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Update on the Operation and Performance Testing of
the TIDD PFBC Demonstration Plant

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UPDATE ON THE OPERATION AND PERFORMANCE TESTING OF THE TIDD PFBC DEMONSTRATION PLANT

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Abstract

The 70 MWe Tidd Pressurized Fluidized Bed Combined-cycle (PFBC) Demonstration Plant is a Round 1 U.S. DOE Clean Coal Technology project constructed to demonstrate the viability of the PFBC combined cycle technology for efficient and environmentally sound coal based power generation. The knowledge and experience realized from this program is intended to assist in the commercial deployment of this technology to provide a viable option for future base load power generation needs, which are presently expected to develop early in the next decade. Consistent with the goals of the program, progress made during the first three years of operation of the facility has yielded a technology that is presently ready for commercial deployment. This paper presents an historic perspective on the Tidd unit as well as recent operating experience and performance data in support of this claim.

Introduction

The Tidd PFBC Demonstration Plant is the first pressurized fluidized bed combustor to operate in combined-cycle mode in the United States. Owned and operated by Ohio Power Company, a subsidiary of American Electric Power, the plant is located in Brilliant, Ohio on the banks of the Ohio River, approximately 75 miles downstream of Pittsburgh, Pennsylvania. Funding for the approximately \$210 million program is being

the Ohio Coal Development Office (\$12.6 million).

The project involved repowering Tidd Unit No. 1, which was a conventional coal-fired steam turbine based generating unit built in the 1940's, with the combined cycle PFBC steam generator/gas turbine system. Engineering and design services for the project were provided by American Electric Power Service Corporation. Technology related equipment was supplied by ASEA Babcock, a partnership between ASEA Brown Boveri Carbon (ABB Carbon) and Babcock and Wilcox Company (B&W). New construction and modification of the existing Tidd facility was carried on by Ohio Power Company.

Construction of the demonstration plant began in April 1988. Unit startup was initiated in November 1990, and the first combined-cycle operation was achieved on November 29, 1990. As part of the original Cooperative Agreement with the U.S. DOE, the Tidd PFBC facility was scheduled to operate for a three-year test period. This initial test period commenced on March 1, 1991 and ended on February 28, 1994. Through the end of that period, the unit logged over 6000 hours of combined-cycle, coal-fired operation. An additional fourth year of operation commenced on March 1, 1994.

Plant Description

The original Tidd plant, which was decommissioned in 1976, consisted of two 110 MWe steam turbine generators supplied steam by conventional coal-fired boilers. For the demonstration project, the Unit 1 steam turbine was repowered at approximately 50% capacity by the PFBC combustor's steam generator and the gas turbine exhaust economizer. Other major additions included in the ASEA Babcock scope of supply were the gas turbine and generator, the coal preparation system, the coal and sorbent feed systems, the gas cleaning cyclones, the cyclone ash and bed ash removal systems and the integrated unit control system. The major balance of plant improvements and modifications included the electrostatic precipitator, the storage areas for the raw coal and sorbent, the sorbent preparation system, the bed ash and cyclone ash storage silos, a revamped control room and the new combustor building. The remainder of the balance of plant functions needed to support the PFBC facility were met through reuse of much of the original Tidd facility's balance of plant components and systems, which were refurbished as needed to insure sufficient reliability for the intended life of the demonstration plant.

The PFBC Power Island, (Figure 1) which has been incorporated into the existing conventional steam cycle, was designed to produce 440,000 pounds per hour of steam flow at 1300 psia and 925 F generating a gross electrical output of 72.5 MWe (57.1 MWe from the steam turbine generator and 15.4 MWe from the gas turbine generator).

Figure 1 - Tidd PFBC Island

Air at approximately 175 psia is provided by the gas turbine compressor to the combustor vessel through the outer annulus of a coaxial air/ gas pipe. Inside the combustor vessel, the air is ducted into the boiler where it fluidizes the bed materials (fresh sorbent, partially reacted sorbent, coal char and coal ash) and provides the oxygen for coal combustion. The bed design temperature is 1580 F, which was set by maximum temperature limitations of the gas turbine. This temperature is well above the minimum coal combustion temperature and generally provides sufficient margin to avoid melting of the coal ash constituents. In addition, this temperature provides a relatively high reaction rate for SO_2 capture by direct sulfation of the calcium carbonate in the sorbent and is well below the temperature at which alkalis vaporize and present a corrosion problem for the gas turbine. Formation of NO_x from nitrogen in the air (thermal NO_x) is essentially nil due to the low combustion temperature and much of the NO_x formed from nitrogen in the coal (fuel NO_x) is reduced to N_2 and O_2 at char sites in the bed, resulting in a very low overall NO_x emission level (less than 0.3 lbs NO_x per 10^6 Btu).

Seven parallel gas cleaning strings collect 99% of the ash elutriated by the gas leaving the bed. Six of the strings incorporate two stages of high efficiency cyclones, the seventh uses a primary cyclone followed by an experimental ceramic Advanced Particle Filter (APF). All of the cyclones are located inside the combustor vessel. The ceramic filter is located outside of the combustor in a separate pressure vessel. The gas from all seven strings is combined inside of the combustor vessel and it is directed to the gas turbine via the inner pipe of a coaxial air/ gas pipe. The gases are expanded through the turbine stages of the ABB Stal GT-35P gas turbine, which

produces shaft power to run the gas turbine compressor (approximately 2/3 of the power at full load) and to drive the gas turbine generator (remaining 1/3 of the power). The turbine exhaust gases then pass through the economizer where excess heat is transferred to the feedwater and then through the electrostatic precipitator for further particulate collection. After this, the gases are ducted to Cardinal Unit No. 1 where they are combined with that unit's exhaust stream and exit to atmosphere via the Cardinal stack.

The steam cycle is a Rankine cycle with a subcritical once-through boiler. Condensate is heated by three stages of low pressure heaters and the gas turbine intercooler as it is pumped to the deaerator. A single high pressure heater and the turbine exhaust gas economizer raise the final feedwater temperature to approximately 480 F. The feedwater then passes through the boiler bottom hopper and furnace wall enclosures where additional subcooled preheating occurs. The feedwater then enters the in-bed evaporator tubes where the steam is generated and attains a slight degree of superheat. The steam then passes through the in-bed primary superheater is attemperated and then attains final steam temperature in the in-bed secondary superheater. At steam flows below 40% capacity a circulation pump maintains sufficient flow rate through the evaporator circuits for cooling protection and the resultant moisture in the evaporator outlet steam is separated by centrifugal action in a vertical separator.

Coal is injected into the fluidized bed as a paste nominally containing 25 percent water by weight. Raw coal of 3/4 inch top size is fed to a double roll crusher which reduces the material to minus 1/4 inch. The crushed coal is conveyed to a screen to collect oversized material then to a mixer where water is added to make the paste. A recycle line, which is located upstream of the screen, returns a portion of the material to the crusher. Recycle is regulated to attain a sufficient quantity of coal fines, which are necessary to make a cohesive and pumpable coal paste. The paste is fed from the mixer into two interconnected surge tanks which supply six hydraulically driven piston pumps. These pumps then feed the paste to individual dedicated fuel nozzles which deliver the paste into the fluidized bed just below the tube bundle.

The sorbent, which is generally dolomite, is crushed to minus 1/8 inch size and dried in a hot air swept hammermill crusher. This material is then injected into the fluidized bed via alternating dual lockhoppers that feed a dilute phase pneumatic transport system. The original transport system design splits the flow into two feed nozzles; however, the system has recently been modified to provide a total of four feed nozzles.

Material is drained from the bed in order to maintain the bed level. This "bed ash" accounts for approximately 40% of the total ash and is generally 99+% larger than 60 mesh (250 microns). The ash is drained in a controlled manner by gravity via two parallel lockhoppers. Material elutriated from the bed and collected in the cyclones, approximately 60% of the ash, is generally 99% smaller than 60 mesh. This "cyclone ash" is removed by means of a pneumatic transport system which depressurizes and

cools it.

Operational Overview

The operating experience from the Tidd PFBC facility has been one of gradual and constant improvement starting with the initial combined cycle operation in November, 1990. Evidence of this is presented graphically in Figure 2, which depicts the quarterly unit availability and capacity factors for the period from 1991 through 1993.

Figure 2 - Unit Availability and Capacity Factors

During the period from November 1990 through September 1991, the unit fired coal for a total of 818 hours, with the longest continuous run being 110 hours. During that period, the unit was plagued with numerous problems, the most significant being cyclone ash removal system plugs, fires at the cyclone gas inlets and in the ash dip legs, coal feed system plugs, economizer fouling, and boiler vertical separator level control problems. In addition, boiler in-bed tube surface was found to be insufficient and the air distribution sparge ducts were experiencing excessive distortion. During

this period a number of minor design revisions were incorporated that led to improved unit operability; however, a twelve-week outage was scheduled in the Fall of 1991 in order to correct the major unit deficiencies. The key modifications performed during the outage include:

- Added surface to the boiler in-bed tube bundle in order to increase the heat absorption and steaming capacity.
- Replaced the expansion joints in the air distribution sparge ducts with a revised design.
- Installed a steam induced mixing system in the boiler freeboard to provide for more even heat release from volatiles and fine char escaping the bed.
- Revised the cyclone ash removal system.
- Installed sootblowers and anti-vibration ties in the economizer.

The unit was returned to service in early December, 1991. After a series of short runs, the unit began to operate more reliably; however, run durations were still limited by operating problems. From mid-December through early March, 1992, the unit fired coal for a total of 530 hours with the longest run being 154 hours. At that point in time, cracks were discovered in the root area of a number of the gas turbine low pressure turbine blades. A nine-week outage was taken in order to replace the blades and to commission the APF piping system.

The unit was returned to service in late May, 1992. The first run was very short lived due to corrosion problems on the expansion joints in the APF piping. Since that problem necessitated a major modification, a decision was made to return the unit to service with the APF system blocked off and only six gas cleaning strings in service. After a two-week outage, the unit was returned to service and was run continuously for thirty-one days with a capacity factor of nearly 70%. The unit was kept on-line in spite of a plugged secondary cyclone ash removal line experienced early in the run, since it was determined that this would not dramatically increase gas turbine erosion. At the end of the thirty-one days, the unit was removed from service in a controlled manner in order to perform equipment inspections. The unit acceptance tests were also conducted during this period.

From July 1992 through February 1993, unit operation was fairly reliable permitting a number of performance tests to be conducted. The most significant problems during this period were fuel nozzle plugs induced by coal paste preparation problems and occasional primary cyclone system plugs. The unit was operated periodically with plugged secondary cyclone ash removal lines. Other factors contributing to unit down time were attempted operation with a magnesian limestone as the sorbent, which caused two unit trips due to excessive bed sintering and operational problems with the APF system which was connected in service from late October through early

December. In addition, the air distribution sparge ducts continued to distort and began to experience localized cracking. In early February, 1993 the gas turbine threw two low pressure turbine blades, which resulted in extensive damage to the machine. As a result, the unit experienced a twenty-week outage to effect the repair. During this time the secondary cyclone ash removal system was completely reconfigured and the air distribution sparge ducts were replaced.

The unit was returned to service in late June, 1993. From that time through the end of February, 1994, the unit operated more reliably and fired coal for a total of 2015 hours with three runs in excess of 400 hours. The improved unit reliability permitted a large number of unit performance tests to be conducted, which established a broad base of test data. During this period, the performance of the secondary cyclone ash removal system was greatly improved. However, plugging of primary cyclone ash removal lines at unit start-ups became a major nuisance causing four unit outages. This problem was attributed to continued degradation of the gaskets in the system.

The initial three year test program for the Tidd PFBC Demonstration plant was completed at the end of February, 1994. Over those three years, the unit fired coal for a total of 6056 hours. In addition to the key system and component problems noted above, it should be recognized that the unit periodically experienced nuisance trips. These included boiler sensing line fitting leaks inside the combustor, control logic problems, local component controller failures and other minor problems. These events collectively had a significant impact on unit down time, particularly since the systems necessary for combustor cooldown, access and restart were not optimized for the rapid return of the unit to service. Another factor impacting unit availability was the lack of redundancy in key systems in this demonstration plant. In order to minimize the cost of the facility, the usual redundancy that would be incorporated into a commercial plant was left out. This factor alone had major impacts, particularly in regard to the coal preparation and injection systems. Finally, one other issue must be recognized when viewing the Tidd operating history. Operation and testing at the Tidd facility has not been done in a manner solely to maximize operating time. Throughout the course of the three-year test program, deliberate operating challenges have been undertaken in the interest of determining the unit flexibility and operating limits and improving unit performance.

Bed Process Findings

Post-Bed Combustion

Initial operation of the unit at intermediate and high loads revealed that combustion was occurring beyond the bed resulting in excessively high temperatures of the gas in selective cyclone strings and of the ash in the primary cyclone dip legs. The dip leg combustion was attributed to excessive unburned carbon carryover; whereas, the gas stream combustion was attributed to carryover of unburned volatiles. It was determined that both of these phenomena were due to high localized fuel release

combined with rapid fuel breakup and devolatilization. Insufficient oxygen was available in these localized regions resulting in plumes of low O_2 gas with unburned volatiles and fine char at each of the six fuel nozzle discharge points. This was documented through oxygen measurements taken in the freeboard above the fuel nozzle discharge points. This problem was gradually minimized over time through improved fuel distribution, apportionment of higher air flow to these regions, reduced fuel splitting, the installation of a steam induced freeboard gas mixing system, and improvements in the coal paste quality. The latter factor proved to have the greatest impact on reducing the degree of post bed combustion.

During recent runs, the unit has operated for extended periods with no signs of post bed combustion. However, upsets in coal paste preparation, such as excessive water addition, still result in upward swings in freeboard gas temperature. Such swings pose a potential trip risk at full bed height due to excessive gas turbine temperatures. At lower bed heights, these swings are not a problem, since the freeboard temperature runs well below the bed temperature due to the convective cooling action of the tubes above the top of the bed.

Sinter Formation

A significant operating issue has been the formation of hollow egg shaped agglomerates in the range of 1 - 2 inches in size. These agglomerates are generally present all of the time in small quantities and pose no major operating problems, since they are drained away at a rate faster than they are produced. However, under some conditions the rate of formation is so great that they accumulate in the bed. When this occurs, bed conditions deteriorate with the bed temperatures and evaporator outlet leg temperatures becoming dramatically uneven and the bed density and tube bundle absorption decaying. When firing Pittsburgh No. 8 coal with dolomite, such excessive sintering has generally been controllable. However, at full bed height, bed temperatures in excess of 1520 F have repeatedly resulted in excessive sinter formation. In the absence of other key variables, this experience seems to indicate that the high localized heat release at high firing rates may play a role in the sintering. This phenomenon is still being investigated.

Another factor which strongly effects the rate of sinter formation is the type of sorbent. When attempting to use a magnesian limestone with significantly less MgO than the dolomite, the sintering has not been controllable under any load condition and has resulted in three unit trips in three attempts. A detailed chemical investigation into the mechanism involved in the sintering revealed that the likely cause is calcium from the sorbent fluxing the potassium-alumina-silicate clays in the coal ash. The nuclei of the sinters appear to be coal paste lumps which become sticky and collect bed ash on their surface. The coal then burns away, leaving the coal ash to react with the bed material. The less aggressive sintering with dolomite is explained by the fact that increased quantities of $MgCO_3$ tend to raise the melting temperatures of $CaO-MgO-Al_2O_3$ mixtures.

Investigations into resolving the sintering problem are presently focusing on attaining stable operation across the load range with Pittsburgh No. 8 coal and Plum Run Greenfield dolomite as the sorbent. The main focus being the size of the split coal paste, since reducing the paste lump size was identified as a possible means to minimize the sintering. Methods to reduce the paste lump size that are being investigated include increased splitting air, decreased paste fines and added paste moisture. Once sintering is resolved with dolomite, attempts will then be made to operate with a limestone. Testing of other coals that have lower swelling and sticking tendencies may also be investigated.

Freeboard SO₂ Concentration Variations

Given the presence of high localized volatile combustion at the fuel discharge points, ABB Carbon suggested that the amount of SO₂ released at these points may be very high creating an uneven bed SO₂ concentration profile which would pose challenges for optimizing sorbent utilization and maximizing sulfur capture. In order to investigate this matter, the multiple point freeboard gas sampling and analyzing system, used previously to identify the low O₂ plumes, was modified to also analyze for SO₂. Measurements taken with this system have verified that the fuel nozzle discharge plumes are regions of high SO₂ release having up to fifteen times the average SO₂ concentration. However, it has also been found that local feed of fresh sorbent to these regions can dramatically reduce the plume SO₂ concentration. Data from the use of this system is assisting in the ongoing work to improve sorbent utilization through changes to the method of sorbent distribution.

Fuel Distribution

The problems of post-bed combustion, sintering, and high local SO₂ release are exacerbated by the limited number of fuel feed points. While not practical at the Tidd facility due to time and cost constraints, additional fuel feed points would help mitigate each of these issues in a new commercial plant design.

Key System/ Component Experiences

Boiler

The in-bed tube bundle has experienced over 6000 hours of fluidized bed operation with no signs of broad based erosion. There has been some local erosion found near the bottom of the bundle; however, this is very minimal and is due to localized flow disturbances. Recently a tube leak was experienced in one furnace water wall tube and two evaporator tubes. The initiating event was a leak in the water wall tube which was due to localized tube erosion caused by a leaking access door seal. This in-turn steam cut the evaporator tubes.

Heat absorption by the in-bed tube bundle was initially only 73% of the design value. Surface was added at the top of the bundle in the fall of 1991 to correct the shortfall; however, this was not completely successful. The present bundle is fully submerged at a bed height of 142 inches, at which point the heat absorption is approximately 93% of the original design value. It is felt that the relatively tight arrangement of the Tidd tube bundle, reduced fluidization velocity due to excessive gas turbine compressor to turbine leakage, and bed agglomerates may be contributing factors to the low absorption rates. Sufficient data now exists from Tidd and the other PFBC units to adjust the design models and better predict performance.

The air distribution sparge ducts experienced gradual deformation and eventual cracking over the first two years of unit operation. Modifications were made to the expansion joints in the ducts in the Fall of 1991; however, degradation of the ducts continued. The ducts were replaced in the Spring of 1993 and a new system was installed to limit duct end forces due to expansion during bed preheating when the ducts reach temperatures as high as 1500 F. The new ducts have shown no signs of degradation.

Economizer

The fin tube turbine exhaust gas economizer has experienced significantly heavier ash fouling than originally anticipated. This situation, caused by the extremely tenacious nature of the ultra-fine ash in the gas stream, has necessitated the installation of eight sootblowers to combat the fouling. However, the economizer absorption is still below design, causing higher exhaust gas temperatures, reduced feedwater heating (reducing boiler steaming capacity), and higher than expected gas side pressure drop. Fouling prior to the installation of the sootblowers resulted in tube failures at the header connections. These were attributed to vibration induced by high gas velocities. Improved cleaning of the economizer and additional anti-vibration ties eliminated this problem. The Tidd experience provides an excellent design basis for selecting an economizer for future commercial units.

Gas Cleaning Cyclones

Cleaning of the combustion gases of particulate matter for protection of the gas turbine has functioned well. The two stages of high efficiency cyclones have consistently cleaned the gases of 98-99% of the ash elutriated from the bed. The only exception to this performance has occurred when the cyclone ash removal systems have plugged.

Cyclone Ash Removal Systems

Since initial unit startup, both the primary and secondary cyclone ash removal systems have undergone numerous design revisions in order to improve their reliability. Presently, both systems are very reliable, rarely causing unit trips once startup is completed.

The biggest problem initially with these systems was the difficulty in determining when they were plugged. Delayed identification of plugged conditions, particularly in the primary cyclone ash removal system, resulted in extended operation with dramatically increased dust loading to the gas turbine. This resulted in some erosion of the blades. The problem was solved through additional instrumentation.

Through minor design changes, plugging in the primary cyclone ash removal was minimized early in the unit's operating life. However, system in-leakage, which adversely impacts transport capacity, still is an issue requiring significant maintenance work on flanged connections to insure adequate system tightness. Due to this leakage, occasional plugs still occur in this system early in the startup when the pressure vessel pressure is low and the transport capacity is reduced. The solution to this problem is to eliminate the flanged fittings in a commercial plant design. In order to combat this problem at Tidd, sand is used as the start bed material to lower the dust elutriation. It is important to note that even though the primary cyclone ash removal stem transports the coarsest and largest fraction of the elutriated ash, no significant erosion related problems have been experienced in over 6000 hours of operation.

The secondary ash removal system, which transports very fine ash (100% less than 13 microns) has undergone extensive modifications to improve its integrity. The tenacious nature of this fine ash necessitates much higher transport velocities to insure system cleanliness. The present system design, installed since the Spring of 1993, has proved very reliable. In addition, provisions incorporated into the system to permit on-line unplugging have been fully effective in the few instances where plugs have occurred. Proper design of this system has resulted in limited erosion of the transport piping in spite of the high transport velocities needed to prevent plugging.

Gas Turbine

The gas turbine has experienced three significant incidents which impacted unit availability. The first occurred in the Spring of 1992 causing a nine week outage. In that event, the low pressure turbine blades were found to have cracks in the root area necessitating their replacement. The second and most significant event occurred in the Spring of 1993 when the gas turbine threw two low pressure turbine blades causing extensive damage to the high and low pressure turbine as well as the high pressure compressor. The cause of the first and second events was not directly related. The repair work, which involved new blading and associated components in the high pressure compressor and high and low pressure turbines, resulted in a twenty week outage. The third incident, which occurred in December 1993, involved the replacement of a number of the stages of guide vanes in the low pressure compressor due to cracking. That repair resulted in extending an in progress outage by approximately 3-1/2 weeks. All of these problems were first of a kind design issues and were not erosion or corrosion related.

The original gas turbine blading, which was in place for 3500 hours of coal fired operation, did experience some measurable erosion. Through periodic inspections it was determined that most of the noted erosion was due to excessive ash carryover events associated with plugged cyclone ash removal lines, particularly those for the primary cyclones. Normal operation without plugged ash removal lines showed very little wear and operation with plugged secondary cyclone ash removal lines caused only a slight increase in the erosion rate. The new blading, installed since the Spring of 1993, has achieved approximately 2500 hours of coal fired operation. During this time period, operation with plugged primary cyclone ash removal lines has been avoided. Periodic inspections of the new blading has confirmed the previous experience that the erosion rate is minimal provided that the cyclone ash removal systems function properly.

In regard to performance, the gas turbine compressor has exhibited below design efficiency and capacity as well as excessive leakage from the compressor to the turbine. These factors resulted in below design unit efficiency and gas turbine generator output. In addition, the reduced compressor capacity and excessive leakage have resulted in reduced air flow available to the combustor, which has limited maximum bed height and firing rate during the warmer months of the year when the overall compressor mass flow delivery capability is reduced. ABBC has identified solutions to all of these problems and these have been applied and proven on other units.

Coal Preparation System

The coal preparation system has evolved significantly from the pre-operation period. Most of the issues centered around the Krupp Polysius double-roll crusher. The design size distribution for making proper coal paste is 1/4 inch top size with approximately 20% finer than 325 mesh. In the beginning, sufficient fines could not be achieved. Without enough fines, the coal paste was not cohesive and required excessive water to make it pumpable. The poor paste quality was a major factor in the high degree of post-bed combustion experienced early on with the unit. A number of changes were made to the crusher and the preparation system in the interest of obtaining sufficient fines. The most effective change was the incorporation of crusher recycle. Through regulation of the recycle flow, the fines concentration of 20% can now be met, which results in a more cohesive and pumpable paste product. This has resulted in reduced incidents of paste pump/ nozzle plugging and significantly reduced post bed combustion.

The preparation system now operates reliably as long as the incoming coal remains consistent. A significant increase in raw coal moisture content will generally result in reduced throughput, prohibiting full load operation. In addition, attempts to operate the unit with coals other than the typical Pittsburgh No. 8 coal have revealed that the crusher capacity is strongly affected by coal type. Attempts to operate with two alternate coals resulted in limits on unit load due to crusher capacity. While the latter

factor has created some problems at Tidd, this issue would likely be resolved through system design capacity changes and added redundancy in a commercial plant. However, a different type of crusher or two steps of crushing might prove to be more appropriate for reliable paste preparation. Notwithstanding the capacity issue and the susceptibility to changes in the coal supply, the double-roll crusher has been reliable and has proven its capability to produce the necessary coal size gradation for making a paste.

Coal Injection System

The coal injection system experienced numerous plugs during the first two years of operation with some of those events precipitating unit trips. During the latest year of operation, the incidence of plugged fuel nozzles has been dramatically reduced resulting in extremely reliable fuel feed. The main factor contributing to the improved system performance was improved coal paste preparation. Occasional line or nozzle plugs still occur, but these usually follow an upset in the preparation system. The biggest issue in commercializing this system will be defining the proper number of coal feed nozzles to ensure adequate fuel distribution and to be able to operate for extended periods with pumps out for service. With only six pumps at Tidd, significant bed temperature imbalances occur when one of the lines is lost, and the degree of imbalance becomes totally unacceptable and necessitates a unit trip if two lines are lost.

The major component issues with this system have been corrosion of the pumps, cracking and subsequent erosion of the fuel nozzle outlets and fuel splitting air configuration. The pump corrosion problem was experienced during the first year of operation and was totally resolved through proper material selection. The fuel nozzle outlet problem was resolved through a change in material. The fuel splitting air configuration issue is not yet fully resolved. This issue relates to the aforementioned balance between fine splitting induced post-bed combustion and coarse splitting induced bed sintering. Much of this problem would readily be resolved through the inclusion of more fuel feed points in a commercial facility; however, activities to optimize the Tidd unit operation with six fuel feed points will continue during the extended fourth year of operation.

Sorbent Preparation System

The most significant issue with the sorbent preparation system has been excessive wear of the components, particularly the crusher, the cyclone separator and the fan. The wear problem has generally been resolved through changes to harder materials and the use of erosion resistant liners.

One of the key issues with this system has been the difficulty in obtaining changes to the product size distribution. Such changes are desirable to permit determination of the optimum sorbent size gradation with respect to sulfur capture and sorbent utilization. It has generally been noted that finer product gradations result in reduced

sorbent demand. The existing system screen, which experiences blinding when finer mesh screen inserts are used, has proven to be the biggest obstacle to product size changes. As such, a new larger capacity screen will be installed later this year. Aggressive changes in sorbent sizing will then be evaluated for impacts on bed conditions, such as heat transfer and bed temperature distribution, as well as for the impact on sorbent utilization.

An additional issue with the sorbent preparation system has been below design capacity. This is generally a crusher and screen issue and is interrelated to the product sizing issue as well as the system component wear issue. While capacity problems with this system have resulted in unit loading limitations, the sorbent preparation system has never been the cause of a unit trip.

Sorbent Injection System

The sorbent injection stem has undergone a number of modifications over the past few years to improve its reliability, but it has not presented any major operating obstacles. The biggest issue was erosion of the pneumatic transport piping and feeder discharge pick-up pot. This was fully resolved through the installation of ceramic linings and the elimination of abrupt flow area changes at the system valves. The sorbent injection system is presently very reliable.

Measurements taken in the boiler freeboard revealed wide variations of SO₂ concentrations. In order to mitigate this, additional sorbent feed points were recently added. The original system design incorporated two feed nozzles injecting just inside the front wall of the boiler. The new design further divides the original two nozzles into a total of four nozzles that feed in through the boiler front wall covering a wider area of the bed with fresh sorbent. A full evaluation of the impact of this change is not complete; however, it appears to improve sorbent utilization and to reduce the magnitude of the higher concentration freeboard SO₂ measurements. Additional improvements to sorbent distribution, such as further splitting via nozzle outlet tees and wyes and extensions of the nozzles further into the bed, will be evaluated in the future.

Paste Feed of Sorbent

A system to feed part of the sorbent in with the coal paste was added in 1993. The system can feed approximately half of the sorbent into the coal paste mixer. With a 500 ton on-site storage silo, off-site preparation of sorbent can then be done to any size desired for a test. Testing with this system so far has concentrated on the feed of ultra-fine sorbent ground to a mean particle size of approximately 7 microns. Results from feeding up to 40% of this fine sorbent with the coal paste have shown a reduction in sorbent demands of approximately 10%.

Bed Ash Removal System

The bed ash removal system has functioned very well with no significant operational problems. The related bed ash cooling system, which cools the ash to below 300 F prior to exiting the combustor, has also functioned extremely well. Both of these systems have operated at capacities in excess of the original design ash removal rate without any difficulty. Control over the rate of ash removal, accomplished through pulsed fluidization of an L-valve, has proven to be very steady for bed level control and the L-valves have not been a problem. The only issue with the system has been increased maintenance on the isolation and lockhopper vent valves as the system has aged; however, this has not severely effected unit operation.

Bed Reinjection System

The bed reinjection system, which transports bed material to and from the bed into storage vessels located inside the combustor vessel to permit relatively rapid bed level changes, has generally functioned well. The system requires very little operator attention while providing reliable control over unit load increases and decreases. Due to bed temperature control issues and the desire to avoid significant unit upsets, the full capability of the system in regards to maximum load change rate has not yet been tested.

Unit Performance

Test results for a number of performance tests at varying bed heights are presented in Table 1 along with the original full load design conditions for the unit.

TABLE 1

TIDD PFBC PERFORMANCE TEST RESULTS AT VARIOUS LOADS

		TEST 6 6/14/92	TEST 16 1/29/93	TEST 17 7/22/93	FULL LOAD EXPECTED
BED LEVEL	INCHES	142.3	118.9	95.0	126.0
FIRING RATE	MWt	188.7	163.2	124.8	204.4
GROSS UNIT OUTPUT	MWe	60.2	52.4	33.0	72.5
GAS TURBINE OUTPUT	MWe	13.2	10.4	4.3	15.4
MEAN BED TEMPERATURE	F	1551	1539	1533	1580
GAS TURBINE INLET TEMP	F	1541	1399	1238	1526
MAIN STEAM FLOW	KPPH	395	350	267	442
ECONOMIZER OUTLET GAS TEMP	F	419	380	543	649
AIR FLOW TO COMBUSTOR	KPPH	588	99.5	99.2	99.0
COMBUSTION EFFICIENCY	PERCENT	99.5	27.4	70.7	25.0
SULFUR RETENTION	PERCENT	92.7	89.2	87.7	90.0
Ca/S MOLAR RATIO	RATIO	2.07	2.34	2.44	1.64
Ca/S RATIO @ 90% SR, 1580F TBED	RATIO	1.71	2.22	2.43	1.64
NOx EMISSIONS	LB/MMBTU	0.17	0.22	0.28	0.30

Unit Output and Efficiency

Comparison of the full bed height test to the expected values reveals reduced unit output. This lower output is due to both limited firing capability and below design cycle efficiency. The main factors contributing to these shortcomings are below design boiler absorption, reduced bed operating temperature due to sintering problems, high gas exit temperatures due to economizer fouling, below design gas turbine compressor efficiency, excessive air leakage from the gas turbine compressor to the turbine, and steam cycle inefficiencies. It is felt that through improved economizer design, proper boiler surfacing, evolutionary improvements to this first-of-a-kind gas turbine, minimization of sintering through improved fuel distribution, integration of the PFBC process with a modern high efficiency steam cycle and elimination of typical steam cycle losses, a commercial plant that achieves the full cycle efficiency potential of the PFBC process can presently be designed, built, and operated.

Sorbent Utilization

Calcium to sulfur molar ratios required for 90% sulfur retention (correlated to 1580 F bed temperature) for unit performance tests at various bed heights are presented in Figure 3 along with the original expected performance. It can be seen from this data that the baseline performance of the unit with the original two sorbent feed points revealed sorbent requirements approximately 30% above the expected values.

Figure 3

It is believed that this discrepancy is due to problems in the scale-up of the required number of fuel and sorbent feed points from the 15 MWt pilot plant to the 200 MWt Tidd unit, which resulted in a significant increase in the ratios of bed plan area per fuel and sorbent feed point. Evidence of the problem of concentrated fuel feed is the low O_2 and high SO_2 plume regions discussed earlier. In order to combat this problem, a change from two to four sorbent feed points was recently incorporated. Initial results from testing in this configuration have revealed an approximate 10% reduction in sorbent demand. Improvements in sorbent utilization were also seen when feeding part of the sorbent as ultra-fine material with the coal paste. This manner of feed has also shown an improvement in sorbent demands of approximately 10%. In addition, recent tests with a finer gradation of pneumatically fed sorbent has shown improvements of approximately 15%. More testing with variations in sorbent feed are planned for the extended fourth year of operation.

Figure 4

In the baseline sorbent feed configuration, performance tests were conducted at varying sulfur retention levels to evaluate the impact of changes in sulfur retention on sorbent demands. Data from these tests are presented in Figure 4. This testing clearly showed that sulfur retention levels in excess of 95% can be attained with the PFBC process.

NOx Emissions

The NOx emissions levels for the Tidd plant are below the original expected values. This is depicted in Figure 5, which compares the NOx emissions from various performance tests to the original expected values on the basis of fuel nitrogen conversion at various flue gas oxygen concentration levels.

Figure 5

Process Controllability

While configuration of the control logic for the unit was an extensive and evolutionary process, the integrated unit controls attained a fairly mature status by the end of the first year of operation. Since that time, the controls have been very reliable, rarely being the cause of a unit trip. This experience is a very positive development given the interdependent nature of the PFBC process.

The most significant configuration work involved the boiler water side controls, particularly the control of the vertical separator level at low loads up through the transition to once-through operation. This aspect alone resulted in numerous unit trips early on. Extensive evolution of the logic was required in order to avoid trips as well

as to ensure that stable level, and hence reliable circulation flow would be maintained under the most demanding trip and upset conditions.

Operating Perspective

From an operator's perspective, the PFBC process is safer and easier to operate than a conventional pulverized coal fired boiler. There are many factors contributing to this, the most notable being that coal preparation and feed are less complicated and changing load does not require placing burners in and out of service. In addition, with the low bed operating temperatures, there are no slagging conditions which present major operating headaches in conventional units.

From the Ohio Power Company perspective, the Tidd facility not only presented the challenge of a new coal firing process, it also presented a new methodology for operating a power generation facility. The Tidd plant was the first unit on the Ohio Power Company system to employ a computer based integrated unit control system for total plant operation. The operator interfaces are touch sensitive cathode ray tubes and keyboards in place of conventional panels, gauges and multi-point recorders. This aspect alone required a rigorous training program for the plant operators, which included the use of a simulator. While this facet of operation required some time to get used to, ready access to piping and valve arrangements, alarm and trip settings and historical trends has proven to be a very ergonomically sound method to operate a power generation facility.

Readiness for Commercial Deployment

Experience from the Tidd plant, as well as its sister units in Sweden and Spain, clearly shows that this process is now ready for commercial deployment. All major issues regarding unit reliability have been resolved and solutions to any remaining technical concerns have been identified. As noted earlier, design enhancements needed to attain the desired overall unit efficiency in a commercial plant are well understood.

Plans for the Tidd Facility

In addition to accumulating more operating time on the PFBC process components, activities in the fourth year of operation will be directed at improvements in sorbent utilization. When the Tidd facility was originally designed, 90% sulfur retention at calcium-to-sulfur molar ratios less than 2.0 was considered acceptable. It is now believed that the PFBC process will need to attain 95% sulfur retention at similar or lower levels of calcium-to-sulfur molar ratio in order to meet the best available technology requirements and maintain its intended cost advantage over competing power generation technologies when using high sulfur coal. The main factor driving this need for improved sorbent utilization is the expected escalation in waste disposal

costs. While studies have shown that the ash produced in the first commercial PFBC facility will likely enjoy ready marketability, there is no certainty that the demand would be sufficient if a large number of facilities were built, nor is there certainty that the environmental waste categorization of these by-products will not change. It is for these reasons that methods to reduce sorbent demands will be explored.

Conclusion

Consistent with the original intent for the Tidd PFBC Demonstration Plant, operating experiences, test results, and design evolution activities associated with the facility has taken the PFBC process from the status of "promising technology" to that of a true commercial option for efficient and environmentally sound power generation from the combustion of coal. Extended operation of the facility will serve to further enhance the long term commercial viability of the PFBC process.

References

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