Power Systems Development Facility

Commissioning Report of M.W. Kellogg Transport Reactor Train, Westinghouse Particulate Control Device, and Associated Balance-of-Plant Equipment: September 1995 - December 1996

DOE Cooperative Agreement Number
DE-FC21-90MC25140

Volume I

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POWER SYSTEMS DEVELOPMENT FACILITY

COMMISSIONING REPORT OF M.W. KELLOGG TRANSPORT REACTOR TRAIN, WESTINGHOUSE PARTICULATE CONTROL DEVICE, AND ASSOCIATED BALANCE-OF-PLANT EQUIPMENT: SEPTEMBER 1995 - DECEMBER 1996

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VOLUME I

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August 1998

POWER SYSTEMS DEVELOPMENT FACILITY

DISCLAIMER

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ACKNOWLEDGEMENT

The authors wish to acknowledge the contributions and support provided by various project managers: Jim Longanbach (DOE), Mike Epstein (EPRI), Marty Fankhanel (MWK), Zal Sanjana (Westinghouse), and Duane Pontius (SRI). Also, the enterprising solutions to problems and the untiring endeavors of many personnel at the site during commissioning of the transport reactor train are greatly appreciated. The project was sponsored by the U.S. Department of Energy Federal Energy Technology Center under contract DE-FC21-90MC25140.

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1.0 EXECUTIVE SUMMARY

This report discusses the commissioning and operation of the transport reactor train and associated balance-of-plant equipment at the Power Systems Development Facility (PSDF) located in Wilsonville, Alabama. 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 device technology, or PCDs) at a component size readily scaleable to commercial systems. During the shakedown, commissioning, and initial operation phases, the transport reactor was operated as a pressurized combustor. A Westinghouse supplied filter system was commissioned and operated along with the transport reactor.

The objectives of the PSDF are to develop advanced coal-fired power generation technologies through testing and evaluation of hot gas clean-up 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 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. The facility is sized to test the components at capacities that are readily scaleable to commercial systems.

The M.W. Kellogg Company (MWK) and Southern Company Services, Inc., (SCS) carried out the design and engineering of the main process and balance-of-plant, respectively. Commissioning began in September 1995 and proceeded in parallel with construction activities. Construction of the transport reactor and associated equipment was completed in early summer 1996. By midsummer all separate components and subsystems were fully operational and commissioning work was focused on integration issues for the entire transport reactor train. A schematic process flow diagram of the transport reactor train is shown in figure 1-1.

During the months of May and June of 1996, three major start-up 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 cured to 1,000°F, and (3) fluidization trials. Before the refractory joints were cured, the start-up burner was commissioned, during which problems associated with the design of the burner were largely corrected. The fluidization trials used alumina as the start-up bed material. The alumina was circulated while using the start-up 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.

The feedstock preparation system, bought as a "turn-key" installation, was commissioned in May and June 1996. The main air compressor (CO0201) designed to supply 365 psia, 400°F air required by the process for combustion, solids conveying, standpipe aeration, and start-up burner, was declared fully operational by mid-July 1996 after commissioning and tuning. The high pressure air compressor used to supply air for backpulsing the Westinghouse PCD during combustion mode was commissioned during July 1996. The high-pressure nitrogen system for use during gasification mode is currently being commissioned.

The service water system, demineralized water system, raw water system, SCS and MWK closed-loop cooling water systems, and circulating water system were fully commissioned during the second quarter of 1996. The chemical injection systems for the MWK steam/condensate system, the SCS and the MWK closed-loop cooling water system, and the circulating water system were tested in April 1996. The MWK steam/condensate system hydrotest and chemical cleaning was completed earlier in November 1995.

Nitrogen is supplied to the plant by a (BOC) cryogenic nitrogen separation plant. The medium- and low-pressure nitrogen piping pneumatic tests were completed with both being commissioned in the second quarter of 1996. Interface lines to the on-site nitrogen generation plant were flushed and blown out. Pneumatic testing of the MWK nitrogen piping was conducted at 110 percent of design on low, medium, and high pressure lines. In early May, BOC filled the backup low and medium pressure liquid nitrogen tanks and began to provide nitrogen product to the facility.

The heat transfer fluid (HTF) system is used to cool the solids that are removed from the transport reactor standpipe, the sulfator, and the fines from the PCDs. The fluid (UCON-500 from Union Carbide) is circulated through both the outer shell and the flights of the screw cooler in all three applications. The HTF system was successfully commissioned during the first quarter of 1996. The diesel generator that serves as the backup power source was operated in the last week of May 1996.

The final hot gas clean-up system (baghouse) was operated periodically from March until June in bypass mode to provide a flow path for thermal oxidizer (BR0401) commissioning activities. The system was functionally checked in June and performed as designed. The bags were then preconditioned and the baghouse ash removal system was operated to remove the ash from the baghouse to the ash silo.

The propane system was pressure tested and the storage tanks filled during the first quarter of 1996. An on-line gas analyzer system is used to measure the moisture, SO_2, NO_X, O_2, and CO present the product gas stream. Parts of the analyzer system were commissioned and ready for operation.

There are five MWK-supplied feeder/transport systems controlled by one PLC program. Commissioning trials of the dense-phase systems inside the process structure were completed in April 1996 by transferring alumina from system to system using temporary piping loops to short-circuit the system for testing. Alumina is being used as a start-up bed material until the process has created enough ash to use as a start-up bed. The test material has a bulk density of 110 lb/ft^3 and mean particle size of 170 μm. As part of the commissioning tests, the solids were transported to the reactor standpipe. The spent solids screw cooler (FD0206) was used to feed the solid from the standpipe to the spent solids transporter system (FD0510) from which the alumina was pneumatically conveyed to the spent solids feeder system (FD0530). The sizing of the alumina corresponds with the specifications for the mill outputs, although the density is more than twice that of coal ground to the same size. This density difference from original design, the easy flowability of alumina, and the hardness of the alumina crystals presented a challenge to some of the equipment.

The rotofeeders on the coal feed system (FD0210), the sorbent feed system (FD0220), and the spent solids feeder system (FD0530) were problematic. The rotofeeders would seize and stop the motor. When the rotofeeder (FD0530) was taken apart for inspection, it was found that the stainless steel rotating part was galling and seizing against the top plate which allowed ash to fall through an open section of the plate while the rotating part takes a fixed volume of ash under the plate to the transport route. The galling was thought to be due to the abrasive nature of the alumina. The plate on top of the rotor was scored and the area near the shaft indicated metal-to-metal galling with the metal possibly causing the binding. The gap between the rotor and the top stationary plate was increased by using shims.

The other problem has been associated with the Spheri valves. The valves tend to bind between the valve hemisphere and the pressure seal. Again, additional spacing has been added to the spent and fines transporter systems (FD0510 and FD0520) and standpipe ash drop tube bottom Spheri valve so that the hemisphere part will not bind but will still allow the inflated seal to provide sealing. After modifications, the systems demonstrated (with some difficulty) injection rates up to 2,000 lb/hr and withdrawal rates of over 3,000 lb/hr. Alumina was conveyed from the coal feed system (FD0210) at a rate of about 70 ft^3/hr or about 7,000 lb/hr.

The recycle gas system consists of the compressor feed cooler (HX0405), a separator, the recycle gas booster compressor intake filter (FL0401), and recycle gas booster compressor (CO0401). In combustion mode, recycle gas is used for aeration of the combustor heat exchanger (HX0203) and spoiling gas to the primary cyclone (CY0201). Gas not being consumed by the process is released from the system to join the main stream of gas flowing to the inlet of the thermal oxidizer.

The recycle gas booster (CO0401) takes suction from the upstream side of the process pressure letdown valve (PV287). Part of this gas goes to the compressor feed cooler (HX0405) where it is cooled from 600 to 120° F by exchange with cooling water. The remaining gas bypasses the cooler to maintain a 300°F compressor discharge temperature thus preventing condensation from occurring elsewhere in the process. Any condensed liquid in the gas leaving the cooler is knocked out in the separator. The gas then enters the recycle gas booster compressor intake filter (FL0401) which consists of one set of fiberglass filter elements mounted in a horizontal pressure vessel to remove any particulate matter.

The recycle gas booster compressor functional checks were completed in May. A preliminary checkout/commissioning with the compressor operating on instrument air at a suction pressure around 50 psig was performed. The compressor was commissioned under normal operating conditions in June with only minor problems encountered and solved.

The thermal oxidizer (BR0401) is a downfired, vertical combustion chambered vessel. Its major components are a combustion air blower (BL0401) and a horizontal waste heat recovery section. The thermal oxidizer functions as an incinerator and as a steam producer and also yields heat for the start-up of the steam system. The waste heat recovery section consists of steam generating and steam superheating coils to supply superheated steam to the reactor during gasification. The MWK steam drum (DR0402) supplies boiler feed water (BFW) to the generating coils via natural circulation. The flue gas exiting the thermal oxidizer's waste heat recovery section will be approximately 600°F.

In May, commissioning of the thermal oxidizer began with functional checking of both the blower control loops and programmable logic controller (PLC) details. The pilot and main burner were lit successfully. Refractory cure of the thermal oxidizer at a maximum temperature of 1,600°F was completed.

Several problems were encountered during commissioning of the transport reactor start-up burner. After installation, the burner did not pass the functional tests due to damage to both the ignitor and the flame detection rod. The originally supplied ignitor and flame detection rod were found to be unserviceable and had to be replaced. The commissioning was further complicated by the lack of a visual flame view port. Several problems have arisen during the course of the start-up burner check. The burner is the vendor's first high-pressure application, and the design was inadequate and unsafe for operation as it was received. Several modifications were made to temporarily use the existing equipment and the burner has been operating since they were completed.

There were several concerns that remained to be addressed: (1) the lack of safe turn-down in fuel flow, (2) the lack of automatic compensation for reactor pressure variations, and (3) the need for separate pilot combustion air. SCS and MWK had discussions and participated in an effort to redesign the burner to better and more safely meet the design specifications. Several problems with the packing on the burner ignitor were corrected with the deletion of the retracting mechanism for the ignitor. Cooling air ports were installed on both the ignitor and the flame rod to prevent failures due to overheating, and there has been no failure during the subsequent light-offs. The pilot orifice and the main burner designs were modified, and the start-up and operation parameters were changed. The modifications made to the original burner, with the vendor's concensus, allowed safe operation and continuation of start-up activities. The burner was originally designed for operation at 50 psig with a firing rate of 3.6 MBtu/hr; the modifications allowed operation of the burner up to 100 psig and 5.0 MBtu/hr.

During the first successful coal combustion characterization test run, the start-up burner was fired to heat the reactor system and alumina was added as the start-up bed material. Coke breeze was used to assist reactor preheat after the reactor temperature reached 1000°F. When coke breeze ignition was established, the start-up 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 on August 18, 1996. 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 to 160 psig during coal combustion. The riser temperature was maintained at between 1,600 to 1,650°F. 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 initial coal combustion tests, excessive solids carryover 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 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 percent 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 percent, the primary cyclone inlet cross-sectional area was reduced by approximately 50 percent 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.

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 with alumina as the start-up bed material. Figure 1-2 shows the solids circulation and coal feed hours that were achieved during the combustion test runs in 1996.

The Westinghouse PCD has been operated throughout the first year of operation. Installation of the filter was completed in June 1996. Figure 1-3 shows the cluster being lifted from the specially designed levels of the maintenance bay. Pressure testing and commissioning began in July. The tubesheet of the PCD is "sandwiched" between two 84-inch flanges. One of the biggest challenges 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 600°F 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 start-up was underway. During subsequent test campaigns, the temperature has been raised first to 1,000°F and is currently operating at nominally 1,400°F.

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 to 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.

An incident occurred during the first coal firing in 1996 when the ash level in the PCD rose above the filter elements, causing the failure of the filter elements. Two positive results 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.

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, prevented water from coming in contact with the metal surfaces. All of the auxiliaries that support the PCD—ash removal, high-pressure air, and high-pressure nitrogen—have also worked well once commissioning was complete.

Southern Research Institute's (SRI) sampling system on the PCD inlet was commissioned during the characterization combustion test runs. The system is now operational and have provided valuable data confirming solids loading to 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. A similar system is in the process of being commissioned to measure the PCD outlet particulate loadings.

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 midsummer all separate components and subsystems 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 has operated up to a maximum pressure of 160 psig on coal feed for more than 200 hours. Expected coal feed rates and solid circulation rates corresponding to the operating pressure have been achieved. Initial problems associated with the start-up burner and the dense-phase solid transport systems have been studied and resolved.

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 it became necessary, solids were preferentially circulated through either one or both the J-legs.

During the first and subsequent combustion characterization test runs the start-up burner was operated at higher firing rates and reactor pressures. Also, the reactor solids circulation and its effect on temperature control; solids feeding into the reactor; the operation of the Westinghouse filter vessel and back-pulse 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.

Throughout the first year of testing the Westinghouse PCD has been in operation. Using the primary gas cooler, the PCD inlet temperature was maintained below 1,000°F 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. 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. Isokinetic samples using a batch sampler and a cyclone manifold have provided valuable data to support the operation of the transport reactor and PCD.

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.

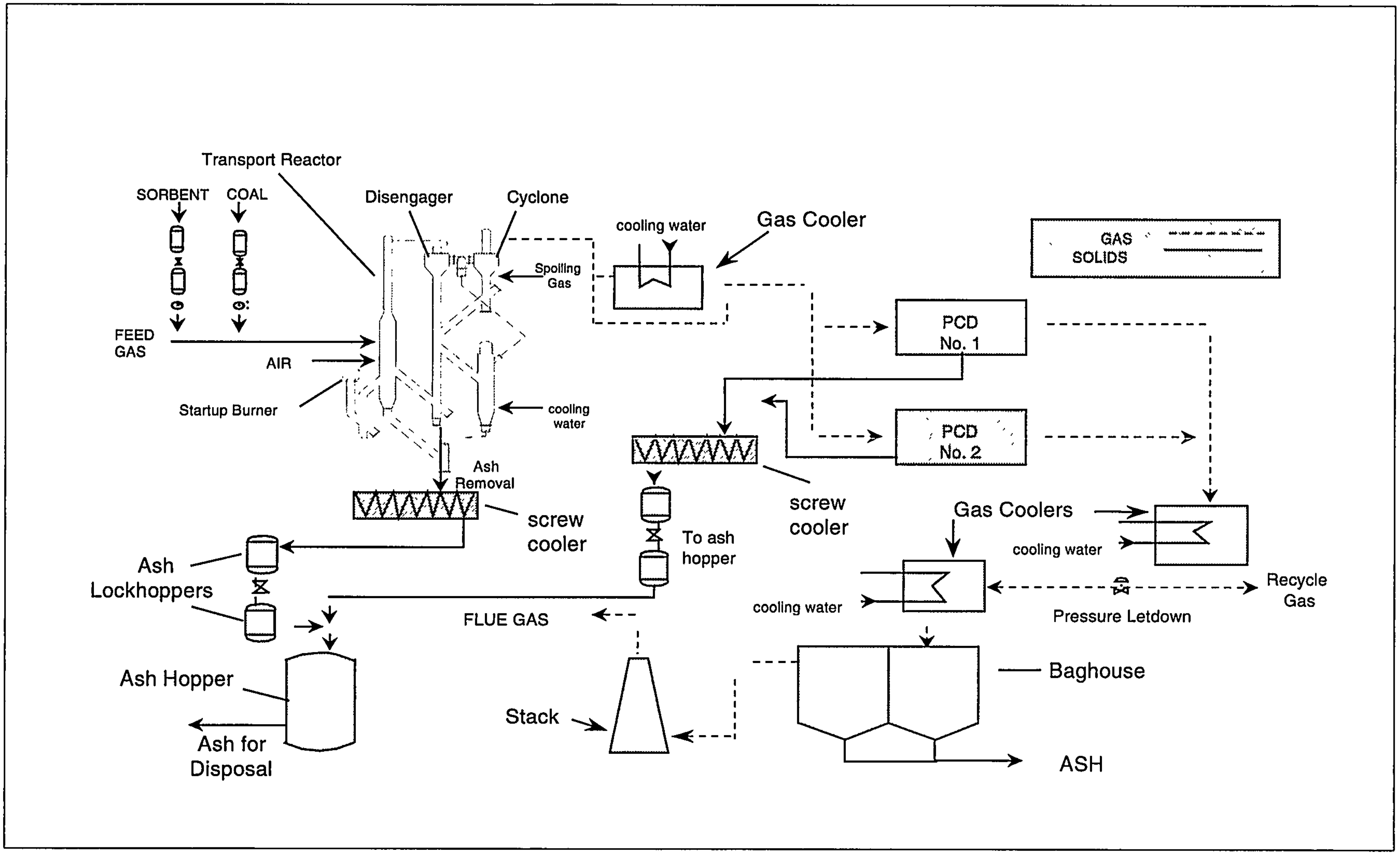

Figure 1-1 Schematic Process Flow Diagram of the Transport Reactor Train

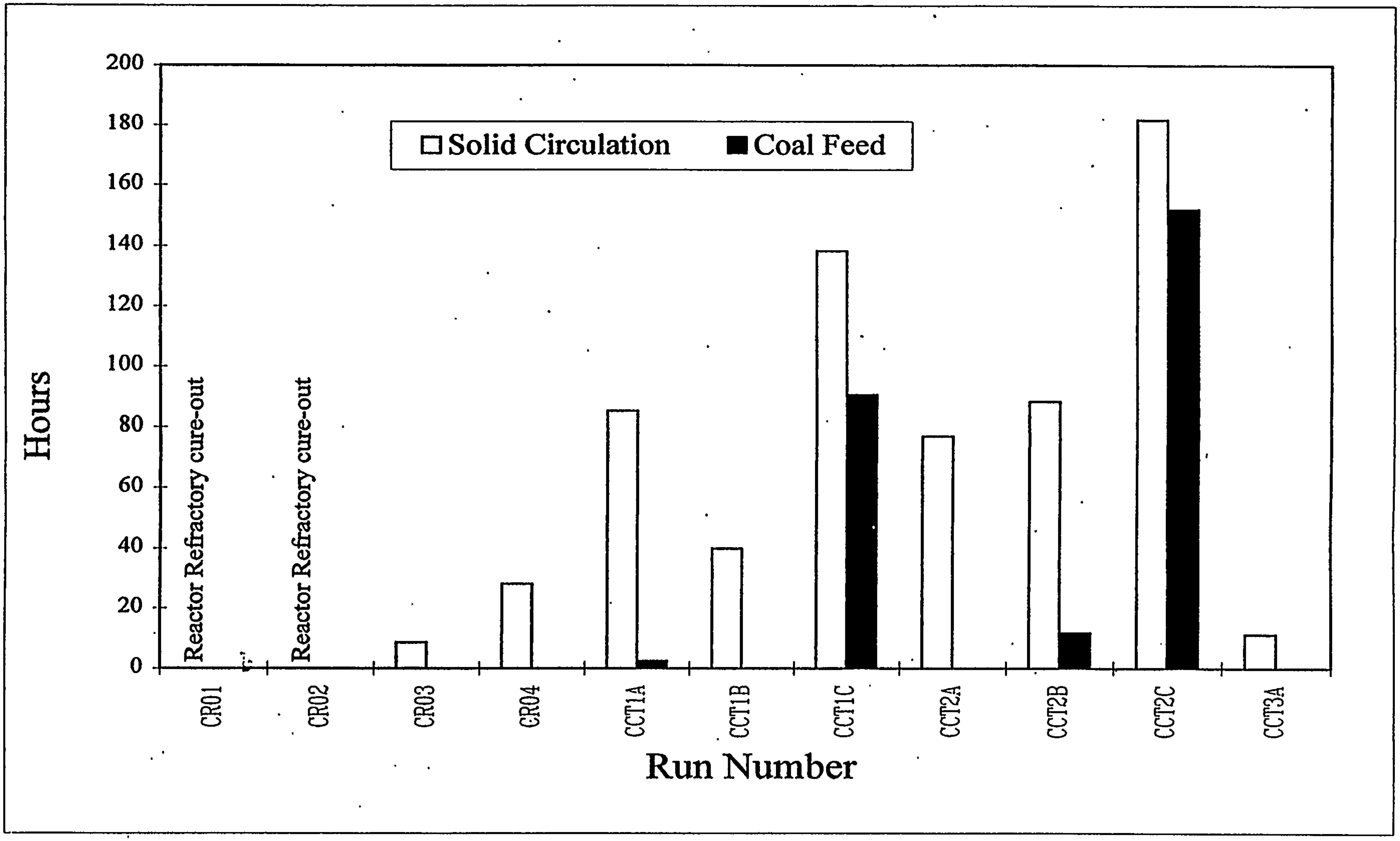

Figure 1-2 Combustion Test Runs With Hours of Solids Circulation and Coal Feed

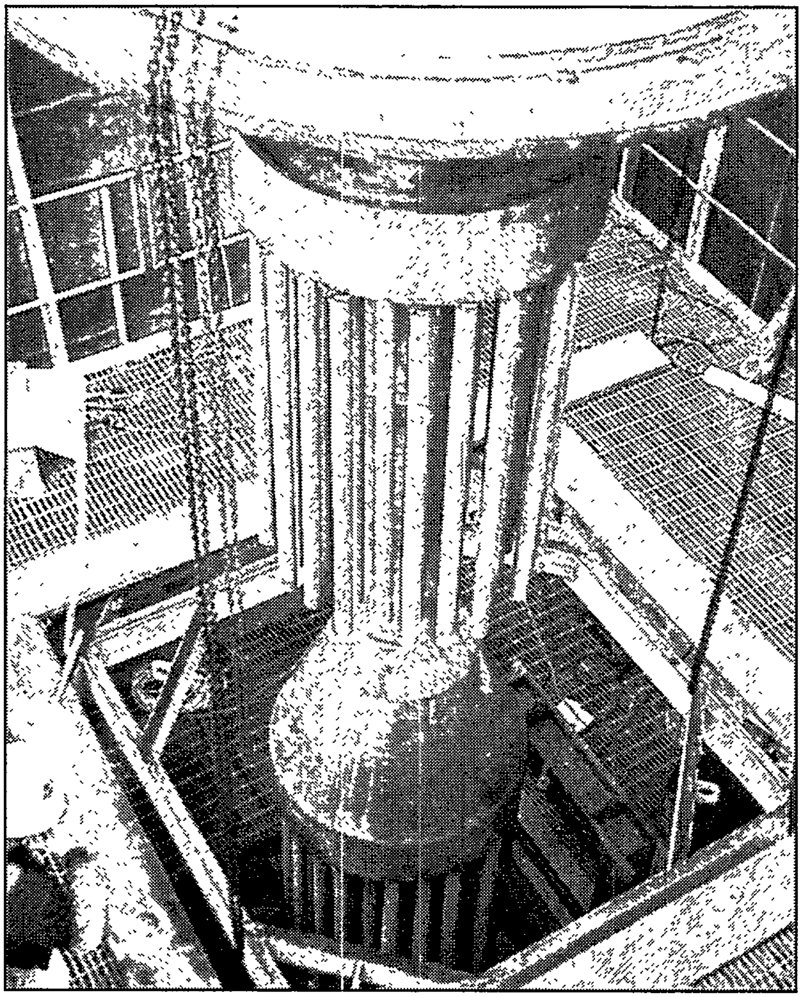

Figure 1-3 Cluster Being Lifted From the Specially Designed Levels of the Maintenance Bay

2.0 INTRODUCTION

This report provides an account of the initial operation of the M.W. Kellogg Company (MWK) transport reactor and the Westinghouse filter vessel at the Power Systems Development Facility (PSDF) located in Wilsonville, Alabama, 40 miles southeast of Birmingham. The PSDF is sponsored by the U. S. Department of Energy (DOE) and is an engineering scale demonstration of two advanced coal-fired power systems. In addition to DOE, Southern Company Services, Inc., (SCS) and the Electric Power Research Institute (EPRI) are cofunders. Other cofunding participants supplying services or equipment include MWK, Foster Wheeler, Westinghouse, Industrial Filter & Pump, Combustion Power Company, and Nolan Multimedia. SCS is responsible for commissioning and operation of the PSDF.

The transport reactor is an advanced circulating fluidized-bed reactor acting as either a combustor or as a gasifier using one of three possible hot gas clean-up filter technologies (particulate control devices or PCDs) at a component size readily scaleable to commercial systems. Design and construction of the transport reactor and required associated equipment were completed in early summer 1996. By midsummer all separate components and subsystems were fully operational and commissioning work focused on integration issues for the entire reactor system. At the same time, the first set of ceramic candles was loaded into the Westinghouse PCD. Initial operation of the transport reactor as a combustor was completed in late August, with further combustion commissioning tests completed in the last quarter of 1996.

2.1 THE POWER SYSTEMS DEVELOPMENT FACILITY

SCS entered into an agreement with DOE/FETC for the design, construction, and operation of a hot gas clean-up test facility for gasification and pressurized combustion. The purpose of the PSDF is to provide a flexible test facility that can be used to develop advanced power system components, evaluate advanced turbine system configurations, and assess the integration and control issues of these advanced power systems. The facility would provide a resource for rigorous, long-term testing and performance assessment of hot stream clean-up devices and other components in an integrated environment.

The PSDF consists of five modules for systems and component testing. These modules include an advanced pressurized fluidized-bed combustion module (APFBC), advanced gasifier module, hot gas clean-up module, compressor/turbine module, and a fuel cell module. The APFBC module consists of Foster Wheeler technology for second-generation PFBC. This module relies on the partial conversion of the coal to a fuel gas in a carbonizer with the remaining char converted in a PFBC. Both the fuel gas and PFBC exhaust gas streams are filtered to remove particulates, then combined to fire a combustion turbine. The advanced gasifier module includes MWK's transport technology for pressurized combustion and gasification to provide either an oxidizing or reducing gas for parametric testing of hot particulate control devices. The filter systems that will be tested at PSDF include PCDs supplied by Combustion Power Company from Menlo Park, California; Industrial Filter & Pump (IF&P) from Cicero, Illinois; and Westinghouse from Pittsburgh, Pennsylvania.

Construction of the transport reactor train along with the necessary balance-of-plant systems was completed by mid-1996. Various equipment and systems were commissioned during the final stages of construction. This was followed by start-up of the entire train and commissioning and combustion characterization tests.

On the APFBC system, the major activities in 1996 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 in the last quarter of 1997.

2.2 TRANSPORT REACTOR SYSTEM DESCRIPTION

The transport reactor train operating in the combustion mode is shown schematically in figure 2.2-1. A taglist of all major equipment in the process train and associated balance-of-plant is provided in tables 2.2-1 and 2.2-2. 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 downtime. The facility is sized to process nominally 2 tons/hour of coal. This size will generate sufficient gas to test the PCDs at a minimum of 1,000 ACFM of gas at the PCD inlet. Indirect cooling of the gas from the transport reactor will allow testing of the PCDs with inlet temperatures between 1,000 and 1,800°F and at pressures ranging from 184 to 283 psia. The PCD in this train will receive coal-ash laden gas from the transport reactor, which can operate in either gasification or combustion mode. The gas exiting the PCDs will be thermally oxidized in the gasification mode, cooled and filtered in a baghouse before discharge from a stack. The ash produced in the gasification mode will be sulfated prior to disposal.

Coal is ground to an average particle diameter of about 100 microns when the transport reactor is operated in gasification mode and to 200 microns average particle diameter in combustion mode. Sorbent is ground to an average particle diameter of about 100 microns. Both coal and sorbent are fed continuously at a controlled rate by feeders to a transfer line where they are picked up by the conveying gas and fed to the transport gasifier/combustor.

Air is compressed to about 350 psia in the main air compressor and fed directly to the transport reactor. For start-up purposes, a burner (BR0201) is provided at the reactor mixing zone. Liquefied propane gas (LPG) is used as start-up fuel. Solids and gas feeds enter the reactor in a mixing zone at the bottom where they mix with recycle solids from the disengager cyclone. Coal conversion begins in this zone and the reaction mixture flows upward into the narrower riser section at high velocity and then flows to the disengager.

The reactor will typically operate at temperatures of 1,600 to 1,650°F in combustion mode. Provision is made to inject air at several different points along the riser to control the formation of NO_X. Limestone/dolomitic sorbents, fed with the coal, are used for sulfur capture thus eliminating the need for downstream facilities to reduce plant sulfur emissions.

Solids and gases leaving the reactor flow to the disengager for bulk separation of the two phases. Most of the solids collected in the disengager are recycled to the reactor. The net solids (consisting of coal ash and spent sorbent) are sent to a solids cooler for cooling prior to disposal. In the combustion mode, heat removal from the reactor system is necessary to control the reactor temperature. This is accomplished by removing solids from the disengager, cooling the solids in the combustor heat exchanger (HX0203), and returning the solids to the reactor system.

The gas leaving the disengager still contains a high loading of particulates. It is then sent to a cyclone system for additional solids recovery prior to being fed to the PCDs. The cyclone is provided with spoiling gas to vary the solids loading in the effluent gas. The conditioned gas enters the PCD where essentially all of the remaining particulates in the gas are removed. The cleaned gas leaving the PCD is sent to a secondary gas cooler (HX0402) and ultimately cooled to about 600°F. All gas and solids cooling are accomplished by generating steam. A portion of the cooled gas is further cooled in the compressor feed cooler (HX0405) and sent to the recycle gas booster compressor (CO0401) which increases the pressure to about 400 psia. This gas is used as carrier gas for coal/limestone feed, for aeration gas, and as fluidization gas for the solids coolers.

The main gas stream from the secondary gas cooler is cooled further by dilution air and cleaned of any remaining particulates in a baghouse before being discharged to a stack.

Table 2.2-1

Major Equipment in the Transport Reactor Train

TAG NAME	DESCRIPTION
BR0401	Reactor Start-Up Burner
BR0401	Thermal Oxidizer
BR0602	Sulfator Start-Up/PCD Preheat Burner
CO0201	Main Air Compressor
CO0401	Recycle Gas Booster Compressor
CO0601	Sulfator Air Compressor
CY0201	Primary Cyclone in the Reactor Loop
CY0207	Disengager in the Reactor Loop
CY0601	Sulfator Cyclone
DR0402	Steam Drum
DY0201	Feeder System Air Dryer
FD0206	Spent Solids Screw Cooler
FD0210	Coal Feeder System
FD0220	Sorbent Feeder System
FD0502	Fines Screw Cooler
FD0510	Spent Solids Transporter System
FD520	Fines Transporter System
FD0530	Spent Solids Feeder System
FD0602	Sulfator Solids Screw Cooler
FD0610	Sulfator Sorbent Feeder System
FL0301	PCD – Westinghouse
FL0302	PCD – Combustion Power
FL0401	Compressor Intake Filter
HX0202	Primary Gas Cooler
HX0203	Combustor Heat Exchanger
HX0204	Transport Air Cooler
HX0402	Secondary Gas Cooler
HX0405	Compressor Feed Cooler
HX0601	Sulfator Heat Recovery Exchanger
ME0540	Heat Transfer Fluid System
RX0201	Transport Reactor
SI0602	Spent Solids Silo
SU0601	Sulfator

Table 2.2-2 (Page 1 of 3)

Major Equipment in the Balance-of-Plant

TAG NAME	DESCRIPTION
B02920	Auxiliary Boiler
B02921	Auxiliary Boiler - Superheater
CL2100	Cooling Tower
C02201A-D	Service Air Compressor A-D
C02202	Air-Cooled Service Air Compressor
C02203	High-Pressure Air Compressor
C02601A-C	Reciprocating N_2 Compressor A-C
CR0104	Coal and Sorbent Crusher
CV0100	Crushed Feed Conveyor
CV0101	Crushed Material Conveyor
DP2301	Baghouse Bypass Damper
DP2303	Inlet Damper on Dilution Air Blower
DP2304	Outlet Damper on Dilution Air Blower
DY-2201A-D	Service Air Dryer A-D
DY2202	Air-Cooled Service Air Compressor Air Dryer
DY2203	High-Pressure Air Compressor Air Dryer
FD0104	MWK Coal Transport System
FD0111	MWK Coal Mill Feeder
FD0113	Sorbent Mill Feeder
FD0140	Coke Breeze and Bed Material Transport System
FD0154	MWK Limestone Transport System
FD0810	Ash Unloading System
FD0820	Baghouse Ash Transport System
FL0700	Baghouse
FN0700	Dilution Air Blower
H00100	Reclaim Hopper
H00105	Crushed Material Surge Hopper
H00252	Coal Surge Hopper
H00253	Sorbent Surge Hopper
HT2101	MWK Equipment Cooling Water Head Tank
HT2103	SCS Equipment Cooling Water Head Tank
HT0399	60-Ton Bridge Crane
HX2002	MWK Steam Condenser
HX2003	MWK Feed Water Heater

Table 2.2-2 (Page 2 of 3)

Major Equipment in the Balance-of-Plant

TAG NAME	DESCRIPTION
HX2004	MWK Subcooler
HX2103A	SCS Cooling Water Heat Exchanger
HX2103C	MWK Cooling Water Heat Exchanger
LF0300	Propane Vaporizer
MC3001-3017	MCCs for Various Equipment
ME0700	MWK Stack
ME0701	Flare
ME0814	Dry Ash Unloader for MWK Train
ML0111	Coal Mill for MWK Train
ML0113	Sorbent Mill for Both Trains
PG2600	Nitrogen Plant
PU2000A-B	MWK Feed Water Pump A-B
PU2100A-B	Raw Water Pump A-B
PU2101A-B	Service Water Pump A-B
PU2102A-B	Cooling Tower Make-Up Pump A-B
PU2103A-D	Circulating Water Pump A-D
PU2107	SCS Cooling Water Make-Up Pump
PU2109A-B	SCS Cooling Water Pump A-B
PU2111A-B	MWK Cooling Water Pump A-B
PU2300	Propane Pump
PU2301	Diesel Rolling Stock Pump
PU2302	Diesel Generator Transfer Pump
PU2303	Diesel Tank Sump Pump
PU2400	Fire Protection Jockey Pump
PU2401	Diesel Fire Water Pump #1
PU2402	Diesel Fire Water Pump #2
PU2504A-B	Waste Water Sump Pump A-B
PU2507	Coal and Limestone Storage Sump Pump
PU2700A-B	Demineralizer Forwarding Pump A-B
PU2701	SCS Closed-Loop System Make-Up Pump
PU2711	Corrosion Inhibitor Pump
PU2713	Waste Water Alum Pump
PU2714	Waste Water Caustic Pump
PU2720	Acid Pump
PU2721	Waste Water Acid Pump

Table 2.2-2 (Page 3 of 3)

Major Equipment in the Balance-of-Plant

TAG NAME	DESCRIPTION
PU2730	MWK Steam System Phosphate Pump
PU2740	Cooling Tower Sodium Bisulfate Pump
PU2741	Cooling Tower Sodium Bisulfate Pump
PU2750	MWK Steam System O_2 Scavenger and pH Pump
PU2900A-C	Chemical Injection Pump A-C
PU2920A-B	Auxiliary Boiler Feed Water Pump A-B
SB3001	125V DC Station Battery
SB3002	UPS
SC0700	Baghouse Screw Conveyor
SG3000-3005	4160V, 480V Switchgear Buses
SI0101	MWK Crushed Coal Storage Silo
SI0103	Crushed Sorbent Storage Silo
SI0111	MWK Pulverized Coal Storage Silo
SI0113	MWK Limestone Silo
SI0114	FW Limestone Silo
SI0810	Ash Silo
ST2601	N_2 Storage Tube Bank
TK2000	MWK Condensate Storage Tank
TK2001	Condensate Tank
TK2100	Raw Water Storage Tank
TK2300A-D	Propane Storage Tank A-D
TK2301	Diesel Storage Tank
TK2400	Fire Water Tank
XF3000A	230/4.16 kV Main Power Transformer
XF3001B-5B	4160/480V SS Transformer No. 1-5
XF3001G	480/120V Miscellaneous Transformer
XF3010G	120/208 Distribution Transformer
XF3012G	UPS Isolation Transformer
VS2203	High-Pressure Air Receiver

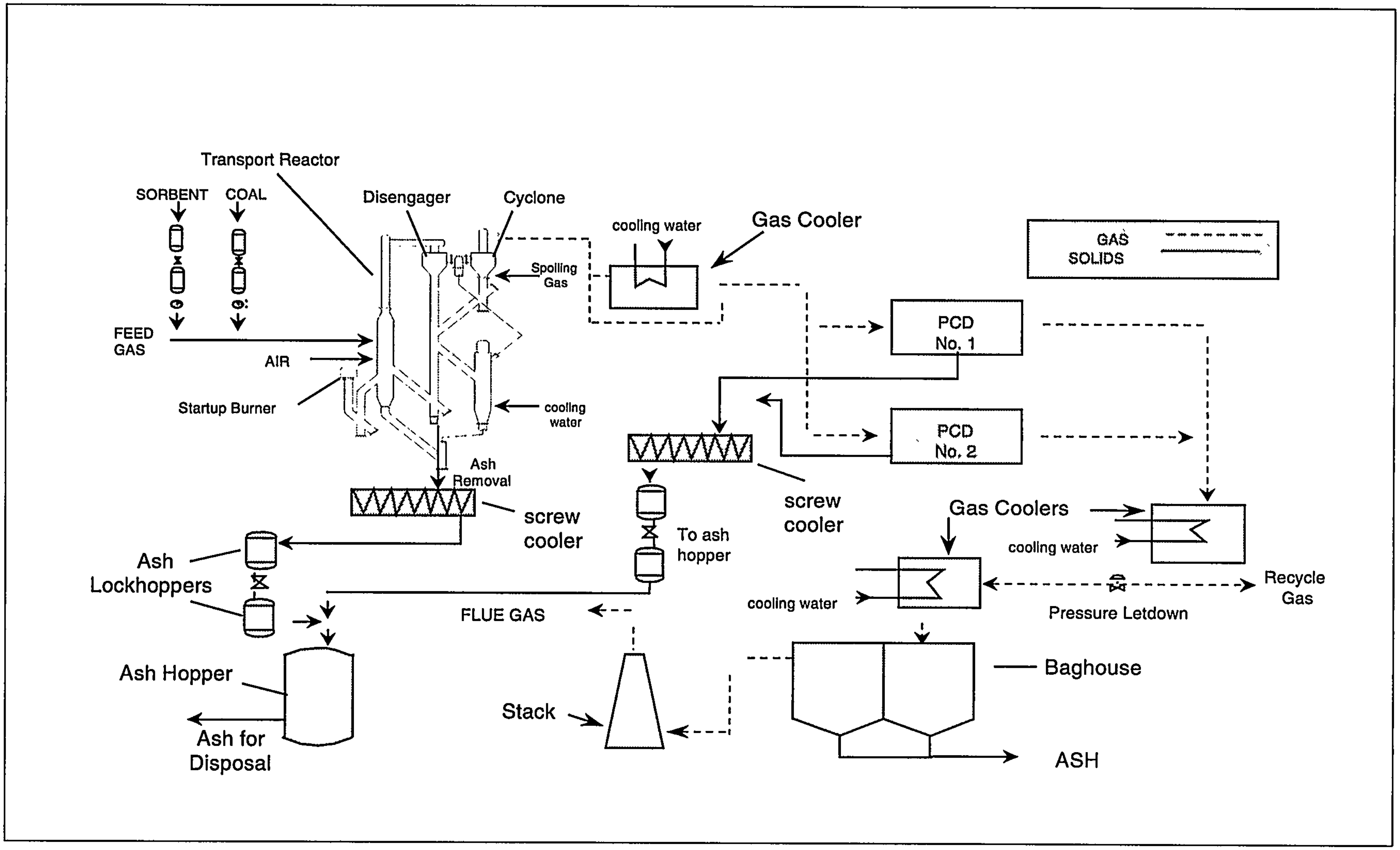

Figure 2.2-1 Flow Diagram of the Transport Reactor Train

2.3 WESTINGHOUSE PARTICULATE CONTROL DEVICE

Three different PCDs will be evaluated on the transport reactor train. The first PCD that was commissioned in 1996 was the filter system designed by Westinghouse. The dirty gas enters the PCD below the tubesheet. The dirty gas flows through the candle filters, and the ash collects on the outside of the filter. 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 a high-pressure gas pulse to the clean side of the candles. The cake then falls to the discharge hopper. During the 1996 commissioning, the transport reactor was operated in combustion mode and the pulse gas was high-pressure air. The pulse gas was routed individually to the two plenum/candle assemblies via injection tubes mounted on the top head of the PCD vessel. The pulse duration was typically 100 to 500 milliseconds (0.1 to 0.5 seconds).

2.4 BALANCE-OF-PLANT

Balance-of-plant to support the operation of the transport reactor train consists of a number of systems, most of which are of conventional design and commercially available. Deviations from conventional design either due to the sizing of the facility or process requirements are discussed in section 4.0. A listing of major components is given in table 2.2-1.

3.0 SCHEDULE OF PSDF START-UP/ COMMISSIONING ACTIVITIES

All of the equipment required for combustion mode operation of the transport reactor system was installed by midsummer 1996. Commissioning began in September 1995 on subsystems as they were completed and proceeded in parallel with the final construction activities. Commissioning tests and combustion characterization followed on the entire train in an integrated operation. Tables 3-1 and -2 provide installation, checkout, and start-up dates of various systems. Table 3-3 provides the commissioning and characterization test run time periods and major events associated with the test runs.

Table 3-1 (Page 1 of 2)

Operational Dates for Various Systems in the Transport Reactor Train Along With Systems Associated With the Westinghouse PCD and Balance-of-Plant

PSDF – SYSTEMS CHECKOUT/START-UP/COMMISSIONING COMPLETION DATES

System	Operational Date
Foxboro IA Distributed Control System	July 1995
Station Service – Electrical	September 1995
Demineralized Water	November 1995
Chemical Cleaning of Steam/Condensate	December 1995
Heat Transfer Fluid System	December 1995
Raw Water	January 1996
Fire Water	January 1996
Service Water	January 1996
Cooling Tower Make-up Water	January 1996
MWK Steam Generation	January 1996
MWK Condensate	January 1996
Screw Cooler - FD0206	February 1996
Screw Cooler - FD0502	February 1996
Sulfator Heat Exchanger and Steam Loops	February 1996
Circulating Water	March 1996
Cooling Tower	April 1996
Instrument Air	April 1996
BOP Closed-Loop Cooling Water	April 1996
MWK Closed-Loop Cooling Water	April 1996
Dense-Phase - FD0210	April 1996
Dense-Phase - FD0220	April 1996
Dense-Phase - FD0510	April 1996
Dense-Phase - FD0520	April 1996
Dense-Phase - FD0530	April 1996
Thermal Oxidizer & Waste Heat Boiler	May 1996
Waste Water Treatment	May 1996
Emergency Electric Generator	May 1996
Propane Supply	May 1996
Transport Reactor Impulse Line Purge	June 1996
Transport Reactor Instrumentation	June 1996
Low-Pressure Nitrogen	June 1996
Medium-Pressure Nitrogen	June 1996
Liquid Nitrogen Supply	June 1996

Table 3-1 (Page 2 of 2)

Operational Dates for Various Systems in the Transport Reactor Train Along With Systems Associated With the Westinghouse PCD and Balance-of-Plant

PSDF – SYSTEMS CHECKOUT/START-UP/COMMISSIONING COMPLETION DATES

System	Operational Date
High-Pressure Back-pulse Air	June 1996
MWK Coal Pulverizer	June 1996
Limestone Pulverizer	June 1996
Transport Reactor Solids Fluidization	June 1996
Transport Reactor Pressure Boundary	June 1996
Dense-Phase - FD0140	July 1996
Dense-Phase - FD0104	July 1996
Dense-Phase - FD0154	July 1996
Dense Phase - FD0820	July 1996
Low-Temperature Baghouse	July 1996
Baghouse Dilution Fan	July 1996
Nitrogen Separation Plant	July 1996
MWK Process Air Compressor	July 1996
MWK Dense-Phase Transport Air	July 1996
Transport Reactor Start-Up Burner	July 1996
Sulfator Start-Up Burner	July 1996
Westinghouse PCD	July 1996
Transport Reactor Pressure Relief Valves	July 1996
MWK Recycle Gas Compressor	July 1996
Process Gas Analysis	July 1996
Solids Sampling	July 1996
Feedstock Reclaim Conveyor	July 1996
MWK Ash Storage and Transfer	July 1996
High-Pressure Back-pulse Nitrogen	September 1996
Sulfator Air Compressor	October 1996
SRI Batch Sampling Systems	October 1996
Dense-Phase - FD0610	November 1996
Dense-Phase - FD0810	November 1996
Flare and Flare Seal Tank	February 1997
Sulfator Pressure Boundary	
Sulfator Pressure Relief Valves	
Sulfator Impulse Line Purge	
Sulfator Solids Fluidization	
Combustion Power PCD	

Table 3-2

Chronology of Major Events During Installation, Checkout, Shakedown, and Commissioning of Westinghouse PCD and Associated Systems

Event Date	**Major Event**
May 1995	Installation of PCD into structure.
May 1995 – March 1996	Completion of MWK refractory lined and process piping.
March 25-29, 1996	Installation of Westinghouse PCD internals and filter elements.
April - May 1996	Installation of Westinghouse PCD instrumentation.
May - June 1996	Check out of pulse skid.
July 14, 1996	Initial pressure test of PCD. Main girth flange leaked.
July 15-18, 1996	Troubleshooting of PCD gasket.
July 19-21, 1996	Pressure test of PCD. Gasket leaked at 180 psig.
July 22-26, 1996	Test Run CCT1A.
August 3-5, 1996	Test Run CCT1B.
August 14 - 21, 1996	Test Run CCT1C (80 hours on coal). At end of run it was discovered that 77 of 91 filter elements were broken.
September 3-6, 1996	Filter elements replaced.
October 2-17, 1996	Test Run CCT2A.
November 4-7, 1996	Test Run CCT2B.
November 14-22, 1996	Test Run CCT2C. Successfully completed 146-hour coal feed.
December 11-12, 1996	Test Run CCT3.

Table 3-3 (Page 1 of 2)

Chronology of Initial Commissioning and Characterization Test Runs

RUN NO.	RUN DATE	HOURS ON COAL	COAL FED, TONS	REASONS FOR TERMINATION	COMMENTS/ MILESTONES
CR01	5/30 - 6/6/96	-	-	Scale deposition in start-up burner propane lines.	Test objective was to cure reactor refractory using start-up burner.
CR02	6/10 - 6/15/96	-	-	Successful test run.	Cured transport reactor refractory up to 1,000°°F.
CR03	6/18 - 6/19/96	-	-	Dust plume in stack.	Gas passed through empty CPC filter vessel.
CR04	6/26 - 7/1/96	-	-	PV287 failure due to erosion.	1. Gas passed through empty CPC filter vessel. 2. Recycle gas booster compressor tested successfully.
CCT1A	7/20 - 7/27/96	-	-	Start-up burner failure, FD0206 jammed.	1. Batch coke breeze feeding was attempted. 2. Pressure letdown valve was later found eroded.
CCT1B	7/31 - 8/6/96	-	-	PV287 failure due to erosion.	No coke breeze fed.
CCT1C	8/14 - 8/21/96	80	32	PCD filter pluggage; loss of level in standpipe resulting in reduced/loss of solids circulation.	Dolomite was used for bed material make-up.
CCT2A	10/2 - 10/17/96	-	-	Start-up burner flame rod failure and excessive loss of bed material.	Silica sand used as starting bed material for the first time.
CCT2B	11/4 - 11/7/96	-	-	Fines screw cooler tripped and was not detected possibly causing high level of solids in PCD.	1. Stopped batch coal feed due to Fines screw cooler trip. 2. Once PCD was clear of solids, burner relight was unsuccessful due to the shorted flame tip.

Table 3-3 (Page 2 of 2)

Chronology of Initial Commissioning and Characterization Test Runs

RUN NO.	RUN DATE	HOURS ON COAL	COAL FED, TONS	REASONS FOR TERMINATION	COMMENTS/ MILESTONES
CCT2C	11/14 - 11/22/96	146	32	Coal feeder problems, loss of standpipe level.	1. Poor solids circulation through combustor heat exchanger. 2. Solids carryover to PCD, at times, was excessive.
CCT3A	12/11 - 12/12/96	-	-	Successful test run.	Tests performed at different circulation rates and riser velocities to evaluate disengager performance.

4.0 DESIGN, PROCUREMENT, AND INSTALLATION

This section covers a number of alternative designs that were considered during the conceptual stage due to the dual mode of operation of the transport reactor and the need for parametric testing of the filter system. Due to first-of-a-kind (FOAK) process design and novel design of a number of pieces of equipment (including the transport reactor at the PSDF scale), certain procurement difficulties were expected which needed a greater than normal interaction with the vendors. This is discussed in section 4.2. Experiences associated with the FOAK installation of the entire transport reactor loop and the nearly seamless transition from detailed engineering design to integrated installation of all process equipment and piping in the transport reactor train are discussed in section 4.3. Major design alternatives, procurement, and installation issues associated with the balance-of-plant equipment are also discussed below.

4.1 CONCEPTUAL DESIGN

4.1.1 Transport Reactor Train

4.1.1.1 Transport Reactor Loop

The transport reactor loop and the transport reactor train built at PSDF are the result of several iterations and compromises made to reduce the overall project cost. Operating experience of transport reactor development unit (TRDU) at the Energy and Environmental Research Center of University of North Dakota (UND/EERC) also resulted in redesign of the holo-flite screw seal. Some of the significant iterations and compromises made are discussed in this section.

4.1.1.2 Dual Role of the PSDF Transport Reactor

Early in the project, M.W. Kellogg Company (MWK) proposed to build two transport reactors. One reactor would operate as a gasifier and the other would operate as a combustor. The U.S. Department of Energy (DOE) did not accept this proposal. A compromise was reached to design a single transport reactor that was capable of operating as a gasifier and a combustor. This posed some design challenges. The ash (in combustion mode) and char (in gasification mode) have dissimilar properties. The ash is more dense and has different flow properties than char. This impacted the cyclone and standpipe design, dipleg height (overall reactor height), and location of dipleg entry into the standpipe.

4.1.1.3 Reactor Operating Pressure

The design pressure of the transport reactor was reduced from 400 to 350 psig to avoid high pressure seal development and associated cost for the holo-flite screw coolers. The vendor's design experience was up to 350 psig.

The maximum reactor operating pressure was reduced from approximately 310 to approximately 290 psig to provide the safety margin required for the design. The transport air booster compressor for the Clyde feeders was eliminated as a result of the reduction in the maximum reactor operating pressure.

4.1.1.4 Feed Systems

Clyde pneumatic feed systems replaced the coal and sorbent feed systems originally proposed. The surge bins and lockhoppers in the final design were integrated for smooth operation. The rotary feeders and associated lockhoppers in the original flow sheet would have caused solids flow problems due to size inconsistency of the coal and sorbent. Clyde pneumatic feed system was also selected for feeding char into the sulfator.

Cooled compressed air (from the main air compressor) with nitrogen backup replaced recycled flue gas (combustion mode) and recycle fuel gas (gasification mode) as coal and sorbent transport gas. This simplified the feed system design. The uncertainty of a suitable source of cooling water for the transport air heat exchanger (HX0204) resulted in several design iterations.

4.1.1.5 Transport Reactor

The design of a single reactor to operate as a gasifier and a combustor resulted in many compromises. The density, particle size, and flowability of the circulating solids in combustion mode are different from those in gasification mode. The solids level in the standpipe required for the desired high solids circulation rate depends on the operating mode and is limited by the dipleg height, which in turn depends on the submergence of the dipleg discharge into the standpipe. Gasification mode controlled the design of the reactor loop. Other design flexibilities were eliminated to reduce the cost of the project.

The design and arrangement of the transport reactor solids separation systems went through several iterations in order to meet the specified range of exit dust loading to the PCD. In the final design, the two parallel two-stage cyclone system (downstream of the disengager) with complex piping arrangement was replaced with one primary cyclone. The compromise made in the final design was driven by the need to:

- Supply the range of solid loading desired.
- Provide sufficient solids traffic through the cyclone to minimize differential thermal growth between the standpipe and cyclone dipleg.

A moderately high-efficiency disengager, followed by a cyclone, satisfied these requirements. Detuning of the cyclone was selected as the method for increasing the dust loading and, probably, the average particle size to the PCD.

Several iterations of the mechanical arrangement of the burner duct, HX0203 and reactor J-leg returns were made to meet process and thermal stress requirements. The flue gas used in the preliminary design as fluidization/aeration gas in combustion mode of operation was replaced with compressed air. Nitrogen quench for BR0201 was added to be used for restart in gasification mode to limit the oxygen concentration in the burner flue gas.

4.1.1.6 Oxygen Gasification Case

The reactor system was rated for future oxygen gasification of coal. This resulted in a more stringent area classification for the reactor area. All instrumentation and electrical connections were required to meet the appropriate electrical code.

The sulfator design was impacted due to the lower conversion resulting in higher carbon feed rate. To meet the required volumetric gas flow to the PCD, the reactor operating pressure was reduced instead of increasing coal feed rate to generate the required 1,000 acfm at 290 psig. Increasing coal feed rate would have increased the size of the coal and sorbent feeders, and solids withdrawal systems and their cost.

4.1.1.7 Solids Withdrawal Systems

Screw Coolers

The fluidized bed cooler for reactor solids and radiation pipe cooler for PCD solids were replaced with holo-flite screw coolers. To prevent gas leakage, the pressure seal design (similar to the TRDU holo-flite screw seal design) went through several iterations after the TRDU holo-flite screw seal design failed repeatedly during operation at 120 psig.

Solids Depressurization and Transport

The spent reactor solids and filter fines withdrawal lockhopper/eductor systems were replaced with Clyde pneumatic transport systems. The spent solids in the final design are conveyed into a common vessel (FD0530) from which they are either disposed of (combustion mode) or fed into the sulfator (gasification mode). The design of FD0530 was integrated with the transporters with sufficient hold up for smooth feeding of the sulfator in gasification mode of operation.

4.1.1.8 Sulfator

Considerable effort was spent in establishing the discharge pressure of the sulfator air blower (CO0601). This was done to keep the size of the blower within a smaller and less expensive frame size. Otherwise, a blower greater than that for larger oversize frame would have been selected at a cost approximately five times the cost of the smaller frame size.

4.1.1.9 Recycle Gas Loop

The recycle gas loop design was improved as follows:

1. The recycle gas supply to the recycle gas compressor (CO0401) was subcooled to 120 instead of 300°F in the conceptual design to permit the purchase of a more conventional compressor thus, reducing the cost and increasing the reliability and availability of the compressor. The condensed moisture was separated from the gas prior to compressing.

2. Temperature control of compressor inlet gas using gas bypass around HX0405 was provided to maintain the compressor inlet temperature at approximately 120°F.

3. An in-line filter was installed upstream of the compressor to protect it from particulate matter in case of PCD failure.

4. Nitrogen back-up was provided for start-up and also when the compressor trips.

5. A nozzle was provided upstream of the compressor for injecting N_2 to lower the H_2 content in the inlet gas to CO0401 to acceptable limits during oxygen gasification mode.

4.1.1.10 Gas Cooling and Pressure Reduction

Several schemes were considered for control of gas inlet temperature and volumetric flow rate to the PCD. These included:

1. Heat exchanger with internal bypass.

2. Heat exchanger with external bypass with valve or restriction orifices (RO).

3. Gas quench.

The use of a high-temperature valve and ROs was considered for reducing the gas pressure at the inlet of the PCD to maintain 1,000 acfm when the inlet temperature is lower than reactor operating temperature.

4.1.1.11 PCD Bypass

Early in the project, a bypass was provided around the PCD for start-up, shut down, and during PCD failure. The bypass was deleted in the final design for the following reasons:

1. The transport reactor system design was required to resemble closely a commercial design in which gas bypass would not be provided.

2. The bypass would require continuous hot gas flow to keep it hot.

4.1.1.12 Filter Particulate Loading Reduction

A preliminary study was conducted to determine equipment requirements for lowering the particle loading to as low as 1,000 ppm(w) without any modification to the existing gas-solid separation system. The lower particle loading was desired for the granular bed filter. It was determined that an additional cyclone, ash cooling, and fines transport system were needed in the process after the primary gas cooler. Preliminary design and equipment layouts have been completed.

4.1.2 Balance-of-Plant

During the course of construction, start-up, and commissioning of the PSDF balance-of-plant equipment and the MWK transport reactor, design shortfalls in several systems and components were discovered and addressed. Several of these were due to assumptions that were made during the early phases of design that were significantly changed during the final design phase. Others were due to a failure to anticipate the requirements of operating at less than design conditions during start-ups and low load operations. A couple of modifications were due to the advancement of technology for this application.

The negative impact of having to modify design assumptions made early in the project was minor in comparison to the overall schedule improvements that resulted from these early assumptions. The wastewater treatment system was one such system that was modified as a result of a tighter than expected NPDES (discharge) permit. The closed-loop cooling water systems and the cooling tower were also subjected to a major revision during the final design iteration due to large increases in the heat rejection requirements (especially by the Foster-Wheeler process). Other design assumptions that significantly affected the procurement cycle of the feedstock preparation equipment were Foster-Wheeler expectations that dolomitic stone would crush exactly the same as coal and their extremely tight particle sizing requirements for the pulverizer systems. The time constraints of the project required that the design tasks that are usually sequential in nature be done in parallel with the additional labor required to adjust for the changes from an assumed design parameter.

Both MWK and Foster Wheeler completed their designs largely based on one operating condition (MWK had one condition for combustion and another for gasification, with gasification taking precedence in conflicts). There were several instances where modifications were required to controllably maintain process conditions at less than the design points, especially due to the velocity/mass flow relationship with respect to pressure (velocity increases at a given mass flow as pressure decreases). A few flow and backpressure valves were modified to allow controllability at the required burner operating pressure of 50 psig, including the custom Whispertrim in the main process letdown valve (PV-287). Instrument purges and fluidizing flows were designed to operate at multiple setpoints, forcing continual adjustment of these valves while adjusting the reactor pressure. On systems connected to a combustion turbine, a single-pressure design is acceptable due to the constant compressor discharge of the combustion turbine with a direct connected generator; but, for systems not connected to a combustion turbine, automatic compensation for changing operating pressures is needed.

On the other hand, several pieces of equipment were designed for excessively wide operating ranges: the propane vaporizer, the MWK condensate coolers (condenser and subcooler), the thermal oxidizer, and the transport reactor start-up burner. In the case of the coolers and the thermal oxidizer, only minor modifications to the operating procedures and controls configuration were needed for adequate operation at 1/20th the design flow. Increased demand or the addition of a smaller vaporizer for low-flow conditions will solve the propane vaporizer problems. The reactor start-up burner has received extensive modifications that are detailed elsewhere in this commissioning document, including raising the firing rate, pressure, and temperature, and modifying the pilot burner.

The technology issues were focused on high-pressure/temperature applications that (for the first time) are being addressed at the PSDF. The combination of both oxidizing and reducing corrosive gases at high temperatures (up to 1,800°F) and pressures (> 20 atmospheres), especially in the high-particulate laden streams, tend to dictate the use of high-temperature stainless steel alloys such as 304H and 316H for clean gas streams and Hastalloys for "dirty" gas streams. Some difficulties and delays in procurement arose due to these requirements; in some cases, the standard alloy is an acceptable substitution, but in others, the process vendors did not allow such replacements. One of the most difficult applications in which to match the metallurgical requirements to the fabrication realities was the SRI sample cutting cyclones, due to the difficulties in complex casting of certain Hastalloy materials. After discussions with the Hastalloy technical representatives, different fabrication methods were devised and different Hastalloy materials specified. These material issues will continue to be a concern in the future as these technologies are scaled up and commercialized. An additional area of concern due to the high process temperatures and pressures includes gas sampling. Issues of condensation due to the high-heat transfer surface-to-thermal mass ratio of the sample streams, both bias the results and cause significant corrosion of the sample tubing, require high-capacity heat tracing installed on the sample tubing and controlled cooling of the sample at the analyzer house. Issues of particulate plugging were never adequately resolved, preventing installation of a sample tap upstream of the PCD; this problem will require significant work before testing of possible chemical interaction between the gas and the PCD candles.

Several simplifications in the design can be easily found (now that construction is completed), many of which could not be found on the drawings and designs. One such simplification would be the use of welded heavy wall tubing for pressure tap purges and fluidization nozzles, rather than welded 1-inch pipe. Heavy wall stainless tubing is rated for several thousand psi at higher temperatures, is easier to form into large radius elbows necessary to allow expansion, and now has automated welders that have been approved by all pressure code promulgators. The transport reactor built at the PSDF has the same number of pressure taps and fluidization nozzles as a full scale reactor, but on this scale these connections make a dense forest of small bore piping that required many pipefitter labor hours to install. The use of inert waste process gas (nitrogen and carbon dioxide mixture) stored on site at pressure and with sufficient volume to snuff any reaction process in the reactor would allow minimum use of nitrogen at the plant site. Such a proposal would be enhanced by the use of sulfur capture systems and NO_X reduction technologies on future reactors.

When designing, constructing, and commissioning any process or component challenges will be faced and solved, and better solutions will be discovered. For the transport reactor at the PSDF several challenges caused by the design choices made were addressed either during final design, during construction, or in commissioning, including issues associated with FOAK technologies and material requirements.

4.2 PROCUREMENT

4.2.1 Transport Reactor Train

4.2.1.1 Transport Reactor

The transport reactor is a FOAK loop reactor. The reactor was fabricated from carbon steel and lined with a monolithic dual cast refractory. Expansion joints were not used in this design because of the high operating temperature and process restrictions. The thermal design was a challenging exercise because of the closed loops without the use of expansion joints. The entire system was fabricated to close tolerances in order to eliminate residual stresses when assembled. The reactor loop, excluding the cyclones and HX0203 before it was lined with refractory, was assembled in the fabrication shop to ensure that critical tolerances were maintained. The majority of the transport reactor sections are small in size, which made accessing the interior difficult. The majority of shop and field circumferential welds were performed after the refractory was installed. A special joint was developed to accomplish this. Because of FOAK fabrication, this entire steel fabrication and refractory installation was a long and tedious process requiring extensive coordination between the vessel and refractory contractors.

4.2.1.2 Sulfator (SU0601)

Unlike the reactor, the sulfator is a more conventional design. The FCC technology was utilized in the mechanical design. The vessel is fabricated with carbon steel and lined with a single layer of refractory. The refractory was gunned in place and thermally dried to process temperature prior to shipping. The vessel is equipped with stainless steel pipe grid distributor to uniformly fluidize the bed. The transitions from carbon steel to stainless steel for the distributor were embedded inside the refractory to reduce the metal temperature. The sulfator also has heat transfer tubes for control of the process temperature. These tubes were fabricated from two different materials: Haynes 556 S.S and rolled alloy RA-85H S.S. Haynes 556 material for the stab-in heat transfer tubes was not readily available in 2-inch ID size; these tubes were, therefore, made by drilling rod stock.

4.2.1.3 Disengager Cyclone (CY0207)

Many of the aspects stated above for the transport reactor were also incorporated in the cyclone design.

4.2.1.4 Refractory Lined Pipe

Fabrication usually involves a primary pipe fabricator plus a subcontractor to do the internal refractory lining. Close coordination is required and time must be allowed for shipping between the two fabricators. Also, some shop trial fit-up is required. On this project the pipe fabricator was in Tulsa, Oklahoma, and the refractory liner was in Houston, Texas. Problems with the shipping time, along with time for dual linings and dual dryouts, resulted in much of this piping being delivered late. On the other hand, the quality of fabrication was good and field fit-up problems were relatively minor.

4.2.1.5 Refractory Lined Valve

There was one refractory lined valve on this project: an 18-inch NPS pipe with dual internal refractory lining. Valves of this type are typically used in FCC units. The major difference for this project was the high process temperature of 1,650 vs about 1,400°F for FCC. This posed design difficulties, and the valve length had to be revised several times, requiring a field adjustment in the matching pipe.

4.2.1.6 Restriction Orifice (RO) Plates

There were two high-temperature restriction orifices on this project that caused some procurement difficulties. These items were designed for 1,850°F and required FOAK design. The ROs were completely internal to the piping and required an internal support cone and mounting plate. The materials were Haynes 556; the thickness of some components required a special millrun and long lead time to produce. Quality control and inspection requirements were stringent.

4.2.1.7 Solids Handling Equipment

Both the coal and sorbent feed systems, and the coarse- and fine-ash handling systems were FOAK design for the process conditions to which they will be subjected. These systems were procured from Clyde Pneumatics Co. in England. Efforts were made to maximize U.S. material content in their fabrication. Difficulties resulted in mismatched flanges, bolt patterns, etc. Acquisition of the original contractor (Simon Air Systems) by Clyde and merging of internal operations contributed to the difficulties in the design and fabrication stage.

4.2.1.8 Primary Gas Cooler (HX0202)

The primary gas cooler was of a unique FOAK design. Consideration for particulate laden stream presented challenges during the design phase.

4.2.1.9 Combustor Heat Exchanger (HX0203)

The Haynes alloy for the lattice (cage) and grid was not readily available. An extensive check of the refractory material was required during the fabrication stage.

4.2.1.10 Secondary Gas Cooler (HX0402)

Computer simulation using finite element analysis technique of the shell and tube was a critical part of the design.

4.2.1.11 Sulfator Start-up Heater (BR0602)

Delay in stack design impacted completion of final design. Options that were considered included dual stack (one for the process gas and one for the sulfator heater) and a single stack. The final design has a single stack with the sulfator heater flue gases routed directly to the stack.

4.2.1.12 Thermal Oxidizer (BR0401)

Boiler design was changed from refractory wall to water wall. Delivery was late. Boiler weight was understated, which impacted unloading.

4.2.2 Balance-of-Plant

The major equipment purchased (balance-of-plant (BOP) equipment) includes all BOP pumps (24, excluding small sump pumps), heat exchangers (8), various water storage tanks, instrument air compressors (4), high-pressure air compressor, cooling towers (6 cells), the nitrogen system including 3 high-pressure compressors, the propane system, the coal and limestone handling system, the solids transport system from the coal handling structure to the MWK structure, the chemical feed system, the fire protection system, the baghouse, and the auxiliary boiler. The valves purchased by Southern Company Services, Inc., (SCS) included all valves, manual and automatic (air operated or motor operated), in both the BOP and MWK systems.

All equipment RFQs were submitted to at least three vendors for bids; the lowest of these three that met all specifications was selected. For this bid process, the standard pumps were put into one group, the manual valves in one group, the control valves in one group, and several systems were bid as a turnkey system.

Detailed specifications were not utilized for the purchase of pumps and valves. Rather, each was purchased from a single data sheet listing all of the pertinent information. This greatly reduced the engineering time required. Most of the pumps were either purchased from Hydromatics (ITT pumps) or Brownlee-Morrow (Goulds pumps). Control valves were purchased from Control Southern (Fisher), safety valves from Dresser Industries (Consolidated), and manual valves from Piping and Equipment. Allowing SCS to purchase all valves worked extremely well in that it provided one point of contact for procurement, which eliminated duplicate orders and also assured all valves would be of basically the same type and quality. Also, the large number of valves procured resulted in lower unit costs for the valves than if ordered in smaller quantities by multiple contracts. The only documentation requested on manual valves was a catalogue cut sheet as opposed to a stamped and approved drawing from the vendor on each valve. These catalogue sheets provided ample information and this also allowed the vendor to offer the valves at a lower cost. One problem associated with valve procurement was that the final number of valves purchased was 48 percent greater than the original estimate, resulting in the purchase of several valves on the job site once construction began. Also, it was difficult to obtain valves with SS alloy 316H internals or bodies. Valves of this type often had a lead time of 6 to 9 months.

The instrument air system was purchased as a package unit from one vendor (Hydromatics). This package included the air compressors (Atlas Copco), air dryers (Pneumatic Products Corporation), air receiver tanks, and aftercoolers. This method had its advantages and disadvantages. The advantages are that it provided only one point of contact for the entire system and also required that the vendor do some design work in assuring that all components worked together as an entire system. The major disadvantage is that the vendor from whom the equipment was purchased was not the same vendor that manufactured the equipment. This situation created a middle agent to go through to obtain technical information during start-up and operation of the equipment.

The high-pressure air compressor (Norwalk) was purchased from a different vendor than the instrument air compressors. The main procurement problem associated with this compressor was that the documentation received was very general and was written to cover a wide range of compressors, therefore making it difficult to interpret exactly what applied to the specific unit that had been purchased. There were also situations where the compressor purchased was a sophisticated machine (therefore making it difficult to start-up and operate).

Procurement of the cooling towers was difficult in that the tower size required was too small to justify the use of the standard concrete tower typically used at power plants but too large to use the typical low-flow cooling towers purchased as package units. To solve this problem, a small tower design was scaled up by Tower Tech to meet the required flow rates. This caused some problems in that this tower was an original design (with serial number 1) and had yet to be proven in operation. All documentation received was for the standard smaller tower typically fabricated by the vendor, therefore making it difficult to obtain the specific information required during construction and start-up of the towers. Also, as a result of the first-time design, operation problems surfaced that had to be corrected.

The nitrogen supply system was a product agreement and not an equipment purchase. BOC Gases was hired to construct, operate, and maintain their own equipment to supply a certain amount of nitrogen to the plant. The only equipment to be purchased by SCS were the nitrogen compressors and associated equipment required to raise the pressure of the gas to 1,500 psi for PCD backpulsing. This system was purchased from one vendor on a skid with all piping provided.

Like the instrument air system, the propane system was also purchased from one vendor (Energistics) as a turnkey job. One major advantage of this was that the vendor did all of the design work; SCS engineers were not required to be experts in designing propane systems. The system was designed for the high-propane-flow rate associated with both the MWK and FW system operating at 100 percent. When only the MWK system is operating, the propane vaporizer has a difficult time operating at the low-flow conditions. Operation could be better if two propane vaporizers had been purchased: one for high flow and one for low flow.

The coal and limestone preparation system was purchased from Williams Patent Crushers. The only major problems associated with this system involved communication difficulties between the vendor and the process engineer over the grinding capabilities of the equipment.

The solids transport system was purchased from Clyde Pneumatics. The sales group for Clyde is in the U.S., but the engineering group is in England. Thus, all technical information had to come from England, and due to time zone differences there were some coordination problems. Keeping track of where the equipment was being manufactured and shipped from was also difficult, with about 63 percent of the equipment fabricated in England and the rest in the U.S. MWK purchased their system from Simon Air Systems, which was combined with Clyde Pneumatics midway through the project. SCS purchased their system from Clyde Pneumatics. This added a further confusion factor when discussing the various systems with the Clyde engineers. Some confusion may have been avoided if both systems had been purchased under one purchase order.

4.3 INSTALLATION

There were several challenges addressed during the installation of the MWK transport reactor and related BOP equipment that were due to the specialized requirements of the high-pressure, high-temperature, circulating fluidized-bed/transport design of the transport reactor.

The reactor vessel itself was one of the biggest challenges to install because of the hard connections designed into the pressure vessel which required very tight tolerances in fabrication and alignment during assembly. The vessel is fabricated from refractory lined steel pipe, and individual pieces weighed up to 40 tons, were up to 20 ft long, and could have compound elbows and bends. Because of an uncertainty in the quality of the fabrication work (which was significantly better than expected), each component was moved several times: first in the "rough set" of the reactor pieces in the process structure, then several times when the pieces were positioned for trial assembly, and finally during the assembly involving chalking joints and welding. This process of trial assembly and alignment was not included in estimates for construction of the transport reactor, nor was any allowance for the additional time spent working the components into the process structure. The vast majority of lost productivity was due to the removal of structural building members, threading spool pieces down through several floors of grating in the process structure, having to use temporary beams, and manually rigging the pieces in place. Design and conceptual changes to reduce the time required to install the transport reactor should include the installation of lifting lugs on every piece of pipe and vessel to be installed, additional (in strategic locations) welded connections to correct for misalignments, and integrating the construction of the building structure with the rough setting of vessels and piping. All of these suggestions would minimize the rigging and handling time of each piece and allow the rough setting and alignment to proceed with a minimum of labor cost. However, the time used could be longer due to the delay between rough setting and alignment to wait on the structure to be completed to a point that it is safe to walk on and work from.

The transport reactor uses several components and many associated pieces of equipment, especially in BOP. They were usually designed for pulverized coal combustion. These components are required to achieve higher tolerances for use by the transport reactor and/or are not supplied with the inherent services (hot air, storage of product, or low static pressure). These extra requirements are addressed by increased complexity of the installations. The pulverizers are an example of this problem. In a PC plant, the pulverizers are supplied with preheated transport air (primary air) which discharges directly into the furnace at near atmospheric pressure and functionally can produce an extremely wide range in product size without impacting the process in the furnace. For the transport reactor, the mills need a separate source for heat and transport air, a need to discharge into an intermediate storage bin or hopper, and (presently) have tight product sizing requirements for the process to satisfactorily operate. The PSDF pulverizer packages include not only the mill and air fan, but also an air heater, top size screeners, product coolers to prevent condensation in the intermediate hopper, and a transport air venting filter system. The requirement for top (and lower) sizing also forces oversize product recycling to minimize wastage, and therefore several ductwork runs for the product transport, the transport air recycle and reheating, segregated size fractions, and bin venting. All of this complexity is reflected in the time and labor expended in installation of the pulverizer systems when compared to similar installations for a PC unit.

A similar source of confusion in estimating the amount of work required for construction of the transport reactor (or any high-pressure process) is the piping required to assure that the pressure taps will not become plugged during operation. Simple pressure taps required on near atmospheric processes become intricate purged systems with flow metering devices, rod out ports, and multiple isolation valves; all of which must be designed to withstand ultimate process conditions (XXS pipe or better, corrosion protection, etc.). While the developmental designs of the transport reactor have requirements for many more pressure measurements, the process will still require several pressure taps for adequate control. One possible simplification in pressure taps would be the replacement of piping with tubing of the same process specifications, as the tubing is easier to handle and install–especially with the automated tubing welders that are available today.

There were several instances when operations personnel who were studying the design of components and systems discovered fabrication errors in components as well as the problems found during component installation. Most of these were simple quality control concerns but could represent significant trouble if left uncorrected before trying to commission the equipment.

Technology, especially the use of computer aided design (CAD) modeling of the piping and process structure, contributed greatly to the planning and sequencing of the construction work. By using the 3-D design review station to find possible interferences and blockouts, labor was not wasted by having to remove piping to gain access to install additional piping runs. Further organization of the piping installation by prioritizing work on trunks, headers, and branches gained additional savings in wasted labor. One area forgotten in the "official" design of the plant was the piping required for flushing, cleaning, and commissioning the condensate and steam generation piping and equipment. By using the design review models, routing of this "temporary" pipe was completed prior to mechanical completion and allowed the chemical cleaning of the piping to be finished long before the steam circuits were needed by the process.

Turnkey procured systems usually gave more trouble during commissioning due to quality issues than equipment and systems procured to be installed by the construction contractor.

In spite of the challenges found during the construction of the transport reactor and the associated BOP equipment and systems, the work was completed with a minimum of rework of site assembled pieces and connections. During all the hydrostatic tests and pressure tests of the components, there was only one weld that leaked done at the site.

Traditional methods for estimating construction work, especially the use of estimating shortcuts developed for powerhouse construction, should not have been used without addressing the differences in processes. Overall, the lessons learned at the PSDF will result in several design enhancements that would positively impact the installation of components and vessels.

5.0 Commissioning of M.W. Kellogg Transport Reactor Train

Sections 5.1.1 through 5.1.10

are contained in Volume I

of this report

5.0 COMMISSIONING OF M. W. KELLOGG TRANSPORT REACTOR TRAIN

5.1 TRANSPORT REACTOR LOOP

This section deals with the commissioning of the following systems: coal feed system (FD0210), sorbent feed system (FD0220), start-up burner (BR0201), transport reactor (RX0201), disengager cyclone (CY0207), primary cyclone (CY0201), combustion heat exchanger (HX0203), spent solids screw cooler (FD0206), spent solids conveying system (FD0510), and pressure letdown system (PV287). The commissioning and performance of BR0201, RX0201, CY0207, CY0201, and HX0203 are discussed in the following sections which describe the various commissioning (test runs CR01 - CR04) and characterization (test runs CCT1A - CCT3A) test runs that were performed in combustion mode of operation in 1996. The feed and solids removal systems (FD0210, FD0220, FD0206, and FD0510) are described in section 5.1.12 following the test runs. The problems associated with the initial operation of PV287 and the corrective actions taken are described in section 5.1.13.

5.1.1 Commissioning Test Run CR01

5.1.1.1 Introduction and Test Objectives

During the months of May and June of 1996 three major start-up milestones in the commissioning of the transport reactor were completed: (1) the first, complete system pressure test, (2) transport reactor refractory cure, and (3) fluidization trials.

The CR01 commissioning test run covered the period between June 3 and June 6, 1996, with the objective of commissioning the start-up burner and proceeding with the curing of the refractory joints. Several attempts were made during CR01 to commission the start-up burner and a number of problems associated with the design of the burner were corrected. The curing of the transport reactor refractory, associated refractory-lined pipe, and refractory joints was completed during CR02 test run and initial fluidization trials were performed during CR03 test run.

Prior to the beginning of the CR01 test run, functional checks on the transport reactor loop (RX0201) and the transport reactor start-up burner (BR0201) were completed in the second quarter of 1996. Beginning May 17 the transport reactor was tested for leaks. After correcting all the identified leaks, the first successful full pressure test was completed in the first week of June. This test was on the complete system from the main air compressor (CO0201), through the reactor and the granular bed filter (GBF) vessel (which was used as a gas flow path during initial tests with the transport reactor), to PV287. CO0201 was used to admit air through the primary and secondary combustion air nozzles on the reactor. The pressure was gradually raised in small increments, with sufficient hold periods allowed after each pressure increase. While the leak test was under way, several leaks were discovered at small nozzle joints. Tightening bolts stopped many of these leaks. However, some other nozzle leaks could not be stopped by bolt tightening, and resulted in the replacement of the "flex" gaskets after depressurization. On June 1 another pressure test was attempted. Using the process air compressor to raise the reactor and all the associated piping pressures, the reactor pressure finally reached the proof pressure of 385 psig. All safety valves were also tested.

By early June the transport reactor start-up burner had not yet passed the operational tests due to damage to both the ignitor rod and the flame detection rod. This equipment did not come with complete instructions to adequately 'bench' test the ignitor and flame detection rod before mounting in the burner. This was further complicated by the lack of a visual flame view port. After much discussion an agreement was reached with the vendor and his subvendors on a method to test the equipment. The originally supplied ignitor and flame detection rod were found unserviceable and had to be replaced. Several problems arose during the course of the start-up burner checkout. The burner was the vendor's first high-pressure application, and the design was inadequate and unsafe for operation as it was received. It appears that the vendor provided a burner optimized for natural gas firing (the PSDF uses propane). Several modifications were made to temporarily use the existing equipment, and the burner has been operating since they were made. Several concerns still existed that were addressed later during the year: the lack of safe turn-down in fuel flow, the lack of automatic compensation for reactor pressure variations, and separate pilot combustion air. SCS and MWK were in discussions and participating in an effort to redesign the burner to better and more safely meet the design specifications. A redesigned burner system from the subvendor was received in July and August. In the meantime, the modifications made to the original burner (with the vendor's consensus) allowed safe operations and the start-up to continue with refractory cure-out and other commissioning activities.

Several problems with the packing on the start-up burner ignitor were corrected with the deletion of the retracting mechanism for the ignitor. Cooling air ports were installed on both the ignitor and the flame rod to prevent failures due to overheating. There have been no failures during the subsequent light-offs.

Until May 1996 the main air compressor was being operated on manual due to several problems associated with automatic operation. The compressor tuning and other changes were made in the first week of June that facilitated automatic operation. The tuning and changes included:

1. Increasing the response time of the inlet guide vanes (IGVs).
2. Incorporating the opening of the IGVs at a surge line of 200 psig decreasing.
3. Increasing the deadband on the blowoff valve to 2 psi.
4. Incorporating the closing of the IGVs at 215 amps on the motor.
5. Setting the IGVs to 10-percent open automatically on the initial start of the compressor.

5.1.1.2 Test Chronology

On June 3 after tuning of the compressor was complete, the reactor pressure was set at 50 psig and purge flows were set for the pressure transmitter and differential pressure transmitter. The following night the start-up burner pilot was lit. After 4 minutes it tripped due to flame failure. Four more attempts were unsuccessfully made to light the pilot at combustion air flows of 500 and 1,100 lb/hr. It was noticed that the propane flow had dropped from 10 to about 3 lb/hr since the initial attempt. Upon inspection trash was found to be blocking the orifice. The orifice was cleaned and the burner was reassembled. During the inspection the pilot seemed to be igniting and burning in the area of the orifice and not at the tip. The flame rod and ignitor wiring appeared to be scorched. The bench scale response of the flame rod to a flame was sluggish.

On June 5 the start-up burner main burner was successfully lit but there were some problems setting the required combustion and quench air flows due to the reactor pressure control. There was a flow restriction problem at PV287. After 3 minutes the burner tripped due to flame failure. Three more attempts were made to light the pilot, but it tripped every time. Some adjustments were made to control combustion air flow prior to flame detection. The pilot and main burner were then successfully lit, but after 7 minutes the burner tripped again. The burner was relit and stayed lit for 14 minutes before tripping again. Additional attempts to light the burner were unsuccessful. The reactor system was shutdown to investigate the flow restriction problem and the start-up burner problems. See section 5.1.13 for more details on corrective action taken to address problems associated with the pressure letdown valve.

5.1.1.3 Test Run CR01 Observations

The main challenges of this run were the flow restriction problems with the pressure letdown valve and the start-up burner operation. The first burner inspection found that trash was blocking the pilot orifice and that the pilot seemed to be igniting and burning in the area of the orifice and not at the tip. Further inspections showed scale deposition in the start-up burner propane lines.