16.5 ºC average deviation)

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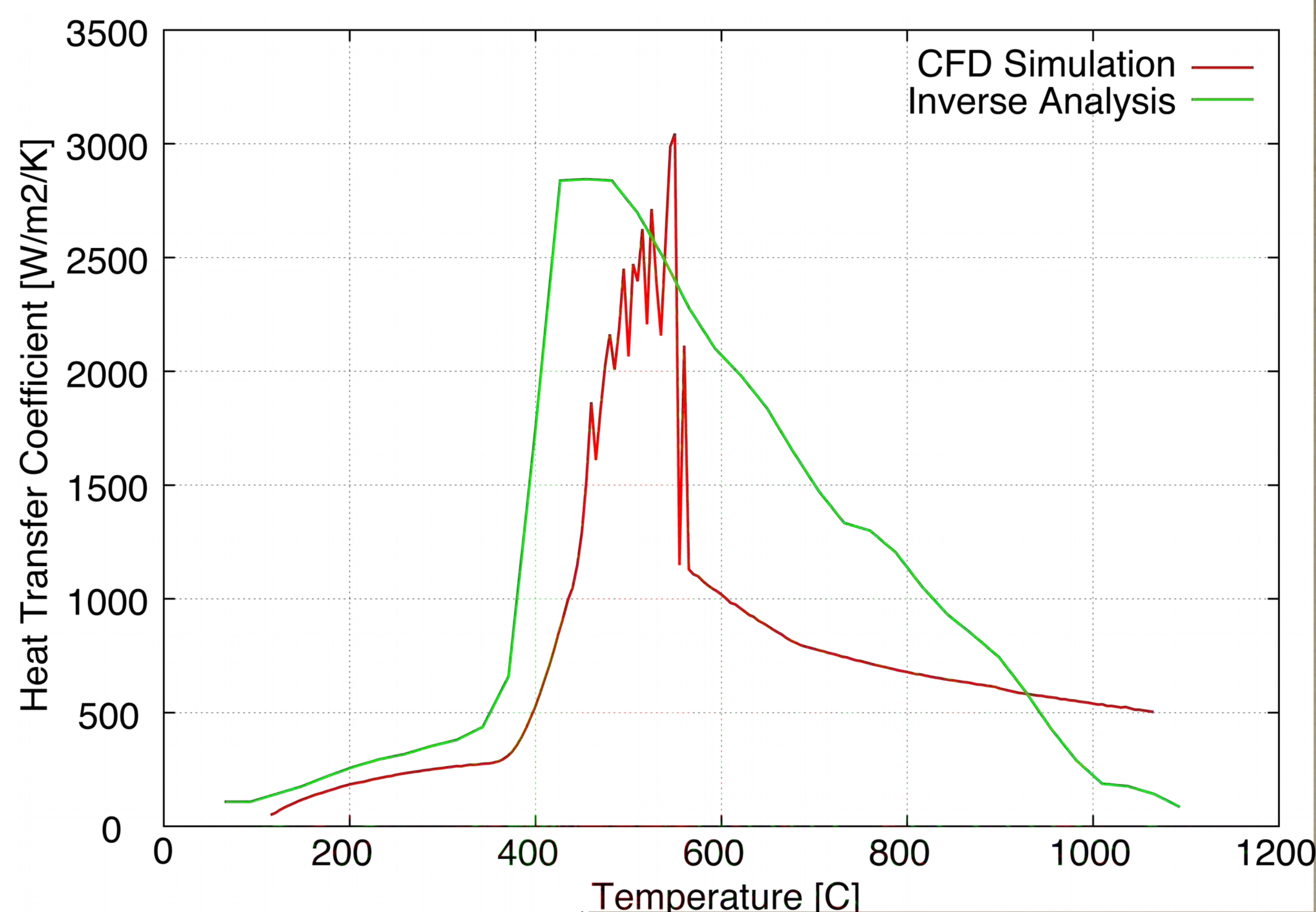
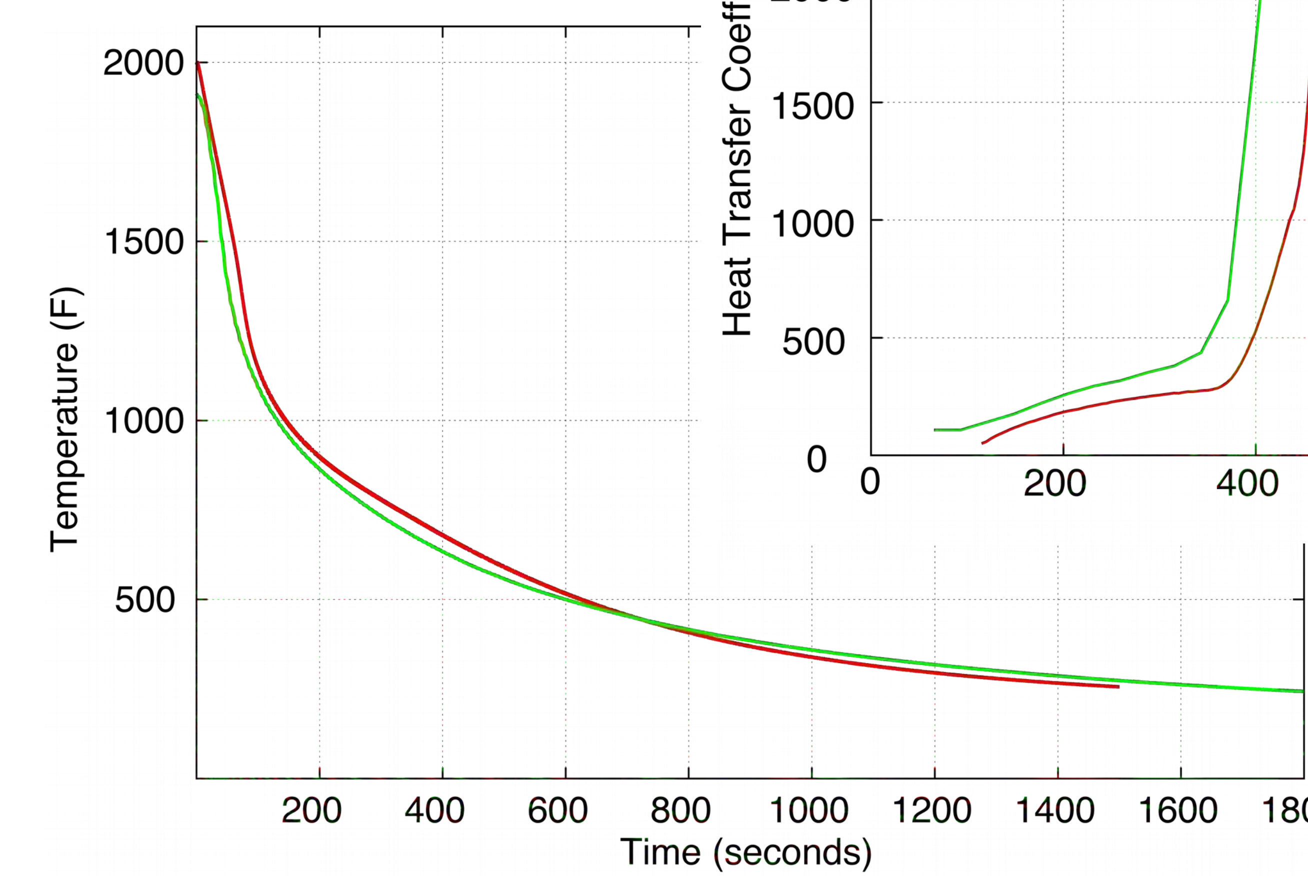
Implications for Surface Heat Transfer Coefficients

Comparison between predicted and inversed HTCs show significant differences





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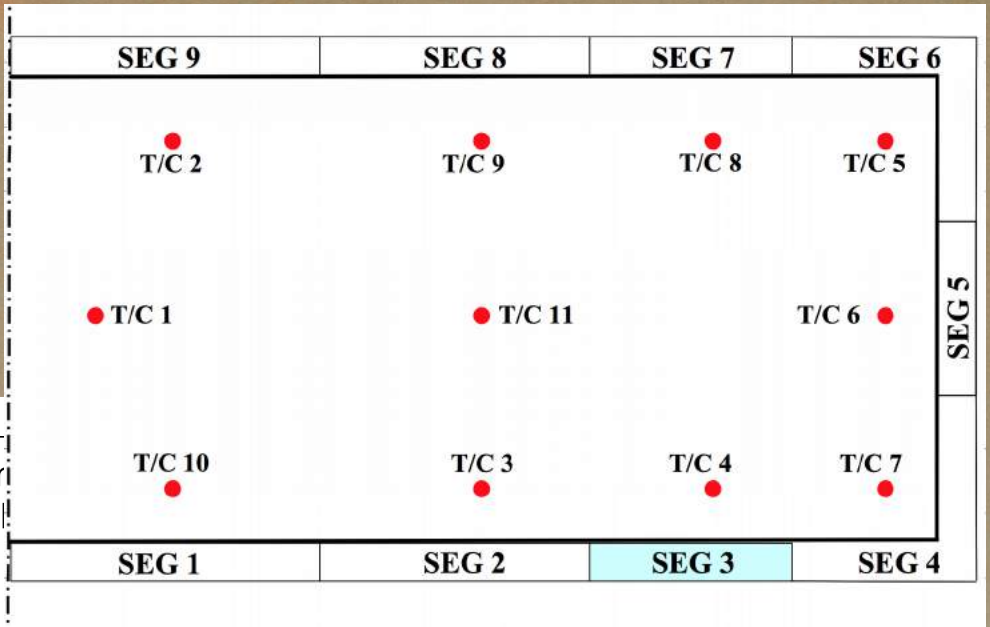

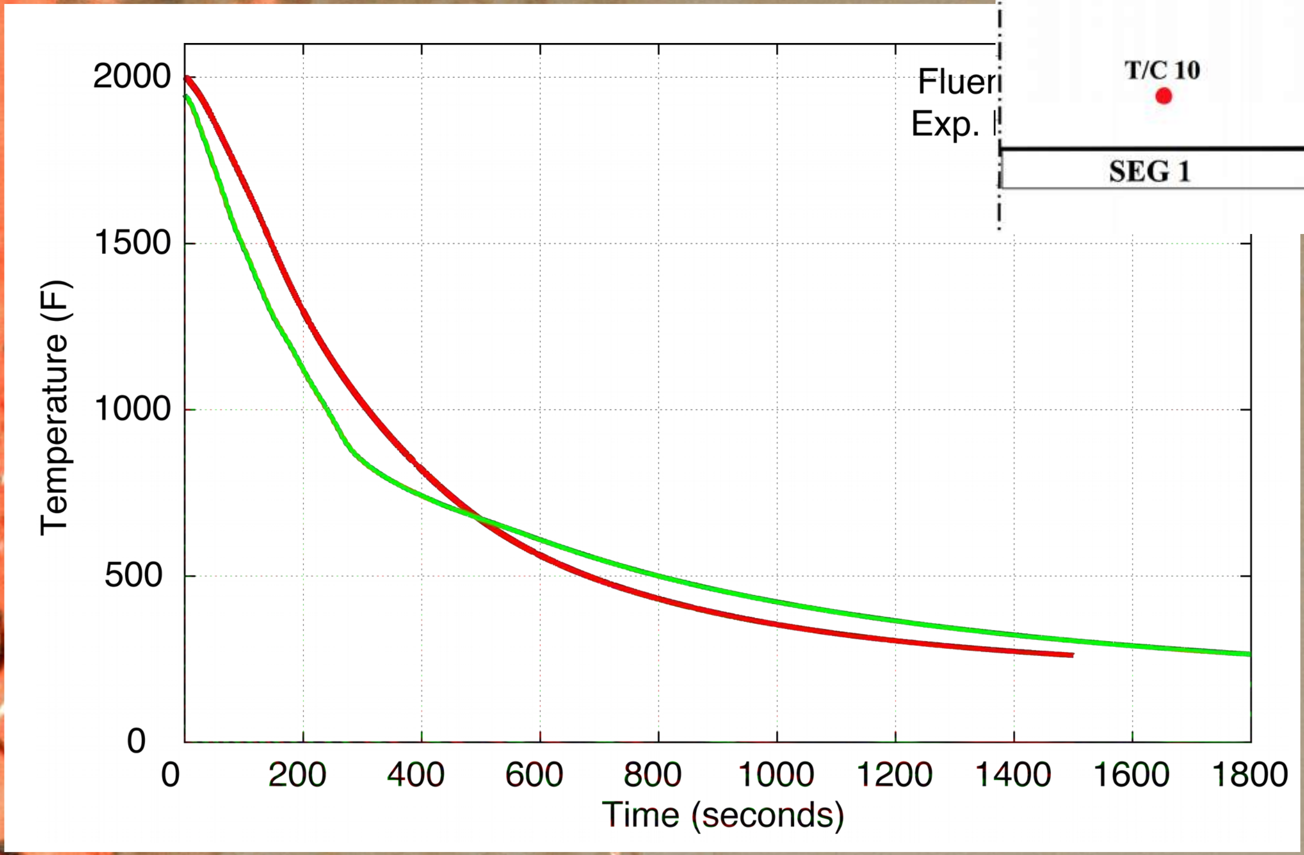

Pancake disk still oil case with lesser match (45.8 ºC average deviation)

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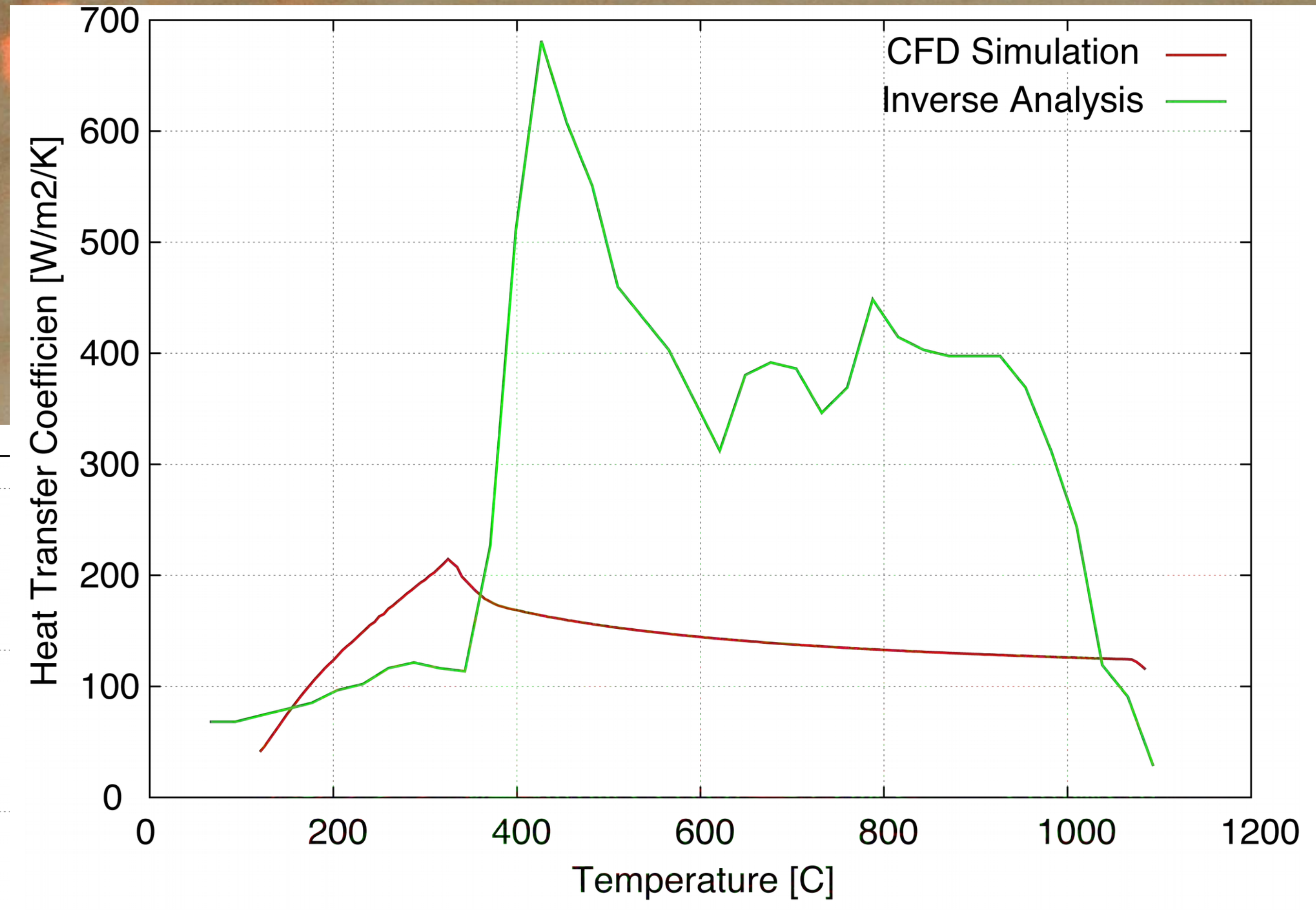
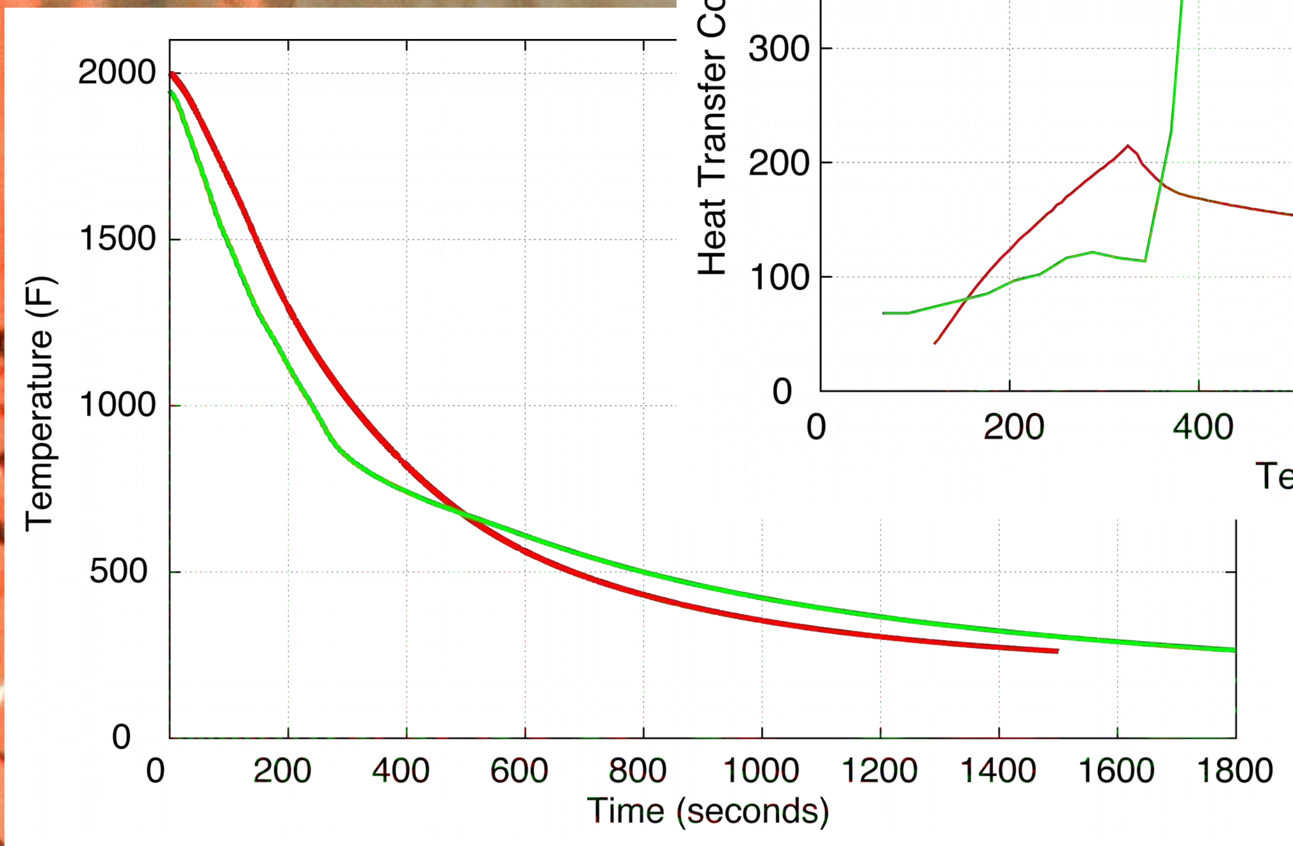
Comparison between predicted and inversed HTCs show significant differences





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Implications for Surface Heat Transfer Coefficients

Simulated temperature values are a good match to thermocouple data
Inverse HTCs are much different than HTCs from CFD/database
Illustrates the issue with non-unique solutions?

How does this affect residual stress and distortion predictions?

Differences in surface HTCs will have greater effect on surface residual stresses than on embedded TCs.

?

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Why Change to this Workflow?

The flow boiling heat flux database is derived, essentially, from quench experiments and inverse heat flux analyses. What makes it better?

- Data are collected under very highly controlled conditions (fluid velocity and temperature)
- Results are correlated to local quenching environment
- Data are collected under near steady-state conditions
- Geometry of the test system allows for less ambiguity in the inverse process
- Additional TCs and filtering/projection techiques improve accuracy

As a result, the “inverse” data generated through this method has broad applicability through coupling with a CFD analysis of the quenching environment.

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Summary

An alternative to quench trials and inverse analysis is proposed for specifying surface heat fluxes during quenching simulations:

- Characterize the flow boiling heat flux characteristics of the quench liquid
- Apply data to part surfaces in a CFD simulation to determine local heat transfer coefficients

-or-

- Couple CFD with FEA for a combined simulation

Resulting curves are more closely tied to actual boiling phenomena

Validation cases suggest that the data have widespread applicability

Cost of oil characterization is projected to be on the same order as a single quench trial

Where do we go from here?

- Based on data for one quench oil, method shows promise
- Additional work needed on bottom side heat fluxes
- Quench data for additional geometry is available for Houghton 3420
- Quench data available for generic turbine disk for Houghton Hanoline oil – that oil has not been characterized

- ♨ The development of a complete library of quench liquid characterizations would facilitate residual stress predictions
- ♨ With sufficient data, development of a more generalized semi-empirical boiling model may be possible

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Thank You!

Questions?

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