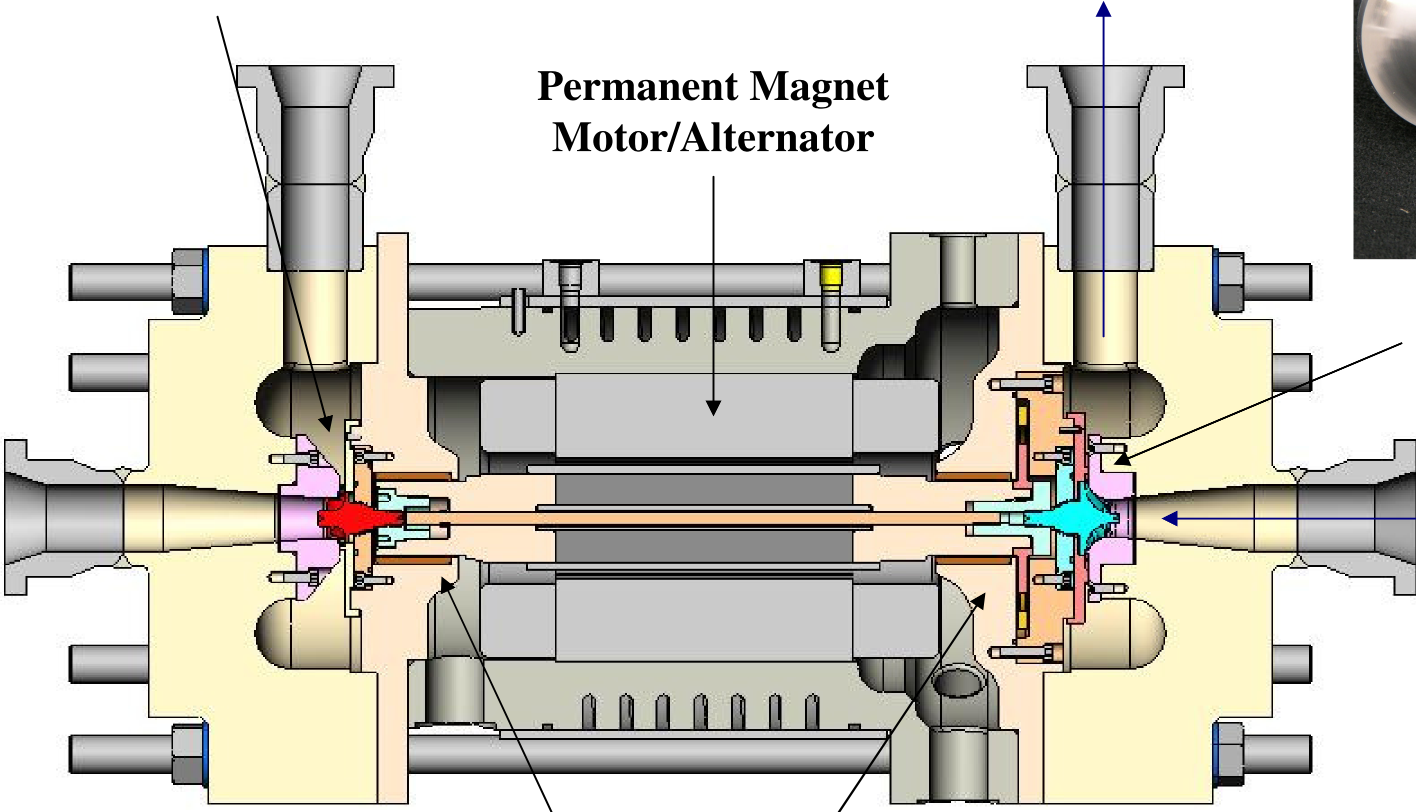
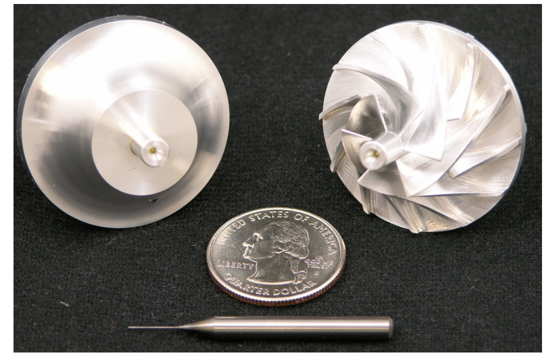
Achievable Efficiency and Stability of Supercritical CO_2 Compression Systems

Jeff S. Noall
Barber Nichols, Inc.

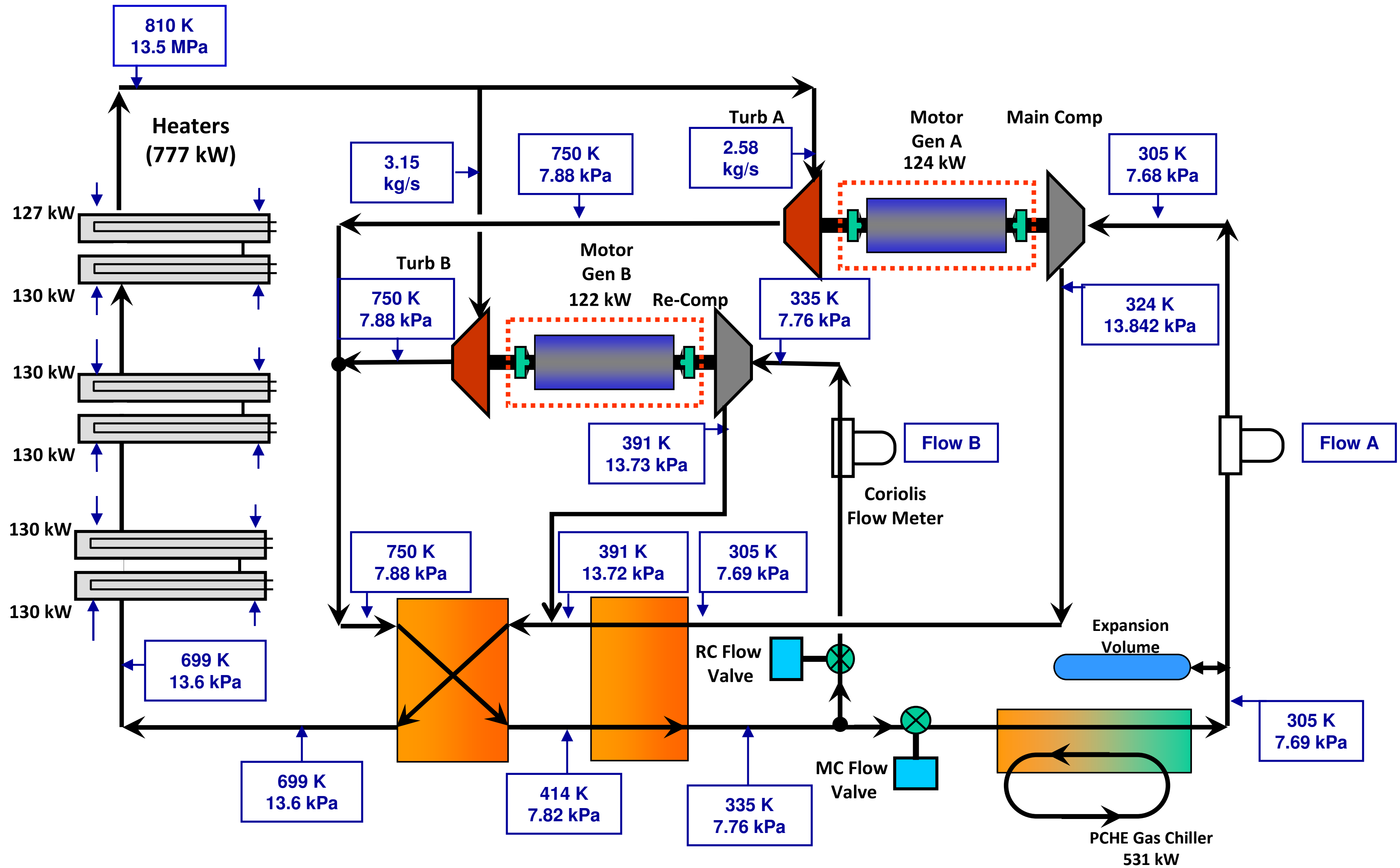
James J. Pasch
Sandia National Labs

Key Elements of the Sandia Turbo-Alternator-Compressor

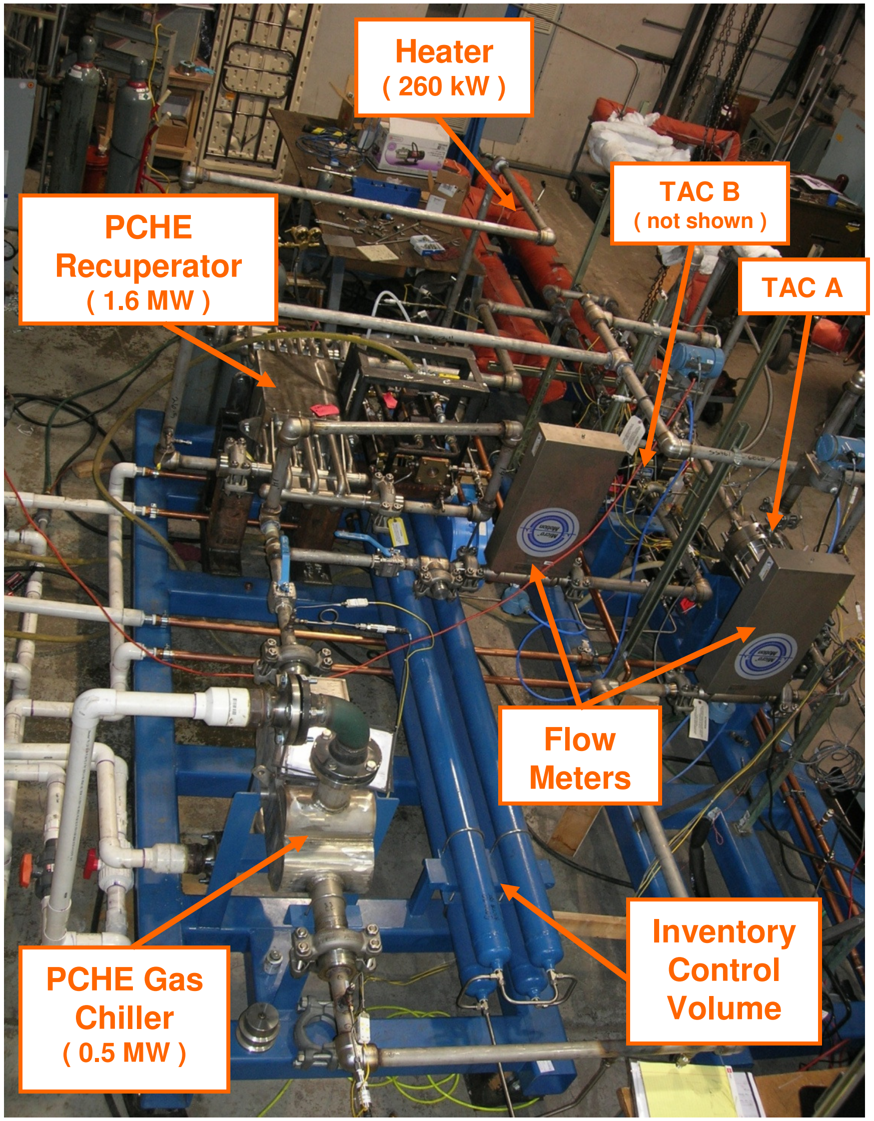




Thermodynamic Cycle Schematic



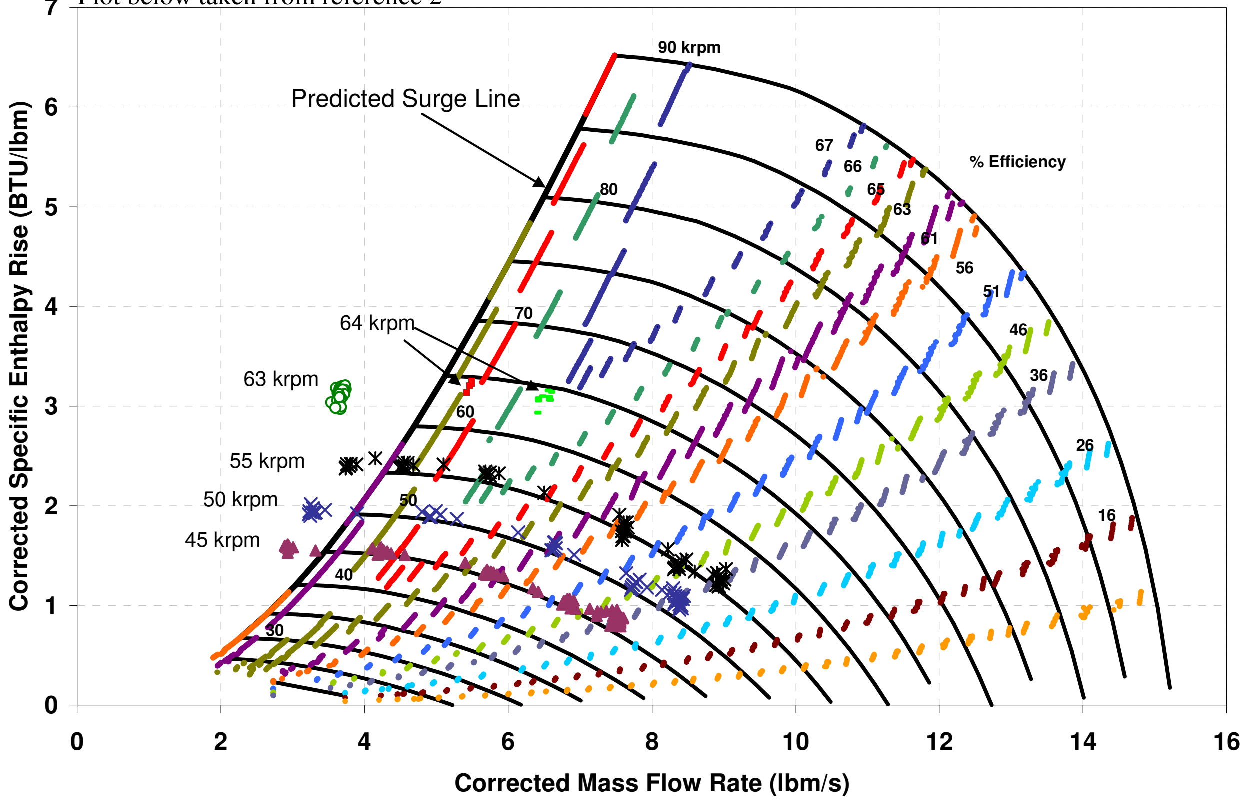
Test Loop Overview



- Coriolis flow meters used to establish fluid density and flow rate. Direct density measurement allows for determination of quality in two phase flow regimes.
- Various configurations tested, including running the recompressor hardware as an alternate for the main compressor.
- Two phase compressor operational data available for both main compressor and recompressor.
- Compressor data presented is from the main compressor due to availability of deeper two phase flow data.
- Recompressor two phase data more limited, but trends and conclusions consistent with main compressor data.

Main Compressor Map – Measured & Predicted Enthalpy Rise

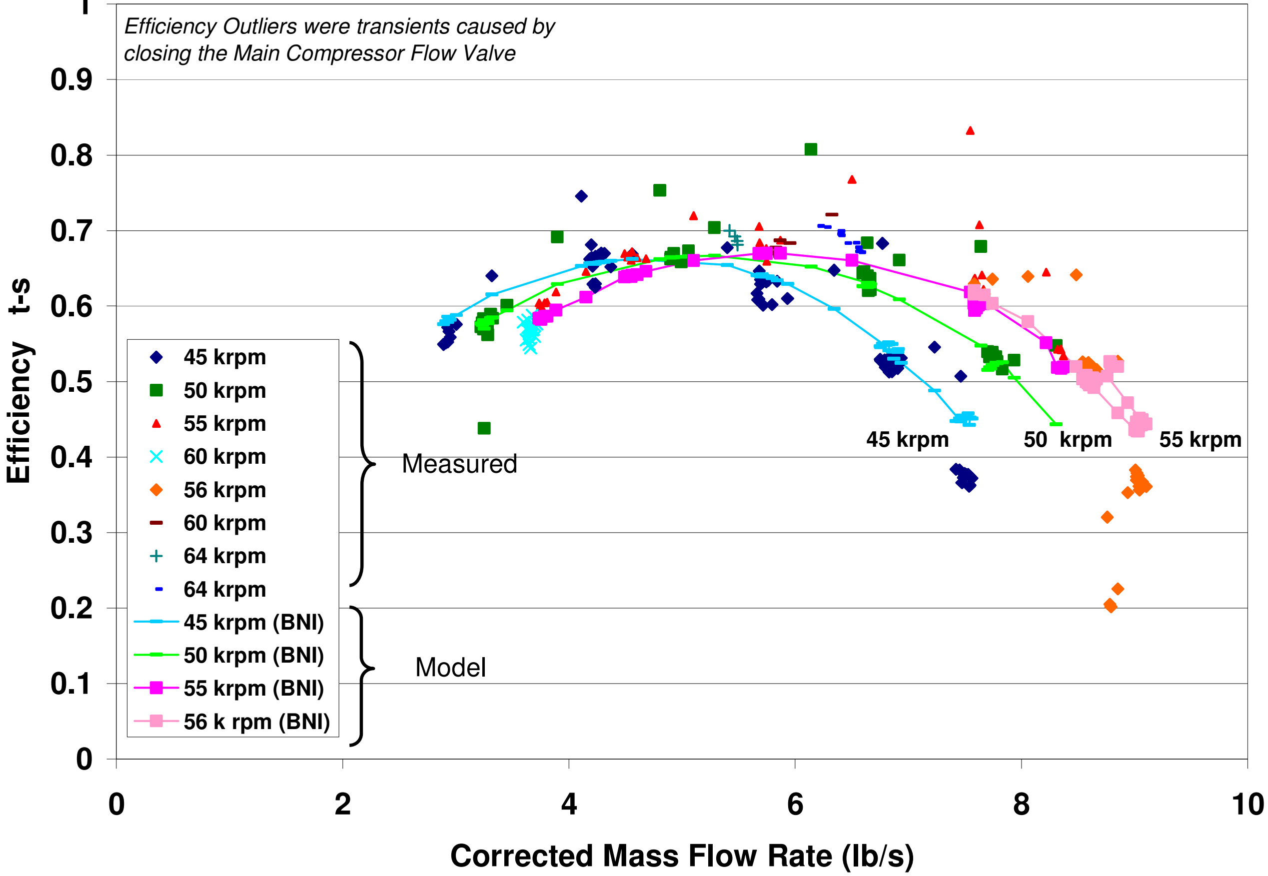
Plot below taken from reference 2



- Test data plotted using corrected flow, speed and enthalpy rise since the inlet density varied from one point to another due to drifts in the pressure & temperature.
- Performance map formulated in terms of enthalpy rise since this quantity scales (corrects) better than pressure ratio near the critical point.
- Tested speed line enthalpy rise vs. flow rate characteristics agree quite well with prediction.
- Test data suggests greater surge margin than predicted.
- Prediction tool slightly anti-conservative for typical applications, implying a surge performance benefit for SCO_2 compression (needs further investigation).

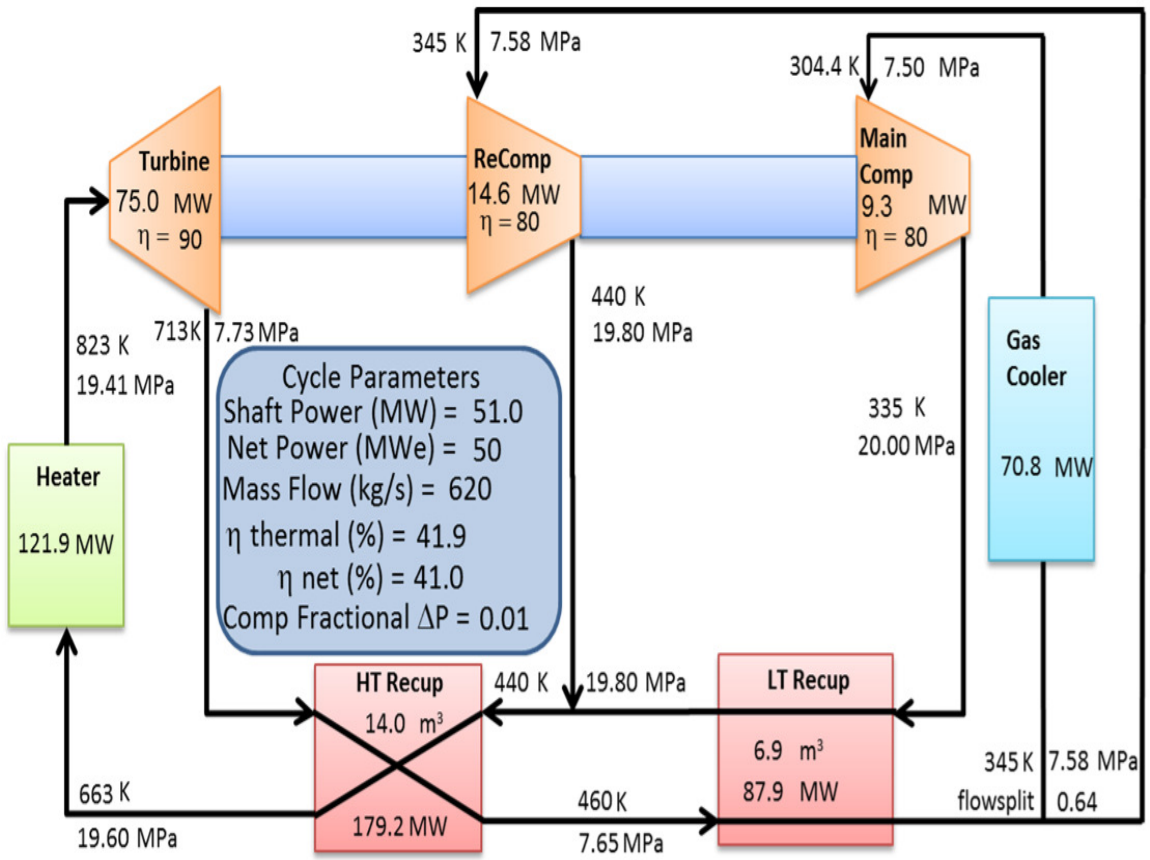
Main Compressor Measured vs. Predicted Efficiency

Plot below taken from reference 2



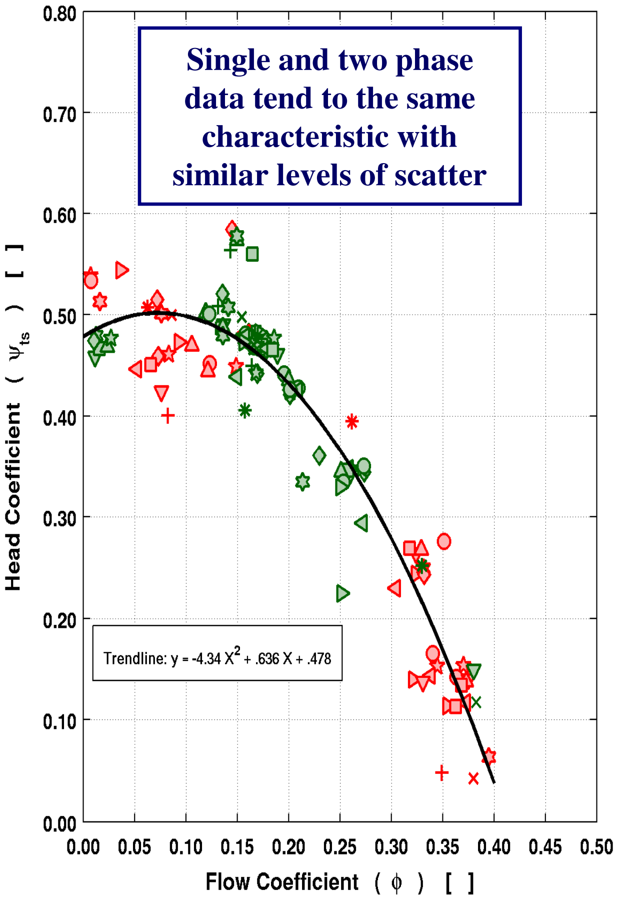
- Blade tip clearance is 12% of impeller exit blade height.
- Design shaft speed limited rotordynamically to 75 KRPM.
- Predicted efficiencies low due primarily to large relative blade tip clearances that result from the small machine scale, and secondarily to sub-optimal specific speed.
- Efficiencies derived from test data based on measured electrical output power in conjunction with assumed motor and controller efficiencies.
- Given the sensitivity of calculated ideal power to pressure & temperature fluctuations near the critical point, test efficiencies agree fairly well with prediction.

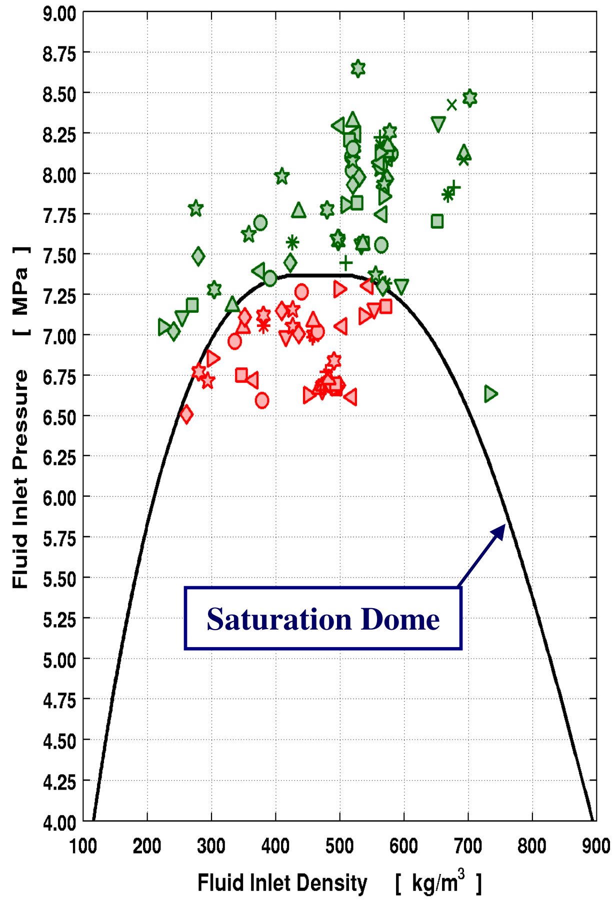
Example Full Scale Cycle



- The cycle shown is a representative full scale (50 MW) cycle. This cycle was used to conduct a performance assessment of a full scale S-CO_2 compressor.
- For this study, a shaft speed of 15 KRPM was selected so that the resulting specific speed is near optimum for a centrifugal compressor at this pressure ratio.
- Assuming a 3600 RPM 50 MWe generator, a very feasible gear box ratio of 4.17:1 is required.
- The resulting compressor design has a very manageable size with an impeller diameter of only 225 mm.
- The combination of high density and comparatively low viscosity tend toward higher compressor efficiency. Preliminary analysis of this design indicates that a compressor efficiency in the range of 83-85% should be realistic.

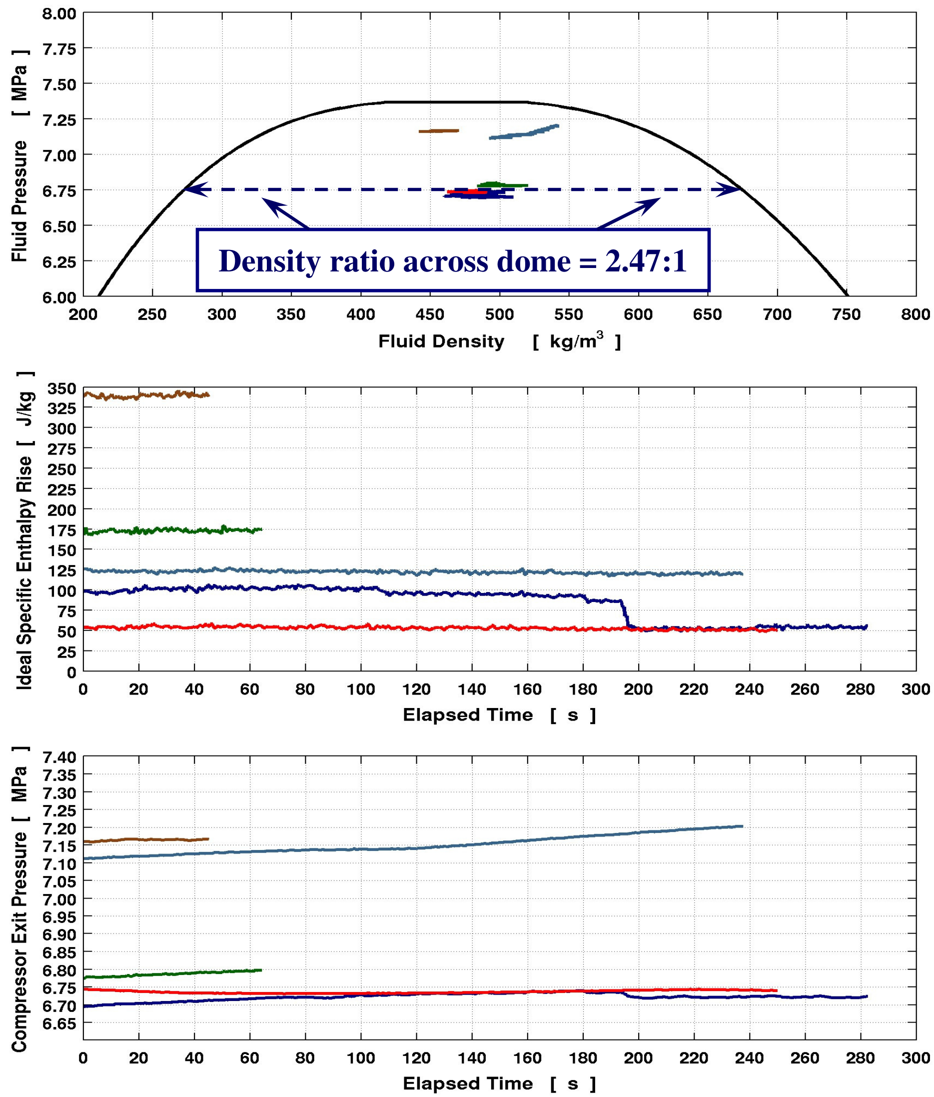
Two Phase Flow Performance





- Over the course of the test program, hours of two phase compressor run time have been accumulated.
- The data plotted in green is single phase compressor operation outside the saturation dome, while the red plotted data indicates two phase operation within the dome.
- Single phase and two phase compressor performance data tend to collapse to a single characteristic with comparable levels of scatter. This further suggests a lack of significant cavitation or flow instability.
- Relatively high level of scatter in the head-flow characteristic (in comparison to pumps) due to compressibility of S-CO2, and to measurement errors related to steep property gradients near the dome.

Stability of Two Phase Compressor Operation



- During testing under two phase conditions, the compressor was noted to be running smoothly with no notable increase in vibration, pressure instability or audible noise.
- Inspection of the aluminum impeller after accumulated two phase operation did not indicate any evidence of surface erosion or other cavitation related damage.
- The low density ratio between vapor and liquid saturation states in the vicinity of the critical point is thought to be the key to why two phase operation of S-CO2 compressors is apparently relatively benign.

Conclusions

- The observed low compressor efficiencies seen in recent sub-scale supercritical CO2 test articles are primarily due to the small scale of the test hardware, and are consistent with design predictions for these sub-scale systems.

- A preliminary performance analysis of a compressor for a full scale 50 MW plant concept indicates that compressor efficiencies in the range of 83% to 85% should be realistically achievable.

- Prolonged, stable compressor operation has been achieved where inlet conditions were two phase and well within the saturation dome.

- Two phase supercritical CO2 test experience has indicated that localized excursions into the saturation dome near the vicinity of the critical point may not present any significant adverse effects.

- It is thought that the small ratio of the saturated liquid and vapor densities near the top of the saturation dome are responsible for the benign nature of two phase operation in this region.

- Such test experience has been limited to relatively slow speeds as compared to the design speed of the compressor. Further two phase compressor testing should be conducted at higher speeds with correspondingly larger pressure ratios to confirm that such smooth, stable operation will persist under these more general operating conditions.

References

[1] Steven A. Wright, Robert Fuller, Paul S. Pickard and Milton E. Vernon Initial Status and Test Results from a Supercritical CO2 Brayton Cycle Test Loop, Proceedings of ICAPP '08 Anaheim, CA USA, June 8-12, 2008, Paper 8266

[2] Steven A. Wright, Paul S. Pickard, Milton E. Vernon, Ross F. Radel and Robert Fuller Supercritical CO2 Brayton Cycle Power Generation Development Program and Initial Test Results, Proceedings of the ASME Power 2009 Conference, ASME Power 2009, Albuquerque, New Mexico, July 21-23, 2009.

[3] Steven A. Wright, Paul S. Pickard, Milton E. Vernon and Ross F. Radel Description and Test Results from a Supercritical CO2 Brayton Cycle Development Program, 7th International Energy Conversion Engineering Conference August 2-5 2009, Denver, Colorado AIAA 2009-4607

[4] A. J. Glassman, Turbine Design and Application, NASA SP-290, pp 58-60.

Acknowledgements

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