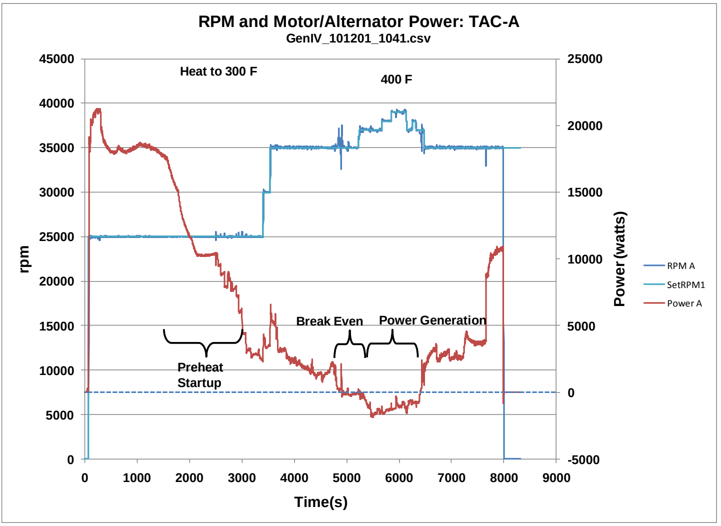
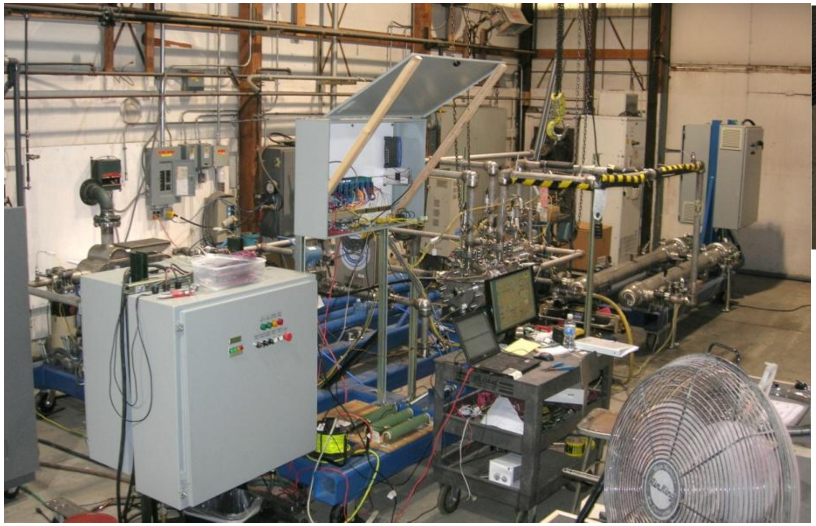
Break-Even Power Transients for two Simple Recuperated S-CO_2 Brayton Cycle Test Configurations

SAND2011-3669C

Steven A. Wright[1],Tom Conboy[1], Gary Rachau[1]
Sandia National Laboratories[1]
6221 Advanced Nuclear Technology
505 845 3014, sawrigh@sandia.gov



SCO_2 Power Cycle Symposium
May 24-25, 2011
University of Colorado, at Boulder



Goals of Presentation

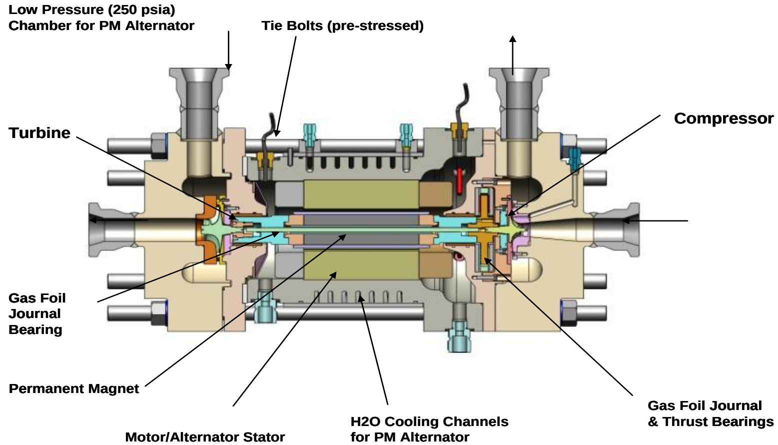
- S-CO_2 Research Program
    - DOE-NE Advanced Reactor Concepts (formerly Gen IV)
  - **Test Results (FY 2010)**
    - **Brayton Loop Descriptions (Main and Re-Compressor)**
    - **Breakeven Power Generation**
    - **Startup**
    - **Transition to Breakeven**
    - **Power Generation**
    - **Off-Design Model Comparisons with Test Results**
    - **Power/Rpm Curves Illustrating "Stable Operations"**

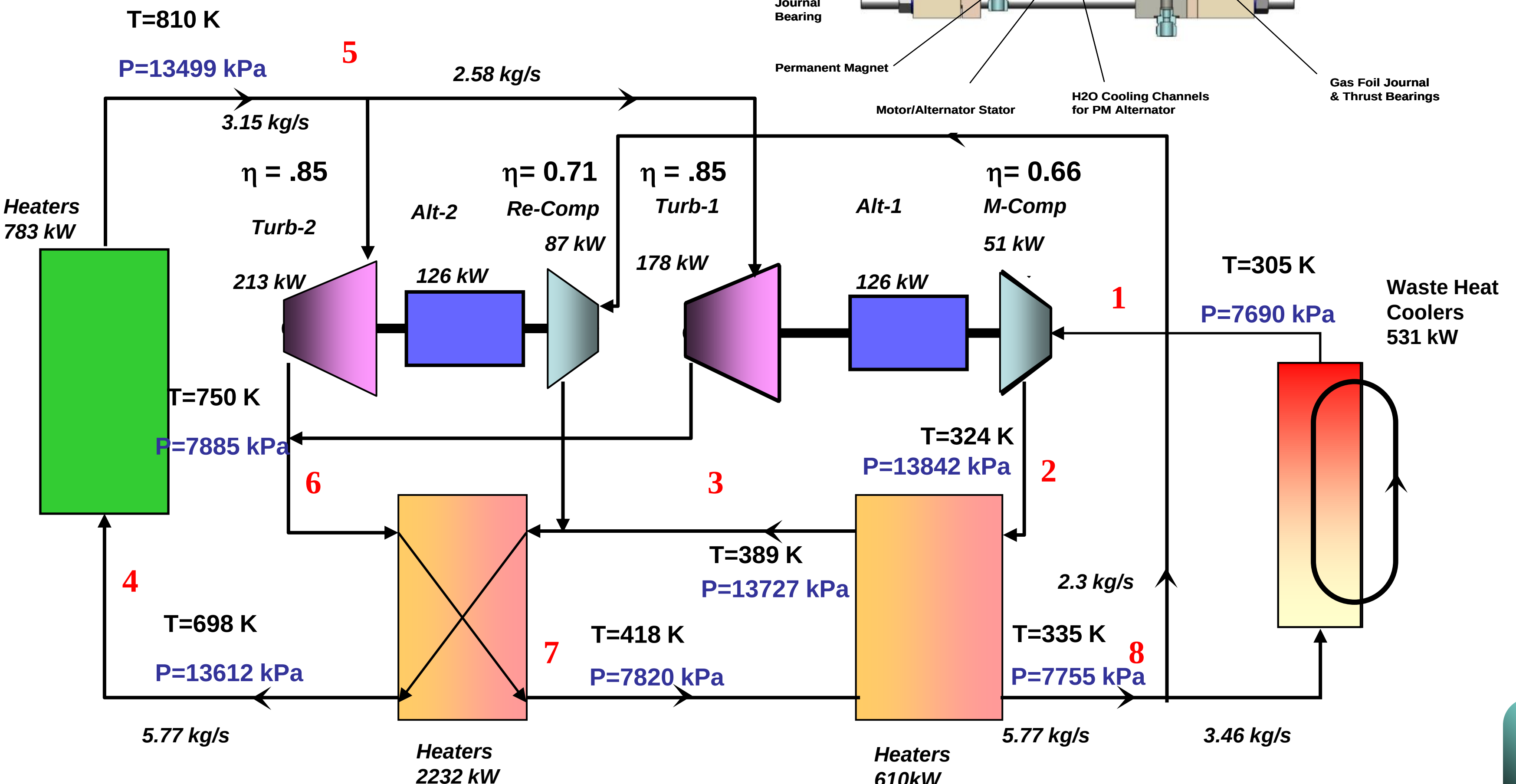
DOE Supercritical CO_2 Test Loop Description

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

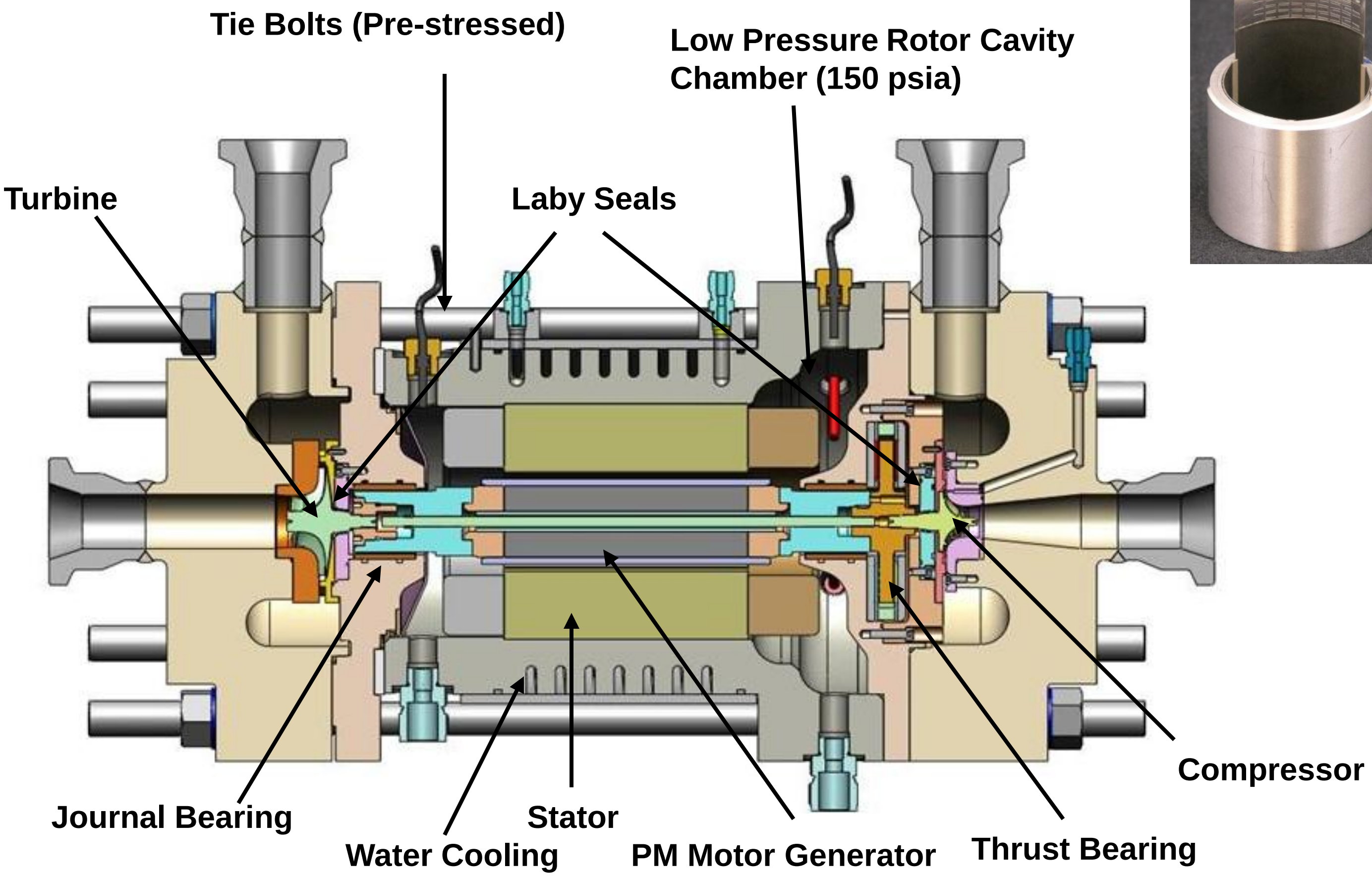
Modified Cycle to Enable Scaled Turbomachinery Development with Lower Risk

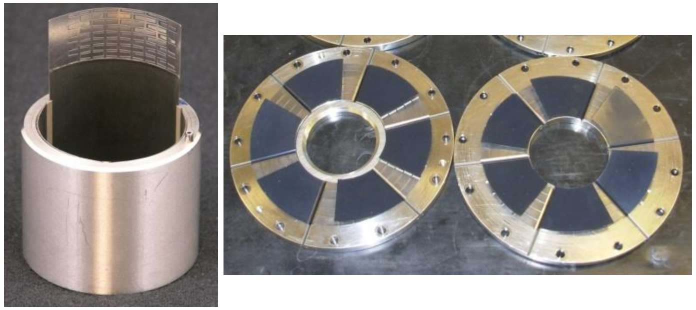
Dual Shafts, Lower Pressure Ratio (1.8 versus 2.6)



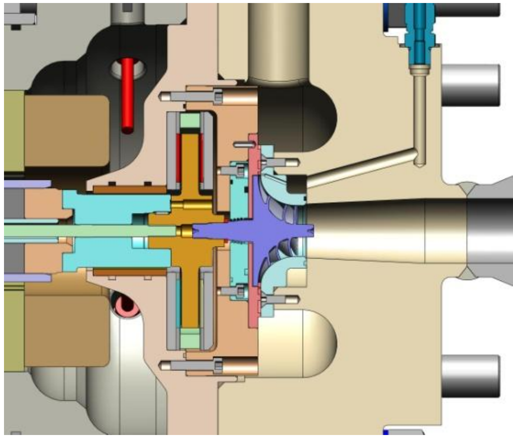


Key Technology
Turbo- Alternator Compressor Design
with Gas Foil Bearings (~24” Long by 12” diameter)
Technology for Small Scale System

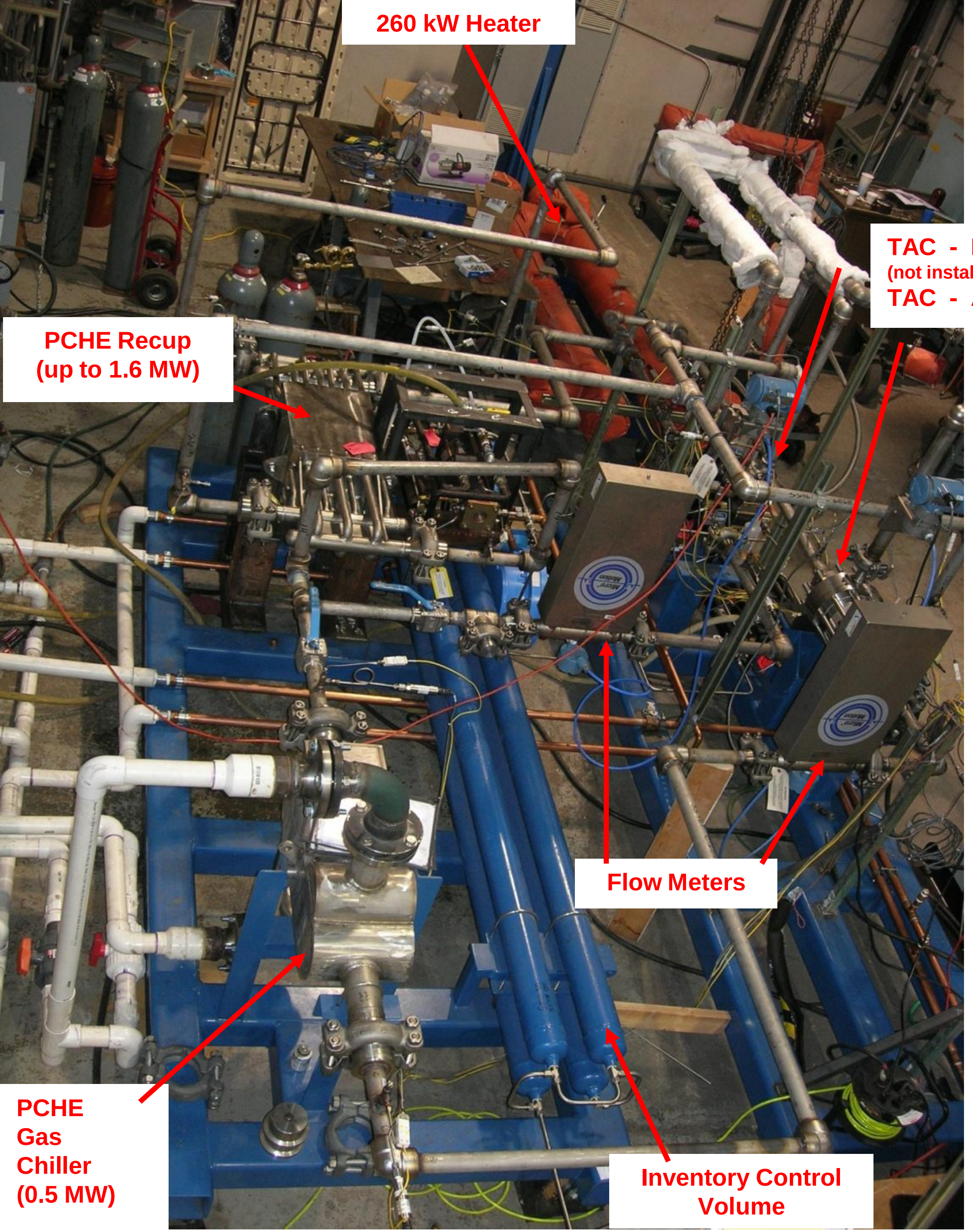


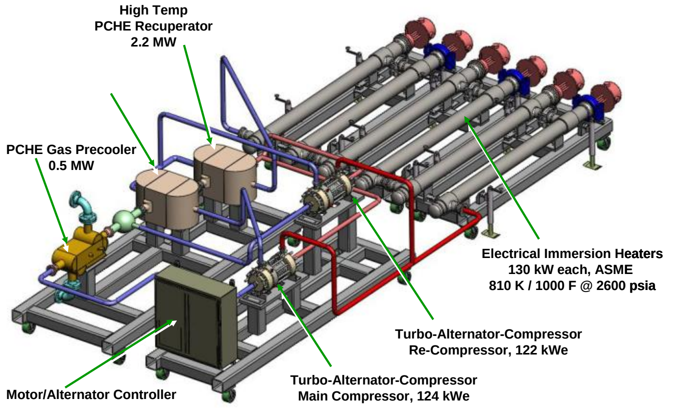


Gas-Foil Bearings



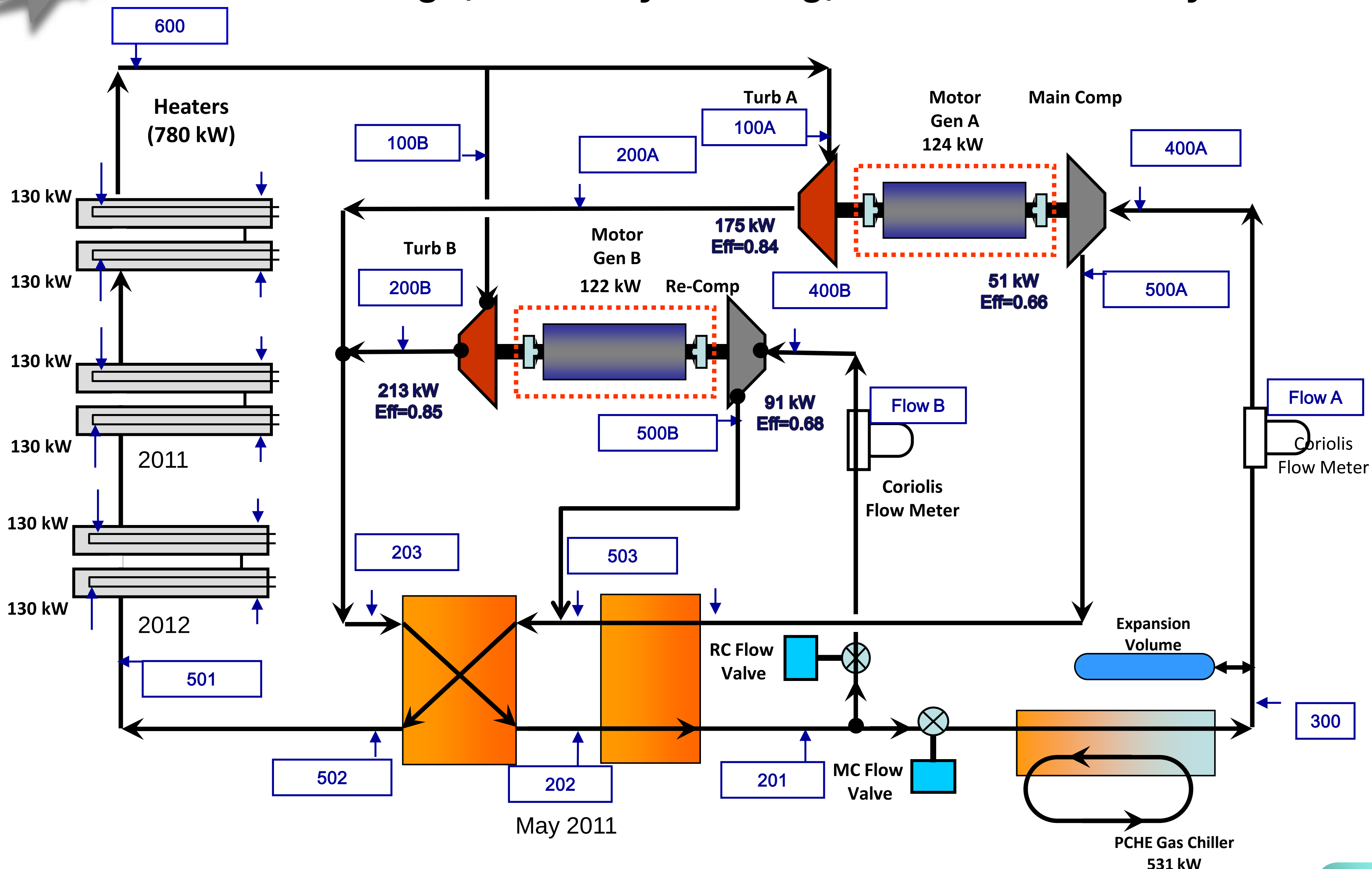
Supercritical S-CO_2 Brayton Cycle
DOE-Gen IV



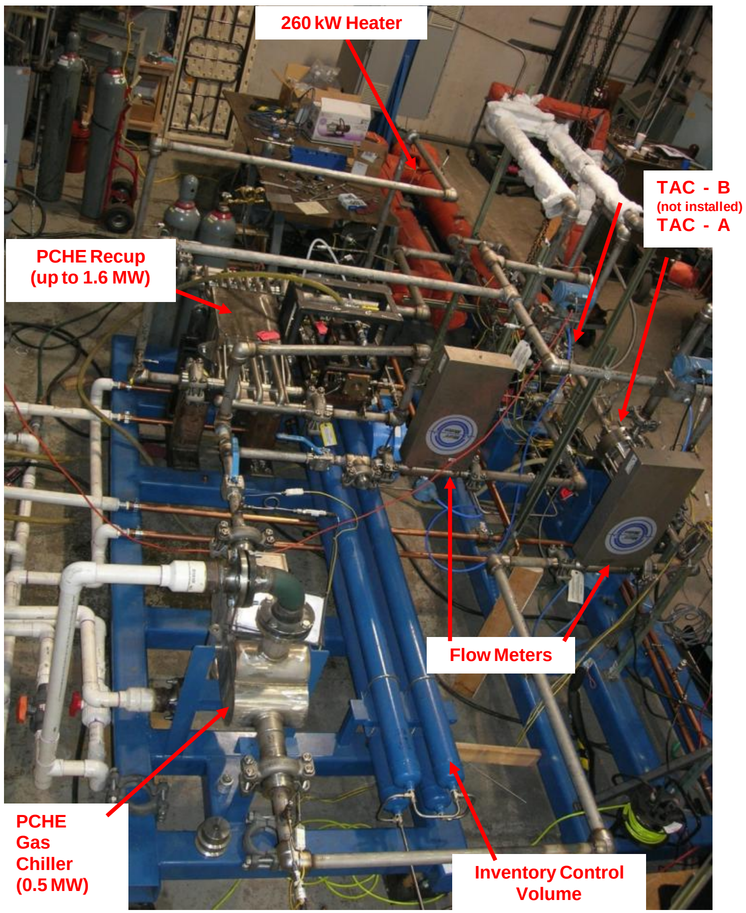


Barber Nichols

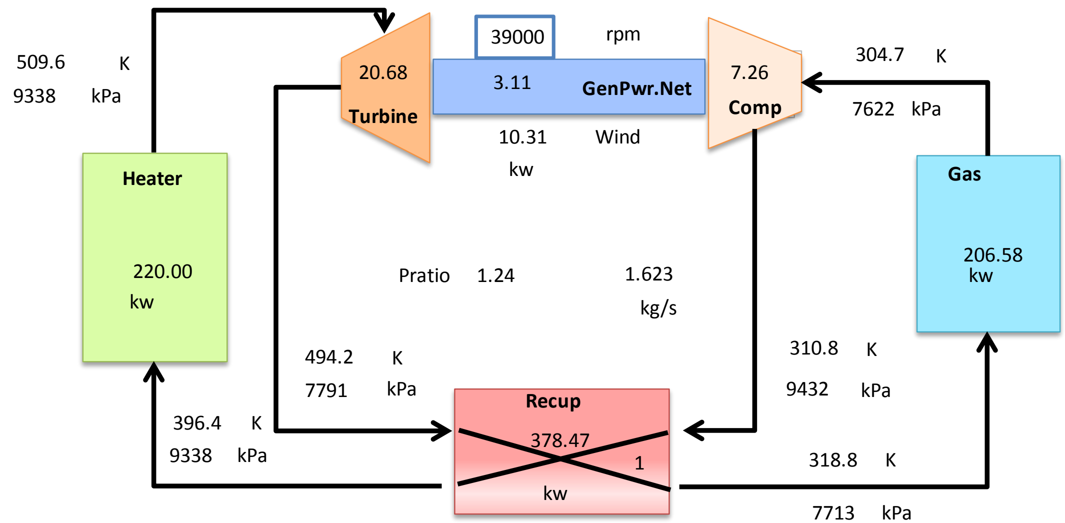
Supercritical CO_2 Brayton Loop
Final Design, Currently Existing, and Alternative Layouts

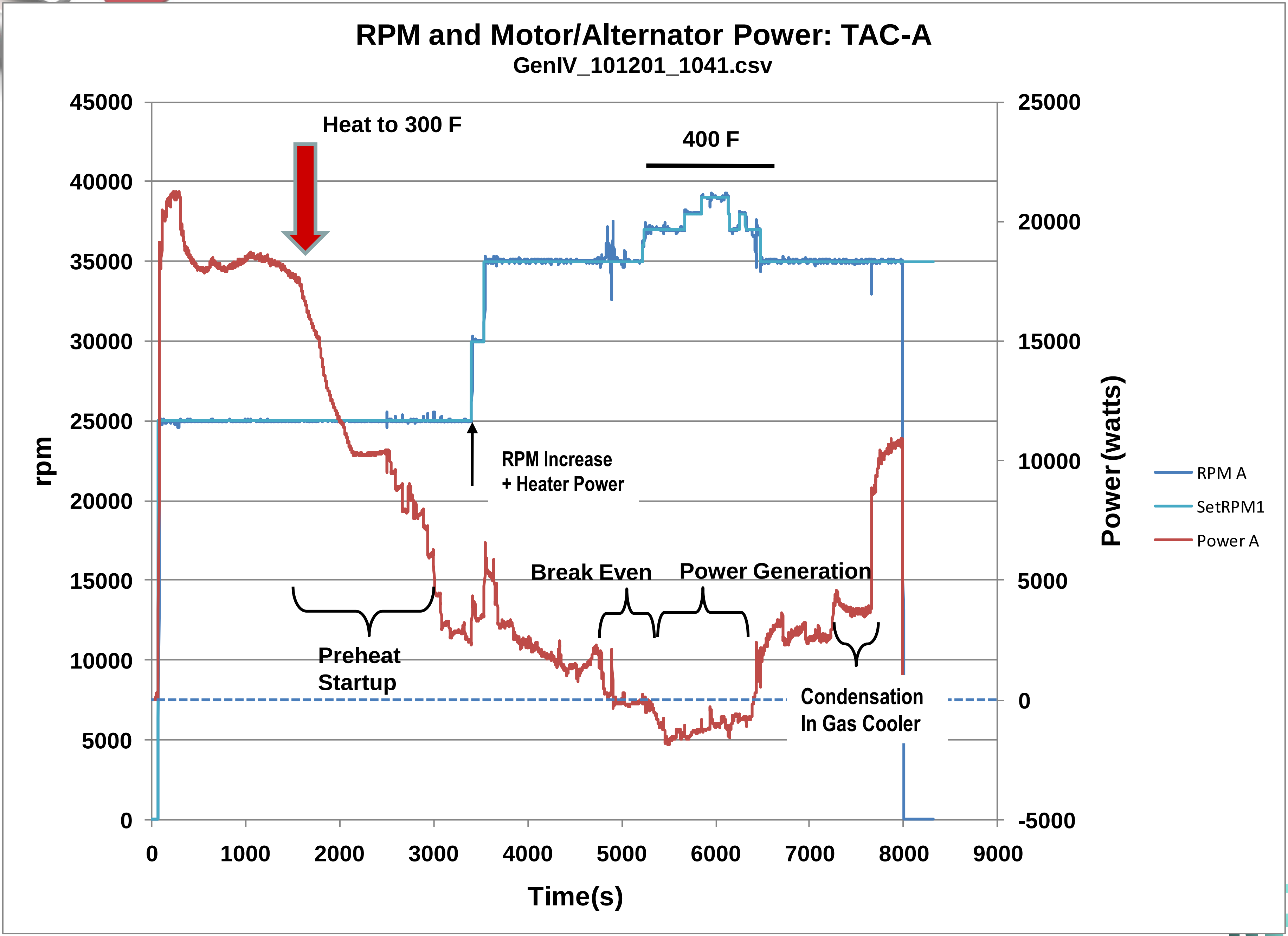


Break-Even Power Generation

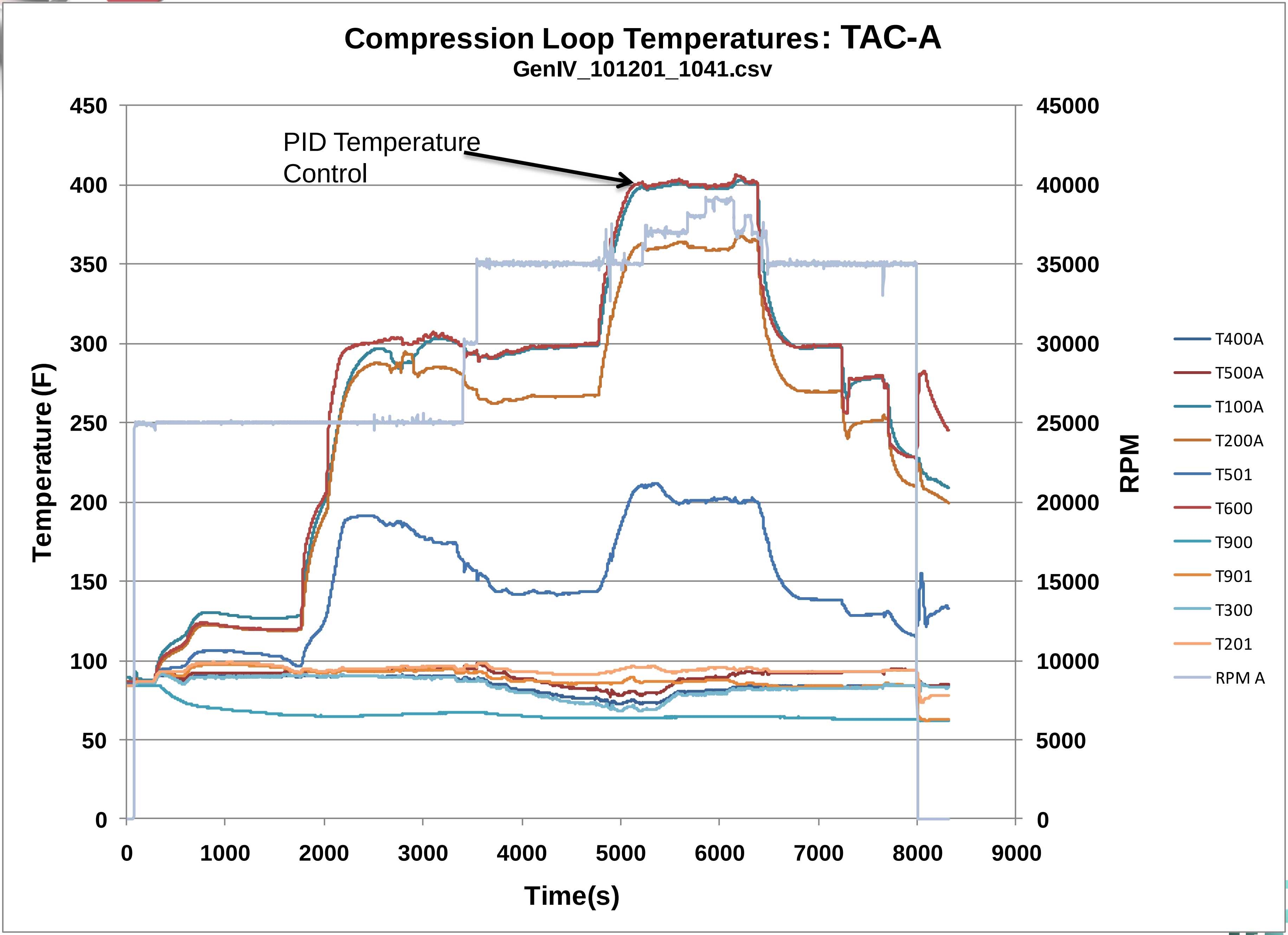


TAC-A

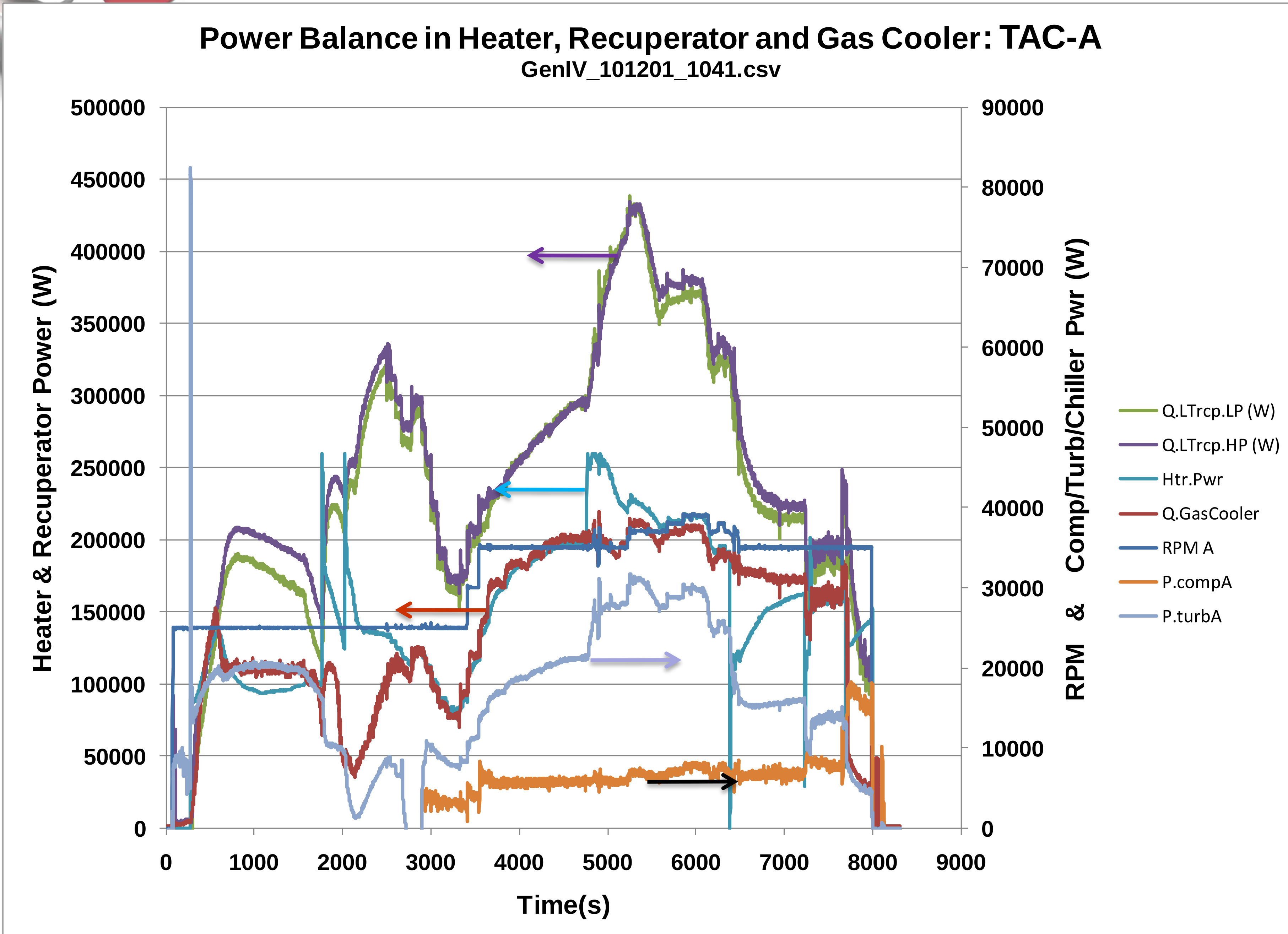




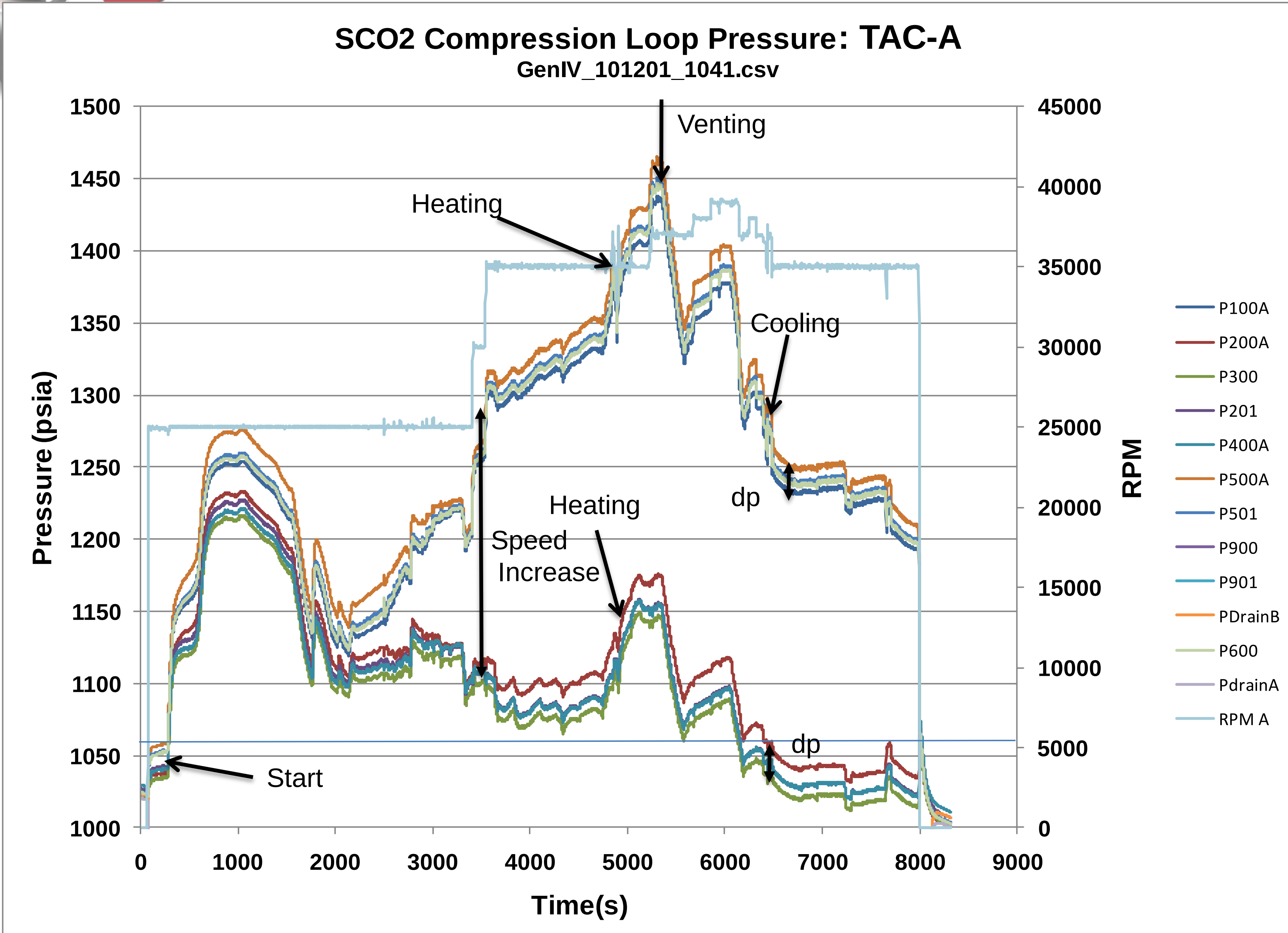
RPM and Motor/Alternator Power: TAC-A
GenIV_101201_1041.csv
Heat to 300 F
400 F
RPM Increase
+ Heater Power
Break Even
Power Generation
Preheat
Startup
Condensation
In Gas Cooler
rpm
Power (watts)
Time(s)
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
25000
20000
15000
10000
5000
0
-5000
0
1000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



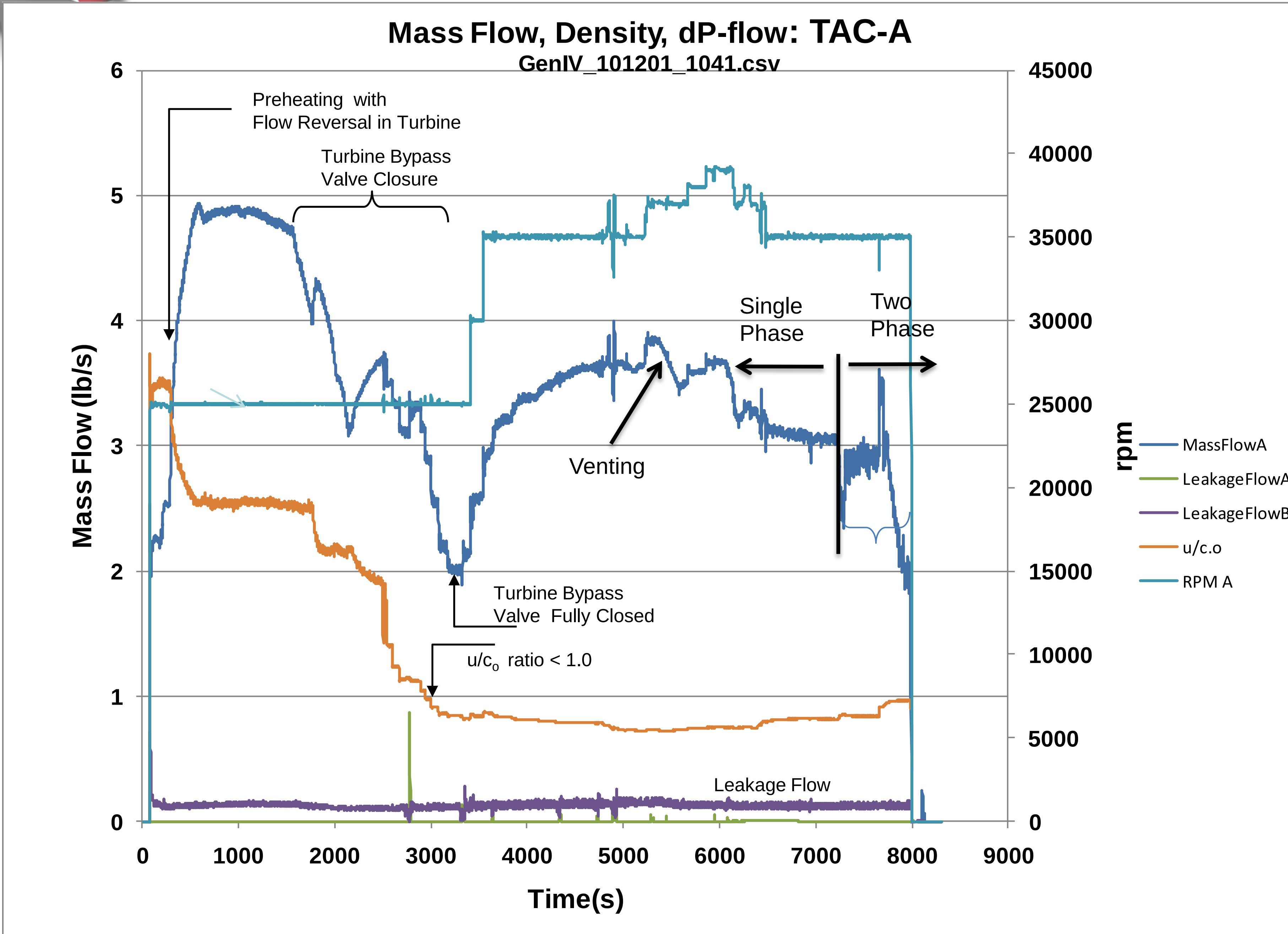
Compression Loop Temperatures: TAC-A
GenIV_101201_1041.csv
PID Temperature Control
Temperature (F)
RPM
Time(s)
0
50
100
150
200
250
300
350
400
450
0
5000
10000
15000
20000
25000
30000
35000
40000
45000
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
T400A
T500A
T100A
T200A
T501
T600
T900
T901
T300
T201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



Power Balance in Heater, Recuperator and Gas Cooler: TAC-A
GenIV_101201_1041.csv
Heater & Recuperator Power (W)
RPM & Comp/Turb/Chiller Pwr (W)
Time(s)
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
50000
100000
150000
200000
250000
300000
350000
400000
450000
500000
10000
20000
30000
40000
60000
70000
80000
90000
Q.LTrcp.LP (W)
Q.LTrcp.HP (W)
Htr.Pwr
Q.GasCooler
RPM A
P.compA
P.turbA



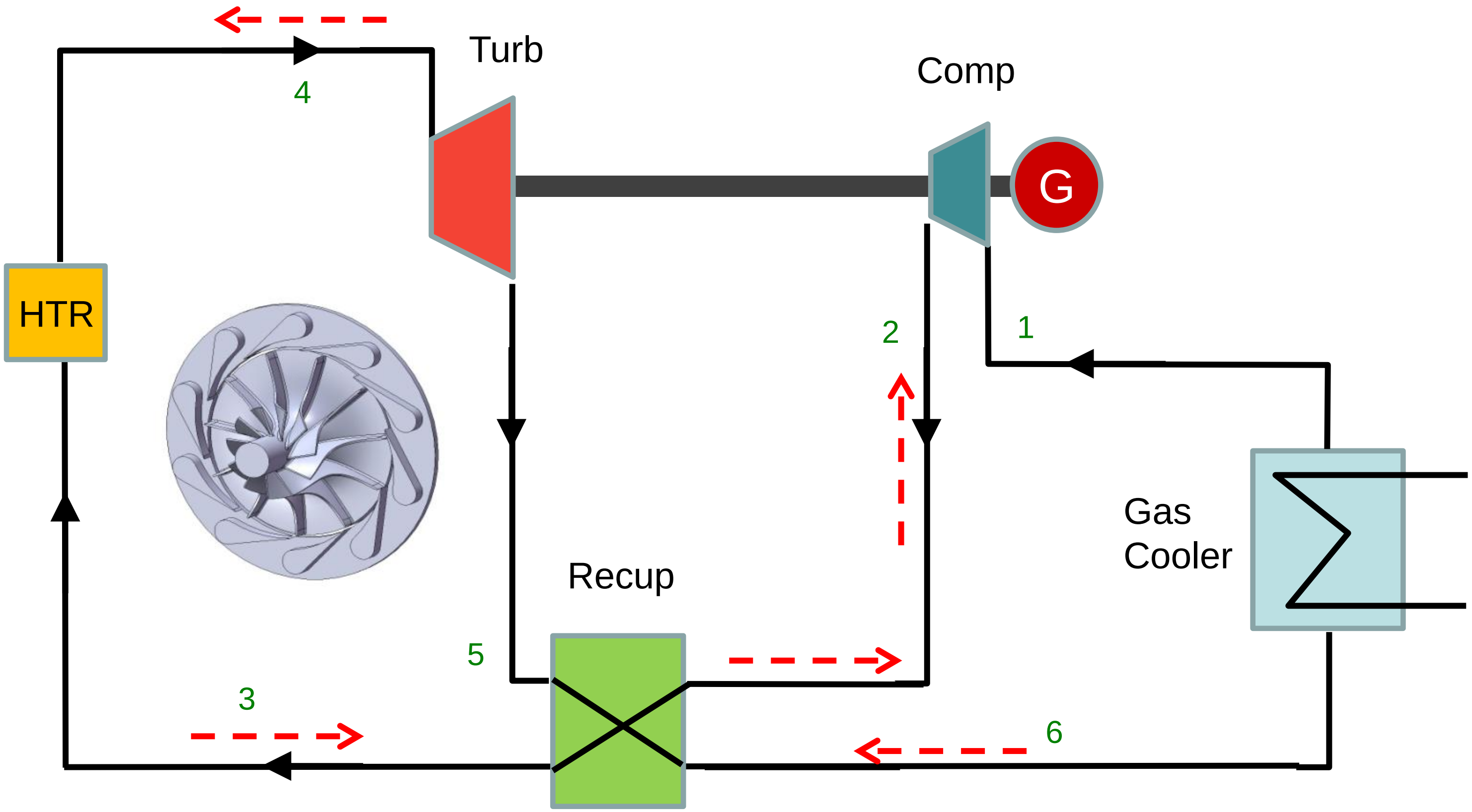
SCO2 Compression Loop Pressure: TAC-A
GenIV_101201_1041.csv
Pressure (psia)
1500
1450
1400
1350
1300
1250
1200
1150
1100
1050
1000
RPM
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
Time(s)
Venting
Heating
Cooling
dp
Heating
Speed
Increase
dp
Start
P100A
P200A
P300
P201
P400A
P500A
P501
P900
P901
PDrainB
P600
PdrainA
RPM A



Mass Flow, Density, dP-flow: TAC-A
GenIV_101201_1041.csv
Preheating with
Flow Reversal in Turbine
Turbine Bypass
Valve Closure
Single
Phase
Two
Phase
Venting
Turbine Bypass
Valve Fully Closed
u/c$_o$ ratio < 1.0
Leakage Flow
Mass Flow (lb/s)
rpm
Time(s)
0
1
2
3
4
5
6
0
5000
10000
15000
20000
25000
30000
35000
40000
45000
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
MassFlowA
LeakageFlowA
LeakageFlowB
u/c.o
RPM A

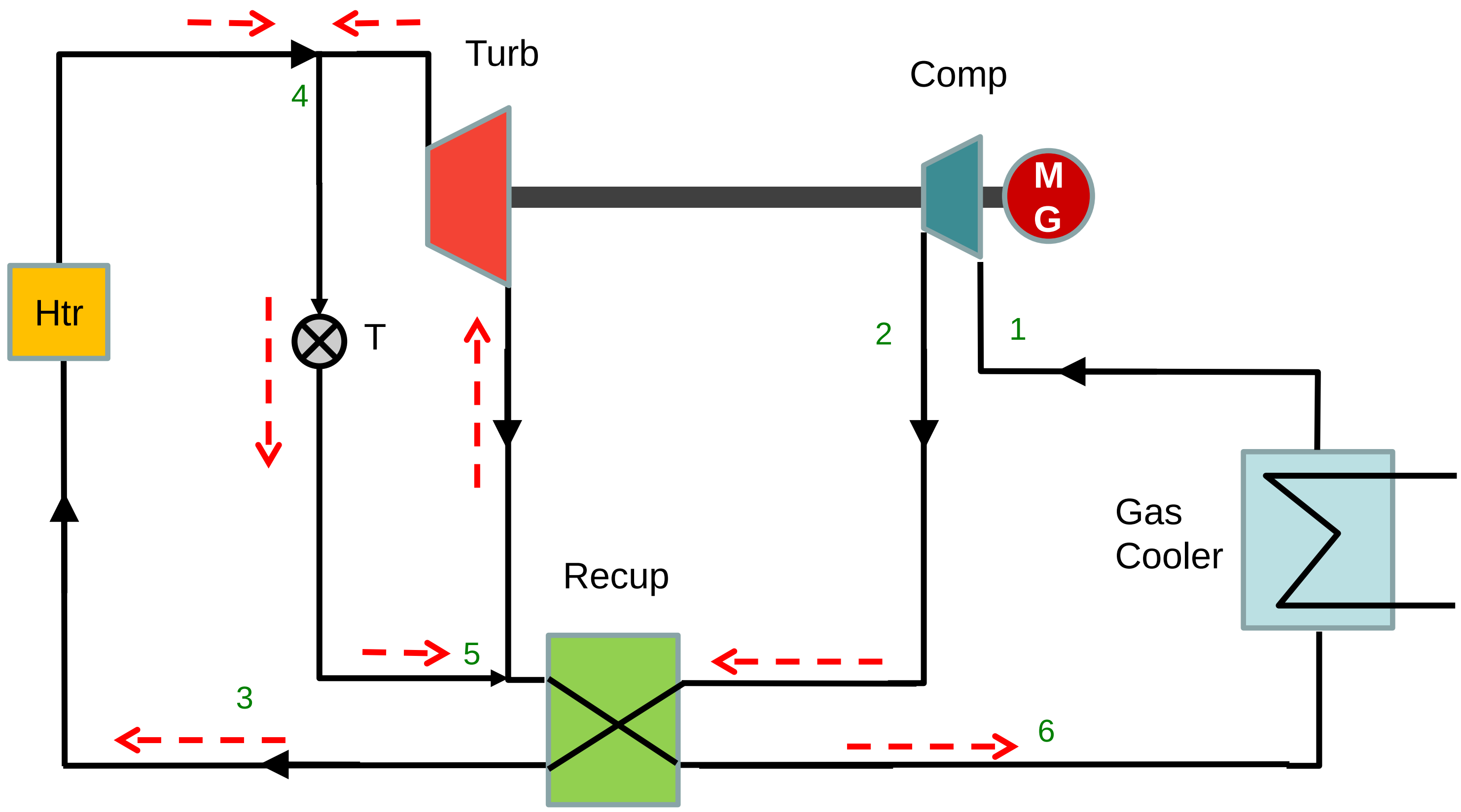
Simple Brayton Cycle

As Designed Flow Direction

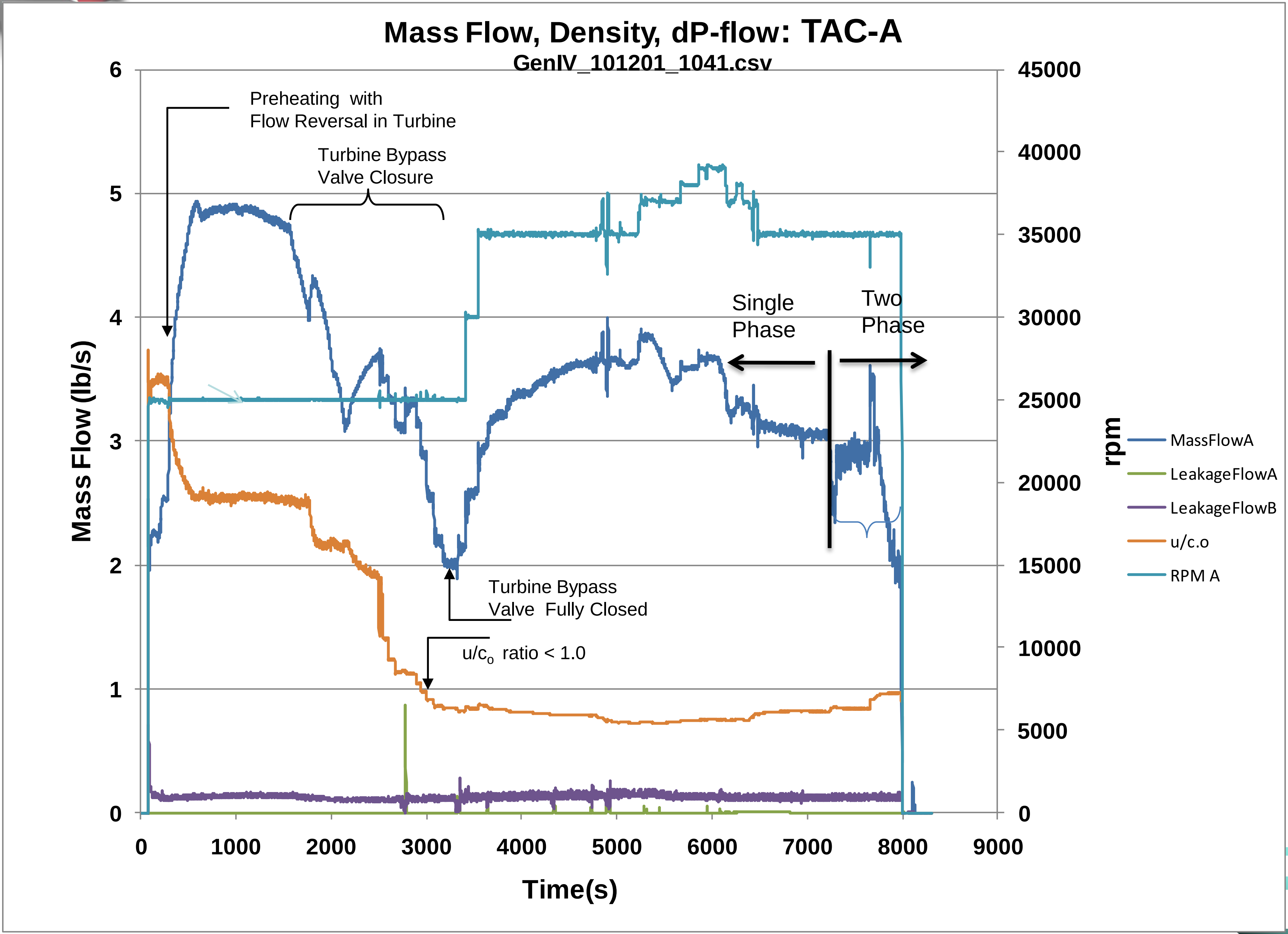


Red arrows show flow direction at cold startup when turbine acts like a compressor
Black arrows show as designed flow direction

Simple Brayton Cycle
Cold Startup Using Turbine Bypass Valve

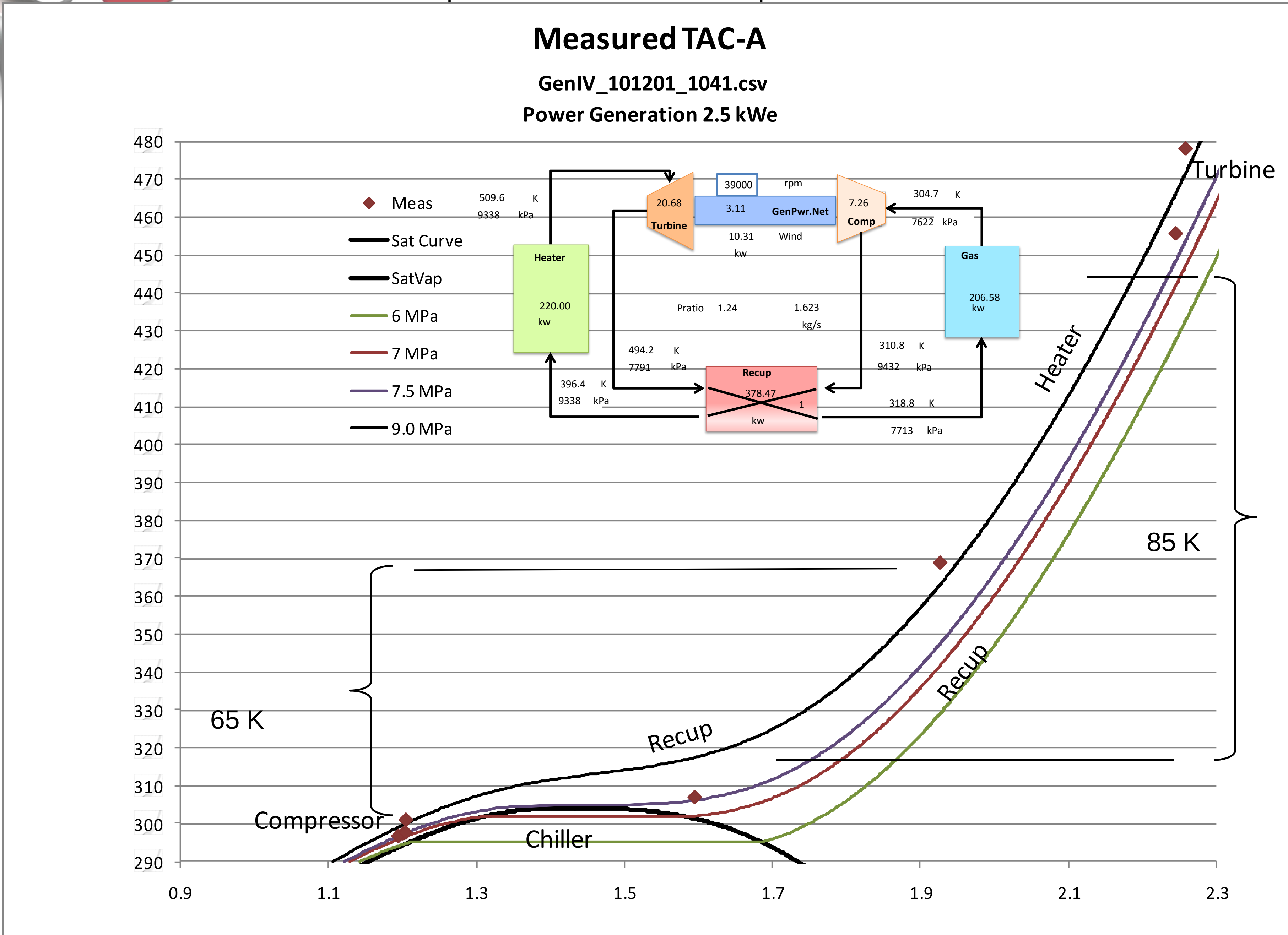


Red arrows show flow direction at cold startup when turbine acts like a compressor
Black arrows show as designed flow direction

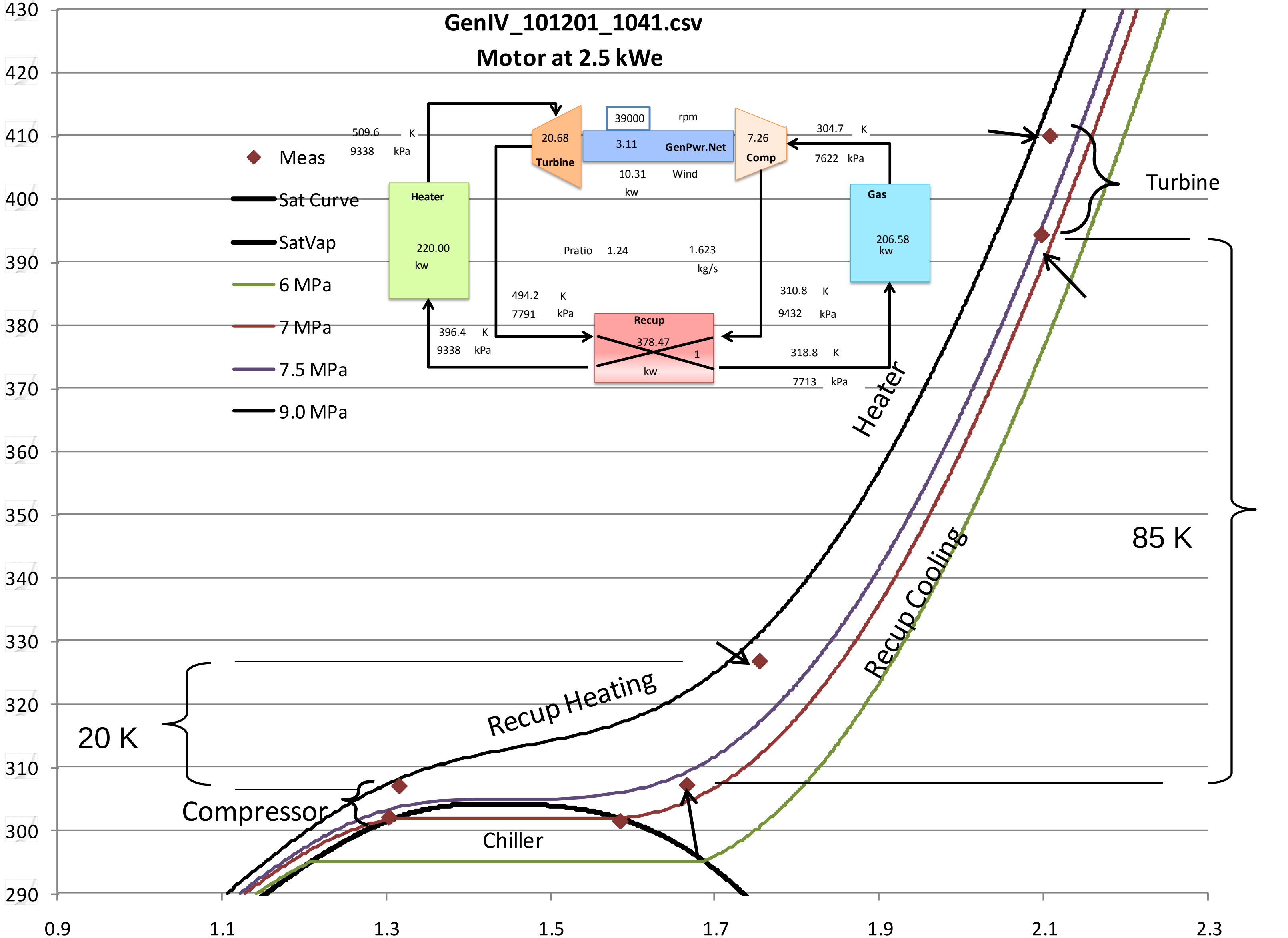


Mass Flow, Density, dP-flow: TAC-A
GenIV_101201_1041.csv
Preheating with
Flow Reversal in Turbine
Turbine Bypass
Valve Closure
Single
Phase
Two
Phase
Turbine Bypass
Valve Fully Closed
u/c$_o$ ratio < 1.0
Mass Flow (lb/s)
rpm
Time(s)
MassFlowA
LeakageFlowA
LeakageFlowB
u/c.o
RPM A
0
1
2
3
4
5
6
0
5000
10000
15000
20000
25000
30000
35000
40000
45000
0
1000
2000
3000
4000
5000
6000
7000
8000
9000

Compressor with Subcooled Liquid Inlet Conditions

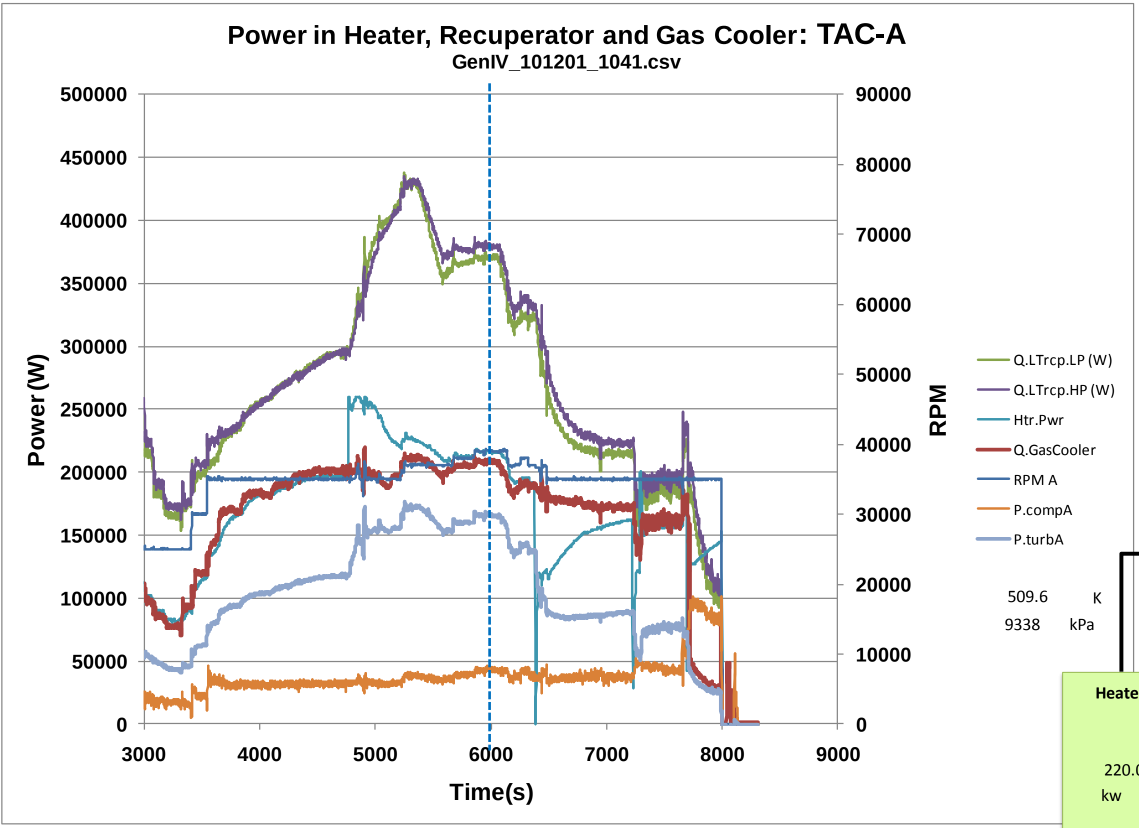


PCHE Condensation



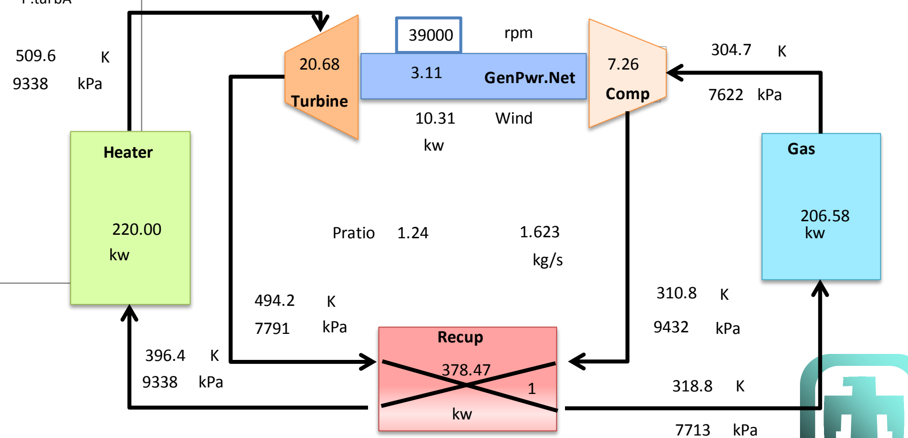
Comparison of Measured Data and Off-Design Cycle Analysis

Measured Data



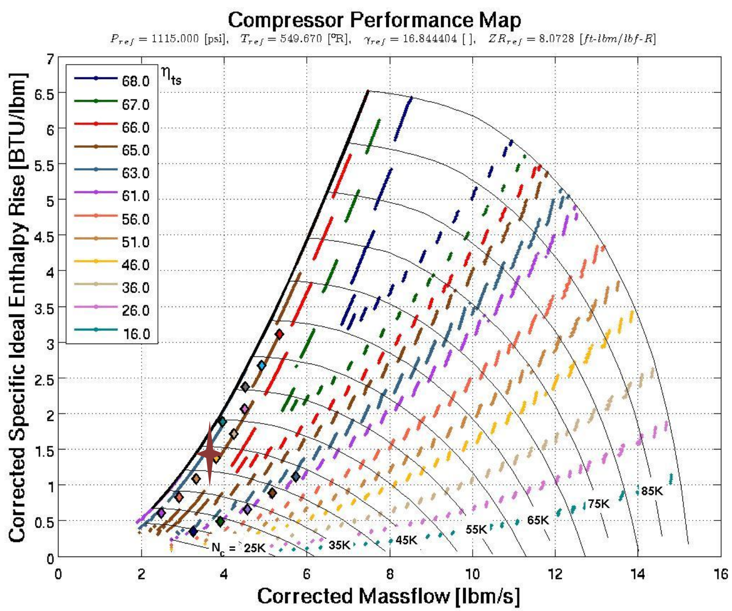
CycleAnalysis-Off-Design

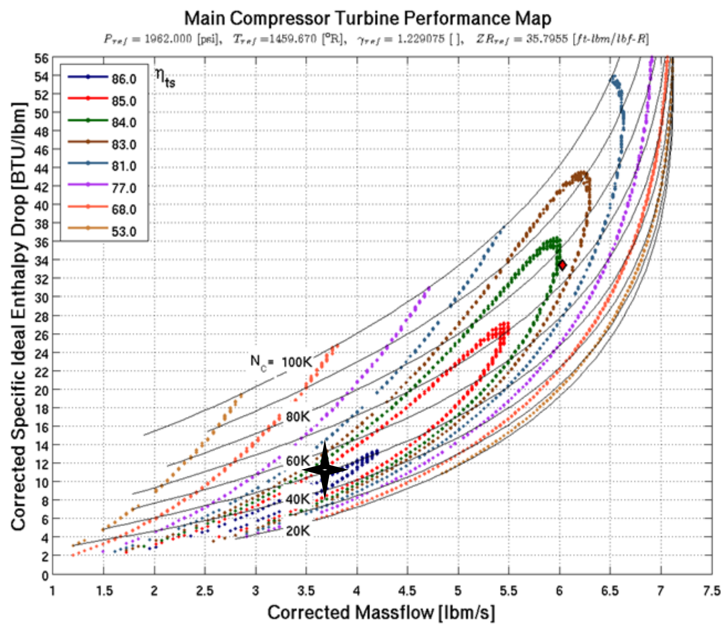
- Steady State System Models (Excel)
- Maps for Turbine and Compressor
- Heat Loss only in Gas Chiller
- LMDT for Recuperator
- UA as based on Heatric Specs
- Input (Heater Power and rpm)
- Models for
- Simple and
- Split-Flow Brayton Cycles



Turbine Compressor Mapping

"Location on the dH vs mass flow Maps"

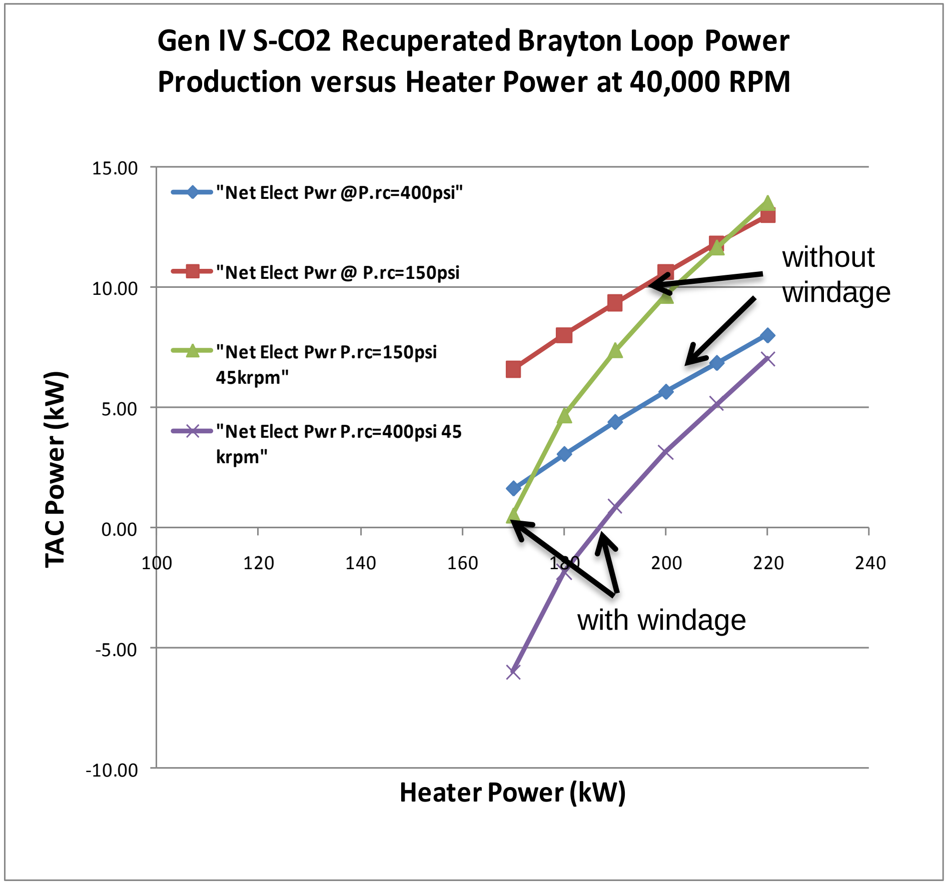


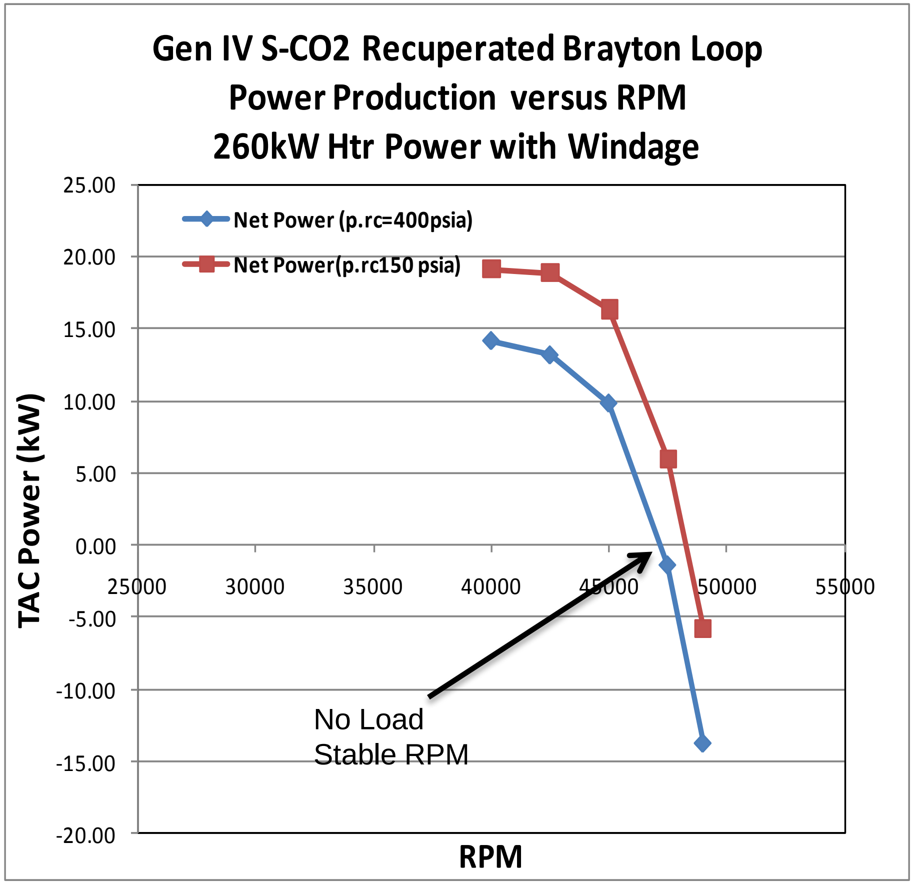


Compressor is operating closer to the surge line than designed.
Turbine is near its as designed operating point.

Mass flow rates are lower than expected or Pratio is larger.

Off-Design Performance

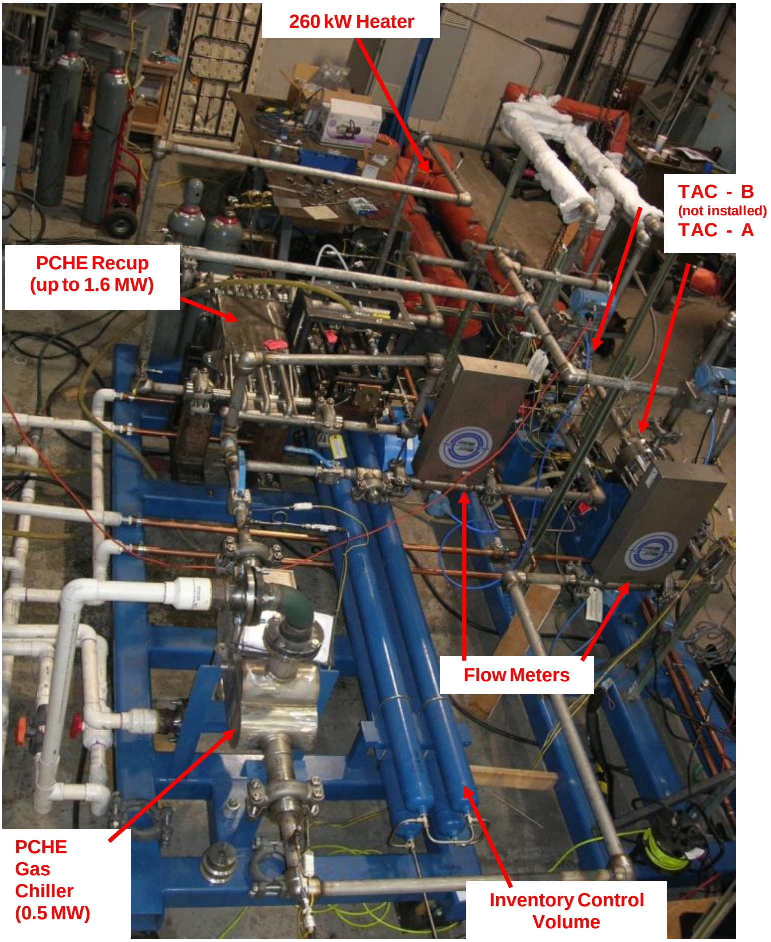




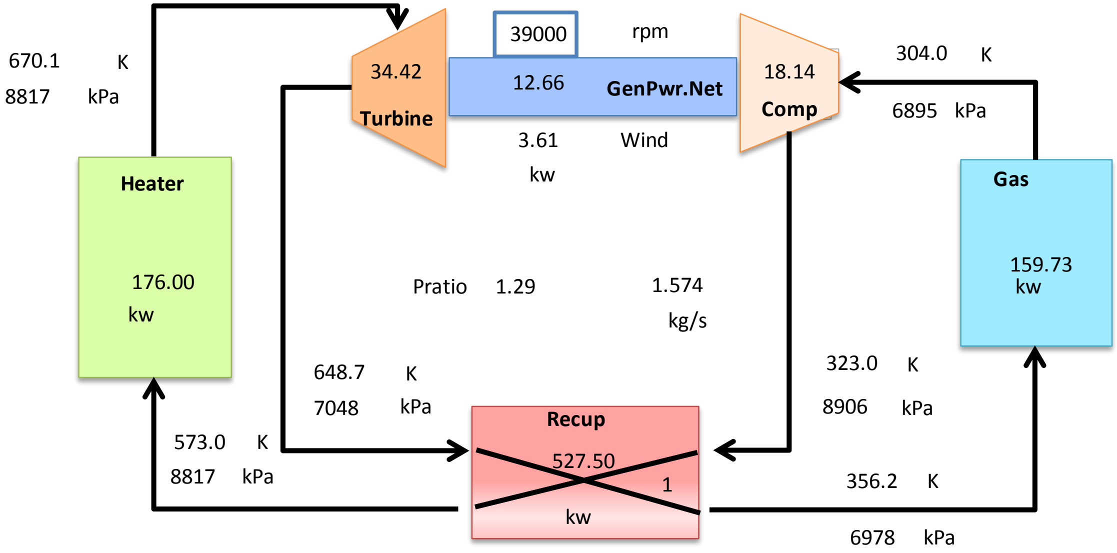
Heater Power must > 180 kW to make power.
Threshold heater powers predicted.

Torque/Power rpm Curves
But at constant heater power not TIT

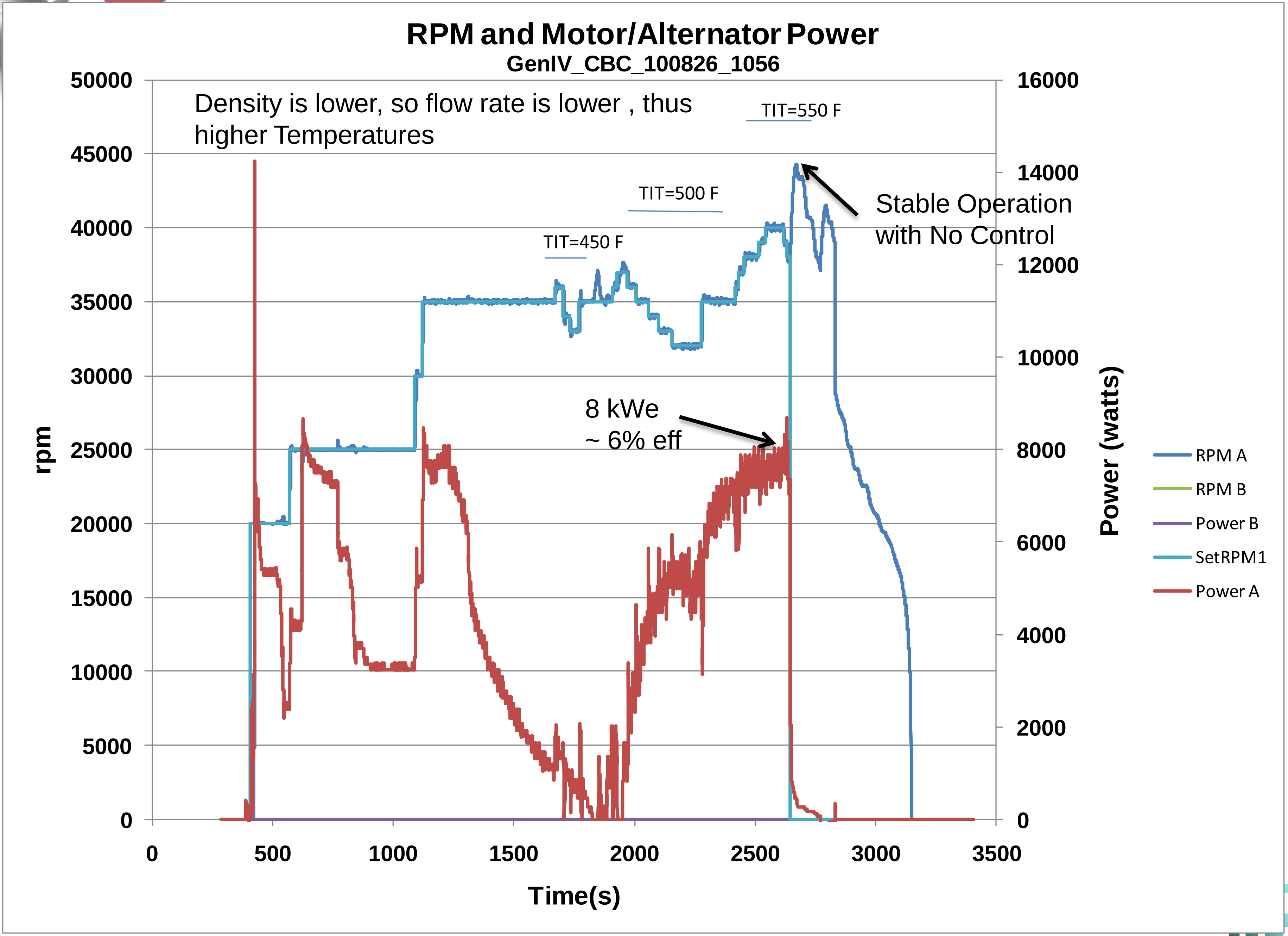
TAC-B

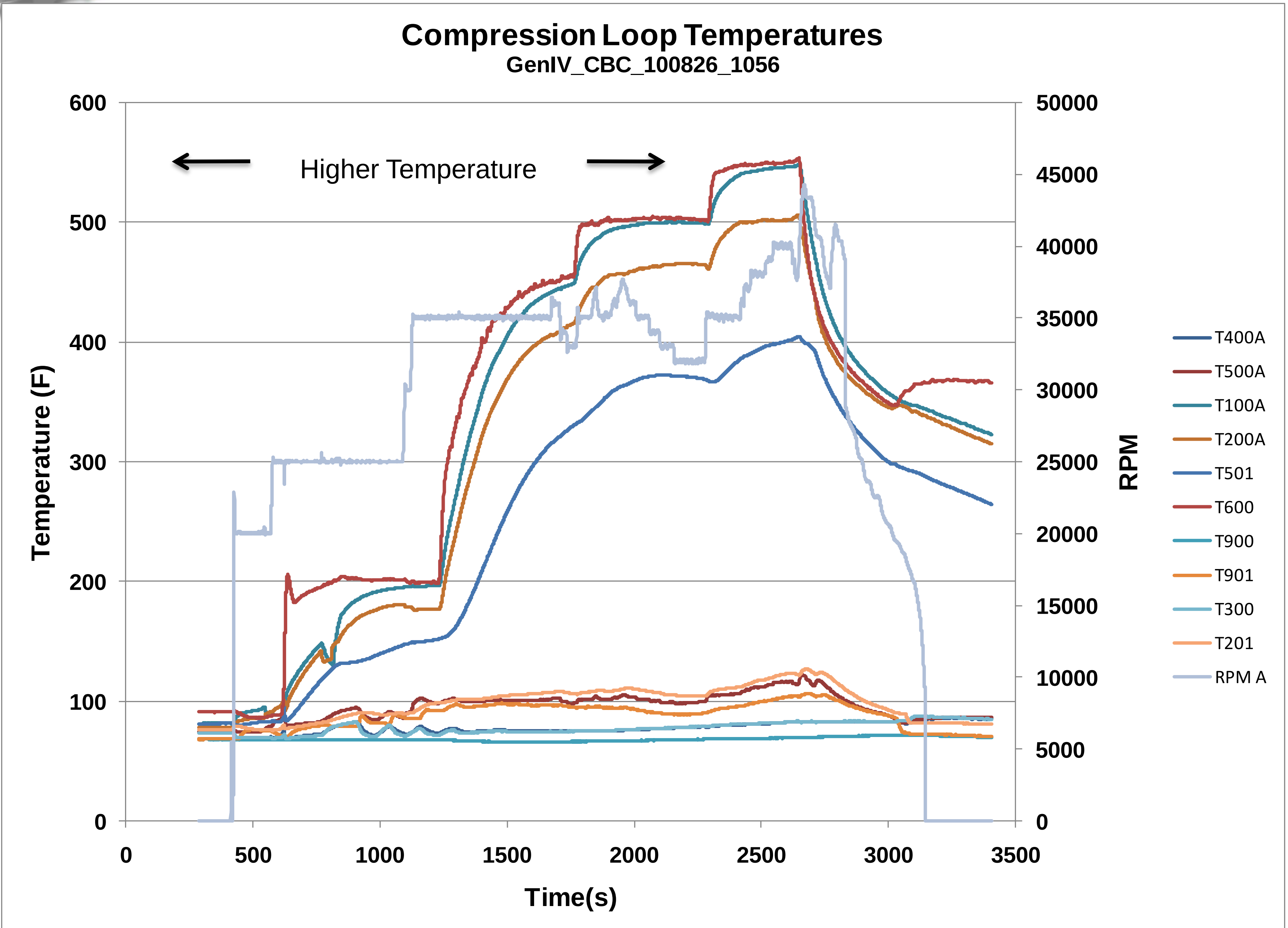


260 kW Heater
TAC - B
(not installed)
TAC - A
PCHE Recup
(up to 1.6 MW)
Flow Meters
PCHE
Gas
Chiller
(0.5 MW)
Inventory Control
Volume



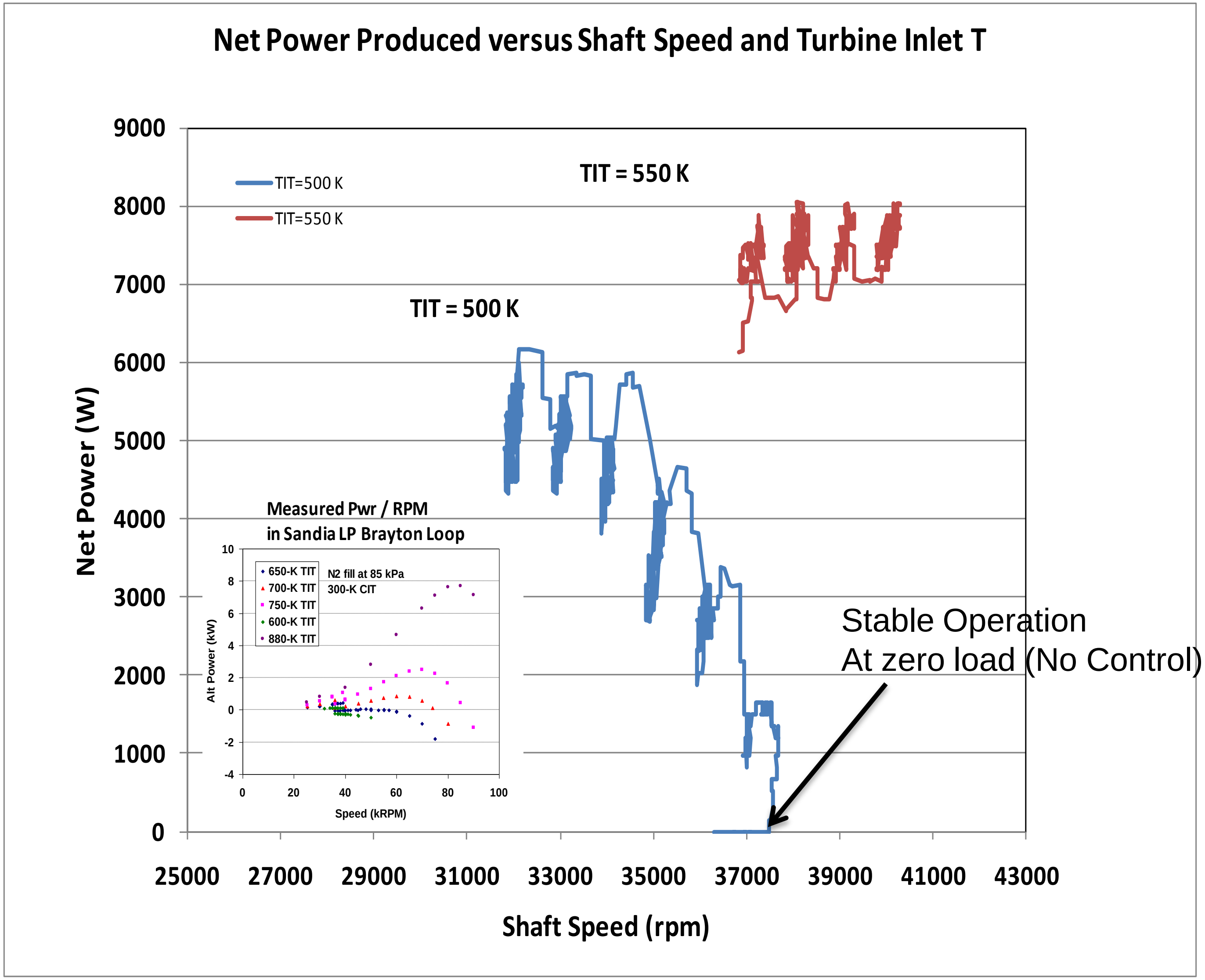
670.1 K
8817 kPa
34.42
Turbine
39000 rpm
12.66 GenPwr.Net
3.61 Wind
kw
18.14
Comp
304.0 K
6895 kPa
Heater
176.00
kw
Gas
159.73
kw
Pratio 1.29
1.574
kg/s
648.7 K
7048 kPa
323.0 K
8906 kPa
573.0 K
8817 kPa
Recup
527.50
1
kw
356.2 K
6978 kPa


RPM and Motor/Alternator Power
GenIV_CBC_100826_1056
Density is lower, so flow rate is lower , thus higher Temperatures
TIT=550 F
TIT=500 F
TIT=450 F
Stable Operation with No Control
8 kWe
~ 6% eff
rpm
Power (watts)
Time(s)
RPM A
RPM B
Power B
SetRPM1
Power A
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
16000
14000
12000
10000
8000
6000
4000
2000
0
500
1000
1500
2000
2500
3000
3500

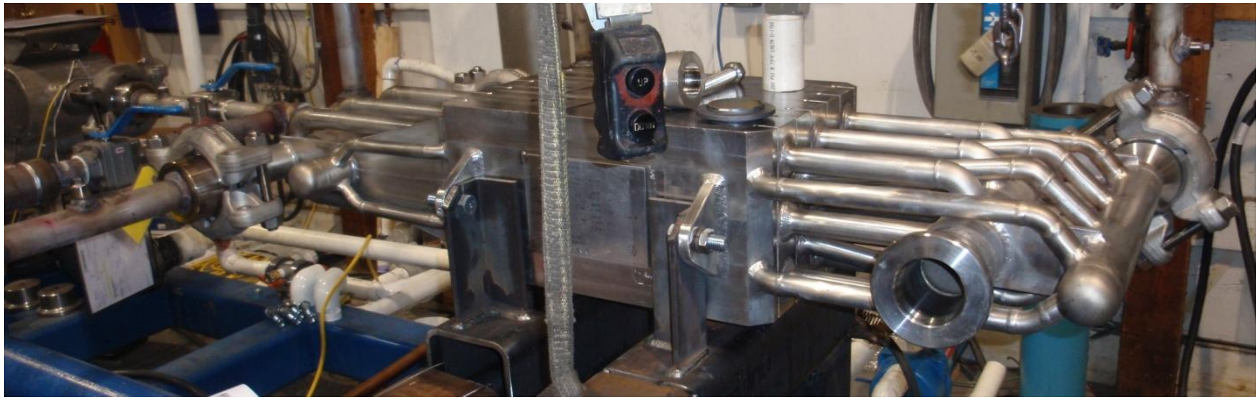


Compression Loop Temperatures
GenIV_CBC_100826_1056
Higher Temperature
Temperature (F)
RPM
Time(s)
0
100
200
300
400
500
600
0
5000
10000
15000
20000
25000
30000
35000
40000
45000
50000
0
500
1000
1500
2000
2500
3000
3500
T400A
T500A
T100A
T200A
T501
T600
T900
T901
T300
T201
RPM A

Torque/Power Versus RPM Curves
Guarantee's Stable Operations



PCHE Performance Comparisons



		Low Temperature Recuperator Performance					
		From turbine			From compressor		
+/-	P(kPa)	T(K)			T(K)	P(kPa)	+/-
41.4	7694.8	456.7			302.7	9666.8	41.37
+/-	dP(kPa)	T(K)			T(K)	dP(kPa)	+/-
58.6	91.0	367.7			308.6	140.0	58.6
	48 kPa	374 K			308.5 K	80 kPa	
	Q.rcp-HP	379.5	kW 379.7 kW	370.8	kW	Q.rcp-LP	

LT Recuperator	A.Ht & Core L / D.h
HP Leg	Heat Transfer Area 196 ft^2 0.4 m, 0.5mm
LP Leg	Heat Transfer Area 194 ft^2 0.4 m, 0.5mm

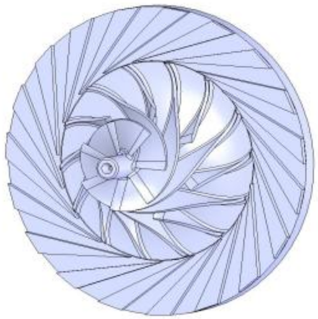
Breakeven Power Production Summary and Conclusions

- **Breakeven Power Generation in Main and Re-Compressor Turbomachines**
  - **Design Point TIT = 1000 F: 780 kW Heater Power:**
    - **Only 260 kW Installed**
    - **Just enough heater power to reach break-even conditions with 260 kW**
    - **Break-even at 350/430 F Main-TAC and Re-TAC**
    - **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 breakeven performance parameters for power, rpm and TIT.**
  - **Partial Torque/RPM Maps and Demonstration of Stable Conditions**
  - **Successful startup/preheat procedures implemented**

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
    - Condensing Cycles with Re-heat
    - Mixtures with low temperature Geo-Thermal Applications
    - Inter-cooling with higher pressure ratios (small size means easier to implement)
    - Higher Pressure systems 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 (favored by some cycles)

Turbomachinery Wheels

Main Compressor | **Re-Compressor** | **Turbine for Re-Compressor** | **Turbine for Main Compressor**




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”