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Initial Operation of the Tidd PFBC HOt Gas Clean Up Filter

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CONTRACT INFORMATION

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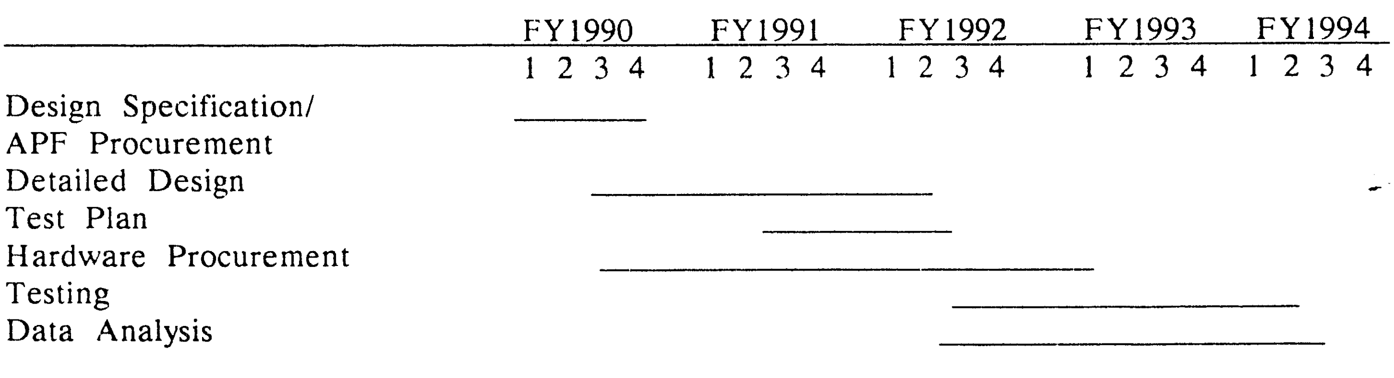
Period of Performance August 2, 1989 to June 30, 1994

Schedule and Milestones

Program Schedule



OBJECTIVES

The objective of this program is to evaluate the design and obtain operating experience for up to two Advanced Particle Filter (APF) systems through long-term testing on a slipstream at Ohio Power Company's Tidd PFBC Demonstration Plant. Performance and reliability of commercial-scale filter modules will be monitored to aid in an assessment of the readiness and economic viability of this technology for commercial PFBC applications.

BACKGROUND INFORMATION

The 70 MWe Tidd PFBC Demonstration Plant in Brilliant, Ohio was completed in late 1990, and is currently in a three-year test program as part of the Department of Energy's Clean Coal Technology Program. Provisions were included as part of the original design to install a slipstream on the PFBC exhaust gases between the fluidized bed and the gas turbine to test an APF system. In November 1988, AEP submitted a proposal to the DOE for the HGCU Program, and in August 1989, a cooperative agreement was signed. In July 1990, AEP awarded a contract to Westinghouse Science and Technology Center to provide a candle-based APF. Installation of the slipstream began in December 1991, and the filter was commissioned in October 1992.

PROJECT DESCRIPTION

System Design

In the original design, the Tidd PFBC Demonstration Plant utilized seven strings of primary and secondary cyclones to remove 98% of the particulate matter from the gases between the fluidized bed and the gas turbine. The full load gas flow of the unit is 700,000 lb/hr at 1580F, and 185 psia. The HGCU slipstream replaces one of the seven secondary cyclones by taking 100,000 lb/hr of gas from the discharge of one of the primary cyclones, to outside of the combustor vessel, and into the APF.

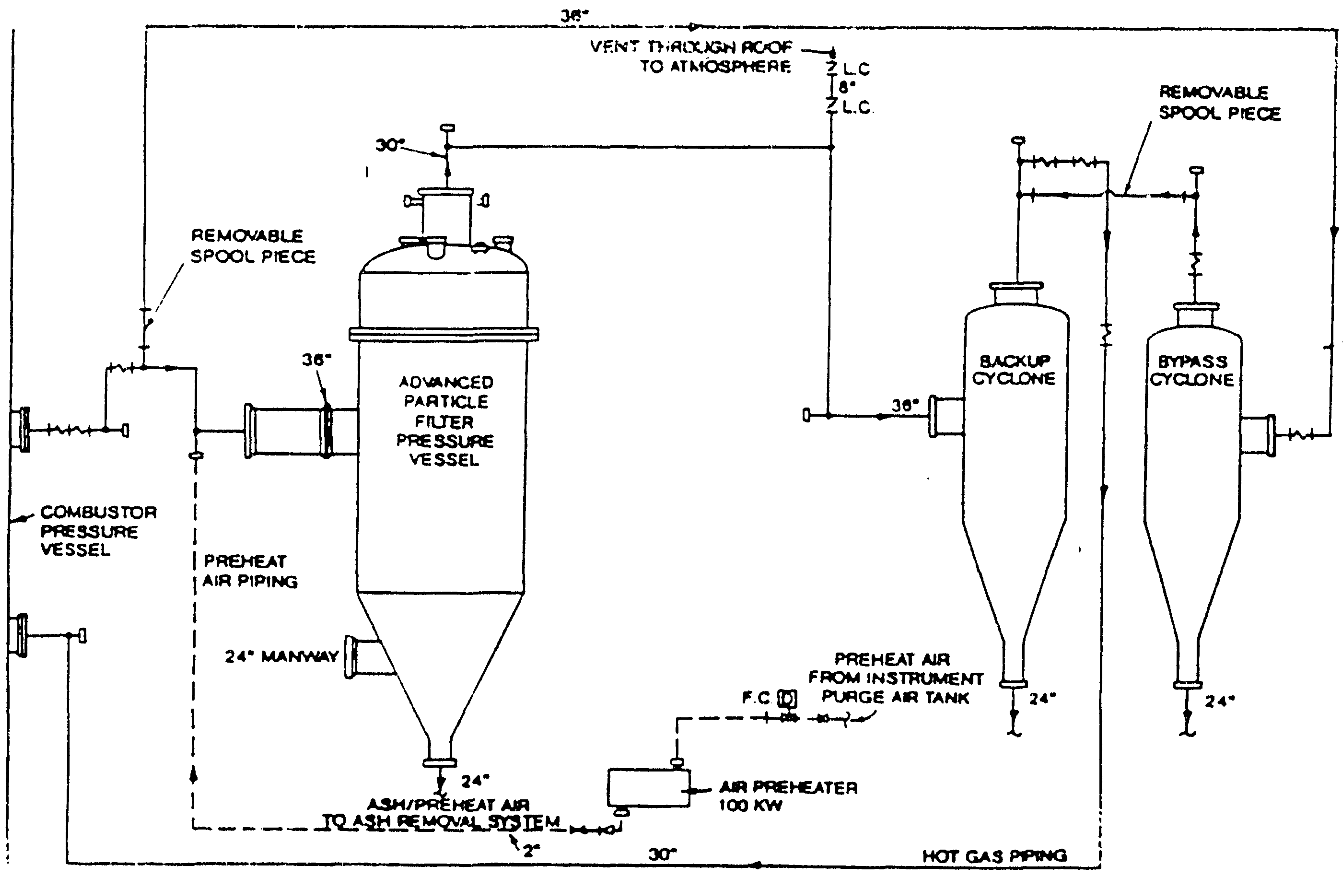


Figure 1. HGCU System Schematic

The gas flows through a backup cyclone, and then returns to the combustor vessel, where the slipstream flow rejoins the combustor gas at the discharge of the other six cyclone strings.

Figure 1 provides a simplified schematic of the APF system, and Figure 2 shows an isometric view of the system.

Gas at 150 psig, 1550F flows into the filter at 7600 acfm with a dust loading of approximately 600 ppmw. Ash collected in the APF is discharged to a screw cooler and intc lockhoppers which feed a vacuum pneumatic ash transport system. A backup cyclone downstream of the filter is installed to clean the gas in case of a filter

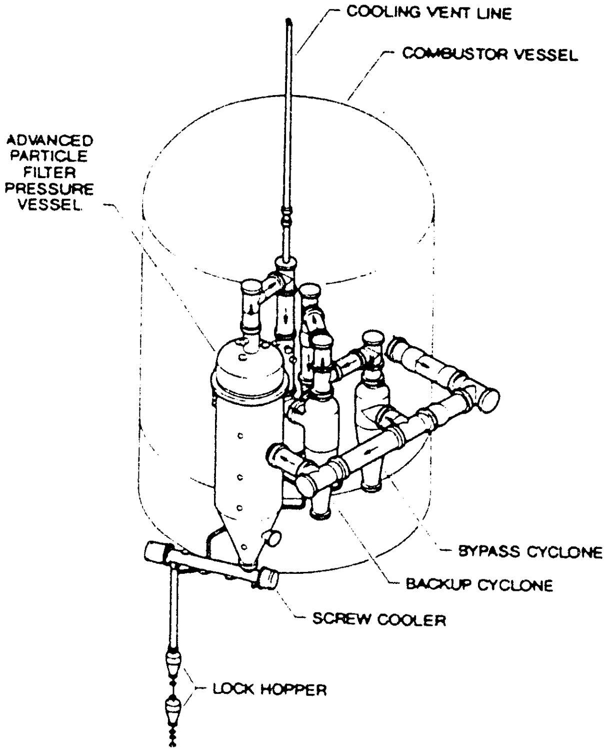


Figure 2. Isometric View of HGCU Slipstream

malfunction, and to balance the pressure drop of the slipstream with the other six cyclone strings.

An air preheating system is used to warm up the system to approximately 350F for start-up of the unit. A vent line is provided to facilitate cooling of the filter internals after a shutdown.

Table 1 provides the design basis of the APF system.

Table 1. APF Design Basis

Maximum Temperature	1670F
Operating Temperature	1550F
Operating Pressure	164 psia
Gas Flow Rate	100,700 lb/hr
Inlet Dust Loading	5000 - 500 ppm
Outlet Dust Loading	<15 ppm
Average Particle Size	1.5 microns
Temperature Drop	5F
Pressure Drop	3 psi

Filter Vessel

The filter vessel is 10 ft. in diameter, and 44 ft. long. It is internally insulated with alumina-silica ceramic insulation, with an internal 310 stainless steel liner to protect the insulation from erosion. The hot gas enters the side of the vessel radially, flows through the candle elements, through the tubesheet, and exits from the top of the vessel head. The exterior of the APF vessel is not insulated, and is coated with temperature sensitive paint.

Filter Internals

The filter, shown in Figure 3, contains 384 candle filter elements, arranged in three clusters, spaced 120° apart. Each cluster holds three plenums, each arranged vertically, with 38 candles in each of the upper and middle plenums, and 52 candles in each of the lower plenums. The candles are attached to the tubesheets in each plenum by bolted collars and high temperature gaskets.

The candles are Schumacher Dia-Schumalith F40 candles consisting of a clay-bonded sintered silicon carbide support matrix that is coated by an aluminosilicate fibrous membrane. Each candle is 2.36 in OD and 4.92 ft long.

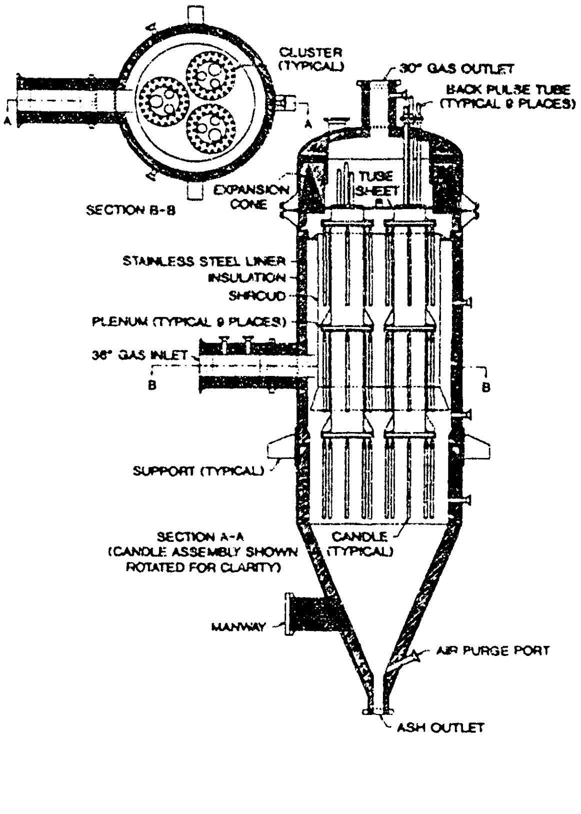


Figure 3. Arrangement of Advanced Particle Filter

The 2 in. thick tubesheet is made of RA-333 alloy, and is supported from an inverted "V" expansion cone.

Backpulse System

The backpulse system receives high-pressure backpulse air from a Norwalk reciprocating compressor rated at 282 scfm and 1500 psig. The air discharges from the compressor to an air dryer, and to a primary air accumulator. The air is then directed to a backpulse skid installed near the APF, which is comprised of secondary accumulators, and the backpulse valves. The backpulse valves are fast acting (200 to 700 msec stroke time) 2-inch pilot-operated Atkomatic solenoid valves. There are three strings of backpulse valves, with redundant valves on each string. References 1 and 2 provide additional description of the system components.

RESULTS

Summary of Operating Experience

The advanced particle filter was first commissioned on October 25, 1992. Through the end of 1992, the APF system logged 464 hours of coal fire operation, with a longest run of 286 hours. The system did not operate during the first half of 1993. It was expected to return to service in March 1993. However, the Tidd Plant has been out of service since early February to repair the gas turbine. The plant and HGCU system are expected to resume operation in August 1993.

The first test of the APF included over 101 hours of operation on coal.

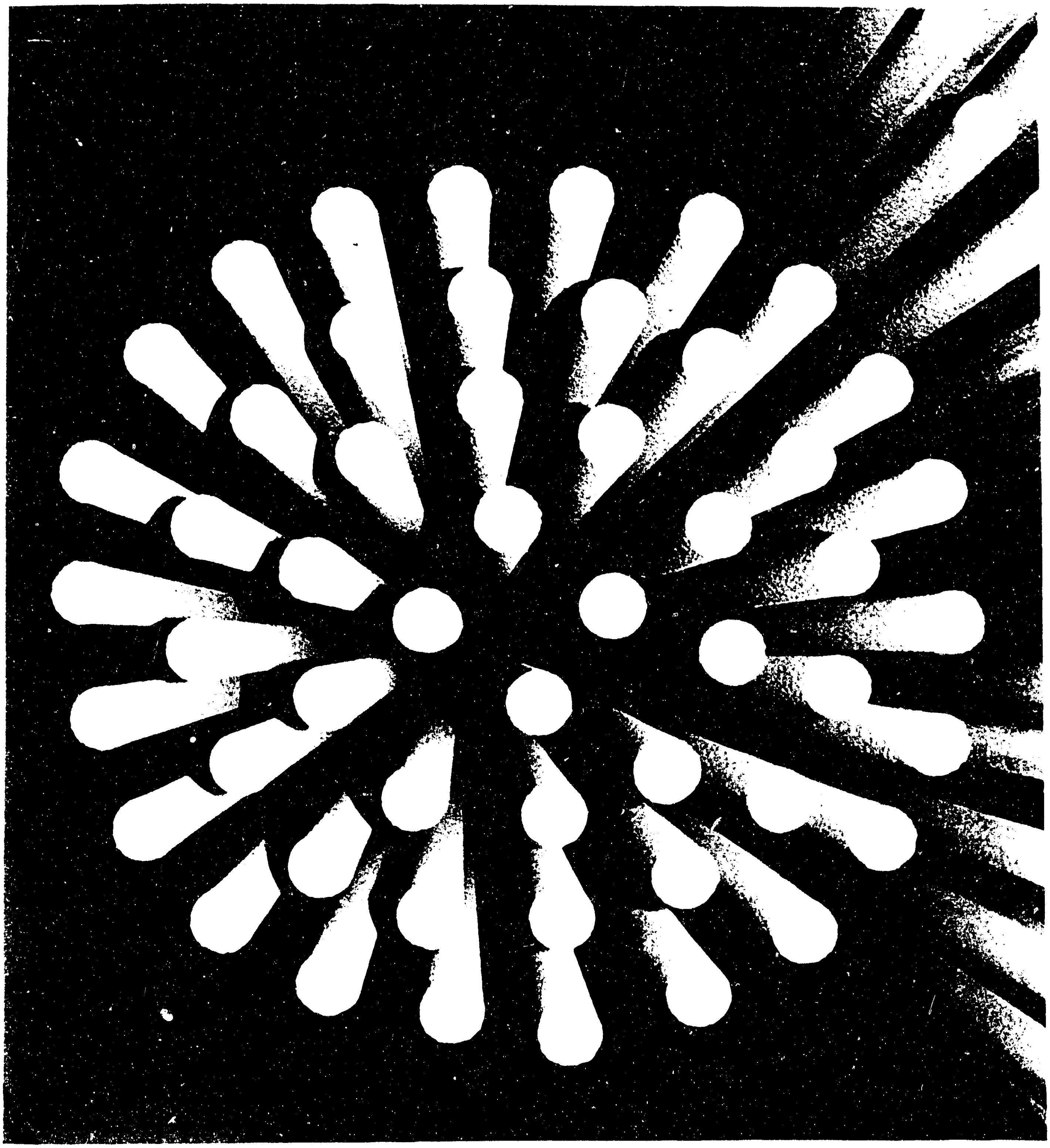


Figure 4. Photograph of Bottom Filter Candles Following Test Run 1

During the initial operation, the APF exhibited a stable pressure drop over a range of plant conditions corresponding to the predicted values. Representative operating conditions for Test Run 1 are shown in Table 2. Although the APF was operated to approximately 90 percent of the design flow with the PFBC at 80 to 85 percent of full load, full plant load was not achieved due to hot spots on the backup cyclone vessel and APF outlet nozzle. This test was ultimately shut down due to ash pluggage of valves and instrument lines associated with the control of the APF ash removal system.

Following shutdown, the filter was visually inspected through access ports in the APF pressure vessel head and ash hopper. The inspection, while limited to the clean gas side of the tubesheet and the three bottom plenums of the three cluster assemblies, indicated the system to be in excellent condition with no evidence of filter failure or dust breach to the clean side of the filter. Furthermore, the filters appeared to be uniformly clean with no indication of ash buildup or bridging.

Figure 4 shows a photograph of the bottom filter candles following Test Run 1.

Following repair and maintenance of the APF outlet nozzle and backup cyclone to eliminate local hot spots and to incorporate continuous instrumentation air purges, operation of the PFBC plant was resumed.

In Test Run 2, the APF was operated for approximately 76 hours on coal, reaching a maximum operating temperature of 1450F and 90 percent of the design flow. Again, stable filter pressure drops were demonstrated over a range of operating conditions. Representative operating conditions for Test Run 2 are shown in Table 2.

Approximately 36 hours into this test, the fourth stage of the APF backpulse compressor failed, thus limiting the ability to clean the filter for 24 hours. During this period, the filter pressure drop reached a value of 180 inches of water. Once a pressurized nitrogen supply system was installed, a stable filter pressure drop was

Table 2. Summary of Operating Conditions

Parameter	Test Run 1	Test Run 2	Test Run 3
Plant Load, MWe	10 - 60	10 - 64	43 - 55
APF Flow, KPPH	65 - 90	50 - 92	50 - 90
Temperature, F	1150 - 1400	1000 - 1450	1300 - 1490
Pressure, psig	85 - 135	70 - 135	125 - 135
Tubesheet Delta P, in wg	25 - 75	40 - 180	45 - 170
Face Velocity, fpm	5.9 - 6.5	4.3 - 6.6	4.4 - 6.4
Total Time, hr	101.4	76.1	285.8
Filtered Ash, lb	4400	3450	12500

once again achieved. However, the original APF baseline pressure drop was never reestablished.

Following the compressor outage and reestablishment of stable filter operation, the performance of the APF was indirectly checked by briefly opening a vent valve on the backup cyclone ash discharge line. Visual inspection of the short burst of gas discharged from the vent valve showed no evidence of dust. This result, along with other operating data, supported the conclusion that no serious damage to the filter resulted from the compressor outage. In this test, the PFBC was shut down due to a paste feed pump issue unrelated to the APF. No visual inspection of the filter was made at this time.

Test Run 3 was a hot restart of the plant following Test Run 2. Test Run 3 accumulated an additional 286 hours of operation on coal. At the start of this test, a nominally low baseline pressure drop was established, apparently due to pulse cleaning during the shutdown of Test Run 2 and prior to restart. During this test, several major events occurred, including high ash level alarm in the APF hopper, a second loss of the backpulse compressor, indications of an unstable pressure drop at temperatures above 1400F, first indications of dust breach, and the first identifiable change in pressure drop indicating a possible loss of filter elements. This test was eventually terminated due to a leak in a pipe expansion joint unrelated to the APF technology. Representative operating conditions for Test Run 3 are provided in Table 2.

Following the conclusion of Test Run 3 and a visual inspection of the filter internals, the tubesheet and cluster assemblies were removed from the pressure vessel. Figure 5 shows a photograph of the filter internals following Test Run 3. Based on a detailed inspection of the filter, the following observations were made:

- A total of 21 broken candle filters were identified occurring only on the bottom three plenums. Seventeen of the broken filters apparently failed near the transition from the dense-to-porous filter region. Plenum A had 15 failed elements, while Plenum B had 2 and Plenum C had 4.

- No broken candles were detected from the top or middle plenums. Some ash bridging was observed on the top and middle plenums between the inner ring of filters and the cluster support pipe.

- Bowing of filters was detected for some elements in the bottom plenum, as well as broken filters removed from the ash hopper.

A possible failure scenario would conclude that ash, unable to properly discharge from the hopper, built up and reached the candle filters of the bottom plenum. Ash at this level then began to fill and pack the interstitial spacing, forming ash bridges between the candle filter elements. As cleaning continued, more ash was packed into the interstitial filter spacing with additional accumulation of ash in the hopper. The high cohesive strength of this ash allowed lateral forces to develop on the filter elements. The lateral forces resulted in filter bowing and high shear loads. The concentration of stresses near the top of the filters resulted in a mechanical failure of the filter elements.

Figure 5. Photograph of Bottom Filter Candles Following Test Run 3

Discussion of Problems and Corrective Action

The initial operation of the HGCU system revealed some problems with the system. Since this was the first test of a large scale hot gas clean up system, it is not surprising that problems arose. Most of the problems discussed below do not involve the APF. Other than the problems of hot spots on the shell of the APF and the ash accumulation in the hopper, the APF performed very well. It will be necessary to eliminate problems associated with the balance of the system in order to achieve successful long-term operation. A summary of the problems encountered and corrective actions is discussed below.

Hot Spots. Hot spots were observed on the backup cyclone, APF vessel head and outlet nozzle, and several instrument nozzles on the hot gas piping. Following Test Run 1, the backup cyclone was heated internally and externally to remove any residual moisture from the refractory lining, and all refractory cracks were repaired. In subsequent tests, the cyclone skin temperature was much lower; however, it still exceeded the nameplate design rating of 200F at several locations. At our request, the cyclone manufacturer recertified the cyclone to 750F by resubmitting ASME code calculations based on this design temperature. This design temperature should provide sufficient margin should hot spots appear in future tests.

Also following Test Run 1, all instrument nozzles that exhibited hot spots were opened and inspected. In all cases, it was found that gaps between the refractory and insulation or instrument device allowed hot gas to reach the nozzle/pipe connection. Insulating caulking was added at these locations to seal the gaps. In subsequent tests, none of these hot spots, with one exception, reappeared. One nozzle reached about 400F. It will be reworked again prior to the resumption of testing.

The APF outlet nozzle and several locations on the top of the APF head exhibited high temperatures (up to 800F) during Test Run 1. Between Test Runs 1 and 2, the insulation in the outlet nozzle was revised to eliminate a likely gas flow path, and potential holes around head liner penetrations were repacked with insulation. The following test showed that the outlet nozzle had been successfully repaired, as well as most of the original hot spots on the top of the APF head. However, a new hot area appeared around the head knuckle. Upon disassembly following testing, this hot area was found to be caused by distortion of the brim of the dome liner which opened up a gap between it and the insulation. The brim has been eliminated and the insulation repaired.

Ash Accumulation in the APF Hopper. Following Test Run 1, the APF hopper was inspected. Some ash was observed on the sides of the hopper near the outlet. However, it appeared to be less than one inch thick. It was cleaned out prior to Test Run 2. During Test Run 2, after approximately 19 hours on coal, the APF liner temperature began dropping, probably indicating ash buildup near the hopper outlet. Subsequent purging with air seemed to correct the problem. Later in the test run, the backpulse air compressor failed and filter cleaning was abnormally low or completely interrupted for about 33 hours. Following resumption of cleaning, the high ash level annunciator alarmed, and the hopper liner temperatures decreased. During Test Run 3, several instances of low liner temperature and/or high ash level alarm occurred. Upon inspection of the APF hopper following the last test, the entire hopper was found to be full of ash. In some areas the ash level appeared higher than the bottom of the candles, leading to candle breakage.

Subsequent inspection revealed a solid plug of material in the 8-in. diameter APF hopper outlet pipe. It is unknown when this plug formed. Chemical analysis indicated that it was calcium sulfate and magnesium sulfate. Condensation of sulfuric acid from the flue gas in the relative cool outlet pipe is thought to have contributed to the formation of the plug.

Several options were considered for improving ash movement through the hopper. These included installing purge air pipes or manifolds in the hopper, increasing the hopper angle, mounting the hopper liner supports on vibrators, and installing a pneumatic vibrator in the APF manway nozzle and linking it to the hopper. The purge air option was rejected since it was considered likely to move ash only in localized areas and cool the gas below the dew point causing the ash to become more sticky. Changing the hopper angle was not selected because laboratory flow tests of the ash indicated that it would be ineffective, given the dimensional constraints of the APF vessel. The last alternative was chosen and preliminary testing at Tidd using a vibrator showed it to be effective in moving ash down the hopper wall. A detailed design was completed by Westinghouse and the vibrator and related hardware will be installed prior to the next test. The screw cooler water temperature will be increased from 320 to 340F (the limit of the system) in order to increase the ash temperature at the screw cooler inlet.

Ash Pluggage in the Lockhopper System. Test Run 1 was terminated due to ash buildup in a lockhopper isolation valve and instrument lines. It was found that the valve purge air contained enough moisture to harden the ash in the valve body. The pressure sensing lines on the ash removal system became plugged with ash, causing erroneous pressure data which resulted in the logic interrupting the sequence of operation. The lockhopper pressure equalization line also became plugged with ash. As a result, ash removal was sporadic during Test Run 1.

Several improvements were made to the ash removal system between Test Runs 1 and 2. The source of air for all valve purging was switched to a drier source. Blowdown valves were added to the purge air lines to remove any residual moisture accumulation. Constant flow regulators were installed to provide continuous instrument air purge to all pressure sensing lines. The lockhopper pressure equalizing line was revised to utilize clean process air instead of gas in the surge hopper for repressurization after ash loading in order to keep ash from plugging the equalizing line. The ash removal system logic was revised to reduce the number of interruptions in the ash unloading sequence. Finally, as a backup, an emergency ash removal system was added between the screw cooler and the lockhoppers. This system will use process air to transport ash from the screw cooler discharge pipe in a manner similar to the method used for the backup cyclone ash removal. Ash removal during Test Runs 2 and 3 was much better than during Test Run 1. However, system logic enhancements continued to be made during and after Test Runs 2 and 3. Visual inspection of the system following Test Run 3 revealed that the lockhoppers were clean.

Expansion Joint Bellows Leak. The expansion joint bellows material was changed from 321 stainless steel to Hastelloy C22 (UNS N06022) following the failure of two expansion joints in May 1992, during initial operation of the system using only the bypass cyclone. (Refer to Reference 2 for a complete discussion of these failures.) The failures were attributed to stress corrosion and pitting corrosion due to sulfuric acid and chlorides. Hastelloy C22 was believed to be the best candidate material for the corrosive conditions created by condensation of the Tidd PFBC flue gas. Also, the revised expansion joints were made with a two-ply bellows, 0.038" (inner) and 0.062" (outer) in thickness. A pressure gauge was installed at each bellows to monitor the interply pressure and thereby detect a leak in the inner ply. A pinhole leak formed in the inner ply of one bellows during Test Run 3. A hot spot (≈540F) was also observed at a localized area in the outer bellows. When the leak was confirmed, the plant was shut down. Subsequent failure analysis confirmed that a pinhole leak was formed by pitting corrosion from hydrochloric acid. The bellows was replaced. A second bellows was removed and examined as well. It also exhibited some pitting corrosion, but to a much lesser degree. It was not replaced. Thus, it was concluded that even Hastelloy C22 is not impervious to corrosion in this system, although it is far superior to stainless steel.

As a result of the failure, it was decided to heat trace and insulate all expansion joints in the hot gas piping system to maintain a temperature of 450F, well above the acid dew point (≈370F) of the flue gas. Necessary instrumentation and controls will be installed prior to the next test run to monitor and control the temperature of the bellows.

Loss of Backpulse Air Compressor. The backpulse air compressor failed on two occasions, once during Test Run 2 and again during Test Run 3. Both failures were believed to be due to insufficient lubrication to the fourth stage cylinder. The manufacturer had modified the lubrication design for the compressor just prior to manufacturing this machine, and was unaware that the new design was faulty. The manufacturer subsequently modified the fourth stage cylinder liner to relocate the oil port to eliminate the problem. The second failure also resulted in a broken crosshead which connects the second/third stage pistons to the crank shaft. The manufacturer suggested that this failure might have been due to excessive oil and moisture building up in the first stage moisture separator and carrying over into the second stage. Therefore, all four moisture separators were equipped with larger drain lines and drain valves, and the first stage separator drain valve will be left open continuously. The compressor has since been successfully operated for over 100 hours.

In addition, two spare compressors, each with approximately half the capacity of the original, have been rented and will be available for immediate use should the compressor fail again during testing.

Backpulse Valves. Piston actuated ball valves are used on the backpulse valve skid to control flow paths during backpulsing. One valve failed during Test Run 3 due to excessive wear at the valve stem coupling. The valve was replaced during the test. Other ball valves also exhibited wear at the couplings. Between Test Runs 1 and 2, bracing was added to the valve operators to reduce misalignment of the stem and coupling during stroking. However, the couplings continued to wear. Following Test Run 3, all couplings, valve bodies, and actuator brackets were replaced with an improved design.

Several of the Atkomatic pulse solenoid valves failed sporadically to operate during operation. In all cases, the parallel backup valve operated successfully. Post-test examination revealed some axial scratches on the piston and cylinder wall. Atkomatic has modified all of the solenoid valves to reduce and hopefully eliminate galling during valve actuation.

Filter Cleanability Above 1400F. Operating experience, both at Tidd and Westinghouse STC's Test Facility, has demonstrated that the filters are difficult to clean, particularly when the ash temperature approaches 1500F. During Test Runs 1 and 2, filter pressure drop increased very moderately (indicative of good cleaning). However, after failure of the backpulse compressor, baseline pressure drop increased considerably. Even after nitrogen was brought onto the site for backpulsing, the baseline pressure drop did not recover. Upon visual inspection, many candles had a "splotchy" appearance. Some intercandle and candle-to-plenum ash bridging was also observed.

Figure 6 shows the increase in filter baseline pressure differential during Test Run 3. The temperature in the APF ranged from 1425 to 1450F during this time period. When the temperature increased to 1470F, the baseline pressure differential increased at a faster rate. It is not clear whether the inability to clean effectively during this phase was due to a temperature effect on the ash or the result of a thick ash cake on the candles that had been partially cleaned by low pressure backpulsing. Once the candles became "splotched," subsequent cleaning may have been ineffective on the previously uncleaned areas. It should be noted that the filter pressure differential stabilized during portions of Test Runs 1 and 2 (prior to the backpulse compressor failure) at temperatures above 1400F, but below 1500F.

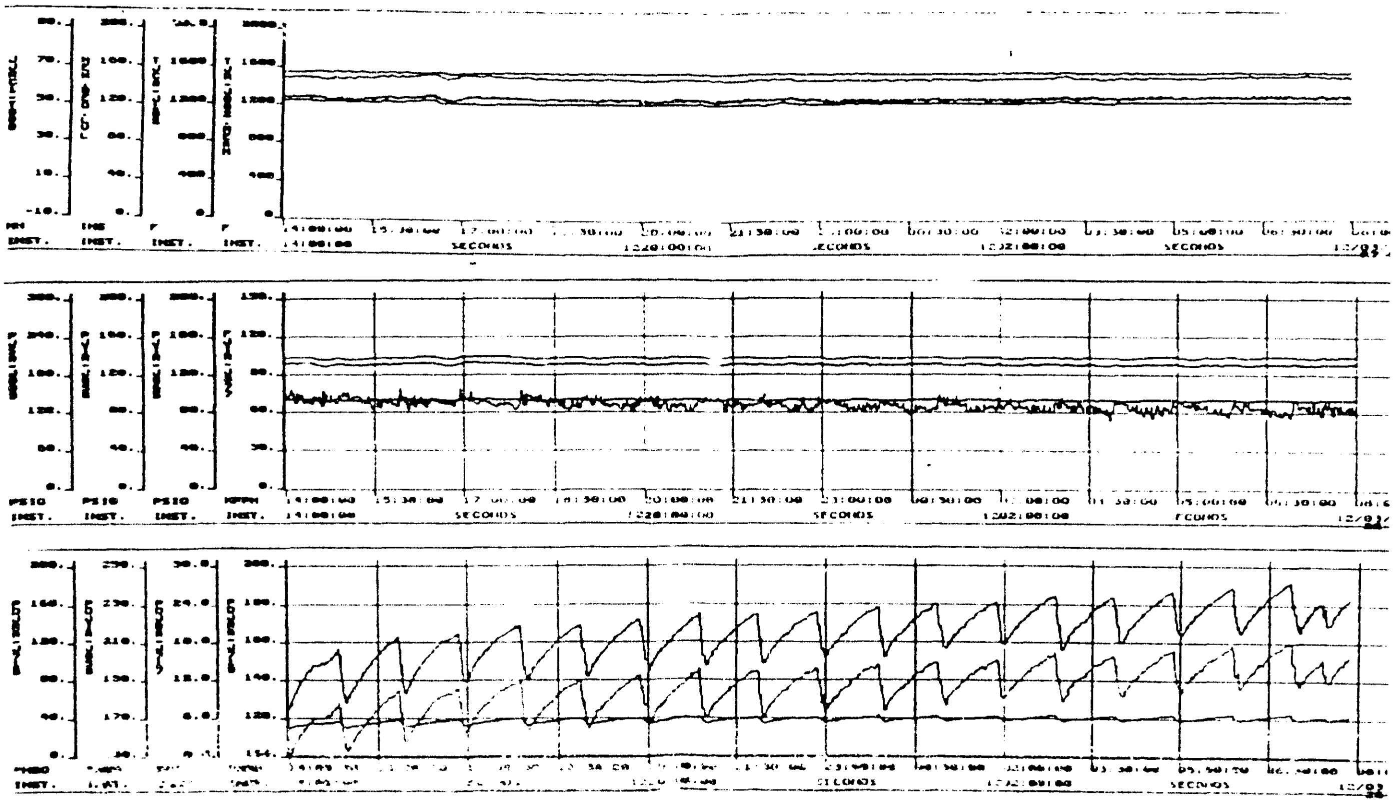


Figure 6. Profile of APF Operation

Top Set of Graphs:
- Top Line: Mean Bed Temperature: 1580F (860C)
- Second Line: Freeboard Temperature: 1550F (843C)
- Third Line: Unit Load: 50 MW
- Bottom Line: Bed Level: 120" (3m)

Second Set of Graphs:
- Top Line: APF Inlet Pressure: 138 psig (9.4 bar)
- Second Line: APF Outlet Pressure: 130 psig (8.8 bar)
- Third Line: Freeboard Pressure: 139 psig (9.5 bar)
- Bottom Line: APF Gas Flow: 60,000 - 75,000 lb./hr. (7.56 - 9.45 kg/s)

Bottom Set of Graphs:
- Top Line: APF DP: Baseline Climbing from 125" H_2O to 165" H_2O (307 to 405 mbar)
- Second Line: HGCU System DP: Baseline Climbing from 150" H_2O to 190" H_2O (369 to 467 mbar)
- Bottom Line: APF Tubesheet DP: Climbing from 5 psi to 6 psi (340 to 408 mbar)

During Test Run 3, unit load was reduced to decrease gas temperature and flow to maintain the APF tubesheet pressure differential below the maximum limit. In order to increase the allowable pressure differential of the filter, stiffener bars were subsequently welded across the bottom filter plenums above the candle holders. The plenum bottoms were determined to be limiting components of the maximum allowable pressure drop of the filter assembly. This modification increased the tubesheet allowable pressure differential from 7 to 9 psi. Further testing will need to be conducted to confirm that the filter will reach a stable pressure drop at the maximum operating temperature of 1550F.

As a backup plan should the filter pressure differential become unstable, a method of detuning the primary cyclone upstream of the APF was devised. The method involves injecting air from the sorbent system upwards into the cyclone dip leg, thereby reducing the cyclone efficiency. The purpose of cyclone detuning is to increase dust loading and the proportion of larger dust particles to the APF in order to improve filter cleaning and/or ash removal and transport, should either become necessary. An analysis was performed to determine the proper air line size to obtain the required air velocity in the cyclone. The system will include a manual globe valve and flow metering orifice outside the combustor to allow the detuning air flow to be adjusted or shut off. The system will be installed prior to the next start-up.

It is expected that effective spoiling of the primary cyclone will result in a less adhesive but more cohesive ash cake, i.e., one that is easier to clean.

FUTURE PLANS

All of the system modifications and enhancements described herein have been or will be implemented prior to the next test run. If these improvements correct the problems previously experienced, long duration filter testing should be accomplished. Some of the objectives of future testing are:

- Establishing baseline data below 1450F.
- Full load (and maximum temperature) operation.
- Ash sampling for APF performance testing.
- Sampling for Hazardous Air Pollutants (HAP's).
- Determining the effect of cyclone detuning on ash loading.
- Optimizing backpulse pressure and frequency.
- Obtaining ash samples for analysis.

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