Summary of the Sandia Supercritical CO_2 Development Program

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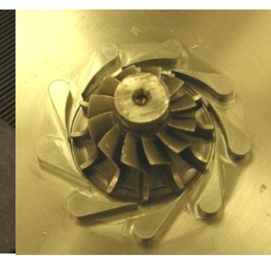
SCO_2 Power Cycle Symposium

May 24-25, 2011

University of Colorado, at Boulder



Goals of Presentation

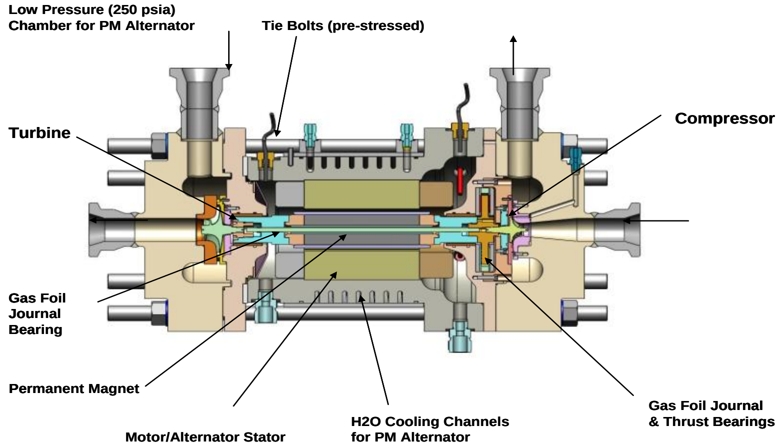
- DOE Gen-IV S-CO_2 Research Program Program
  - Major Research Areas
    - **Testing**
      - **Brayton and Compression Loop Descriptions**
      - **Compressor Performance Mapping**
      - **Breakeven Power Generation**
      - **Mixtures**
      - **Condensation Cycles**
      - **Thrust Bearing Heating**
    - Modeling
    - 10 MW_e Development and Demonstration Program Plans and Cost
    - Ability of Sandia S-CO_2 Brayton Loop to Reproduce Other Cycles

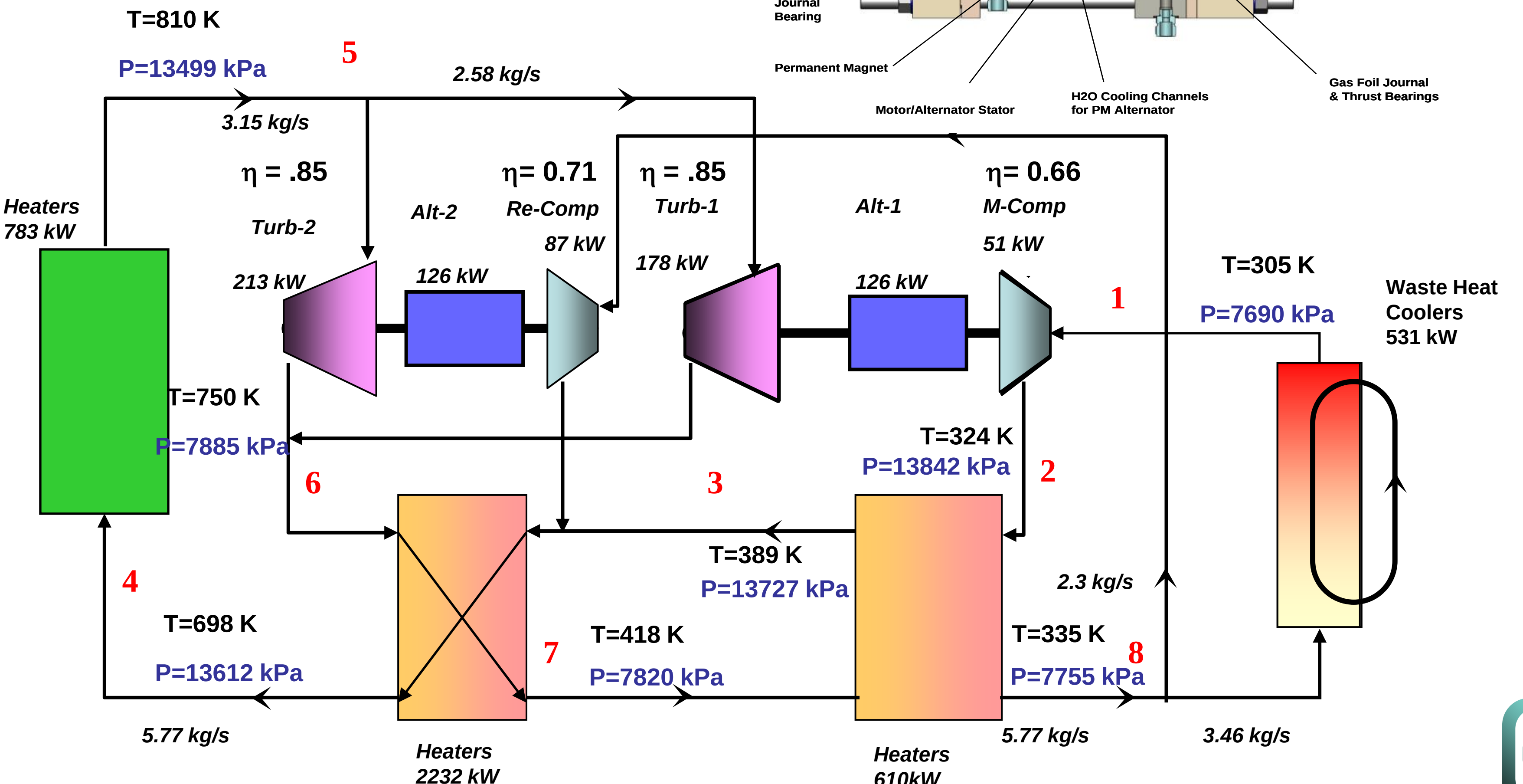
DOE Supercritical CO_2 Program Description

SNL/DOE Design Target for Proof-of-Principle Split-Flow Re-compression S-CO_2 Brayton Cycle

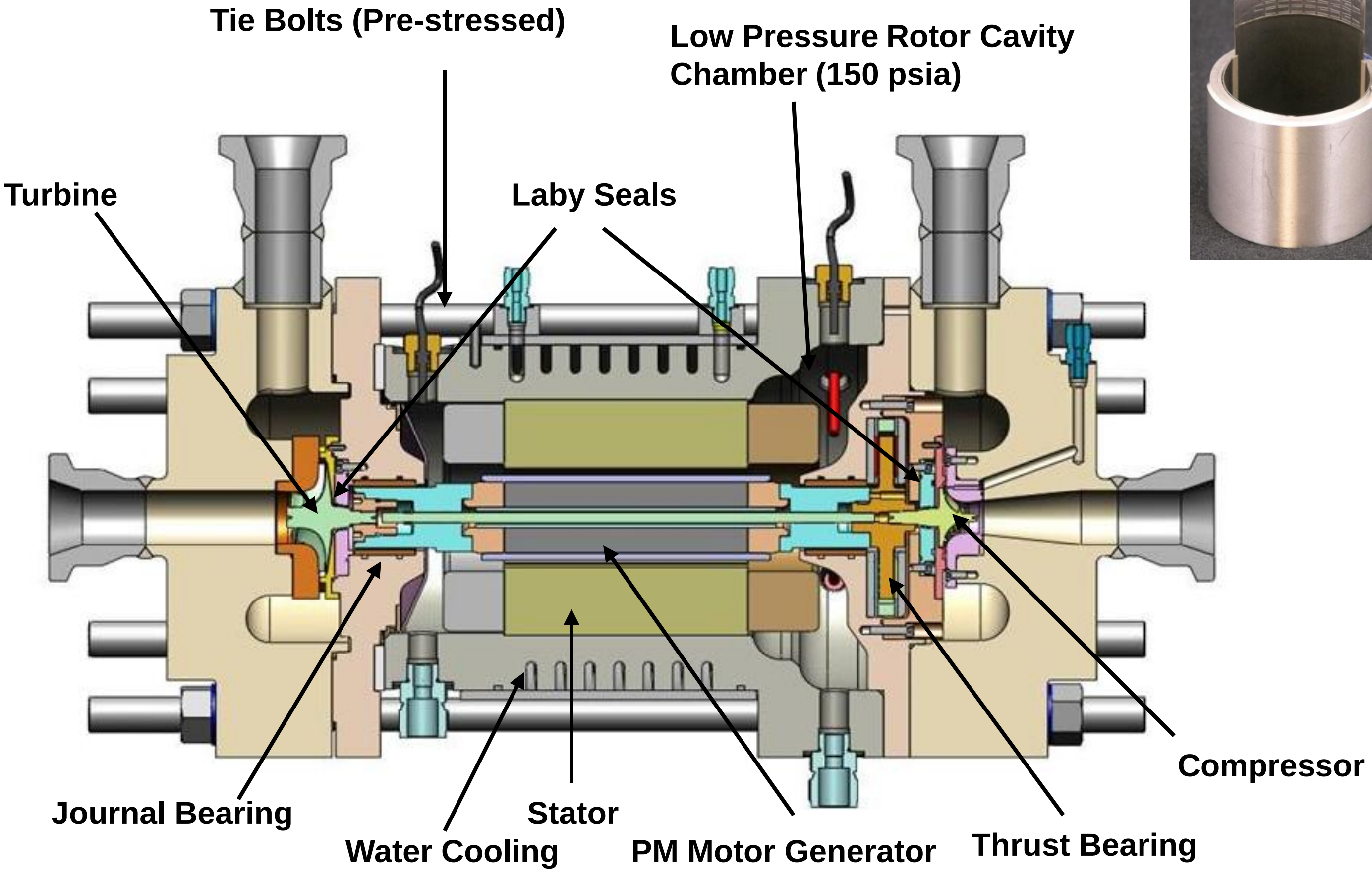
Modified Cycle to Enable Scaled Turbomachinery Development with Lower Risk

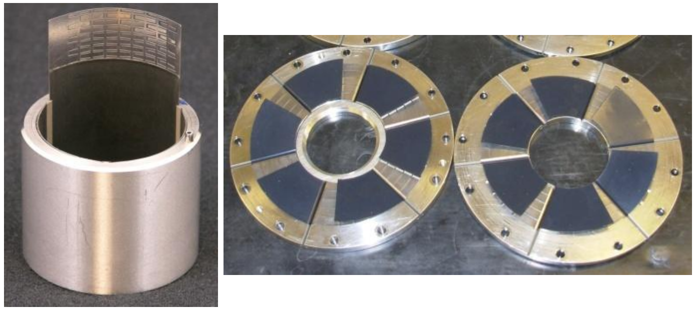
Dual Shafts, Lower Pressure Ratio (1.8 versus 2.6)



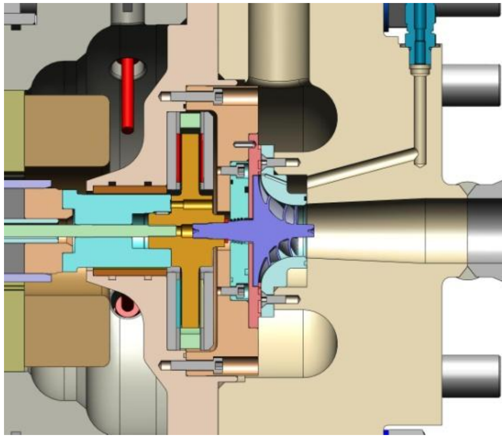


Key Technology
Turbo- Alternator Compressor Design with Gas Foil Bearings (~24” Long by 12” diameter)
Technology for Small Scale System





Gas-Foil Bearings



Patent Application is in Process for All major Features of this Design

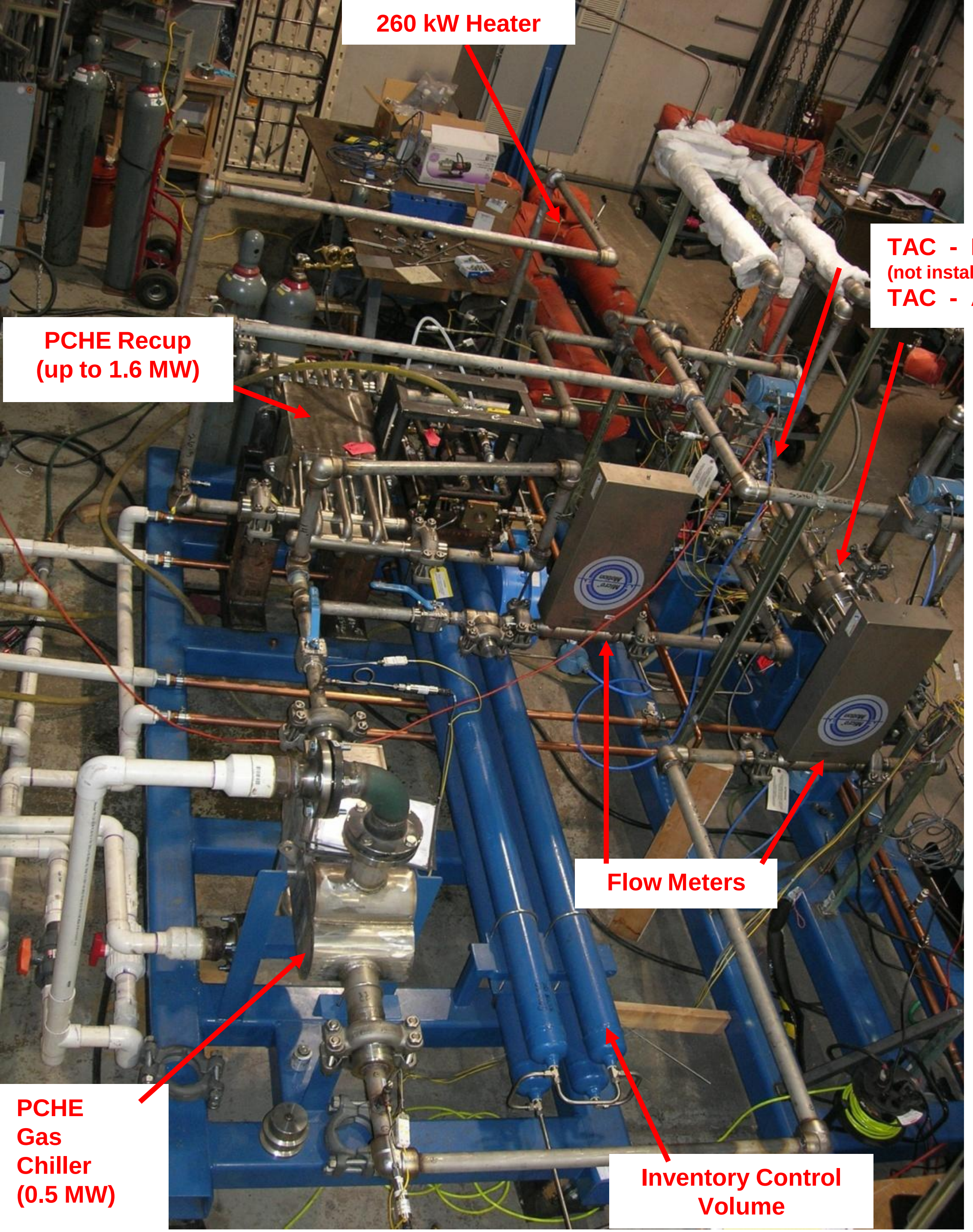
S-CO_2 Development Sequence

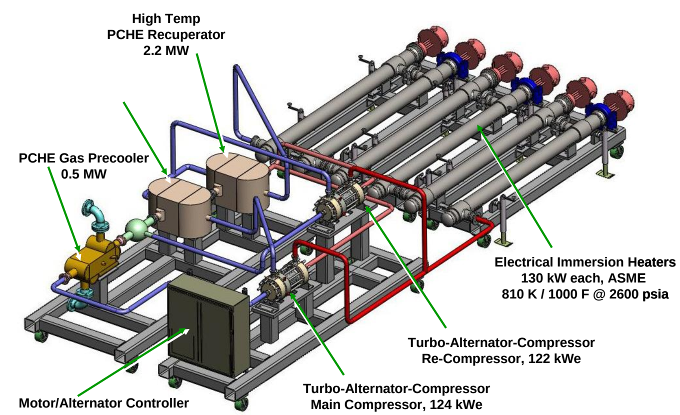
Sandia Single Compressor Loop

DOE Gen IV Split-Flow Re-compression Brayton Loop

Supercritical $S\text{-}CO_2$ Brayton Cycle

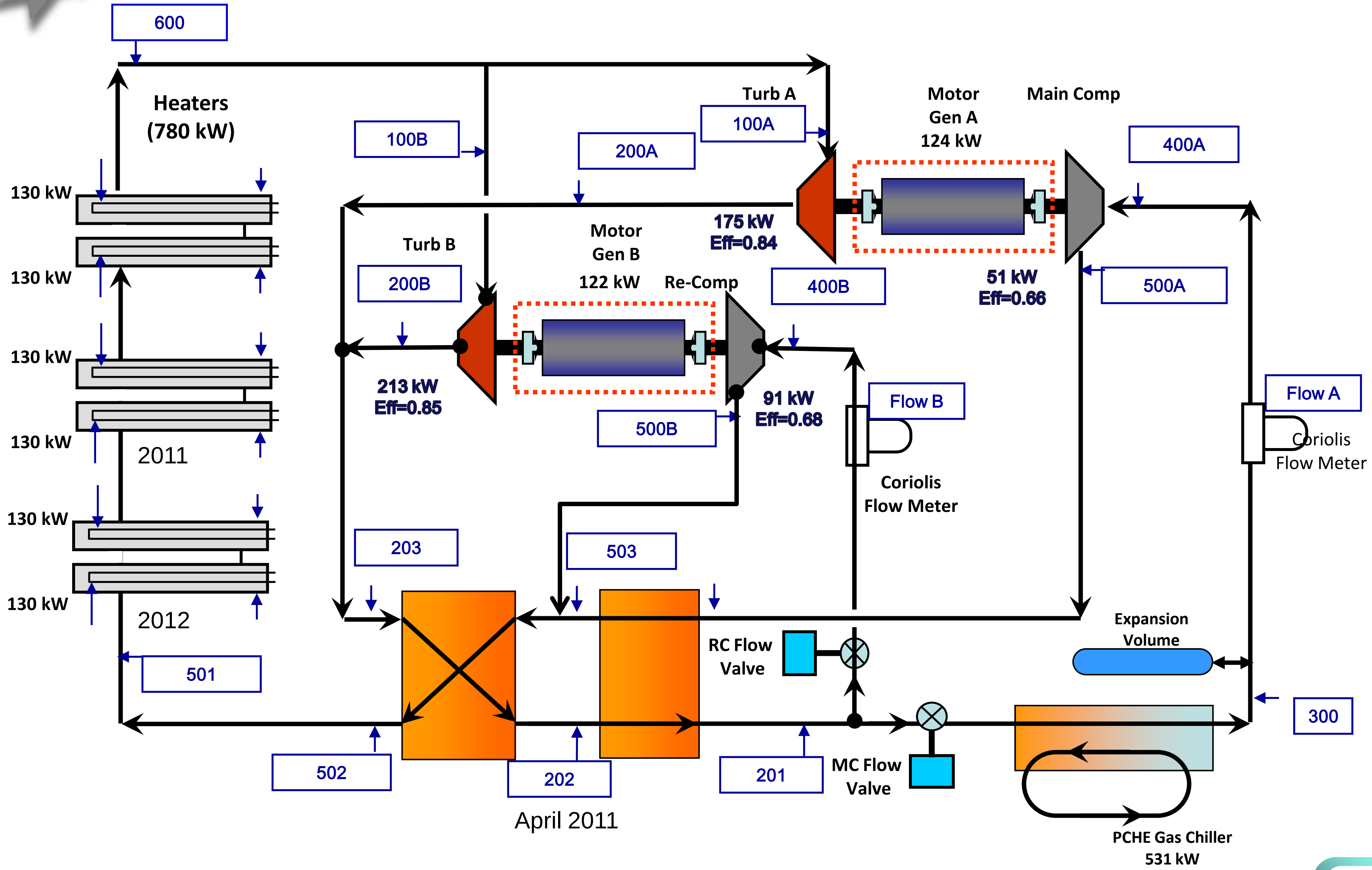
DOE-Gen IV





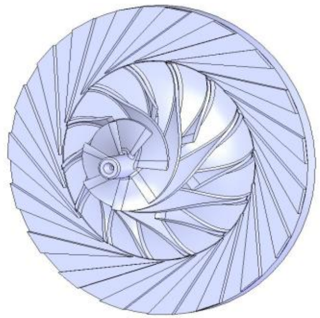
Barber Nichols

Supercritical CO_2 Brayton Loop
Final Design, Currently Existing, and Alternative Layouts



Mapping

Turbomachinery Wheels



Main Compressor

Re-Compressor

Turbine for Re-Compressor

Turbine for Main Compressor

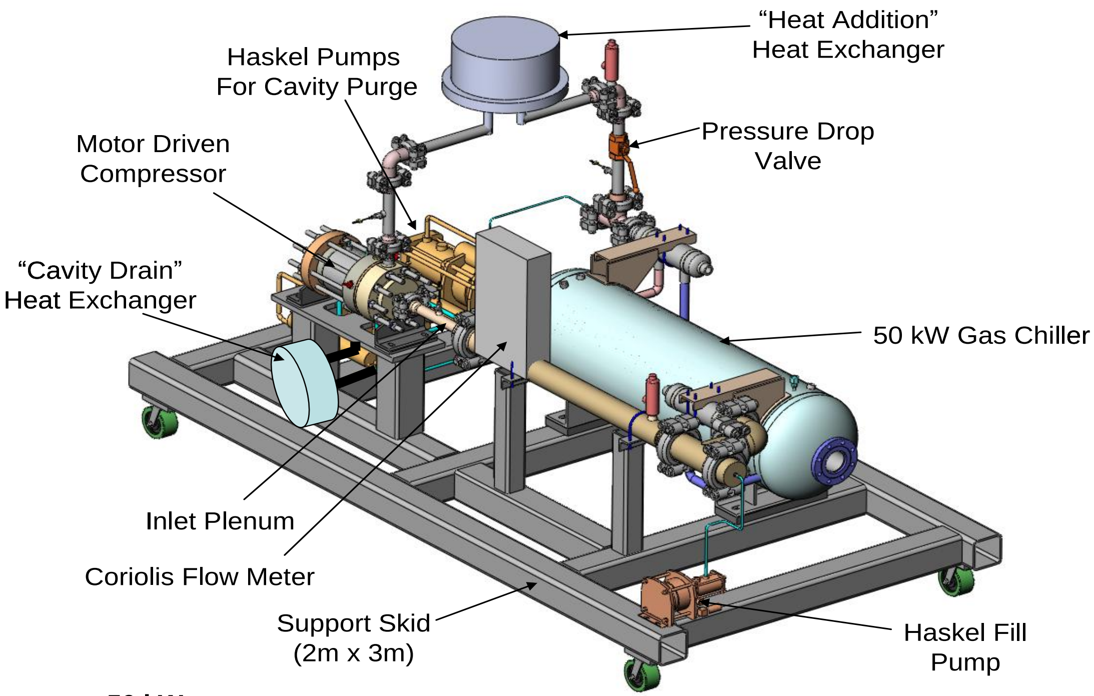
OD=37.3 mm
1.47”

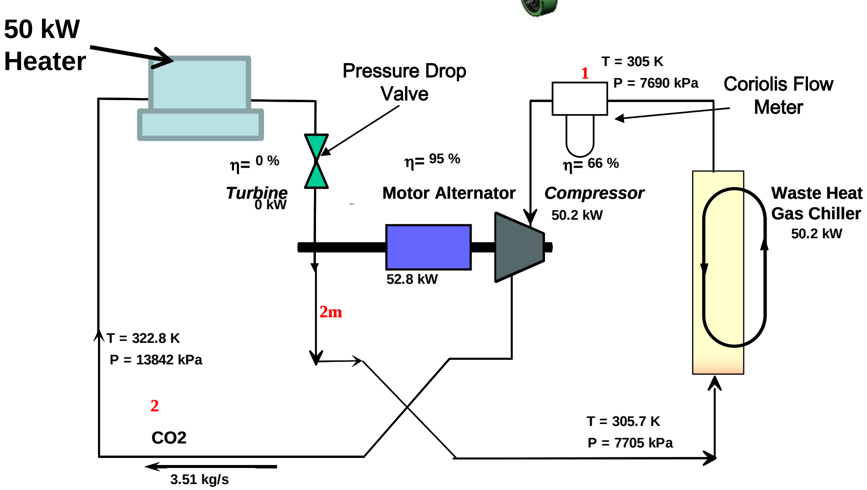
OD=57.9 mm
2.27”

OD=68.3 mm
2.69”

OD=68.1 mm
2.68”

Sandia S-CO_2 Compression Research Loop

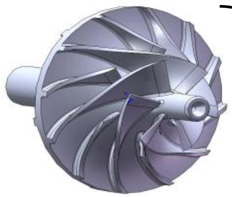


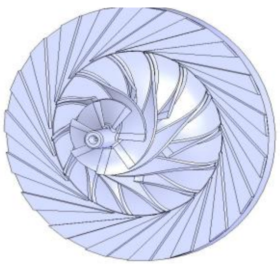


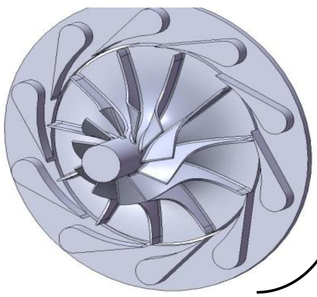
- Sandia S-CO_2 compression loop, consists of a compressor, heater, flow control valve, and chiller
- Instrumented with T,p sensors at 4 key state points, and a density meter at compressor inlet
- Used for mapping compressor performance near the critical point, bearings & seals R&D, windage tests, fluid mixtures and natura circlation

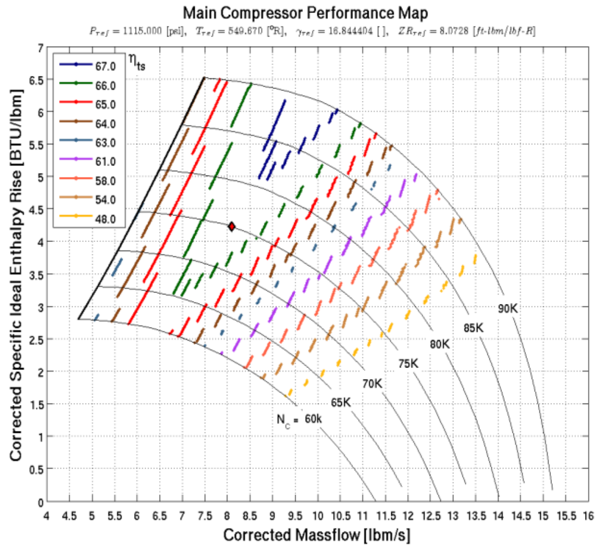
Performance Maps

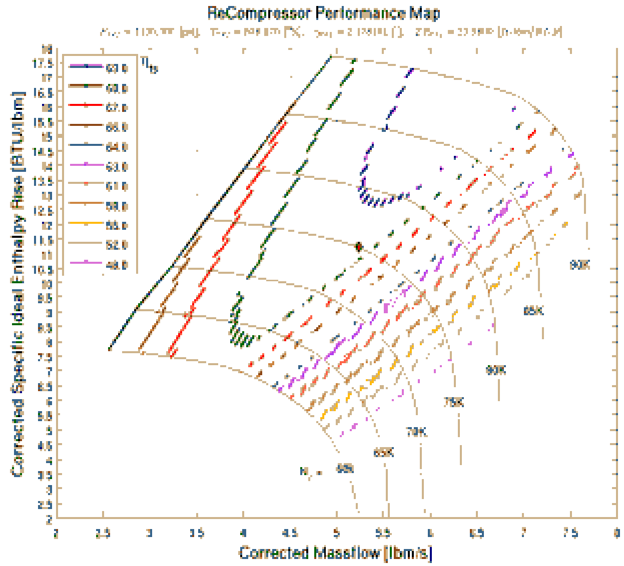
Barber-Nichols Model Predictions

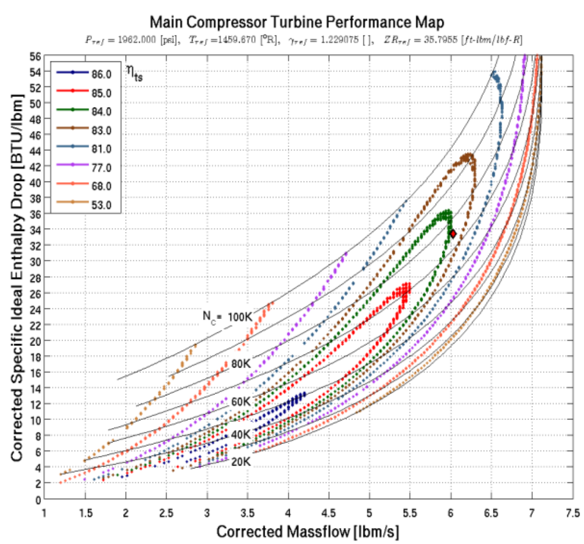


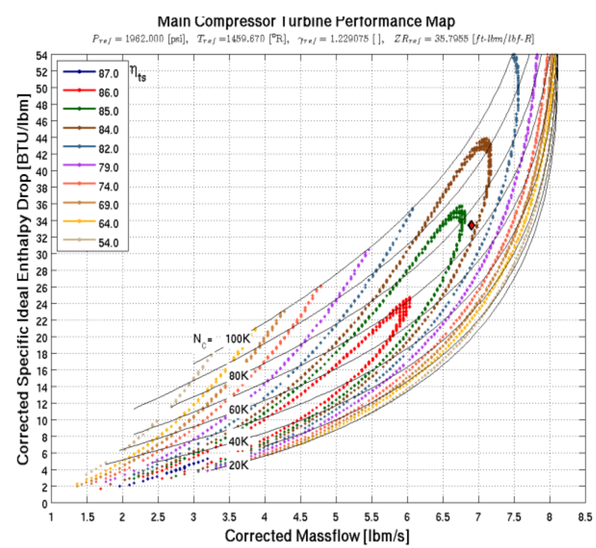




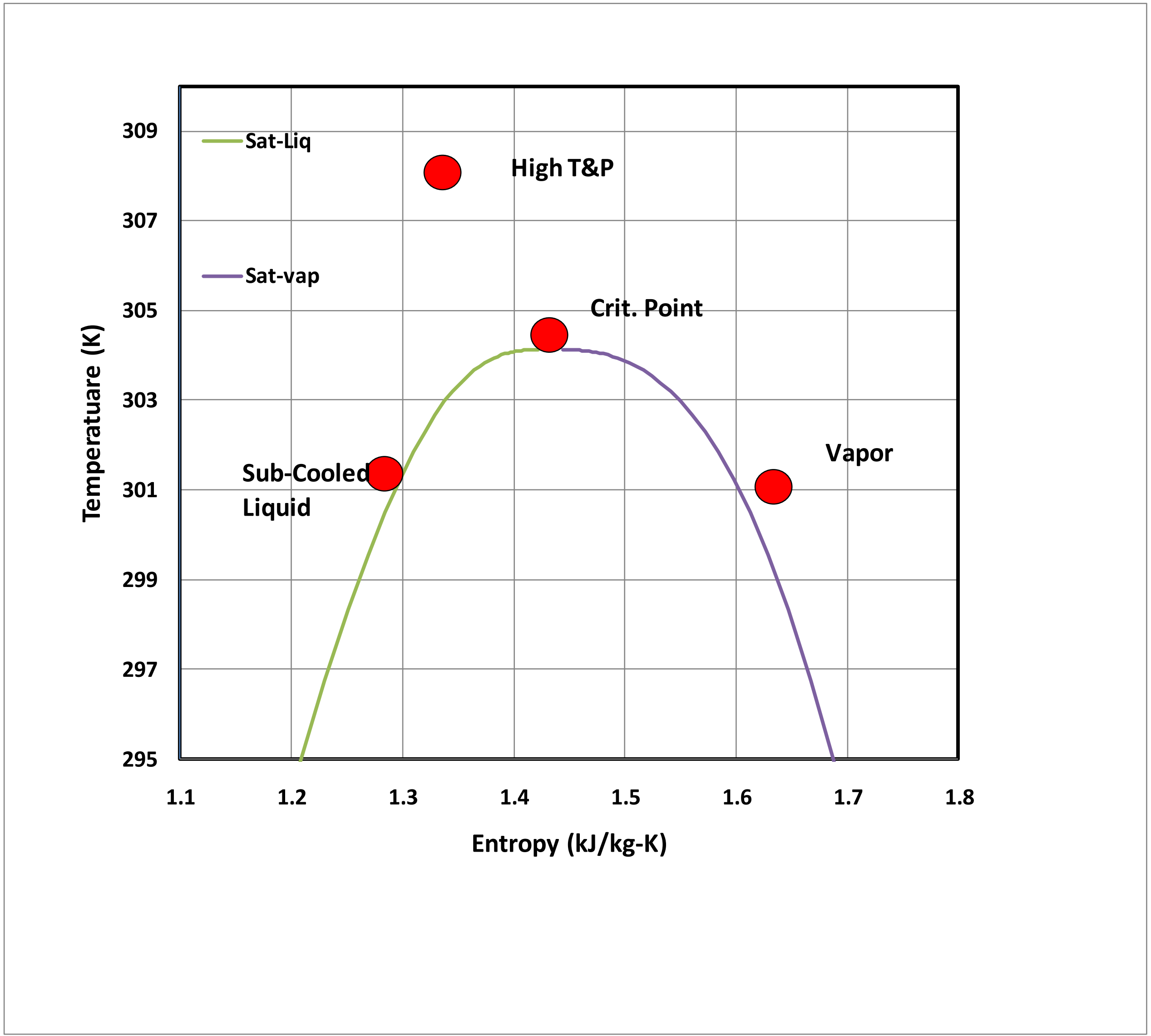




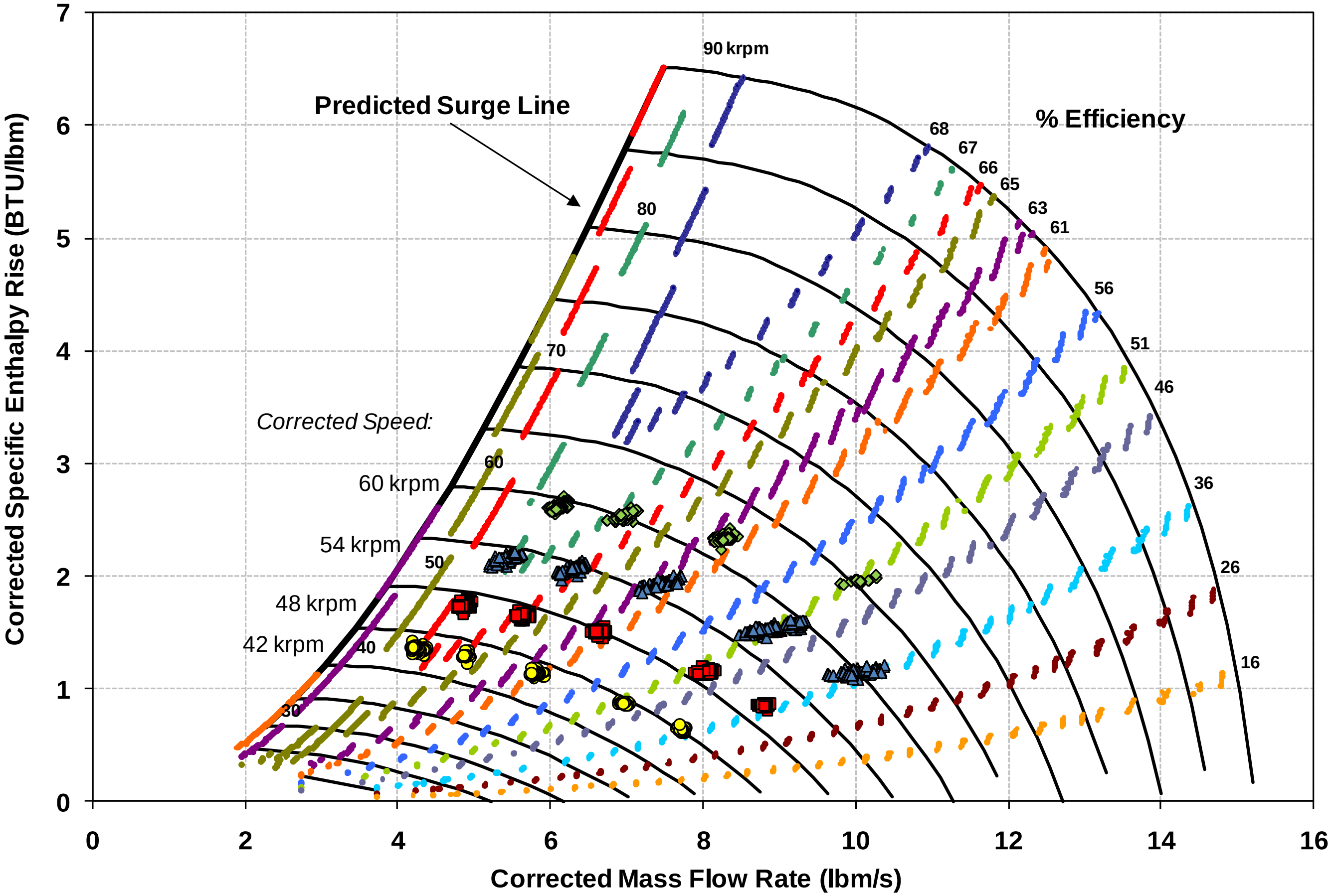




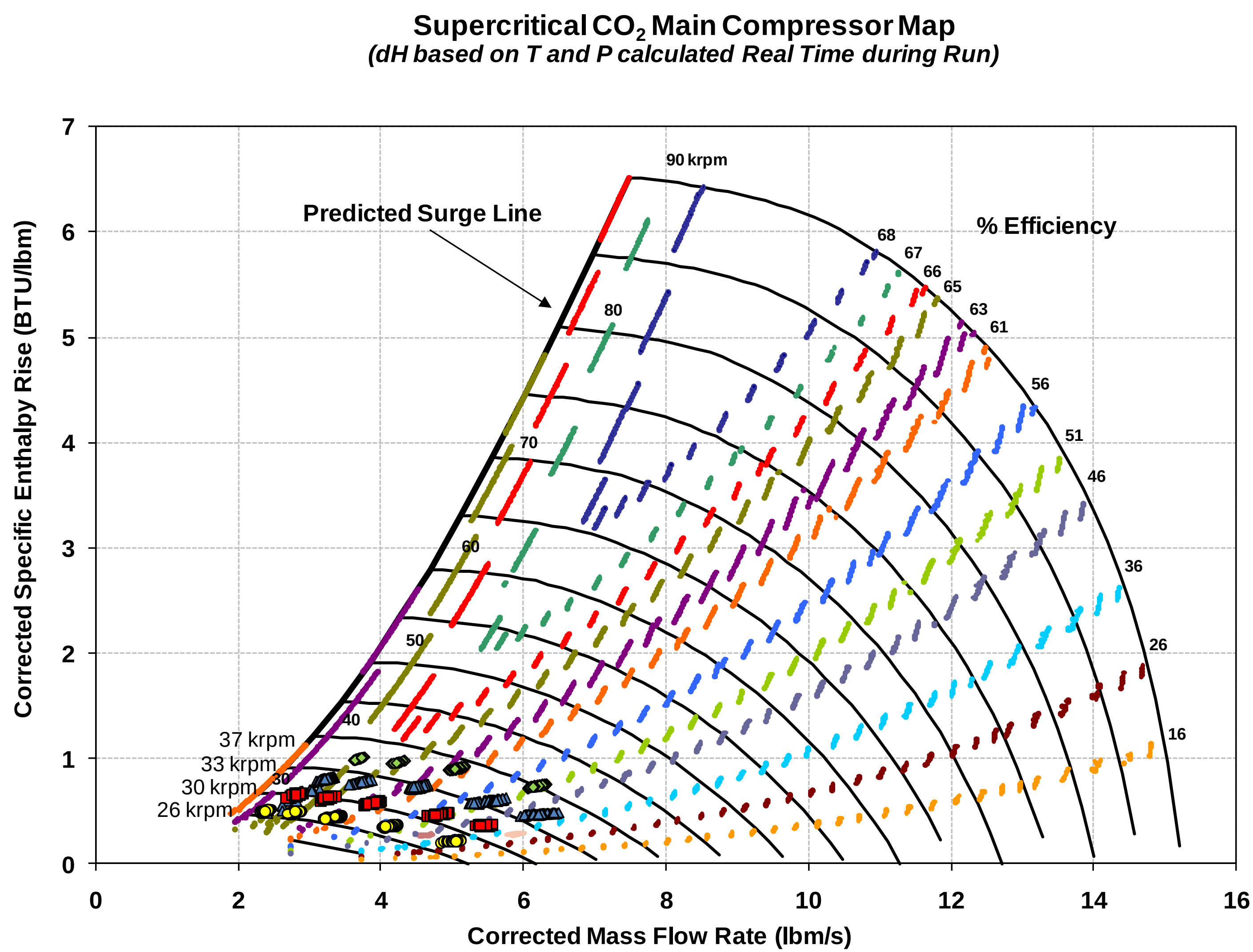
Compressor Inlet Conditions for Map Measurements (50 krpm) Performed September 2010 at Sandia



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



For CO_2 liquid, compressor maps



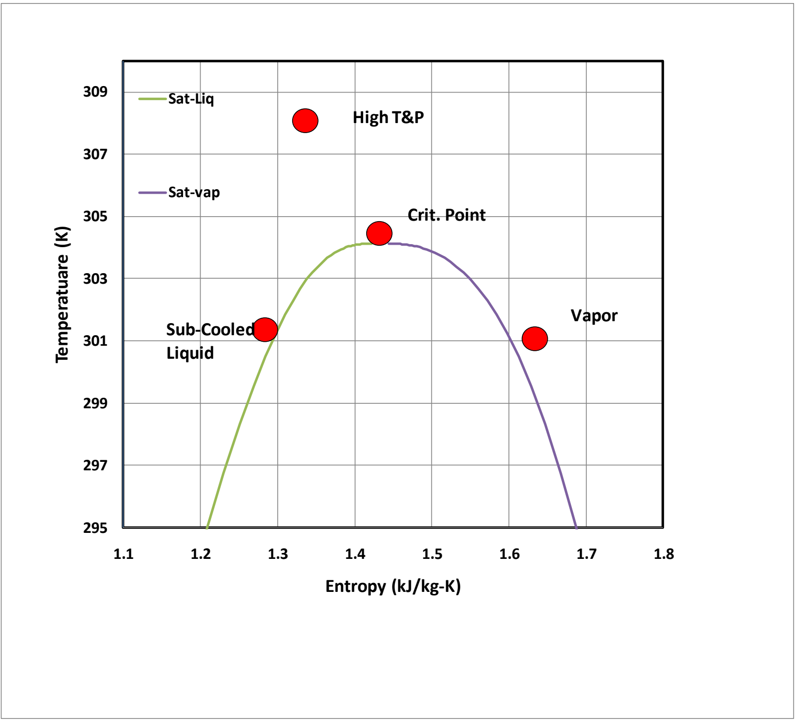
Vapor, compressor maps are near predictions for supercritical CO_2.

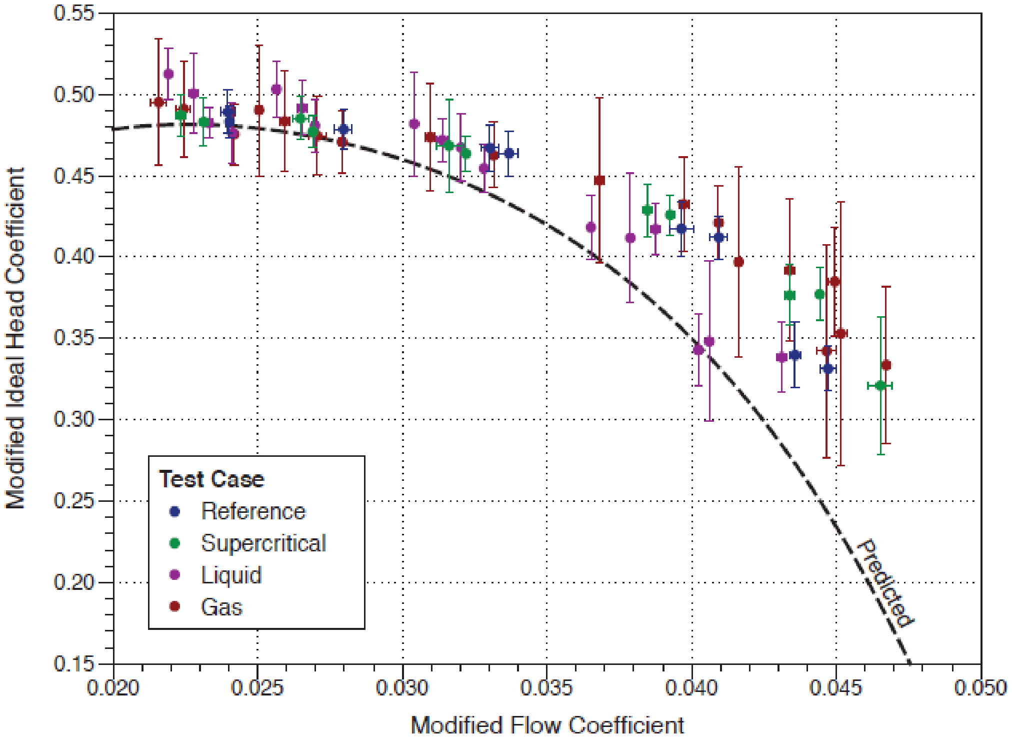
Generalized Measured and Predicted Maps

Modified ideal head coefficient versus modified flow coefficient

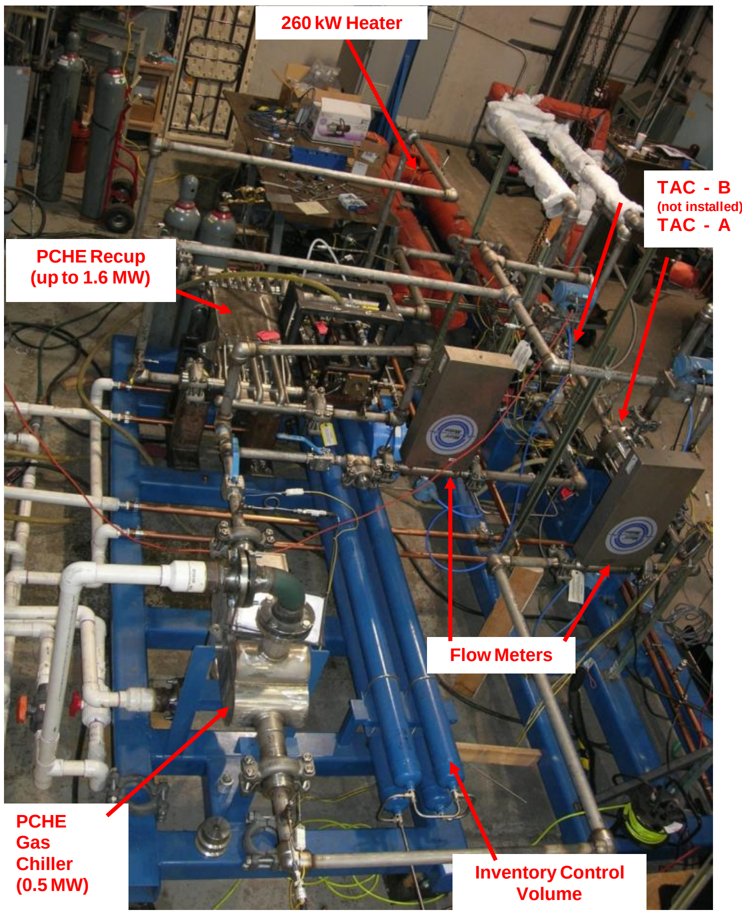
J. Dyreby (Univ. of Wisconsin Madison)

Similar Results by Bob Fuller (Barber-Nichols)

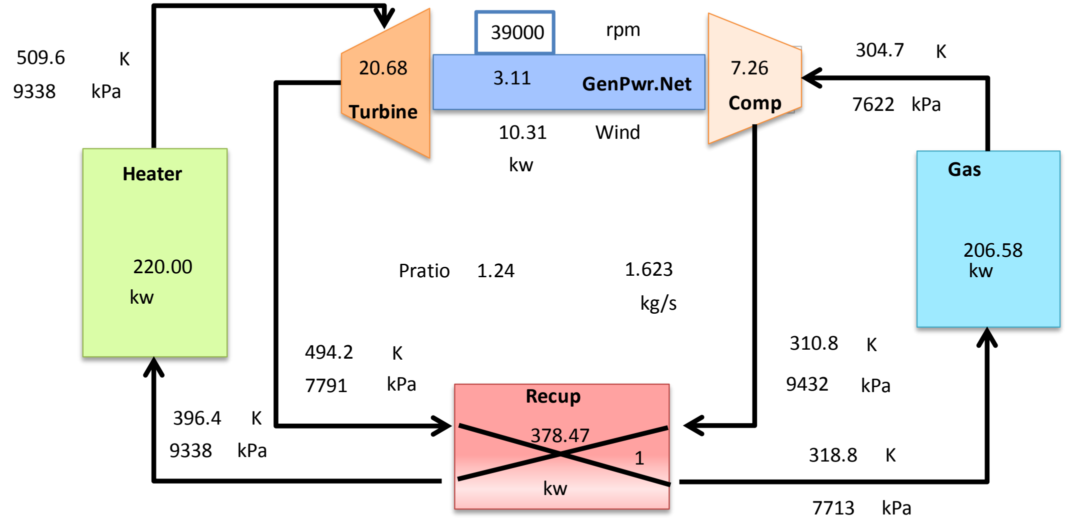




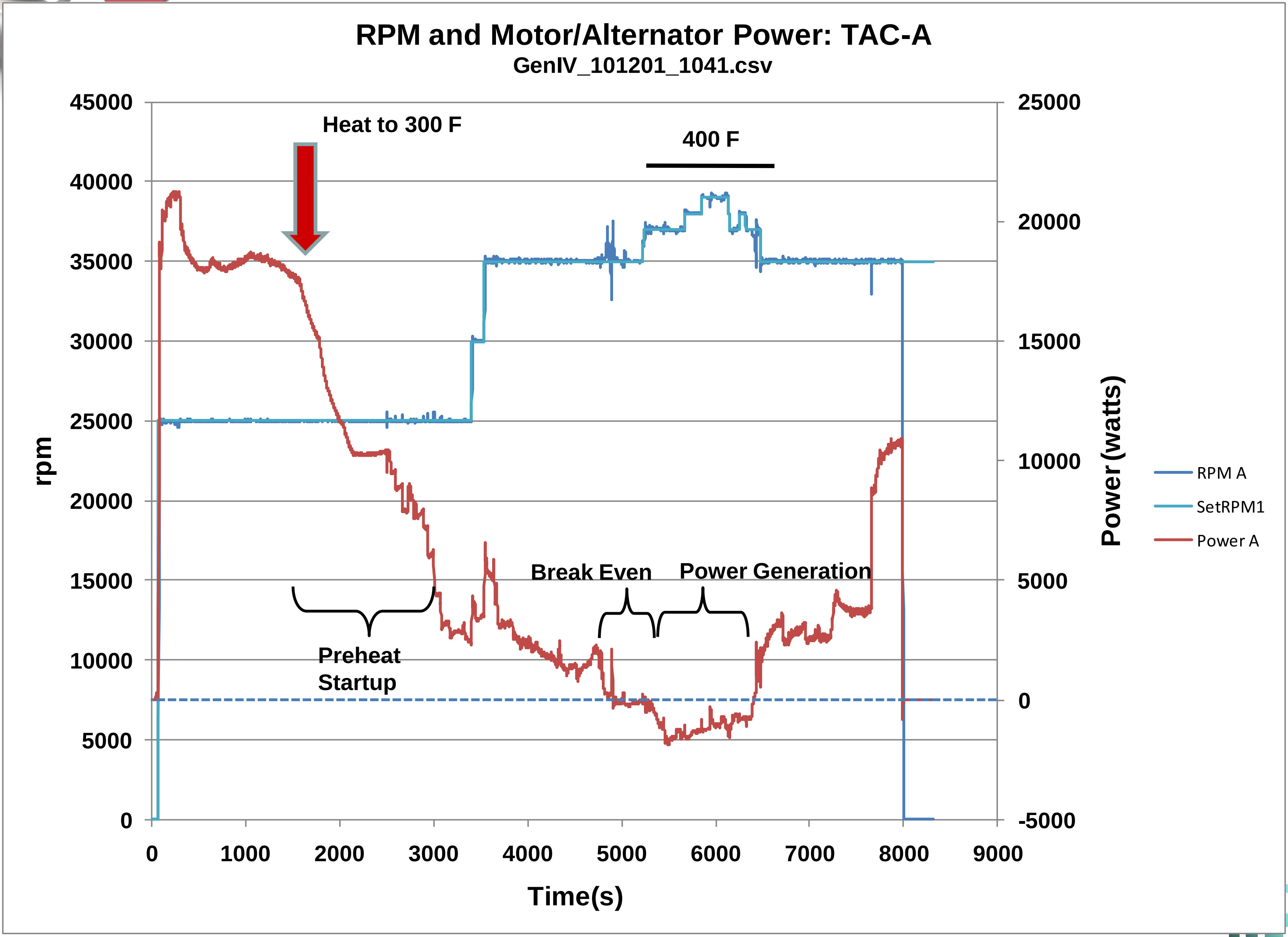
Break-Even Power Generation



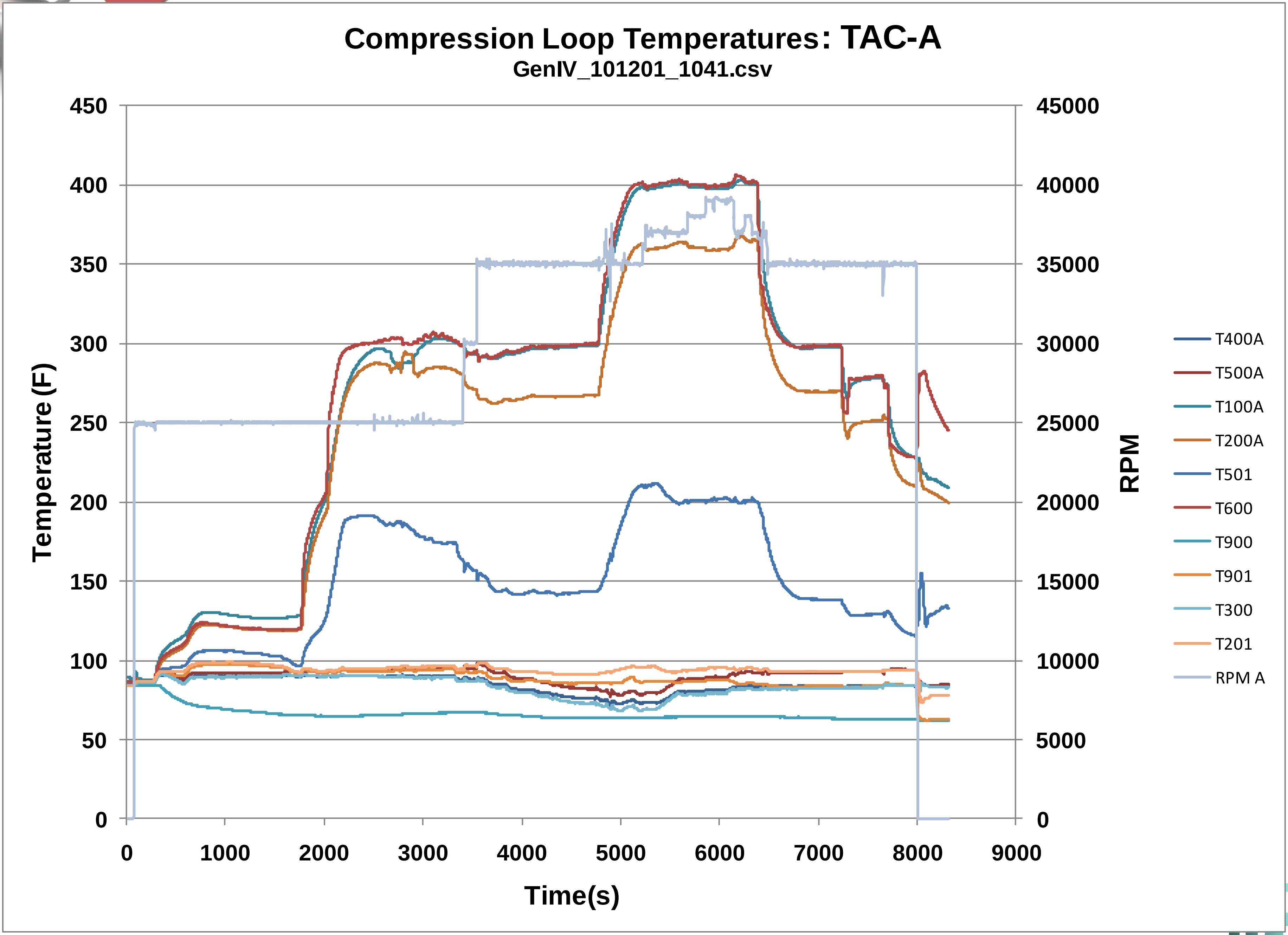
TAC-A



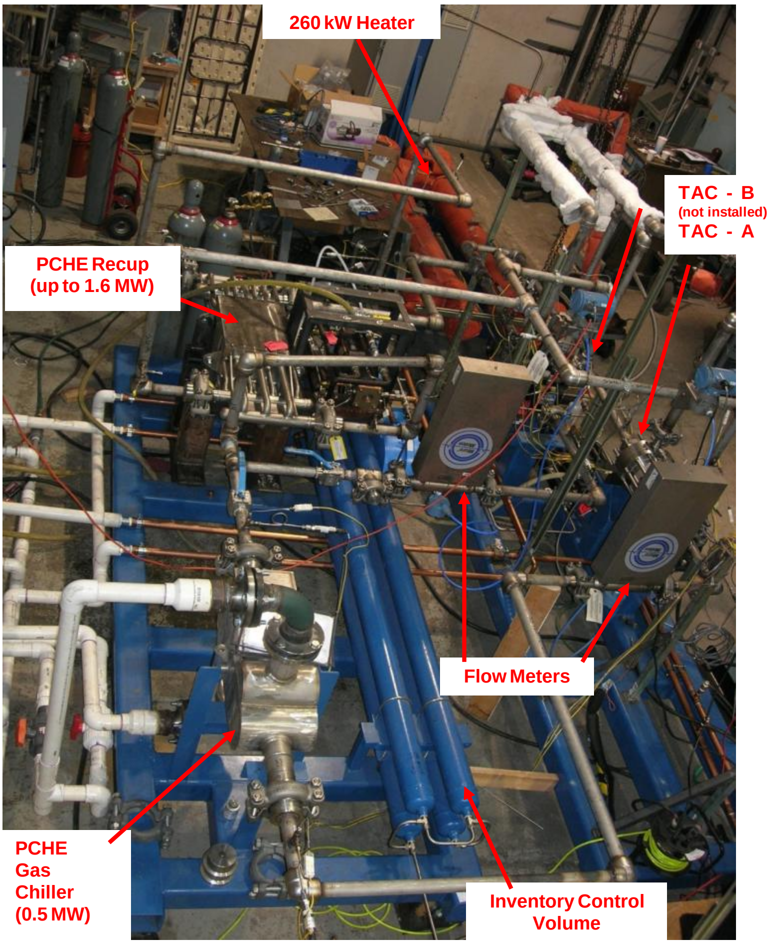
Off Design Cycle Analysis

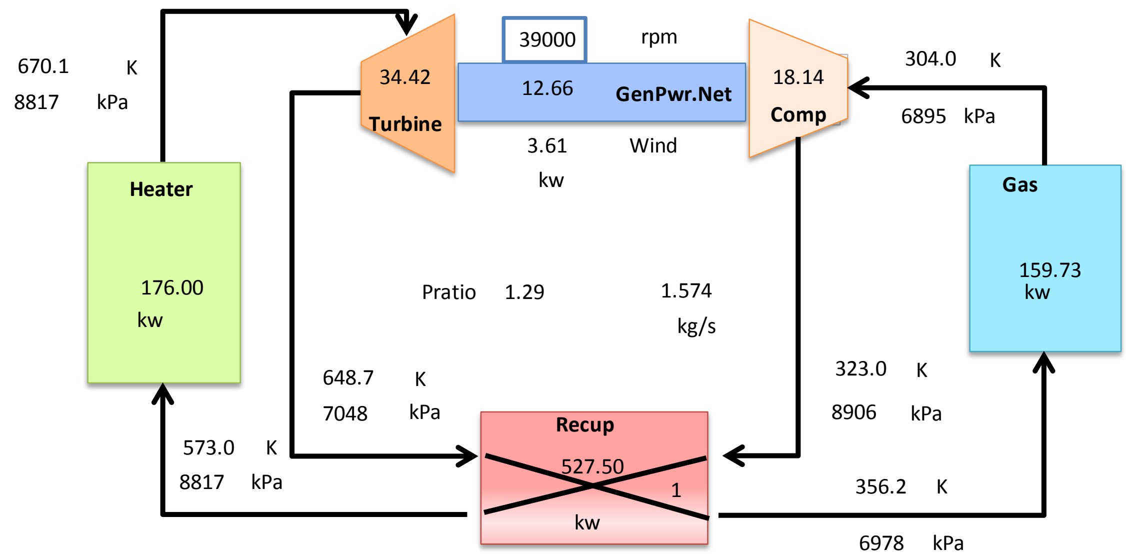


RPM and Motor/Alternator Power: TAC-A
GenIV_101201_1041.csv
Heat to 300 F
400 F
Break Even
Power Generation
Preheat
Startup
rpm
Power (watts)
Time(s)
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
25000
20000
15000
10000
5000
0
-5000
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
RPM A
SetRPM1
Power A

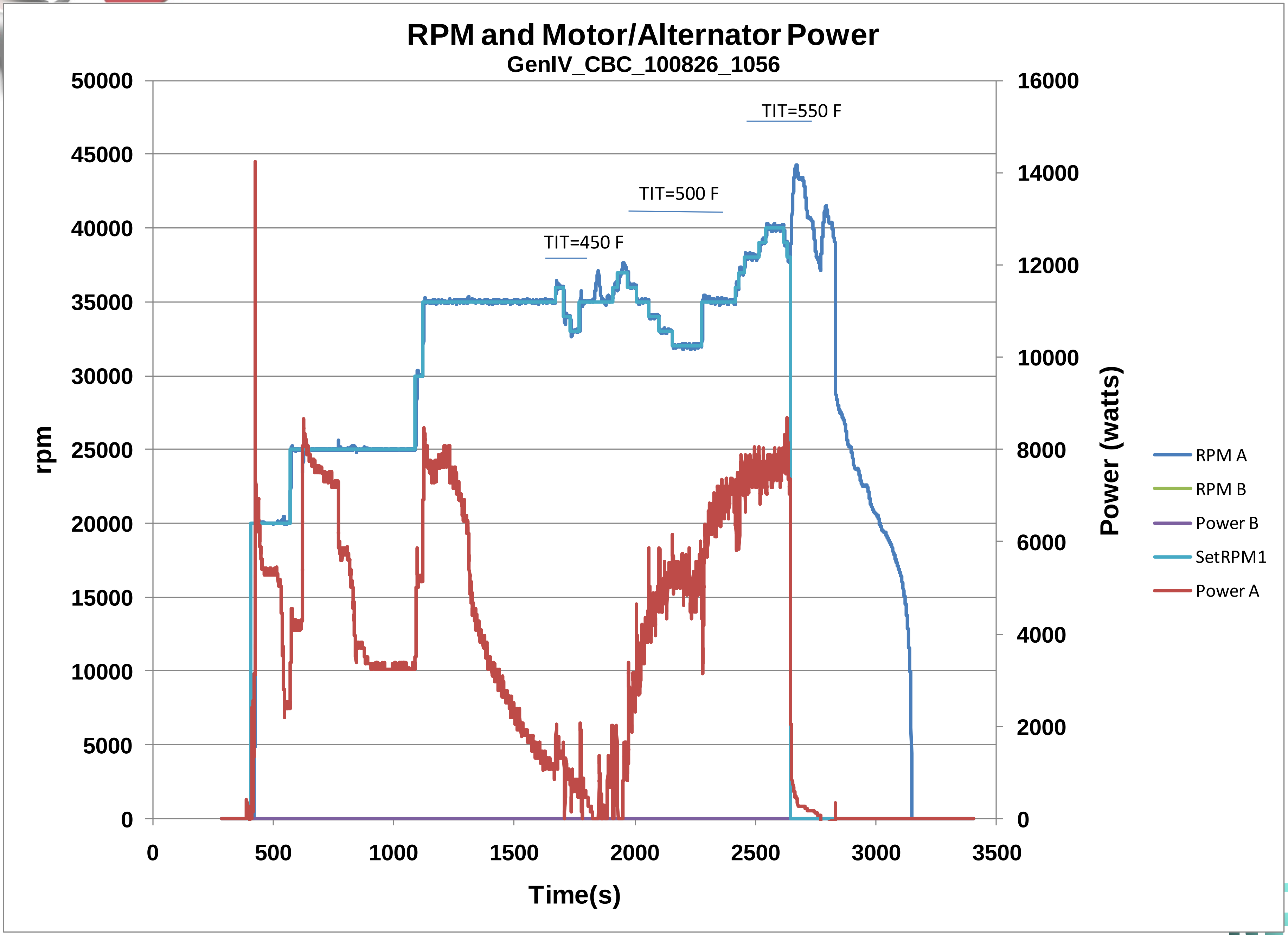

Compression Loop Temperatures: TAC-A
GenIV_101201_1041.csv
Temperature (F)
RPM
Time(s)
0
50
100
150
200
250
300
350
400
450
0
5000
10000
15000
20000
25000
30000
35000
40000
45000
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
T400A
T500A
T100A
T200A
T501
T600
T900
T901
T300
T201
RPM A

TAC-B

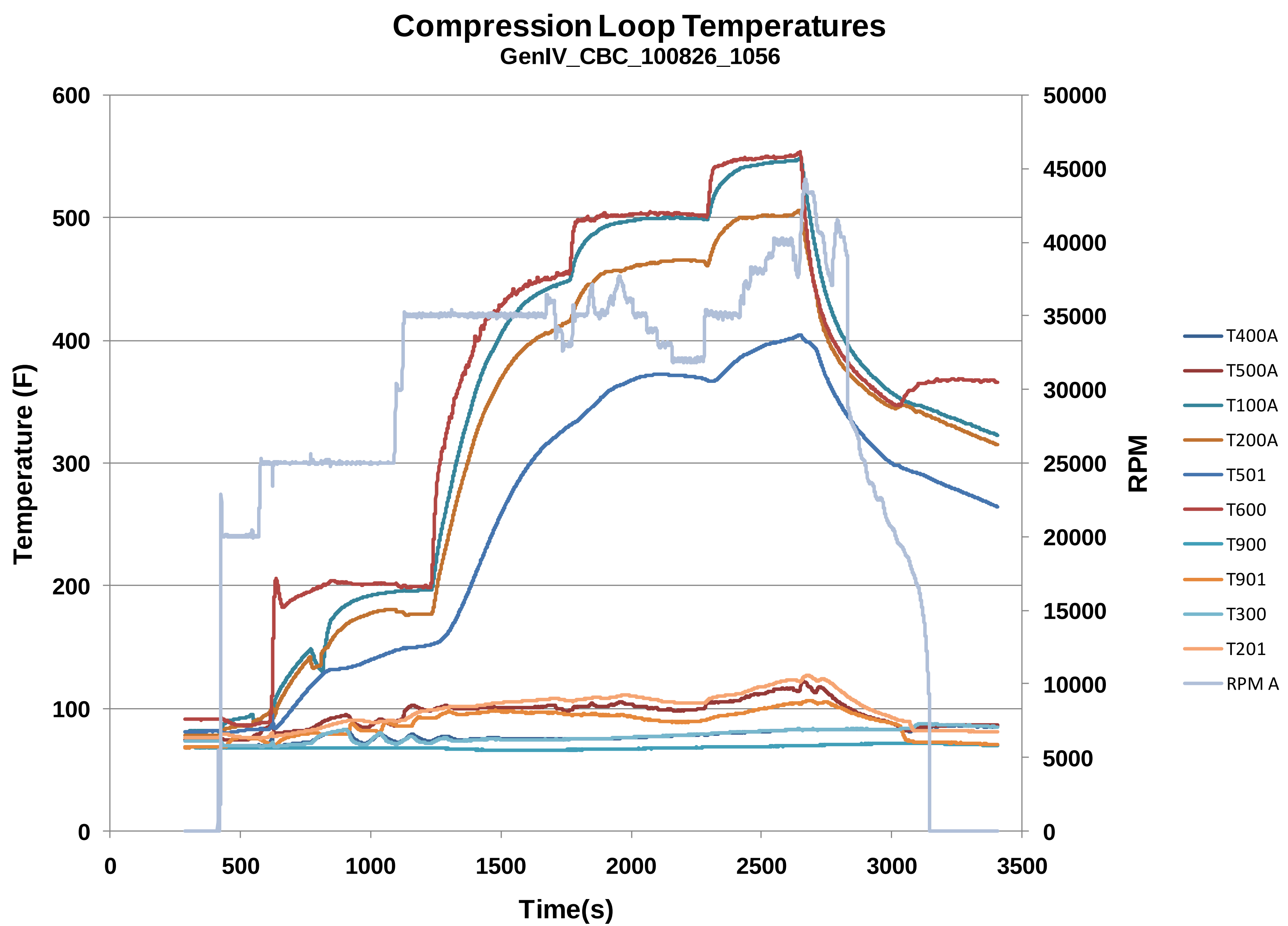




Off Design Cycle Analysis



RPM and Motor/Alternator Power
GenIV_CBC_100826_1056
rpm
Power (watts)
Time(s)
TIT=450 F
TIT=500 F
TIT=550 F
RPM A
RPM B
Power B
SetRPM1
Power A
0
5000
10000
15000
20000
25000
30000
35000
40000
45000
50000
0
2000
4000
6000
8000
10000
12000
14000
16000
0
500
1000
1500
2000
2500
3000
3500



Compression Loop Temperatures
GenIV_CBC_100826_1056
Temperature (F)
0
100
200
300
400
500
600
RPM
0
5000
10000
15000
20000
25000
30000
35000
40000
45000
50000
Time(s)
0
500
1000
1500
2000
2500
3000
3500
T400A
T500A
T100A
T200A
T501
T600
T900
T901
T300
T201
RPM A

Break-Even Power Production Summary and Conclusions

- **Simple Recuperated Brayton configurations have just enough heater power to reach break-even conditions with 260 kW of heater power**
- **Too much flow in the re-compression Brayton cycle to make power in both TACs**
- **Break-even at 350/430 F Main-TAC-A and Re-TAC-B**
  - **Main-compressor: Peak Temperatures to 400 F, 3.2 kWe**
  - **Re-compressor: Peak Temperatures to 600 F, 8 kWe, ~ 6%**
- **Off design models predict these break-even performance parameters for power, rpm and TIT.**
- **Successful startup/preheat procedures implemented**

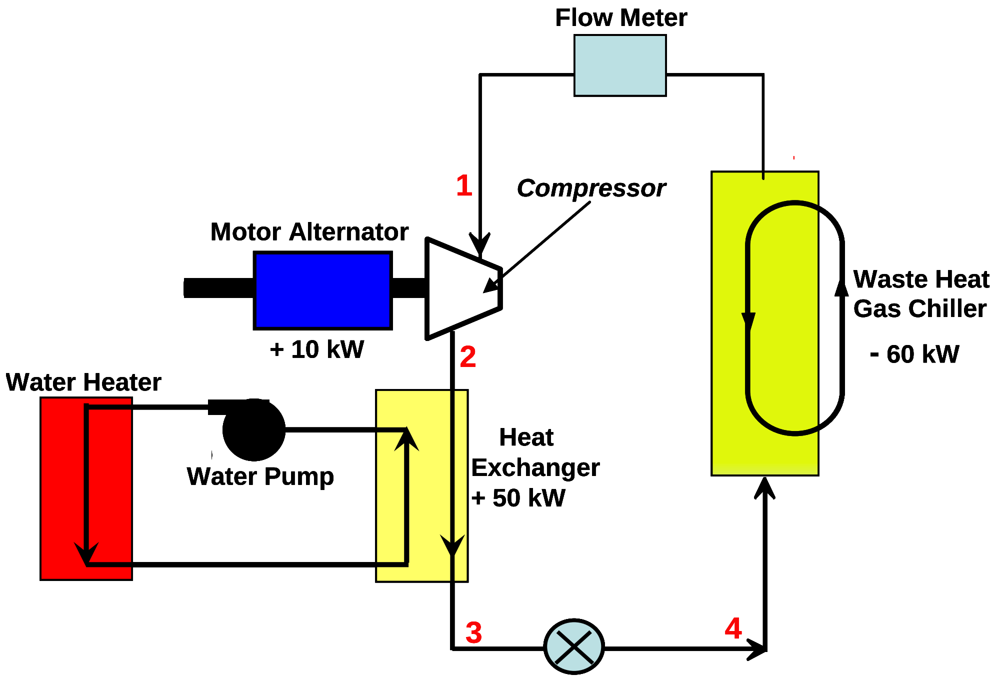
Mixtures

S-CO2 Compression Loop Used to Measure Effects of Gas Mixtures: Motivation is Efficiency Improvements

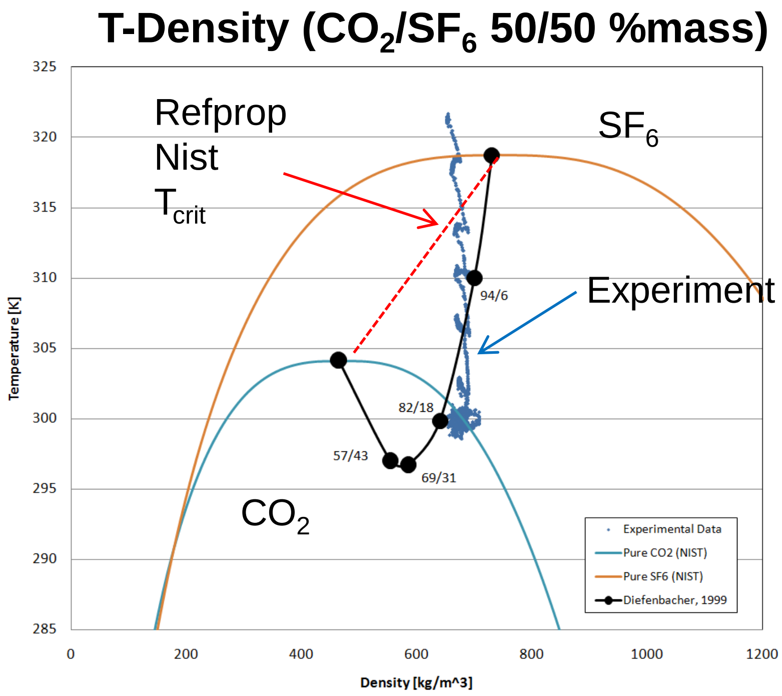
Measured (EOS: T_{crit}, P_{crit}, Compressor Maps)

Mixtures Tested

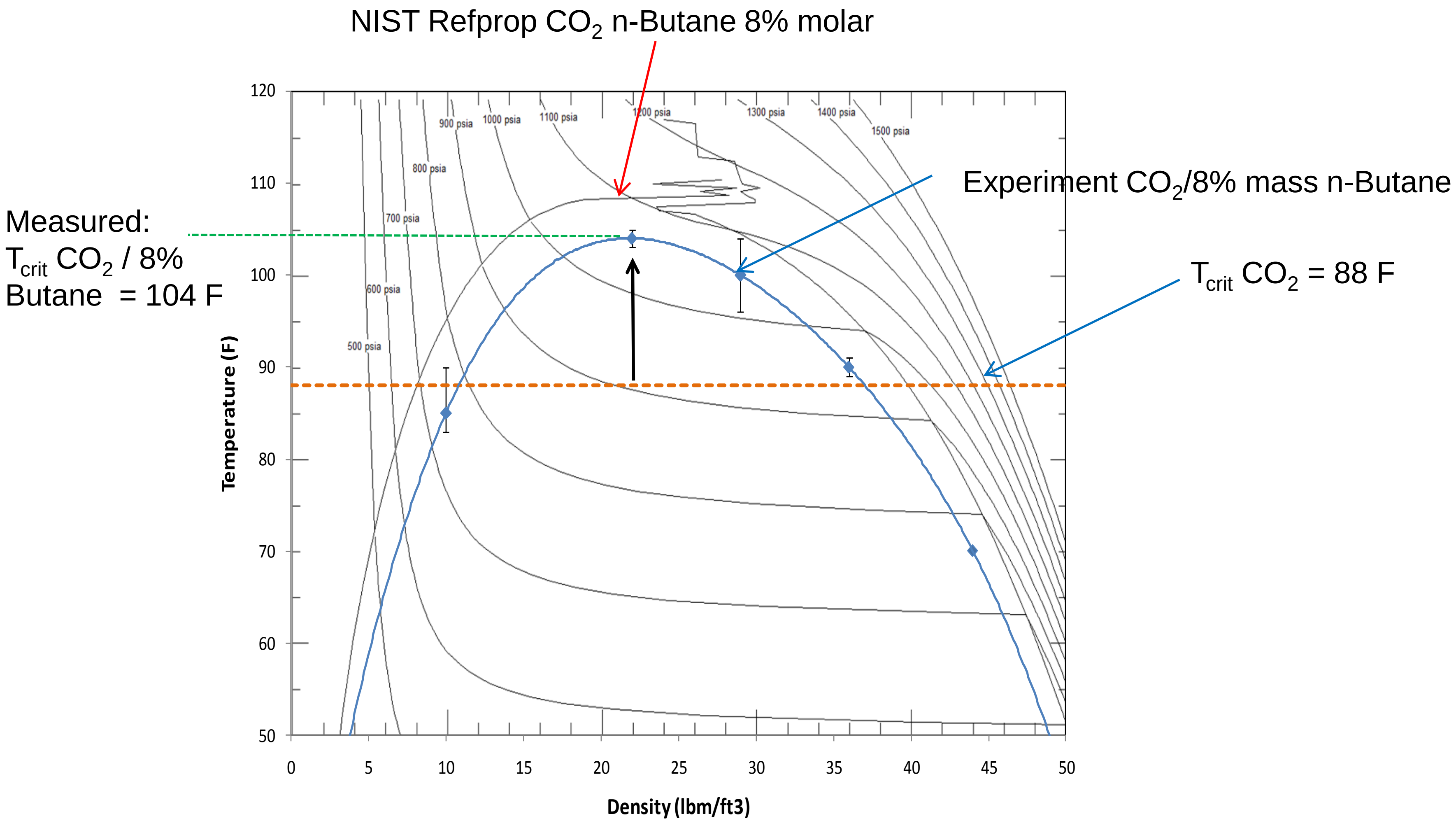
CO2	CO2 butane	CO2 Neon	CO2/SF6	CO2/SF6	CO2/SF6	SF6
100%	8% molar n-butane	4% molar Neon	30/70 %mass SF6	40/60 %mass SF6	50/50 %mass SF6	100%



Compression Loop Schematic



CO_2-Butane Mixture



1) Gas Mixtures can be used to Increase or Decrease the Effective Critical Point.
2) Gas Brayton/Rankine cycles can increase the cycle efficiency with these mixtures compared to pure CO2

With a Low Temperature S-CO2 Power Cycle

160 C Turbine Inlet Temperature With Dry Cooling (at 47 C)

Eff=18.1% with CO_2/Butane Mixture

Eff=14.5 % with pure CO_2

			CO2 + 10% Butane	CO2
Inlet Values	**Variable Name**	**Units**	**Value**	**Value**
Turbine Inlet T	T.5	K	**433.15**	**433.15**
Fractional Pressure drop	f.dp		**0.0071**	**0.0071**
Compressor Pressure Ratio	r.c		**2.64**	**2.21**
Compressor Inlet Pressure	p.1	kPa	**8500**	**8500**
Compressor Inllet Temperature	T.1	K	**320**	**320**
Mass flow rate	mdot	kg/s	**50**	**50**
Split flow frac thru chiller	f.split		**0.8272**	**0.6074**
Recup Approach Temp	dT.appr	K	**4.00**	**4.00**
Compressor Isentropic Eff	***0.85***	***0.9***	***0.921954446***	***0.921954446***
Re Comp Isen Efficiency	***0.87***	***0.9***	***0.87***	***0.87***
Turbine Isen Effic	***0.9***	***0.93***	***0.965489385***	***0.965489385***
Fraction of Carnot			0.691	0.555
Carnot Efficienc			0.261	0.261
Power				
Heat Transferred in HP leg of LT Recup		kW	6706.41	5234.17
Heat Transferred in LP leg of LT Recup		kW	6706.41	5234.17
Heat Trnsfrd in HP leg of HT recup		kW	0.00	0.00
Heat trnsfrd in LP leg of HT recup		kW	0.00	0.00
Rx Pwr	**P.Rx**	**kW**	**7204.99**	**5493.44**
Main Comp Pwr	P.Comp	kW	448.39	444.74
Maon Comp Pwr b	P.Comp.B	kW	550.24	300.62
ReComp Pwr	P.ReComp	kW	376.16	828.52
Turb Pwr	P.turb	kW	2675.32	2369.87
Chiller Heat Trnsfr	Q.Chill	kW	5904.46	4697.44
TAC Pwr	P.TAC	kW	**1300.53**	**796.00**
	P.TAC-chk	*kW*	*1300.53*	*796.00*
Eff Cycle			**0.181**	**0.145**

Substantial improvement in efficiency using S-CO_2 power cycle using CO_2 Butane Mixture

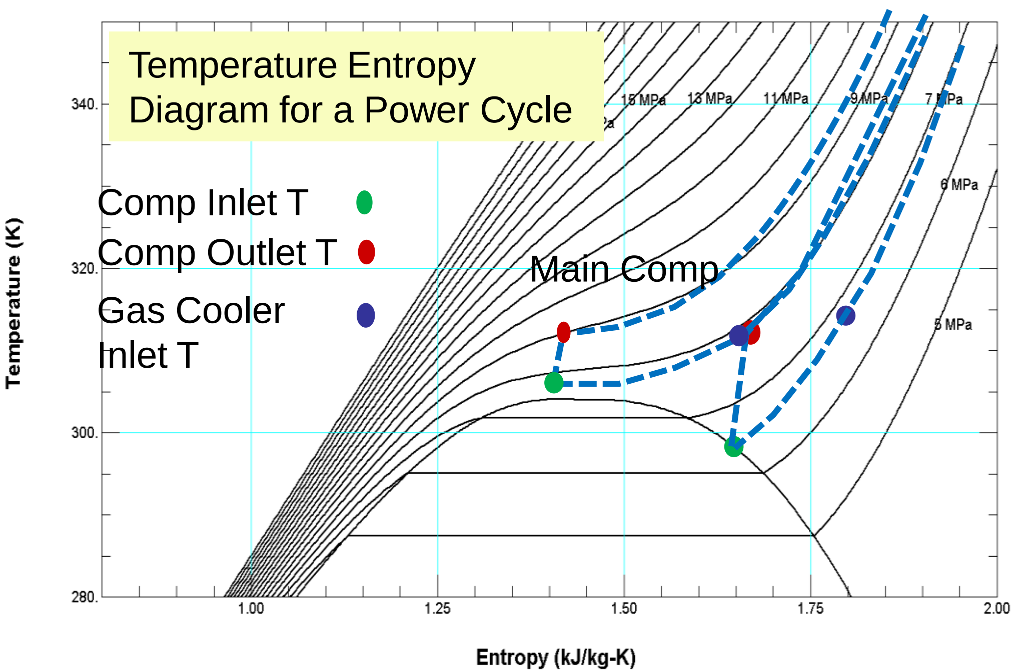
Condensation

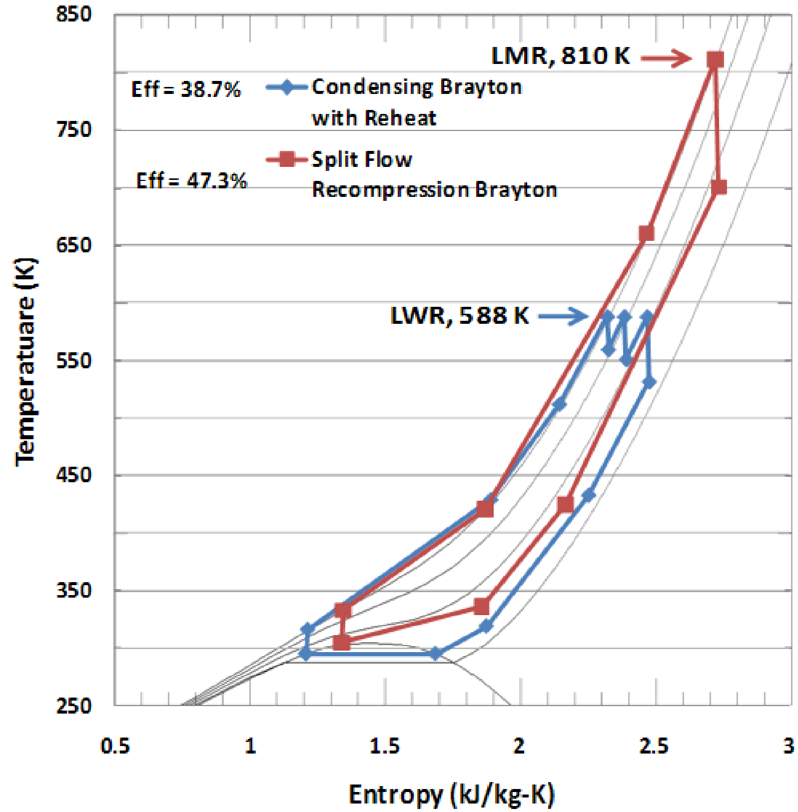
Condensation Motivation

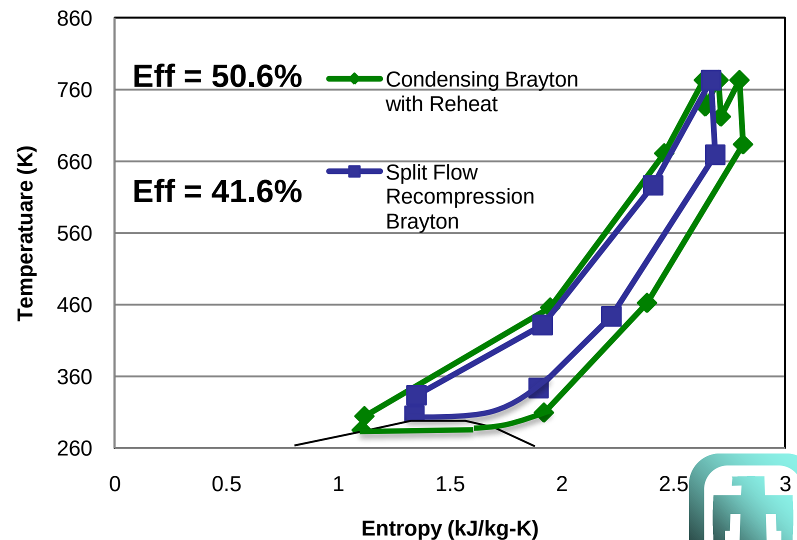
- At Sandia, ongoing research into analysis of advanced S-CO_2 power cycles:
    - reheat, condensing, intercooling, etc.

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

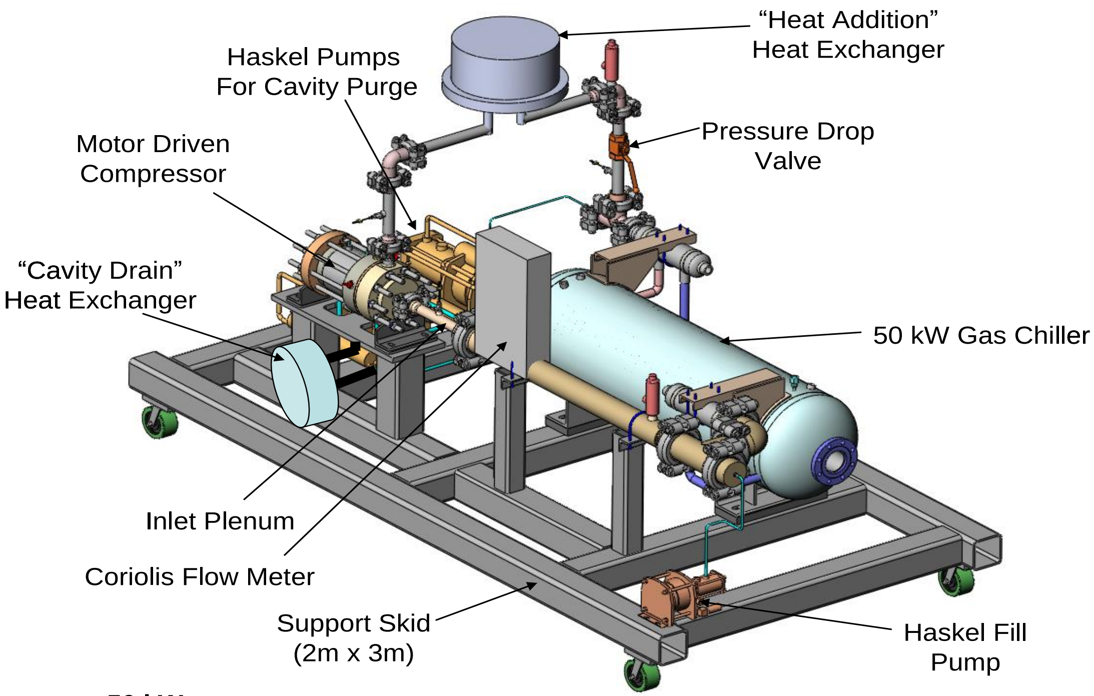
- Experimental tests have been performed to verify performance under these conditions

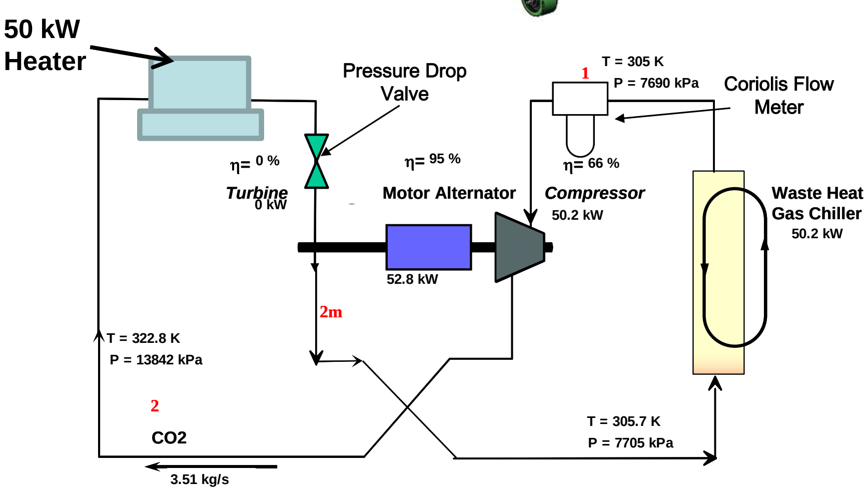






Test Equipment





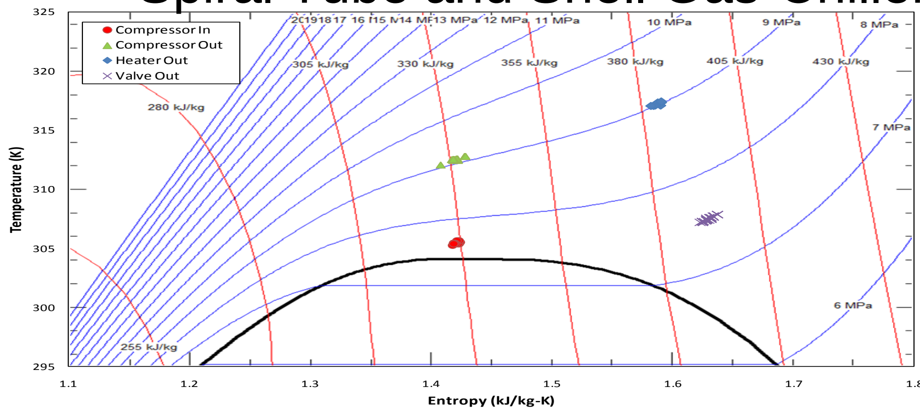
-Tests used the Sandia S-CO_2 compression loop, which consists of a compressor, heater, flow control valve, and chiller.

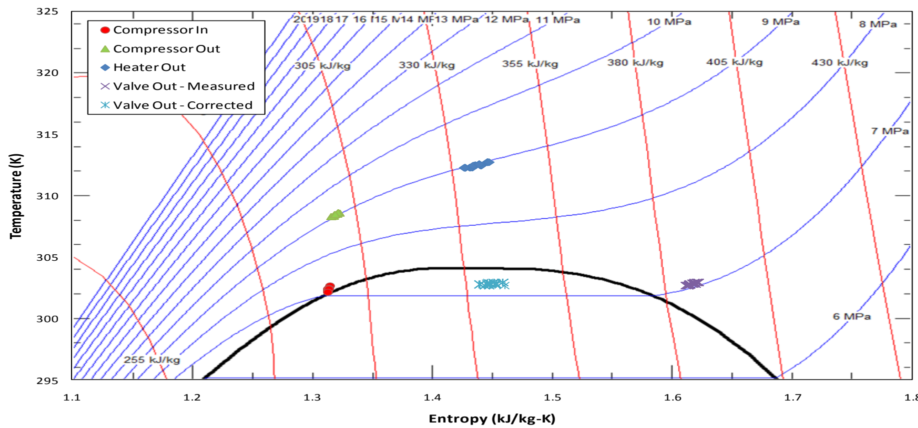
- Instrumented with T,p sensors at 4 key state points, and a density meter at compressor inlet

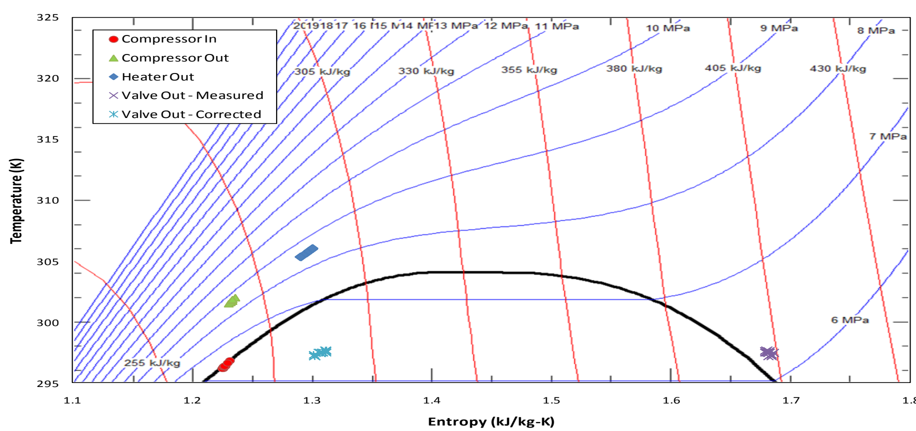
- Previously used for mapping compressor performance at the critical point, bearings & seals R&D, windage tests, etc.

Condesation in Sandia Compression Loop

Spiral Tube and Shell Gas-Chiller

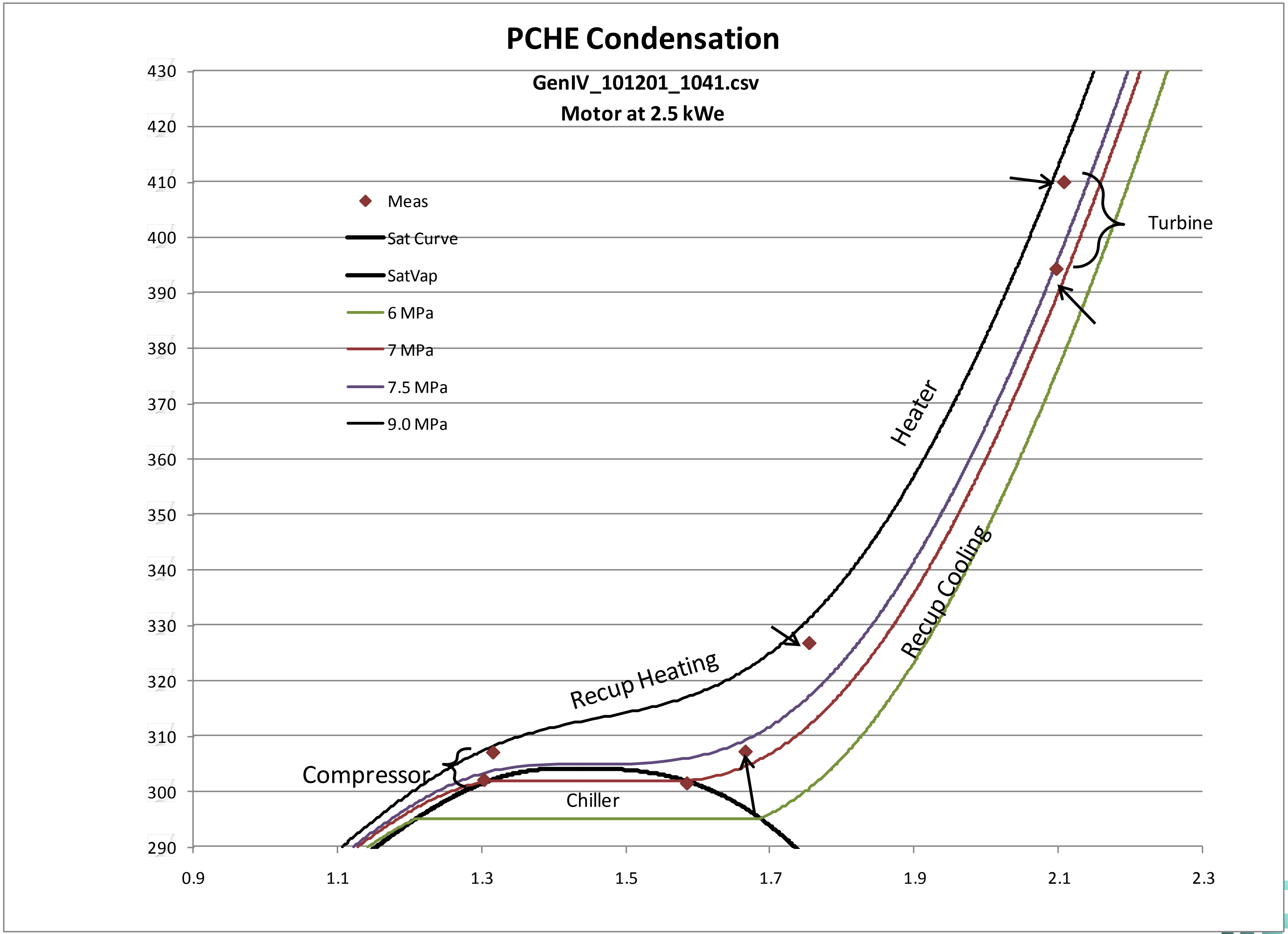






Condesation in Brayton Loop (TAC-A)

PCHE Gas-Chiller



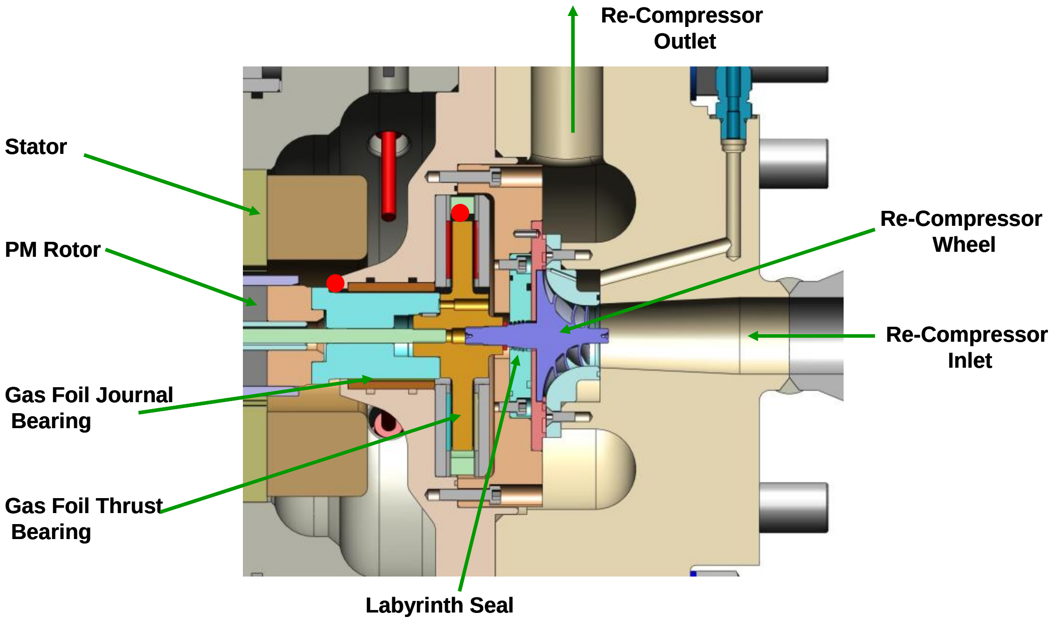
Condensation Conclusions

- Both Tube and Shell and PCHE can be used to condense CO_2
- Significance: Brayton Cycle can improve cycle efficiency by using condensation when environmental conditions permit.
- S-CO2 Power cycles are not constrained to operate only at the critical point
  - Appears so far that the compressor inlet can be positioned at different T,p to improve efficiency depending on environmental conditions (night, day, summer, winter, latitude).

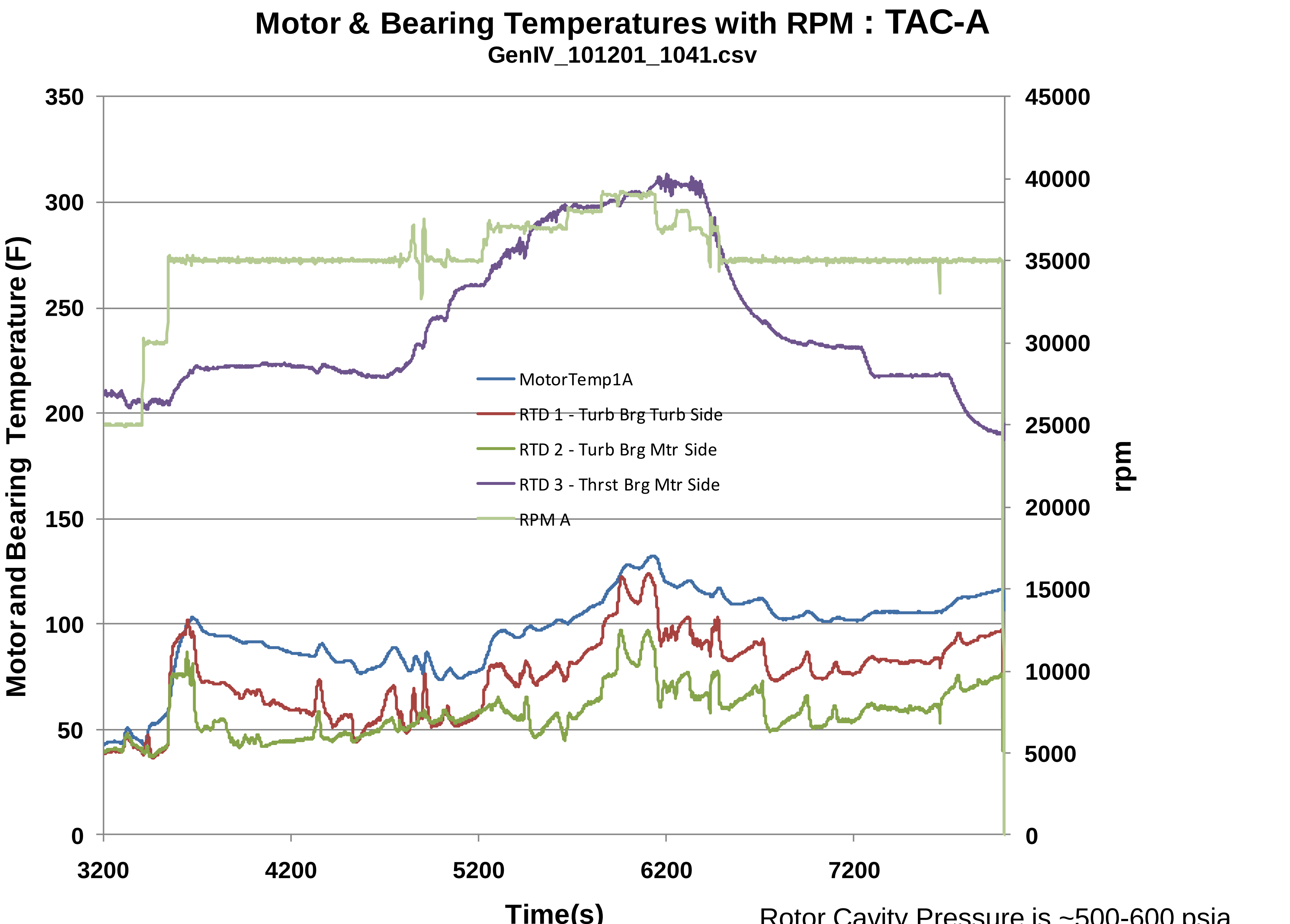
Gas-Foil Bearings

Gas Foil Bearings

$$Pwr = \pi C_d(\mathrm{Re})\,\rho\, r_{rotor}^{4}\,\omega^3 L_r$$



- At near supercritical pressures losses are large
- Strongly sensitive to radius and frequency
  - Penalizes small high speed systems
- Requires reduced rotor cavity pressure
- Model developed for Air and Steam
  - Not supercritical CO_2
  - Model is accurate for S-CO_2



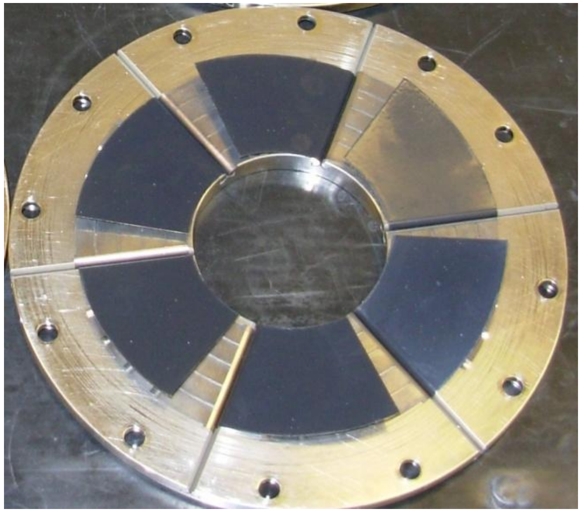
Rotor Cavity Pressure is ~500-600 psia

Gas Foil Bearings

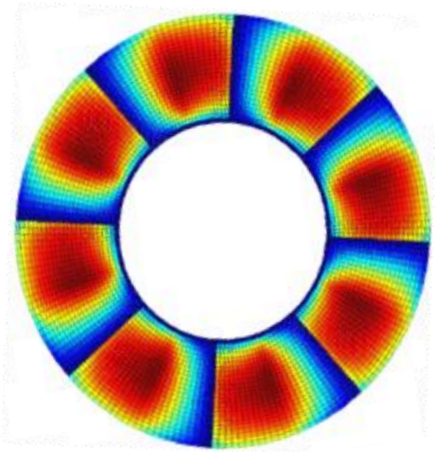
Model for Gap Thickness, Power, Heating,Temperature

Tom Conboy

S-CO2 Gas-Foil Thrust Bearing Pads



Reynolds Model for Pressure Under Pad



- Model is currently for laminar flow.
- Needs upgrade to turbulent to account for real gas
- Effects with high Reynolds numbers
  due to high density, high velocity, low viscosity

$$\mathrm{Re} = \frac{\rho v D}{u}$$

Natural Circulation Flow
And
Decay Heat Removal

Natural Circulation Summary

- **Powerful Natural Circulation Forces**
  - **Large density changes with small temperature changes near critical point**
- **Developed Simple Scoping Calculation Models in Excel**
  - **Based on theory described by D. Milone**
  - **Validated against experiments in a ½” OD Loop 72” Tall**
- **Modified Scoping Model to Apply it to**
  - **Reactors, Heat Exchangers, Gas-Chiller**
  - **Evaluated Proposed SNL Experiment**
- **Developed a 3 D CFD model by modifying a fire code C3D**
  - **Implement Nist Calls**
  - **Modified Energy Equation to use Enthalpy**
  - **Verified against D. Milone Report**
  - **Explored Natural Circ in Rx, with HXs and with Gas Chiller**

Natural Circulation in S-CO_2 Gas Cooled Fast Reactor (GCFR-CO_2)

A) Experiment (Milone)
B) Scoping Model
C) C3D Model
D) Geometry

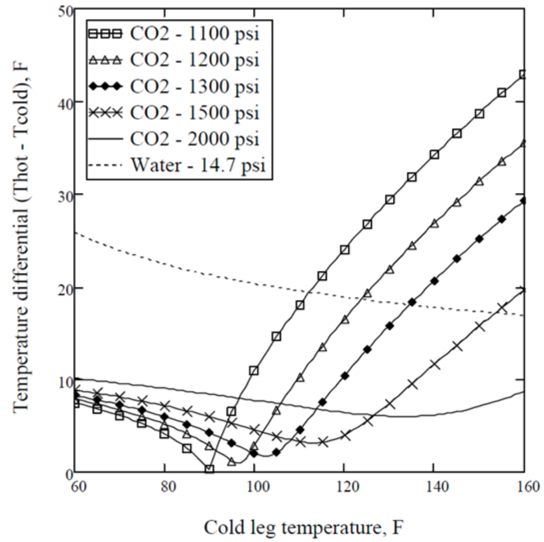
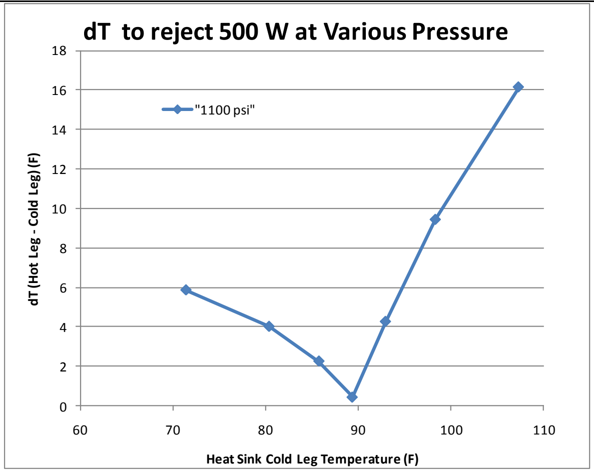


FIGURE 3: ANALYTICAL MODEL RESULTS
D = 0.45 IN (A = 0.159 IN^2), Q = 500 W, H = 6 FT

A



Sandia Lumped Parameter Natural Circulation Model Results for the Test Results Reported by Milone, 2009.

B

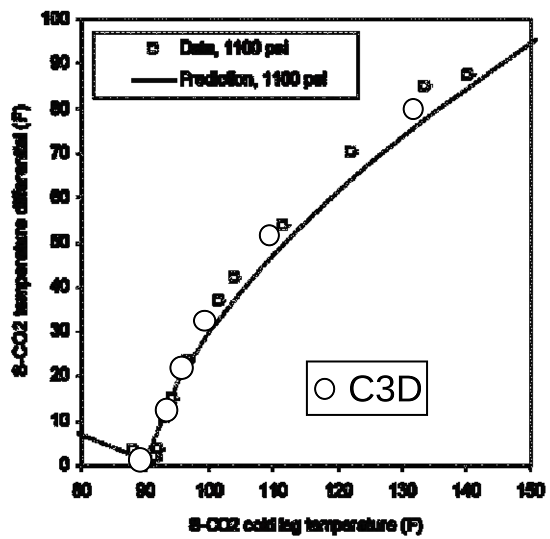


FIGURE 6: NC TEST DATA VERSUS PREDICTION
1100 PSI LOOP PRESSURE
T_{ps} = 90.0°F

C

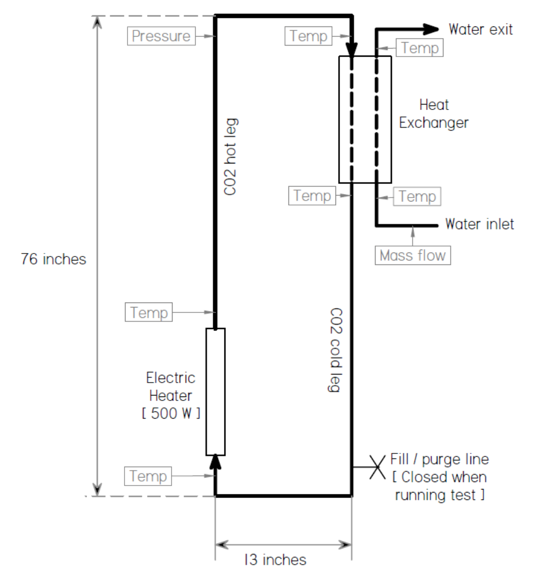
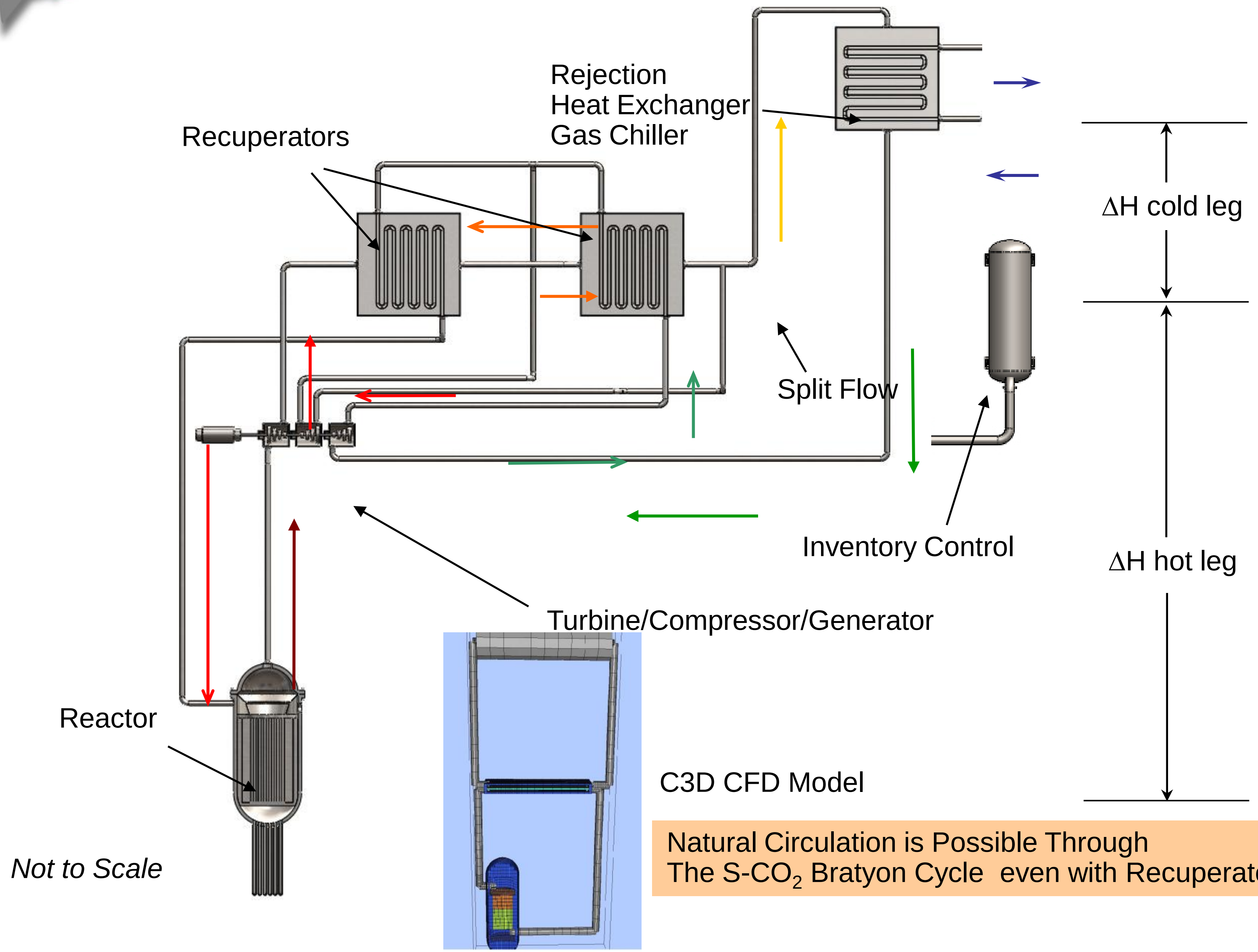


FIGURE 4: NATURAL CIRCULATION TEST FACILITY

D

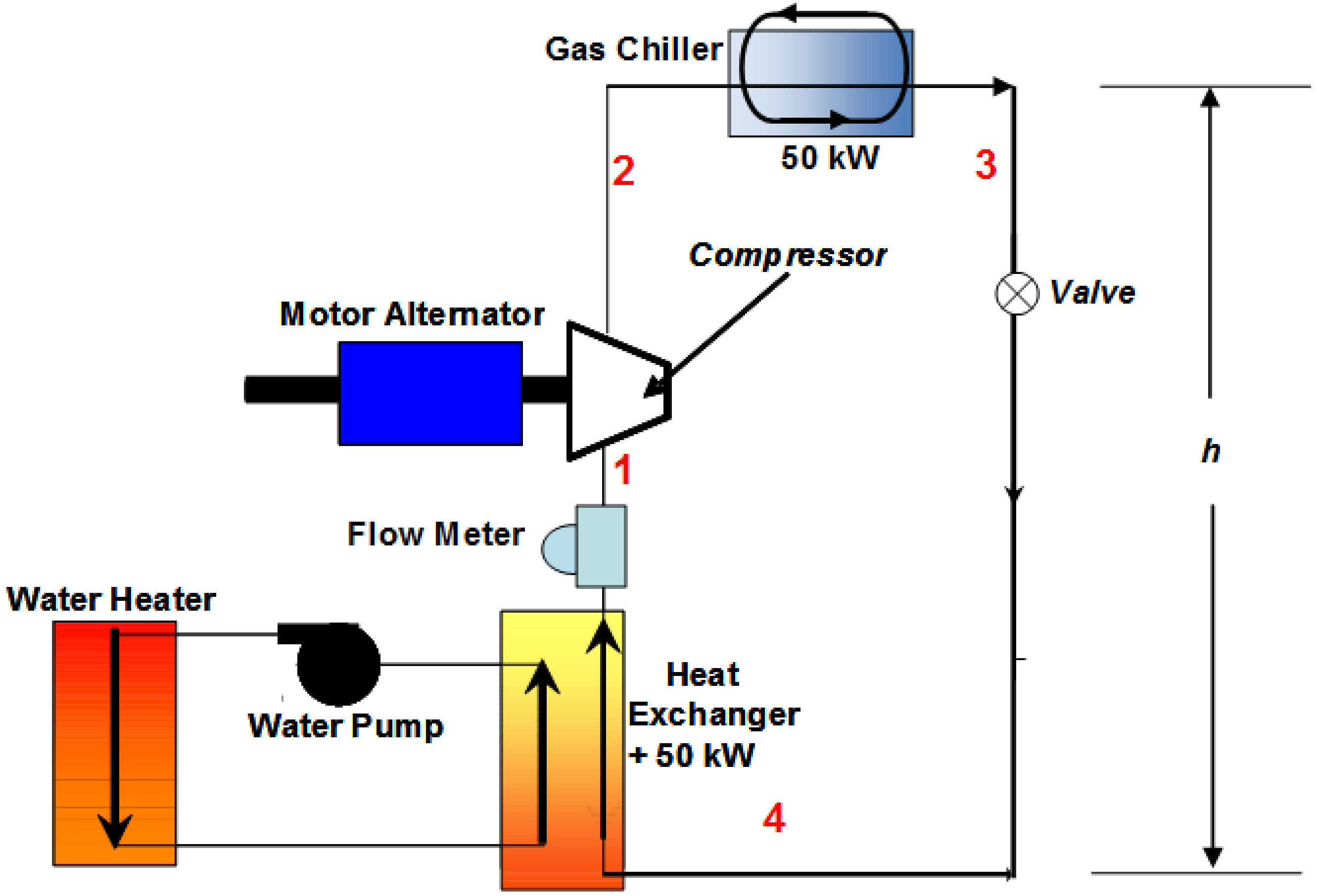
Natural Convection Flow in GFR-SCO2



C3D CFD Model

Natural Circulation is Possible Through
The S-CO_2 Bratyon Cycle even with Recuperators

$S\text{-}CO_2$ Natural Circulation Tests
are planned for Compression Research Loop



Need to Switch the location of the Cooling and Heating
Tests will provide measured data at high power levels 20-50 kW in complicated Geometries

Conclusions

- $S\text{-}CO_2$ Power Conversion Systems
  - Smaller, Simpler, As/more Efficient Than Existing Gas or Steam Power Systems in the (500-525 C) temperature range
  - Better Materials Compatibility
  - Can be built with existing technologies
  - Models of System and Component Performance are Accurate
  - Growth Potential (performance exceeds existing technologies)
    - Higher Temperatures (750 C) >50% Efficiency
    - Smaller
    - Fluid Mixtures to modify supercritical properties to higher or lower temperatures
    - PCHE and Tube and Shell HXs can be operated in the condensing mode with no changes
    - Inter-cooling with higher pressure ratios (small size means easier to implement)
      - IC allows for Higher Pressure systems to increase efficiency
    - Re-heat is an effective way to increase efficiency
  - Higher Temperature Ability and Smaller Size
    - Cost competitive higher efficiency power systems for all heat sources
  - Advanced cycles may increase SMR efficiency to 38% for LWR and 50 % for LMRs with a simpler and smaller plant
  - Useful for all heat sources (Nuclear, Solar, Fossil, Geothermal)
  - Numerous early non-nuclear Products (Marine, Fossil, Solar)
  - Can improve the economics of nuclear systems
  - Dry Cooling is Possible