Power Systems Development Facility: Commissioning and Initial Operation of a Transport Reactor System with a Westinghouse Candle Filter

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Abstract

The Power Systems Development Facility (PSDF) is a Department of Energy (DOE) sponsored, engineering scale demonstration of two advanced coal-fired power systems including hot gas cleanup. This paper provides a summary of the operation of The M.W Kellogg Transport reactor and the Westinghouse filter vessel at the PSDF, located in Wilsonville, Alabama. The construction status and startup schedule of the second train, a second generation PFBC system designed by Foster Wheeler, is also briefly discussed.

The Transport reactor is an advanced circulating fluidized bed reactor designed to operate as either a combustor or a gasifier using one of two possible hot gas clean-up filter technologies (Particulate Control Devices or PCDs) at a component size readily scaleable to commercial systems. Construction of the Transport reactor and associated equipment was completed in early summer 1996. By mid-summer all separate components and sub-systems were fully operational and commissioning work was focused on integration issues for the entire Transport reactor train.

Initial operation of the Transport reactor as a combustor was achieved in August 1996. Since then the Transport reactor with the Westinghouse filter vessel in the process has operated on coal feed for more than 750 hours up to a maximum pressure of 180 psig. Expected coal feed rates and solid circulation rates corresponding to the operating pressure have been achieved. Initial problems associated with the startup burner and the dense phase solid transport systems have been studied and resolved.

Throughout the first year of testing, the Westinghouse PCD has been in operation. The PCD inlet temperature was increased from 600ºF to 1380ºF as experience was gained with Transport reactor operations. Due to problems with the cyclone operation, the particulate loading and particle size to the PCD were much larger than desired in initial testing. However, the loading has substantially decreased over the year and design values have now being achieved. The PCD pressure drop has remained low throughout all runs.

Operationally, the PCD has worked well, with few mechanical problems. Ceramic filter elements from Pall, Coors and Schumacher have been tested to date.

Southern Research Institute's sampling systems on the PCD inlet and outlet are now operational and have provided valuable data confirming solids loading to and from the PCD during the testing periods. Isokinetic samples using a batch sampler and a cyclone manifold have provided valuable data to support the operation of the Transport reactor and PCD. Samples taken from the outlet of the PCD indicate that the collection efficiency of the PCD is high, as measured outlet particulate loadings are typically below 1 ppm.

Introduction

The objectives of the PSDF are to develop advanced coal-fired power generation technologies through testing and evaluation of hot gas cleanup systems and other major components at the pilot scale and to assess and demonstrate the performance of the components in an integrated mode of operation. The facility is sized to test the components at capacities that are readily scaleable to commercial systems.

The primary focus of the PSDF project is to demonstrate and evaluate high temperature PCDs that are the single most important component required for successful development of advanced power generation systems. High temperature PCDs are a common component of advanced gasification and APFBC technologies, both of which will be evaluated at the facility.

Project Description

Initially, the five modules at the PSDF will be configured into two separate test trains. The Transport reactor train will be used to produce a particle-laden gas for testing of two of the PCDs. The APFBC module will be integrated with the topping combustor and gas turbine for long term testing of the PCDs in an integrated system and assessment of the control and integration issues associated with the APFBC system.

***Transport Reactor*:** The M.W. Kellogg Transport reactor technology, under development at the PSDF at a scale of about 2 tons/hour of coal feed, can operate either as a gasifier or combustor. Tests will be conducted in both configurations. In the gasifier mode, coal is introduced and fired substoichiometrically. The coal devolatilizes, the volatiles pyrolize and the residual char is steam gasified. This staging of the gasification reaction forces oxygen to react with char rather than volatiles, as is characteristic in fluid bed gasifiers. As a result, the size of the gasifier (and the capital cost) is reduced because the amount of char to be gasified by reaction with steam (which is slow at the expected operating temperature) is reduced substantially. Operation in the combustion mode is similar, but the reactor is fired with excess air and a fluidized bed heat exchanger is included in the reactor loop to remove the heat released from the system.

Advanced PFBC: The APFBC continues to emerge as a viable coal-based advanced power generation technology in the utility industry for both repowering and new plants. First generation PFBC technology offers the advantages of being more compact and efficient, compared to pulverized coal units, and has a simpler design than most advanced power generation systems. However, first generation PFBC systems have limited efficiency due to low temperature operation and the use of ruggedized turbines. To improve efficiency, PFBC systems must employ hot particulate removal and a topping cycle in order to use advanced turbine designs. These second-generation APFBC designs are expected to be capable of achieving 45% net plant efficiency. Advancing the development of APFBC systems is one of the primary goals of the PSDF.

At a scale of 3 tons/hr, the Foster Wheeler APFBC system under development at the PSDF utilizes a topping cycle. It is a hybrid system that combines partial gasification with PFBC. Coal is first fed to a pressurized carbonizer, where it is converted to a low-Btu fuel gas and char. The char produced in the carbonizer is transferred to a circulating PFBC (CPFBC) where it is subsequently burned. Sulfur is removed in the process by the addition of limestone into the carbonizer and CPFBC. The carbonizer fuel gas and CPFBC flue gas are cleaned of particulates in separate ceramic filters, after which the fuel gas is fired in a specially designed topping combustor outside a high-temperature gas turbine using the CPFBC flue gas as the oxidant.

Multiannular Swirl Burner (MASB)/Turbine: To withstand the expected severe conditions in the combustor in topping application, a Multi-Annular Swirl Burner (MASB) is chosen to combust the fuel gas from the carbonizer and increase the temperature of the CPFBC vitiated air to 2350°F. The wall cooling challenge in the MASB is met by effectively utilizing the 1600°F vitiated air from CPFBC and maintaining a cooling air layer of substantial thickness through concentric annular passages in MASB. The hot gas is expanded through a gas turbine (Allison Model 501-KM), powering both the electric generator and air compressor.

Particulate Control Devices: At the PSDF, four different PCDs will be evaluated initially. Industrial Filter & Pump Mfg. Co. (IF&P) will supply one PCD that will be tested on the Transport reactor train. The IF&P PCD is sized to match the gas flow requirements from the MWK Transport reactor and the fuel gas from the Carbonizer in the APFBC system and can be interchanged between the two trains.

Westinghouse will provide two PCDs. One will be tested on the MWK Transport reactor and is interchangeable with the Carbonizer PCD in the APFBC process. The Westinghouse PCD will be capable of operating with several types of filter elements, but the initial configuration will use candle filters. The APFBC system requires two PCDs. The second Westinghouse PCD will be used to treat the vitiated air from the combustor in the APFBC system, and will not be interchangeable with other PCDs at the facility. The fourth PCD is a moving granular bed filter from Combustion Power Company (CPC). This PCD will be tested in both oxidizing and reducing environments with gases from the

Transport reactor. Because of its substantially different configuration, it is not expected to be tested on the APFBC system.

Fuel Cell: Integration of a fuel cell with the Transport gasifier will be completed after stable operation of the system is assured. The fuel cell will be connected to the advanced gasifier downstream of the PCD and the secondary gas cooler. This Integrated Gasification/Fuel Cell (IG/FC) system will be the first to operate with a hot gas cleanup system. IG/FC systems have the potential of achieving system efficiencies above 55% with extremely low emissions.

Project Status

Construction of the Transport reactor train along with the necessary balance-of-plant systems was completed last year. Various equipment and systems were commissioned during the final stages of construction. Commissioning of the entire train and combustion characterization tests followed this.

On the APFBC system, the major activities during the past year have been completion of final stages of design and procurement of major equipment and bulk items. The APFBC train is currently under construction and commissioning activities associated with simple cycle operation will start later this year. Commissioning of the CPFBC portion of the APFBC system will begin next year.

Transport Reactor Train

This paper discusses the commissioning and operation of the Transport reactor train with the Transport reactor operating as a pressurized combustor. The Transport train operating in the combustion mode is shown schematically in Figure 1. Two PCDs are shown in this flow diagram, however during operations, only one PCD will be tested at a given time with the Transport reactor. The intent is to be able to install, change out, or provide maintenance on a second PCD while another is being tested. This will result in increased flexibility for the test facility and will reduce down time. The Transport reactor train is sized to process sufficient coal generating 1,000 acfm of gas to test the PCDs. Indirect cooling of the gas from the Transport reactor will allow testing of the PCDs with inlet temperatures between 650°F and 1,500°F and at pressures in the range 100 psia to 280 psia. The PCD in this train will receive coal ash laden gas from the Transport reactor operating in either gasification or combustion mode. The gas exiting the PCDs will be thermally oxidized in the gasification mode, cooled and filtered in the baghouse before discharge from the stack. The ash/char mixture produced in the gasification mode will be oxidized in the Sulfator prior to disposal.

A Westinghouse supplied filter system was used during commissioning of the Transport train. The dirty gas enters the PCD below the tubesheet and flows through the candle filters, and the ash collects on the outside of the filters. The clean gas passes from the plenum/candle assembly through the plenum pipe to the outlet pipe. As the ash collects on the outside surface of the candle filters, there will be a gradual increase in the pressure drop across the filter system. The filter cake is periodically dislodged by injecting high pressure gas pulse to the clean side of the candles. The cake then falls to the discharge hopper. When the Transport reactor is operated in combustion mode, the pulse gas will be high pressure air. The pulse gas is routed individually to the two plenum/candle assemblies via injection tubes mounted on the top head of the PCD vessel. The pulse duration is typically 100-500 milliseconds.

Commissioning Tests

All of the equipment required for combustion mode operation of the Transport reactor system was installed by mid-summer 1996. Commissioning began in October 1995 on subsystems as they were completed and proceeded in parallel with the final construction activities. During the months of May and June of 1996, three major startup milestones in the commissioning of the Transport reactor were completed: (1) the first, complete system pressure test up to 385 psig, (2) Transport reactor refractory joints cure to 1000 °F, and (3) fluidization trials. Before the refractory joints cure, the startup burner was commissioned during which problems associated with the design of the burner were corrected. The fluidization trials used alumina as the start-up bed material. The alumina was circulated while using the startup burner as a source of hot gas for heating the reactor. Following fluidization trials, borescope inspections revealed that the reactor loop and cyclone refractories were in good condition.

Combustion Characterization Tests

During the first successful coal combustion characterization test run, the startup burner was fired to heat the reactor system and alumina was added as the startup bed material. Coke breeze was used to assist reactor preheat after the reactor temperature reached 1000°F. When coke breeze ignition was established, the startup burner was gradually ramped down and was finally shut down. The reactor preheat with coke breeze combustion was continued until the reactor temperature was high enough to prevent coal tar formation. Coal feed injection into the reactor was then initiated. Locally available Calumet mine Alabama bituminous coal and Plum Run dolomite were used as the test coal and sorbent.

The reactor pressure was gradually increased from 100 psig to 160 psig during coal combustion. The riser temperature was maintained between 1600 - 1650°F. During the test run, a hot re-start was attempted three hours after completely shutting down the reactor loop by slumping the bed and turning down the aeration flows to minimum standby flows. Once the startup sequence was initiated, it took less than a half hour to feed coal and observe immediate combustion and establish control of the process. About 86 hours of on-stream coal feeding was achieved resulting in approximately 32.2 tons of coal fed to the unit. Dolomite was used as make up bed material because of low starting bed level in the reactor and combustion heat exchanger. Consequently, its feed rate was higher than required for *in situ* sulfur capture.

During the first and subsequent combustion characterization test runs, the startup burner was operated at higher firing rates and reactor pressures. Also, the reactor circulation and temperature control, solids feeding into the reactor, the operation of Westinghouse filter vessel and backpulse system and the operation of the spent solids, fines discharge and transfer systems were successfully demonstrated. Coke breeze assisted combustion preheat and coal combustion start-up sequences were also successfully demonstrated.

During the initial coal combustion tests, excessive solids carry-over was experienced. It was suspected that the cause was due to either poor disengager and primary cyclone collection efficiencies, unstable cyclone dipleg operation, or both. To determine the cause, disengager efficiency tests were performed using silica sand. The riser velocity and solids loading to the disengager were varied to investigate their effect on disengager operation. The reactor was operated at approximately 60 psig and 200°F. Solid samples were taken from the reactor and the discharge of the PCD to measure the size distribution exiting the disengager. The PCD solids at the end of each test run period was transferred to the ash silo and a solid sample was taken for analysis. The particle size distribution was relatively finer at the beginning of the test. Using the solids circulation rate and the solids collected by the PCD, the average disengager efficiencies varied between 84% and 99% under various test conditions.

The following general conclusions were drawn from the disengager efficiency tests: the disengager efficiency was lower than would be expected for the coarser particle size distribution used for this test; the disengager appeared to be more efficient at low riser superficial velocity; and the performance of the disengager during this test did not appear to be significantly different from its performance during previous test runs. Based on these results, and assuming a lower disengager efficiency than the design value of 97.6%, the primary cyclone inlet cross-sectional area was reduced by approximately 50% and the circular inlet was changed to a rectangular inlet cross-section to improve the efficiency of the gas-solids separation system. In subsequent test runs, it was planned to address the cyclone dipleg stability problems through manipulation of dipleg aeration.

Following the modifications to the primary cyclone, the Transport reactor was operated on coal feed for 223 hours in CCT4 and 279 hours in the CCT5 combustion test runs. During this time, approximately 269 tons of coal was processed. A fast track start up was implemented with the period between start of propane pre-heat and steady state on coal reduced to less than 12 hours. A preliminary understanding of the operation of the cyclone/cyclone dipleg was developed. Through manipulation of cyclone dipleg aeration, a stable seal was established with solids in the dipleg. Because the cyclone dipleg solids seal was stable, the Transport reactor operation was very stable. For the first time, the solids loss rate out of the reactor was much less than solids input rate. This allowed solids level in the reactor to build up. Also, the solids circulation rates were much higher because the cyclone and the cyclone dipleg were working more effectively. The PCD backpulse induced instabilities in the reactor loop that sometimes caused the cyclone dipleg seal to become unstable resulting in momentary high solids loss rate. By making adjustments to the PCD pulse parameters the effect of PCD backpulse was lessened to some degree.

Dolomite was fed into the reactor for *in situ* sulfur capture and to improve solids flowability in the cyclone dipleg. Higher coal feedrates were achieved because the solids circulation through the combustor heat exchanger was higher and smoother. Also, the PCD was tested at a higher inlet temperature than previously and the inlet dust loading was lower and closer to the design rate. Figure 2 shows the solids circulation and coal feed hours that were achieved during various combustion test runs.

Performance of Westinghouse PCD

The Westinghouse PCD has been operated throughout the first year of operation. Installation of the filter was completed in June 1996, and pressure testing and commissioning began in July. The tubesheet of the PCD is “sandwiched” between two 84” flanges, and the biggest challenge during commissioning was sealing this joint. Flexitallic spiral wound gaskets were used on two occasions, but the vessel could not operate under full operating pressure until the gasketing material was changed to a 3125SS material manufactured by Garlok.

During the initial testing, the PCD inlet temperature was limited to approximately 600ºF by flowing all of the gas from the Transport reactor through a gas cooler. The primary reason for operating at the low temperature was to minimize the potential for ash deposition and bridging while the Transport reactor startup was underway. During subsequent test campaigns, the temperature has been raised first to 1000ºF and is currently operating at nominally 1400ºF.

Throughout the testing, the biggest challenge has been to control the solids carryover to the PCD from the Transport reactor. During upsets, the particulate loading to the PCD has been measured in excess of 70,000 ppm. However, as experience has been gained with the operation of the Transport reactor, the particulate loading has decreased substantially and is typically in the design range of 4,000 to 16,000 ppm. In addition to the large particulate loading, the particle size entering the PCD has been quite large. Samples taken from the PCD ash outlet often had a median particle diameter exceeding 100 μm. As with the loading, the particle size entering the PCD has decreased with operating experience.

The large particle size is credited with the low baseline pressure drops measured across the PCD. Typical values of baseline pressure drop have been 20-25 inches of water at a face velocity of 3 to 4 ft/min. The pulse system logic will activate either due to a high-pressure drop or after a mandatory timer, which is usually set for 30 minutes. Typically the pulse system only activates after this 30-minute timer and between pulses the pressure drop usually rises about 10 INWG above its baseline pressure drop. The PCD was inspected after each run and to date, there has been no ash bridging within the PCD.

Two incidents to date have occurred which have caused the failure of filter elements. Both these incidents were related to startup and commissioning of the Transport train. The first incident occurred during the first coal firing when the ash level in the PCD rose above the filter elements, causing their failure. Two positive result from this failure were that the Westinghouse failsafe devices operated successfully and there was very little particulate found downstream of the filter vessel. Also, methods were developed to detect the ash level in the PCD cone. The second incident was in April 1997 and was caused by a thermal transient during startup. A quantity of coal was fed into the Transport reactor inadvertently while the reactor and the PCD were still at low temperatures. Apparently, the coal dust ignited on the surface of the filter elements creating a thermal incident, which substantially cracked almost all of the filter elements installed. The PCD temperature at the time of the event was 360ºF.

Ceramic filter elements from Pall, Coors and Schumacher have been tested to date. Overall, the PCD has worked extremely well during its first year of operation with very few mechanical problems. There has been some dew point corrosion at the vessel manways and the tubesheet flanges. Increasing the width of the gasket material controlled the corrosion. The gasket material covers the flanged surfaces, preventing water from coming in contact with the metal surfaces. All of the auxiliaries that support the PCD - ash removal, high-pressure air and nitrogen - have also worked well once commissioning was complete.

Summary

The Transport reactor train and all associated balance-of-plant systems were commissioned during the first year of operation. A number of characterization tests were performed with the Transport reactor operating as a pressurized combustor. A few equipment problems that arose during commissioning were successfully addressed. Stable and controlled solid circulation was established through both the reactor and combustion heat exchanger j-legs. As necessary, solids were preferentially circulated through either one or both the j-legs.

The Westinghouse PCD inlet temperature has varied from 600ºF to 1380ºF as experience was gained with Transport reactor operations. Due to problems with the cyclone dipleg operation prior to CCT5 test run, the particulate loading and particle size to the PCD were high. However, the loading has substantially decreased over the year and was within the design range during recent runs. Isokinetic samples using a batch sampler and a cyclone manifold have provided valuable data to support the operation of the Transport reactor and PCD. Samples taken from the outlet of the PCD indicate that the collection efficiency of the system is quite high, as measured outlet particulate loadings are typically below 1 ppm.

In future tests, the cyclone dipleg operation will be further characterized and modified as necessary as it is key for stable reactor operation. A long duration test will be performed to test the durability of the filter candles with the Transport reactor operating in the combustion mode. Once stable cyclone dipleg operations can be proven under varying operating conditions, the Transport train will be operated in gasification mode and the filter candles will be tested under reducing environment with char and ash mixture.

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Transport Reactor Train Process Flow Diagram Combustion Mode

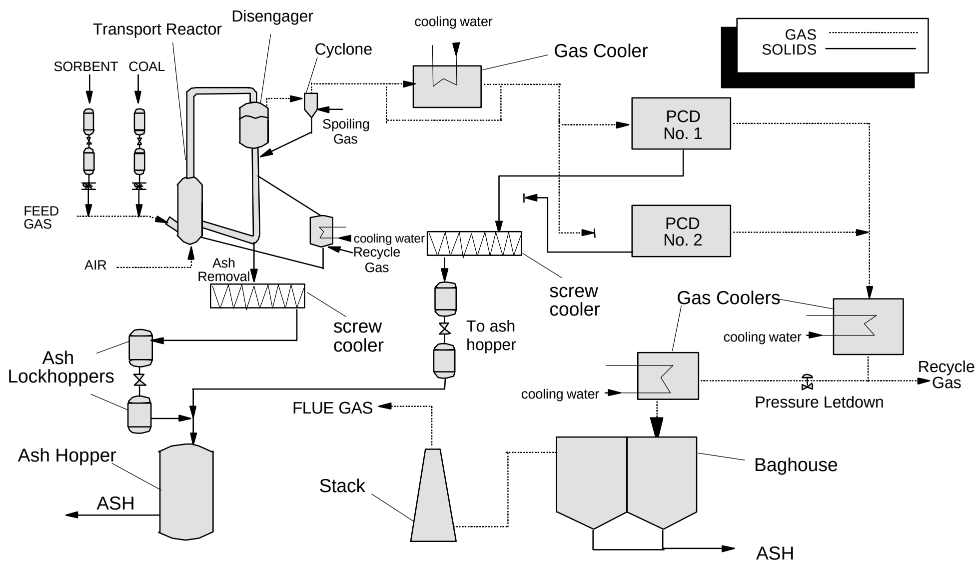

FIGURE 1

Transport Reactor Run Summary

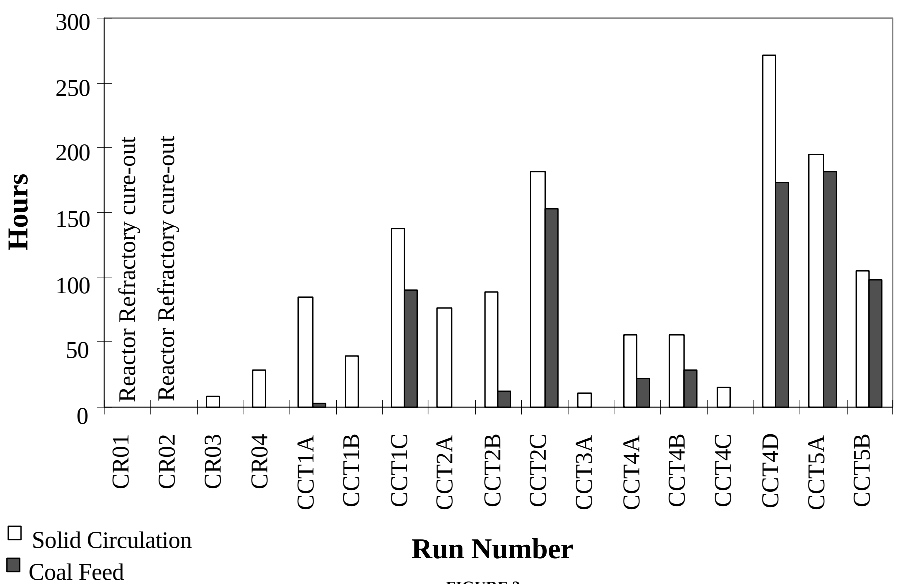

FIGURE 2