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# UPDATE ON GASIFICATION TESTING AT THE POWER SYSTEMS DEVELOPMENT FACILITY

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## INTRODUCTION

The Power Systems Development Facility (PSDF) located in Wilsonville, Alabama was established in 1995 to lead the United States' effort to develop cost-competitive, environmentally acceptable, coal-based power plant technologies. The PSDF is an engineering scale demonstration of key components of an Integrated Gasification Combined Cycle (IGCC) power plant, including a KBR (formerly Kellogg, Brown, & Root) Transport Gasifier, a Siemens Particulate Control Device (PCD), syngas cooling, and high pressure solids handling systems. These components are designed at sufficient size to provide data for commercial scale-up. As of April, 2008, the PSDF gasification process had been operated for more than 10,800 hours, providing valuable operational data for future commercial scale IGCC power plants.

The Transport Gasifier is a circulating fluidized bed reactor designed to operate at higher circulation rates and riser densities that result in higher throughput, better mixing, and higher mass and heat transfer compared to conventional circulating bed units. Since the gasifier uses a dry feed system and does not slag the ash, it is particularly well-suited for high moisture and high ash fuels such as subbituminous coal and lignite. The gasifier has operated in both air-blown and oxygen-blown modes. This paper will discuss recent testing of the gasification process at the PSDF.

## PROJECT DESCRIPTION

Figure 1 below illustrates the general flow diagram of the gasification process at the PSDF. A lock hopper assembly supplies fuel to the pressurized gasifier, while a separate system supplies sorbent, if necessary, to capture sulfur in the fuel. A burner is available to heat the gasifier from ambient conditions to a temperature suitable for adding coal, but is only necessary during startup.

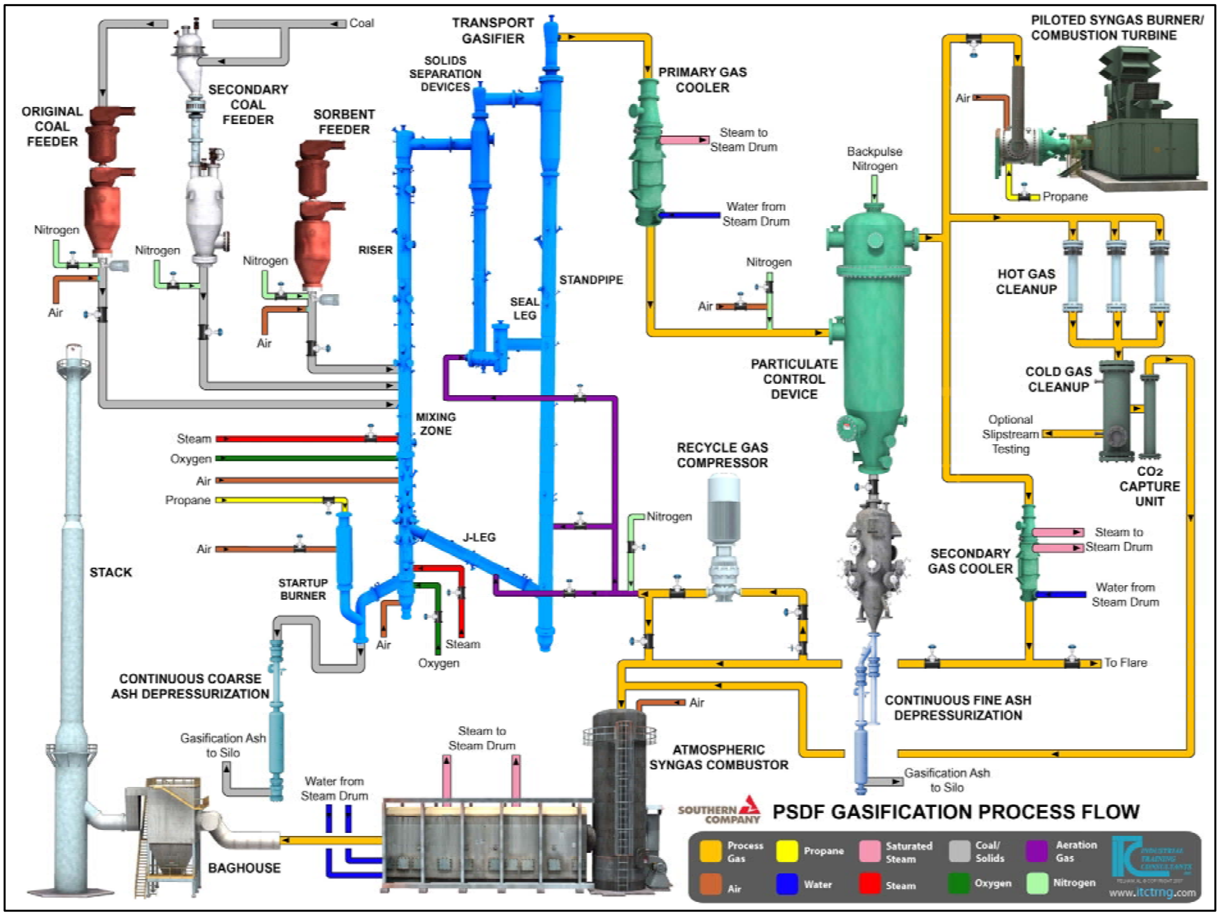

Figure 1. PSDF Gasification Process Flow Diagram.

The gasifier consists of an assembly of refractory-lined pipe that includes a mixing zone, riser, solids separation and collection unit, and solids recycle section. The solids from the separation and collection unit enter the lower portion of the mixing zone and combust to provide the heat necessary for the gasification reactions. The coal and sorbent are fed to the gasifier in the upper mixing zone, where the hot circulating solids traveling upward from the lower mixing zone provide the heat necessary to devolatilize and gasify the coal in the riser, producing syngas and gasification ash. The continuous coarse ash depressurization (CCAD) system, located beneath the gasifier, allows for the removal of gasification ash to control the gasifier bed inventory. The Transport Gasifier operating temperature for Powder River Basin (PRB) subbituminous coal and lignite is nominally 1750°F. The PSDF gasifier has a maximum operating pressure of 294 psig and a thermal capacity of about 50 MMBtu/hr.

The syngas and solids mixture from the mixing zone flow through the riser to the solids separation unit. The separation system removes the majority of solid particles and sends them via the recycle section to the lower mixing zone for combustion, while the syngas exits the solids separation unit and proceeds to the primary gas cooler and the PCD.  Although the carbon content in the circulating solids is relatively low, the high circulation rate ensures that sufficient carbon is present to provide the heat necessary to maintain sufficient gasifier temperatures. Nitrogen or recycled syngas is used to fluidize the solids recycle sections to ensure that the circulating solids flow properly. Air or oxygen is used for combusting the recycled carbon, while steam provides a means for dispersing the oxidant and regulating the temperatures when using pure oxygen.

After leaving the solids collection unit of the gasifier, the syngas flows into the primary gas cooler at a temperature of approximately 1700°F. The primary gas cooler decreases the syngas temperature to about 800°F before the gas enters the PCD. The gas flows into the vessel through a tangential entrance, around a shroud, and through the filter elements into the plenums. Virtually all the particulate from the syngas is removed by the PCD shown in Figures 2 and 3, which uses candle-type filters. The PCD contains a tube sheet holding up to 91 filter elements that are attached to one of two plenums. A failsafe device located on the clean side of each element is designed to stop solids leakage in the event of a filter failure by acting as a back-up filter. High pressure gas is used to periodically pulse clean the elements to remove the accumulated solids, forcing the filter cake to fall to the PCD cone and into the continuous fine ash depressurization (CFAD) system. A common ash silo collects the solids removed via the CCAD and CFAD systems for disposal.

Figure 2. PCD Internals.

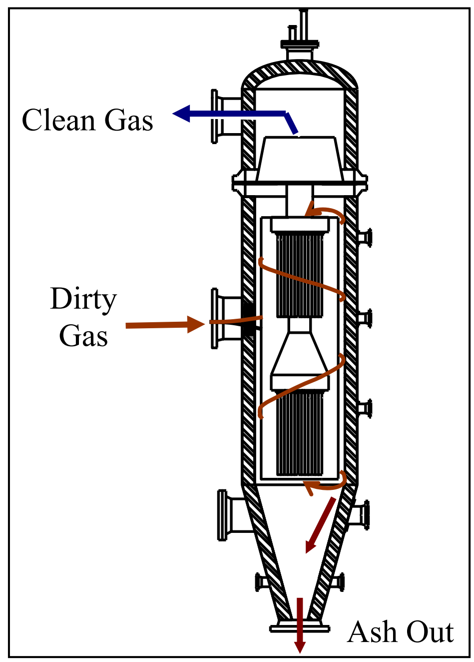


Figure 3. Schematic of PCD.

The filtered syngas exiting the PCD continues to either a combustion turbine for producing electricity or to the secondary gas cooler and the atmospheric syngas combustor, where the gas is burned and all reduced sulfur compounds ($H_2S$, COS, $CS_2$) and reduced nitrogen compounds ($NH_3$, HCN) become oxidized. Upon leaving the syngas combustor, the flue gas flows through a heat recovery boiler to cool the gas and to generate steam. The cooled gas then passes through a baghouse and out an exhaust stack. A slipstream test unit is also available for testing various catalysts and sorbents for removing syngas contaminants before sending the syngas to the atmospheric syngas combustor or to a fuel cell. To improve heating value and reduce nitrogen consumption, a recycle gas system can send a portion of the syngas back to the gasifier as fluidization gas.

## OPERATIONAL HISTORY

System commissioning and the initial test campaigns were performed in combustion mode from 1996 to 1999. Operation in air-blown gasification mode began in September 1999. Four gasification commissioning tests, each lasting nominally 250 hours, were completed by early 2001. Since then, 20 test campaigns, each nominally 250 to 1,500 hours in duration, have been completed resulting in over 10,800 hours of gasification testing. Powder River Basin subbituminous coal has been tested extensively totaling about 7800 hours. Three bituminous coals and four different lignites have also been tested. Transport reactor operation during combustion mode operation has been previously described (Vimalchand, 1999), as has operation in early gasification testing (Loganbach, 2005).

Prior to 2006, the Transport Gasifier configuration was based on a combined combustor/gasifier design that limited its performance as a gasifier. In early 2006, changes to the gasifier provided a new, more robust solids separation system as well as a larger diameter riser. These changes consisted of replacing approximately 85 percent of the refractory-lined gasifier. The primary objectives were to improve the solids collection efficiency and to increase the residence time in the gasifier with the goals of increasing carbon conversion and syngas heating value and testing a solids collection system better suited for commercial scale-up.

## RESULTS

In addition to the continued development of the Transport Gasifier, significant progress has been made in the development of supporting technologies for the gasification process. Some major areas of technology development at the PSDF include the following:

- Transport Gasifier – Gasifier modifications have resulted in increased carbon conversion and more stable operations for various fuels tested.
- Coal Feeding—High pressure offline system provides testing flexibility for optimization of conventional lock hopper feeders as well as the development and testing of novel feeder designs.
- Ash Removal—A new design concept for fine and coarse ash cooling and depressurizing was developed and successfully tested at the PSDF, providing reliable ash removal.
- Sensor Development and Process Automation—A continued focus on development of advanced sensors for gasification technology in general has continued to provide critical progress in this area.
- Hot Gas Filtration—Testing and research continues to yield critical information needed for commercial design (Yongue, 2007).
- Syngas Analysis and Sampling—Advances in syngas sampling and analysis continued to improve the operational reliability of the systems and provide the data needed for technology development and process understanding.
- Advance Syngas Cleanup—A slipstream unit has provided a very flexible test platform for testing numerous syngas contaminant removal technologies.

Coal Feed Systems

A coal preparation and feeder development program has been implemented to demonstrate and quantify reliable systems that will optimize process performance, reduce capital cost, and improve reliability. Work to date includes determining the effect of feed particle size on gasifier operations and performance and developing the operating envelope for different fuel types based on testing with a lock hopper based rotofeed system. Test runs have confirmed an optimal particle size (250-600 microns mmd) and maximum moisture content (less than 20 percent) to effectively feed via lock-hopper systems to high pressure vessels. Running at these recommended conditions minimizes feeder trips due to discharge line plugging and lock vessel packing.

To further expand PSDF coal feed testing capability, a high pressure recycle loop was designed and commissioned in 2007, providing flexibility to test feeder systems independent of gasifier operations. System pressures of 500 psig have been tested, and the system incorporates a solids collection and backpulse system closely simulating gasifier feed conditions. The offline test system provides a flexible platform for the testing of feeders such as the new, innovative PSDF designed developmental system. Successful development and testing of this new feeder in offline mode was followed by 34 hours of fuel feed to the gasifier.

Transport Gasifier Performance

The transport gasifier was modified in 2006 to improve the solids capture efficiency of the gasifier solids collection system and to increase the residence time in the gasifier. In August of 2006, the system was successfully commissioned and tested with PRB coal, achieving the most stable gasifier operations to date, and demonstrating improvements in the solids collection efficiency, syngas heating value, and carbon conversion. The increase in separator efficiency led to a decrease in particle size and bulk density of the solids circulating in the gasifier; however, gasifier operations were not adversely affected. Data analysis of PRB operations reveals a 20 percent increase in raw syngas lower heating value and average carbon conversions increasing from 95.4 percent to 98.1 percent. Coals tested in the current configuration have produced syngas with projected lower heating values acceptable for combustion turbine operation, and the new design is suitable for commercial scale-up with PRB. Testing has now expanded from design validation and optimization to include increased emphasis on demonstrating fuel flexibility by developing operating envelopes for various fuels. Recent testing has been focused on lignite coals, including lignite with high moisture and sodium content, as well as low-volatile bituminous coal.

Lower rank coals such as subbituminous and lignite represent 46 percent of the nations demonstrated reserve base [EIA, 2007]. However, certain species of lignite provide operational challenges to gasification. Gasification studies have shown that sodium vapor released from high-sodium lignites can react with silica to form sticky sodium silicates. These sticky sodium silicate compounds naturally tend to glue particles together leading to the formation of agglomerated deposits in the gasifier. Extensive evaluation of various additives to prevent ash consolidation was performed and reported at the PSDF [Leonard, 2007]. Figure 4 shows the results of consolidation testing with meta-kaolin. Based on these evaluations, meta-kaolin was chosen to test in a 2008 run, resulting in a successful test campaign of over 300 hours with no deposition in the gasifier. Also, lignite with very high moisture content (greater than 40 percent) was evaluated. Gasification testing resulted in projected LHV of 119 BTU/scf and carbon conversions averaging 97.2 percent; however, coal feed issues were a problem during the run. Coal feed issues were primarily a result of the lignite moisture content exceeding coal mill system design conditions. A lignite dryer was designed, installed, and tested in 2008 at the PSDF.

Bituminous coal is a less reactive fuel and thus requires higher operating temperatures, nominally 1850°F, to achieve higher carbon conversions and eliminate formation of tars. Recent testing of bituminous coal was performed to establish operating conditions with this coal for the current gasifier configuration. Analysis of results is underway, but high carbon content in the ash made for a challenging run. Larger bituminous coal particles are less prone to gasify, so screening of larger particles in the milling process can reduce carbon content in the gasifier ash. Also, temperature distribution was difficult to control with the air flow distribution in this test run. Adjustments to air flow distribution should improve the temperature profile. Finally, introduction of coal at the appropriate temperature is critical to eliminate tar formation, and enhancements to the current gasifier start-up burner are necessary to achieve the appropriate temperature.

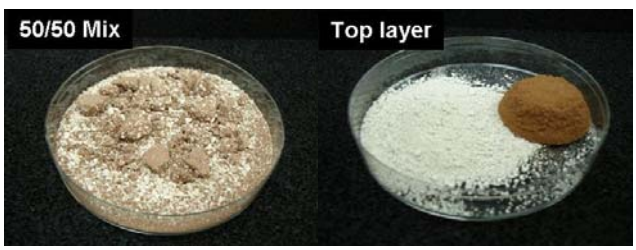


Figure 4. Results of tests with CK46 meta-kaolin – 50/50 mix of meta-kaolin with deposit (left), meta-kaolin as a top layer over deposit (right)

Ash Removal Systems

Two new ash removal systems were designed and tested. These PSDF proprietary systems (CCAD and CFAD) have no moving parts and do not require a pressurizing gas. Solids transport is accomplished by using the entrainment gas, and only a small amount of solids-free gas is vented. These ash removal systems have together operated over 8,000 hours with 100 percent availability over a range of particle size distributions. Figure 5 shows the range of particle sizes discharged successfully by the CFAD and CCAD systems.

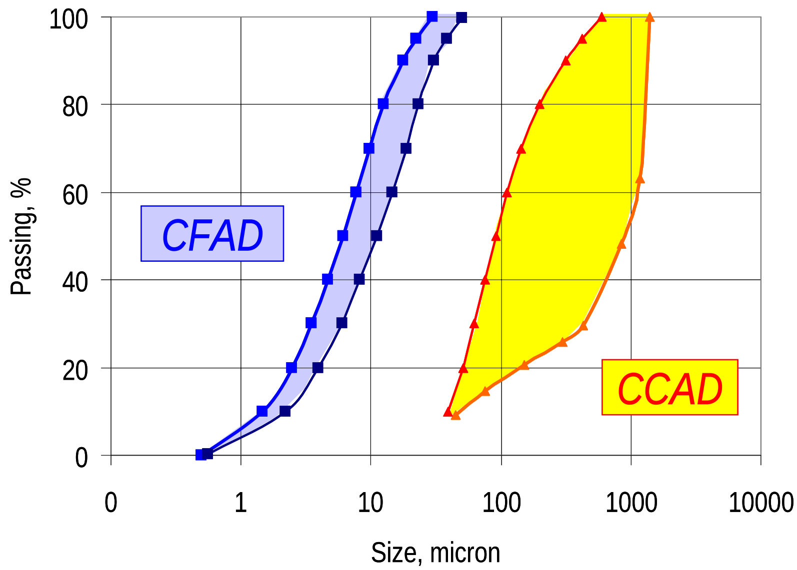

Figure 5. CFAD and CCAD Particle Size Distribustions.

Development is underway to further optimize the ash removal systems, specifically focusing on capital cost reduction and automation. Local controls have been installed on CFAD equipment to minimize the amount of control valves to operate and maintain. Logic has also been installed and tested to automatically keep solids discharge flowing smoothly, reducing operator attention required during normal operations.

Sensor Development/Automation

Significant progress with sensor development and process automation has been achieved. Development of reliable and accurate sensors for the gasification process has concentrated on coal feed, Transport Gasifier, and PCD systems. Extensive testing of a nuclear based coal feed rate measurement revealed limitations in the measurement capability. A combination of capacitance velocity and nuclear density was tested and proved to be an accurate instantaneous coal feed rate measurement.

To improve gasifier temperature measurement reliability, various materials and instrument configurations have been tested. The effect of thermowell insertion length has also been studied. At the current range of operating conditions, thermowells with HR-160 tips have proven reliable, accurate, and durable. Also, ceramic thermowells manufactured by Foreman Industries have shown promise in high velocity regions in the previous gasifier design and lasted over 1,000 hours with minimal wear. The rigidity of materials and higher cost of the ceramics make HR-160 the current preferred material. The optimum insertion length was found to be 2 inches, providing minimal tip erosion and accurate temperature measurement.

It has been noted that HR-160 thermowells have performed well in gasifier operating conditions. Thermowell tip degradation has been evaluated to provide a more thorough understanding of long-term service of thermowells in gasification service. Figure 6 is a microscopic view of thermowell tip exposed to unusually erosive operating conditions. While wear was not extensive enough to fail the thermocouple, the unusual operating conditions provided an opportunity to evaluate HR-160 thermowells in severe service. An erosion-corrosion mechanism brought about by sulfidation corrosion and large abrasive standpipe ash is theorized to be the mechanism of wear [Leonard, 2007].

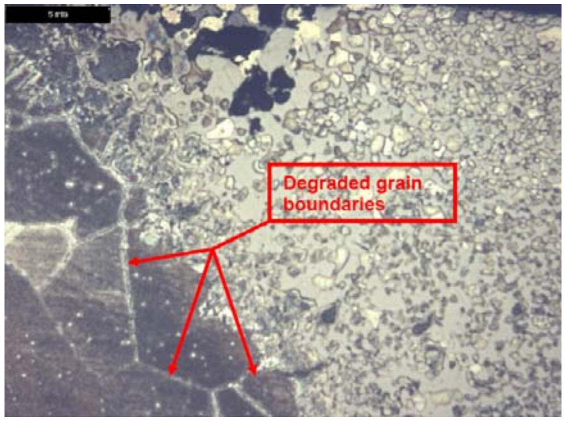

Figure 6. Microsopic analysis of HR-160 Thermowell Tip.

Additionally, a new material, a molybdenum-boron-silicon composite, developed at Oak Ridge National Laboratory for thermowell application in gasification service has been tested at the PSDF. Although tip wear was significant during typical gasifier operating conditions, post-run evaluation will provide valuable insight that can be incorporated into future materials testing.

Another area of sensor testing has been on-line particulate monitoring at the PCD outlet. The PCME Dust Alert 90, which infers a particulate concentration from the electrical charge flowing near the probe, has proven to reliably detect significant particle penetration through the PCD. For detection of very small levels of particulate penetration, which is much more typical, the Process Metrix, Inc. Process Particle Counter (PPC), an extractive, laser-based single-particle counter has been tested in recent runs. The PPC appears to be able to reliably detect mass concentrations as low as 0.5 ppmw and can potentially predict particle size distributions as well. Although more development is needed, real-time, reliable particulate monitoring has been realized.

Particulate Control Device

Central to the particulate control device (PCD) test program is the evaluation of filter elements in terms of collection efficiency and corrosion resistance. Collection efficiencies must meet combustion turbine manufacturer specifications. Figure 9 shows typical outlet concentrations with respect to turbine specifications, revealing the current PCD exceeds requirements [Yongue, 2007]. Corrosion resistance must be sufficient for PCD internals to meet cost constraints and not cause undue downtime. Several candle filter materials have been tested, with recent focus on iron aluminide (FEAL) and HR-160 materials. In general, the FEAL sintered metal powder elements offer superior particle collection, but they have shown signs of corrosion over time. Filters constructed of HR-160 material have tested at lower corrosion rates, albeit with lower cumulative test hours, yet allow more particle penetration. Cumulative maximum run hours for FEAL filters exceed 9500 hours, while HR-160 candles have been tested for approximately 3000 hours.

Higher ash coals such as lignite increase loading to the PCD. Recent testing of lignite resulted in PCD loading twice that of PRB subbituminous coal. However, outlet concentrations remained under manufacturer specifications of 2.5 ppm.

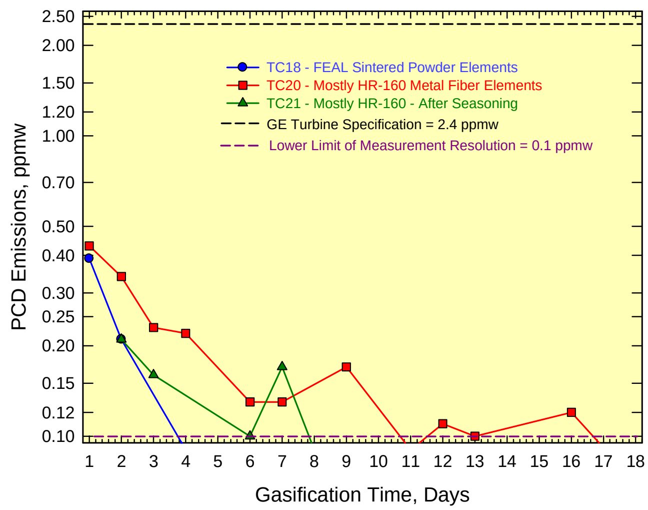


Figure 9. PCD Emissions as compared to Turbine Specification.

Loss of particulate control can be catastrophic to combustion turbine internals, making failsafe design for filter candles a critical design component and a focal point for PSDF testing. Since the implementation of the failsafe development program, six different types of failsafes have been used and tested at the PSDF: (1) a PSDF-designed failsafe (a metal platform and metal fiber media), (2) a Pall iron aluminide sintered powder fuse, (3) a Pall HR-160 metal fiber failsafe, (4) a Specific Surface ceramic honeycomb failsafe, (5) a CeraMem ceramic honeycomb failsafe, and (6) a Pall HR-160 reversed-media failsafe. A detailed presentation of the failsafe test program and results obtained has been published previously (Howard, 2007). Because of the development program, reliable failsafes have been identified that effectively prevent particle penetration. With these failsafes, filter element failures have been undetectable during test campaigns.

<u>Gas Analysis and Sampling</u>

There have been several recent advances in the areas of gas analysis and sampling. Often performed in coordination with vendors, these include design changes to existing instruments, the employment of performance coatings, and novel applications of sampling techniques in conjunction with laboratory instruments. For example, there have been changes made to a Gasmet Fourier Transform Infrared (FTIR) analyzer manufactured by Temet. These changes include the relocation of several electrical components and the installation of a deflector directly into the sample cell. These changes have dramatically increased this analyzer's effectiveness.

Accurate and timely gas analysis is critical to advanced syngas cleanup development. New laboratory methods have enabled on-site analysis of carbon dioxide capture gas streams. Also, a high pressure impinger system was designed and constructed at the PSDF, providing portable sample conditioning for water-gas shift and sulfur capture testing.

<u>Advanced Syngas Cleanup</u>

In order to develop commercially viable syngas cleanup systems to achieve ultra low emissions from coal gasification processes, a slip stream test facility was implemented in mid-2003. The cleanup facility is a flexible unit, and testing can be done simultaneously for individual components or removal technologies or for combinations thereof. In addition to testing with syngas when the Transport Gasifier is in operation, tests are conducted during plant outages using bottled gases.

The equipment includes several small reactors, knock out pots, and scrubbers which operate at varying temperatures, pressures, and flow rates. Table 1 below lists the major equipment including approximate sizes and operating conditions. The small reactors and solution scrubbers are shown in Figures 10 and 11, respectively.

Table 1. Advanced Gas Cleanup Major Equipment.

| Equipment | Temperature °F | Pressure psig | Syngas Flow Rate lb/hr |
|---|---|---|---|
| Mini Reactors (1.5" X 3') | 1800 | 14 | 1 |
| Small Reactor RX700A (5.1" X 4') | 800 | 350 | 100 |
| Small Reactor RX700B (5.1" X 4') | 1400 | 45 | 50 |
| Small Reactor RX700C (5.1" X 4') | 700 | 350 | 100 |
| Mini Reactor RX700D (2" X 4') | 1600 | 200 | 20 |
| 2 Water Scrubbers (12" X 4') | 250 | 100 | 30 |
| 2 Knock out Pots (4" X 6') | 40 | 100 | 30 |
| 2 Solution Scrubbers (12" X 4') | 150 | 100 | 30 |
| $CO_2$ Capture Test Unit | 400 | 2000 | 6 |

Figure 10. Small Reactors in Syngas Cleanup Facility.

Figure 11. Solution Scrubbers in Syngas Cleanup Facility.

Several hundred hours of testing have been achieved thus far using various contaminent removal technologies. The main contaminants of interest and the general technologies employed are shown below in Table 2. Recent focus has been on sulfur, trace metals, and $CO_2$ removal from the syngas. Capital reduction is a key parameter for commercialization of these technologies, and innovative ideas such as the integration of water gas shifting and particulate control are currently being developed and tested. Testing has also been performed of catalyst for trace metals and sulfur removal at higher temperatures favorable for increased IGCC heat rates.

Table 2. Syngas Cleanup Contaminants and Removal Technologies.

| Syngas Contaminant | Technology | Examples of Sorbents/Catalysts |
|---|---|---|
| Ammonia | High Temperature Cracking; Hot Gas Sorbents | Nickel-based catalysts; Zeolites |
| Alkali, Trace Metals | Hot Gas Sorbent; Scrubbing | Various materials; condensate scrubbing |
| Carbon Dioxide ($CO_2$) | Solution Absorption/Regeneration | Conventional solvents |
| Carbonyl Sulfide (COS) | COS Hydrolysis Catalysts | Activated aluminum oxide; titanium dioxide |
| Chloride | Acid Gas Cleanup Solutions and Sorbents | Trona sorbent |
| Sulfur | Hot Gas Sorbents and Solutions; Direct Oxidation | Nano materials; Iron and zinc based sorbents; Conventional solvents |
| Mercury | Acid Gas Cleanup Solutions | Activated carbon; Coated sorbents |
| Organics | High Temperature Cracking | Fluid Catalytic Cracking catalysts; Nickel-based catalysts |
| Sulfur | Hot Gas Sorbents | Iron based and zinc-based sorbents; activated alumina |

The slip stream facility has been used to provide outside researchers and developers a platform for testing of various technologies, such as fuel cell testing and trace metals removal. For example, TDA research has tested trace metals removal catalyst, Media Process and Technology has installed a hydrogen membrane separation unit for testing on syngas, and the DOE has a fuel cell on-site ready for testing and evaluation. The DOE fuel cell testing was on hydrogen, and future plans are to operate the fuel cell on syngas during the next test run.

**CONCLUSIONS**

The PSDF continuously endeavors to improve all aspects of the gasification process. The PSDF Gasification Process has been successfully tested with the gasifier operating in air-blown and oxygen-blown gasification modes for over 10,800 hours. Recent modifications in the gasifier design have improved carbon conversion, syngas heat content, and operational stability to the extent that the gasifier is commercially viable. A commercial deployment group has been created to bring the technology to the market. Demonstration of various fuels is a current area of focus, including testing of high sodium lignite, high moisture lignite, and bituminous coal. These fuels will require different operating conditions and system enhancements, and evaluation and testing of various additives for high sodium lignite operations, installation and operation of a feed dryer for high moisture lignite, and operation with bituminous coals illustrate the development of IGCC with Transport Gasifier technology. Recent accomplishments at the PSDF include installation of a more robust, representative high pressure offline feed test system, optimization and design enhancements of ash removal systems, materials testing and evaluation to improve reliability in particulate control and temperature measurement, and evaluation of various gas cleanup technologies developed by the PSDF and various third party participants.

While testing at the PSDF has broadened in scope recently, each test has a common goal of bridging the gap between fundamental research and commercial deployment of cost-competitive, environmentally acceptable, coal-based power plant technologies.

**FUTURE TESTING**

The focus of the PSDF is evolving from the development of the front end of the IGCC process, including the gasifier and related processes, to gas cleanup, including $CO_2$ capture. The PSDF is proposing a broad array of technology development activities that will support a pathway to a cost-effective advanced coal-generating plant with $CO_2$ capture. Pre-combustion $CO_2$ capture, post-combustion capture, and oxycombustion development are included in the PSDF long-term R&D plan. The backbone of capture technology development will be a high-pressure, flexible facility designed to test an array of solvents and contactors in a $CO_2$ capture test facility.

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