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Supercritical CO_2 Compression Loop Operation at Off-Nominal Conditions

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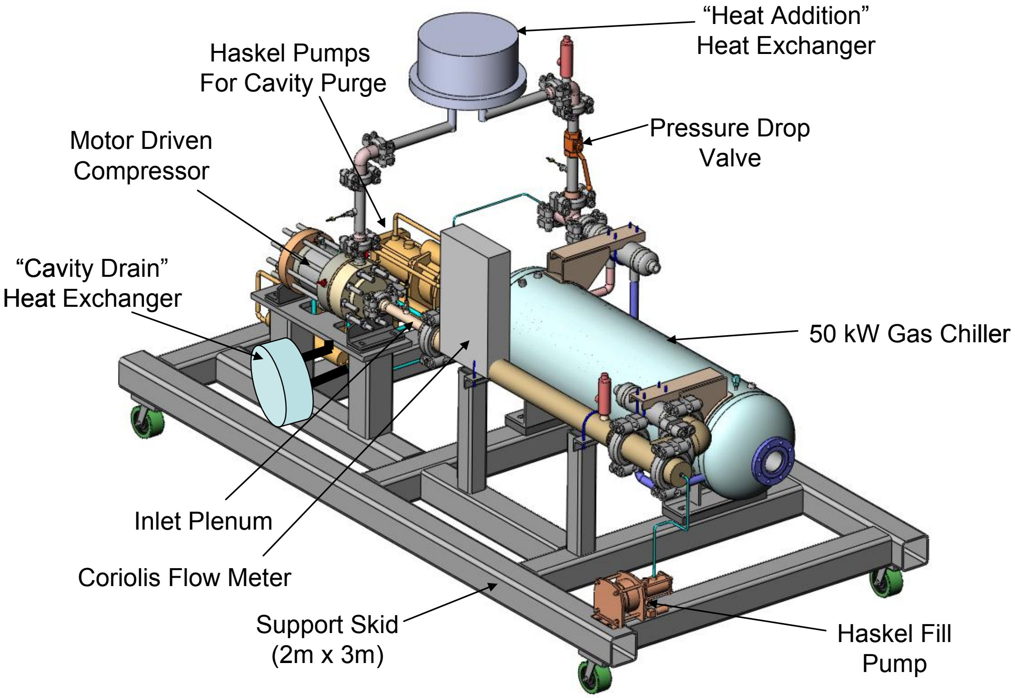

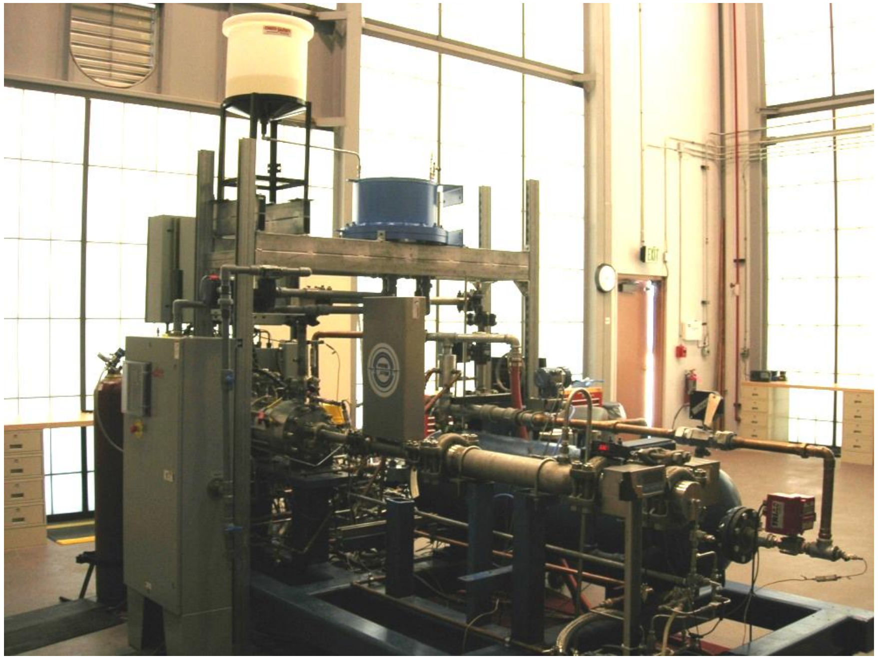

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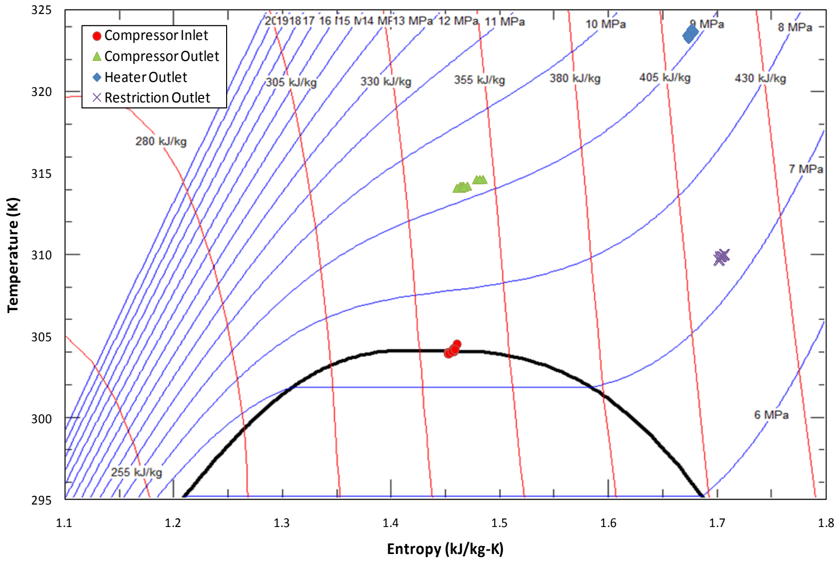
Outline

Intro: What is the S-CO_2 Brayton Cycle, and what are its advantages?

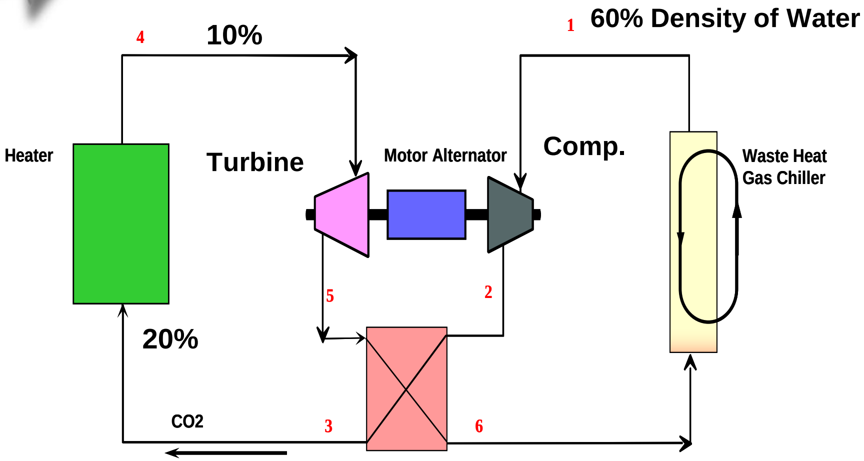
Background: S-CO_2 Brayton Cycle Hardware Development at Sandia

Operation at Off-Nominal Conditions:

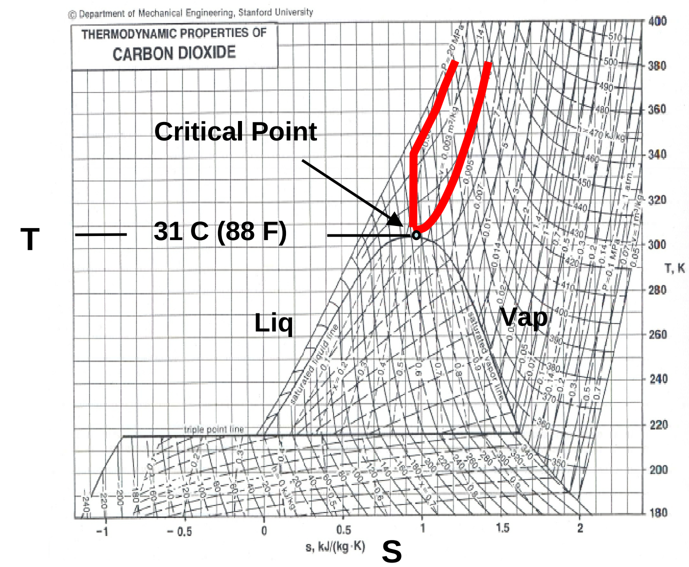
(1) Motivation
(2) Procedure & Equipment
(3) Data/Observations
(4) Conclusions
(5) Future work



What is a Supercritical CO_2 Brayton Cycle? How does it work?



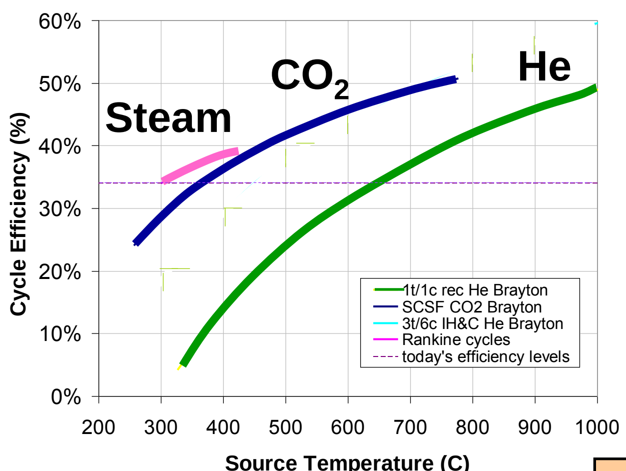
Liquid like Densities with CO_2
Very Small Systems,
High Efficiency due to Low Pumping Power



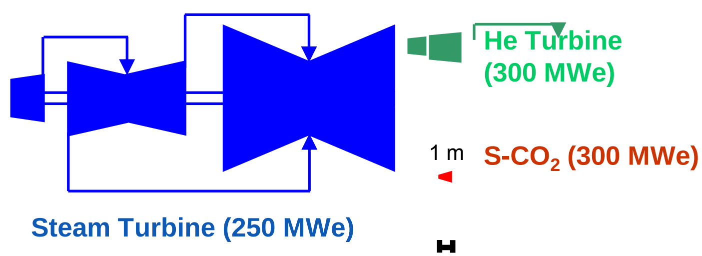
Rejects Heat
Above Critical Point
High Efficiency ***Non-Ideal Gas***
Sufficiently High for Dry Cooling

Critical Point
88 F / 31 C
1070 psia / 7.3 MPa

Cycle Efficiencies vs Source Temperature
for fixed component efficiency



High Efficiency at Lower Temp
(Due to Non-Ideal Gas Props)



High Density Means Very Small Power Conversion System
Non-Ideal Gas Means Higher Efficiency at Moderate Temperature

Supercritical CO_2 Cycle Applicable to Many Thermal Sources

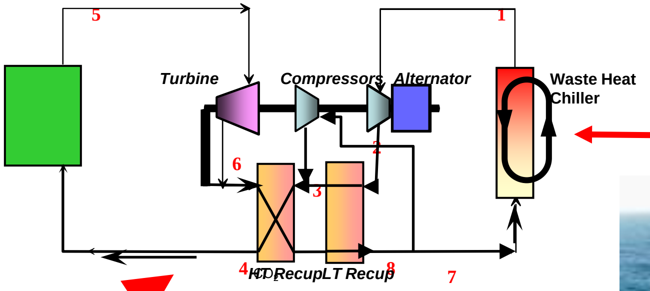
Solar

SNL Solar Tower

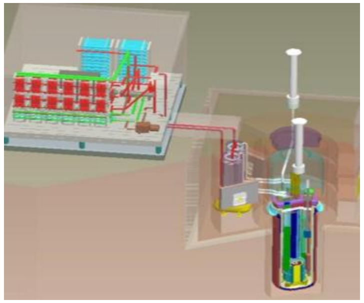
Geothermal

ARRA

Supercritical CO_2 Brayton Cycle

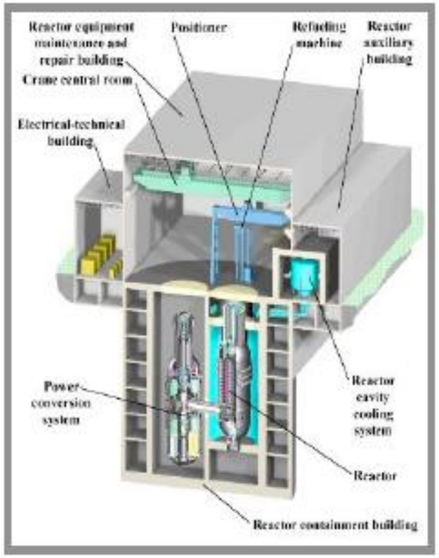


Military



Nuclear

(Gas, Sodium, Water)



DOE-NE
Gen IV

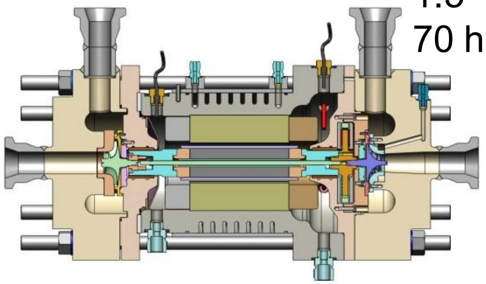
Fossil

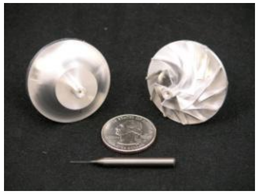
INERI
NRCan CANMET &
SASK Power

Key Features to a Supercritical Brayton Cycle

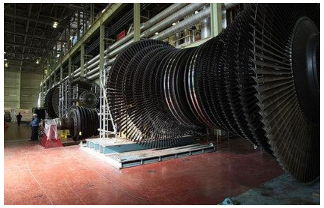
- **Peak Turbine Inlet Temp is well matched to a Variety of Heat Sources (Nuclear, Solar, Gas, Coal, Syn-Gas, Geo)**
- **Efficient ~43% - 50% for 10 - 300 MW_e Systems**
  - **1000 F (810 K) ~ 538 C Efficiency = 43 %**
  - **1292 F (1565 K) ~ 700 C Efficiency =50%**
- **Standard Materials (Stainless Steels and Inconels)**
- **High Power Density for Conversion System**
  - **~30 X smaller than Steam or 6 X for Helium or Air**
  - **Transportability (Unique or Enabling Capability)**
  - **HX's Use Advanced Printed Circuit Board Heat Exchanger (PCHE) Technology**
- **Modular Capability at ~10-20 MWe**
  - **Factory Manufacturable (10 MW ~ 2.5m x 8m)**

Fabricated and Testing
1.5" Compressor
70 hp

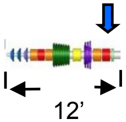




Steam Turbine



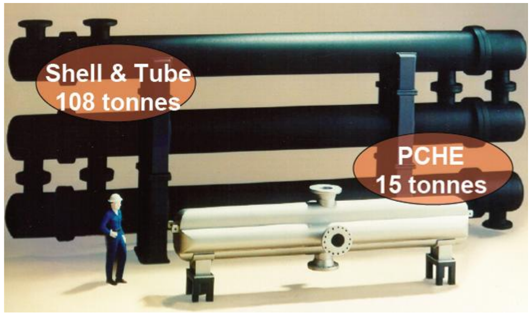
Turbine Building



S-CO_2

Efficiency at Lower Operating Temps
Standard Materials, Small Size
Modular & Transportable
AFFORDABLE and FABRICABLE

Modular & Self Contained
Power Conversion Systems
~ 1.5 m x 8 m



Advanced
Heat Exchangers
Meggit / Heatric Co.

S-CO_2 Development Sequence at Sandia

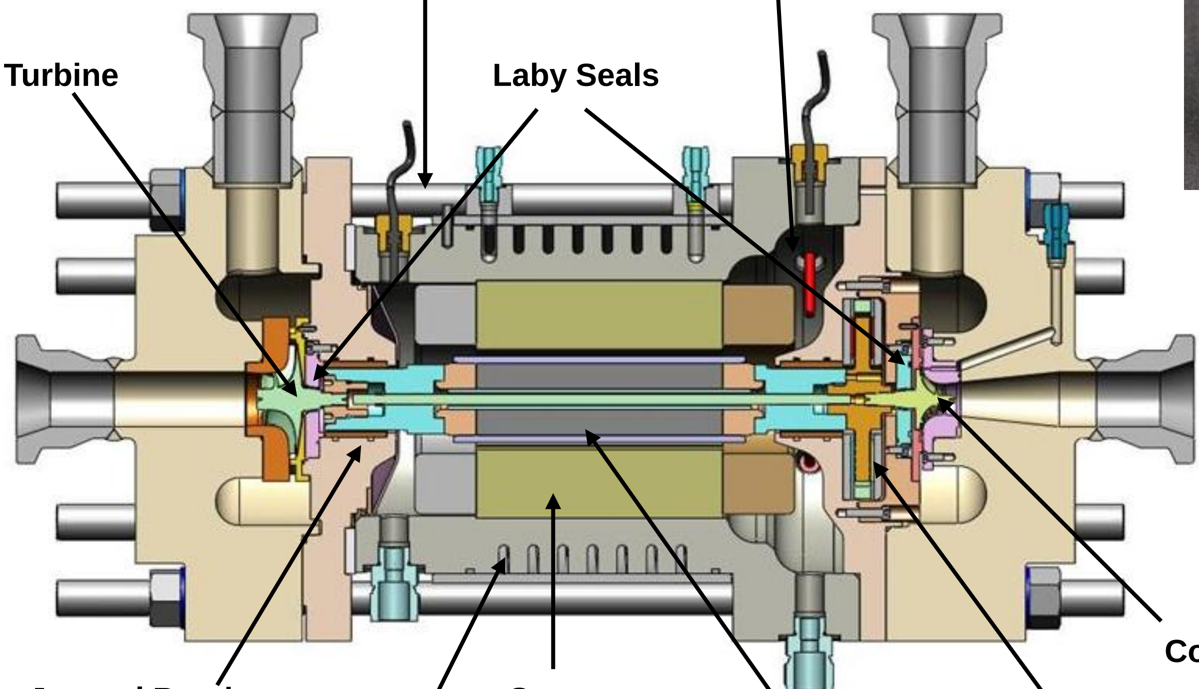
Sandia Single
Compressor Loop

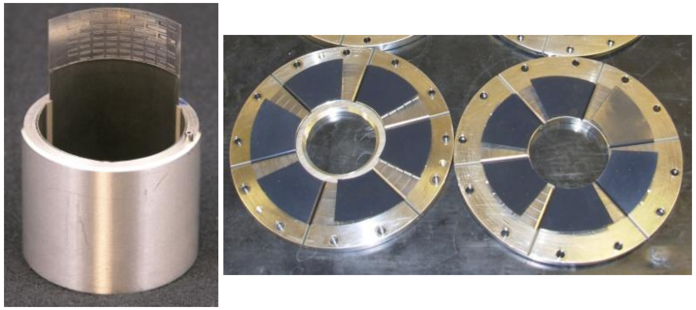
Heated
Unrecuperated
Brayton Loop

DOE Gen IV Split-Flow
Re-compression
Brayton Loop

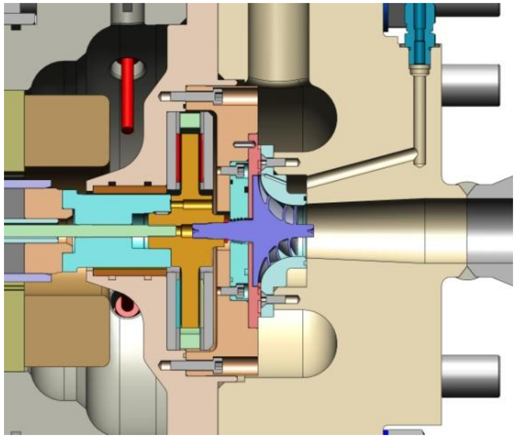
Key Technology:
Turbo-Alternator-Compressor Design with Gas Foil Bearings

(24” Long by 12” diameter)





Gas-Foil Bearings

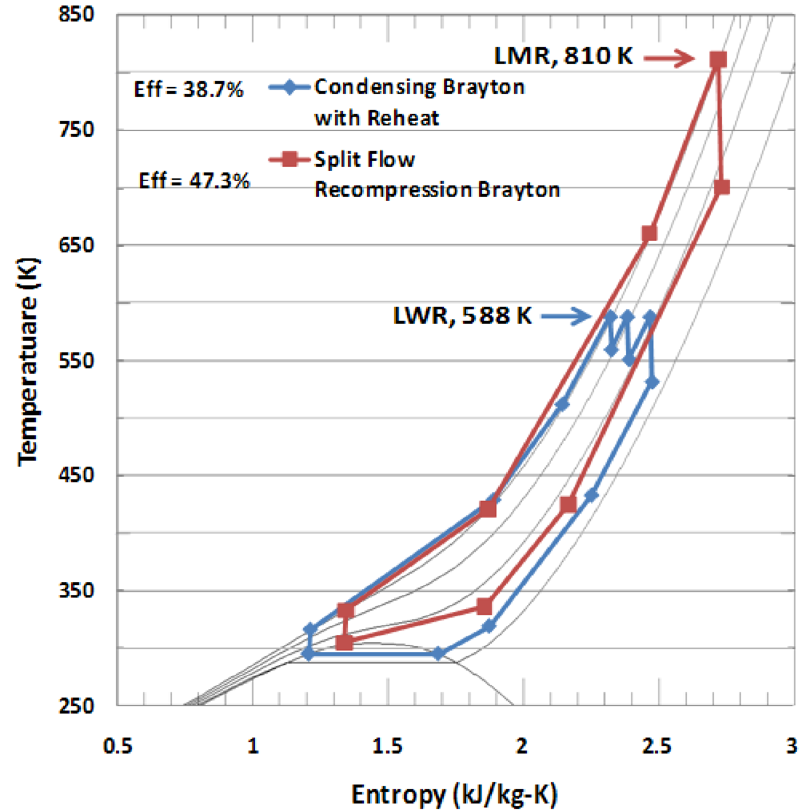


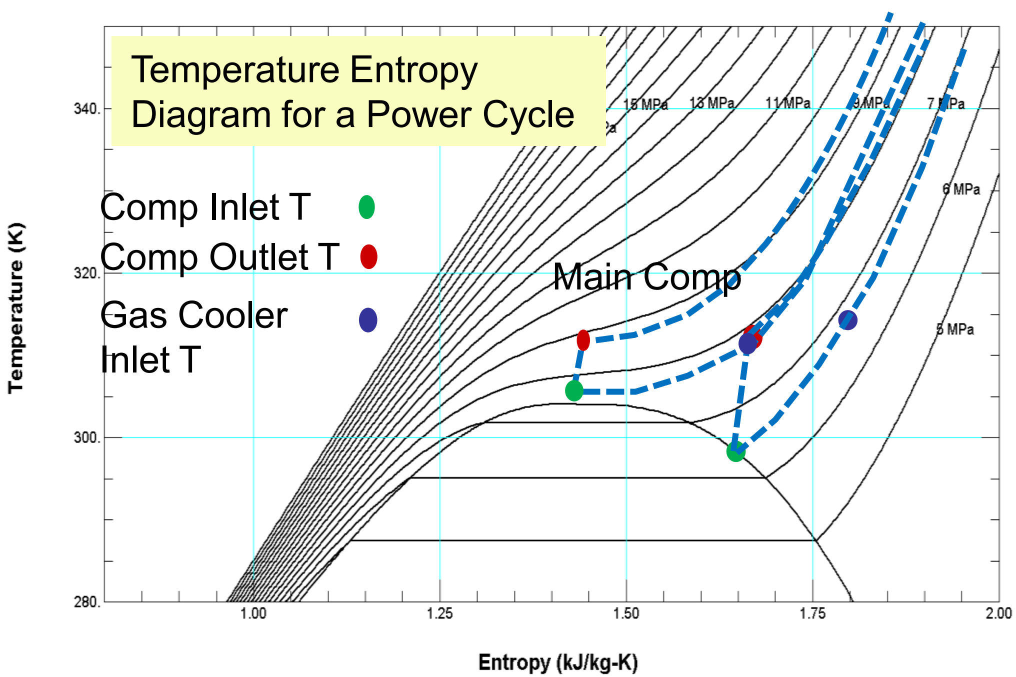
Motivation

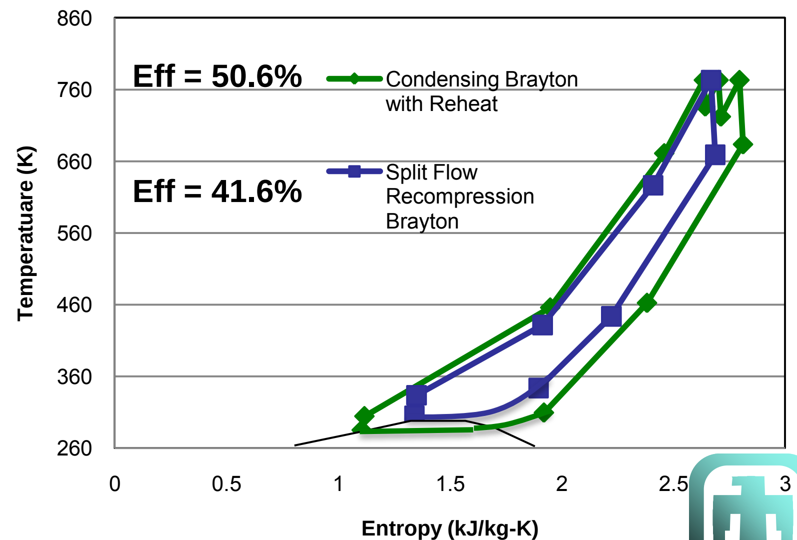
- At Sandia, ongoing research into analysis of advanced S-CO_2 power cycles:
    - reheat, condensing, intercooling, etc.

-This will require compressor and chiller operation in a variety of new, unproven operating regimes

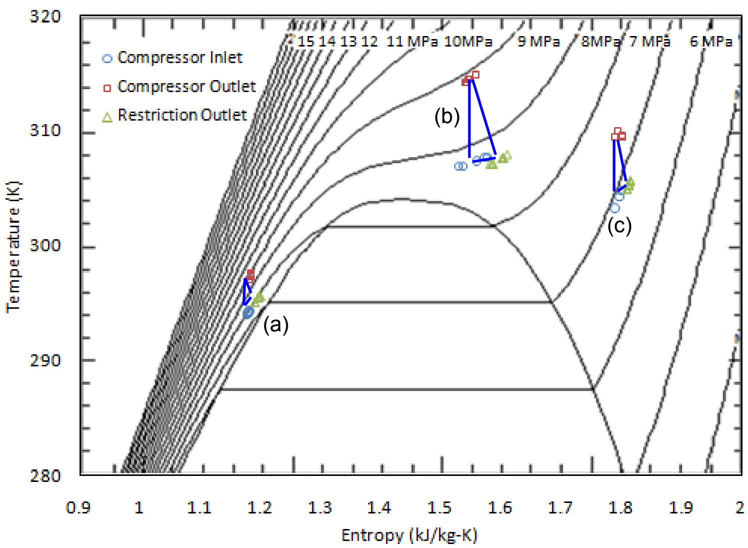
- Experimental tests needed to verify performance under these conditions







Goals



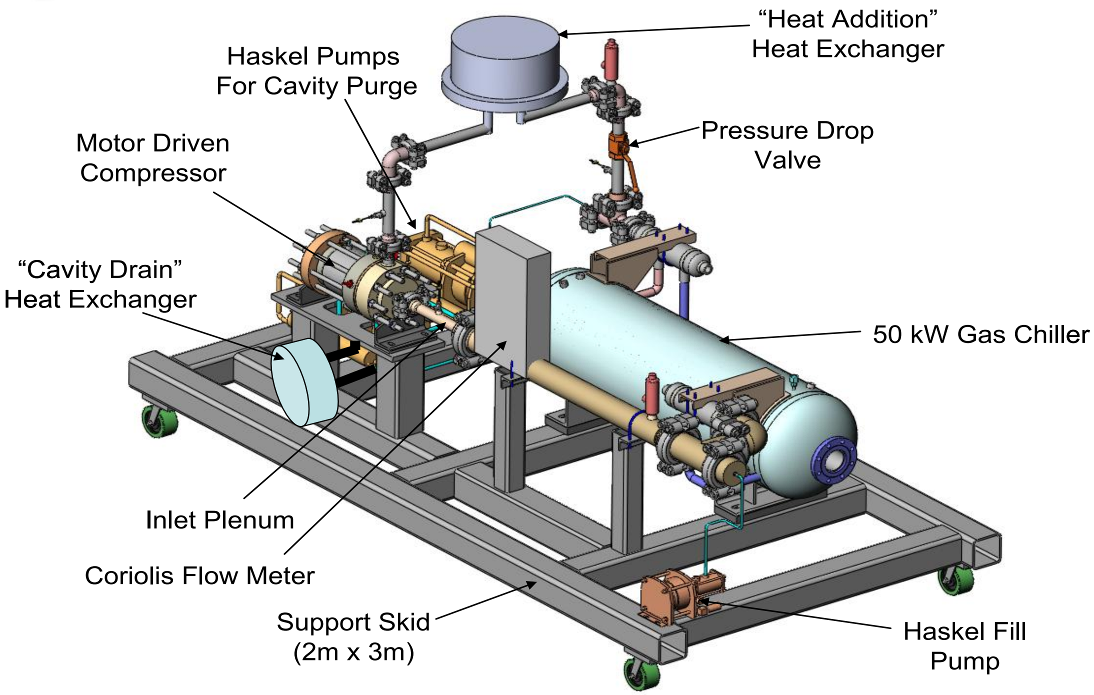
Primary goals for this testing were the evaluation of:

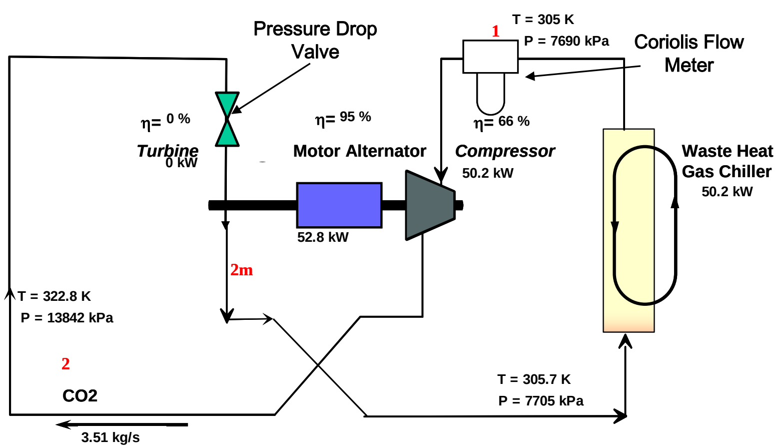
- S-CO_2 compressor performance under liquid, gas, and two-phase conditions, near the critical point

- S-CO_2 gas chiller performance when operating as a condenser. (No hardware modifications made to either component)

- The CO_2 equation of state

Test Equipment





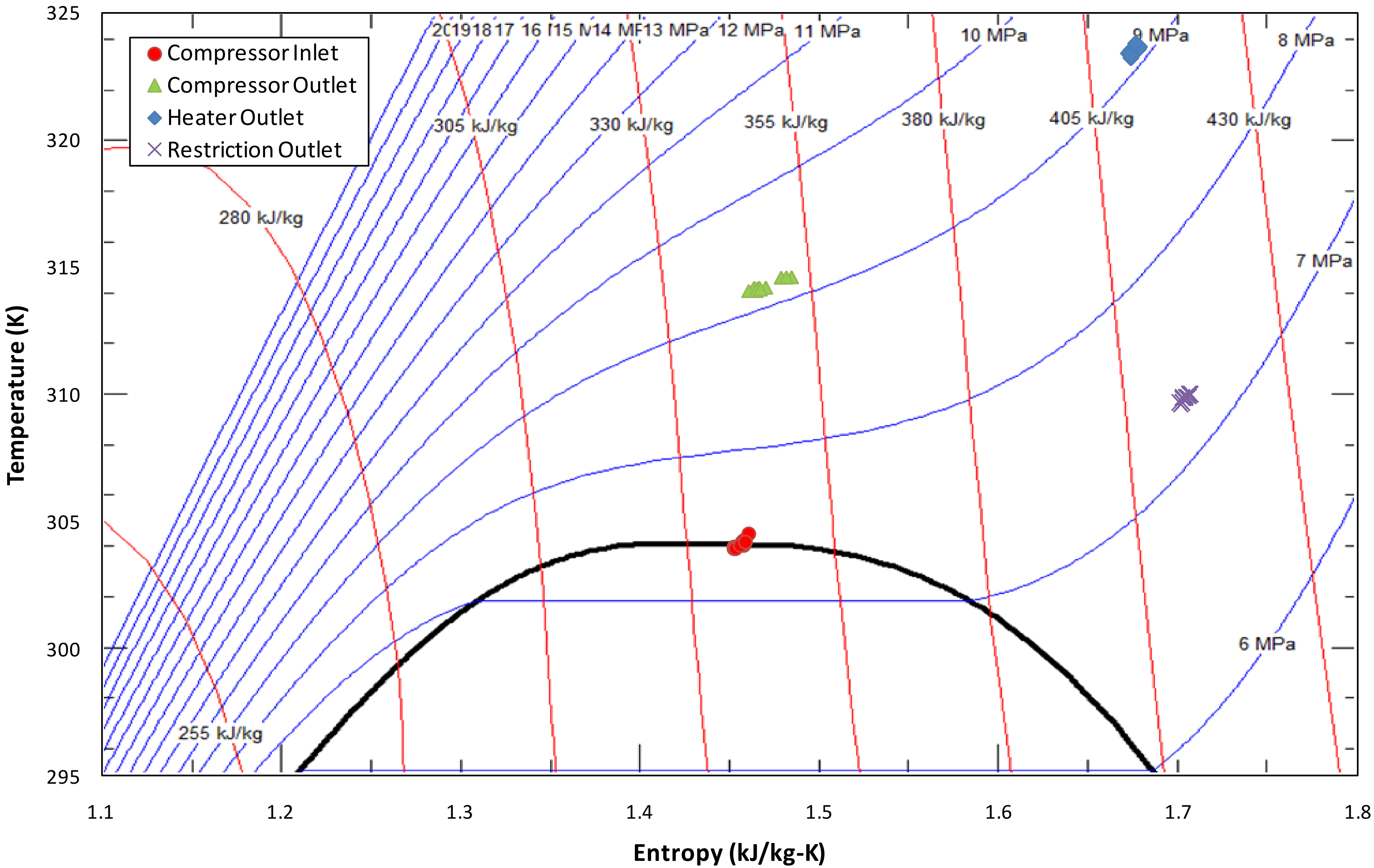
-Tests used the Sandia S-CO_2 compression loop, which consists of a compressor, heater, flow control valve, and chiller.

- Instrumented with T,p sensors at 4 key state points, and a density meter at compressor inlet

- In the past, used for mapping compressor performance at the critical point, bearings & seals R&D, windage tests, etc.

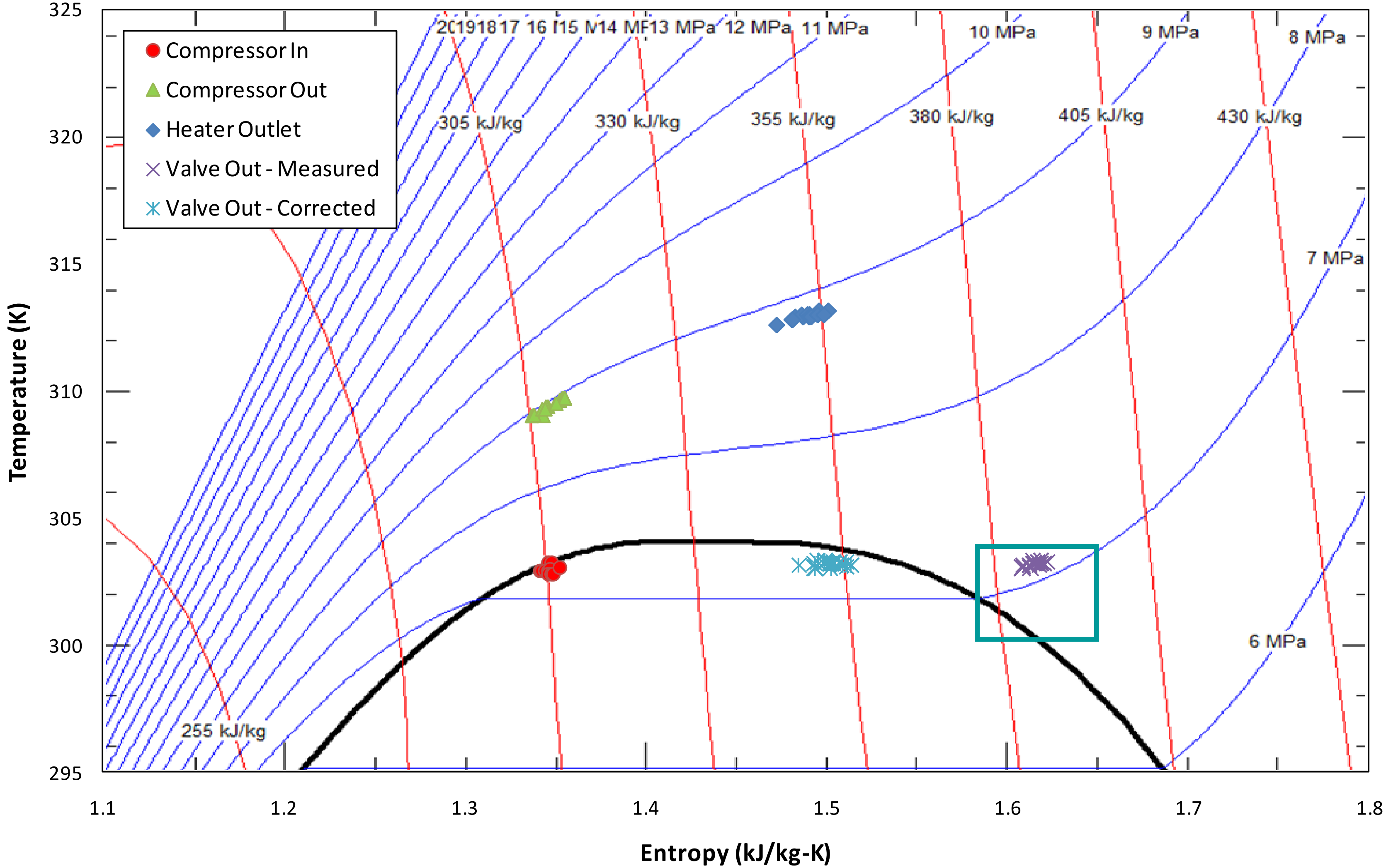
Barber Nichols

Data: Supercritical CO_2 at Compressor Inlet



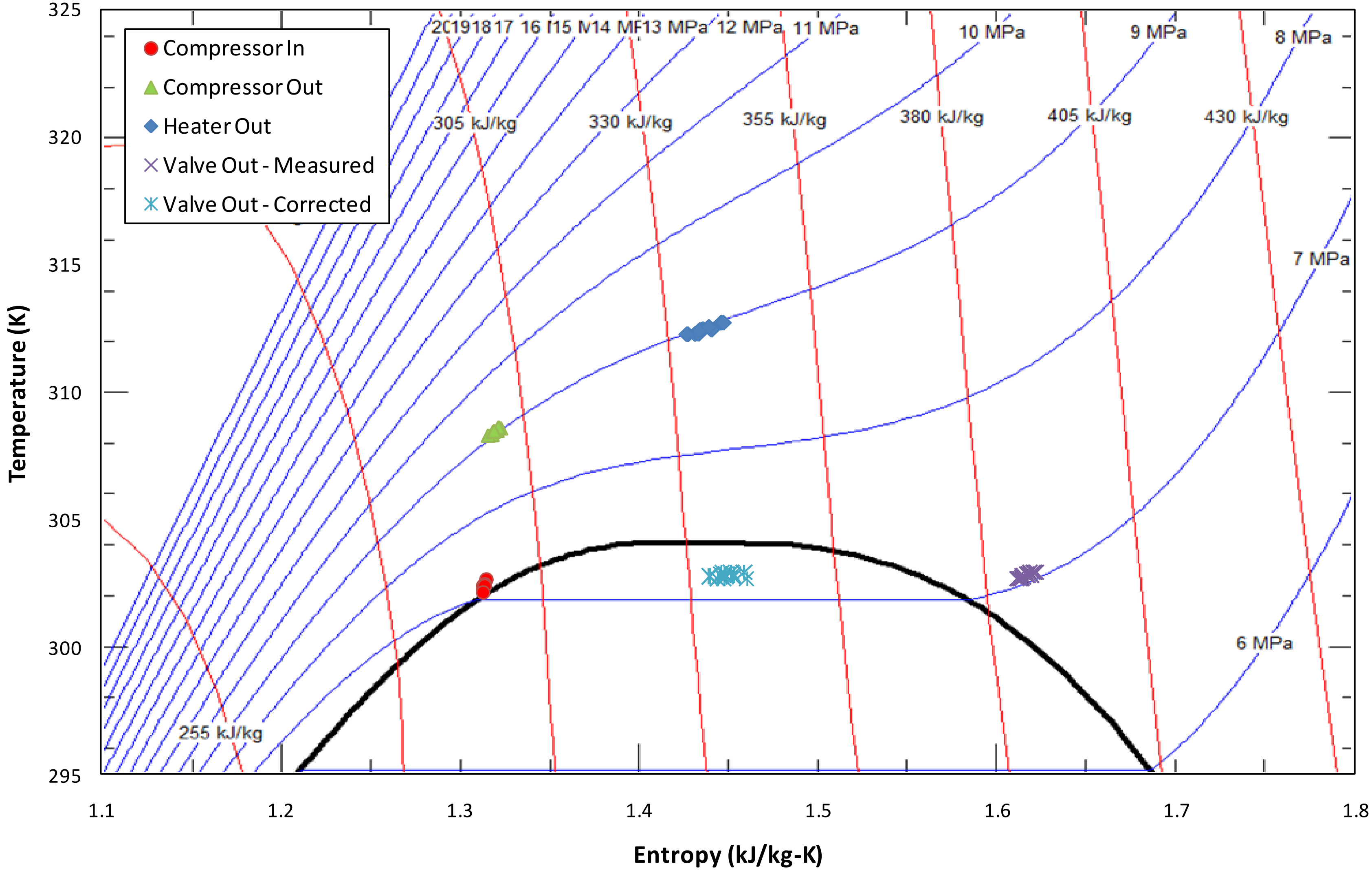
The compressor can be operated directly at the critical point.

Data: 303K Liquid CO_2 at Compressor Inlet



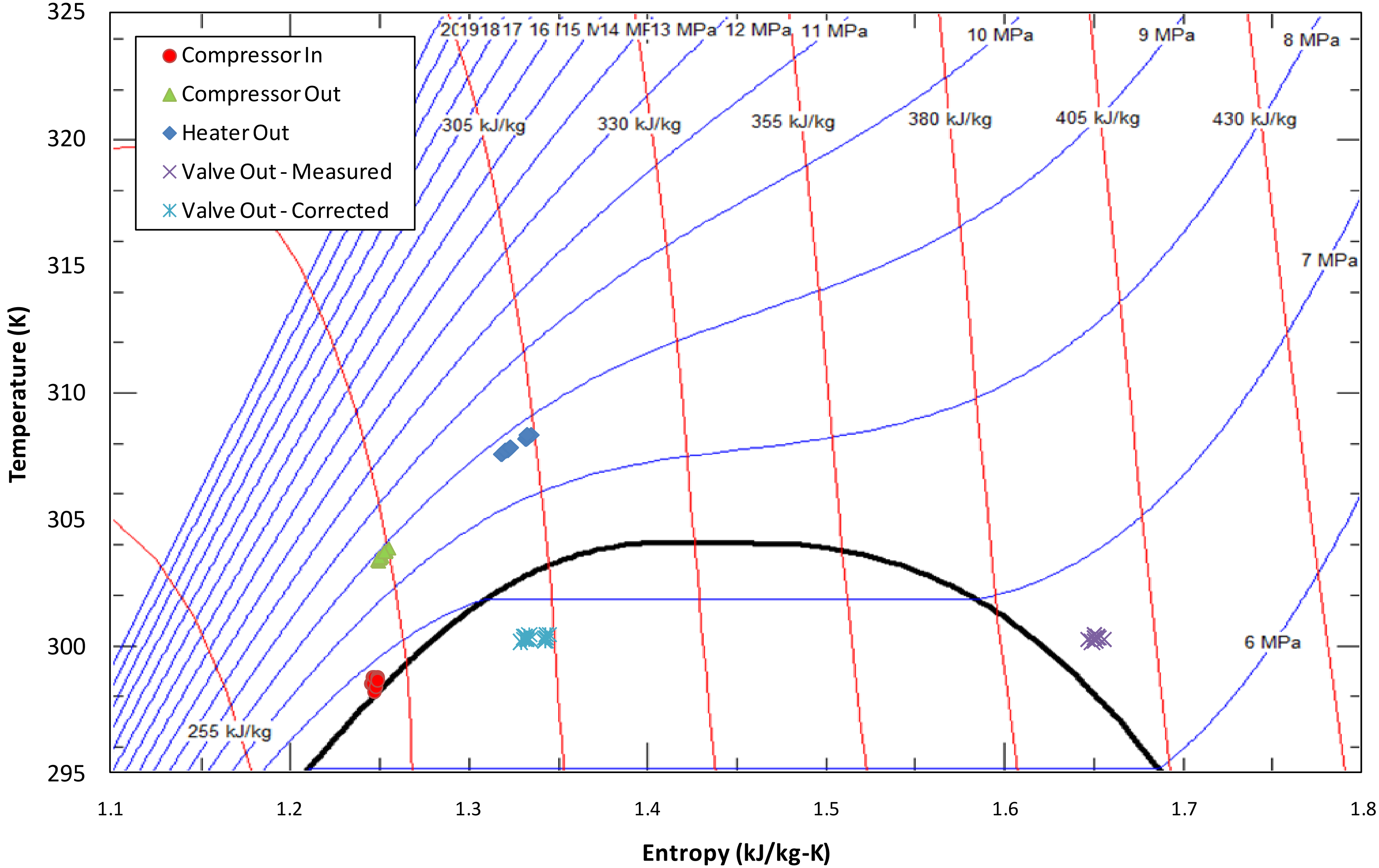
The condensing cycle: liquid at the compressor inlet and condensation within the chiller, cutting across the entire two-phase dome from gas to liquid.

Data: 302K Liquid CO_2 at Compressor Inlet

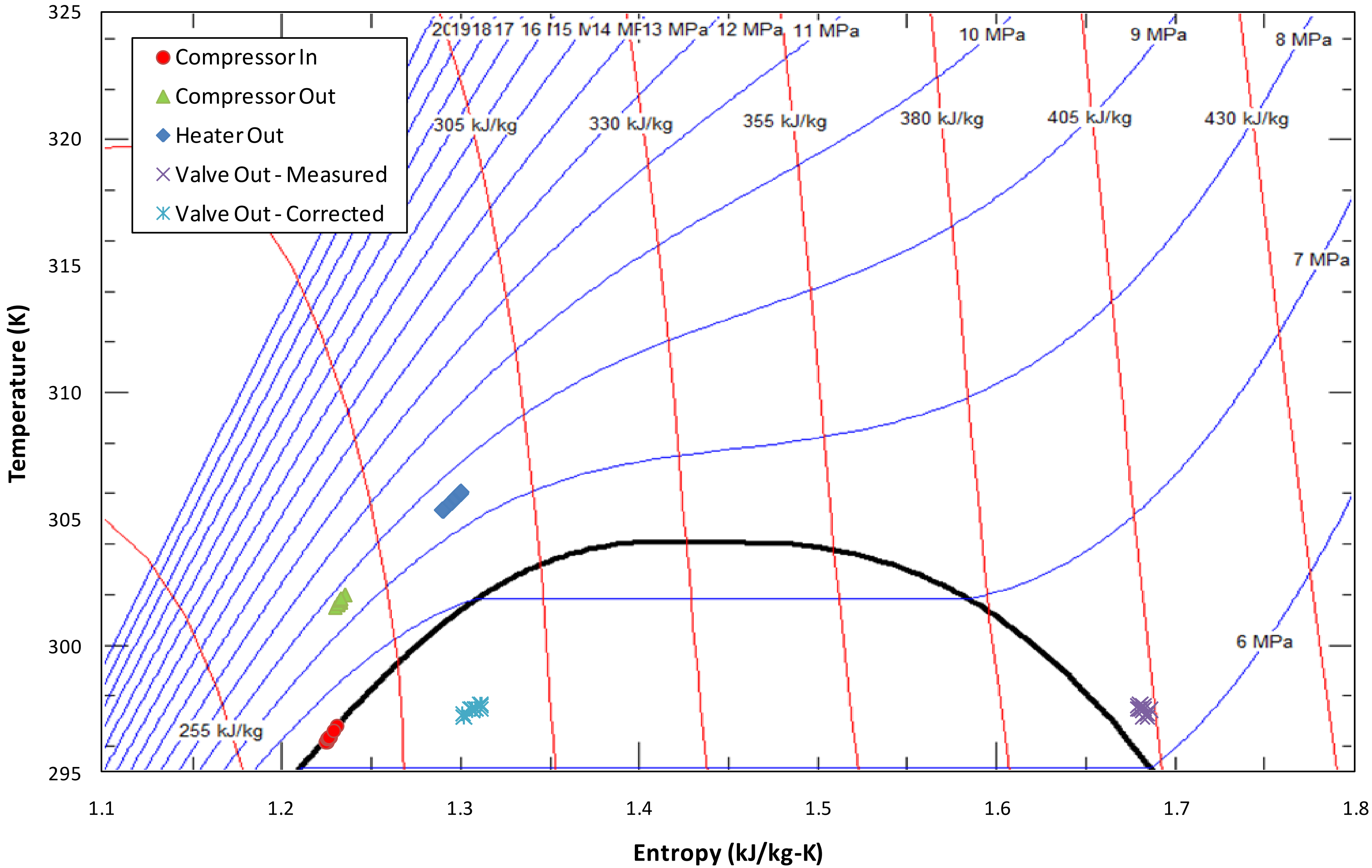


Even cooler liquid at the compressor inlet, and two-phase conditions at the chiller inlet

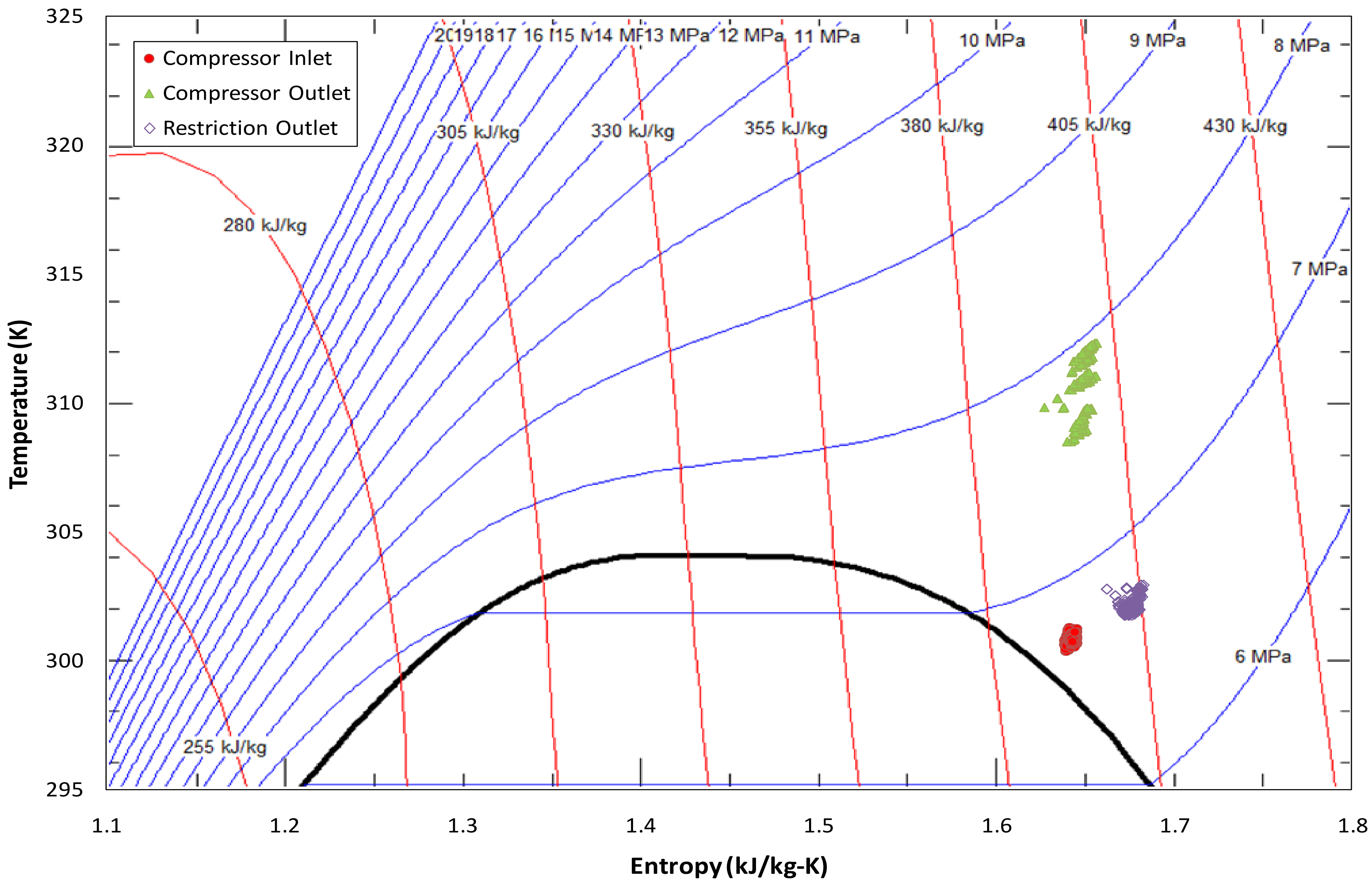
Data: 298K Liquid CO_2 at Compressor Inlet



Data: 296K Liquid CO_2 at Compressor Inlet

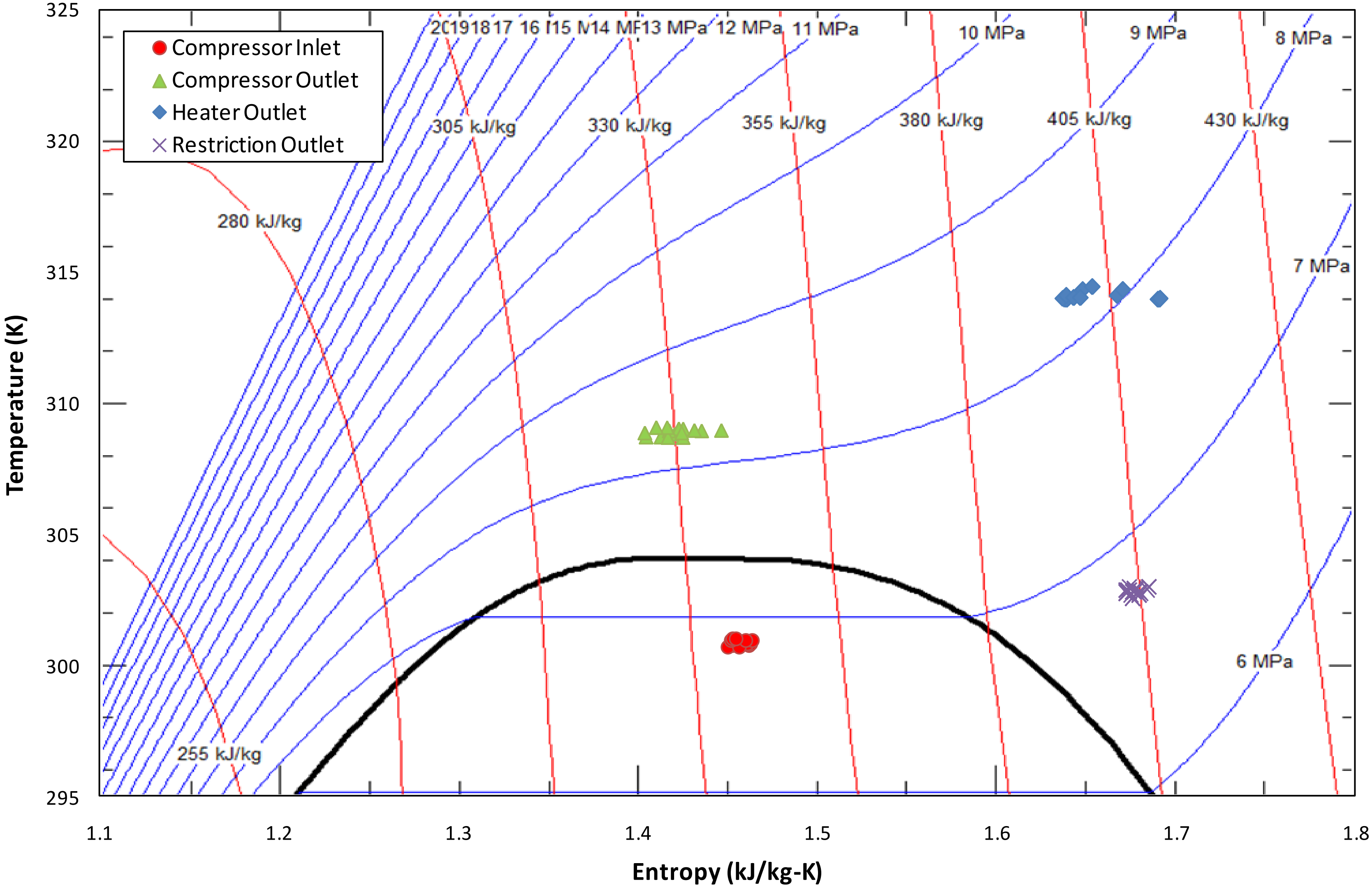


Data: 300K CO_2 Vapor at Compressor Inlet



Vapor-phase CO_2 is also no problem at the compressor inlet.

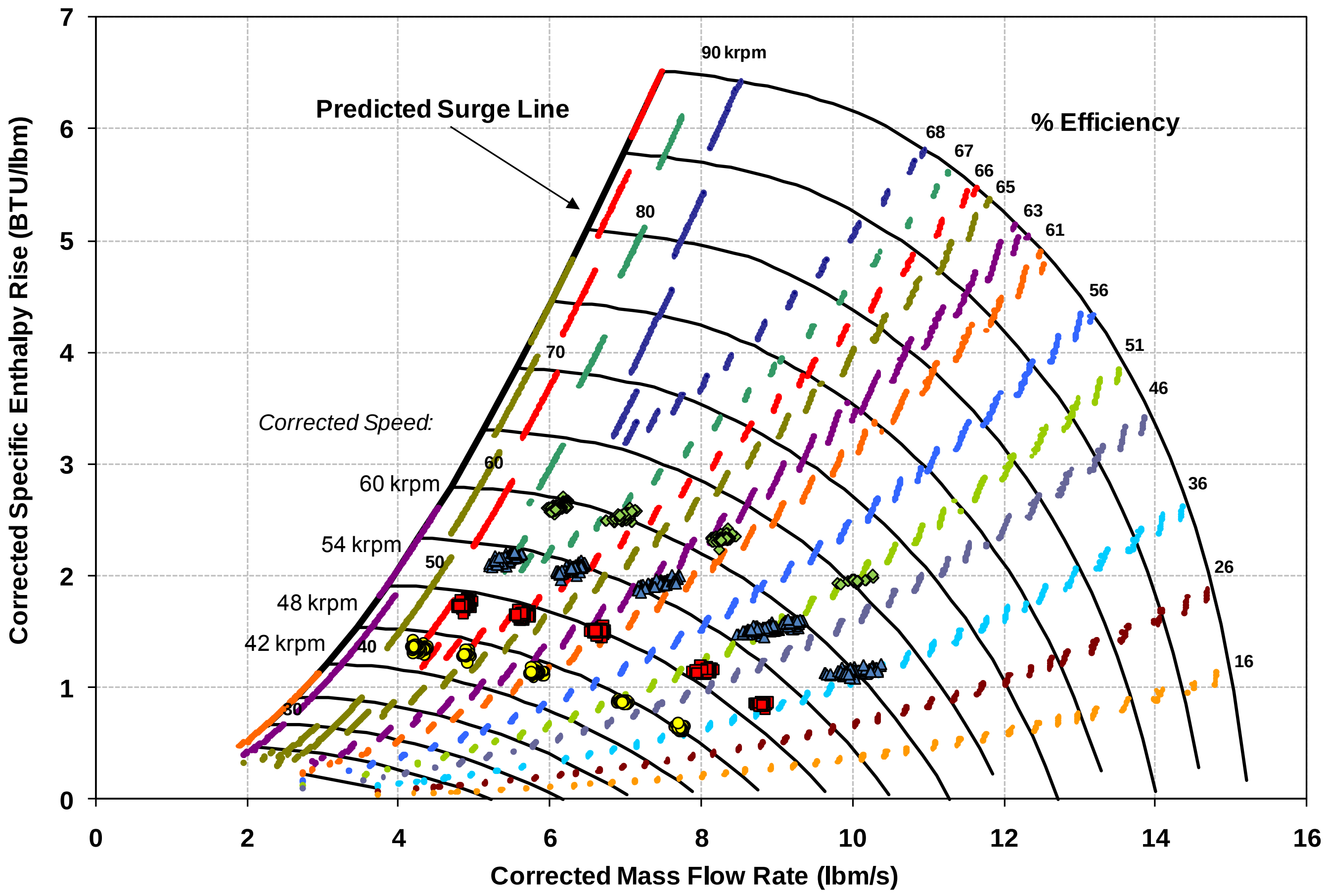
Two-Phase CO_2 at the Compressor Inlet



The compressor can even operate with two-phase CO_2 at inlet!

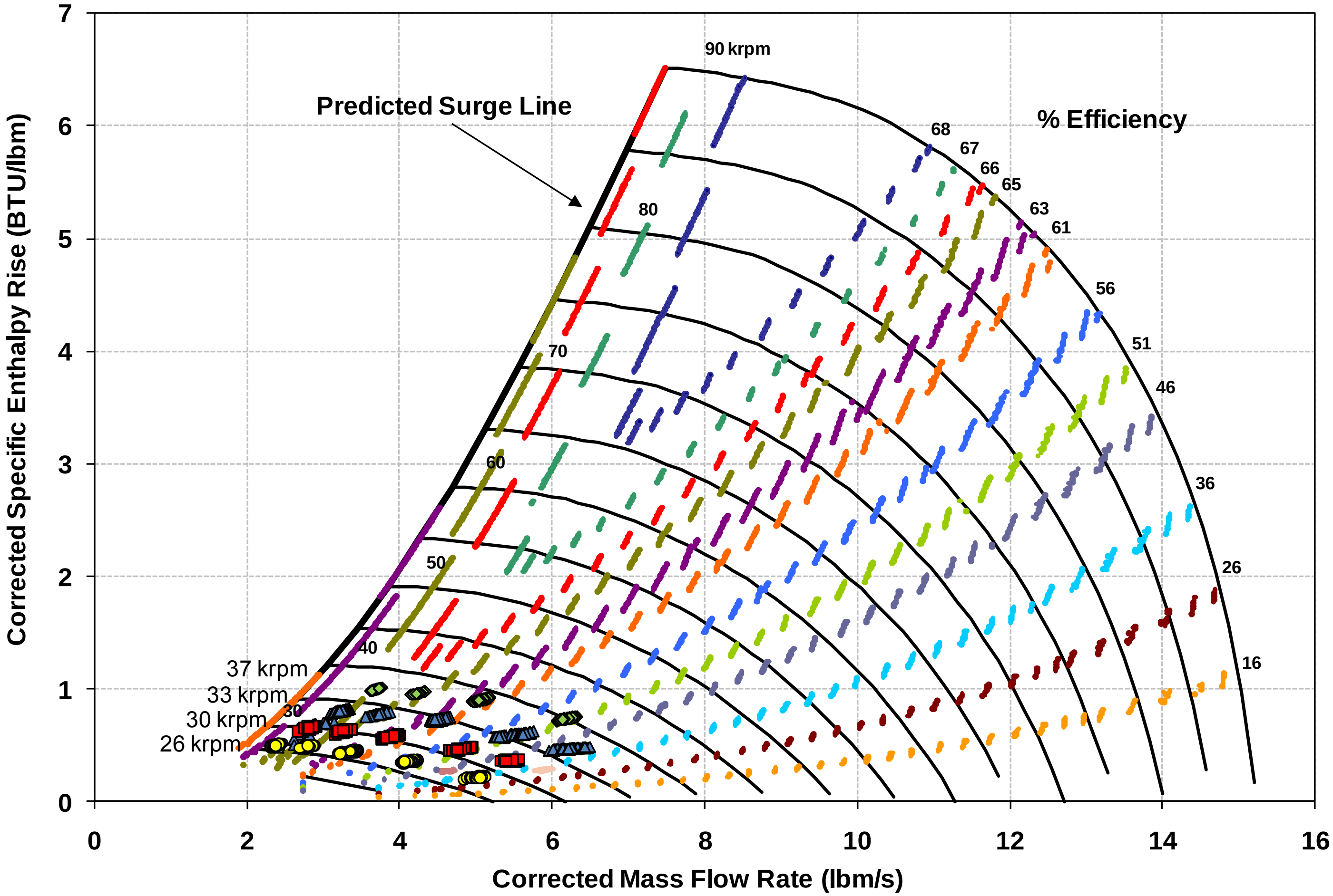
Supercritical CO_2 Main Compressor Map

(dH based on T and P calculated Real Time during Run)



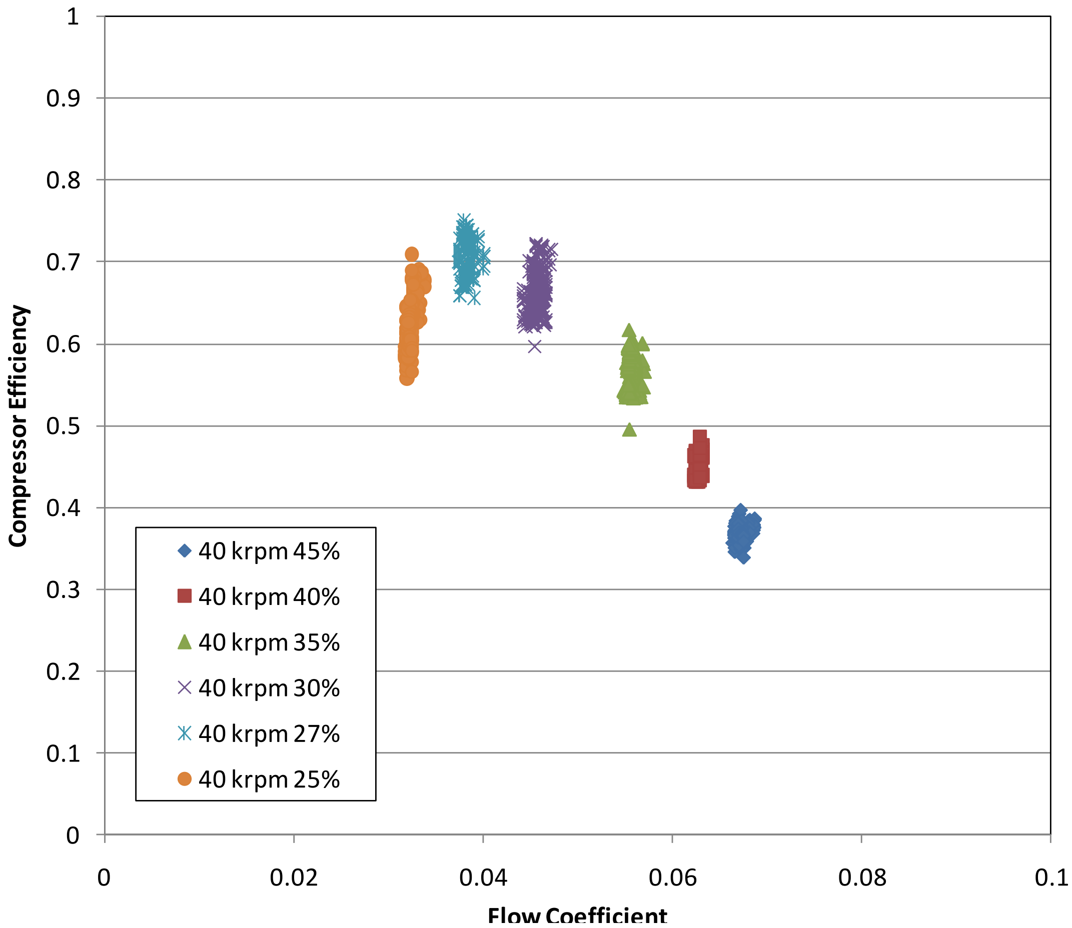
For CO_2 liquid, compressor maps were found to fall near predictions for supercritical CO_2, though not precisely.

Supercritical CO_2 Main Compressor Map
(dH based on T and P calculated Real Time during Run)



Again for CO_2 vapor, compressor maps were found to fall near predictions for supercritical CO_2.

Compression Efficiencies Evaluated



Efficiency:

$$\eta = \frac{\Delta h_{ideal}}{\Delta h_{actual}}$$

$$\Delta h_{actual} = \frac{\dot{Q}_{motor} - \dot{Q}_{windage}}{\dot{m}}$$

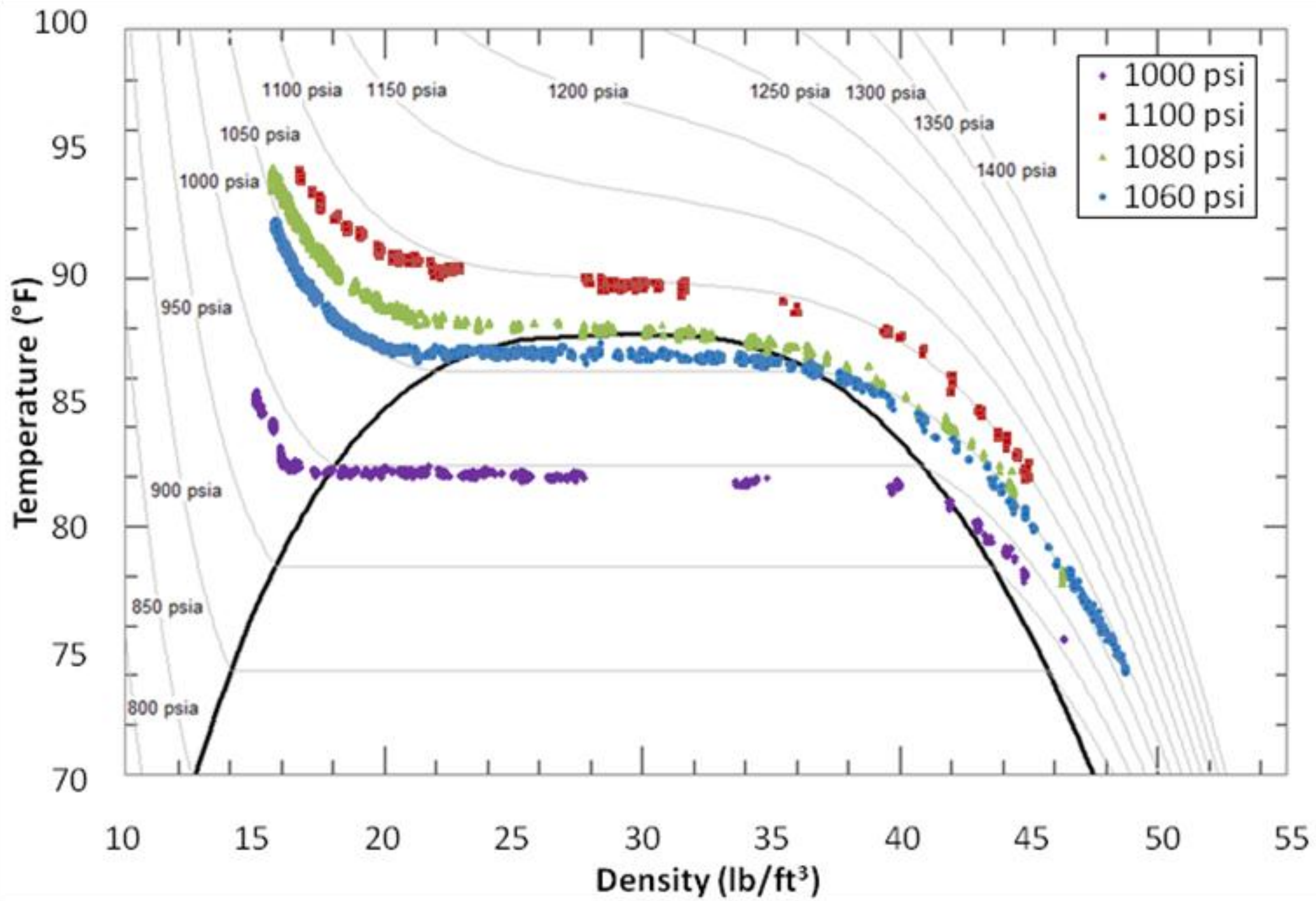
$$\Delta h_{ideal} = f(p, D)$$

Flow coefficient:

$$\phi = \frac{\dot{m}}{\rho \Omega D^2}$$

Efficiency curves were found to be similar at all conditions investigated.

In Summary, the SNL Compression Loop Has Operated with *Many* Different Compressor Inlet Conditions



The Radial S-CO_2 Compressor Works with Liquid, Vapor and Two-Phase Fluids near the Critical Point

Conclusions:

- S-CO_2 radial compressor (and gas foil bearing, seals, etc.) can operate in any of the regions investigated with similar levels of efficiency

- Compressor can even operate with two-phase inlet conditions at high pressure (>1000 psi), where density difference between phases is small

- Spiral HX can operate as a CO_2 condenser, without modification

- Advanced power generation cycles operating off of (but nearby) the critical point are unlikely to be problematic for machinery

- This work preceded successful operation of the larger Sandia Split-Flow Brayton facility in “condensing” mode -- electrical power production with liquid CO_2 at the compressor inlet.

Future Work:

- Testing is ongoing for supercritical fluid mixtures (small % additives to CO_2) to “tune” the critical temperature as desired for optimum efficiency; ORNL is participating in this effort.

- Alternative supercritical fluids are being investigated:
SF_6, predicted to operate at higher efficiency and lower pressure, and is of particular interest.

Questions?

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