Inventory Management Operational Strategies for a 10 MWe sCO_2 Power Block

Brittany Tom
Research Engineer
Southwest Research Institute
San Antonio, TX, USA

January Smith
Research Engineer
Southwest Research Institute
San Antonio, TX, USA

Meera Day Towler, P.E.
Research Engineer
Southwest Research Institute
San Antonio, TX, USA

AUTHORS

Brittany Tom is a Research Engineer in the Power Cycle Machinery Section at Southwest Research Institute in San Antonio, Texas. Her research activities at SwRI include optimization, development, and testing of advanced power cycles including pumped heat energy storage and supercritical CO2 for power generation and waste heat recovery applications.

January Smith is a Research Engineer in the Power Cycle Machinery Section at Southwest Research Institute in San Antonio, TX. His research at SwRI includes advanced turbomachinery design for additive manufacturing and control of supercritical CO_2 power cycles.

Meera Day Towler, P.E., is a Senior Research Engineer at Southwest Research Institute in San Antonio, Texas. She specializes in controls, with a focus in robotics for space applications and custom mobility robots for inspection and maintenance. In previous assignments, she worked as a turbomachinery controls engineer, and research was in fields such as power generation, supercritical carbon dioxide turboexpanders, pipeline compressors, and compressor dry gas seals. She graduated from Southern Methodist University with undergraduate degrees in Mechanical Engineering and Mathematics. Her Master's degree is also in Mechanical Engineering, with a specialization in Controls and Dynamic Systems. Finally, her master's thesis focused on using pressure transducers as an indicator of impending surge in centrifugal compressors.

ABSTRACT

Efficient operation of a supercritical carbon dioxide (sCO_2) power cycle includes utilizing inventory control for partial load operations. However, inventory control is only one role of an Inventory Management System (IMS) for a 10 MW sCO_2 Recompression Closed Brayton Cycle (RCBC). Additional roles include managing system fill, replacing sCO_2 leaked to atmosphere, and supplying auxiliary seal supply flows to the dry gas seals (DGS). In the event of an emergency, the IMS must ensure auxiliary flows are maintained, to prevent the risk of damaging hardware. This paper provides an overview of critical components including an sCO_2 storage tank and emergency protection devices. Passive and automated control strategies for IMS operation and RCBC protection are discussed.

INTRODUCTION

Supercritical carbon dioxide (sCO_2) power cycles are an attractive option for a variety of applications such as Concentrating Solar Power (CSP), Fossil, Nuclear, and Waste Heat Recovery (WHR). Regardless of the application, system performance is dependent on efficient operation throughout the plant operating envelope. The power block must be able to efficiently ramp up and down in power to meet the changing demand. In his study, Dostal [1] examined using two control methods for ramping power: inventory control and bypass control. He concluded that while bypass control provides a quick solution to ramping power, inventory control results in higher efficiencies than bypass control at part load. Since then, numerous studies [2-3], transient models [4-5], and a couple small-scale (less than 500 kW) demonstrations and model validations [6-11] of inventory control have been completed. Tang et al. [5] summarized each of these investigations before discussing the transient model and potential control methods for DOE's Supercritical Transformational Electric Power (STEP) program. Tang et al., concluded that his model was in line with previous studies.

The STEP program, led by Gas Technology Institute (GTI), Southwest Research Institute® (SwRI®) and General Electric Global Research (GE-RC) is an active project (at the time of publication) to design, construct, commission, and operate a 10 MWe sCO_2 pilot plant facility on SwRI's campus in San Antonio, TX [12]. One of the technical risks that the STEP facility will mitigate is system operation to include load following. Load following at part loads will be demonstrated using turbine throttle control as well as inventory control. The target cases for the facility are included in Table 1 and further detailed by Marion et al [12].

Table 1: STEP Cycle Conditions [12]

Model Names	Cycle Configuration	Description	Load %	Net Power Level (MWe)	Cooler Exit Temperature	Turbine Inlet Temperature	Cycle Efficiency
133	Simple	Simple cycle minimum load case	Min	2.5	35°C	500°C	22.6%
136	Simple	Simple cycle maximum load case	Max	6.4	35°C	500°C	28.3%
151	Recompression	Baseline case	100%	10.0	35°C	715°C	43.4%
152	Recompression	"Hot" Day Case	70%	6.6	50°C	675°C	37.4%
153	Recompression	"Cold" Day Case	100%	9.9	20°C	525°C	36.8%
154	Recompression	Partial load case using inventory control	40%	4.0	35°C	715°C	37.0%
155	Recompression	RCBC at 500°C turbine inlet temperature	70%	6.9	35°C	500°C	32.5%
157	Recompression	Partial load case using TSV throttling (transient condition)	40%	4.2	35°C	715°C	30.8%
157a	Recompression	Partial load case using TSV throttling	40%	3.9	35°C	675°C	29.6%

The Inventory Management System (IMS) of the STEP facility manages the flow of working fluid into and out of the closed Brayton cycle during operation and off-design operation. The IMS must accommodate load steps and system transients for the cycles of interest. The IMS will be responsible for controlling the amount of CO_2 in the system. The amount of CO_2, or inventory, in the system controls the pressure of the main process and in turn the operating load of the facility. Managing the flow of working fluid in and out of the process includes three main functions. First, the fill system that includes the bulk liquid tank, a cryogenic pump, and electric vaporizer, is used during initial fill and to replace inventory leaked to atmosphere. Second, the IMS performs inventory control of the power block. Inventory control includes achieving cycles of interest and completing load steps and system transients. Finally, the IMS supports the auxiliary supply flows, such as those required for the Dry Gas Seals (DGS). A high-level diagram of the IMS is shown below in Figure 1.

The IMS is affected by the design of the entire sCO_2 power block. Cycle conditions, component selection, and piping volumes affect the capacity of the fill system, inventory storage tank, and cooling requirements. Operational requirements such as acceptable time between load steps, acceptable fill time, and auxiliary supply flow requirements also affect the design requirements. In addition, lessons learned from previous test campaigns are incorporated in the design requirements. Finally, design specifications detailed below are the result of a tradeoff between reasonable design and cost. For example, the inventory storage tank can be fabricated from carbon steel instead of stainless steel. At the expected operating temperatures, carbon steel corrosion is expected to have a minimal concern and periodic checks can be implemented to monitor corrosion [13]. Stainless steel would have less corrosion concerns, but a storage tank fabricated from stainless steel is expected to be three times the cost of a carbon steel option. This paper discusses the major components and controls of the IMS system.

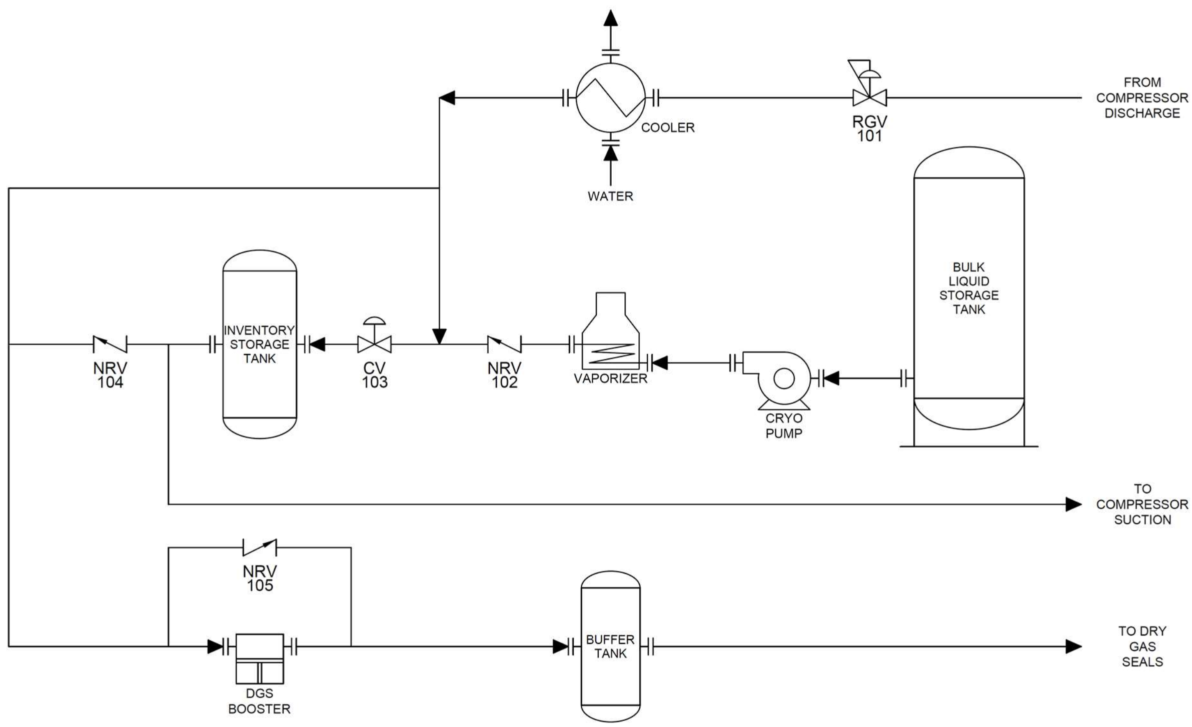

Figure 1: High Level IMS Diagram

FILL SYSTEM

The IMS fill system includes the traditional inventory components: a bulk liquid CO_2 tank, a cryogenic liquid pump, and a vaporizer. The fill system is responsible for the initial fill of the facility and replacing inventory that is vented to atmosphere during operation. During initial fill, after maintenance, or recommissioning of the facility, there will be air in the process piping. This air must be displaced by cyclic pressurization and venting of CO_2. The fill system must charge the system with a set amount of inventory to achieve a desired pressure and then the piping must be vented. After the required dilution is achieved, the fill system must support the startup procedure.

Component Design

Bulk Liquid Tank

The bulk liquid tank is a standard component for an inventory system. The largest design consideration of the bulk liquid tank, is how large of a tank is needed. Considerations for the tank include: the required inventory of the power block, the estimated leakage of the system, and the frequency of tank refills. Typical sizes of bulk liquid tanks are 14, 30, and 50-ton tanks holding 12,700, 27,000, and 45,000 kg respectively. The STEP IMS will utilize a 30-ton liquid tank. This allows the operators to have enough liquid supply to fill the loop and operate for approximately two weeks between refills. The second design consideration of a bulk liquid tank, is ensuring that the tank can maintain the required withdraw rate. This is done by adding a pressure building vaporizer to the liquid. Bulk liquid tank vendors can supply this vaporizer as part of the tank rental.

Cryogenic Pumps

Downstream of the bulk liquid tank, the IMS will have two cryogenic pumps in parallel to boost the pressure of the liquid CO_2 from approximately 300 psi in the tank to the required fill pressure. Each pump is designed to handle the full flow of the system, so the system is redundant in the event of a pump failure. During Sunshot testing, the operators experienced issues filling the loop while not forming dry ice [14]. To prevent dry ice formation during fill, the pumps and vaporizer should have a large turndown ratio. Using a lower initial fill pressure and sufficiently heated flow, can help maintain a vapor phase after expansion. The heat input will come from a combination of the electric vaporizer, discussed below, and the DGS panel heaters. A Variable Frequency Drive (VFD) will control the pump speed and discharge pressure.

Vaporizer

Following the cryogenic pumps, the electric vaporizer heats the liquid CO_2 to approximately 50°C, converting the CO_2 into the supercritical or vapor phase. The vaporizer must be sized to handle the maximum pressure and flow rate of the cryogenic pumps. An electric vaporizer was selected over an ambient vaporizer for a few reasons. First during the fill process, the added heat helps ensure no dry ice formation. Second, after the fill process, the loop is at a higher starting temperature than if an ambient vaporizer was used. This decreases the startup time required. Finally, the added heat ensures that cold sCO_2 flow is not introduced into the inventory storage tank downstream of the vaporizer during the IMS charge process. NRV-102 downstream of the vaporizer ensures that no backflow to the fill system occurs.

Controls and Operation

The IMS shall maintain the required amount of inventory in the main cycle to achieve the desired operating condition. System leaks are expected from the primary vents of the DGS. The IMS must replace this leakage to maintain constant inventory in the main loop. The makeup supply flow will be pulled from the bulk liquid tank at regular intervals and injected into the main loop after passing through the inventory storage tank. The inventory storage tank will act as an accumulator for the fill system.

Charging the IMS using the bulk liquid tank, cryogenic pumps, and vaporizer can be done either manually or automatically. When the inventory storage tank pressure drops below 5 bar above the maximum of the main compressor suction pressure, bypass compressor suction pressure, and turbine discharge pressure, the inventory system will need to charge inventory storage tank from bulk storage tank. This will involve turning on the pumps and vaporizer to meet a set flow rate, without overwhelming the vaporizer. The start permissives for the tank charging are the respective pump block valve opened (downstream of the pumps) and the liquid tank level greater than a minimum setpoint.

The fill pumps are parallel and fully redundant. One pump at a time, alternating between starts, will initially be started. If a pressure rise for the pump that has been started is not detected within a designated time frame, the corresponding pump will shut off, and the control will send an alarm and attempt to start the other pump. If both pumps fail to start within a set time frame, the fill process will be stopped (both pumps will be turned off) and an alarm will be sent to the operator.

After opening the normally closed CV-103, the tank will be filled for 5 minutes or until the tank pressure in the inventory storage tank exceeds a set pressure rise above the maximum of the main compressor suction pressure, bypass compressor suction pressure, and turbine discharge pressure. CV-103 will close when the charge process is complete.

The charge process will stop (and not be able to be restarted or be activated) if the liquid storage tank drops below its minimum setpoint. Additionally, the charge process will stop (and not be able to be restarted or activated) if both pumps have an active trip indication or the vaporizer has an active trip indication.

INVENTORY CONTROL

As stated above, the IMS shall manage the flow of the working fluid in and out of the cycle during operation. This includes accommodating load steps and transients in the system. The IMS has been designed to accommodate a load step between Case 151- baseline case at 100% and Case 154- partial load at 40% using inventory control (Table 1). In order for the facility to transition between Min and Max loads in the simple cycle and 40% and 100% RCBC loads, the IMS must move inventory between the power block and the inventory storage tank. When decreasing load, high pressure main compressor discharge will flow from the main cycle to the storage tank (red dashed line in Figure 2). The flow will be cooled using the inventory cooler and then CV-103 will open to fill the inventory storage tank. The tank will be kept at pressure between the compressor suction and discharge. When increasing the system load, a control valve from the IMS to the compressor suction (not shown) will open, and the higher pressure in the storage tank will drive the inventory back into the main cycle prior to the main process cooler (green dotted line in Figure 2). Both connections- from the compressor discharge to the IMS and from the IMS to the compressor discharge have a check valve prevent backflow between systems (not shown).

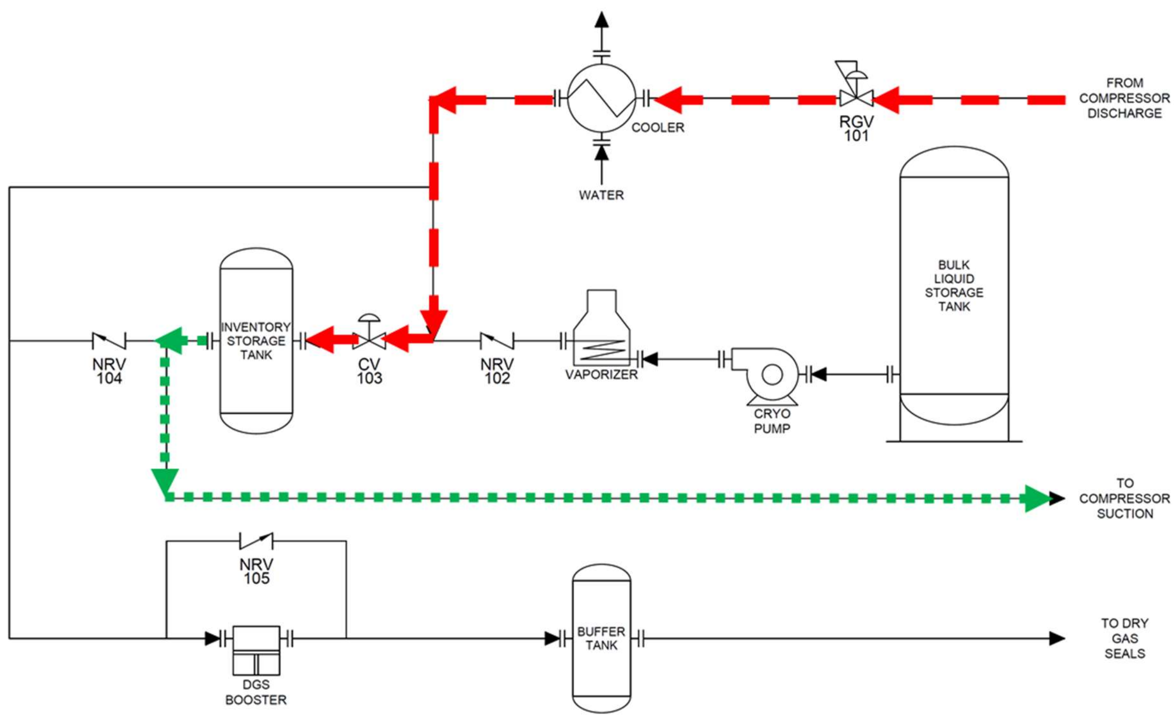

Figure 2 Inventory Control Schematic

When the facility is shutting down for maintenance, the main cycle can be brought down to 40% load before shutdown and venting in order to minimize CO_2 lost to the atmosphere.

Component Design

Inventory Storage Tank

The required volume of the inventory storage tank is dependent on the load change mass, cycle pressures, temperature in the vessel, and the results of the transient analysis. The load change mass is the difference in power block inventory between Case 151 and Case 154. A margin of 20% was added to this delta mass to accommodate transients and off-design operations. The cycle pressures, i.e. the main compressor suction and discharge pressures at both Case 151 and Case 154 were also used to calculate the required tank volume. In order for inventory control to work, the pressure in the storage tank must be between the main compressor suction and discharge.
Figure ***3*** depicts the cycle and storage tank pressures at Case 151 and Case 154.

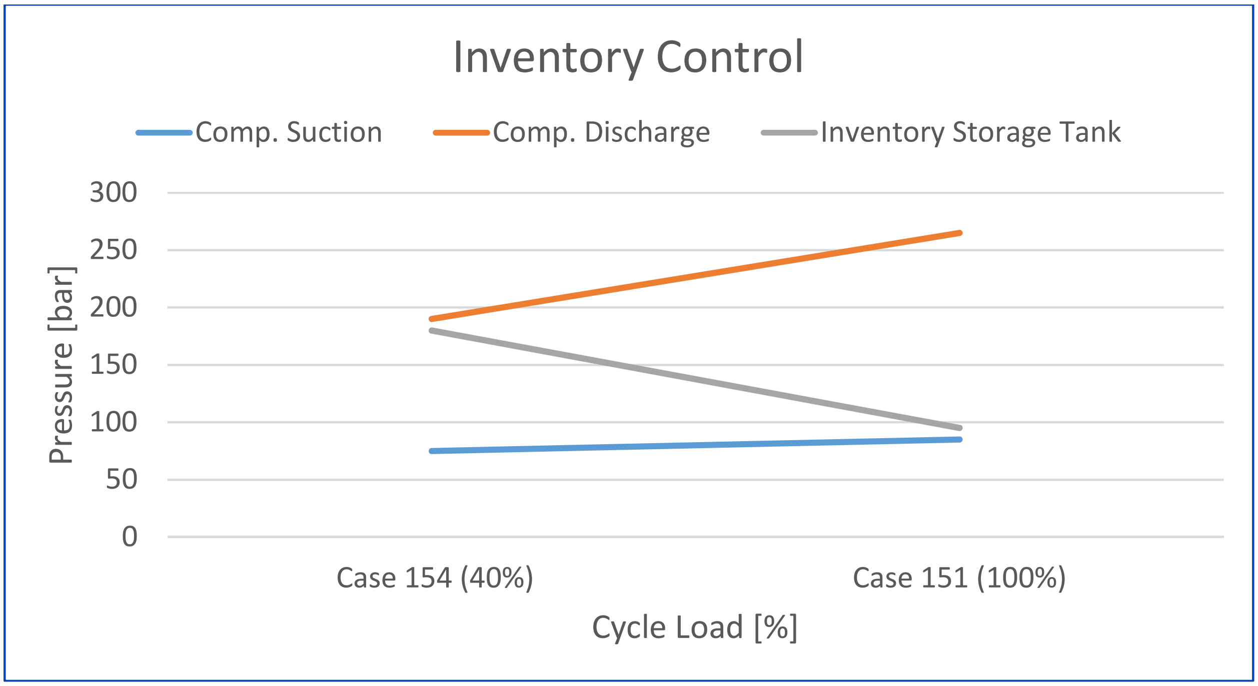

Figure 3: Inventory Control Pressures

While a range in temperatures in the inventory storage tank is expected when charging and discharging due to compression and expansion, there is an optimal storage temperature that minimizes the storage tank volume. Minimizing storage tank volume is important to minimize system cost. Analysis has shown approximately 50-60°C to be the optimal storage temperature. This is due to a large difference in stored inventory density at the 100% and 40% cases. The plot in
Figure ***4*** helps to illustrate this effect. The volume calculation is based on a hypothetical 1500 kg difference between 100% and 40% load and utilizes Equation 1.

$$\text{Initial Tank Volume} = \frac{\Delta m}{\rho_{40\%} - \rho_{100\%}} \qquad (1)$$

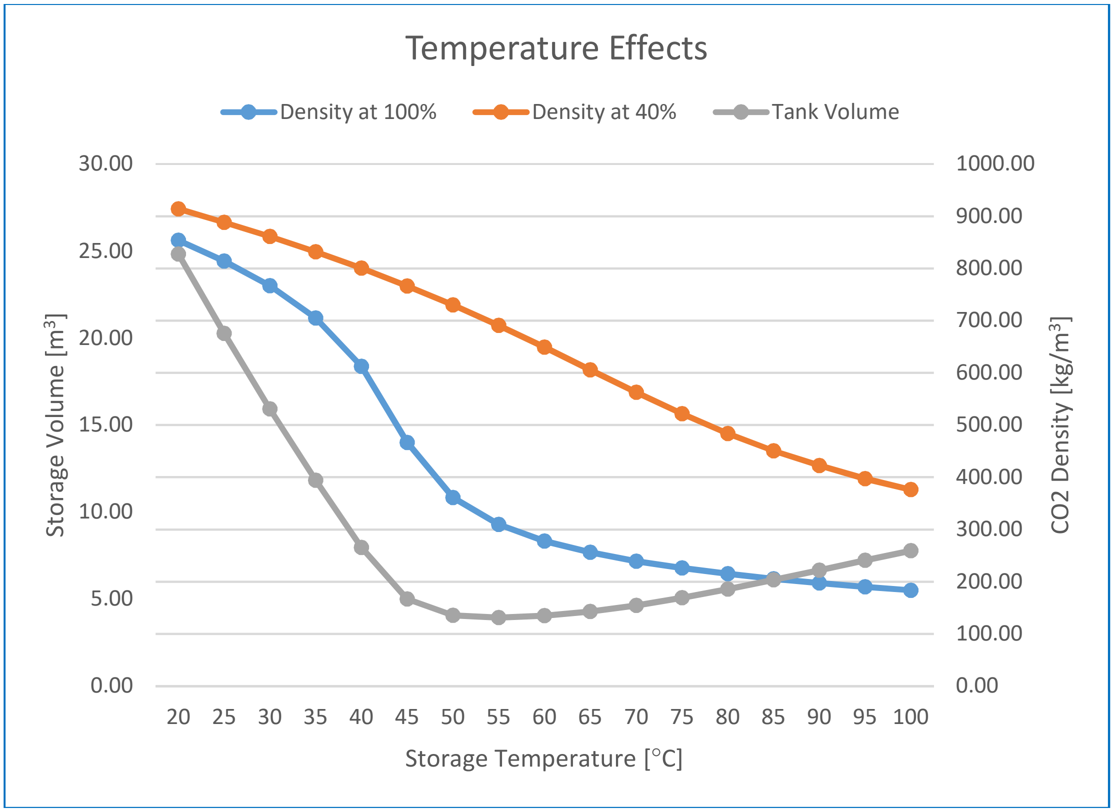

Figure 4: Optimal Storage Temperature

Finally, a transient simulation of the IMS and storage tank has been completed in Synergi Pipeline Simulator [15]. The model was used to understand the charge and discharge process of the system (adding and removing inventory to the main process), understand how the pressure and temperature of the storage tank varies overtime, and size the tank and control valves. The transient model indicates how the temperature of the storage tank increases during the load change from 100% to 40%. The model calculated the inlet and exit temperature of the storage tank. Assuming a constant inventory cooler exit temperature of 45°C, the storage tank exit temperature is expected to increase to 90°C during the approximately 25-minute process (Figure ***5***). Note, tank mixing was not accounted for in this transient model. Final storage tank performance will be calculated in STEP transient model.

The inventory storage tank will be insulated and heat traced. Both will be used to maintain temperature in the storage tank.

Inventory Cooler

To reduce the heat added to the inventory storage tank from compression, the sCO_2 can be cooled prior to entering the storage tank. Due to the transient behavior of filling the storage tank, the flow rate, inlet pressure, and inlet temperature of the sCO_2 varies over the charge operation. The transient analysis was used to determine specifications for the cooler.

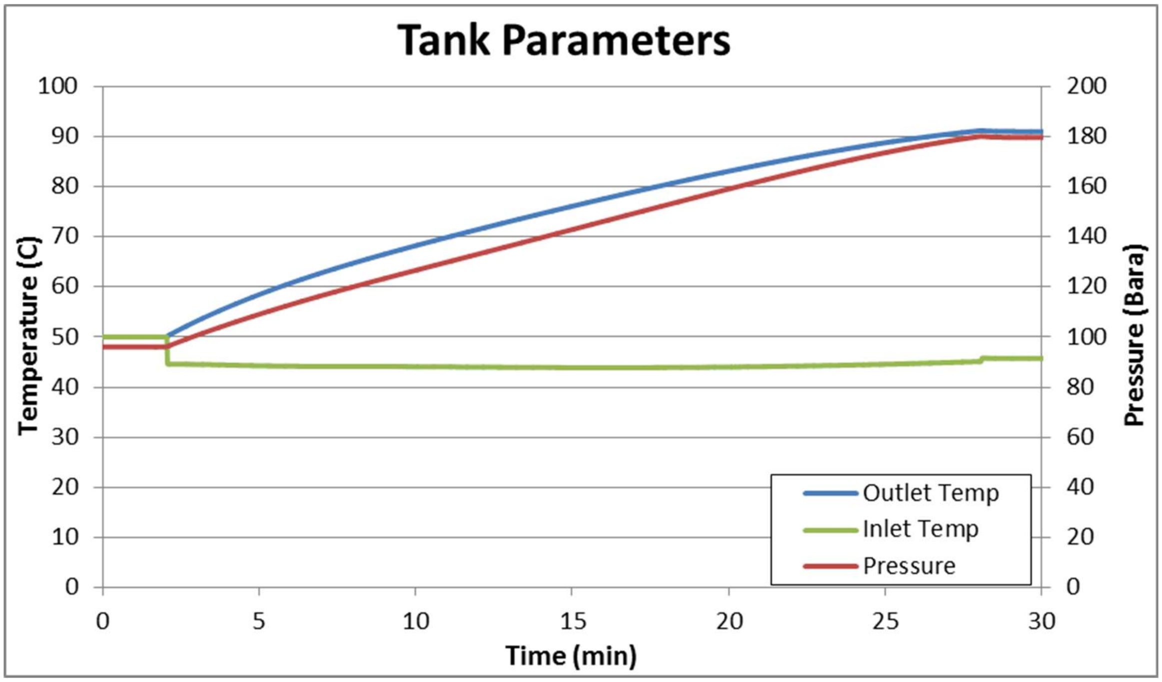

Figure 5: Inventory Storage Tank Transient Results

Controls and Operation

The IMS needs to maintain loop mass at a variable setpoint depending on the desired system operating point via a controller. The loop mass will be calculated based on the list of temperatures and pressures and their corresponding internal loop volumes throughout the facility. Additionally, loop pressure control will also be available to be used instead of the inventory mass control loop. Inventory mass control and loop pressure control cannot be active at the same time. The main and bypass compressor loops have independent pressure control loops for when the loops are isolated (i.e. during start-up).

When the main and bypass compressor loops are isolated, both “MC Loop Pressure Control” and “BC Loop Pressure Control” shall be active. Inventory Mass Control will not be used while the compressor loops are isolated since the two loops will not be in communication. After the main and bypass compressor loops are joined, the “BC Loop Pressure Control” will be turned off. At this point the system will use the “MC Loop Pressure Control” alone. Presently, the bypass compressor loop cannot automatically remove mass from the loop; venting will be required if mass needs to be removed from the bypass compressor loop.

The valve that removes inventory from the Main Compressor loop shall remain full open during operation to support DGS supply flow. To remove additional mass from the system during a load change, a valve upstream of the inventory storage tank (CV-103) will be used. These control loops shall be implemented so that the fill and vent valves do not fight each other or experience “jitter.” To achieve this, a pressure or mass band (or range) is implemented as a bias above or below the points at which valve actuation is initiated.

The IMS Cooler Control shall be able to be toggled on or off by the operator. When enabled, the controller will modulate the water side flow rate to achieve a temperature setpoint at the inventory storage tank. The identified use case for the IMS cooler is when CO_2 is being packed into the inventory storage tank. At all times, the water-side control valve must be at least 5% open to allow some water to flow through the cooler to prevent boiling the water in the cooler**.**

DGS SUPPLY FLOWS

The IMS is responsible for providing supply flow to the Dry Gas Seals. Dry Gas Seals require supply flow whenever the process is pressurized above ambient conditions to prevent contamination in the seals. For both the compressors and turbines, the supply flow must be above the low side loop pressure to overcome pressure losses in the supply panel and to maintain positive buffering flow within the turbomachinery at the highest process pressure. During normal operation, the DGS supply flow will be pulled from the compressor discharge and supplied to the DGS panels. The compressor discharge pressure will be sufficient to provide flow to the DGS panels. The flow path is shown in Figure 6. Recall, the inventory storage tank will be at a pressure lower than the compressor discharge, so NRV-104 will remain closed during normal operation. The cooler will also have a minimal water flow, so that the DGS supply flow is not over cooled.

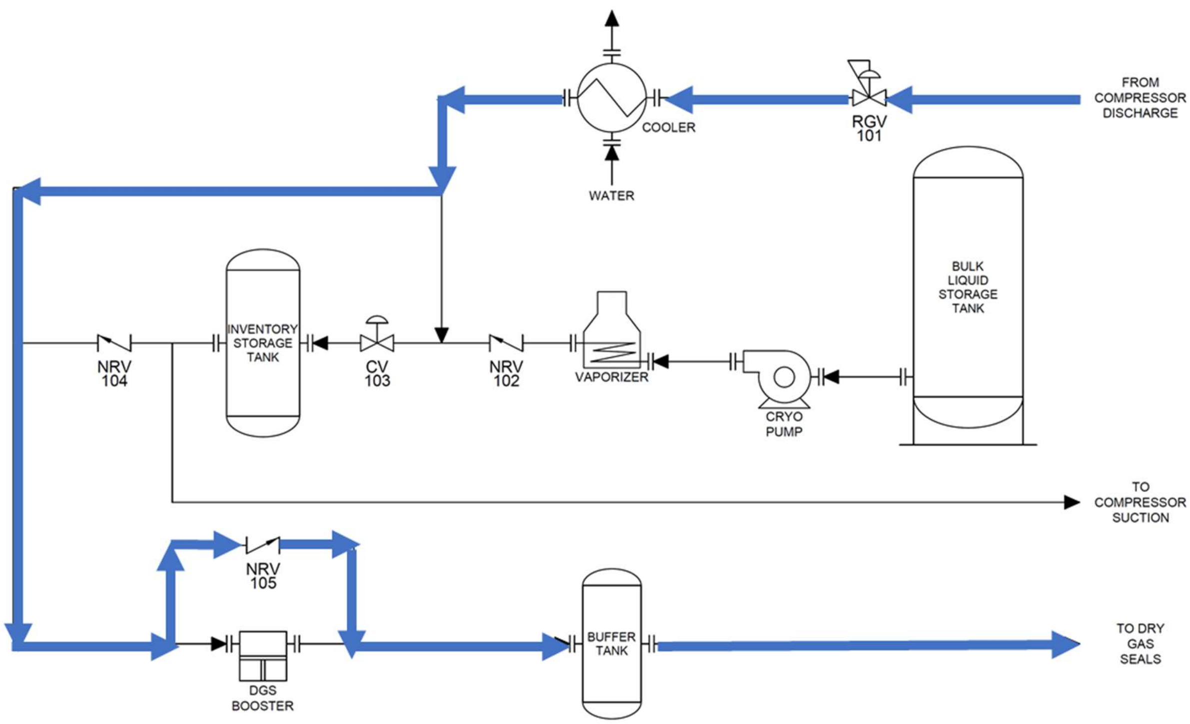

Figure 6: Normal Operation DGS Flow Path

During startup, shutdown, pressurized holds, or abnormal events, the pressure ratio of the cycle may not be high enough to maintain positive buffering flow. In these cases, the IMS must boost the supply flow upstream of the DGS panels. The check valve (NRV-105) will close and the DGS booster will turn on, ensuring adequate pressure to the DGS panels. The air-driven DGS boosters are designed to handle the expected flow rate for all six DGS in the RCBC cycle (two per turbomachine). Similar, to the cryogenic fill pumps, there is an extra DGS booster in parallel (not shown in the high-level diagram) in the case of a pump failure.

A buffer tank at the DGS panels is used to limit pulsations from the boosters and provide residual volume if the supply flow is lost.

Controls and Operation

DGS boost pumps will be activated by the control system. When pressure at the inlet to the boosters is less than 10 bar over the maximum sealing pressure across the facility, the boosters will be started by activating the air supply to the appropriate boost pumps.

Booster speed is controlled by the amount of shop air supplied. If one booster fails (indicated by a low DP across that booster even when shop air is supplied), the control will turn on the extra booster by opening the appropriate air-side valve. After 15 seconds of operation at full speed, the air supply to the boosters will be decreased to achieve the flow rate setpoint of the dry gas seals.

EMERGENCY PROTECTION

The IMS is designed to accommodate several failure modes. Pressure relief valves and a pressure regulating valve (RGV-101) ensure the IMS is not over pressurized. The pressure regulating valve allows the IMS to have a lower max allowable working pressure (MAWP) than the main compressor. The IMS MAWP is still above the expected main compressor discharge pressure for normal operations and supports all required activities. Increasing this pressure to match the MAWP of the main compressor discharge would require more expensive components, piping, and valves. The pressure relief valves throughout the IMS will reflect this MAWP.

In the event of a trip, loop pressure control or mass control will be deactivated. The DGS boosters will be turned to fully on. Once the turbine speed has reached 0 rpm, the DGS flow to the turbine seals will be reduced to a lower setpoint to avoid the risk of thermally shocking the hot turbine case with relatively cool DGS supply flow. If supply flow from the main compressor discharge is unavailable, the inventory storage tank provides passive backup. NRV-104 will open when the inventory storage tank is at a higher pressure than the discharge flow and the storage tank can provide DGS supply flow. The fill system is also available as a backup supply flow.

CONCLUSION

In conclusion, the STEP IMS has been designed to support a variety of operational states and power levels. The IMS can support system fill, inventory control during load transitions, pressure and mass control of the power block, and provide auxiliary supply flows. In the event of an emergency, the IMS can provide DGS supply flow via the DGS boosters and/or passive backup from the inventory storage tank and fill system. System component specifications are affected by the planned operating cases, volume in the RCBC cycle, IMS requirements and overall cost. The IMS will be demonstrated with the simple cycle configuration by January 2021 and the RCBC cycle configuration by September 2022 [12].

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ACKNOWLEDGEMENTS

This information, data or work presented herein was funded in part by the National Energy Technology Laboratory (NETL), U.S. Department of Energy, under Award Number DE-FE0028979.

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