

Ruth Ann Martin  
Southern Company Services  
P.O. Box 1069  
Wilsonville, AL 35186  
rumartin@southernco.com  
(205) 670-5088  
(Primary Contact)

Xiaofeng Guan  
Southern Company Services  
P.O. Box 1069  
Wilsonville, AL 35186  
xguan@southernco.com  
(205) 670-5891

Ben Gardner  
Southern Company Services  
P.O. Box 1069  
Wilsonville, AL 35186  
bfgardne@southernco.com  
(205) 670-5926

Howard Hendrix  
Southern Company Services  
P.O. Box 1069  
Wilsonville, AL 35186  
hlhendri@southernco.com  
(205) 670-5876

**Power Systems Development Facility:  
High Temperature, High Pressure Filtration in Gasification Operation**

Keywords: hot-gas filtration, coal gasification, filter elements, integrated gasification combined cycle (IGCC)

**Introduction**

High temperature, high pressure gas filtration is a fundamental component of several advanced coal-fired power systems. This paper discusses the hot-gas filter vessel operation in coal gasification mode at the Power Systems Development Facility (PSDF). The PSDF, near Wilsonville, Alabama, is funded by the U.S. Department of Energy (DOE), Southern Company, and other industrial participants currently including the Electric Power Research Institute, Siemens Westinghouse Power Corporation, Kellogg Brown & Root Inc. (KBR), and Peabody Energy. The PSDF is an engineering scale demonstration of key features of advanced coal-fired power systems designed at sufficient size to provide data for commercial scale-up.

**Project Description**

The KBR Transport reactor which operates at the PSDF is an advanced circulating fluidized bed reactor which can operate in either combustion or gasification mode. The particulate-laden gas exiting the reactor is filtered by a downstream Siemens Westinghouse Particulate Control Device (PCD). In gasification mode, the objective of this filter vessel is to clean the gas sufficiently so that it can be utilized in a gas turbine or a fuel cell. The Transport reactor and Siemens Westinghouse PCD have now operated for about 5000 hours in combustion mode and more than 2700 hours during gasification, providing valuable operational data for a commercial scale integrated gasification combined cycle (IGCC) power plant.

A schematic of the Siemens-Westinghouse PCD, a hot-gas filter vessel using candle type filters, is shown in Figure 1. This PCD utilizes a tube sheet holding up to 91 filter elements which are attached to one of two plenums. Process gas flows into the PCD through a tangential entrance, around a shroud, and through the filters into the plenums. High pressure nitrogen is used to pulse clean the filters periodically to remove the accumulated solids and control the pressure drop across the tube sheet. A failsafe device is located on the clean side of each filter and is designed to stop solids leakage in the event of a filter failure. Maintaining a sufficiently low solids emissions level and controlling the baseline and the peak pressure drop across the tube sheet are the major operational objectives of the filter system.

### **Operational History**

System commissioning and initial test campaigns were performed in combustion mode from 1996 to 1999, and gasification operation began in late 1999. Four gasification commissioning tests (GCTs), lasting nominally 250 hours, were completed in early 2001. Since then, three test campaigns (TCs), usually of longer duration, have been performed. The most extensively tested fuel has been Powder River Basin (PRB) sub-bituminous coal, although several bituminous coals, including Illinois #6 and two types from Alabama mines have been used. The Transport reactor has operated in air-blown mode in all runs except the most recent one, where 100% oxygen-blown mode was achieved. The gasification runs completed to date are listed below, including the number of hours on-coal, and the fuel type.

- GCT1, September – December 1999, 233 hours, PRB, Alabama bituminous and Illinois #6
- GCT2, April 2000, 217 hours, PRB
- GCT3, January 2001, 183 hours, PRB
- GCT4, March 2001, 242 hours, PRB
- TC06, July – September 2001, 1025 hours, PRB
- TC07, January – April 2002, 442 hours, PRB and Alabama bituminous
- TC08, June 2002, 364 hours, PRB

Filter vessel operation changed considerably in response to the change in system conditions and particle characteristics seen after the transition to gasification mode. A comparison of typical operating parameters during combustion and during gasification can be seen in Table 1. Filter material selection has also been modified to accommodate operating conditions. Three filter media types, monolithic ceramic, composite ceramic, and metal, were tested in the earliest gasification runs; however, beginning in March 2001, metal filters have been used exclusively. The most extensively tested metal filter materials include Iron Aluminide sintered powder, Hastelloy-X sintered powder, and several Haynes sintered fiber alloys. More information regarding filter material testing at the PSDF can be found in a companion paper in these proceedings (Spain, 2002).

### **Results**

During the final combustion tests, stable PCD operation and very low particulate emissions were maintained. The operational experience gained during combustion operation, as detailed in

Davidson et al. (1999) and in Gardner et al. (2001), facilitated the transition to gasification. However, problems such as high solids loading and excessive tar formation caused unstable PCD operation in early gasification operation. Several problems with PCD operation have been addressed, and PCD performance has significantly improved over the course of gasification operation.

#### Particulate Collection Performance

Particulate collection performance is based on isokinetic, in-situ sampling performed by Southern Research Institute (SRI). During operation, samples are periodically taken at the PCD inlet and outlet, providing information on the performance of the PCD as well as reactor operations. Also, an on-line particulate monitor, the Dust Alert 90 from PCME Inc., is used to detect real-time particulate emissions. This monitor has been shown to reliably detect particle emissions as low as 0.5 to 1 ppmw and has accurately detected leaks resulting from filter failures.

Inlet sampling indicated that as system operations transitioned to gasification mode, the PCD particulate loading initially increased. During the first two gasification runs, particulate loading concentration averaged from 22,000 to 30,000 ppmw. In mid-2000, after these two initial runs, modifications to the reactor were completed, one effect of which was reducing the solids loading to the PCD, largely by improving gasification and coal conversion in the reactor. A loop seal was added in the recycle loop of the reactor, which improved solids retention and circulation. In the runs following the reactor modifications, solids loading usually averaged 13,000 to 20,000 ppmw. The effects of the recycle loop modifications are further discussed in a companion paper in these proceedings (Dahlin et al., 2002).

The PCD outlet loading has improved significantly since the first gasification run. Outlet loading has been below the sampling system lower limit of resolution, 0.1 ppmw, for extended periods of operation, yielding a collection efficiency of >99.999%. Figure 2 shows the collection performance over the course of gasification operation to date. As seen from this graph, severe leaking occurred during the first gasification run due to inadequate sealing of instrumentation and filter-to-plenum gaskets. As sealing mechanisms improved, the sources of significant leaks have solely been broken filters. When filter failures have not occurred, outlet loading has generally been maintained below 0.1 ppmw. However, beginning in 2002, some outlet loading measurements have been slightly higher—from 0.3 to 2.6 ppmw—and particles on the sample filters at these times have been very large, many well over 100  $\mu\text{m}$  in diameter. It is unlikely that they leaked through the filter vessel, as the particle size distributions found from the sample filters are larger and dissimilar to the size distributions of filter vessel solids samples. The source of these particles was probably debris in piping adjacent to the PCD outlet duct that was found on inspection following TC08. The debris likely accumulated from leaks and tar deposition in early runs, and it was removed to prevent the reappearance of these large particles.

#### Pressure Drop Performance

The transition from combustion to gasification operation brought significant changes that affected PCD pressure drop. One of the major changes was the increased drag of gasification char as compared to that of combustion ash. Particle dustcake drag, a measurement of resistance to flow, is discussed in detail in a companion paper in these proceedings (Dahlin et al., 2002).

Compared to combustion mode, gasification operation necessitated a reduction in PCD temperature and face velocity as well as an increase in pulse cleaning frequency and pressure to control pressure drop.

Pressure drop performance has improved considerably over the course of gasification operation, and has been controllable and relatively stable in most of the recent runs. Baseline pressure drop (pressure drop just after cleaning) for the gasification runs to date are presented in Figures 3 and 4. These measurements have been normalized for a constant face velocity of 3.5 ft/min (1.8 cm/s) and a constant temperature of 750°F (399°C). Each run and the major factors affecting the baseline pressure drops are discussed below:

- GCT1—During the first gasification run, the pressure drop was not stable. One reason for the continuously increasing baseline was that the significant leaking caused back-side blinding when solids that leaked through were blown into the clean side of the filters during pulse cleaning. Tar deposition on the filter surfaces also contributed to the unstable pressure drop.
- GCT2—Filter vessel operation was much more stable, as sealing was improved and tar formation was minimized.
- GCT3—Reactor modifications increased particle dustcake drag, increasing the pressure drop. Because of numerous re-starts necessitating coal feed at low reactor temperatures, tar formation was significant. Char bridging was found on inspection.
- GCT4—A very high and unstable baseline was seen in this run, largely due to severe tar deposition. Char bridging was also found after this run.
- TC06A/B—Because of the introduction of an alternative fuel system used for reactor heat-up prior to coal feed, tar formation was minimized. Therefore, the baseline pressure drop was more stable than in the previous runs, although char bridging occurred, which contributed to the pressure drop increase.
- TC07B/C/D—Improvements in operation such as optimizing pulse cleaning parameters apparently helped to prevent char bridging in TC07B and D. In the TC07C portion of the run, which was marked by unusually unstable system operations, severe bridging occurred, causing a rapidly increasing pressure drop. Based on lab measurements, the drag of the char produced during the majority of the run was lower than that seen previously, so during normal operations, the baseline pressure drop was relatively low. It is not certain why the char drag was reduced, but is possibly due to variations in coal composition or reactor operation.
- TC08—During this run, a fairly stable baseline pressure drop was maintained. No char bridging occurred, and again, the measured char drag was lower than in the runs prior to TC07.

During early runs, the baseline pressure drop increased continuously during operation. In the recent operating periods, TC07D and TC08, baseline pressure drop has been fairly low and more stable. Future runs of longer duration will be helpful in more fully characterizing PCD pressure drop.

### PCD Operational Issues

Several major challenges in PCD operation have been encountered, including tar deposition, char bridging, thermal transients, and filter failures coupled with inadequate failsafe performance. Tar deposition on the filter surfaces can cause an excessively high pressure drop across the tube sheet by forming a thick residual cake, increasing the baseline pressure drop, and reducing the effectiveness of pulse cleaning. Char bridging can also have a significant effect on pressure drop performance. When char is not completely dislodged during pulse cleaning, the char can eventually span the space between the filters and become permanently lodged. Bridged material can severely restrict flow, both of synthesis gas and of pulse cleaning gas, thereby increasing pressure drop and creating a continuously worsening situation. Another operating issue has been the occurrence of thermal transients, sudden rises in temperature, on the filter surfaces caused when oxygen breakthrough to the PCD occurs, often following a coal feeder failure or during system re-starts. Thermal transients can cause filter failure, particularly when large amounts of combustible material are present. All instances of filter failures during gasification led to system shutdowns, as the particular failsafes above these filters did not adequately stop solids flow.

Tar deposition on the filter surfaces was seen early in gasification. During the early runs, operation of the Transport reactor required the introduction of coal at a reactor temperature of about 1000°F (538°C), the highest temperature achievable by the propane start-up burner. Unreliable coal feeder operation also necessitated frequent restarts at low temperature. Gasification at this low temperature led to excessive tar formation and minimal tar cracking. During run GCT4, tar deposition was pronounced, and the thick, strongly-adhering residual filter cake found on inspection undoubtedly contributed to the rapidly rising pressure drop across the tube sheet during this run. Figure 5 shows the deposition found on the filters, and this residual cake was approximately 0.1 inches (0.25 cm) thick, ten times thicker than previously seen residual cakes. In mid-2001 following the GCT4 run, an alternate fuel feeder was commissioned, and this feeder has been used to heat the reactor up to about 1700°F (927°C) prior to coal feed during start-up and re-starts. The feed that is currently being used for heat up is coke breeze, which produces virtually no tar when gasified at low temperature. Because of the use of the alternative feed system, tar deposition on the filter surfaces has virtually been eliminated, and as seen on recent inspections, pulse cleaning has left only extremely thin residual cakes.

Char bridging, as depicted in Figure 6, has occurred in several gasification runs and continues to be a pressing concern with PCD operation. In addition to causing increasing pressure drop, bridging is potentially damaging to filters, as bridged deposits can constrain the movement of the filters and provide significant amounts of fuel in the event of oxygen breakthrough. In gasification operation, char bridging has been a recurrent problem, although the exact mechanism of char bridging in gasification is as yet unknown. (Ash bridging had been observed in one combustion test run using pet coke as fuel, and this was thought to have been the result of dolomite consolidation during high temperature—about 1400°F (760°C)—operation). Examinations of bridged deposits have shown no evidence of chemical consolidation, and the

material is free-flowing once dislodged. Bridging has occurred almost exclusively on the bottom plenum of filters, suggesting the tiered design of the filter vessel internals may have some influence in the formation of bridging in this PCD.

Instrumentation has been useful in detecting char bridging during operation. Filter surface thermocouples covered with char bridging have shown slightly higher temperatures—usually 10 to 20 F° (5.5 to 11C°)—than nearby thermocouples. Although the reason for the elevated temperatures is not well understood, the correlation is well-supported by operational and inspection data. More thermocouples than previously used have been added to the bottom plenum filters and have been placed at various levels on the filters in an effort to determine the mechanism of char bridging growth. In addition, several electrical resistance probes, made from modified thermocouples, have been added and placed on two filters facing each other. These experimental probes were designed to detect char bridging by reading an electrical resistance between the probes when covered with char.

The frequency of char bridging has decreased and has in the last four test segments occurred only once when system operations were particularly unstable. Several changes have occurred which may have helped reduce the bridging tendency, including reduced tar deposition on the filters and optimization of pulse cleaning parameters. As mentioned above, tar deposition, which could facilitate char bridging by forming a sticky surface on the filters, was essentially eliminated by changes in the system heat-up procedure. Also, pulse cleaning parameters were changed to improve filter cleaning and thereby prevent bridging. In early gasification runs, the back pulse cycle time was dependent on the pressure drop across the tube sheet, keeping the pressure drop below about 250 inH<sub>2</sub>O (0.62 bar) to protect the mechanical integrity of the filter vessel components. This method at times employed a relatively long pulse frequency of 15 to 20 minutes when the pressure drop was low. Beginning in 2002 with test campaign TC07, the strategy shifted to frequently pulse cleaning the filters, usually every five minutes, regardless of the pressure drop. Also in recent runs, instead of using the same pulse pressure for both plenums, a higher pulse pressure has been used on the bottom plenum than on the top plenum of filters. Pressure measurements have shown that with the same pulse gas source pressures for both plenums, the differential pressure across the filters on the bottom plenum is lower than that on the top plenum. This difference is largely due to the longer pipe distance between the source and the bottom plenum and the larger number of filters on the bottom plenum. To maintain sufficient pulse cleaning intensity, the pulse gas source pressure on the bottom plenum is now maintained at about 200 psi (14 bar) higher than that on the top plenum during coal feed. Optimization of pulse cleaning parameters is thought to be a key factor in preventing bridging.

Thermal transients have also continued to be a pressing concern. Transients have been observed when oxygen breakthrough occurs, most often when coal feed is unexpectedly lost and oxygen concentration increases. The char cake, which generally has an elemental carbon content of about 35%, can ignite, causing a rapid increase in filter temperature and potentially causing filter failures. Metal filters have been able to survive intact most thermal transients; however, during gasification, three metal filters have failed, and at least one of these failures was apparently caused by a thermal transient. The filter failures occurring during gasification are further discussed below. During normal operation, reactive measures, such as automatic nitrogen dilution and emergency pulsing triggered by rapid filter temperature increases, have proved

useful in controlling temperatures. Also, the addition of an alternative feed system has reduced the frequency of thermal transients by helping to keep a constant solids feed rate.

The two instances of metal filter failures occurred during off-coal periods, and both instances were associated with oxygen breakthrough to the filter vessel when char bridging was apparently present. The first instance occurred during the test campaign TC06, when the system's main air compressor was tuned on-line due to its unreliable operation. Prior to the tuning, coal feed was stopped and the system was allowed to cool following several days on coal, and PCD temperatures were slightly under 500°F (260°C). It was believed that the PCD was empty of char, as it had been pulsed cleaned continuously, and any char that might have remained would not combust at this temperature. However, immediately following the introduction of about 10% oxygen into the PCD, two filter thermocouples in one area of the plenum showed high temperatures, up to 800°F (427°C), in a localized area on the bottom plenum of filters, and the elevated temperatures lasted for 20 minutes. Discoloration and bowing observed on some filters in the area of elevated temperatures during inspection indicated that localized temperatures may have been significantly higher than the thermocouples indicated (Spain, 2002). Although no bridging was found on inspection, the prolonged period of elevated temperatures in a small section of the filter vessel suggested the combustion of a significant amount of char in the form of char bridging. Immediately following the onset of apparent combustion, the PCME on-line particulate monitor indicated significant solids leakage. One cracked Iron Aluminide filter was found on inspection, and this filter is shown in Figure 7.

During a portion of TC07 in February 2002, two metal filters failed when the bottom plenum of filters was apparently severely plugged with char bridging. Not only did filter thermocouples indicate bridging, the pressure drop reduction following the pulse cleaning of the bottom plenum became negligible after only a few hours of coal feed, suggesting very little flow through the bottom plenum. During this portion of TC07, an Alabama bituminous coal was used. Bridging had not occurred in the two earlier periods of bituminous coal feed, and this instance of bridging was likely due to unstable system conditions. Because steady reactor conditions could not be maintained, coal feed was stopped, and later, immediately following oxygen breakthrough to the filter vessel, the on-line particulate monitor indicated char leaking at the PCD outlet. Two cracked Iron Aluminide filters were found on inspection. It is not known exactly what caused these filter failures, as no significant thermal excursion was detected by filter thermocouples. As with the Iron Aluminide filter failure of TC06, these filters failed at a weld or weld-affected area.

Keeping solids emissions at an acceptable level necessitates reliable failsafe performance in the event of a filter failure. Several failsafe devices have been installed to assess their compatibility with the operating environment and their performance in the event of filter failures. To extensively characterize the performance of various failsafe devices under typical filter failure conditions, a failsafe testing apparatus was commissioned. The apparatus includes a fluid-bed feeder used to inject char into the clean side under each failsafe to be tested. Pressure taps were also added inside each filter so that the pressure differential across the filter and across the failsafe could be monitored during the solids injection. During the most recent run in June, 2002, failsafe testing was performed using both the Pall Iron Aluminide fuse, a miniature candle filter that is welded into the main filter, and a PSDF-designed device using a Haynes alloy from Pall/Fluid Dynamics. Char was injected at a concentration of about 200 to 500 ppmw into the

clean side of the filters to simulate a small leak typical of a cracked metal filter. The PSDF designed failsafe immediately plugged, stopping flow through the filter. The Pall fuse did not plug as quickly and leaked a measurable quantity of char—about 0.3 ppmw—although the leakage was reduced with time, and during a subsequent injection period, the measured loading was 0.15 ppmw after a total of 7.5 hours of char injection. Further testing with the PSDF designed failsafe, the Pall fuse, and other designs will be conducted in upcoming runs.

### **Future Activities**

Operations will continue to focus on improving PCD system performance and reliability. Some of the items planned are listed below.

- Failsafe testing—Improving failsafe performance will continue to be a high priority. Further solids injection tests will be conducted on various failsafe designs.
- Filter material testing—Filter materials will continue to be evaluated for long-term material properties such as corrosion resistance and durability. Extended testing will be conducted for the most promising materials.
- Char bridging—PCD operation will focus on learning more about bridging mechanisms should it continue to occur. Additional operational measurements will be made to further optimize pulse cleaning parameters and to track bridging formation.
- Real-time particulate monitors—Several on-line particulate monitors will be evaluated in future runs, including monitors such as the HPPPC (High Pressure Process Particle Counter) being developed by Process Metrix, Inc. and the LIBS (Laser-Induced Breakdown Spectroscopy).
- Char auto-ignition testing—To determine safe operating parameters in various situations, such as during re-starts, when oxygen concentrations can be higher than normal, it will be useful to determine the auto-ignition point of char at different temperature and oxygen levels. To simulate PCD conditions and obtain accurate data, the construction of a heated pressurized flow-through char auto-ignition tester is planned.

### **Summary**

PCD performance has significantly improved over the course of gasification operation. As of June 2002, the following achievements have been realized at the PSDF:

- The PCD has operated for over 2700 hours in gasification mode. Several fuels have been used during gasification, including bituminous and subbituminous coals.
- Improvements in sealing mechanisms have allowed consistent PCD collection efficiencies of over 99.999%.
- Improved system and PCD operation has allowed relatively stable pressure drop during recent runs.



- Tar deposition problems have been greatly reduced by changes in the system start-up procedure.
- Metal filters have been tested extensively. Many of these filters have accumulated over 2000 hours of exposure during gasification operation, and thus far appear to be chemically compatible with the gasification environment.
- Several materials and designs of filter failsafes have been exposed during gasification operation. Preliminary results of failsafe testing under simulated filter failure conditions have shown promising results with two failsafe designs.
- In-situ, isokinetic particulate sampling at both the PCD inlet and outlet has proven to be a reliable, accurate method of testing PCD filtration performance as well as Transport reactor performance. Also, a PCME on-line particulate monitor has shown promise for real-time char leakage detection.

### **Acknowledgments**

The authors wish to acknowledge the contributions and support provided by various project managers: Jim Longanbach (DOE), Neville Holt (Electric Power Research Institute), Cheryl Chartier (KBR), Zal Sanjana (Siemens Westinghouse) and Vann Bush (SRI). This project is supported by the DOE under contract DE-FC21-90MC25140.

The authors would also like to thank Rich Dennis and Ted McMahon of DOE, Stuart Starrett, Bob Dahlin, Carl Landham, and Jack Spain of SRI, John Foote of Siemens Westinghouse, and everyone who has been involved in supporting hot-gas filter testing.

### **References**

Dahlin, R.S., E.C. Landham, *Use of Laboratory Drag Measurements in Evaluating Hot-Gas Filtration of Char from the Transport Gasifier at the Power Systems Development Facility*. Presented at the 5<sup>th</sup> International Symposium on Gas Cleaning at High Temperature. Morgantown, West Virginia. September 18-20, 2002.

Davidson, M.D., R.S. Dahlin, E.N. Galloway, X. Guan, H.L. Hendrix, E.C. Landham, and P.T. Scarborough. *Power Systems Development Facility: High-Temperature, High-Pressure Filter System Operations in a Combustion Gas*. In: *Proceedings of the 15<sup>th</sup> International Conference on Fluidized-Bed Combustion*. American Society of Mechanical Engineers. New York, New York. 1999.

Gardner, B.F., M.D. Davidson, X. Guan, H.L. Hendrix, B.J. Shirley, Commercial Readiness of Hot-Gas Filtration for Pressurized Combustion. In: *Proceedings of the 16<sup>th</sup> International Conference on Fluidized-Bed Combustion*. American Society of Mechanical Engineers. New York, New York. 2001.

Spain, Jack D., *Characterization of Filter Elements for Service in a Coal Gasification Environment*. Presented at the 5<sup>th</sup> International Symposium on Gas Cleaning at High Temperature. Morgantown, West Virginia. September 18-20, 2002.

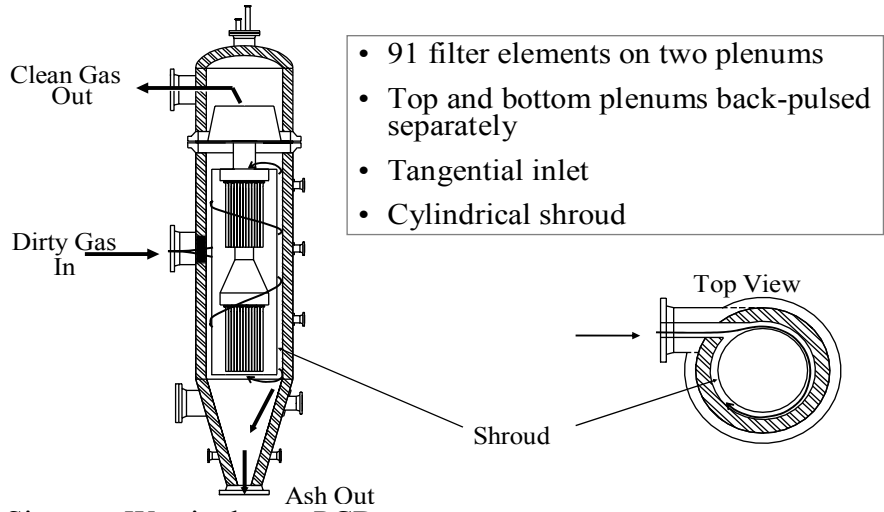
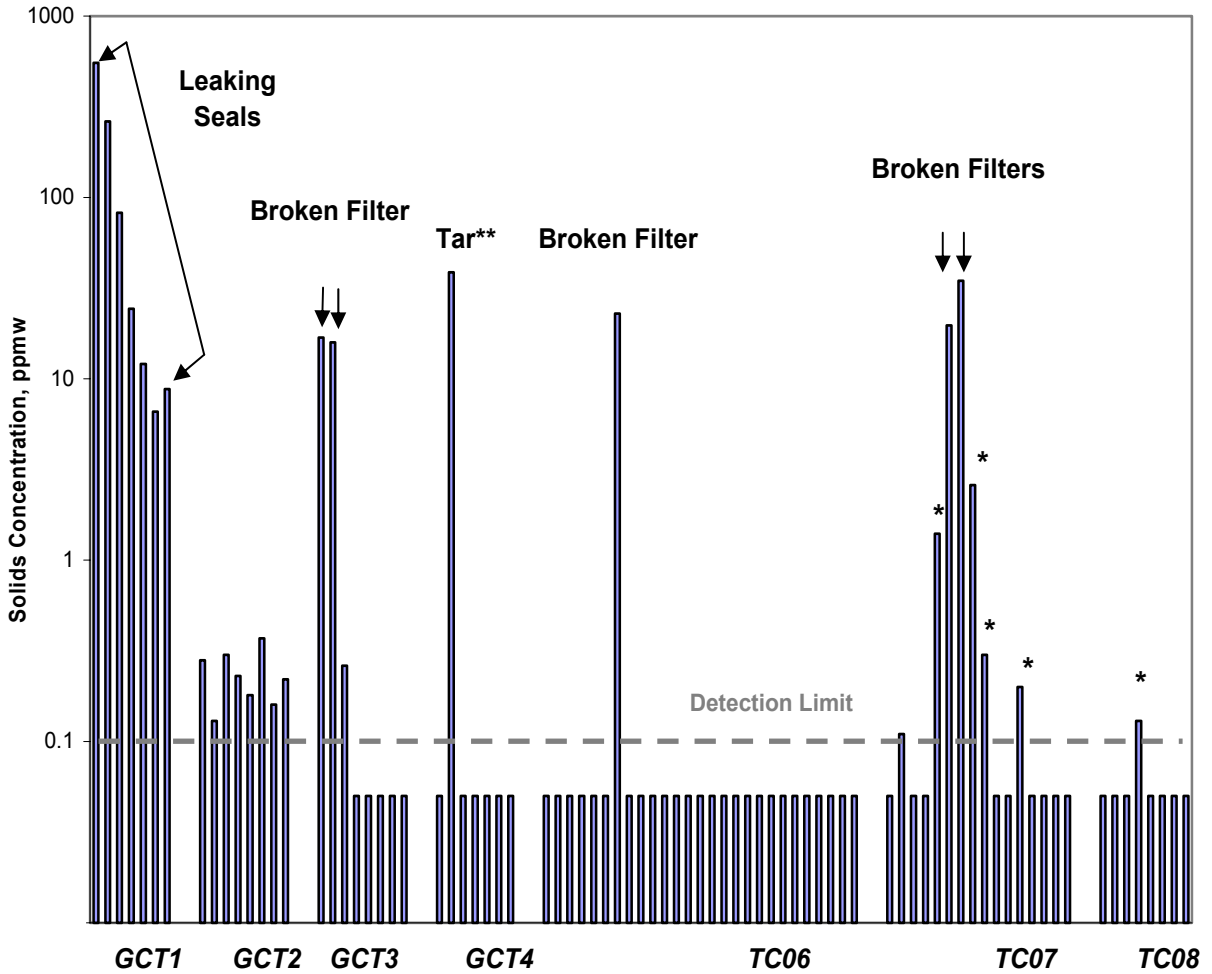


Figure 1. Siemens-Westinghouse PCD



\*\*Tar found on sample filter during start-up, no indication of char leakage

\* Large particles found on sample filters, no indication of PCD leak

Figure 2. Filter Vessel Collection Performance

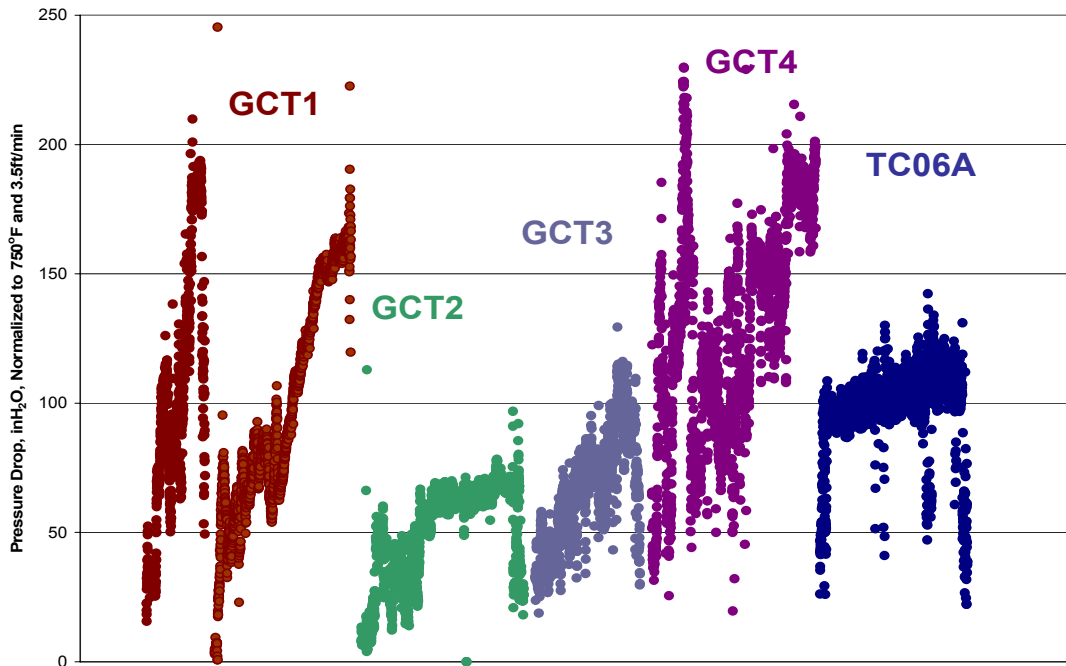


Figure 3. Normalized Baseline Pressure Drop, September 1999 through July 2001

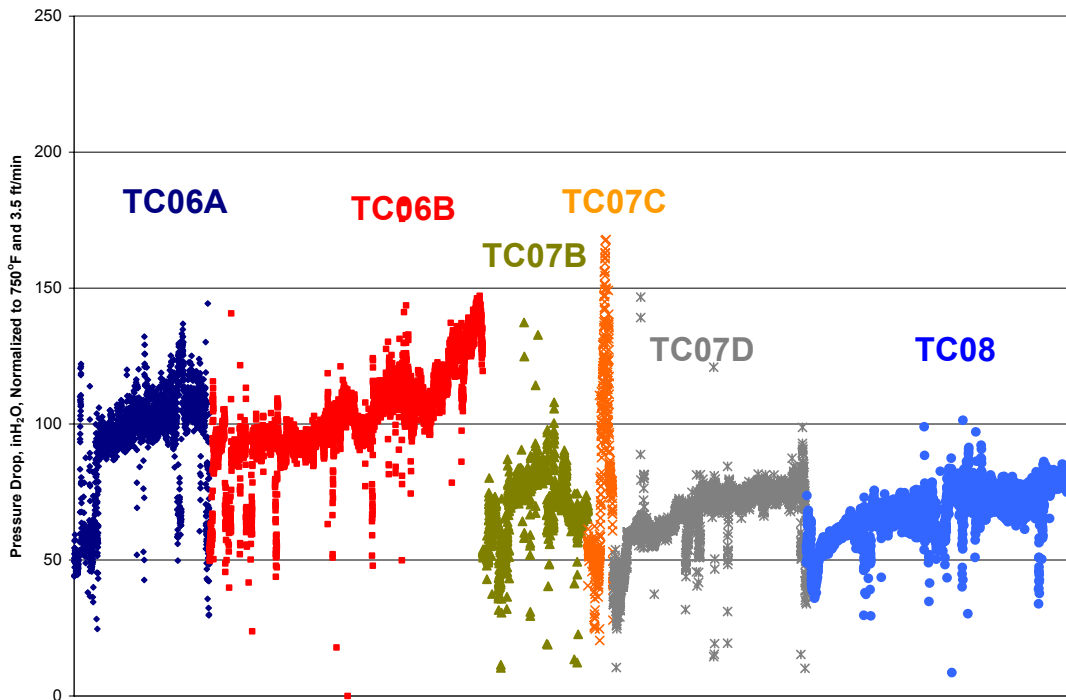


Figure 4. Normalized Baseline Pressure Drop, July 2001 through May 2002



Figure 5. Tar Deposition on Filter Surface



Figure 6. Char Bridging

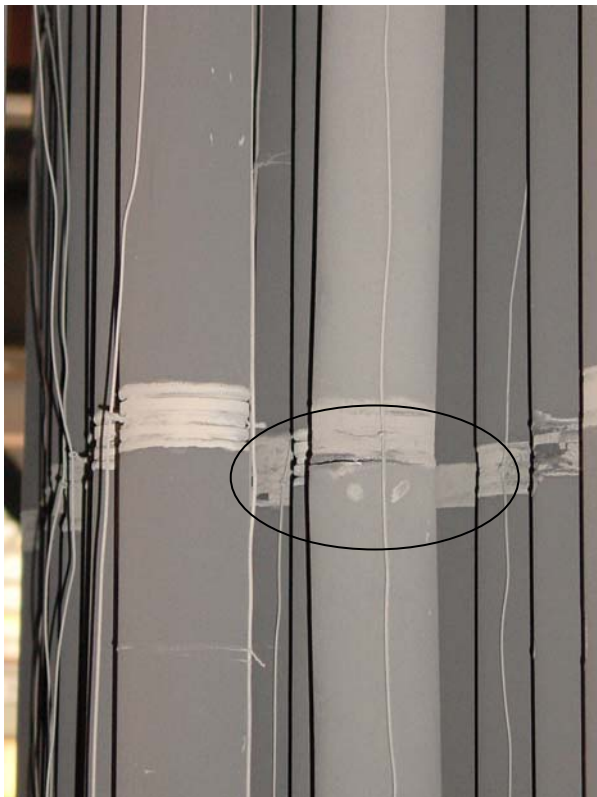


Figure 7. Iron Aluminide Filter Failure

Table 1. Typical Filter Vessel Operating Conditions in Combustion and Gasification		
	Combustion	Gasification
Particle Drag, mbar/(cm/sec)/(g/cm <sup>2</sup> )	100	1000
Temperature, °C (°F)	750 (1375)	400 (750)
Pressure, bar (psig)	14 (200)	16 (240)
Face Velocity, cm/s (ft/min)	3 (6)	1.8 (3.5)
Baseline ΔP, bar (inH <sub>2</sub> O)	0.2 (80)	0.2 (80)
ΔP Rise Rate, bar/min (inH <sub>2</sub> O/min)	0.0025 (1)	0.025 (10)
Pulse Frequency, min	40	5
Pulse Duration, sec	0.2	0.2
Pulse Pressure, bar (psig)	35 (500)	41-58 (600-840)
Inlet Loading, ppmw	10,000	13,000
Particle MMD, μm	20	15