

**SUPERCritical CO₂ TURBOMACHINERY CONFIGURATION AND CONTROLS FOR A ZERO
EMISSION COAL FIRED POWER PLANT: SYSTEM OFF DESIGN & CONTROL OF SYSTEM
TRANSIENTS**

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Abstract

In the present work, startup, shutdown, and off-design operation of a supercritical carbon dioxide (sCO₂) based Recompression Brayton Cycle (RCBC) powered using an oxygen fired coal pressurized fluidized bed combustor (PFBC) were studied. In Aerojet Rocketdyne's (AR) Zero Emission Power and Steam (ZEPS™) system, carbonaceous solids such as coal/petcoke are combusted with oxygen at pressure in a fluidized bed to produce a flue gas containing predominantly CO₂ and H₂O after removal of impurities. Part of the CO₂ in the flue gas is sequestered, and the remainder is recycled back to the PFBC to control the temperature of the combustion products. The heat produced during combustion is used to indirectly heat the working fluid (sCO₂) in an in-bed heat exchanger, in a closed-loop RCBC power plant.

The plant system model was updated to account for the pressure drop and updated performance maps for the turbines, compressors, and heat exchangers. The location of various valves and their operation in the RCBC power island loop were identified for the startup, shutdown and off design/transitional states. Quasi-steady state and transient analyses showed that system start-up, shutdown, and steady-state control can be successfully achieved for the ZEPS™ system. Several control system configurations were evaluated, and an integrated PFBC and Supercritical CO₂ Turbomachinery (SCOT) system start-up process was defined that pre-heats the bed to a safe temperature for coal combustion (~1100°F) by burning natural gas and air, and then transitions to a steady state operating temperature of 1600°F. This paper summarizes the configurations studied, analysis methods, key findings identified, and recommended next steps.

Introduction

The ZEPS™ net plant efficiency has been analytically shown to be very attractive in previous studies when compared to the efficiency for an atmospheric oxy-fired supercritical steam pulverized coal plant with carbon capture. The objective of this effort was to determine if the ZEPS™ plant system with the SCOT equipment can be operated under the defined start-up, shut-down and transient conditions.

Approach

AR previously completed a study for Leonardo Technologies, Incorporated (LTI), to define a reference 550 MWe plant ZEPS concept as shown in Figure 1. A follow on effort to evaluate the SCOT configuration from a system control perspective is reported in this paper. First, the system model was refined to include realistic estimates of the pressure losses in the closed sCO₂ loop. This updated system baseline was then used to generate revised performance maps for the SCOT turbines, compressors, and recuperators. Next, sensitivity analyses were completed for the updated system baseline to understand the key control parameters during off-design operation including start-up and shutdown. Finally, a system control methodology was defined and demonstrated with the system model.

SCOT System Definition

First, performance maps at varied sCO₂ mass flow rate were developed for the main and recycle compressors as well as the power turbine and compressor drive turbine. NIST REFPROP data was used for the sCO₂ properties. In addition, heat transfer surface area models for enhanced shell & tube heat exchangers were developed and used in the updated system model. Future work should include high compactness heat exchangers such as printed circuit heat exchangers (PCHE) to minimize recuperator volume, weight, and cost as well as pre-heat time. Finally, a plant layout was developed and used to measure the length of piping,

CO₂ volume, and pressure drops in the system. These features were used as inputs for the system model. The plant layout is shown in Figure 2.

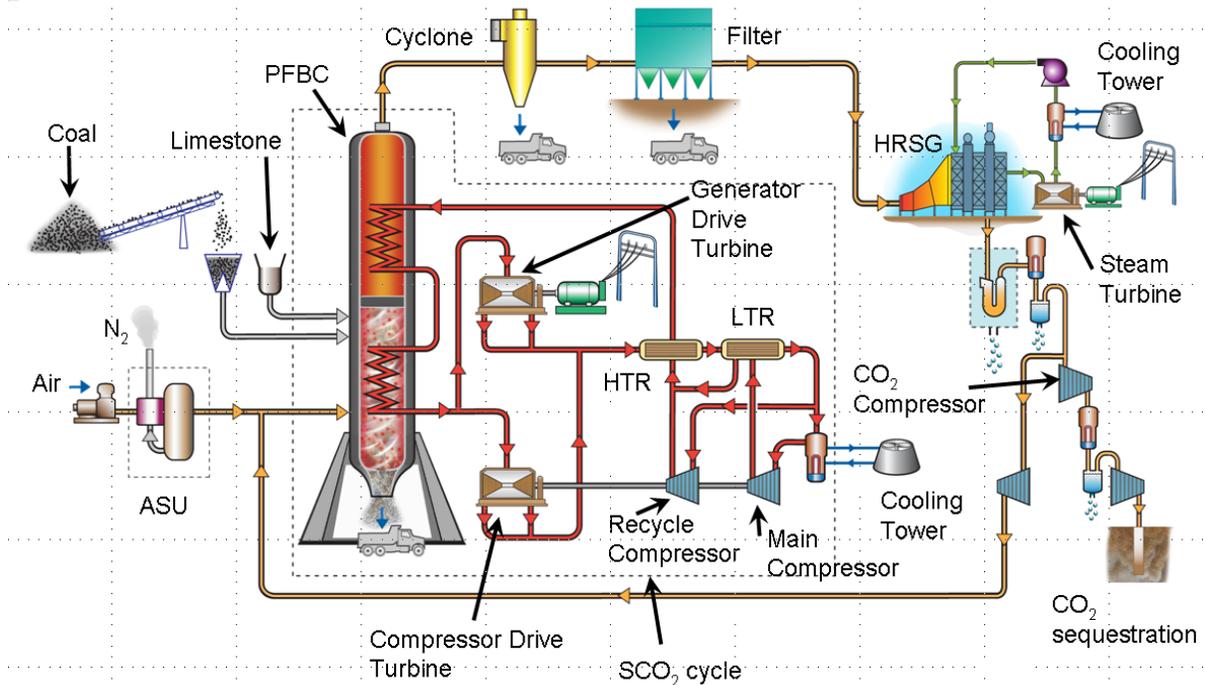


Figure 1: Zero Emission Oxy-Combustion Coal Power Plant with sCO₂ Brayton Cycle

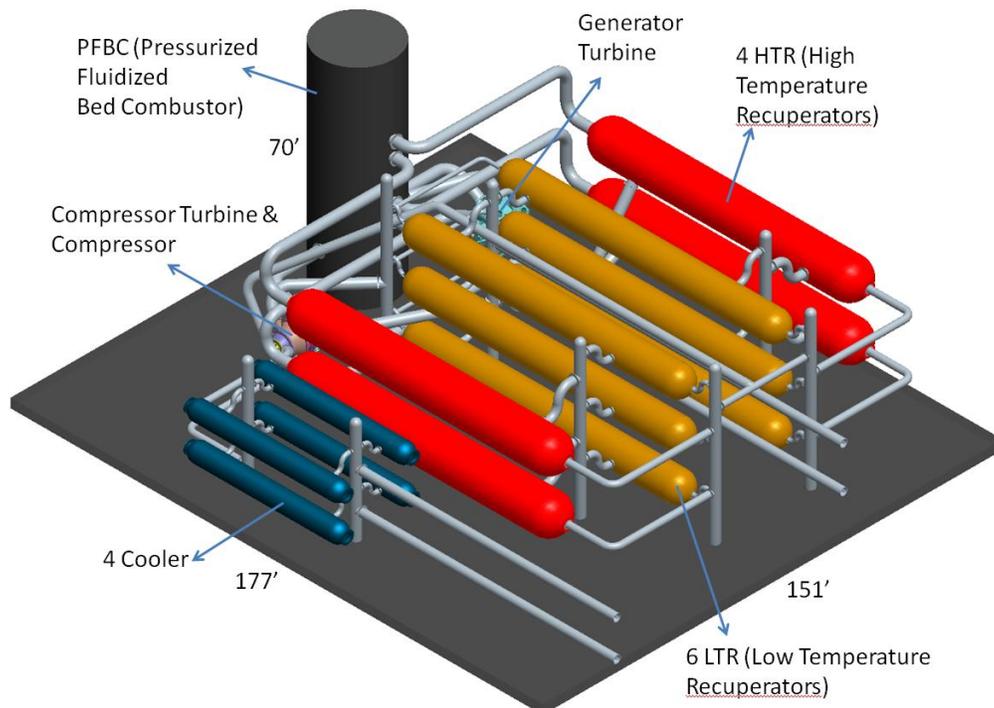


Figure 2: Plant layout of the SCOT Island with key dimensions (support structure not shown for clarity).

The component performance maps and piping system and resulting pressure drops were used in the updated system model shown in Figure 3. The efficiency of the SCOT island is 50.4%. The figure reflects the final PFD after the trade studies and off-design operating cases were completed. Analyses indicate the SCOT system efficiencies remain high (> 47%) even when throttled down to 65% power level.

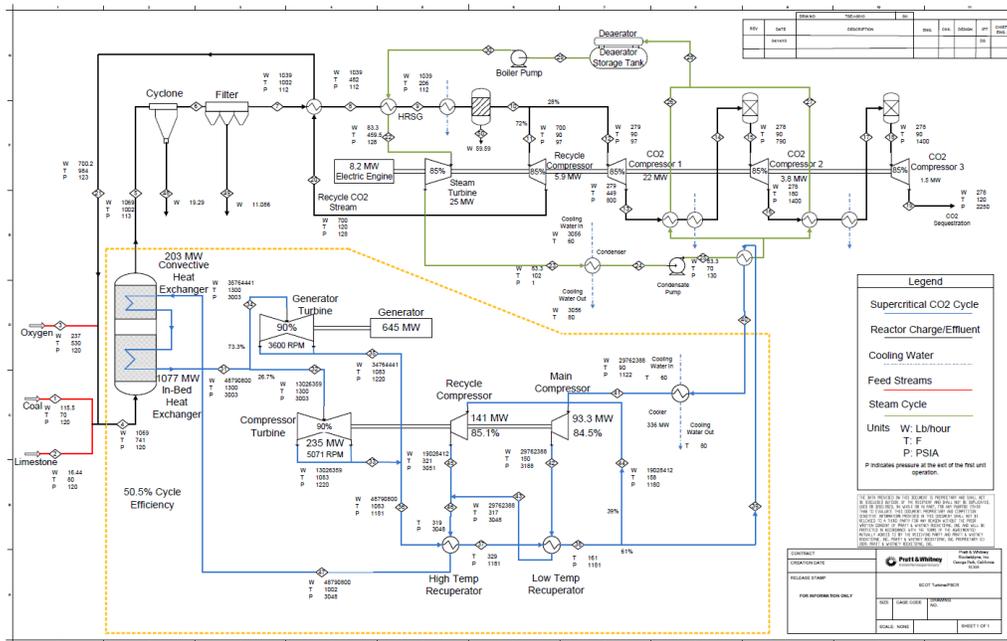


Figure 3: PFD for the resulting SCOT cycle – the efficiency is 50.4% and net plant efficiency is 37.3% (HHV). The focus of this study is enveloped by the orange box.

The SCOT island system volume was calculated after the piping system and components were sized. The CO₂ mass was calculated to be 229 tons for the SCOT island operating at 100% power. The CO₂ storage system must be able to add 6% mass at lower power levels and in some operating conditions the CO₂ storage system will need to remove and store approximately 2% of the mass based on analysis. The make-up location will be at the inlet to the cooler to avoid impact to the main compressor. The drain location will be at the compressor outlet since the pressure is high and the temperature is low and compatible for storage without compression or cooling.

System Start-Up Approach

Initially a variety of start-up and shutdown methods were evaluated that required fourteen valves, four bypass legs, and one CO₂ storage system. After preliminary evaluation, two start-up approaches were selected to be analyzed in more detail including a spin start and a motor assist bootstrap. The spin-start approach utilizes a sufficiently large source of CO₂ to overcome system inertia and develop sufficient power across the compressor turbine to initiate the operation of the compressors. To accomplish this, a fairly high temperature must be present within the bed (over 500°F), and the initial flow of colder CO₂ would be high enough to thermally shock the in-bed heat exchanger tube bundles which would shorten their life. This eliminated the spin start start-up approach from consideration and the motor assist bootstrap start-up was selected.

Start-up requirements include the following items to mitigate damage to the system:

- Prevent compressor stall
- Do not exceed LTR and compressor temperatures
- Prevent heat exchanger overheat
- Do not overspeed turbines
- Avoid low Main Compressor Inlet Temperature/Pressure

The motor assist bootstrap start-up was initially assessed based on a 10% flowing heat-up. The transient model included the thermal inertia of the PFBC, turbines, compressors, and recuperators. The model was a time-marching model with PFBC heat duty as the independent variable. Flow across the bypass leg was adjusted to balance compressor turbine power, and convergence was achieved at each time step by iterating HTR hot-side discharge temperature until it balanced heat duty and temperatures of both recuperators. The transient modeling showed that nearly all of the heat bypassed the Low Temperature Recuperator (LTR) due to the large thermal inertia and surface area of the High Temperature Recuperator (HTR), resulting in a very slow heat-up of the LTR (greater than 36 hours). Due to the HTR capturing all of the heat and transferring it to the cold side of the HTR, the bed heats up too quickly. The PFBC bed is therefore ready for operation nearly 20 hours before the LTR is at an acceptable condition to begin loading the system.

The bootstrap start-up was re-evaluated with the operating flow split between the recycle and main compressors changed, and improved the balance, but there was still a significant time delay between the PFBC and the LTR being at operating condition. It was believed that a lower CO₂ flow would enable the system to heat more uniformly, and the system model was evaluated with 2% of the maximum system flow. The results showed the system could operate (compressor turbine making sufficient power for the compressors, and none of the compressors were near stall). The transient model was redone with the 2% flow and found that the system heat-up was uniform and acceptable.

Once the PFBC startup procedure was established, the SCOT system could be refined. The valves and bypass legs were evaluated and reduced to six valves and one bypass leg. The CO₂ storage system was retained, but the discharge was re-routed closer to the discharge of the Low-Temperature Recuperator (LTR). The final arrangement is shown in Figure 4.

PFBC Start-Up Procedure

The SCOT system is integrated with a heat source. For this study, it was assumed that the heat source is the Oxy-PFBC in the ZEPS concept. To describe the startup process of the SCOT system the PFBC startup process must first be briefly described. After a standard safety examination, the bed material is loaded including insulating ash and/or sand up to the air grid/bubble cap height. Air flow is initiated at a low enough velocity to allow the ash and/or sand to settle. The air flow is then increased until the bed is in a bubbling regime. Once a minimum bubbling velocity is achieved, a gas-fired burner is initiated. A heating rate of 50-100°F per hour is maintained. Once the bed temperature reaches 150°F, the CO₂ working fluid system (SCOT) and coal feed cooling systems are started. The coal feed is initiated when bed temperature reaches safe levels for coal combustion, ~ 1100°F. Once coal combustion is verified via O₂ and CO₂ concentration, the recycle CO₂ system is started. The gas-fired burner is turned off and the system begins to use enriched air (oxygen injection) until pure O₂ is being injected. The pressure is increased to the operating pressure. Oxygen/recycled CO₂ and coal feed rates are next increased to the minimum operating conditions.

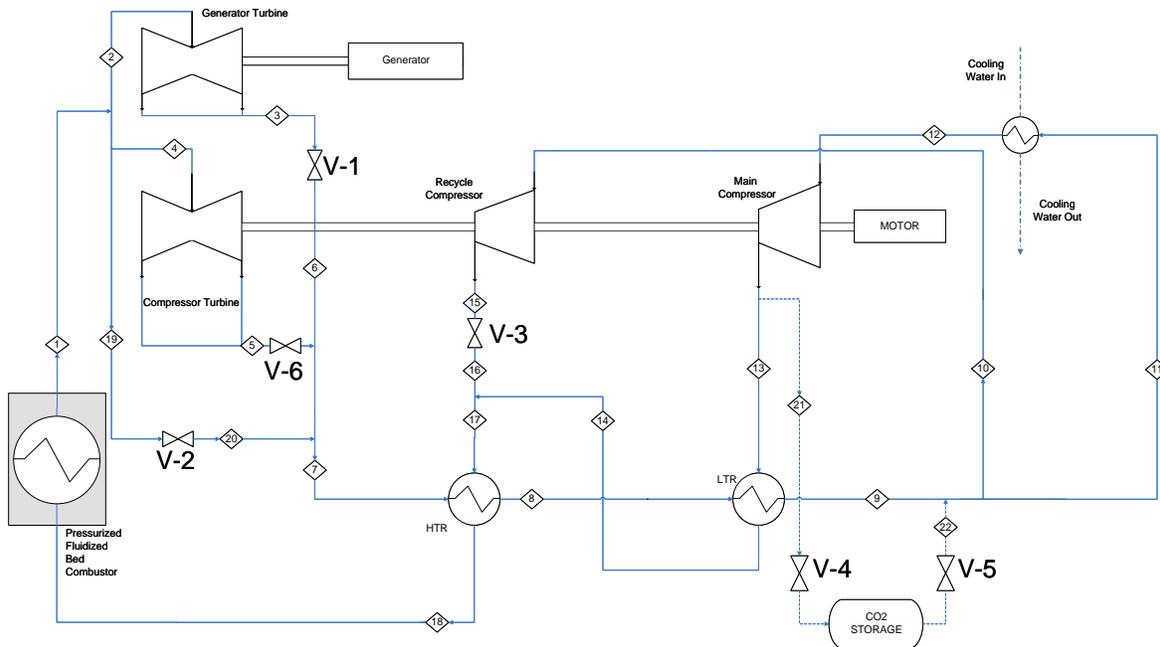


Figure 4: Revised SCOT System Arrangement with Reduced Valves and ByPass Loops to Reduce Cost and Complexity of Operation

SCOT System Start-up

The SCOT system will be pressurized once the PFBC bed temperature reaches 150°F, and this is accomplished by opening valve V-5 on the CO₂ storage tank or, to limit the storage volume, filling from CO₂ tanker trucks using a vaporizer. Once the system is filled, valve V-5 is closed, the generator turbine valve (V-1) is closed, and the recycle CO₂ flow is controlled by adjusting valve V-3 (see Figure 5). A motor on the compressor shaft will be used to force circulation and initiate preheat of the SCOT system. The compressor turbine will quickly begin offsetting motor power until it can supply all of the compressors power requirements as shown in Figure 6. The system will be controlled to a low flow during the initial heat-up period by bypassing greater flow through valve V-2 than through the compressor turbine. Once the recuperators have reached their average temperatures (710°F for the HTR and 244°F for the LTR), and the bed has reached 1100°F, the PFBC is switched to coal firing. The bypass valve admits more flow to the compressor turbine, increasing SCOT pressure and flow. The bed heat duty continually rises and increases the flow to 50% of maximum flow.

During this ramp, the generator turbine will be preheated by slightly opening valve V-1 as shown in Figure 7. Once 50% flow is reached, the generator turbine flow will be increased by further opening valve V-1, and will be synchronized with the grid frequency. Once connected to the grid, the system will increase heat duty to the desired load (Figure 8). Additionally, the system control will be transitioned to the turbine compressor by closing valve V-2 and throttling valve V-6, completing the startup. A system model of the heat-up and start-up to full power was analyzed and is shown in Figure 9.

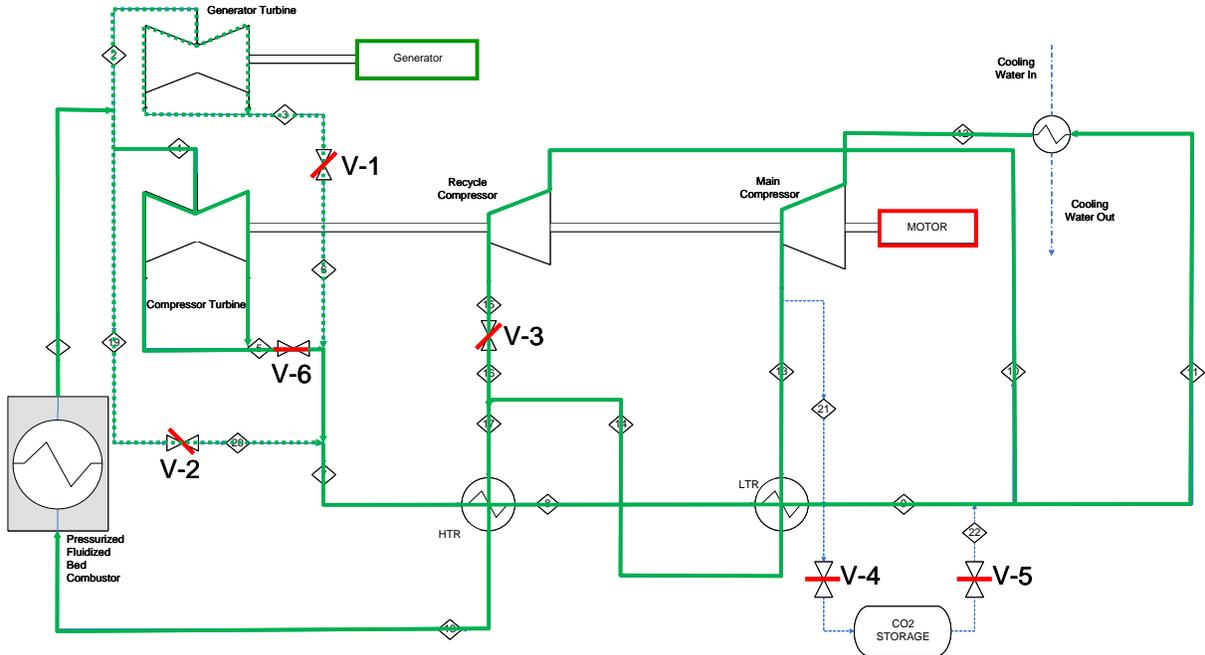


Figure 7: Power Turbine is Preheated by Partially Opening Valve V-1

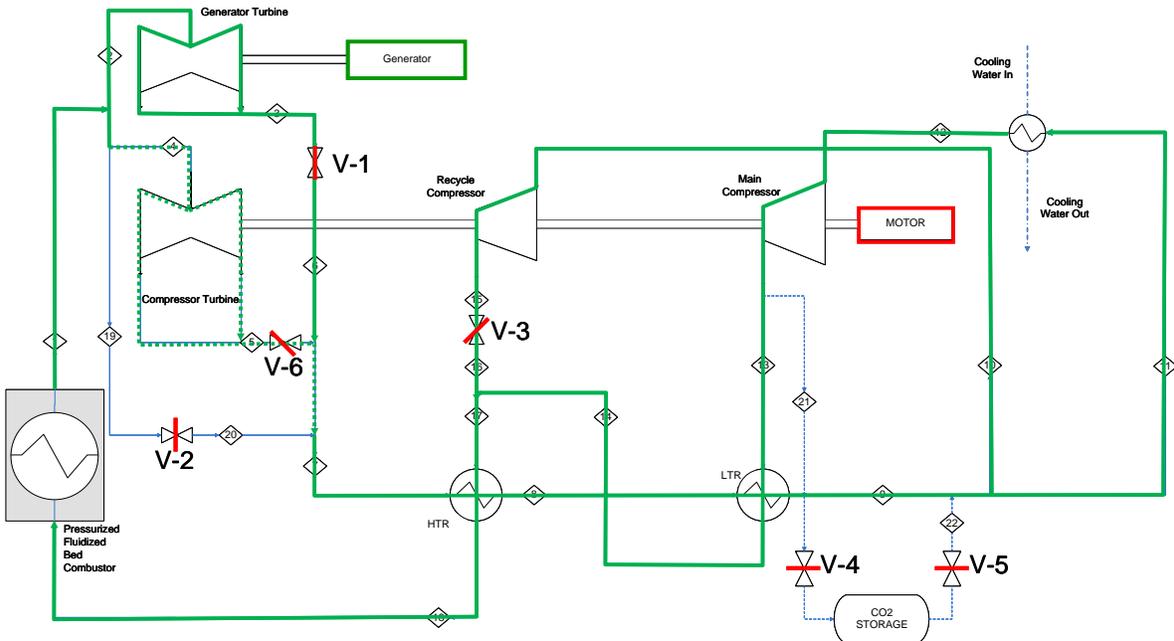


Figure 8: SCOT Transition to Power Generation is Complete with Synchronization of the Generator Turbine to the Electrical Grid

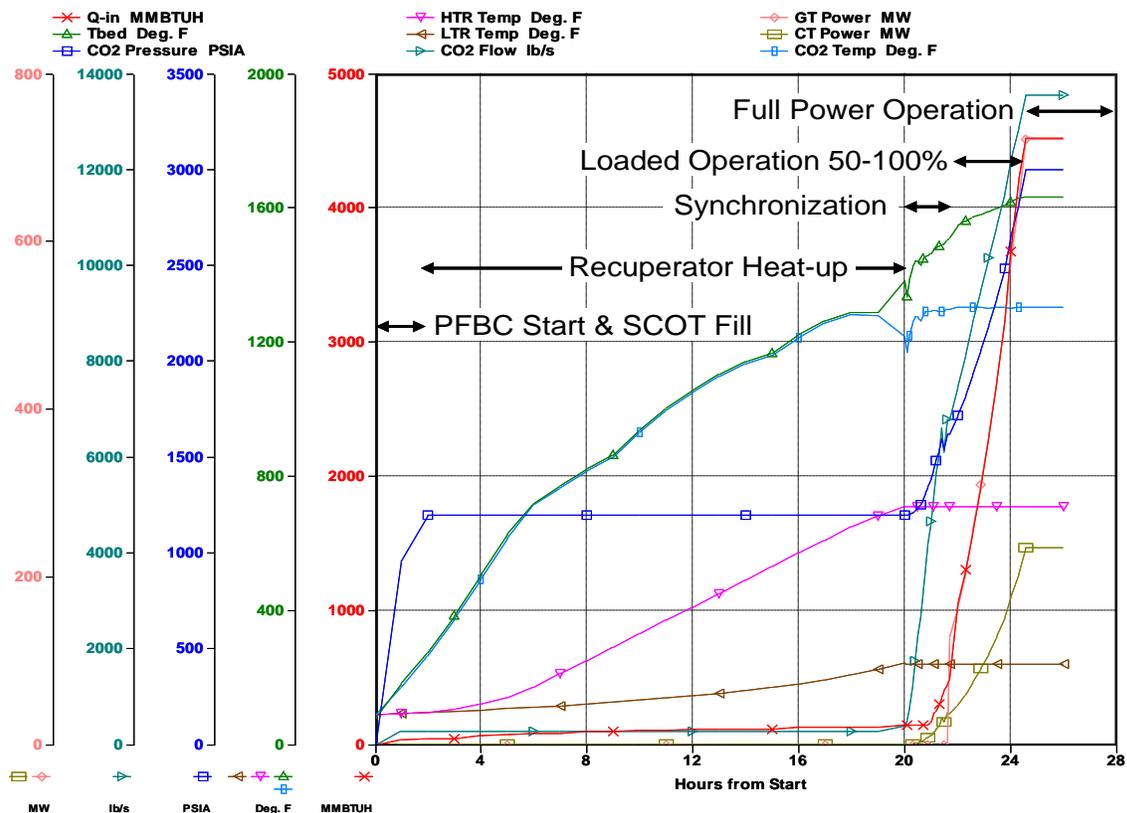


Figure 9: PFBC and SCOT Cold Start Transient

SCOT System Shutdown

There are three shutdown scenarios envisioned:

- Planned Shutdown
- Emergency Shutdown
- Disconnect from Grid Shutdown

When a planned shutdown occurs, the system will drop to 50% loaded power with the PFBC following the load. At 50%, the fuel will be cut to the unload setting. During this time, the bed temperature will drop, and the generator turbine isolation valve (V-1) will close and the bypass valve (V-2) will open to maintain power to the compressor turbine. Once this has stabilized, the fuel to the PFBC will be cut and the oxygen will be switched to air. Depending on whether the shutdown interval is for a hot or cold restart, the SCOT CO₂ flow will be circulated until appropriate bed temperatures are met before CO₂ circulation is stopped.

Emergency shutdown and disconnect from grid are envisioned to have the same shutdown procedure. In either case, the system does not have the luxury of gradually reducing heat load and generator turbine power. At the initiation of this type of shutdown event, the fuel supply will be stopped as well as the oxygen supply. The bed will continue to be circulated with the recycle CO₂. In parallel, the generator turbine flow will be stopped by closing valve V-1, and the bypass valve V-2 will be opened to a point where flow supplied to the compressor turbine is maintained. The CO₂ temperature will decay and SCOT CO₂ flow will drop until the bed reaches a safe temperature. At that time, the compressor turbine flow will be decreased by further opening the bypass valve V-2 until the SCOT flow stops.

There is risk of bed overheating during shutdown. Two methods are utilized to control temperatures within the PFBC during emergency shutdown. First, the coal and oxygen feeds are stopped immediately. This allows for minimal heat to be removed once the coal and oxygen are stopped. Second, water is added to the flue gas and recycle systems to offer immediate protection of the PFBC and the solids handling equipment.

Off Design Operation

The turbines can operate aerodynamically without limitation during startup and shutdown since the turbine operating conditions are far away from the dome. The only restriction on the turbines will be rotordynamic and structural limits, which will be assessed during turbine detailed design. Start-up and shutdown operation of the main compressor using sCO₂ are within the surge, choke, and speed limits. Operation of the main compressor near the critical point offers thermodynamic efficiency advantages using sCO₂ but poses a risk of localized two-phase flow within the main blade passage. AR's preliminary investigation has shown that localized condensation within the blade passages will not have sufficient time to damage the blades if precise system control of compressor inlet conditions can be achieved. Start-up and shutdown operation of the main compressor and recycle compressor are within the surge limits.

Summary

A compact arrangement was defined for the SCOT power island that minimized piping lengths and therefore pressure drops. The unique configuration utilized stacked heat exchangers to ensure that even with the large recuperators the plant fits within a relatively compact (151' X 177') footprint. Pressure drops were calculated for the piping lengths and included in the system model. The total pressure drop in the entire SCOT power island was calculated to be approximately 120 psi. Updated performance maps were created for the turbines, compressors, and heat exchangers, and these were included in the system model along with the pressure losses to create a new baseline PFD. The SCOT power island efficiency was 50.4% after the pressure drops were included. The ZEPS™ power plant net efficiency (HHV) with these cycle efficiency numbers is 37.3%. The ZEPS™ power plant with sCO₂ Brayton cycle offers about an eight percentage point efficiency improvement over the state-of-the-art oxy-fired SCPC and about a four percentage point improvement over a steam Rankine based ZEPS™ power plant.

After the PFBC startup procedure was refined and the SCOT system control needs were evaluated, a final system configuration with six valves, one bypass leg, and the CO₂ storage system was defined. Quasi-steady state and transient analyses showed that system start-up, shutdown, and steady-state control can be successfully achieved for the ZEPS™ system. An integrated PFBC and SCOT system start-up process was defined that pre-heats the bed to a safe temperature for coal combustion (~1100°F) by burning natural gas and air, and then transitions to a steady state operating temperature of 1600°F.

Two SCOT system start-up approaches were analyzed in detail and a motor assist bootstrap was selected. A motor on the compressor shaft will be used to force circulation and initiate preheat of the SCOT system. The compressor turbine will quickly begin offsetting motor power until it can supply all of the compressors' power requirements. Analyses showed that a low system flow rate (2% of the full power design flowrate) was sufficient to thermally condition all equipment and avoid life limiting thermal shock with the high thermal inertia of the LTR being the limiting item.

Finally, the SCOT system will be pressurized once the PFBC bed temperature reaches 150°F. The motor on the compressor shaft will be used to force circulation and initiate preheat of the SCOT system. Once the recuperators have reached their average temperatures, and the bed has reached 1100°F, the fuel is switched to coal firing in the integrated sequence. The bed heat duty continually rises and increases the flow to 50% of maximum flow. Once 50% flow is reached, the generator turbine flow will be increased and will be synchronized with the grid frequency. Once connected to the grid, the system will increase heat duty (and flow rate) to the desired load.

Conclusions

The study results show that the ZEPS™ plant system with the SCOT equipment can be operated under the defined start-up, shut-down and transient conditions. Next steps should include evaluating compact heat exchangers for the recuperators to minimize recuperator volume, weight, and cost as well as pre-heat time. The ZEPS™ system baseline with realistic accounting for the pressure losses was analyzed to have a net plant efficiency of 37.3% and remains highly attractive when compared to the 29.2% efficiency for an atmospheric oxy-fired supercritical steam pulverized coal plant with carbon capture.