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Sandia National Laboratories

Closed Brayton Cycle Research & Development

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Industry Day

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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Recompression Closed Brayton Cycle - outline

- Activities to date
  - Historical tests
  - Design recompression cycle complications, analysis, and planned resolution
  - Major program improvements and discoveries
  - Collaborative activities
- Status of the Sandia Brayton project
  - Known obstacles to achieving design operating point
  - Plans to overcome obstacles
- Planned activities to advance the project
  - Testing activities to inform the design of a demonstration system
  - Testing activities to demonstrate recompression cycle performance
    - Achieve optimal system performance
    - Model baselining and extrapolation to conditions of interest
    - Controllability

CBC Tests

- First tests with the DOE-NE funded test assembly were in the simple CBC configuration in April, 2010.
- 37 tests in the simple configuration have been completed between April 2010 and July 2011.
  - Tests operated with both main compressor and recompressor wheels.
  - Earliest of these tests used 1 recuperator and 260 kWe of heating.
  - Each compressor wheel was operated at its design conditions. This affects mass flow and temperature.
- 21 tests in the design RCBC configuration in May and July, 2010.
- 22 tests in the modified RCBC configuration between September, 2011 and September 2012.

Main compressor wheel

Recompressor wheel

Simple CBC Tests

Thermodynamics – SCO2 RCBC vs. Steam

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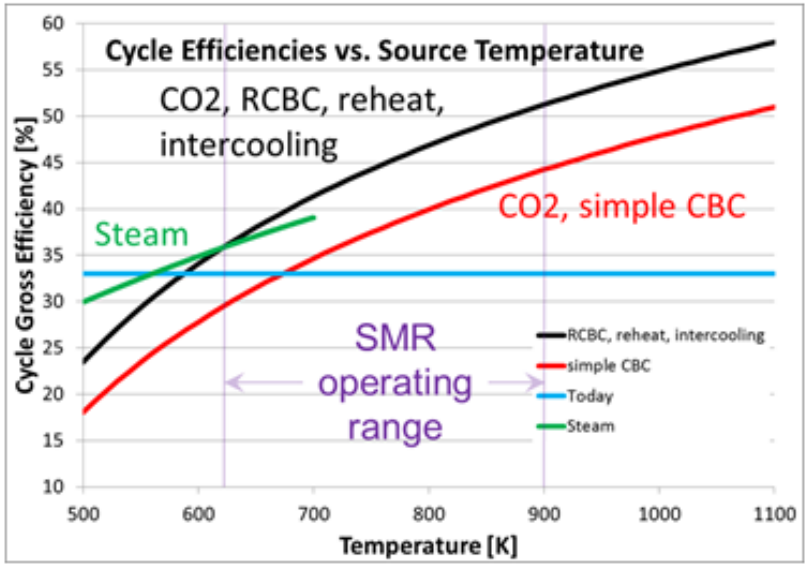
- SMR performance strongly linked to RCBCs.



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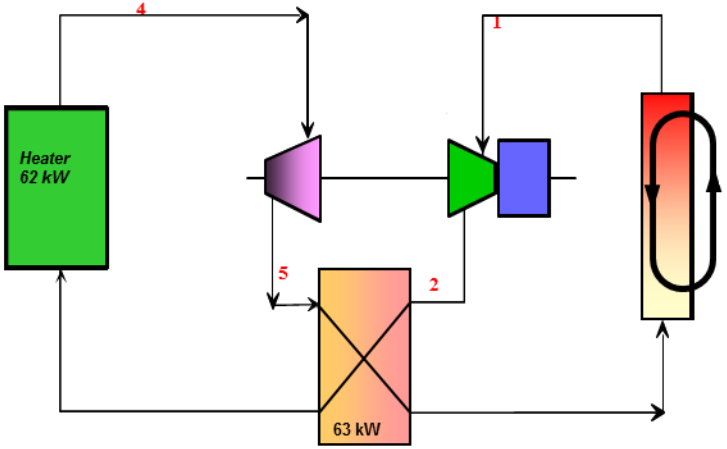
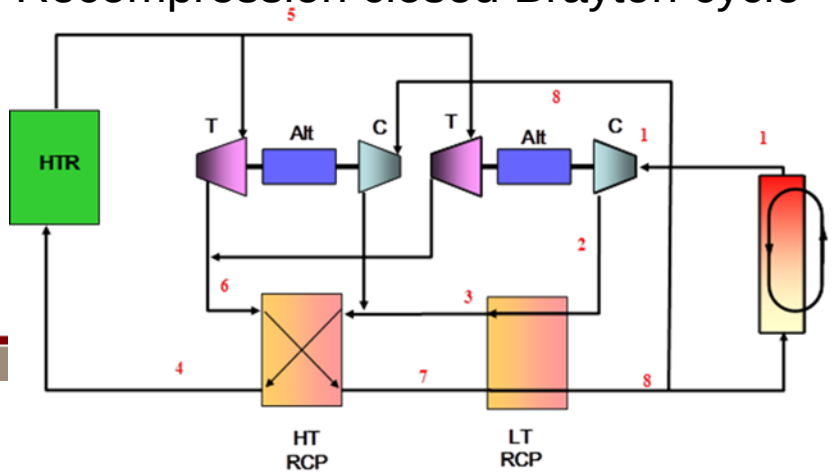
Simple closed Brayton cycle



Recompression closed Brayton cycle



RCBC Testing Summary

- Summary of modified RCBC tests to date

System prestart		120925	120918_1	120911	120906	120818	120809	120720	120719	120417	111027
Pressure	kPa	4482	5050	4844	4668	4758	4930	5488	4882	5020	4860
Temperature	K	292.2	295.0	293.1	294.4	294.2	295.6	298.5	296.1	295	291
Density	kg/m^3		139	132.7						140	138
Fill mass	kg	97.5			95.3	93.4	95.5	102.5	91.2		
Test Duration	seconds	8450	7684	8871	9210	5950	3213	7774	7610	4264	9006
Max system temperature	K	750	746	678	716	639	587.5	670	610	670/712*	642
Max system pressure	kPa	9920	10350	10375	9850	9130	8700	12100	8664	8275	10600
TAC A											
Max speed	kRPM	37	37.5	36.5	34	33	30	34	30	31	43
Max compressor pressure ratio	-	1.325	1.385	1.38	1.324	1.23	1.2	1.42	1.19	1.24	1.425
Max compressor inlet density	kg/m^3	450	480	475	475	360	350	650	397	345	425
Max power generation	kW	-9.9	-12	-12	-8.7	-2	-3.5	-14.2	-2	-2.8	-4.5
Max flow rate	kg/s	2.15	2.4	2.6	2.29	1.85	1.372	3.2	1.66	0.85	1.6
Max comp to turb dP	kPa	360	420	425	350	290	220	495	258	220	580
TAC B											
Max speed	kRPM	45	48	46.5	43	36	37	46	37	39	59
Max compressor pressure ratio	-	1.283	1.335	1.33	1.285	1.2	1.192	1.37	1.17	1.218	1.41
Max compressor inlet density	kg/m^3	240	255	245	240	230	223	271	250	205	230
Max power generation	kW	-4.2	-6.5	-5.7	-6	-1.2	2.5	-15.5	-3.5	-10**	2.2
Max flow rate	kg/s	1.08	1.21	1.16	1.05	0.9	1.21	1.44	1.12	0.86	1.3
Max comp to turb dP	kPa	150	170	180	170	80	70	170	70	70	470

Summary of RCBC findings

Parameter	Max Value/Design value
Speed, TAC A [krpm]	59/75
Turbine inlet Temp [K]	760/810
Pressure [MPa]	12.1/13.8
Pressure ratio	1.42/1.8
Power (total) [kW]	30(45)/250
Mass flow [kg/s]	4.65/5.8

Summary of RCBC findings

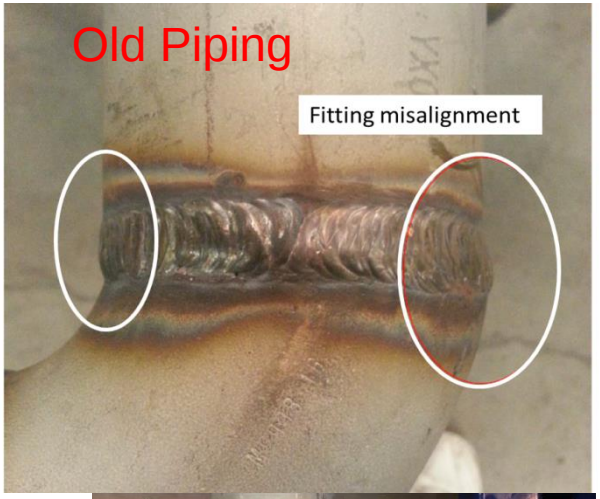
- Turbine bypass capability necessary if turbine blade tip speed is greater than fluid speed.
- Design RCBC (with main compressor and recompressor) demonstrates extremely unstable operation, with each compressor surging often.
- Modified RCBC (with the larger recompressor wheel assembly installed in the main compressor position) is significantly more stable.
- Parallel compressor operation stability is highly dependent on changes in heat rejection.
- Main compressor, and parallel compression operation, operates acceptably during two-phase inlet flow.
- The loop is stable during heat input transients.
- RCBC operation appears to be viable.

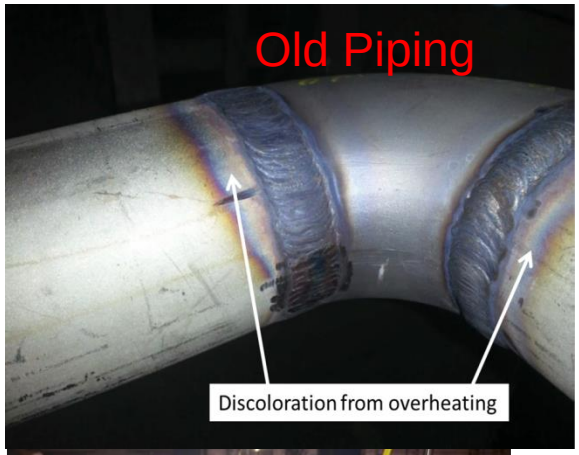
Program Advancement: 2011-Present

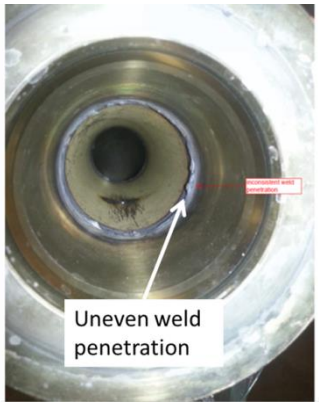
- Strategic activities to advance the Brayton program
  - Efficiency
  - Productivity
  - Capabilities
  - Quality of operations
  - Safety
  - Best practices from Space Shuttle Main Engine (SSME) program
  - Competitive positioning
  - Achieving design point

Safety

- Quality of welding by BNI raised safety concerns. B31.3 piping code required.
- New piping was ordered and welded to much more strict B31.1 code



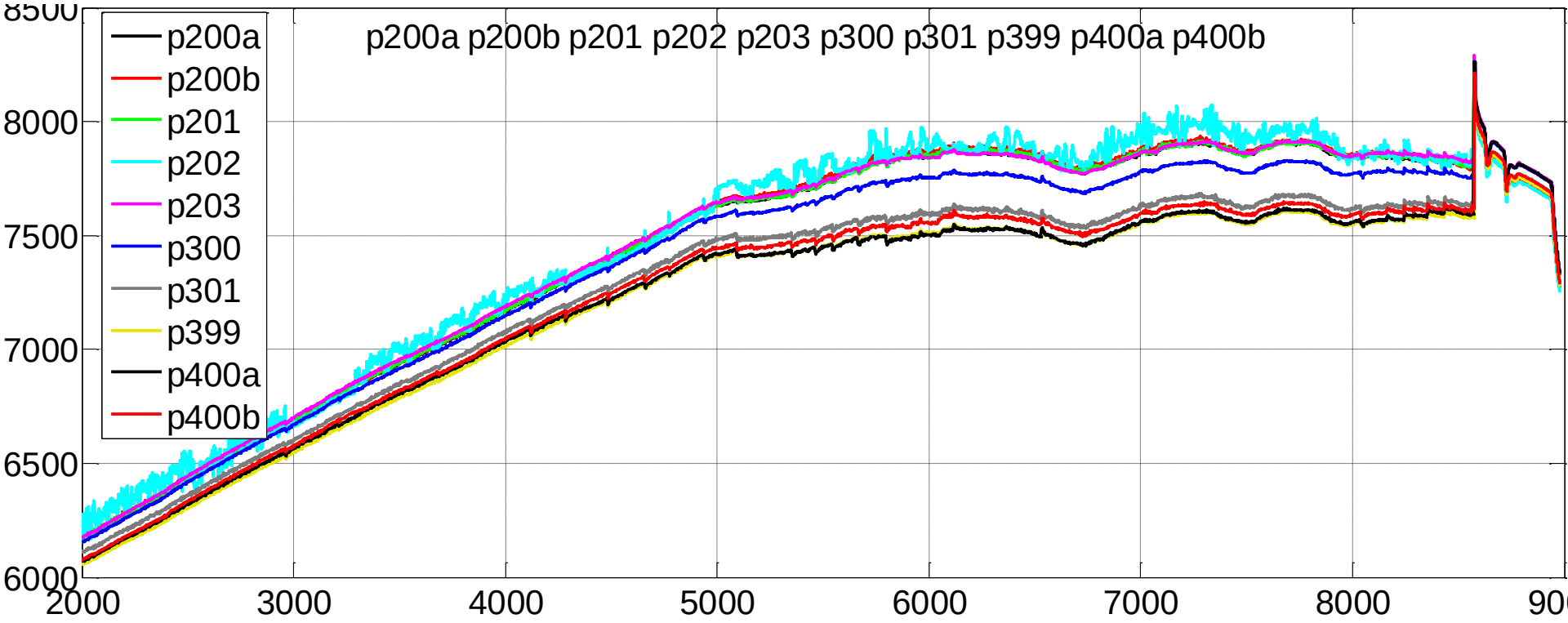




No evidence of overheating, fittings properly aligned, 3 weld passes, even penetration, no concavity

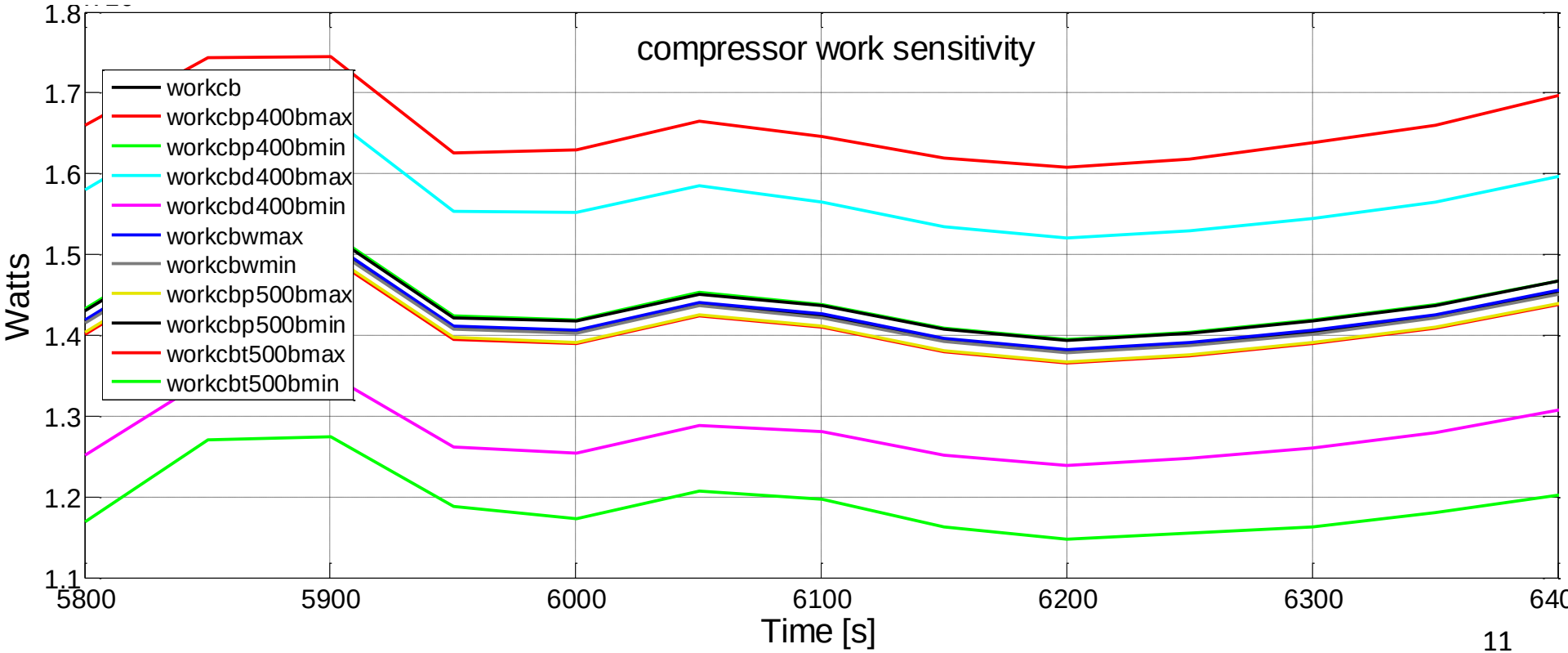
Quality of operations

- Instruments are evaluated for erroneous readings after each test.



Quality of operations

- The impact of instrumentation uncertainty is assessed for the performance of all components



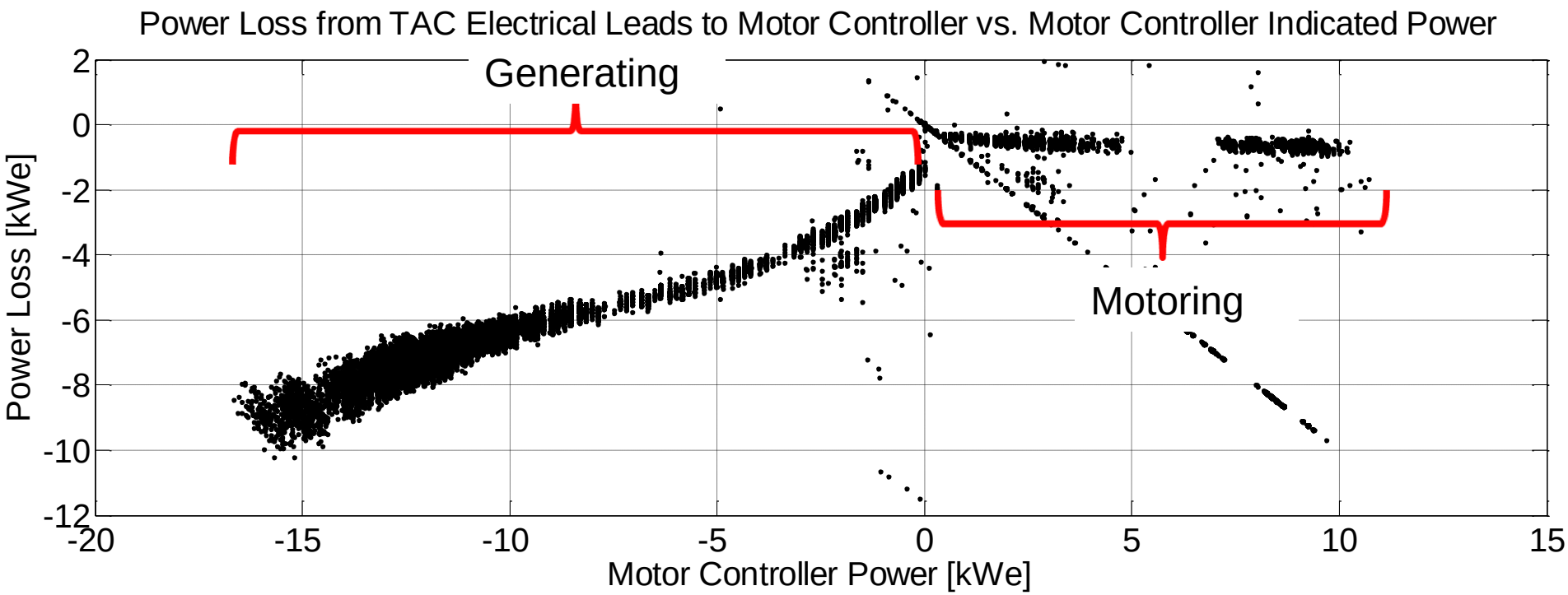
Efficiency, Productivity, Best Practices

- We have extensively implemented computer programs in LabView and Fortran to process and evaluate data.
  - In-depth data analysis
  - Greatly expedited and streamlined processing
- Data and knowledge management is a priority.
- Permanent records with extensive data analysis and observations for each test are developed maintained.
- Best practices from the SSME program implemented in the Brayton project

Achieving design point

- Old insulation was very thin, had large gaps, and exhibited signs of melting after high temperatures were attained.
- New insulation is 4” thick, and has a jacket specifically designed for these heaters and insulation.

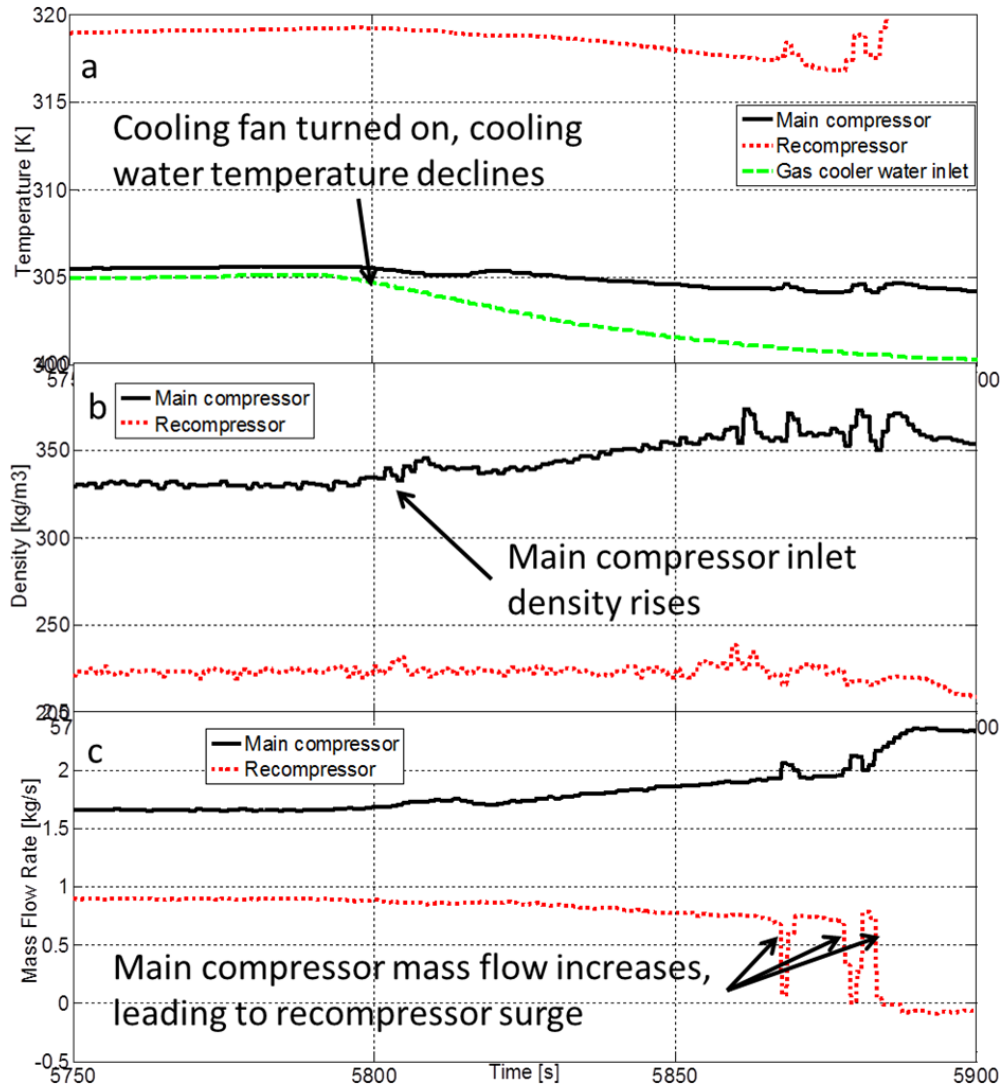
Quality of operations



Indicated power generation comparisons between the motor controller and at the TAC terminals (with the Yokogama instrument) shows that, while generating power, there is as much as 50% power loss between the TAC electrical terminals and the motor controller measurement.

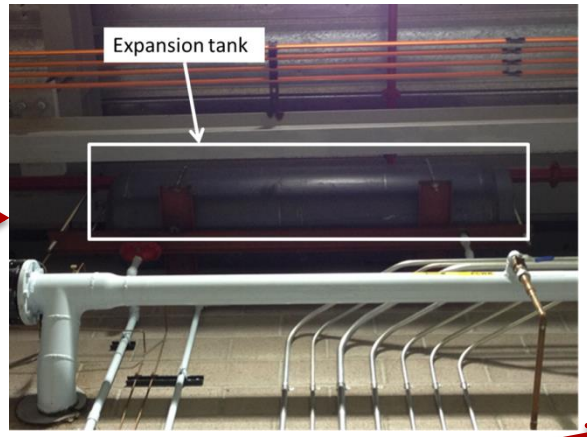
Quality of Operations

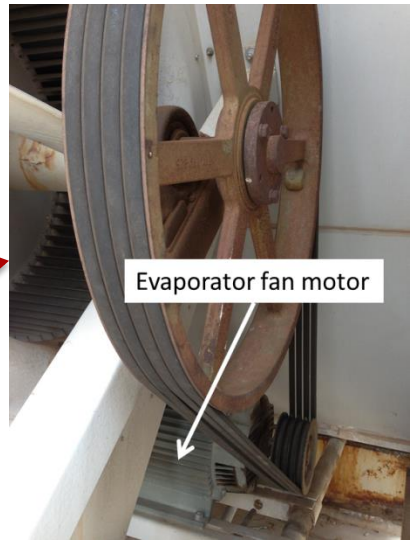
- Compressor stability is extremely sensitive to changes in cooling.
- Evaporative cooling tower had an on/off fan.
- A number of modifications improved control over heat rejection.

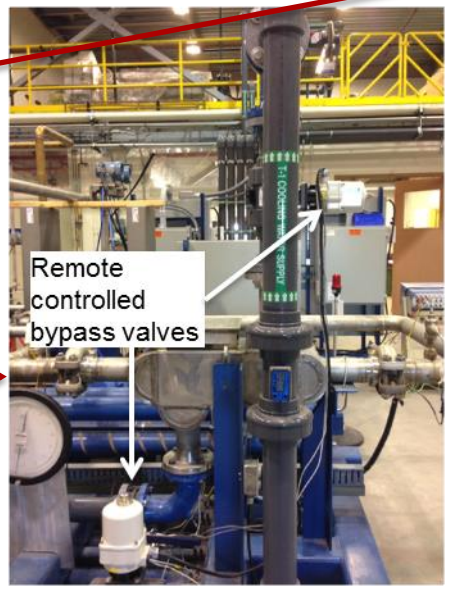


Quality of Operations

- Stiff cooling circuit risked rupturing PVC lines as cooling water heated and expanded. Expansion tank accommodates water expansion.
- Variable frequency drive installed on fan motor.
- Remote controlled bypass valves.

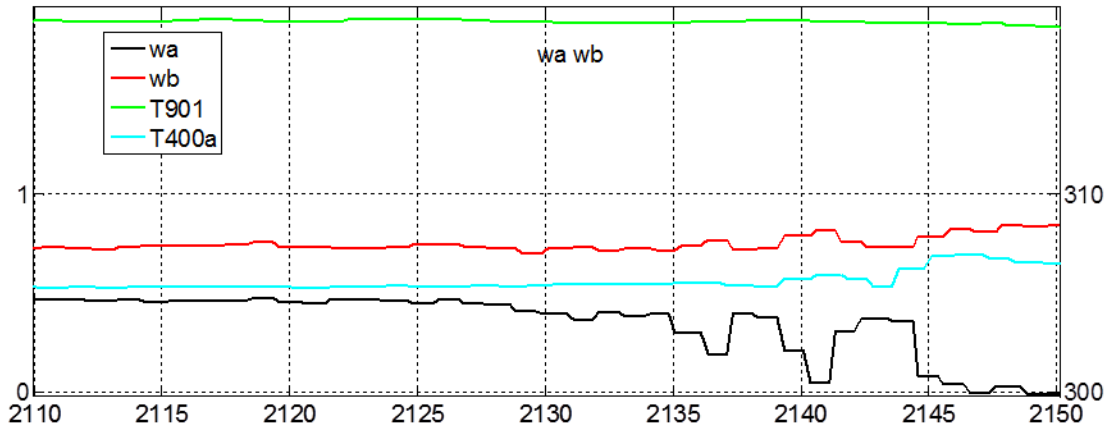




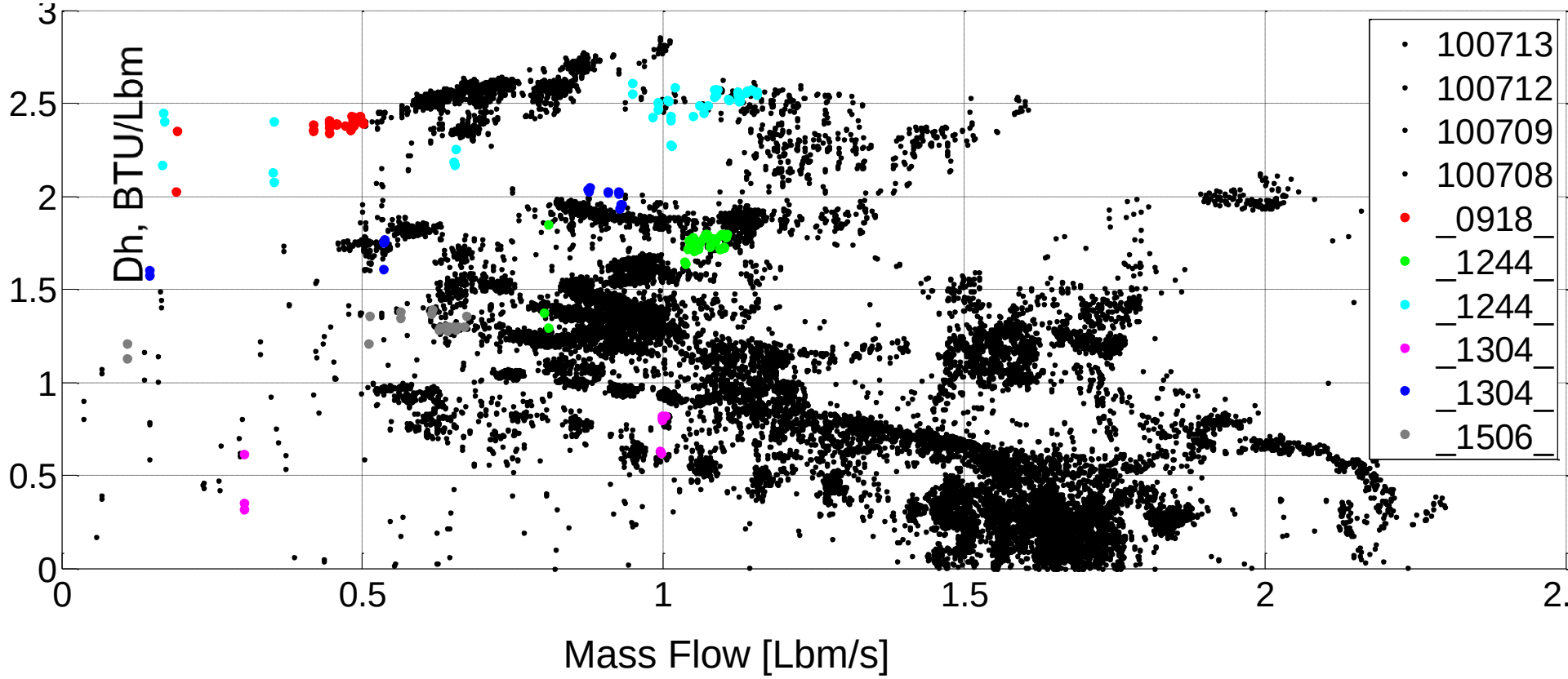


Surge Prevention

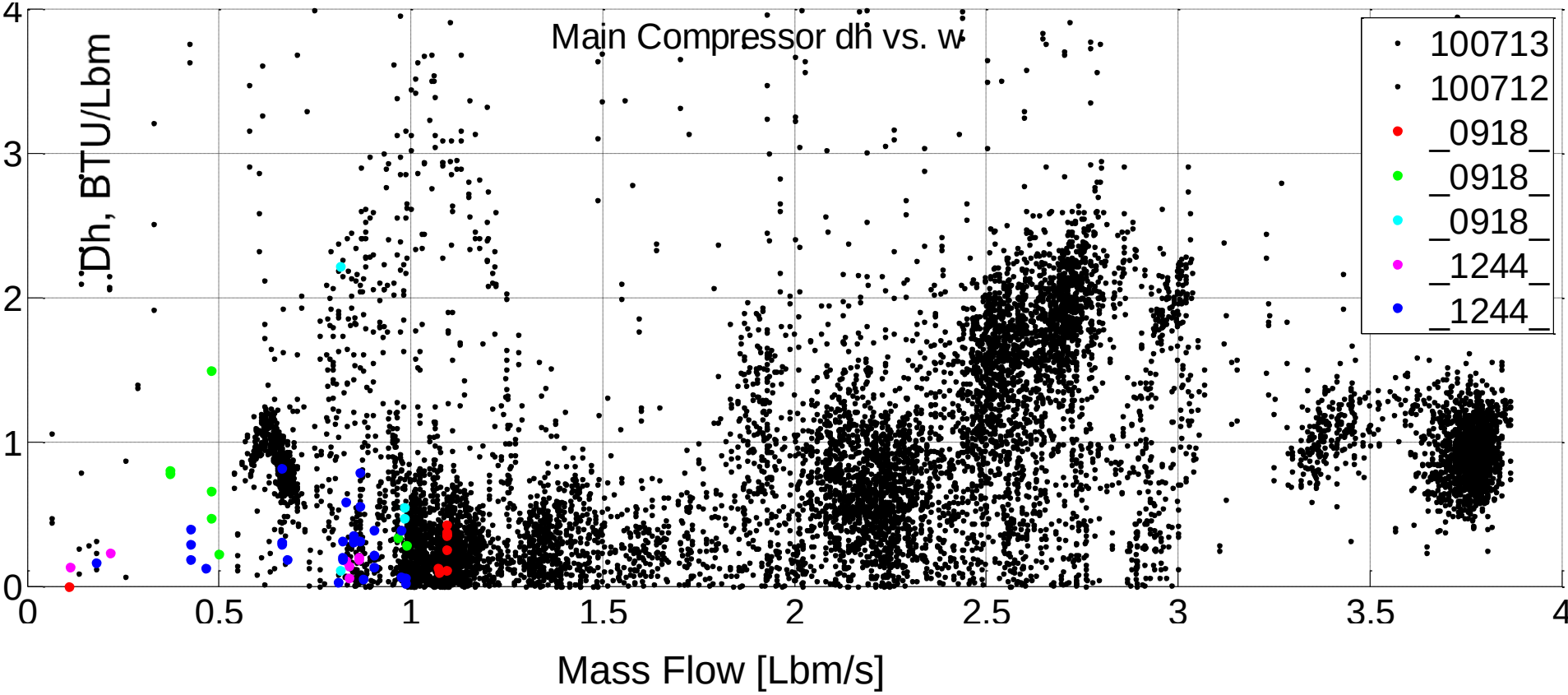
- Design RCBC tests were performed in summer of 2010.
- Main compressor and recompressor surging was common.
- Method to avoid surging not identified at the time.
- Design RCBC tests were abandoned after test 100713.
- Assessment of data from those tests revealed four tests that provide relevant insight to prevent surging.
- Thirteen surge events in both compressors were identified and thoroughly investigated to identify causes and contributing factors.



Surge Analysis: Recompressor, Uncorrected Parameters

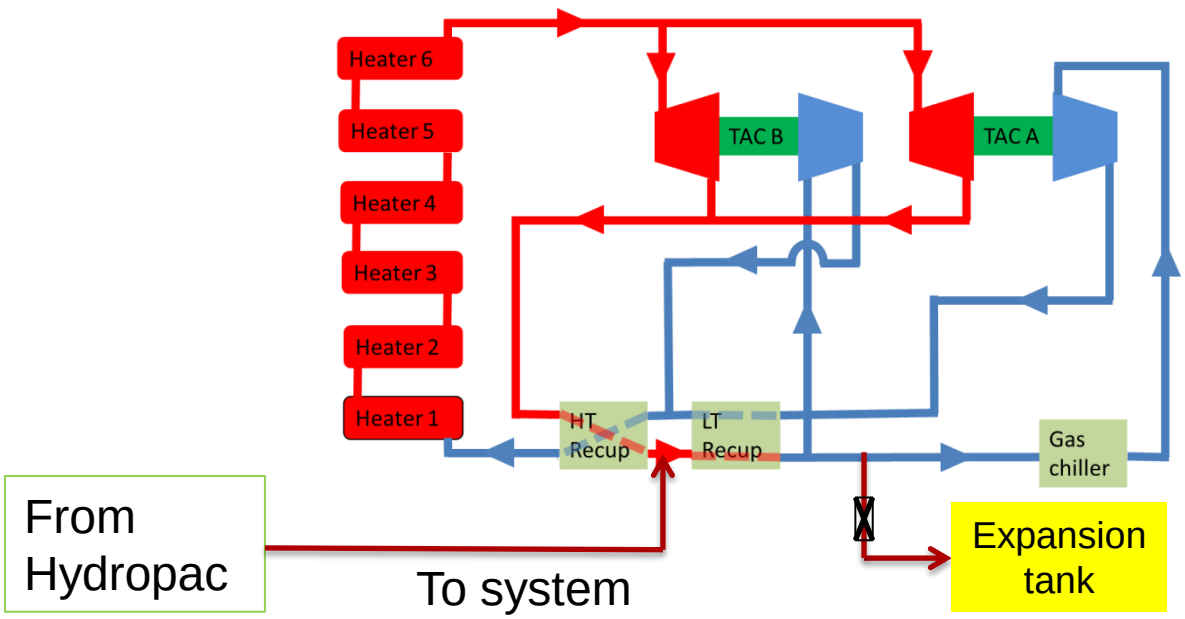


Surge Analysis: Main Compressor, Uncorrected Parameters



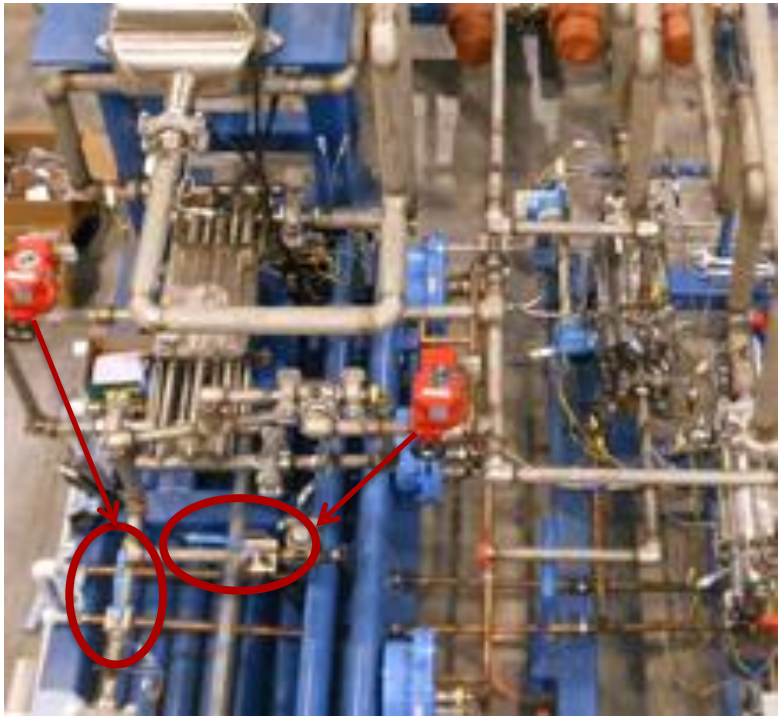
FY14 Testing Risks: surge prevention

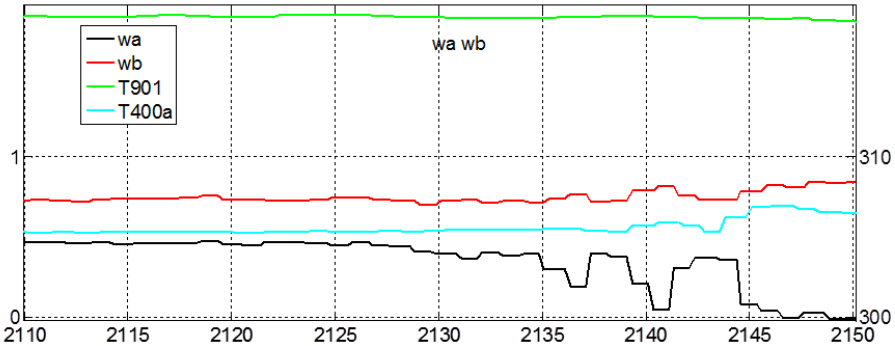
- Increase Mass Flow
  - Load the system with enough CO2 to increase mass flow early in the test
  - This procedure requires a syphon tank to remove CO2 after heating up.
  - Is also important to remove the 12 expansion tanks
    - Introduces large uncertainty in active cycle loading
    - May be introducing rust



FY14 Testing Risks: surge prevention

- Install two remote controlled valves just downstream of the flow split to the compressors to manually control mass flow split.
- Operate at conditions that generate greater margin to surge
  - None of the old RCBC tests in 2010 had positive margins to surge on compressor A.
- Install design mods to support testing at the safer conditions
  - Install large (1/2 of loop volume) syphon tank.
  - Heat CO2 prior to test start.



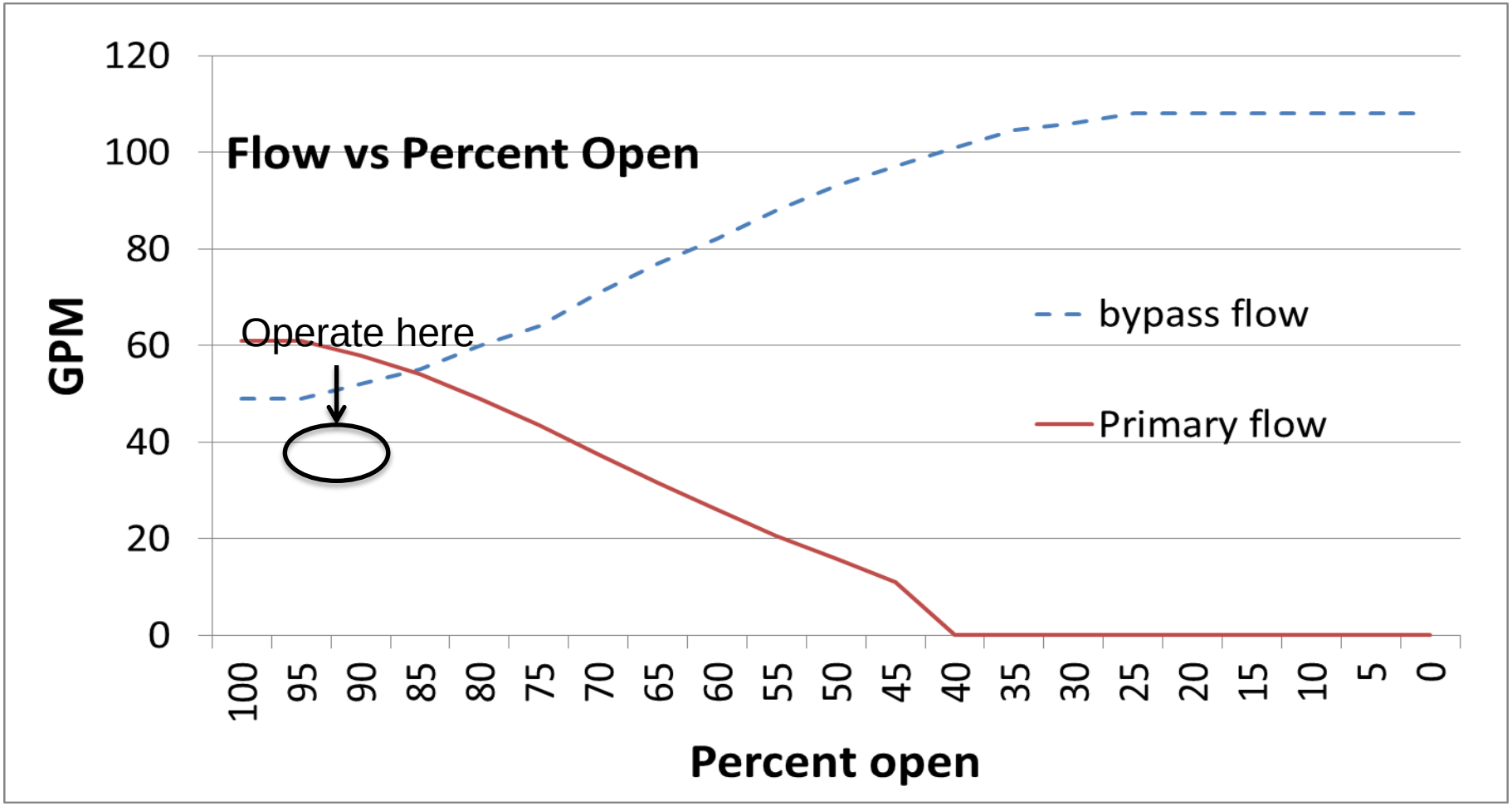


FY14 Testing Risks: surge prevention

- Install two remote controlled valves just downstream of the flow split to the compressors to manually control mass flow split.
- Need to understand the flow versus valve position characteristics to effectively implement flow control.

Surge Prevention

- Valve tests to establish control authority range

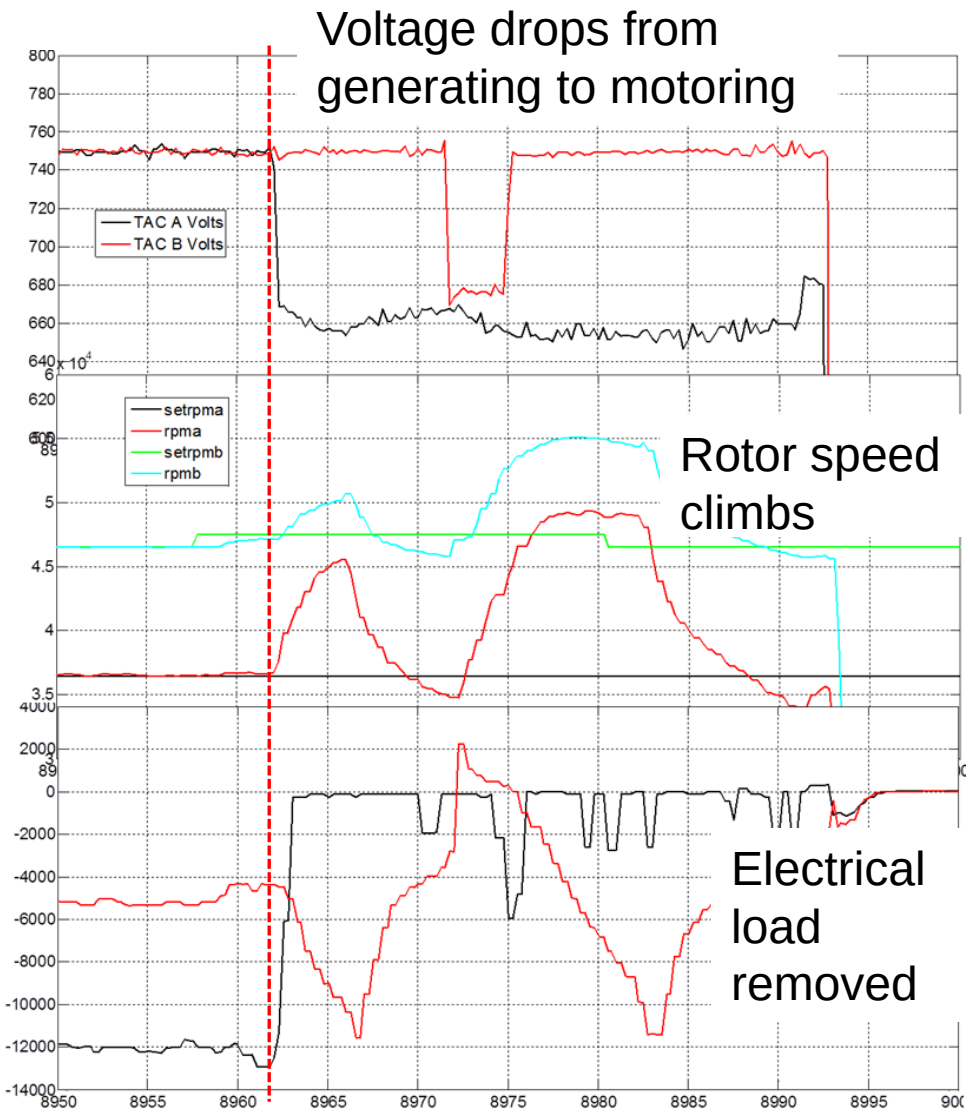


EPRI CRADA

- EPRI initiated a CRADA in summer, 2013
  - compare RCBC performance with selected cycles.
  - Perform a literature search of various relevant topics.
  - Future tasking possible
- Primary cycle comparisons were with projected Advanced Ultra Supercritical Steam cycles.
  - The basic RCBC efficiency equaled or exceeded the most complex steam cycles being considered.
  - Including one stage of reheat and compressor intercooling adds several percentage points of performance to the RCBC.
- CRADA results and final report were completed on time and delivered to the satisfaction of the CRADA partner.
- Most important results of this CRADA were
  - Application of Sandia Brayton Cycle Models
  - formation of a strong working relationship
  - recognition of our common objective to fully understand the various benefits of this technology
  - Continued sharing of information

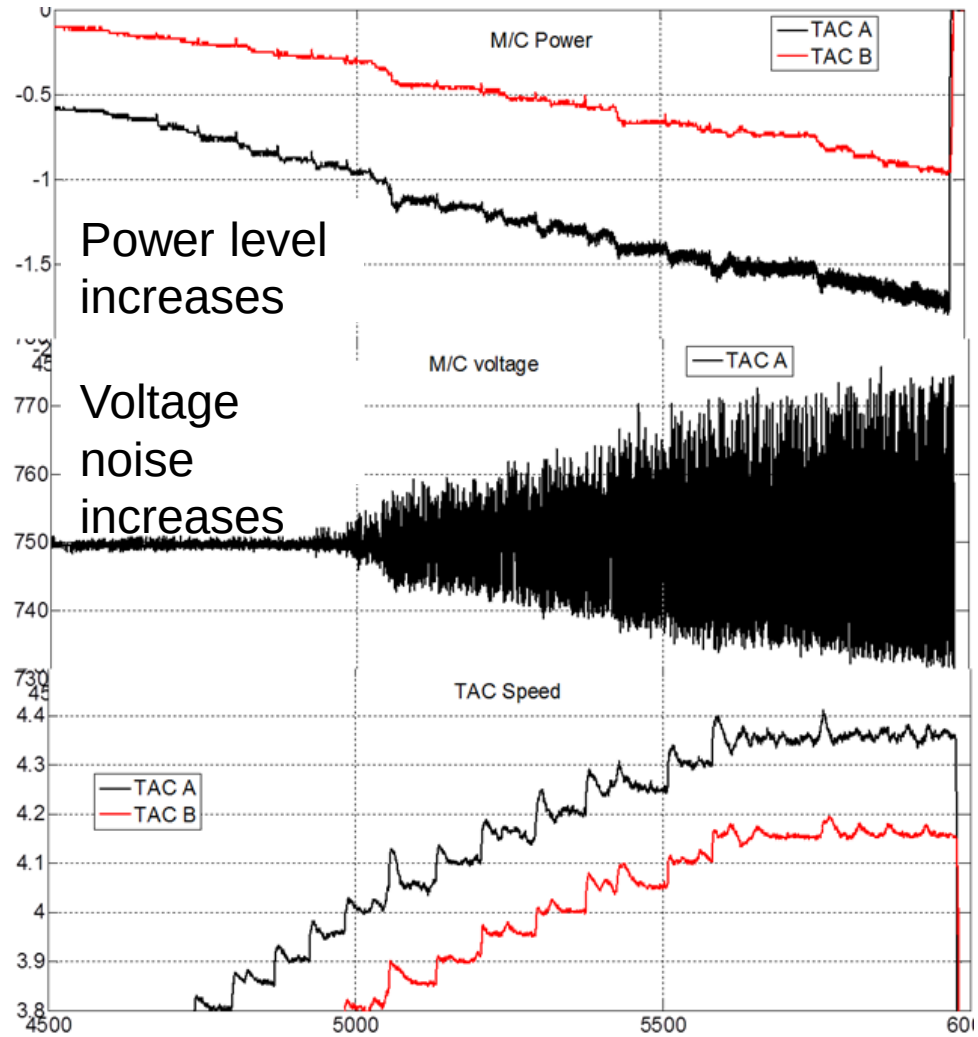
Motor Controller Issue #1

- TAC A voltage drops from generating level of 750 V down to the motoring level of 680 V.
- This causes the electrical load applied by the motor controller to TAC A to be removed, allowing the rotor to spin up to balanced power speed.



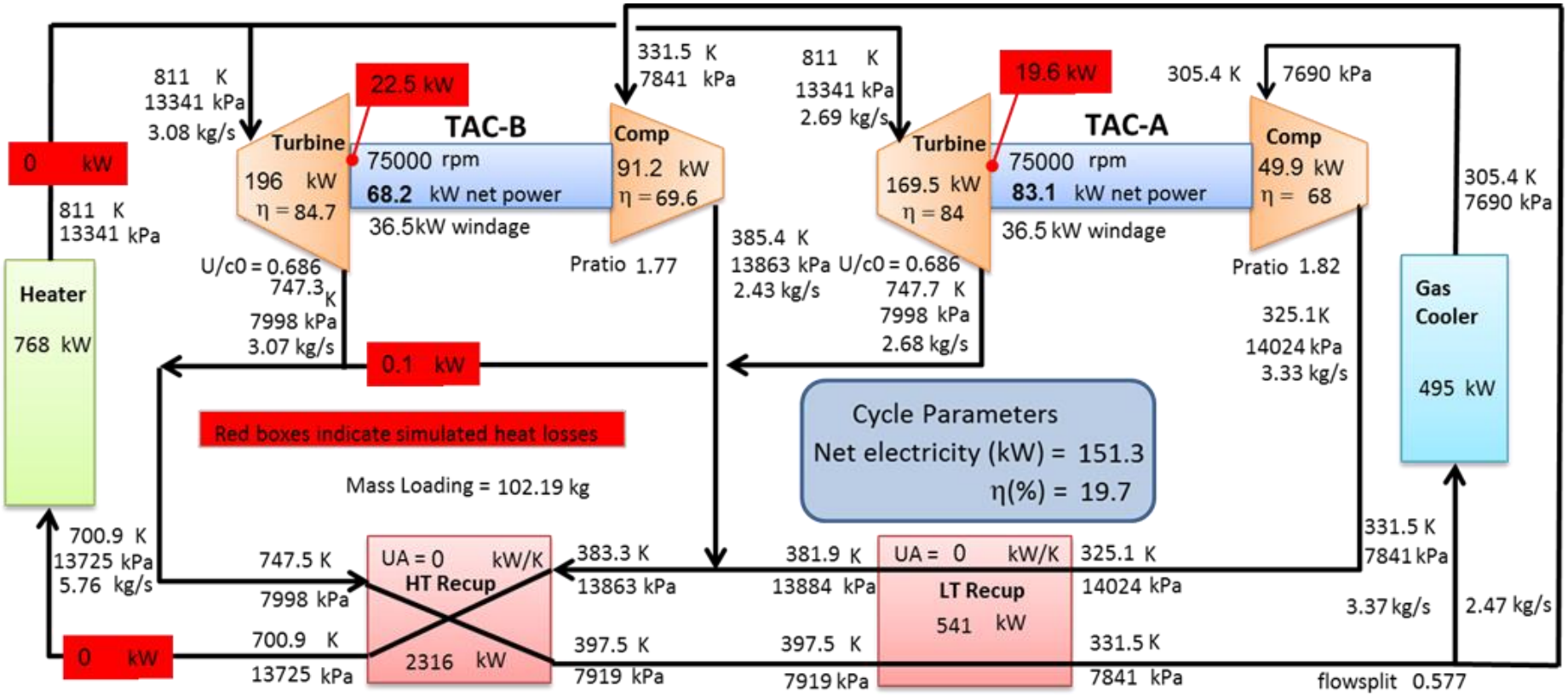
Motor Controller Issue #2

- TAC A voltage noise level increases as power generation increases.



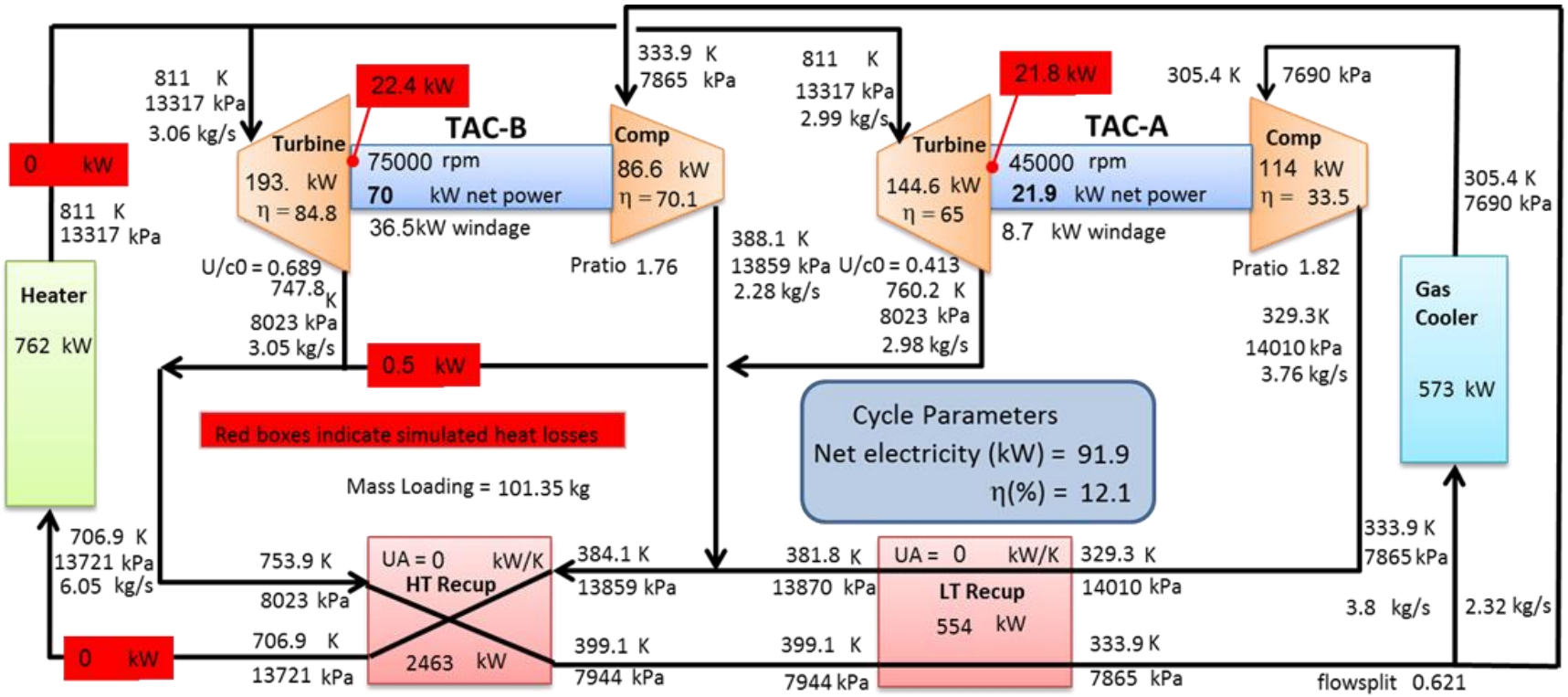
Achieving Optimum Performance

- Current best estimate of achievable power with design RCBC, at design speeds and heater power, is 151 kWe, with ~ 20% conversion efficiency.



Achieving Optimum Performance

- Current best estimate of achievable power with modified RCBC is 92 kWe, with ~ 12% conversion efficiency.



RCBC Tests - Objectives

- Demonstrate cycle performance at design conditions
- Generate data to baseline computer models of the RCBC
  - Steady state
  - Transient
- Establish robust startup, steady state, shutdown, and emergency operating procedures
- Establish optimum operating conditions as a function of boundary conditions
  - Optimum efficiency
  - Optimum stability
  - Optimum flexibility
- Investigate ancillary, but important, processes
  - Corrosion
  - Erosion

RCBC Tests - Testing Outline

- Table below is outline of RCBC tests to achieve objectives

Test series #	Objective
1	evaluate extent of performance improvement with remagged rotors
2	test new rotor position sensing mechanism
3	Achieve design point (75 krpm, 811 K TIT, 1.8 PR, 305.4 K CIT and 7.68 MPa CIP)
4	Perturb CIT from design point to establish CIT trades and system response time
5	Perturb CIP from design point to establish CIP trades and system response time
6	Perturb TIT from design point to establish TIT trades and system response time
7	Perturb individual TAC speeds from design point to establish mass flow split trades and system response time
8	Establish optimum operating point for dry cooling conditions (321 K CIT)
9	Perturb CIT from optimum dry cooling point to establish CIT trades and system response time
10	Perturb CIP from optimum dry cooling point to establish CIP trades and system response time
11	Perturb TIT from optimum dry cooling point to establish TIT trades and system response time
12	Perturb individual TAC speeds from optimum dry cooling point to establish mass flow split trades and system response time
13	Investigate safe startup and shutdown margins as a function of control parameters
14	investigate system response to input power transients (reactor transients)
15	investigate system response to various accident scenarios
16	investigate effects of working fluid additives

Achieving Optimum Operating Point

- Test assembly design modifications are being implemented, guided by
  - Review of 2010 design RCBC data guiding surge prevention techniques
  - Review of recent test data showing various losses and operational control limitations
- If stability with design RCBC remains an issue, consider continued testing in the modified RCBC configuration.
- Keep focused on objectives
  - Justifying investment in a demonstration system
  - Informing the design and operation of the demonstration system