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Milestone Report

RCBC Automatic Monitoring and Control Recommendations

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RCBC Automatic Monitoring and Control Recommendations

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Abstract

The recompression closed Brayton cycle (RCBC) test rig at the Sandia Brayton Laboratory provides a development platform to accelerate the commercialization of key technologies for supercritical CO_2 (sCO_2) closed loop Brayton cycles. The test rig enables testing to gain experience and confidence with new technologies, equipment, and processes, and automating monitors and controls will enhance Sandia's ability to perform the types and amounts of testing needed. This report identifies candidates for automatic monitoring and control to ensure the loop remains within design limits and minimize risk to equipment due to off-normal events or conditions.

Contents

Nomenclature

AC	alternating current
CBC	closed Brayton cycle
DOE	Department of Energy
HTR	high temperature recuperator
KEB	KEB America, Inc.
LTR	low temperature recuperator
PE	power electronics
PID	proportional-integral-derivative
PMG	permanent magnet generator
RCBC	recompression closed Brayton cycle
sCO_2	supercritical carbon dioxide
SNL	Sandia National Laboratories
TAC	turbo-alternator-compressor

Introduction

Sandia's Recompression Closed Brayton Cycle (RCBC) test rig at the Brayton Laboratory has been developed to provide leading-edge development of technologies required for commercialization of the closed Brayton cycle (CBC) for power generation using supercritical carbon dioxide (sCO_2). The closed Brayton cycle with sCO_2 offers potential advantages including high thermodynamic efficiencies, small physical footprint, dry cooling, and potentially lower capital costs than traditional cycles such as the Rankine cycle.

We have identified near-term and longer-term steps to improving robustness and efficiency of Sandia's RCBC operations/performance through improved automation of monitoring and controls. Specific recommendations include adding the ability for two currently independent LabView monitoring and control systems to communicate with each other, automated monitoring of design limit conditions with warning lights and emergency shutdown, and trend monitoring for predictive maintenance and avoidance of catastrophic failures.

Overview of Sandia's RCBC Test Loop

The RCBC test loop at Sandia National Laboratories' Brayton Lab has been designed to demonstrate CBC and RCBC performance, prove and mature technologies for power generation using sCO_2 Brayton cycles, and provide industry with the confidence to further develop CBC technologies for commercial power generation. Primary elements of the loop consist of one or two turbo-alternator-compressors (TACs; one if running a simple CBC and two if running RCBC), a heater for preconditioning the loop and maintaining the sCO_2 turbine inlet temperature, a cooler for returning the cycle to sCO_2 inlet conditions at the main compressor, and two recuperators[1] to reduce the required heating and cooling. This is achieved by transferring heat from the hot low-pressure side to the cooler high-pressure side. In the RCBC cycle, the two compressor streams merge between the recuperators. Schematic sketches of the main loop in simple CBC and RCBC modes are shown in Figure 1.

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[1] Sandia's existing test rig uses two recuperators in both the simple CBC and RCBC modes. In principle, only one recuperator is required for a simple CBC loop.

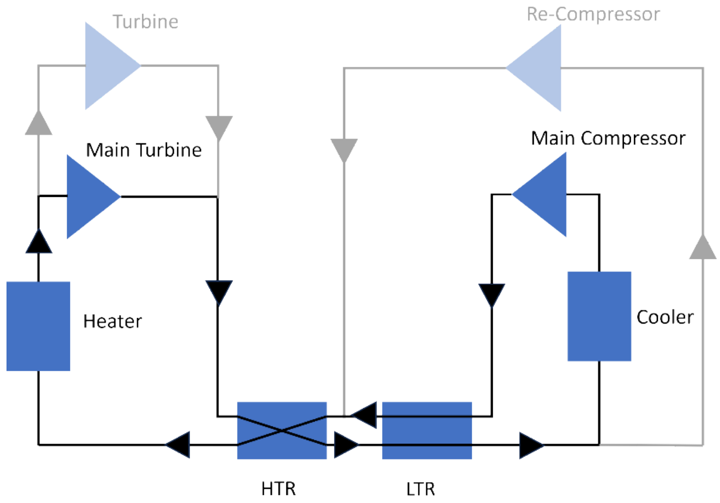


Figure 1: Simplified process diagram for an RCBC system. The light blue equipment, gray flow lines, and gray text indicates hardware required for a recompression cycle that is not required for a simple recuperated CBC. Note: the high temperature recuperator (HTR) and low temperature recuperator (LTR) can be replaced by a single recuperator when running a simple recuperated CBC.

Power conversion is performed by KEB power electronics (PE). The PE converts the permanent magnet generator (PMG) output, which is AC power at a frequency that depends on the shaft speed, to a frequency suitable for connecting to the grid. The PE controllers are capable of moving power in both directions, either providing power to the TAC for motoring, or back to the grid when generating. The KEB PE also controls the shaft speed in Sandia's test rig by varying the motoring power or load applied to the TACs.

Operating a CBC loop also requires auxiliary systems not shown in the simplified sketches of Figure 1.Auxiliary systems include a Hydro-Pac pump to reduce pressure in the alternator cavity or cavities and return it back to the cycle, a CO_2 supply system for the porous media bearings at the turbine and compressor ends of each TAC, a heat rejection system for the primary cooling water, and an auxiliary water cooling system for equipment in the loop.

Existing Control System Description

A control system has several key elements:

- Provide control interface for manual monitoring and operation
- Starting to idle
- Maintaining a steady set point
- Orderly change between set points
- Provide levels of warnings for limits (amber, red)
- Automated shut down for safety violation
- Shutdown and Emergency Stop
- Data capture for post-test analysis
- Key parameter trending for health monitoring
- Data fast capture for 30 seconds prior to an unplanned shutdown (automated or manual)

Control operation of Sandia’s RCBC loop is provided by a “man-in-the loop” control system with only the heating and cooling subsystems automated to control the turbine inlet temperature and compressor inlet temperature respectively. The overall control system consists of two independent LabView systems. The primary LabView system provides a control panel for sCO_2 valves throughout the system, heater power, and the primary cooling system; this system records these parameters along with temperatures and pressures and more at locations throughout the RCBC loop at approximately 17 Hz. The secondary LabView system provides a control panel for the KEB motor controller; this system also monitors and records power flows and related parameters and temperatures in the TACs at approximately 9 Hz. These two LabView systems currently do not communicate with each other.

The primary LabView system control panel provides the interface for the heaters, cooler, and flow split for the test article (Figure 2; note that although a recompression TAC is shown, the system is not currently set up to run RCBC). The temperatures and pressures at various locations around the loop are relevant for performance monitoring as well as monitoring system limits on the loop piping and equipment. The “SNL immersion heaters” are controllable by user-specified percentage of full power, with the option for PID control based on a user-specified outlet temperature. The “SNL cooler” is a sCO_2 to water heat exchanger. Cooling is controlled primarily by two valves on the cooling water loop, and secondarily by the fan speed on the cooling system for rejecting heat from the cooling water. The cooling water valves are controlled by user-specified percent open, with the option for PID control based on a user-specified compressor inlet temperature; the fan speed is controlled by user-specified percentage of full speed. The “SNL HTR” high-temperature recuperator and “SNL LTR” low-temperature recuperator simply exchange heat between low-temperature and high-temperature sCO_2 flow streams based on first-principles physics. The primary valves in the main loop are the recompression valve “RC Valve” (not currently controllable because we are not currently running the second TAC for RCBC) which controls the flow split between the main compressor and the recompressor, turbine control valve “TCV” which allows us to adjust turbine exit back pressure. Valve “BV6” on the main loop line is open during normal operations but can be closed during preconditioning.

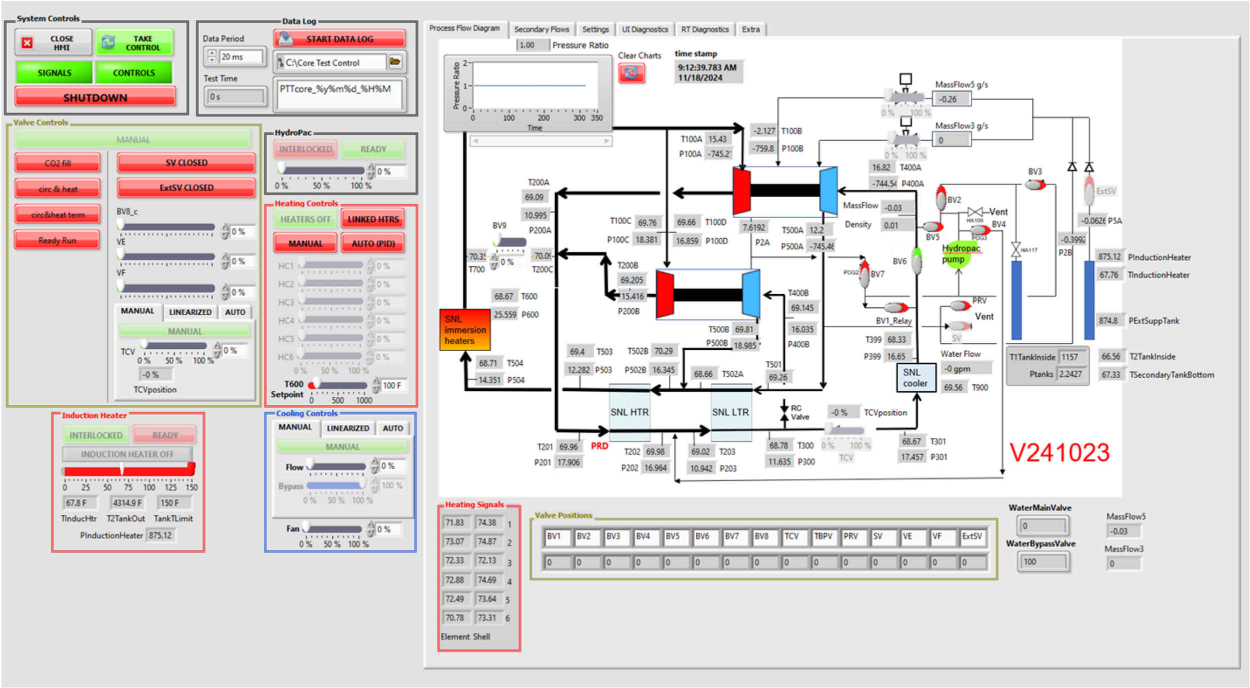
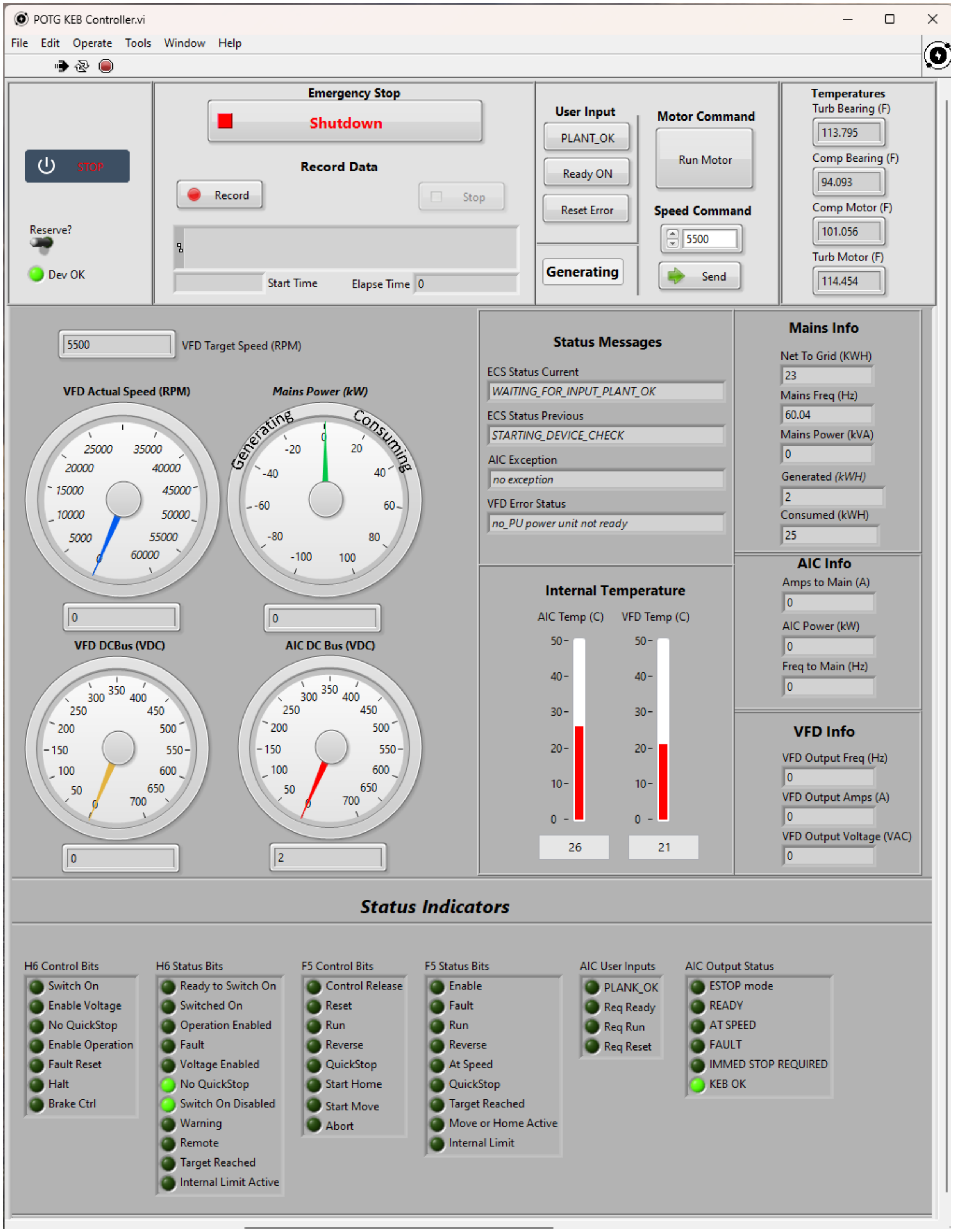


Figure 2: Primary LabView control panel (current as of early December 2024).

The primary LabView control panel also provides the interface for the porous media sCO_2 bearings and the Hydro-Pac pump. The “VE” and “VF” valves for the primary TAC porous media sCO_2 bearings are controlled by user-specified percent of fully open; the “ExtSV” valve is open while running the bearings to supply CO_2 from tanks if pressure from the cycle is insufficient. The primary purpose of the Hydro-Pac pump is to scavenge sCO_2 from the TAC PMG cavities to reduce windage losses, and repressurize to replenish the cycle. This is accomplished by pulling through valve “BV7” through the Hydro-Pac, returning the sCO_2 to the loop through “BV4.” Note: The Hydro-Pac is also used to circulate CO_2 through the system to precondition the loop. This is accomplished by pulling through valve “BV1” through the Hydro-Pac, returning the CO_2 to the loop through “BV5,” with “BV6” closed to force flow to go the long way around the loop. Valves “BV1” through “BV7” and “ExtSV” are either fully open or fully closed.

The secondary LabView control panel for the KEB controller is shown in Figure 3. The main function of the KEB controller is to maintain a user-specified shaft speed. If the thermodynamics of the loop are insufficient to maintain this shaft speed, the control supplies power from the grid to motor the shaft to maintain the specified speed. The KEB controller extracts power from the alternator and supplies it back to the grid when the thermodynamics of the loop dictate that the power extracted by the turbine is greater than the power required by the compressor. Parameters relevant to the electrical power generation are monitored and recorded with this LabView system, along with temperatures in the TACs near the bearings and the stator windings.



Start Time
Elapse Time 0

Speed Command 5500

Temperatures
Turb Bearing (F) 113.795
Comp Bearing (F) 94.093
Comp Motor (F) 101.056
Turb Motor (F) 114.454

VFD Target Speed (RPM) 5500
VFD Actual Speed (RPM) 0
Mains Power (kW) 0
VFD DCBus (VDC) 0
AIC DC Bus (VDC) 2

Status Messages
ECS Status Current WAITING_FOR_INPUT_PLANT_OK
ECS Status Previous STARTING_DEVICE_CHECK
AIC Exception no exception
VFD Error Status no_PU power unit not ready

Internal Temperature
AIC Temp (C) 26
VFD Temp (C) 21

Mains Info
Net To Grid (KWH) 23
Mains Freq (Hz) 60.04
Mains Power (kVA) 0
Generated (kWH) 2
Consumed (kWH) 25

AIC Info
Amps to Main (A) 0
AIC Power (kW) 0
Freq to Main (Hz) 0

VFD Info
VFD Output Freq (Hz) 0
VFD Output Amps (A) 0
VFD Output Voltage (VAC) 0

Figure 3: Secondary LabView control panel for the KEB controller (current as of early December 2024).

The sCO_2 test loop performance may at times depend on devices that are not remotely controllable. These include the auxiliary cooling water pump and cooling system, the pump for the primary cooling water, water flow for cooling water that cools the primary cooling water in the EVAPCO coolers outside on the north side of the building, and manual valves on the secondary sCO_2 lines and auxiliary cooling water lines. These inputs are set prior to the test, and do not typically require adjustments during a test. These inputs are not discussed further in this report.

Desired Monitoring and Control Functionality Improvements

The functionality of the RCBC test loop control system can be improved by automating monitoring and control. Parameters to monitor fall into several categories: Safety, Operation, and Degradation. Automatic monitoring is to ensure:

- Design limits of the system are not exceeded
- Achieve desired response of the test article
- Warn of performance degradation

Responses include providing one or two levels of warnings to operators, followed by automatic intervention in select instances to maintain conditions within design limits. Automatic intervention will require communication between the two LabView systems that are currently independent, because criteria for automatic shutdown may be determined from data collected on either system, and because the automated shutdown procedure will involve control inputs on both systems. Warnings will be communicated through warning lights: green if good; amber or red if an undesirable condition would be reached within a specified time period based on current readings and rates (two levels based on the predicted time to reach the condition). Automated shutdowns could be prescribed differently depending upon the issue triggering the shutdown, but would typically involve stopping the TAC shaft, cutting heater power, and configuring valves for shutdown. A list of recommended issues to monitor and control is provided in Appendix A. A list of control inputs is provided in Appendix B.

The control system currently implements one automatic control feature, which is that it monitors the pressure near the Hydro-Pac pump and closes (and locks out) valves on the secondary lines to the Hydro-Pac if a threshold pressure is exceeded. This prevents the pressure in the Hydro-Pac exceeding its design limit of 1500 psi, which is much lower than the maximum pressures in the RCBC loop.

TAC Warning key parameters:

- Turbine inlet temperature
- Temperature ramp rate (relative to limits)
- High Temperature Recuperator Inlet Temperature
- Compressor delivery over-pressure
- Compressor inlet temperature low (2-phase onset)
- Inlet temperature ramp rate (relative to limit)

TAC Auto shut down parameters:

- Exceeds Turbine inlet temperature
- Rate of Turbine inlet temperature increase in proximity to limit
- Exceeds High Temperature Recuperator Inlet Temperature
- Rate of High Temperature Recuperator Inlet Temperature increase in proximity to limit
- Exceeds Compressor delivery over-pressure
- Exceeds rotor speed limit

The KEB controller has its own set of shutdown and monitoring parameters, including on an over current or over temperature limit. Temperature and current are monitored and displayed on the secondary LabView controller system. Enabling communication between the primary and secondary LabView systems would enable automated warnings if these conditions are being approached, and automatic shutdown of the loop through the primary LabView controller if a shutdown condition is triggered in the KEB controller.

The automated monitoring for failure events can be very complex. Some are known and can be implemented because root causes are obvious or established by prior analysis. Others, as new components and test conditions change, are unknown. Thus, the control system is a living document, requiring updates as new lessons are learned. We recommend starting with automating responses to issues as highlighted in this section (see Appendix A for a more complete list of issues and responses). Additional responses to potential equipment or instrumentation failures can be implemented in the future based on lessons learned in additional testing.

Other Considerations

Besides developing CBC cycle control protocols and exploring different and sometimes novel methods, the TACs are used for component development. Bearings and seals are critical components which require further test and validation prior to use in commercial technology, but there may be others. Therefore, it is critical to be able to modify the control system to accommodate instrumentation that will permit these variations and provide the level of detail to protect and validate these components.

One very important aspect that must be investigated is the PMG cavity pressure. Lowering the cavity CO_2 pressure reduces the drag losses on the rotor system, but adds another energy input (the Hydro-Pac pump), which should also be accounted for in the total round trip cycle efficiency. Having instrumentation, and being able to control the main parameters effecting this relationship is critical.

Developing a control system for a test engine is very different than with a commercial engine in that its operational control parameters are being developed and how it behaves and speed of response have to be learned. Changes to improve the monitoring, protection, and operation have to be implemented virtually on the fly, or in successive tests. It is not critical to have complex algorithms to initially control the cycle, with large safety margins finesse is not as important as testing, and these can later be refined. It is more important that the control system is developed and improved with each test. The mass of material in the recuperators will have a large impact on transient operation, as will the flow split between compressors in the RCBC configuration. A key function is also the protection of hardware from over-speed, over-pressure, or over-speed, especially during rapid transients. The complexity of the functional interrelationships, and time constants involved, varying from slow to fast, will make it difficult to predict by modelling alone, and exploring these relationships should first be approached with large factors of safety, while having a built-in step to reverse input to avoid unintentional shut downs.

The success of the test loop is paramount, it's the culmination of all of loop improvements, and component testing carried out on numerous rigs. With very little run time to analyze, one option to improve the speed of development and help understand the system is to build a simulation. It could be a very crude representation to start with, using component representations that are informed by actual tests. Ultimately, the model could be further expanded and refined to enable its use for general applications.

Appendix A: Issues To Monitor and Control

category	**issue**	**response 1**	**response 2**	**response 3**
design limits exceeded	overpressure on high-pressure side of the loop	warn when approaching (amber and red)	vent through PRV and/or SV if some threshold exceeded	initiate a soft shutdown if another threshold exceeded
design limits exceeded	overpressure on low-pressure side of the loop	warn when approaching (amber and red)	vent through PRV and/or SV if some threshold exceeded (even though these are on the high-pressure side)	initiate a soft shutdown if another threshold exceeded
design limits exceeded	Hydro-Pac overpressure	warn when approaching (amber and red)	close and lock out Hydro-Pac-related valves when pressure on Hydro-Pac lines exceeds some threshold	
design limits exceeded	turbine inlet temperature too high	warn when approaching (amber and red)	cut heater power and add cooling if some threshold exceeded	initiate a soft shutdown if another threshold exceeded
design limits exceeded	high temperature recuperator inlet temperature too high	warn when approaching (amber and red)	cut heater power and add cooling if some threshold exceeded	initiate a soft shutdown if another threshold exceeded
design limits exceeded	low temperature recuperator inlet temperature too high	warn when approaching (amber and red)	cut heater power and add cooling if some threshold exceeded	initiate a soft shutdown if another threshold exceeded
design limits exceeded	compressor inlet temperature too high	warn when approaching (amber and red)	cut heater power and add cooling if some threshold exceeded	initiate a soft shutdown if another threshold exceeded

design limits exceeded	KEB electronics overtemperature	warn when approaching (amber and red)	set a lower shaft speed via the KEB [reduce power output from TAC]	increase cooling to KEB, if possible
design limits exceeded	TAC overtemperature	warn when approaching (amber and red)	reduce heater output and increase cooling to sCO_2	increase Hydro-Pac pumping out of cavity
design limits exceeded	TAC over amperage	warn when approaching (amber and red)	reduce heater output and/or restrict flow [reduce power output from PMG]	if motoring, set a lower shaft speed via KEB
design limits exceeded	TAC over voltage	warn when approaching (amber and red)	reduce heater output and/or restrict flow [reduce power output from PMG]	set a lower shaft speed via the KEB
design limits exceeded	TAC overspeed [unlikely in SNL's RCBC test rig due to KEB speed control]	warn when approaching (amber and red)	set a lower shaft speed via the KEB	inventory control if slow response, turbine bypass if fast response
risk to equipment	loss of load	KEB controller shuts down and applies braking to the PMG		
risk to equipment	turbine rub or close to it [requires additional instrumentation]	warn if approaching	initiate a rapid shutdown if rub occurs	
risk to equipment	compressor rub or close to it [requires additional instrumentation]	warn if approaching	initiate a rapid shutdown if rub occurs	
risk to equipment	porous media bearing flow rate too low	warn when approaching (amber and red)	initiate a soft shutdown if some threshold reached	
possible two-phase flow	compressor inlet temperature below critical point temperature	warn		

possible two-phase flow	compressor inlet pressure below critical point pressure	warn		
possible two-phase flow	CO_2 to porous media bearings below critical point temperature	warn		
performance related	pressure in alternator cavity getting higher than intended	warn		
performance related	relatively slow CO_2 leak somewhere in the system	warn		
performance related	surge or stall	warn if approaching surge or stall lines for compressor	initiate automatic inventory control measures if another threshold reached	
performance related	identification of degraded performance	warn		

Appendix B: Potential System Control Inputs

name	physical description	control capability	purpose
BV1	small gray/black Swagelok/ASCO valve near turbine end of TACs	an analog rather than digital valve, per the config file	appears to allow the Hydro-Pac to pull flow from the low-pressure side of the loop (especially if BV7 is closed)
BV1_Relay	the signal going into BV1 is labeled BV1_Relay	either fully open or fully closed	appears to provide a binary open or closed signal to BV1
BV2	small gray/black Swagelok/ASCO valve near compressor end of TACs	either fully open or fully closed	appears to allow the CO_2 tanks to add gas to the loop [assumption: the CO_2 tanks are the highest pressure in the system]
BV3	small gray/black Swagelok/ASCO valve near turbine end of TACs	either fully open or fully closed	allows alternate flow paths, but I haven't yet determined how we use them
BV4 (aka POG3)	small gray/black Swagelok/ASCO valve near turbine end of TACs	either fully open or fully closed	allows the flow from the Hydro-Pac pump to go into the low-pressure side of the loop, entering between the two recuperators (used during normal operations; when we pull CO_2 from the TAC cavities, we put it back into the loop through BV4)
BV5	small gray/black Swagelok/ASCO valve near compressor end of TACs	either fully open or fully closed	appears to allow the flow from the Hydro-Pac pump to go into the low-pressure side of the loop, entering just before the "A" TAC compressor
BV6	big blue "CompACT" valve located between the cooling loop and the TACs	either fully open or fully closed	appears to allow the flow to circulate through the low-pressure side of the loop (between the SNL cooler and the "A" TAC compressor)
BV7 (aka POG2)	small gray/black Swagelok/ASCO valve near turbine end of TACs	either fully open or fully closed	opens or closes the flow path from the TAC alternator cavities to the Hydro-Pac pumps and the rest of the system (used during normal operations; when we pull CO_2 from the TAC cavities, we pull it through BV7)

BV8	[I didn't see BV8 in the schematic or on any of the physical valves]	either fully open or fully closed	
BV9 (aka TBPV)	big blue and yellow Marwin Valve ER-6-30-4 valve on S side of rig	controllable by percent open	during startup, allows flow between the turbine inlets and turbine outlets without going through the turbines (per Darryn we open this during startup because we have been told it helps get the flow going in the right direction; closed prior to really running the loop); not used during normal operations because the valve has a limit of 400 deg F, but in principle a turbing bypass line and valve would allow rapid changes in power output
PRV	small gray/black Swagelok valve up high near SW corner of rig	either fully open or fully closed	appears to be a pressure reducing valve acting as a vent along with the SV; in the original schematic it appears to be connected to the high-pressure side of the loop, but in the new schematic it also appears to be connected to the secondary gas bottles through a weird path [does this also allow the seconday bottles to pressurize the system?]
RC Valve	big red Triac WEM-690 valve (marked "FC3")	not currently controllable from LabView	appears to allow some of the flow to go through the "B" TAC for recompression rather than going through the SNL cooler, with high-pressure flow from the compressor rejoining the main loop flow between the two recuperators
TCV	big red Triac WEM-690 valve (marked "FC2")	controllable by percent open	between the low-temperature side of the LTR and the SNL cooler; allows us to add a flow restriction to control back pressure (used in the Peregrine rig because we weren't putting load on the grid, if I understood Logan right)
SV	two small valves with yellow Swagelok actuators on the same line near PRV [signal is split and goes into both]	either fully open or fully closed	Darryn says these valves provide redundant ability to close a vent pathway

VE	relatively small FlowServe/Logix MD+ valve on N side of electrical panel by KEBs; N/A if we are not using porous media bearings	controllable by percent open	used to control sCO_2 flow to the turbine-side porous media bearing
VF	relatively small FlowServe/Logix MD+ valve on N side of electrical panel by KEBs; N/A if we are not using porous media bearings	controllable by percent open	used to control sCO_2 flow to the compressor-side porous media bearing
ExtSV	small valve with yellow Swagelok actuator near SW corner of rig; N/A if we are not using porous media bearings	either fully open or fully closed	appears to allow flow from secondary CO_2 tanks to the porous media air bearings; N/A if we are not using the porous media air bearings
Hydro-Pac pump	big blue equipment on NE and SE corners of rig; we currently use only the equipment in the SE corner	controllable by percent of maximum	pulls CO_2 out of the alternator cavities of the TACs to keep the pressure down; we also use it to circulate CO_2 through the system during warm-up
[cooling water "Flow" valve]	big white FlowServe/Logix 420 valve on the cooling water loop, kind of in the middle	PID controllable or accepts user-specified inputs	allows cooling water to flow through the SNL cooler; in start-up we have it closed so that we don't freeze the water
[cooling water "Bypass" valve]	the other big white FlowServe/Logix 420 valve on the cooling water loop, at the N side	PID controllable or accepts user-specified inputs	allows cooling water to bypass the SNL cooler; in start-up we have it open, but we start to close it after the main valve is fully open to force more water through the SNL cooler rather than the bypass line

[cooling water cooling fan]	in the big EVAPCO cooling equipment outside, N of the building	controllable by percent speed	runs the fan on an evaporative cooling system, which cools the purified water in the closed SNL cooler loop
SNL immersion heaters	big insulation-wrapped cylinders and associated electrical panels at E side of rig	PID controllable or accepts user-specified inputs	heat addition stage of the Brayton cycle, acting on the high-pressure side of the loop (after exiting the compressor, prior to entering the turbine)
["A" shaft speed]	"A" TAC (lower and closer to the S side of the rig)	specified through KEB controller	one of the key parameters governing how much we are compressing sCO_2 and how much energy we are extracting from it
["B" shaft speed]	"B" TAC (higher and a little less close to the S side of the rig; currently not installed)	specified through KEB controller; not used for simple CBC	one of the key parameters governing how much we are compressing sCO_2 and how much energy we are extracting from it