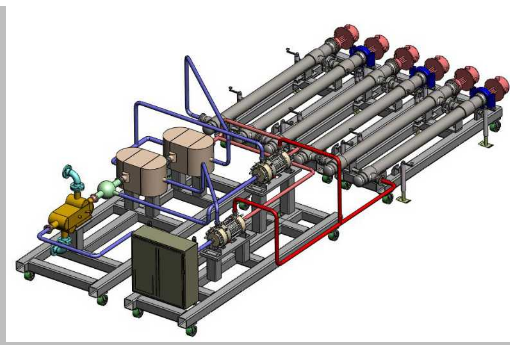
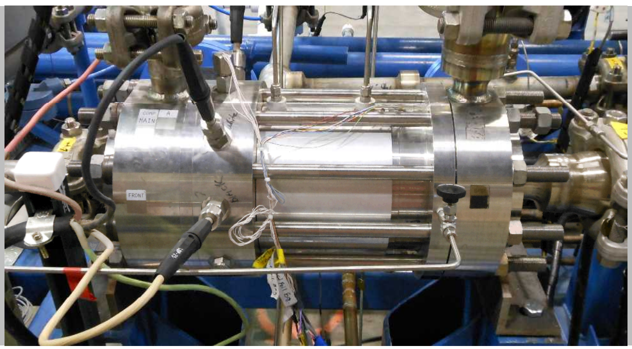
SAND2014-4857C

*Exceptional service in the national interest*

Sandia National Laboratories





# STEADY STATE SUPERCRITICAL CARBON DIOXIDE RECOMPRESSION CLOSED BRAYTON CYCLE OPERATING POINT COMPARISON WITH PREDICTIONS

Jim Pasch, (505) 284-6072, jjpasch@sandia.gov
6221 Advanced Nuclear Concepts
Nuclear Energy Systems Laboratory/Brayton Lab (ne.sandia.gov/nesl)

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000. SAND NO. 2011-XXXXP

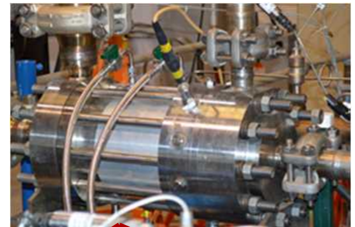
# Overview

- Discussion of Sandia recompression closed Brayton cycle (RCBC) test assembly.
- Compressor performance and comparison with predictions
- Turbine performance and comparison with predictions
- Recuperator performance modeling
- Summary and conclusions

# DOE SCO2 Recompression Loop at Sandia National Labs

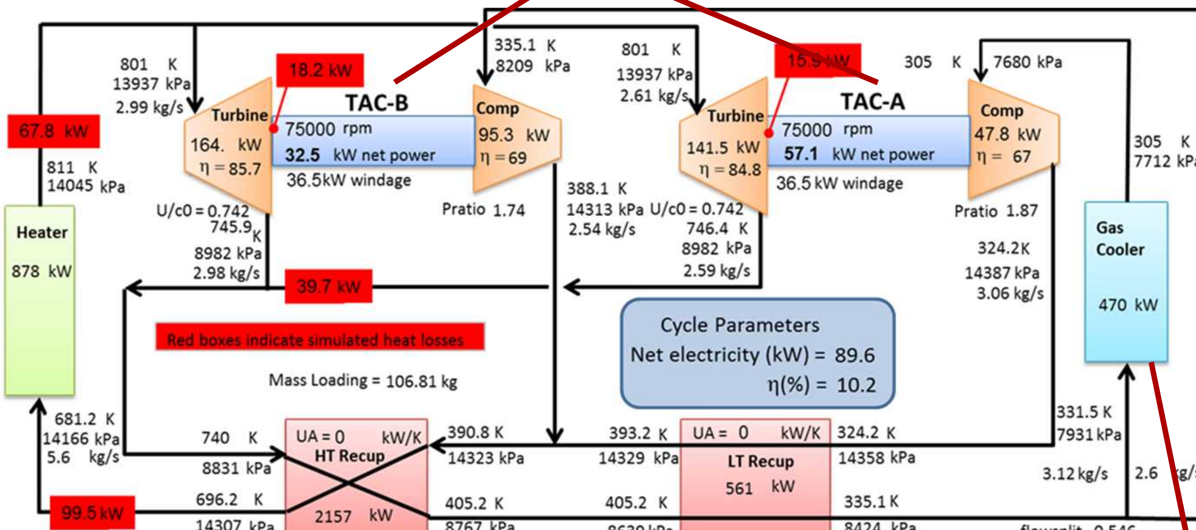
Sandia National Laboratories

- DOE had established a supercritical carbon dioxide (SCO2) recompression closed Brayton cycle (RCBC) test assembly in the spring of 2010.
- Upgrades to complete the final design were completed in the summer of 2012.

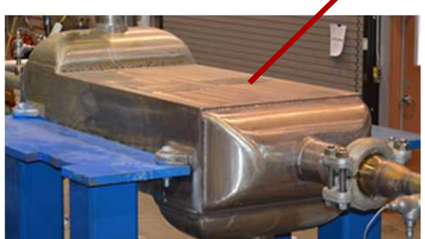


Each of 2 TACs designed to generate 125 kWe

780 kW of heat input




2300 kW duty high temp recuperator



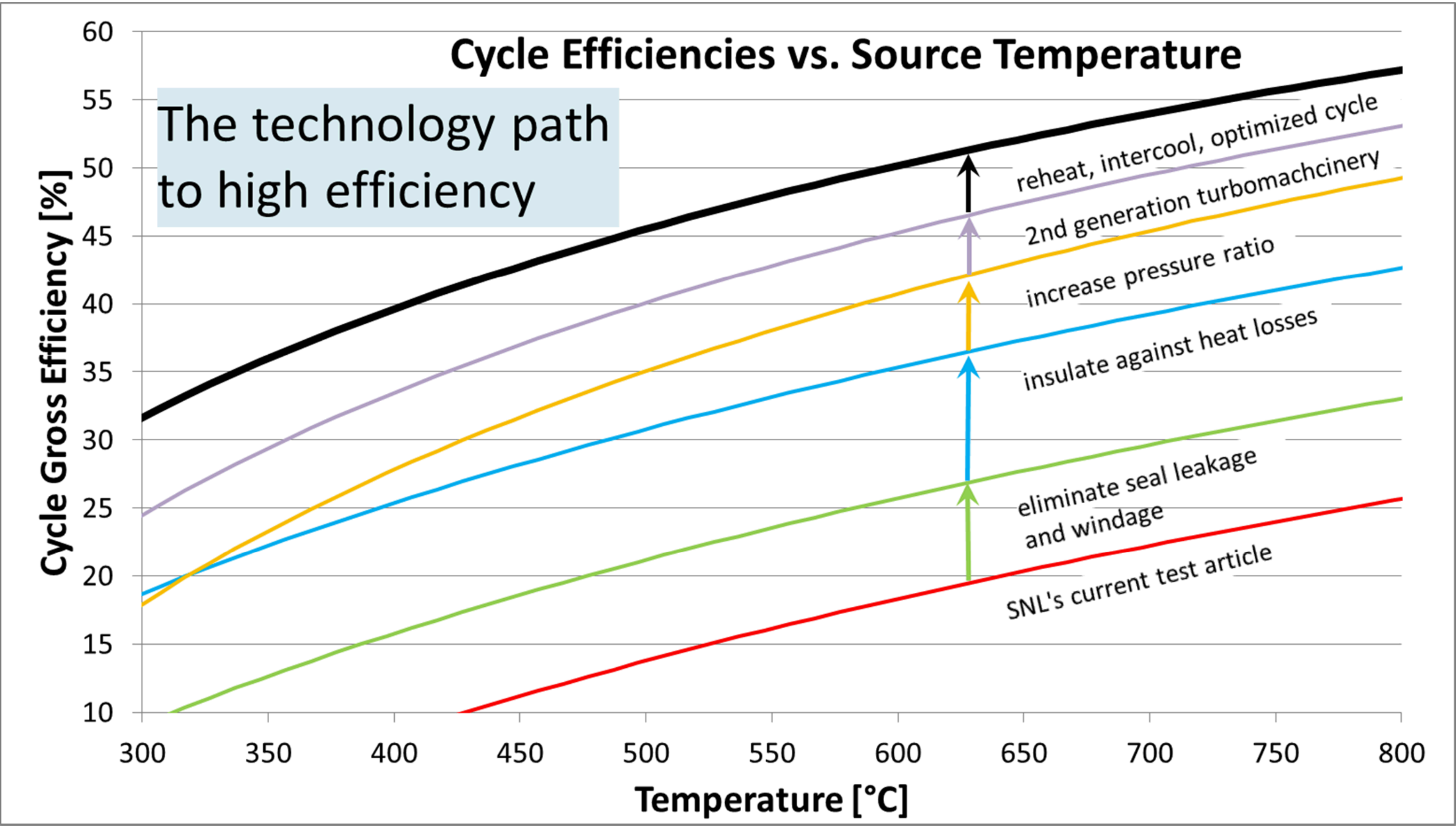
1700 kW duty low temp recuperator

560 kW duty heat rejection

# Purpose of Paper and this Presentation

- The DOE RCBC at Sandia is an engineering scale test article (TA), intended to (among other things) demonstrate that the RCBC using SCO2 performs as predicted.
- TA will not demonstrate performance that is commercially interesting
  - design point is very modest
    - PR = 1.8
    - Tmax = 538 C
  - Various losses, some of which are inherent in the small design
    - leakage flow rates around labyrinth seals are ~ 5% of total flow. Significant windage results and loss in turbine power.
    - Heat losses around the loop, some of which are not easily insulated.
- The best conversion efficiency expected from the TA without significant design changes is about 20%.
- Results from the Sandia TA must be used to show RCBC potential by extrapolating from demonstrated performance using baselined models.
- The Sandia Brayton team must demonstrate understanding of the RCBC and component performance, and this understanding must be represented in a robust computer model.

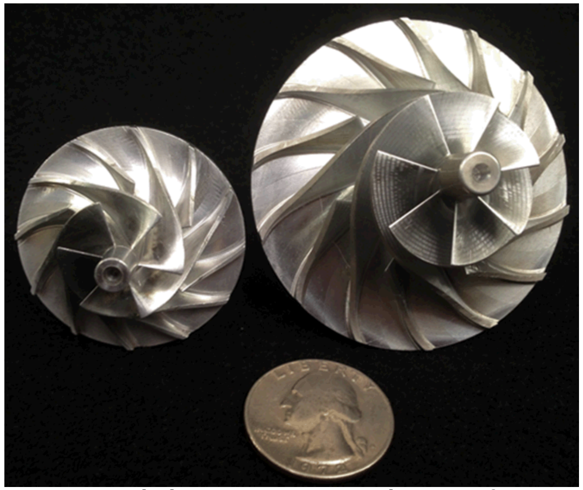
# The Path to High Efficiency



# RCBC Testing Background at Sandia Nat. Labs

- First tests in 2010 with the RCBC demonstrated the difficulty of maintaining stable operation with parallel compression.
- Multiple compressor surging events occurred during numerous tests in the design RCBC configuration.
- The design configuration uses a smaller main compressor wheel that operates in the vicinity of the critical point [30.98 C, 304.13 K, 87.76 F, 547.43 R 7.377 MPa, 1070 psia], and a larger recompressor wheel that operates significantly farther away from the critical point

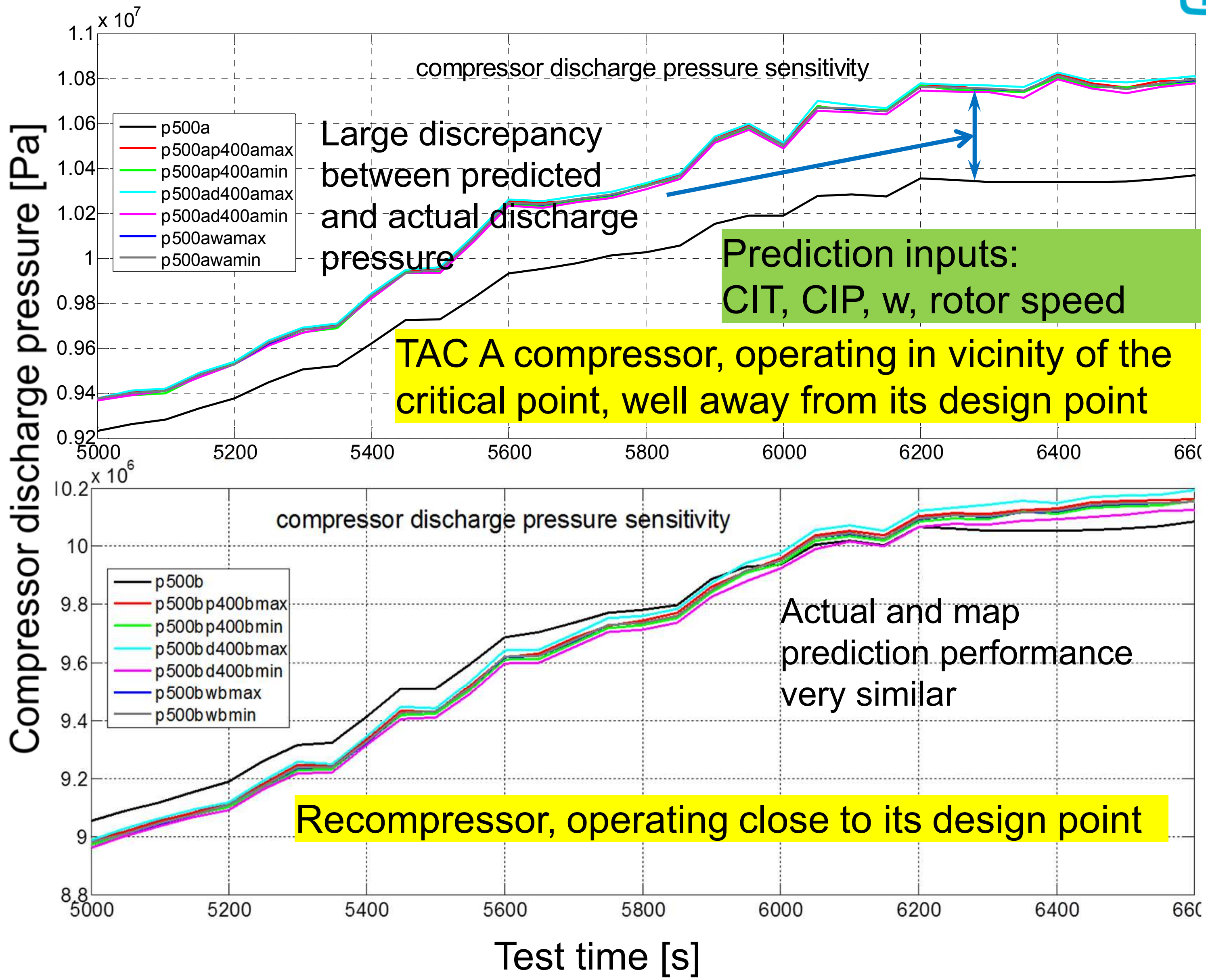
Main compressor wheel
Design operating point
T = 32.4 C (1.4 C above critical temperature)
P = 7.69 MPa



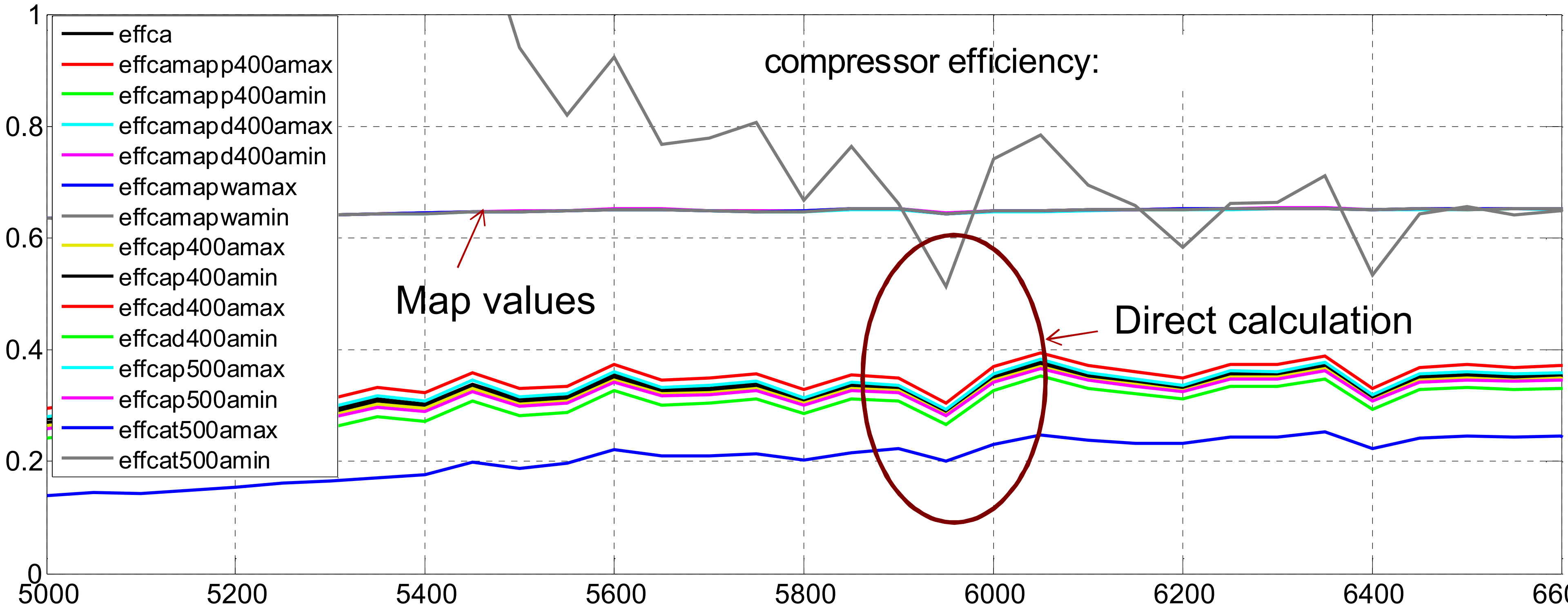
Recompressor wheel
Design operating point
T = 59.4 C (well above critical temperature)
P = 7.79 MPa

- The main compressor assembly was replaced with a recompressor assembly to establish more stable operations – the modified RCBC

# Compressor Performance Assessment



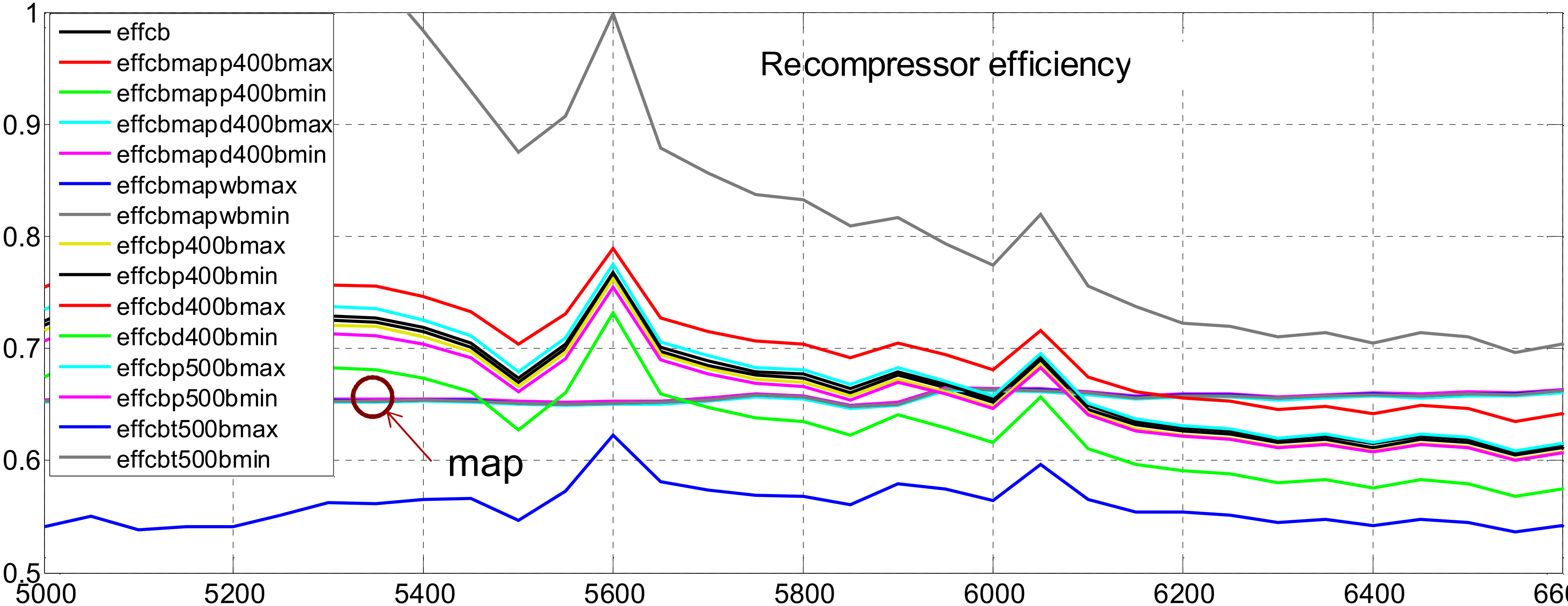
# Compressor Performance Assessment




Compressor A measured efficiency is largely independent of all measurement uncertainties except discharge temperature. High discharge temperature leads to low calculated compressor efficiency. This shows that accurate measurements of discharge temperature are very important to accurately calculate compressor work.

Map efficiency predictions are virtually independent of input uncertainties.

# Compressor Performance Assessment



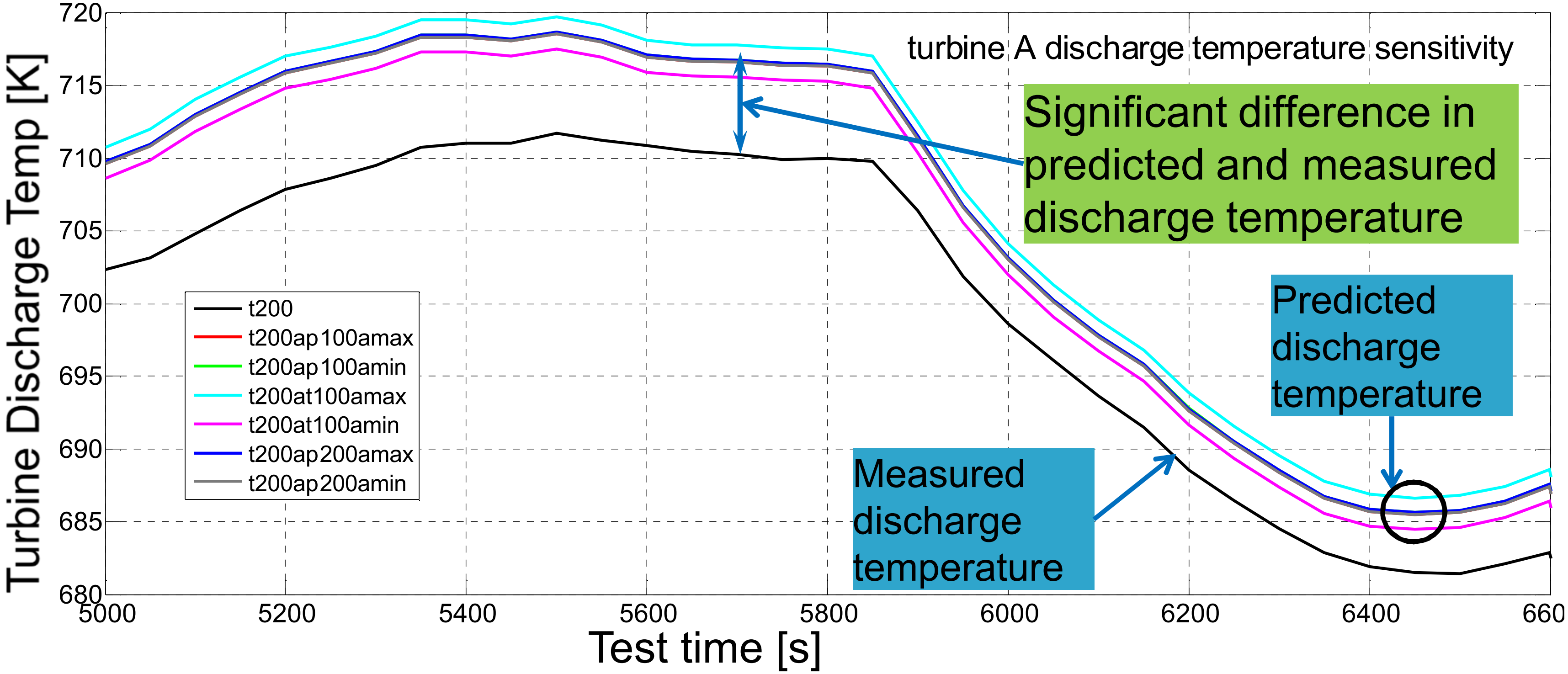

Recompressor efficiency very sensitive to discharge temperature, with high discharge temps generating low efficiencies. Efficiency is also sensitive to d400b, with high density leading to higher efficiency. This shows that accurate measurements of discharge temperature are very important to accurately calculate compressor work.

Map efficiency predictions are minimally affected by input uncertainties, with inlet density having some impact.

# Compressor Performance Observations

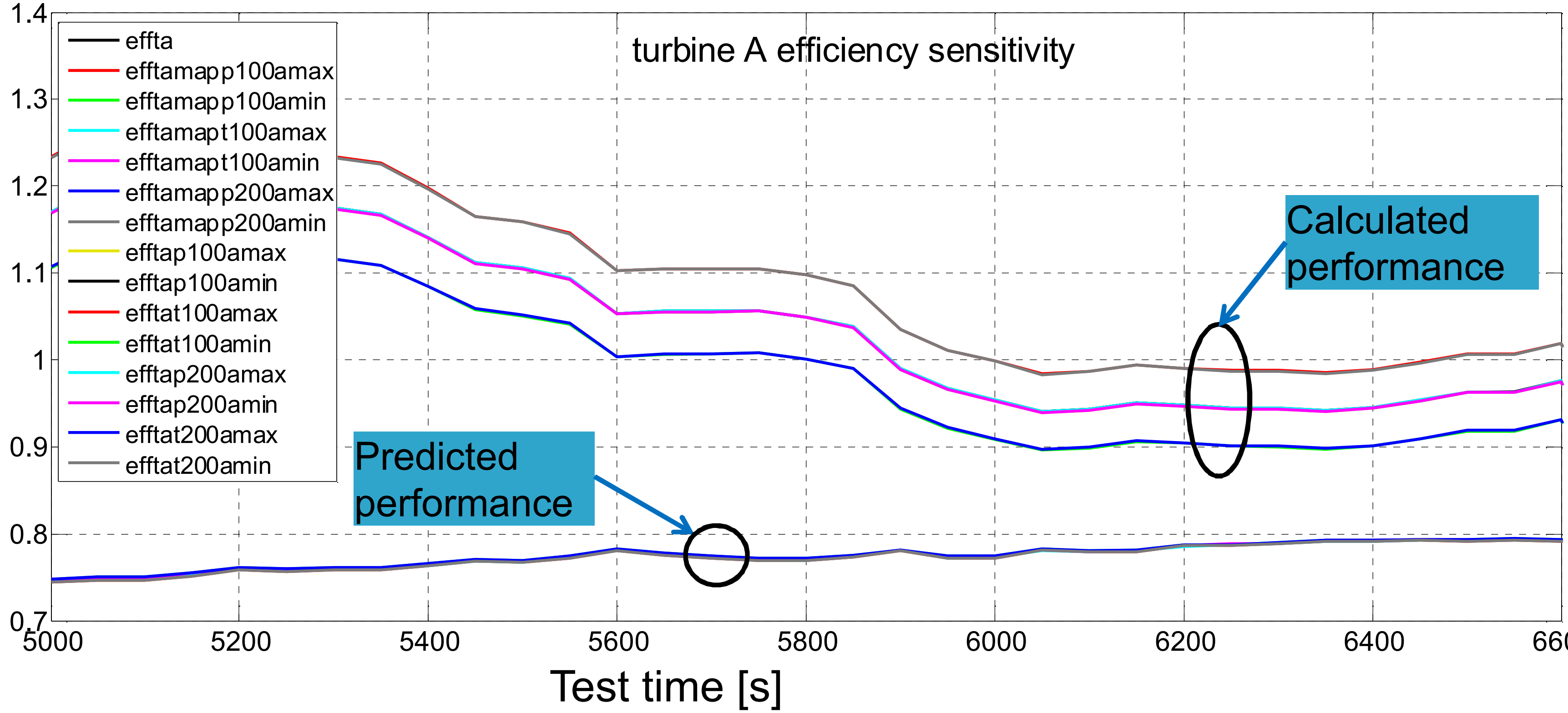
- Recompressor performance predictions using maps agree well enough with testing performance.
- TAC A compressor performance predictions
  - consistently much better (higher pressure rise, much higher efficiency) than testing performance.
  - input perturbations do not reconcile the disparaty.
- With the same compressor assemblies in both TAC A and B, it is logical to conclude that the difference in predicted and test performance arises from the inputs to the predictions.
  - Inlet temperature and pressure, mass flow rate, rotor speed.
  - Design temperature is 59.4 C, while actual inlet temperature is nearer the critical temperature of 31 C.
- The temperature difference introduces a very large error during performance map interrogation.

# Turbine Performance Observations




Turbine discharge temperature is slightly sensitive to inlet temperature uncertainty, and is virtually independent of the other inputs. The higher predicted discharge temperature compared with measured can be attributed to thermal losses in the volute. In this plot, if the turbine inlet temp were reduced by about 5 K, measured and predicted values would agree.

# Turbine Performance Observations

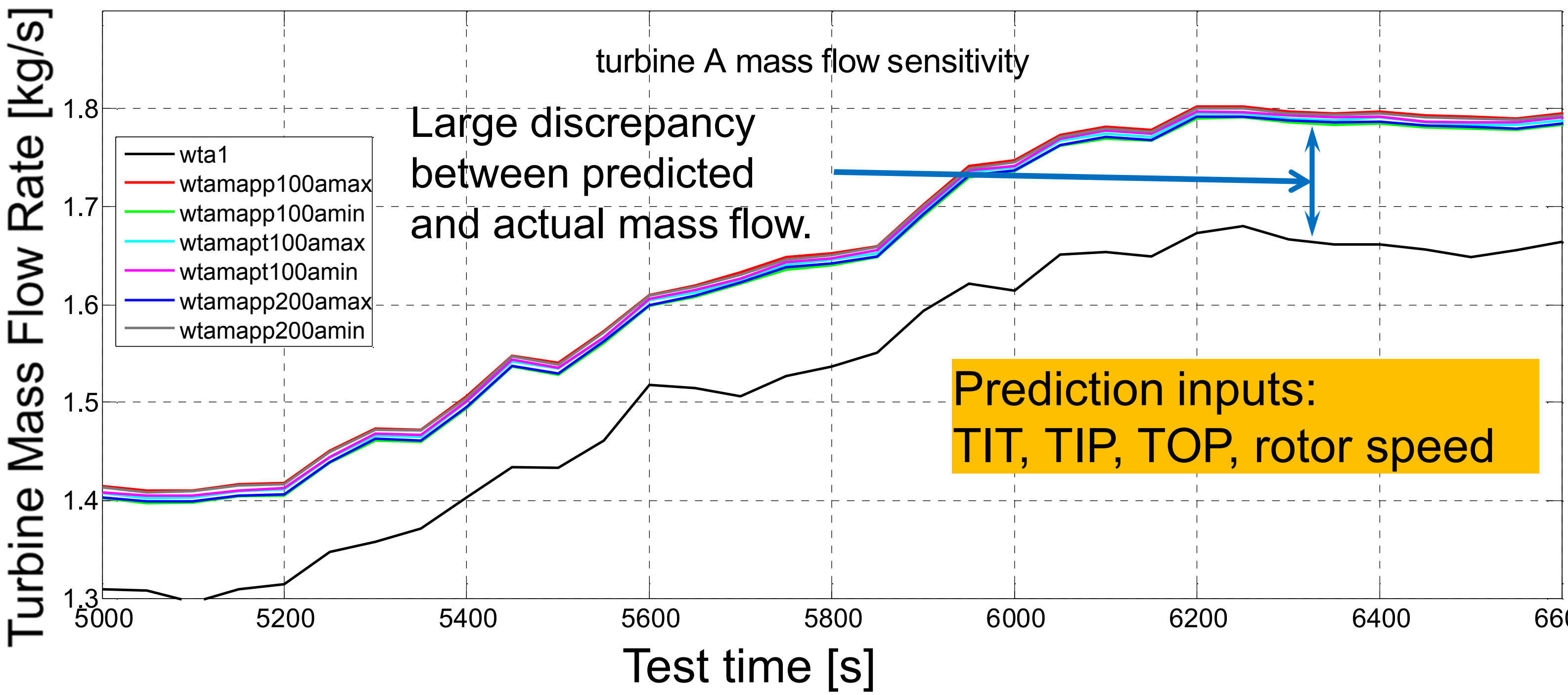



Turbine map efficiencies are independent of input uncertainties. Calculated efficiencies are equally sensitive to measured inlet and discharge temperatures, with maximum inlet temp and minimum discharge temp generating equally high calculated efficiencies. This shows the importance of knowing the true turbine inlet temperature.

# Turbine Performance Observations

- Turbine calculated performance is significantly higher than map prediction.
- Turbine discharge temperature is significantly lower than map prediction.
- A common cause for these observations can be attributed to heat loss within the turbine inlet volute, which has been established in previous work.
- The current approach used to apply this knowledge to test data and modeling is to reduce the measured turbine inlet temperature such that predicted and measured discharge temperatures are matched.
- This method brings measured and predicted efficiencies into agreement as well.
- This method assumes that the maps are correct.

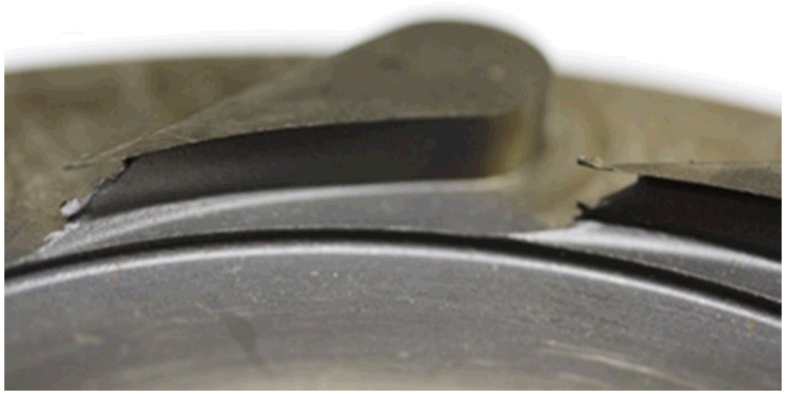
# Turbine Performance Observations




Turbine mass flow is almost independent of input parameter uncertainty. The disparity of ~ 7% between measured and calculated values is likely due to turbine performance deviations from design, possibly due to wear and erosion and clearances.

# Turbine Performance Observations

- Several factors likely contribute to reduced mass flow relative to predicted.
- Turbine-to-shroud clearances are likely larger than assumed during the design and modeling process.
  - This has been by intention to help avoid damaging rubbing events.
  - As experience at more aggressive operating conditions (TIT, PR) accumulates, the clearances may be closed up. At that time, an assessment of the validity of this theory will be possible.
- Erosion has been observed at the turbine inlet nozzles and back plate. This will certainly affect performance, and possibly mass flow as well.



# Recuperator Performance

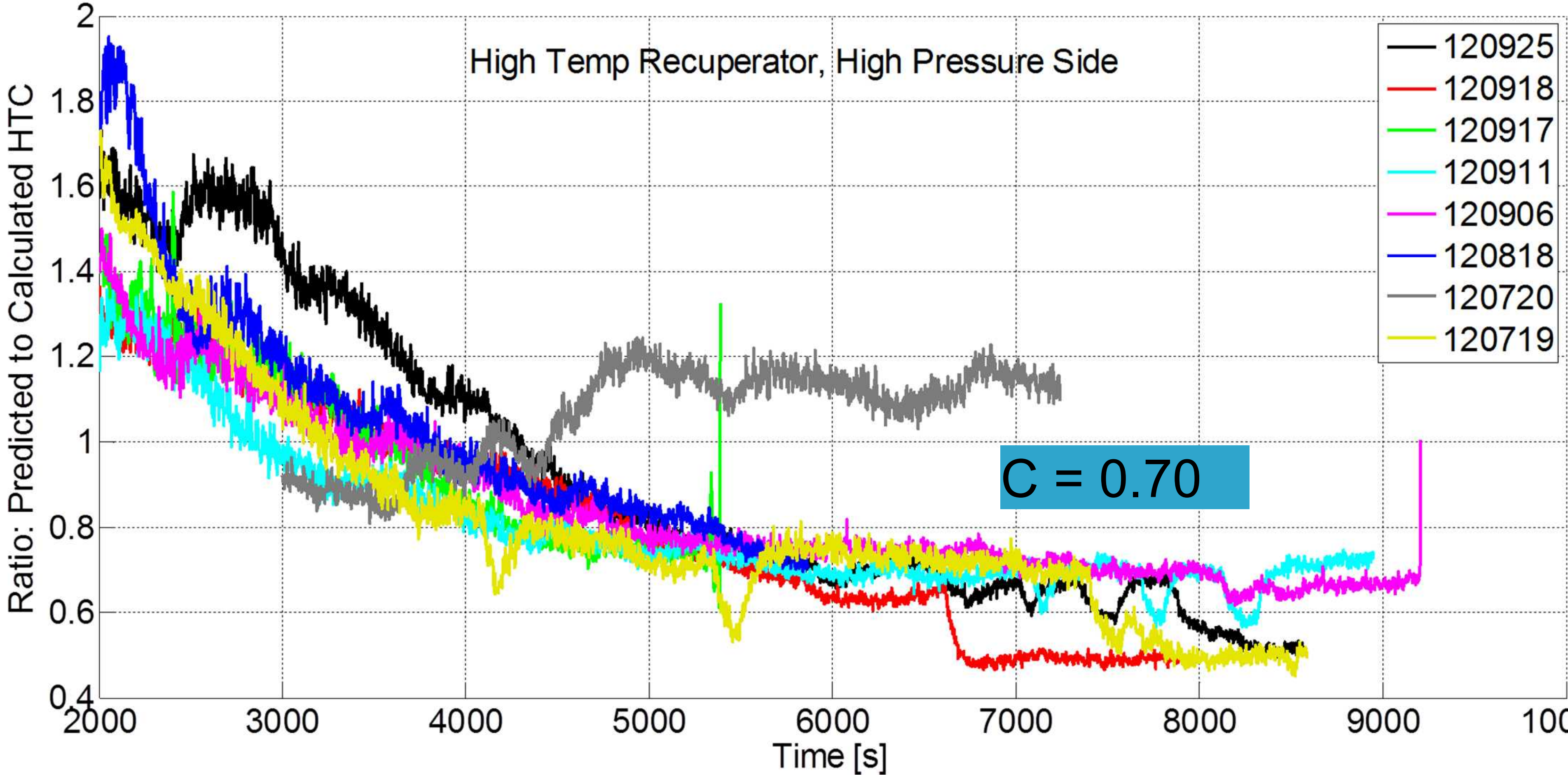
- Recuperator heat transfer predictions using Dittus Boelter, with a modifying factor derived from data.
- Implementation is complicated by the proprietary nature of the PCHE technology that prevents a complete description of the component.
- Heatric has provided recuperator passage volume and surface area
- Using a representative length, this is enough info to calculate number of passages and passage hydraulic diameter

$$A = \pi D L N \qquad V = \frac{\pi D^2}{4} L N$$

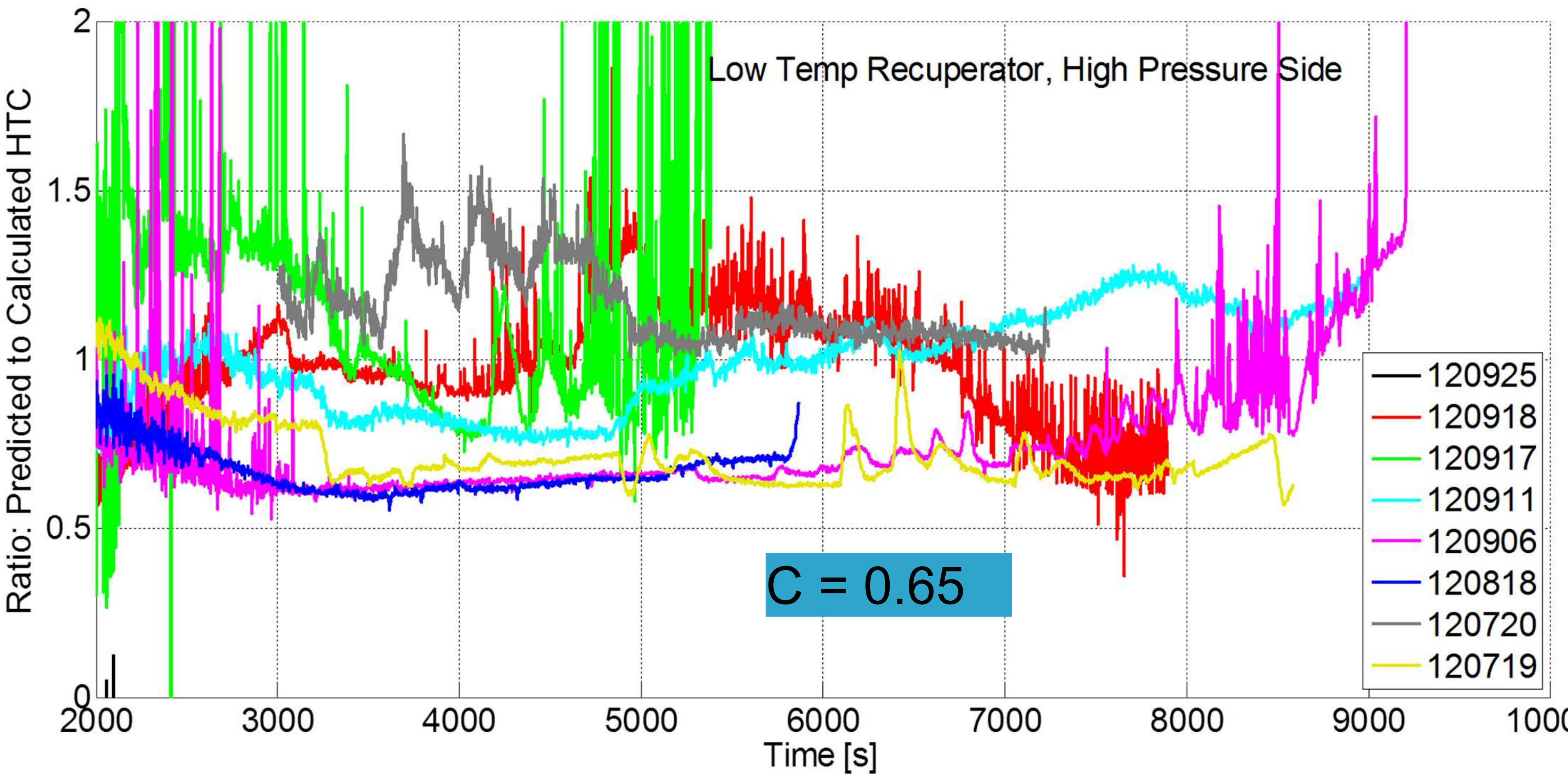
$$h = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.3}\,\frac{k}{D}\,c \qquad Q = hA\left(T_h - T_c\right)$$

- With these equations and measured P/T, ‘c’ can be calculated.
- Predictions are much more realistic, and much closer to data.
- Correlations for each recuperator are specific to the Sandia system, since the recuperator length is assumed.

# Recuperator Performance

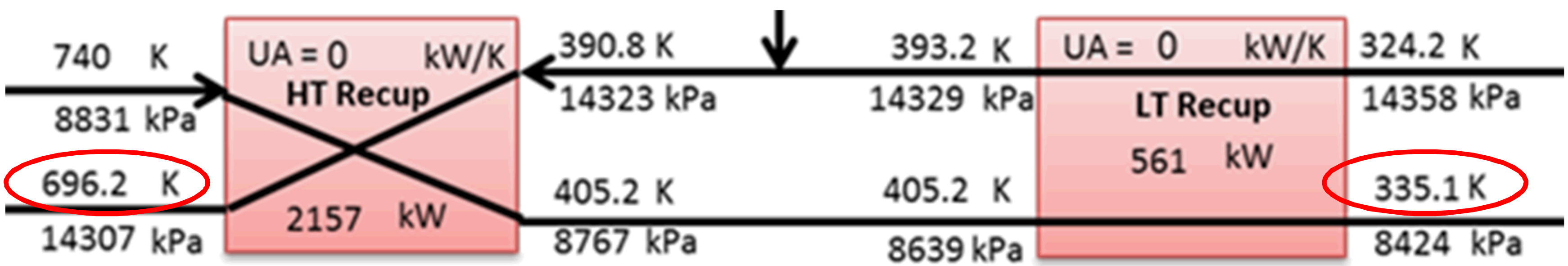


# Recuperator Performance



# Recuperator Performance Observations

- The performance prediction of the two recuperators in a recompression cycle are closely linked, and is iteratively solved as a unit.
- In modeling, two temperatures of particular interest are the HTR cold leg discharge, and the LTR hot leg discharge. These are the streams that flow into the heater and the cooler, respectively, so predictive accuracy is important.
- Results from a sampling of 16 points from six different tests yield RMS predictive accuracies for the temperature rise of the cold stream across both recuperators of 2.7%, and the temperature decline of the hot stream across both recuperators of 0.29%. These predictive results are far superior to those from the LMTD method, which would consistently underestimate the cold stream temperature rise by over 10%.



# Momentum loss

- Similar approach has been implemented for momentum loss
- Approach is to develop a friction coefficient factor to be applied to the standard momentum loss correlation

$$dP = f\frac{\rho v^2}{2}\mathrm{dx}\,\mathrm{c}$$

- For most pipe runs in the Sandia TA, pressure loss is relatively small
- Coupled with instrumentation noise, calculations for the correction factor, ‘c’, has been problematic.
- Several components and pipe runs have been successfully modeled with this approach.
- Extensive effort has been expended recently to reduce or eliminate noise in data acquisition system.
- Initial results will be available this summer.

# Summary - Turbomachinery

- TAC A compressor pressure rise should be decremented to account for the predictive errors arising from operation well away from the thermodynamic.
- TAC B compressor performance is well enough predicted.
- Turbine isentropic efficiency can be predicted by decrementing the measured inlet temperature by the amount necessary to make predicted and measured discharge temperatures match.
- Turbine mass flow rate should be decremented about 7% to account for discrepancy between measured and predicted mass flows that arise from large turbine-to-shroud clearances and eroded components.

# Summary - Recuperators

- High temperature recuperator performance prediction using the Dittus-Boelter heat transfer coefficient method with a data-derived modification factor significantly improves performance predictions compared with using the OEM-supplied UA.
- The low temperature recuperator performance prediction, using the same D-B method, is less successful, likely due to the larger properties variations with a fluid closer to the critical point.
- Overall, the recuperating process is much better modeled using the D-B method with modification factors.
- A similar method has recently been implemented that uses a standard frictional pressure drop correlation with data-derived modification factors for each segment of pipe and each component.