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Hot-Gas Filter Testing with a Transport Reactor Gasifier

Key Words: Integrated Gasification Combined Cycle, Particulate Control, Candle Filter Testing, Trace Element Measurement

Introduction

Today, coal supplies over 55% of the electricity consumed in the United States and will continue to do so well into the next century. One of the technologies being developed for advanced electric power generation is an integrated gasification combined cycle (IGCC) system that converts coal to a combustible gas, cleans the gas of pollutants, and combusts the gas in a gas turbine to generate electricity. The hot exhaust from the gas turbine is used to produce steam to generate more electricity from a steam turbine cycle. The utilization of advanced hot-gas particulate and sulfur control technologies together with the combined power generation cycles make IGCC one of the cleanest and most efficient ways available to generate electric power from coal. One of the strategic objectives for U.S. Department of Energy (DOE) IGCC research and development program is to develop and demonstrate advanced gasifiers and second-generation IGCC systems. Another objective is to develop advanced hot-gas cleanup and trace contaminant control technologies. One of the more recent gasification concepts to be investigated is that of the transport reactor gasifier, which functions as a circulating fluid-bed gasifier while operating in the pneumatic transport regime of solid particle flow. This gasifier concept provides excellent solid-gas contacting of relatively small particles to promote high gasification rates and also provides the highest coal throughput per unit cross-sectional area of any other gasifier, thereby reducing capital cost of the gasification island.

Objectives

The goal of the advanced high-temperature, high-pressure transport gasification program at the Energy & Environmental Research Center (EERC) is to demonstrate acceptable hydrodynamic and gasification performance of the transport reactor development unit (TRDU) under a variety of operating conditions and using a wide range of fuels. The current objectives are focused on understanding and improving the operation of the transport reactor gasifier itself. A secondary objective of the program is to demonstrate acceptable performance of hot-gas filter elements on the hot dust-laden fuel gas stream coming from the pilot-scale TRDU system prior to long-term demonstration tests. The goal of hot-gas particulate control is not simply to meet current New Source Performance Standards (NSPS) with respect to particulate emissions, but also to protect high-efficiency gas turbines and to control particulate emissions to sufficiently low levels to meet more stringent regulatory requirements anticipated in the future.

Approach

Specific objectives of the proposed work include:

- Continue development of the transport gasifier by investigating oxygen-enrichment or oxygen-blown operation, determining effectiveness of J-legs, or L-valves for maximizing solid recirculation, and optimizing mixing zone geometry for improved product gas quality.
- Demonstrate acceptable performance of hot-gas filter elements in a pilot-scale system prior to long-term demonstration tests. The primary focus of the experimental effort is the testing of hot-gas filter element performance (particulate collection efficiency, filter pressure differential, filter cleanability, and durability) as a function of temperature and filter face velocity during short-term operation (100–200 hours).

Project Description

Advanced Transport Reactor

The TRDU has an exit gas temperature of up to 980°C (1800°F), a gas flow rate of 325 scfm, and an operating pressure of approximately 120 psig. The TRDU system can be divided into three sections: the coal feed section, the TRDU, and the product recovery section. The TRDU proper, as shown in Figure 1, consists of a riser reactor with an expanded mixing zone at the bottom, a disengager, primary cyclone, standpipe, and dip leg. The standpipe collects solids from the disengager and is connected to the mixing section of the riser by an L-valve transfer line which utilizes steam to move the solids back to mixing zone. Additional solids are collected by the primary cyclone into the dip leg that returns these solids into the standpipe through a seal pot. All of the components in the system are refractory-lined and designed mechanically for 150 psig and an internal temperature of 1090°C (2000°F).

For oxygen-blown operation, the TRDU loop seal was modified to allow more solids circulation through the mixing zone. Higher solids circulation rates will dissipate more of the heat release in the mixing zone. The loop seal was changed from a J-leg to an L-valve configuration, which allowed the length of the mixing zone to be increased substantially for increased solids residence time. In addition, the diameters of the standpipe, dip leg and L-valve return legs were increased to reduce the amount of wall friction and gas bubble holdup caused by the small inside diameters of these sections. Another modification was to install a seal pot on the bottom of the dip leg. This will allow the bed material height in the standpipe to be operated independently of the level in the dip leg without having the primary cyclone performance spoiled by gas bypassing up the dip leg when the solids level dropped below dip leg solids return point.

The premixed coal and limestone feed to the transport reactor can be admitted through three separate nozzles located at varying elevations. Two of these nozzles are near the top of the mixing zone (gasification), and the remaining one is near the bottom of the mixing zone (combustion). During operation of the TRDU, feed is admitted through one predetermined nozzle at a time. The coal feed is measured by an rpm controlled metering auger. Oxidant is fed to the reactor through two pairs of nozzles at varying elevations within the mixing zone. For the combustion mode of operation, additional nozzles are provided in the riser for feeding secondary air. Hot solids from the standpipe are circulated into the mixing zone, where they come into contact with the nitrogen and the steam being injected into the J-leg. This feature enables spent char to contact steam prior to the fresh coal feed. This staged gasification process is expected to

enhance the process efficiency. Gasification or combustion and desulfurization reactions are carried out in the riser as coal, sorbent, and oxidant (with steam for gasification) flow up the reactor. The solids circulation into the mixing zone is controlled by the solids level in the standpipe.

The riser, disengager, standpipe, and cyclones are equipped with several internal and skin thermocouples. Nitrogen-purged pressure taps are also provided to record differential pressure across the riser, disengager, dip leg, and the cyclones. The data acquisition and control system scans the data points every one-half second and is saving the process data every 30 seconds. The bulk of entrained solids leaving the riser is separated from the gas stream in the disengager and circulated back to the riser via the standpipe. A solids stream is withdrawn from the standpipe via an auger to maintain the system's solids inventory. Gas exiting the disengager enters a primary cyclone. Gas exiting this cyclone enters a jacketed-pipe heat exchanger before entering the hot-gas filter vessel (HGFV). The cleaned gases leaving the HGFV can either be depressurized and combusted in a thermal oxidizer or can enter a quench system before being depressurized and vented to a flare.

The quench system uses a sieve tower and two direct-contact water scrubbers to act as heat sinks and remove impurities. All water and organic vapors are condensed in the first scrubber, with the second scrubber capturing entrained material and serving as a backup. The condensed liquid is separated from the gas stream in a cyclone that also serves as a reservoir. Liquid is pumped either to a shell-and-tube heat exchanger for reinjection into the scrubber or down to the product receiver barrels.

Hot-Gas Filter Vessel

The filter design criteria are summarized in Table 1, and a schematic is given in Figure 2. This vessel is designed to handle all of the gas flow from the TRDU at its expected operating conditions. The vessel is approximately 48 in. ID and 185 in. long and is designed to handle gas flows of approximately 325 scfm at temperatures up to 815°C (1500°F) and 150 psig. The refractory has a 28-in. ID with a shroud diameter of approximately 22 in. The vessel is sized such that it could handle candle filters up to 1.5 m long; however, mostly 1-m candles have been utilized in the 1000°F (540°C) gasification tests to date. Candle filters are 2.375 in. OD with a 4-in. center line-to-center line spacing.

The total number of candles that can be mounted in the current geometry of the HGFV tube sheet is 19. This enables filter face velocities as low as 2.5 ft/min to be tested using 1-m candles, although most tests have been conducted using 12 to 13 candles, providing a face velocity between 4 to 4.5 ft/min. The openings for the removed candles have been blanked off. This program has tested an Industrial Filter & Pump (IF&P) Fibrosic and REECER candles, silicon carbon fiber and silicon oxide ceramic fiber candles from the 3M company, along with sintered metal (iron aluminide) and Vitropore silicon carbide ceramic candles from Pall Advanced Separation Systems Corporation, ceramic fiber filters from both McDermott and Dupont Lanaxide, and granular SiC candles from U.S Filter/Schumacher. Candle filter failsafes from Westinghouse Science and Technology Center were also tested.

The ash letdown system consists of two sets of alternating high-temperature valves with a conical pressure vessel to act as a lock hopper. Additionally, a preheat natural gas burner attached to a lower inlet nozzle on the filter vessel can be used to preheat the filter vessel separately from the TRDU. The hot gas from the burner enters the vessel via a nozzle inlet separate from the dirty gas. The high-pressure nitrogen backpulse system is capable of

backpulsing up to four sets of four or five candle filters with ambient-temperature nitrogen in a time-controlled sequence. The pulse length and volume of nitrogen displaced into the filter vessel is controlled by regulating the pressure (up to 800 psig) of the nitrogen reservoir and the solenoid valves used to control the timing of the gas pulse. Figure 1 also shows the filter vessel location and process piping in the EERC gasifier tower. High temperature valves allow the HGFV to be bypassed if desired, however, this feature is rarely utilized since bypassing of commercial filter systems will not be possible. Since all the filter tests are to be completed in the 540°–650°C (1000°–1200°F) range, a length of heat exchanger was used to drop the gas temperature to the desired range. In addition, sample ports both upstream and downstream of the filter vessel have been utilized for obtaining particulate and hazardous air pollutant (HAP) samples.

Results

TRDU Fuel Analysis

The fuels which have been tested in the TRDU have included a Powder River Basin (PRB) subbituminous coal from the Wyodak seam at the Belle Ayr mine in Gillette, Wyoming, an Illinois No. 6 bituminous coal from Seam 6 of the Baldwin mine in Baldwin, Illinois, a western bituminous coal mined from the Hiawatha seam at the SUFCo mine in Salina, Utah, a petroleum coke from the Hunt Oil Refinery in Tuscaloosa, Alabama, a bituminous coal from the Calumet mine in Alabama, and lignite from the Falkirk mine in North Dakota. Table 2 shows the proximate, ultimate, heating value, and XRF analyses of the Wyodak, Illinois No. 6, SUFCo, and Falkirk coals and the Petroleum Coke. All fuels except the lignites were mixed with Plum Run dolomite from the Greenfield formation before testing in the TRDU. The lignite gasification tests utilized limestone from the Montana limestone company in Wyoming. The calcium-based sorbent was mixed with the respective coals to provide a Ca/S ratio of approximately 2 on a sorbent-only basis for the fuels being gasified (~5 wt% for the PRB and SUFCo coals, 17 wt% for the Illinois No. 6 coal, and 7 wt% for the Alabama bituminous and North Dakota lignites) and at a Ca/S ratio of 1.5 (~28 wt%) for the petroleum coke tests.

TRDU Operation

Operation with most of these fuels has been completed in both air-blown and oxygen-blown mode, generating over 2000 hours of operating in gasification, with approximately 1500 hours in air-blown and over 500 hours in oxygen-enriched and full oxygen-blown operation. A summary of the TRDU operation in both air-blown and O₂-blown modes is given in Table 3. Operation of the TRDU on these fuels has been smooth with only occasional process upsets for fuel feed plugs or loss of circulation due to deposit formation in the mixing zone. In general, gasification performance has favored the more reactive low-rank fuels although acceptable fuel gas heating values have been achieved with higher rank bituminous coals and petroleum coke at the expense of reduced carbon conversion.

HGFV Operation

There have been no failures of these candle filters in the last 1800 hours of testing the gasification mode. The HGFV has been operated between 460°–570°C at a face velocity of approximately 3.8 to 4.5 ft/min. Backpulse operating parameters were 270 to 400 psig reservoir pressure with either 1/4- or 1/2-second pulse valve opening times. The average particulate loading going into the HGFV ranged from approximately 4500 ppm up to 45,000 ppm, with a d₅₀

between 7 μm to 22 μm , depending on the fuel type, quantity of sorbent utilized for sulfur control, and whether solids were being recirculated from the dip leg back into the standpipe. A substantial increase in the “cleaned” filter baseline (from ~ 40 to >90 H_2O) was observed in a few of the tests and generally seems to be associated with higher tar emissions levels. This filter ash averaged 40 to 60 wt% carbon and had a low bulk density of approximately 20 lb/ft^3 . The small size, the lack of the cohesiveness seen in other filter ashes, and the low density of the ash suggests that a high percentage of the filter cake will be reentrained back onto the filters after they are backpulsed.

Changes in the backpulse operating conditions were also made in an attempt to improve filter performance. An increase in pulse duration did not appear to provide any improved backpulse performance; however, an increased backpulse reservoir pressure did appear to provide a small (~ 1 minute) decrease in the backpulsing frequency, but did not significantly lower the “cleaned” baseline differential pressure. The mechanical operation of the N_2 backpulse system and the filter vessel ash letdown system has presented no operational problems.

Off-line cleaning tests were completed using the high-temperature ball valve to bypass the filter vessel every time it was to be backpulsed. Total off-line cleaning times were varied from 160 to 330 to 450 to 690 seconds and backpulse pressure was varied from 180 to 240 to 300 psig. The total off-line cleaning time included the time to take the filter vessel off-line (approximately 60 seconds) and the time taken to backpulse all four manifolds and bring the filter vessel back on-line. From the time of the last backpulse to the time the filter was back on-line was approximately 45, 140, 280, and 520 seconds, respectively. This data showed that as backpulse reservoir pressure was increased, the length of time until the next backpulse trigger increased slightly by approximately 30 seconds with each increase. Figure 3 shows the effect of settling time on the HGFV differential pressure traces, which were obtained with a 240 psig backpulse reservoir pressure. This figure shows that at a settling time above 330 seconds, there was not much difference in the pressure traces; however, when the settling time was dropped to 160 seconds, two backpulse sequences were observed in the time it was taking for one backpulse sequence at the higher settling times. This occurred because the baseline filter differential pressure was approximately 20 in. H_2O higher at this lower settling time. It appears that reentrainment of filter ash is resulting in a 20- to 30-in. H_2O increase in the baseline filter differential pressure. Off-line cleaning tests indicated that 20 to 25 inches of the baseline increase is due to reentrainment of fine filter ash back on the candles and that off-line cleaning times up to 300 sec were needed to allow the backpulsed ash to clear the filters.

In gasification mode, the pulse frequency has been short, with pulses occurring every 8 to 15 minutes. This rapid pulsing is thought to be due to the high-carbon, low-density dust, with a high aerodynamic drag minimizing the porosity of the filter cake on the surface of the candle. This results in a rapid rise in pressure drop across the filters.

During earlier tests, the filter system initially was bypassed during process upsets; however, it was later decided to leave the HGFV on-line during any type of process upset or system shutdown on the TRDU, since commercial plants would not be able to bypass the filter system. These system upsets can be characterized as three different types: 1) system shutdown due to loss of circulation in the TRDU; 2) system upset due to loss of coal feed to gasifier such as with a coal feed plug; and 3) a controlled system shutdown where coal feed was maintained, but at a rate less than that needed to fully consume the air being fed into the mixing zone. The temperature spikes in the HGFV generally occur over a 15- to 20-minute period and have resulted in temperature spikes of 300° to 375°F (150° to 190°C) for the (type 1) system

shutdown due to loss of circulation; approximately 120° to 210°F (50° to 100°C) for a (type 2) system upset such as a coal feed plug; and less than 120°F (50°C) for the (type 3) controlled system shutdown. This data shows the type of thermal transient that the candle filters might have to survive during a system upset or shutdown on a commercial scale gasifier if oxygen breakthrough to the filter occurs. The reason for these different temperature spikes is due to the rate and quantity of oxygen breaking through to the HGFV in each situation. In the first case, a loss of circulation results in a very rapid breakthrough of a higher oxygen concentration gas stream since no carbon is being circulated from the standpipe back to the mixing zone to consume most of the oxygen in the air fed into the zone. In addition, the coal feed has to be quickly shut off to prevent a high-temperature run away in the riser of the TRDU. No candles broke during these excursions, but the high heat release occurring on the surface of the candles in these cases should be avoided. In this case, since system shutdown is necessary to clear the blockage, the system should be flooded with an inert gas and the bed material allowed to slump in the bottom of the gasifier.

The intermediate temperature spikes that occur in the second case when coal feed is lost is due to the carbon being recirculated from the standpipe back to the mixing zone, consuming the air and greatly slowing the breakthrough of oxygen to the HGFV. The slower breakthrough and longer time frame it takes to reach the final oxygen concentration of the air helps to limit the temperature spike. Whether this temperature spike is still modest enough to expect long-term survival of most candle filter elements is unknown at this time. For a commercial-scale system, the issue in the second case is whether a large enough inert gas source can be afforded to keep the bed material circulating while a coal feed plug is cleared; or whether oxygen is allowed to breakthrough to the HGFV; or whether the gasifier should be flooded with an inert gas and the bed material allowed to slump in the bottom of the gasifier. Slumping the bed material in the reactor can present problems during re-startup with plugging of the J-leg and mixing zone nozzles if not enough flow is maintained on these nozzles. In the third case with the controlled system shutdown, the low-temperature spikes are due to the decreased coal feed rate, allowing a very slow oxygen breakthrough to the HGFV, and an oxygen level limited to the excess air ratio of air and coal being feed in the mixing zone. The limited heat release observed under these conditions should be survivable by current filter elements and presents one potential way to shutdown and startup a commercial scale unit.

TRDU Gasification Trace Element Emissions

The EERC TRDU/HGFV testing program offered a unique opportunity to examine the trace element partitioning within a pressurized circulating fluid-bed gasifier and at the inlet and outlet of an HGFV. During these tests, a Wyodak subbituminous coal-dolomite blend was used as the feedstock. The PRB coal is from the Belle Ayr Mine in Wyoming. The average temperature of the TRDU gasifier was 875°C. The sampling of trace elements within the high-temperature ($\approx 540^\circ\text{C}$) pressurized environment of the HGFV warranted the use of specialized sampling equipment. A high-pressure and high-temperature sampling system (HPHTSS) was constructed and utilized to extract ash-laden flue gas isokinetically and isothermally from the high-temperature pressurized product gas. The probe for the system is a disposable 304 stainless steel tube (3/8 in. OD and 1/8 in. ID). The primary component of the system is a pressurized vessel designed to withstand the harsh sampling environment within the HGFV. Conventional sampling systems can be housed within the vessel. The pressure differential between the nitrogen gas within the vessel and the flue gas within the sampling device is maintained at <5 psig. A

multicyclone assembly and a modified EPA Method 29 sampling train were used to sample the gasification product gas. The modification to EPA Method 29 involved the use of teflon-coated stainless steel impingers rather than glass impingers, in addition to doubling the strength of hydrogen peroxide solution and ensuring the potassium permanganate solution was at its maximum concentration to increase the allowable sampling time before the reducing species in the flue gas would consume these oxidizing species. Sampling was performed for an hour during each test. The inlet to the HGFV was sampled during both tests using the modified EPA Method 29 train. During Test PO51, the gas stream was also sampled at the HGFV inlet using a multicyclone assembly, followed by the modified EPA Method 29 sampling train, and at the HGFV outlet using the modified EPA Method 29 sampling train. The EPA Method 29 samples taken around the HGFV (filter and impinger solutions) were analyzed for 7 trace elements (Hg, Se, As, Pb, Cd, Cr, and Ni) using graphite furnace atomic absorption spectroscopy, cold vapor atomic absorption spectroscopy, or inductively coupled plasma-atomic emission spectroscopy.

The trace element analysis results for the multicyclone and EPA Method 29 samples are provided in Tables 4 and 5. During the PO51 test, a multicyclone was used in series with the modified EPA Method 29 train to determine ash and elemental mass size distributions at the HGFV inlet. Five stages (aerodynamic cut diameters [D_{50}] of 11.9 μm , 5.49 μm , 3.11 μm , 2.22 μm , and 0.89 μm) and a filter (D_{50} nominally 0.4 μm) were used to collect ash. The mass of trace elements collected in the impinger solutions of the modified EPA Method 29 impinger train were arbitrarily assigned to a D_{50} of 0.1 μm . The particle size distribution for the HGFV inlet ash is bimodally distributed into a supermicron and submicron mode. The elemental mass size distributions for As, Cd, Cr, Ni, and Pb mimic the ash size distribution. Selenium, however, was partitioned much more strongly to the 0.1 μm D_{50} fraction (i.e., gas phase). The bimodal distribution of ash and trace elements with respect to size has been documented in numerous investigations of coal fly ash. Laboratory investigations (Natusch, et.al. 1974; Sarofim, et.al. 1977; Taylor and Flanagan, 1982; Linak and Peterson, 1984) have demonstrated that the submicron ash particles are produced by the nucleation and subsequent coalescence and coagulation of a portion of the vaporized fly ash.

The trace element composition of the gasification product gas was determined at the inlet to the HGFV using the modified EPA Method 29. The partitioning of trace elements between gas and solid phases was also evaluated based on the EPA Method 29 measurements. It is assumed in this evaluation that the sample filter and impingers of the modified EPA Method 29 train remove all the particle-associated trace elements and gaseous trace elements, respectively, from the particle-laden flue gas stream. Presented in Figure 4 is the trace element composition and partitioning results for test P051. Mercury, Se, As, and Cd showed consistent partitioning behavior: Hg was volatile, Se semi-volatile, and As and Cd were non-volatile. Lead is generally regarded as a semi-volatile metal, while Ni and Cr are generally regarded as non-volatile metals in coal conversion systems (Clark and Sloss, 1992). Consequently, the differences in Cr and Ni volatility must be related to compositional differences. Thermodynamic modeling was performed to determine if the product gas compositions are influencing the volatility of Cr and Ni. The modeling results indicate that greater concentrations of CO and H₂O in the gas promote the formation and stability of volatile Ni tetracarbonyl (Ni[CO]₄) and Ni and Cr oxyhydroxide compounds at the temperature conditions of the HGFV inlet. The existence of volatile transition metal compounds, such as Ni(CO)₄, in gasification product gases was speculated by Beishon et al. (1989).

The trace element concentrations and gas-solid partitioning results determined at the inlet and outlet of the HGFV during Test PO51 are presented in Figure 5. Trace element removal efficiencies for the HGFV are presented in Table 6. As expected, these results indicate that the HGFV is effective in removing the non-volatile trace elements (As, Pb, Cd, Cr, and Ni), but relatively ineffective in removing semi-volatile Se and volatile Hg.

Application

The high level of solid particulate control and lack of operational problems associated with the performance of the HGVF on the transport reactor gasifier located at the EERC should promote the acceptance of hot-gas filtration in high efficiency advanced power systems. The removal of the solid phase trace element species is encouraging, but further work to remove the more volatile trace element species from hot or warm flue gas will be required to effectively control some species such as mercury and selenium.

Future Activities

Future research activities on the TRDU and HGFV include continued oxygen-blown testing on the transport reactor while investigating its potential with alternative feedstocks such as petroleum residues, biomass, and other high reactivity fuels. Testing of candle filter elements, possibly at slightly lower temperatures, will continue, as well as testing of potential safeguard devices in the filter system. Emphasis will also be placed on controlling the emissions of volatile trace element species, with an emphasis on the control of mercury without having to cool the gas to near ambient temperatures in order to utilize conventional removal technology. If the gas can remain at a temperature above the dew point of water, the extra mass flow from the water vapor will offset some of the efficiency losses associated with reduced fuel gas temperatures. Both the demonstration of continuous emission monitors (CEMs) and the evaluation of mercury removal sorbents or catalysts will be investigated.

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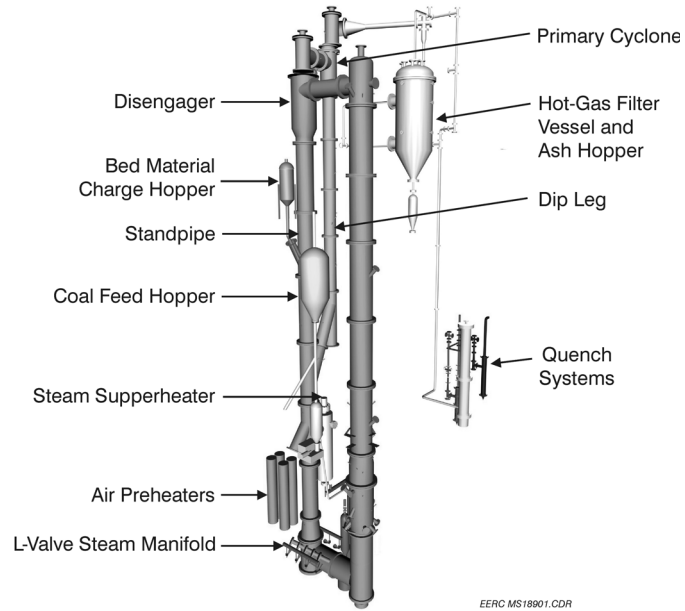


Figure 1. TRDU and Hot-Gas Vessel in the EERC Gasification Tower.

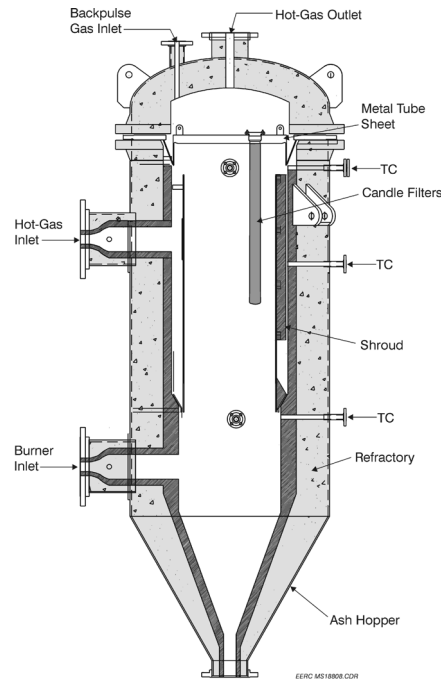


Figure 2. Schematic of the Filter Vessel Design with Internal Refractory, Tubesheet, and Shroud.

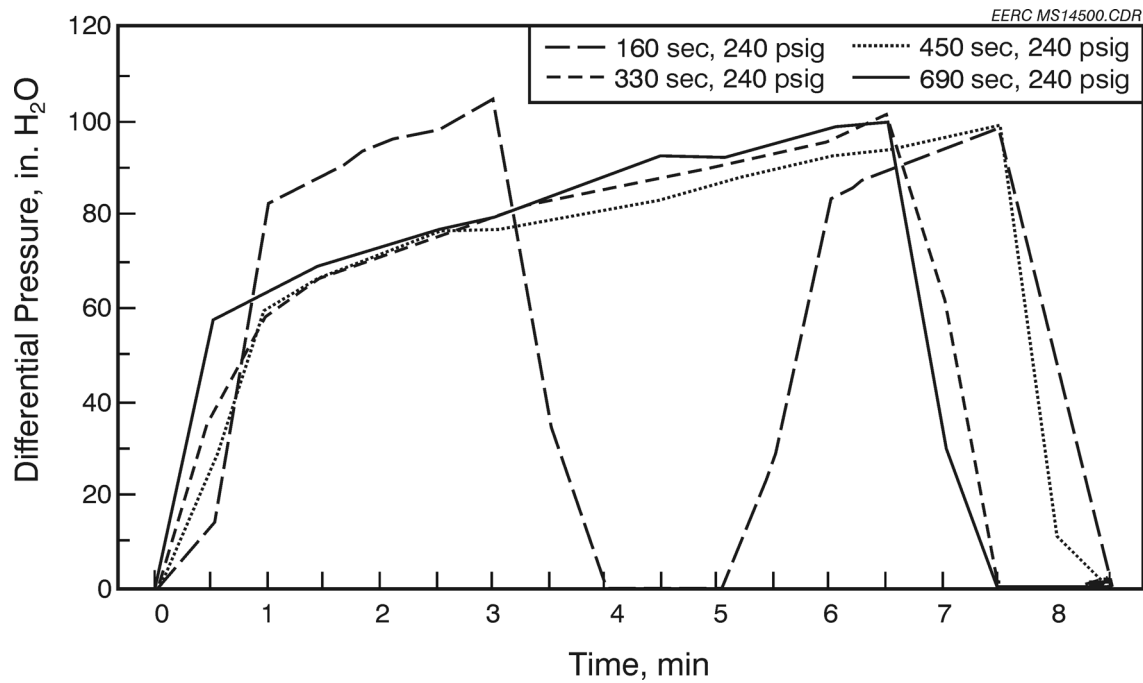


Figure 3. Effect of Off-Line Settling Time on the HGFV Differential Pressure Traces.

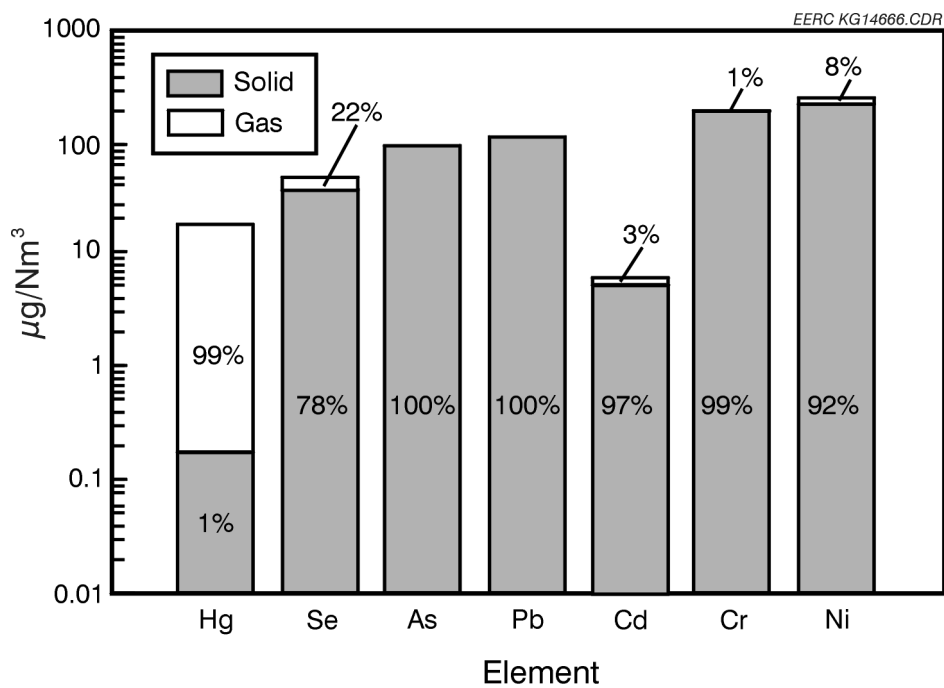


Figure 4. Trace Element Composition and Partitioning Results for Test P051.

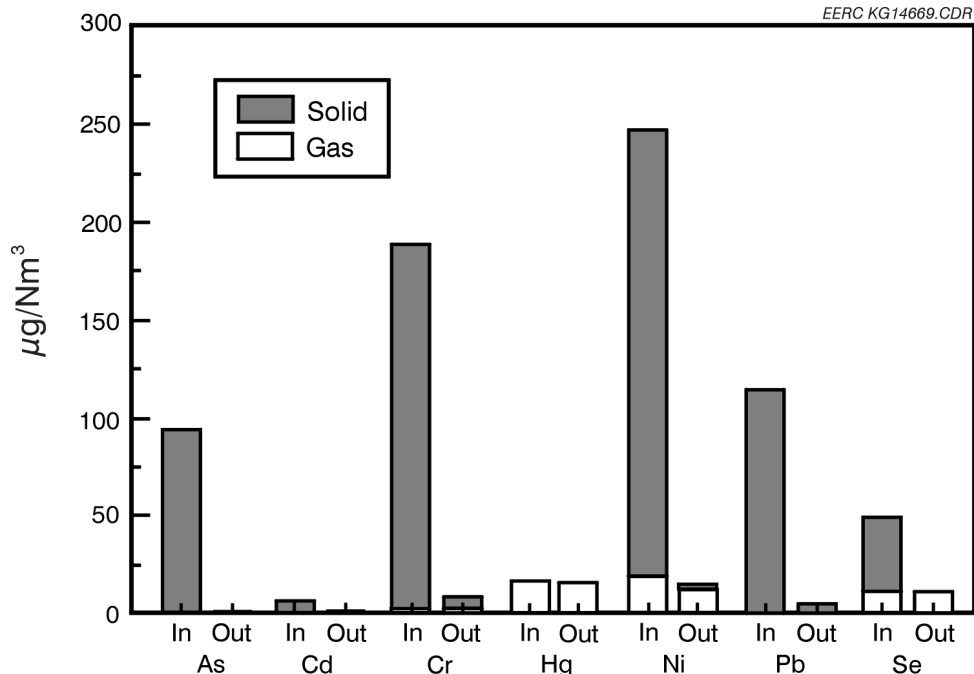


Figure 5. Trace Element Concentrations and Solid-Gas Partitioning Measured at the Inlet and Outlet of the HGFV during Test P051.

Table 1. Design Criteria and Actual Operating Conditions for the Pilot-Scale Hot-Gas Filter Vessel

Operating Conditions	Design	Actual
Inlet Gas Temperature	540°–840°C	460°–580°C
Operating Pressure	150 psig	120 psig
Volumetric Gas Flow	325 scfm	350 scfm
Number of Candles	19 (1 or 1.5 meter)	13 (1 meter)
Candle Spacing	4 in. \varnothing to \varnothing	4 in. \varnothing to \varnothing
Filter Face Velocity	2.5–10 ft/min	4.5 ft/min
Particulate Loading	<20,000 ppm	4,000 – 40,000 ppm
Temperature Drop Across HGFV	<30°C	25°C
Nitrogen Backpulse System Pressure	up to 800 psig	250 to 350 psig
Backpulse Valve Open Duration	up to 1-s duration	½-s duration

Table 2. Proximate and Ultimate Analyses of Illinois No. 6, Wyodak, SUFCo and Falkirk Coals, and Tuscaloosa Petcoke

	-10-mesh Wyodak		-10-mesh Illinois No. 6		-10-mesh SUFCo Bituminous		-10-mesh Falkirk Lignite Coal		-10-mesh Tuscaloosa Petroleum Coke	
	Subbituminous Coal	Bituminous Coal	Bituminous Coal	Bituminous Coal	Coal	Coal	Falkirk Lignite Coal	Petroleum Coke	Tuscaloosa Petroleum Coke	Petroleum Coke
Proximate Analysis, as run, wt%										
Moisture	20.0	8.5	9.5	77.10	29.50	90.65			0.9	
Volatile Matter	38.9	36.0	39.1	4.61	30.92	3.89			9.6	
Fixed Carbon	36.4	44.8	43.8	1.29	27.89	1.70			88.5	
Ash	4.7	10.7	7.6	0.36	11.69	5.49			1.0	
Ultimate Analysis, MF¹, wt%										
Carbon	69.06	69.27	77.10	58.64	58.64	90.65			90.65	
Hydrogen	5.19	5.03	4.61	4.04	4.04	3.89			3.89	
Nitrogen	0.84	1.1	1.29	0.81	0.81	1.70			1.70	
Sulfur	0.44	3.55	0.36	1.06	1.06	5.49			5.49	
Oxygen	18.63	9.34	8.29	18.87	18.87	0.0			0.0	
Ash	5.85	11.7	8.4	16.58	16.58	1.0			1.0	
Ash Composition, % as oxides										
Calcium, CaO	26.6	3.2	16.3	15.5	15.5	11.9			11.9	
Magnesium, MgO	7.0	1.6	3.0	8.9	8.9	5.1			5.1	
Sodium, Na ₂ O	1.3	1.1	4.6	0.7	0.7	1.0			1.0	
Silica, SiO ₂	27.8	53.9	38.3	41.3	41.3	18.9			18.9	
Aluminum, Al ₂ O ₃	13.1	21.2	9.3	12.8	12.8	4.8			4.8	
Ferric, Fe ₂ O ₃	5.5	13.6	6.1	4.5	4.5	7.6			7.6	
Titanium, TiO ₂	1.3	0.9	0.8	0.5	0.5	0.0			0.0	
Phosphorus, P ₂ O ₅	1.0	0.2	0.2	0.2	0.2	0.1			0.1	
Potassium, K ₂ O	0.3	1.9	0.2	0.4	0.4	0.7			0.7	
Sulfur, SO ₃	16.0	2.5	21.1	14.3	14.3	13.8			13.8	
Vanadium, V ₂ O ₅	ND ²	ND	ND	ND	ND	30.2			30.2	
Nickel, NiO	ND	ND	ND	ND	ND	6.0			6.0	
High Heating Value										
Moisture-Free, Btu/lb	11,700	12,080	12,200	9,963	9,963	15,300			15,300	
As-Received, Btu/lb	9,750	11,300	11,040	7,024	7,024	15,150			15,150	

¹ Moisture-free.

² Not determined.

Table 3. Comparison of TRDU Operating Conditions for Air-Blown versus Oxygen-Blown Operation

Coal Type	Illinois No. 6		SUFCo		Wyodak		Falkirk	
	Air-Blown	O ₂ -Blown	Air-Blown	O ₂ -Blown	Air-Blown	O ₂ -Blown	Air-Blown	O ₂ -Blown
Operating mode								
Moisture Content, %	8	8	9	9	23	23	36	36
Steam: Coal Ratio, lb/lb	0.51	1.8	0.72	1.59	0.58	0.93	0.23	0.92
Air: Coal Ratio, lb/lb	3.54	0.23	2.29	0	2.16	0	2.08	0
O ₂ : Coal Ratio, lb/lb	0.82	0.96	0.53	0.74	0.5	0.61	0.48	0.47
Coal and Sorbent Feed Rate, lb/hr	277	295	412	296	476	406	428	502
% Sorbent in the Feed, wt%	17	17	4	4	4	4	10	10
Max. Mixing Zone Temp, °C, avg.	986	972	880	900	823	892	845	815
HHV of Fuel Gas, Act., Btu/scf	5586	102257	68112	114254	6893	137253	60123	116233
HHV of Fuel Gas, Cor., Btu/scf								
Conversion, %	86	81	76	83	80	96	83	85
Riser Velocity, ft/s	31.2	61.4	57.1	57.2	54.8	44	36.5	42.4
Circulation Rate, lb/hr	3300	4625	5925	4250	6850	5835	1580	4000

Table 4. Trace Element Compositions of Fuel Gas Samples (modified EPA Method 29) for Test PO51

Element	HGFV Inlet at 580°C		HGFV Outlet at 525°C	
	Filter + Multicyclone, $\mu\text{g}/\text{m}^3$	Impingers, $\mu\text{g}/\text{m}^3$	Filter, $\mu\text{g}/\text{m}^3$	Impingers, $\mu\text{g}/\text{m}^3$
Hg	0.18	17.38	0.02	16.2
Se	38.45	10.55	1.59	10.55
As	93.38	ND ¹	1.12	ND
Pb	113.9	ND	4.88	ND
Cd	5.65	0.19	0.81	ND
Cr	186.13	1.99	6.21	2.23
Ni	226.93	19.24	3.36	11.79

¹Not detected.**Table 5. Trace Element Composition of Multicyclone Ash Samples, $\mu\text{g}/\text{g}$**

Element	Aerodynamic Diameter (D_{50}), μm					
	Multicyc 1	Multicyc 2	Multicyc 3	Multicyc 4	Multicyc 5	Final Filter
Element	11.9	5.49	3.11	2.22	0.89	0.3
Sample Mass, g	0.80592	3.08772	1.30379	0.1373	0.25011	2.42718
Hg	ND ¹	0.1	ND	ND	ND	ND
Se	8.9	7.8	10	44	4.7	4.3
As	20.8	22	23.6	81.5	11.5	8.6
Pb	37.5	25.5	28.6	90.1	12.4	9
Cd	3.9	1.1	0.8	3.8	0.3	0.4
Cr	45	37	41	130	21	30
Ni	65	45	52	290	24	25

¹Not detected.**Table 6. Trace Element Removal Efficiencies of the HGFV**

Element	HGFV Removal Efficiency, %
Hg	2.6
Se	77.5
As	98.8
Pb	95.7
Cd	85.9
Cr	95.6
Ni	94