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Demonstration of a Full-Scale Retrofit of the Advanced Hybrid Particulate Collector Technology

A DOE Assessment

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Disclaimer

Technology Nomenclature

When this technology was originally developed, the device was referred to as the "Advanced Hybrid Particulate Collector." Since the original development, from concept to this demonstration, the name of the technology was changed to "Advanced Hybrid™." The name was trademarked by W.L. Gore and Associates, Inc. to aid in the commercialization effort and to maintain the continuity of the successful history to date. Either "Advanced Hybrid Particulate Collector" (AHPC) or "Advanced Hybrid™" refers to the same process and equipment.

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EXECUTIVE SUMMARY

The Power Plant Improvement Initiative (PPII) is a follow-up to the U.S. Department of Energy's (DOE's) Clean Coal Technology Demonstration Program (CCTDP) whose purpose was to offer the energy marketplace more efficient, cost effective or environmentally benign coal-fired power production options by demonstrating these technologies in commercial settings. One of the projects selected under PPII was "Demonstration of a Full-Scale Retrofit of the Advanced Hybrid Particulate Collector Technology". The project was carried out at Otter Tail Power Company's (OTPC) Big Stone Power Plant. The plant, operated by OTPC, is jointly owned with Montana-Dakota Utilities and NorthWestern Energy. The Big Stone Power Plant consists of a single 450 MWe (nominal) cyclone-fired boiler fueled primarily with Powder River Basin (PRB) subbituminous coal. The plant also burns seeds (primarily corn and soybean) and tires.

The Advanced Hybrid™ technology was developed by the University of North Dakota's Energy and Environmental Research Center (EERC). Early work, supported by the DOE, resulted in the development of a 200 acfm (actual cubic feet per minute) unit at EERC. Based on the results of the 200 acfm unit, a 9,000 acfm was built and operated at the Big Stone Power Plant. This early work was carried out under DOE's Advanced Environmental Control Technologies for Coal-Based Power Systems Program.

The project was selected for award on September 26, 2001. A cooperative agreement was awarded July 2, 2002. The National Environmental Policy Act (NEPA) process was completed with the issuance of the Environmental Assessment in June 2002 and the Finding of No Significant Impact (FONSI) on June 11, 2002. Construction commenced in July 2002 and was completed in October 2002. The installation replaced the last three fields of the existing electrostatic precipitator (ESP), but the first field was left intact. Startup was initiated on October 22, 2002. The demonstration period was originally scheduled to last until November, 2004, but was extended through January 2006. The first six months of operation (November 2002 – April 2003) showed very good particulate removal efficiency, but at a higher than anticipated pressure drop.

Performance testing has shown that the average collection efficiency of the Advanced Hybrid ™ is 99.997 percent when the bags are intact. Other than some mechanical issues related to either design or installation, start up went smoothly. However, problems soon developed. The pressure drop across the Advanced Hybrid™ began to increase. An unusually large amount of soybeans was burned early in the project, which led to severe fouling of the boiler and caused an outage to wash the boiler. During the outage some of the bags were washed and the remaining bags were replaced (polytetrafluoroethylene [PTFE] membrane bags were replaced with polyphenylene sulfide [PPS] membrane bags). This temporarily improved performance, but the pressure drop soon began to increase. The pressure drop issue turned out to be an on-going problem throughout the project. The high pressure drop led to increased bag cleaning which contributed to premature bag failures, high power requirements for the pulse air compressor and ID fan and ultimately to derates as high as 55 MW. OTPC took a number of steps to remedy the problem and conducted tests to determine the cause. It was determined that the ESP portion of the Advanced Hybrid™ was not achieving the particulate removal levels that had been anticipated; a portion of the incoming flue gas was bypassing the ESP components, and the pattern of gas flow within the unit was not as expected. After trying various membrane bag types and installing baffles to minimize the amount of gas bypassing the ESP failed to remedy the situation, OTPC installed Advanced Hybrid™ components in the first field of the ESP casing. This was intended to increase collection of the particulate matter by the ESP components and to increase the bag area. The increased bag area would reduce the air-to-cloth ratio. It was noted that the Advanced Hybrid™ operated reasonably well when the plant was derated due to non-Advanced Hybrid™ factors which reduced the air-to-cloth ratio. There were problems with maintaining plate alignment in the new field that actually resulted in less particulate precollection, and high pressure drops continued to be observed.

At the end of the project, OTPC decided to replace the Advanced Hybrid™ technology with a pulse jet bag house particulate removal system. Although the Advanced Hybrid™ showed the ability to remove particulate matter to very low levels, the expense of bag replacement and derates were determined to be unacceptable.

I. INTRODUCTION

The Power Plant Improvement Initiative (PPII) is a follow-up to the U.S. Department of Energy's (DOE's) Clean Coal Technology Demonstration Program (CCTDP) that was successfully implemented in the 1980s and 1990s. The purpose of the CCTDP was to offer the energy marketplace more efficient and environmentally benign coal-fired power production options by demonstrating these technologies in commercial settings.

On October 11, 2000, the PPII was established under U.S. Public Law 106-291 for the commercial scale demonstration of technologies to ensure a reliable supply of energy from the Nation's existing and new electric generating facilities. Congress directed that PPII was to "demonstrate advanced coal-based technologies applicable to existing and new power plants… The managers expect that there will be at least a 50 percent industry cost share for each of these projects and that the program will focus on technology that can be commercialized over the next few years. Such demonstrations must advance the efficiency, environmental controls and cost-competitiveness of coal-fired capacity well beyond that which is in operation now or has been operated to date."

To fund the PPII, $95 million in previously appropriated funds were transferred from the U.S. Department of Energy's CCTDP. The PPII program solicitation was issued on February 6, 2001, and 24 applications were received. On September 26, 2001, eight applications were selected for negotiation of a cooperative agreement. One of the projects selected was "Demonstration of a Full-Scale Retrofit of the Advanced Hybrid Particulate Collector Technology," carried out at Otter Tail Power Company's (OTPC) Big Stone Power Plant. OTPC and its partners, Montana-Dakota Utilities and NorthWestern Energy, installed the Advanced Hybrid Particulate Collector (AHPC) technology into the 2nd, 3rd and 4th fields of an existing electrostatic precipitator (ESP) structure at the Big Stone Power Plant. The overall goal of the project was to demonstrate the AHPC concept in a full-scale application. Specific objectives were to demonstrate 99.99 percent collection of all particles in the 0.01 to 50 micron size range, low pressure drop, overall reliability of the technology, and long-term bag life. The initial project cost was $13,397,445 of which DOE contributed $6,491,000 or 48.4 percent. After completion of the original project, DOE granted OTPC a no-cost extension to the period of performance of the financial assistance in order to provide time for operational problems to be worked-out. During this extension, OTPC (at their own expense) installed Advanced Hybrid™ components in the first field of the ESP structure to provide more ESP and fabric filter surface area. However, due to unresolved issues, the Advanced Hybrid™ was not able to consistently meet the project goals.

II. PROJECT/PROCESS DESCRIPTION

A. Project Site

The Big Stone Power Plant, located in Big Stone City, SD, was commissioned for service in 1975. It consists of one base-loaded Babcock and Wilcox cyclone-fired boiler, rated at 450 MW. All the flue gas passes through an ESP, which consists of four chambers each having four fields. The specific collection area (SCA) is approximately 475 square feet per 1,000 actual cubic feet per minute (acfm). More than 70 OTPC employees operate and maintain the plant for the three owners. SO_2 emissions meet the permit requirements through the use of low-sulfur coal, and the NO_x emission limit is met with the use of overfire air. The plant cooling water system uses a series of cooling ponds rather than a cooling tower.

B. Project Goals

The project had seven goals, which, if met, would have effectively established the commercial readiness of the Advanced Hybrid™ technology. These were to:

- Demonstrate that the AHPC technology could be retrofitted into an existing ESP at the full commercial-scale level.
- Demonstrate the ability of a retrofitted AHPC to meet performance specifications without derating the plant because of high opacity.
- Demonstrate the ability of the AHPC to provide >99.99 percent particulate collection efficiency for all particle sizes greater than 0.01 microns.
- Demonstrate reliability, as defined by acceptable maintenance requirements, of the AHPC that is the same as, or better than, standard ESPs or baghouses.
- Demonstrate the ability of the AHPC to achieve low pressure drop (guaranteed) at an air-to-cloth (A/C) ratio of 12 feet per minute (fpm).
- Demonstrate the long-term operability of the AHPC.
- Demonstrate the economic viability of the AHPC.

C. Project Description

The Participant for this project is OTPC. Other team members include the University of North Dakota's Energy and Environmental Research Center (EERC) (concept developer), W.L. Gore & Associates, Inc. (Gore) (licensee and filter bag provider), ELEX AG (ELEX) (original equipment manufacturer), Montana-Dakota Utilities (co-host) and NorthWestern Public Service (co-host). OTPC provided the site, a financial commitment, and technical assistance to the project and had overall responsibility for managing the project. As the managing entity, OTPC had responsibility for technical direction, operations, data acquisition, and coordinating the activities of the team members, including liaison with the DOE.

EERC developed the Advanced Hybrid™ technology and is the technology owner and supplier. Gore was a technical and financial partner and the exclusive licensee of the Advanced Hybrid™. All of the original filter bags were provided by Gore, along with technical guidance in support of this project. In addition to providing bags, Gore also developed and provided operational information, including removal of bags periodically from the Advanced Hybrid™ and testing to evaluate performance and determine bag wear. ELEX, a subcontractor to OTPC, was responsible for the design and installation of the Advanced Hybrid™. Montana-Dakota Utilities and NorthWestern Public Service are part owners of the Big Stone Power Plant.

The project consisted of removing the ESP components from the last three fields of the existing ESP and installing Advanced Hybrid™ components in those areas. Installation was completed in late October 2002. The project was originally scheduled to last through November 2004; however, problems with pressure drop and bag life were encountered. Problems with excessive pressure drop caused the plant to be derated on several occasions. The project received a no-cost extension through January 2006, and OTPC decided to replace the remaining ESP components in the first field with additional Advanced Hybrid™ components.

D. Technology Description

In recent years, regulators have been increasingly concerned about respirable particles, those that are less than 2.5 microns in diameter ($PM_{2.5}$). For these particles, the collection efficiency of a modern ESP could approach about 99 percent; and the efficiency of a well-designed fabric filter (FF) would be about 99.9 percent. Higher levels of control might be possible with an ESP, but only by a significant increase in the SCA.

ESPs are the most common particulate control devices used by the electric power industry. They can be located upstream of the air preheater (hot side ESP) or downstream of the air heater (cold side ESP). Cold side ESP's are the most common. Both types of ESPs are divided into compartments that can be isolated for maintenance. Each typically contains 2 to 4 fields in series. These fields consist of a number of parallel collection plates and discharge electrodes. The discharge electrodes impart an electrical charge to the incoming particles which causes them to migrate to the collection plates. Some particles can also migrate to the electrodes. Both the plates and electrodes are periodically rapped or shaken to dislodge the agglomerated particles causing them to fall into a hopper for disposal.

Fabric filters, also referred to as baghouses, are fairly common in the electric power generation industry. They are a vessel with a large number of bag filters which filter the particles from the flue gas. The vessel is divided into some number of chambers that can be isolated either for periodic on-line bag cleaning or for off-line maintenance. The two most common types of baghouses are distinguished based on the cleaning technique. The pulse jet uses a short high energy burst of compressed air to clean the bags. Much of the dust that is dislodged by the pulse is agglomerated and falls into a hopper for disposal, with some portion promptly returning to the bags. The second type is the reverse gas baghouse. In this type of unit the chamber to be cleaned is isolated and a longer, lower energy pulse of gas is used to remove the dust. While there is less chance of particulate matter being recaptured by the bags, this type of baghouse must be more conservatively designed since allowance must by made for two compartments being out of service - one for maintenance and one for cleaning. Baghouses operate at face velocities in the range of 1.5 to 5 fpm, with 1.5 to 2.5 fpm being the most common for the reverse gas baghouse and 3 to 5 fpm being typical for pulse jet baghouses.

Studies have shown that FF collection efficiency is likely to deteriorate significantly when the face velocity is increased. For high collection efficiency, the pores in the filter media must be effectively bridged. With conventional fabrics at low A/C ratios, the residual dust cake serves as part of the collection media, but at high A/C ratios, only a very light residual dust cake is acceptable, so the cake cannot be relied on to achieve high collection efficiency.

The Advanced Hybrid™ uses a combination of electrostatic precipitation and fabric filtration to achieve high collection efficiency. The ESP component of the Advanced Hybrid™ removes the bulk of the particulate matter before the flue gas reaches the bags. Extremely high efficiency is achieved by using membrane filter bags. Removing most of the particulates with the ESP component allows the membrane bags to operate at high A/C ratios, thus reducing the number of the relatively expensive membrane bags.

In the preferred application the system replaces an inadequate ESP and is installed in the vessel from which all the ESP hardware has been removed. The ESP at OTPC's Big Stone Power Plant had deteriorated to the point where improvements were needed. This ESP had a total of four fields, the last three of which were removed so that the AHPC could be installed.

The Advanced Hybrid™ consists of alternating electrostatic precipitation and fabric filtration elements in a single casing to achieve exceptional removal of particulate matter (PM) in a compact unit. Very high removal is achieved by removing at least 90 percent of the PM before it reaches the fabric filter and using a membrane fabric to collect the particles that reach the filter surface. Residual charge on the particles also enhances collection and minimizes pressure drop, since charged particles tend to form a more porous dust cake.

ESP models predict that 90 percent or greater collection efficiency can be achieved with an SCA of less than 100 square feet per 1,000 actual cubic feet per minute (ft^2/kacfm). Approximately two-thirds of existing ESPs have SCAs between 200 and 600 ft^2/kacfm with around one-third of the remainder having SCAs over 600 ft^2/kacfm and the remainder having SCAs below 200 ft^2/kacfm. Conventional pulse jet fabric filters (PJFF) typically operate at face velocities in the 3.5 to 4 fpm range, but models predict that face velocities greater than 12 fpm are possible if the dust loading is low and the bags are adequately cleaned. The challenge is to operate at high A/C ratios (8–14 ft^3/min/ft^2) for economic benefits while achieving high collection efficiency and controlling pressure drop. The combination of membrane filter media, small SCA, high A/C ratio, and unique geometry of the Advanced Hybrid™ was intended to meet this challenge.

Combining precollection with the ESP elements and membrane filter bags results in a small, economical unit that can achieve very high collection of all particle sizes. Early work was done on a 200 acfm test unit. The results of this work led to the construction and operation of a pilot unit sized at 9,000 acfm (2.5 MW equivalent) at Big Stone. Work on the pilot unit lead to a new arrangement of the internals for the Advanced Hybrid™. This new arrangement used perforated plates instead of the solid plates used in the earlier versions. This arrangement is shown in Figure 1.

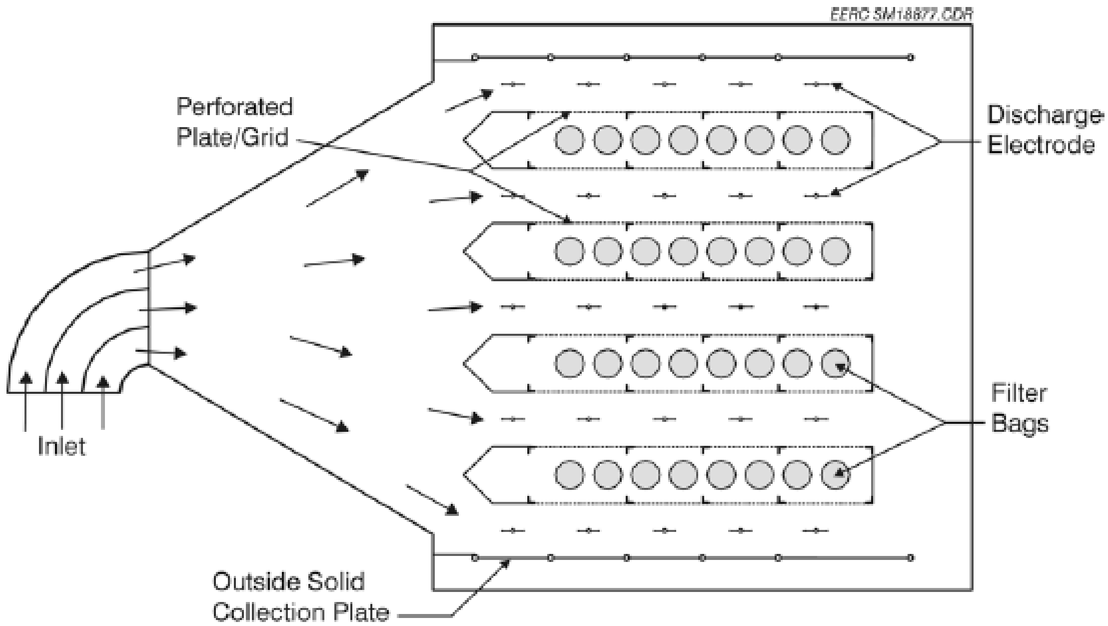


Figure 1. Advanced Hybrid™ Arrangement at Big Stone

In the new configuration, the distance from the discharge electrodes to the perforated plates, as well as the distance from the bags to the perforated plates, can be reduced without compromising performance. Therefore, one of the advantages of the perforated plate configuration is the potential to make the Advanced Hybrid™ significantly more compact. Another difference is that directional electrodes are not required with the perforated plate design, thus allowing conventional electrodes to be used. With the previous design, directional electrodes (toward the plate) were needed to prevent possible sparking to the bags. Electrode alignment is also less critical because an out-of-alignment electrode would simply result in potential sparking to the nearest grounded perforated plate; whereas, with the earlier design, an out-of-alignment electrode could result in sparking to a bag and possible bag damage.

The perforated plates have approximately 45 percent open area to provide adequate particulate collection while not restricting the flow of flue gas toward the bags during normal operation. The 9,000 acfm results, as well as the 200 acfm results, showed better ESP collection than the previous design while maintaining good bag cleanability. Furthermore, all of the flue gas passes through the perforated plates before reaching the bags. In the earlier design some of the flue gas would flow toward the bags rather than the plates, causing some of the PM to bypass the ESP zone.

For the commercial demonstration, the perforated plate design was installed in the existing ESP casing. Since the ESP was relatively large, the Advanced Hybrid™ components needed to occupy only three of the four ESP fields. The first field was left in place, but not energized. Top and side views of the Advanced Hybrid™ filter full-scale retrofit configuration are shown in Figure 2 and Figure 3, respectively.

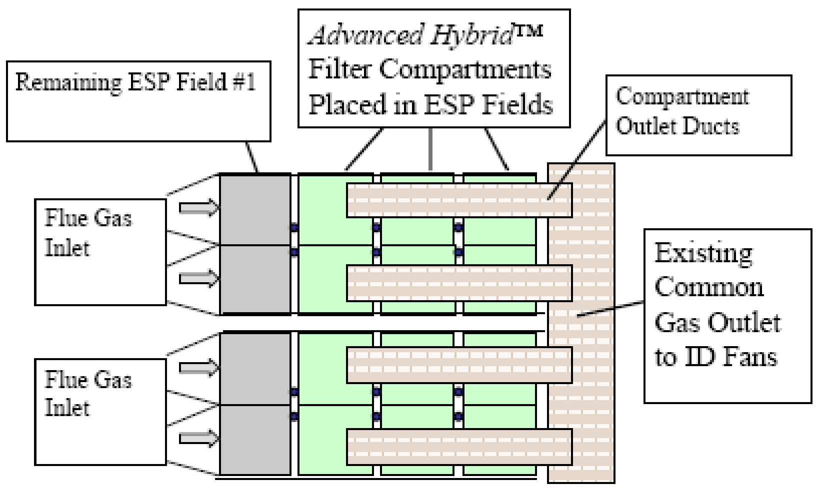


Figure 2. Top View of the Advanced Hybrid™ Filter Full-Scale Retrofit Configuration at Big Stone

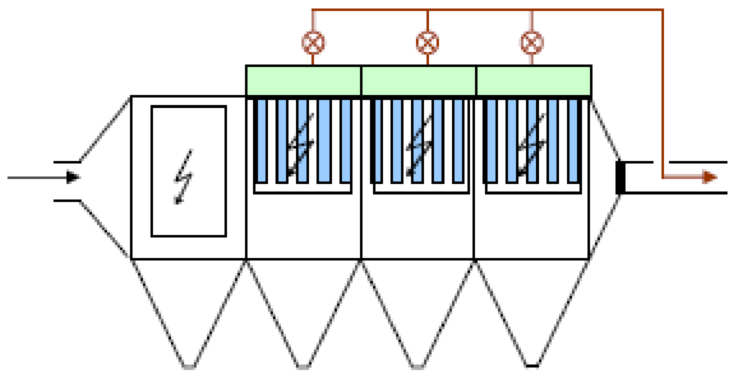


Figure 3. Side View of the Advanced Hybrid™ Filter Full-Scale Retrofit Configuration at Big Stone

The main differences between the 2.5 MW pilot Advanced Hybrid™ and the full-scale unit are listed below:

- The pilot unit has a small precollection zone consisting of one discharge electrode, while the full-scale unit has no precollection zone. The expected impact would be better ESP collection in the pilot unit.
- The pilot unit has shorter bags (15 ft versus 23 ft). This is expected to result in better bag cleaning in the pilot unit.
- The full-scale Advanced Hybrid™ has an ESP plate spacing of 12 inches (in.) compared to 13.5 in. for the pilot-scale unit. The expected result is somewhat better ESP collection efficiency in the full-scale unit.
- The entrance velocity of the flue gas is 4 to 8 feet per second (fps) for the full-scale unit and 2 fps in the pilot-scale unit which should result in better ESP collection efficiency in the pilot unit.
- The pilot unit has uniform side inlet flow distribution, while the full-scale Advanced Hybrid™ has flow from the side for the first filter compartment and from the bottom in the back two compartments. In the pilot unit, all of the flow is uniformly distributed from the side, and none of the flow comes from the bottom.

In the full-scale Advanced Hybrid™, flow entering the first filter chamber comes from the side. Flow to the back two compartments must first travel through the first compartment, below the first compartment and then either directly up from the bottom into the compartment or up from the bottom into the areas between compartments and then horizontally into the compartments. In addition, the Advanced Hybrid™ components do not occupy the entire width of each compartment. This arrangement creates an 'alley' that allows some of the flow to travel alongside the first compartment, off the back wall and into the third compartment from the back. Advanced Hybrid™ components could not be installed in the full width of the compartments because of the need to allow room for the pulse headers.

The original design details are presented in Table 1.

Table 1. Original Design Details

Advanced Hybrid™ Fields	
ESP Collecting Surface	170,500 ft^2
Number of Discharge Electrodes	2,706
Number of Filter Bags	4,833
Filter Bag Dimensions	23 feet long, 6 inches diameter
Filter Bag Surface Area	36.07 ft^2
Filter Bag Material	Conductive Gore-Tex® Membrane/ Conductive Gore-Tex® Felt
Pulse Pressure	80 pounds per square inch (psi)
Cleaning Mode	Threshold cleaning
Rating of Advanced Hybrid™ Field	1,500 milliamps (ma), 55 kilovolts (kV)
Inlet ESP Field Data	
Rating of Inlet ESP Field	2,000 ma, 55 kV
Inlet Field Dimensions	40 feet high, 14 feet deep
Inlet Field Plate Area	50,400 ft^2
Inlet Field Electrodes	Wheelabrator Bed Frame "Star" electrodes

E. Fuels

The primary fuel for the first 20 years of operation at the Big Stone plant was North Dakota lignite, but in 1995, the primary fuel was switched to Powder River Basin (PRB) subbituminous coal. This fuel has approximately one-half the moisture and one-third more heating value than North Dakota lignite. Almost all of the effects of this new fuel have been positive. However, one challenge is a decrease in the particulate collection efficiency of the ESP because of an increase in the resistivity of the fly ash. The combination of a very fine particle size produced by the cyclone-fired boiler and high ash resistivity has resulted in problems, both in terms of meeting opacity requirements and in maintaining the ESP. The plant also burns significant quantities of seeds (primarily corn and soybean) and tires. In general, when co-fired, tires usually account for 1.5 percent or less by weight of the total feed to the boiler on a monthly basis. Early in the demonstration, seeds accounted for up to 6 percent of the feed on a monthly basis and approached 20 percent on some days. Later in the demonstration, seed use dropped to less than 1 percent by weight. Fuel analyses are shown in Table 2.

Table 2. Typical Fuel Analyses, As Received

Fuel	Coal	Soybeans	Corn
Total Moisture	29.39	9.85	14.51
Ash	4.71	4.28	1.03
Carbon	48.13	48.97	40.12
Hydrogen	3.71	7.50	6.79
Nitrogen	0.67	5.71	1.14
Sulfur	0.34	0.31	0.35
O_2 By Difference	12.06	33.23	50.57
Na_2O	1.46	---	---
HHV, BTU/lb	8,539	9,338	6,925

III. REVIEW OF TECHNICAL AND ENVIRONMENTAL PERFORMANCE

This section discusses the performance of the Advanced Hybrid™ particulate control system installed at the Big Stone Power Plant. A chronological presentation was chosen to facilitate the readers understanding of events and issues that occurred during the operation of the project. Several graphs are included in the appendix that show critical data for the three plus years of operation.

Initial startup took place in late October 2002. Overall, startup went relatively well with only some minor mechanical problems. In November of 2002, three bags were found in the hoppers. It was determined that this was due to either improper installation or ill-fitting bags.

Stack tests were conducted from November 18 – 22, 2002 by EERC. Samples were taken at the inlet ducts for the two inside chambers (see Figure 1) and at the 288 foot level of the stack. Each chamber has a separate inlet duct but all four chambers discharge to a common duct. The test methods are shown in Table 3 and the fuel burned during the tests is shown in Table 4.

Table 3. Sampling Test Matrix

Activity	Sampling Location	Nov. 18		Nov. 19		Nov. 20		Nov. 21		Nov. 22	
		AM	PM	AM	PM	AM	PM	AM	PM	AM	PM
Set-Up and Takedown		Setup								Takedown	
APS/SMPS[1]	Stack			APS/SMPS							
EPA Method 29[2]	Advanced Hybrid™ Inlet			X		X	X				
EPA Method 29	Stack			X		X	X				
EPA Method 17	Stack		X			X		X			
Multicyclones	Advanced Hybrid™ Inlet				X			X	X		
Impactor	Stack					X					
Coal Samples and Hopper Ash				X		X		X		X	

[1] Aerodynamic particle sizer (APS)/scanning mobility particle sizer (SMPS).
[2] U.S. Environmental Protection Agency.

Table 4. Fuel Burned During Testing

Day	Coal, %	TDF, %	Waste Seed (Corn), %
Nov. 19	96.5	0.4	3.1
Nov. 20	100	0	0
Nov. 21	100	0	0
Nov. 22	95.0	2.2	2.8

These tests confirmed that the Advanced Hybrid™ is highly effective in capturing total particulate matter with the average collection efficiency being greater than 99.995 percent. The results are tabulated in Table 5 [Hrdlicka and Swanson, 2006]. The results for respirable particulate matter are presented in Figure 4 and Figure 5. It is worth noting that the particulate loading in the stack is lower than some of the readings obtained for the ambient air.

Table 5. Advanced Hybrid™ Stack Test Results

Date	Sample Method	Advanced Hybrid™ Inlet Dust Loading, grains/scf	Advanced Hybrid™ Inlet[1] Dust Loading, lb/10^6 Btu	Stack Dust Loading, grains/scf	Stack[1] Dust Loading, lb/10^6 Btu	Particulate Collection Efficiency, %
11/18/2002	EPA Method 17			0.00002	0.00003	99.998
11/19/2002	EPA Method 29	1.02092	1.38378			
	Multicyclones	0.64099	0.86882			
11/20/2002	EPA Method 17			0.00006	0.00008	99.994
	EPA Method 29	0.85856	1.16372			
	EPA Method 29	0.92151	1.24904			
11/21/2002	EPA Method 17			0.00003	0.00004	99.997
	Multicyclones	0.66113	0.89611			
	Multicyclones	0.70044	0.94940			

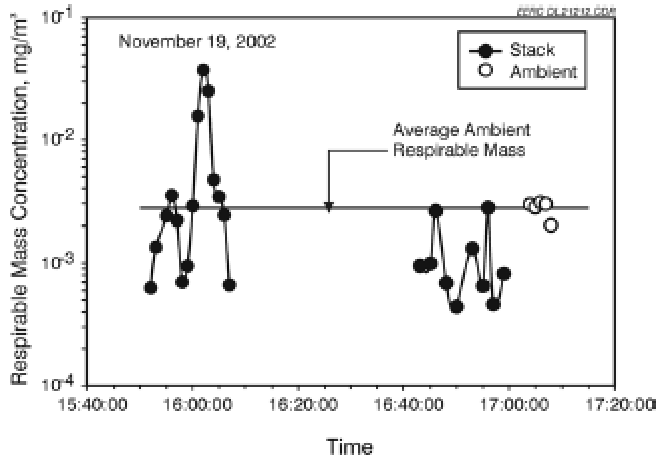


Figure 4. Respirable Mass Measurements at the Stack of the Big Stone Power Plant for November 19, 2002

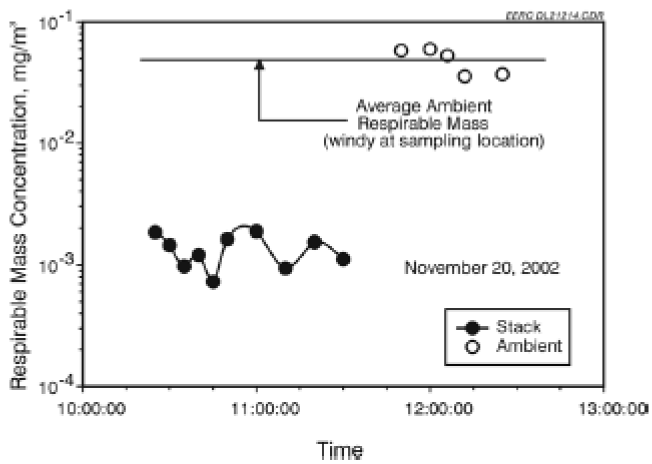


Figure 5. Respirable Mass Measurements at the Stack of the Big Stone Power Plant for November 20, 2002

In addition to testing the Advanced Hybrid™ performance for total and respirable particulate matter, the testing included tests for a number of trace elements. With the exception of mercury, the Advanced Hybrid™ is also highly efficient in removing trace elements as shown in Table 6 [Hrdlicka and Swanson, 2002 and Hrdlicka and Swanson, 2006]. It is relatively ineffective for removing mercury since much of the mercury is in the vapor state.

Table 6. Comparison of the Concentration of Trace Elements at the Advanced Hybrid™ Inlet and Stack

Day	11/19/02		11/20/02		11/20/02	
Time	11:08		09:25		13:25	
Fuel	PRB, TRF, and Corn Seed		100% PRB		100% PRB	
Trace Element	Advanced Hybrid™ Inlet, $lb/10^{12}$ Btu	Stack, $lb/10^{12}$ Btu	Advanced Hybrid™ Inlet, $lb/10^{12}$ Btu	Stack, $lb/10^{12}$ Btu	Advanced Hybrid™ Inlet, $lb/10^{12}$ Btu	Stack, $lb/10^{12}$ Btu
Antimony	15.8	ND[2]	10.4	ND	8.9	ND
Arsenic	31.7	ND	28.4	ND	30.5	ND
Beryllium	1.7	ND	3.8	ND	1.6	ND
Cadmium	4.4	ND	3.1	ND	2.9	ND
Chromium	30.1	0.2	29.6	0.3	40.0	0.3
Lead	151.3	2.4	129.0	0.9	128.4	ND
Mercury	4.6	3.2	5.7	3.6	8.6	3.8
Nickel	137.1	1.8	116.0	1.0	102.9	0.6

[1] All values shown are calculated based on Tables 8 and 9 and the Fd factor shown in Table 5 for 100% PRB.
[2] ND (not detected) is defined as those results where both the gas-phase and particulate bound forms of the trace elements are below detection limits.

After Big Stone resumed burning alternate fuels, primarily soybeans, on November 1, 2002, it was noticed that differential pressure across the bags had risen over the first months of operation. The impact of the soybeans on the Advanced Hybrid™ is not known. As a result of the increased differential pressure, Big Stone personnel decided to energize the unmodified first ESP field on December 12, 2002 to reduce the particulate loading to the Advanced Hybrid™.

During the second quarter of operation (Jan–Mar 2003), high differential pressure across the bags continued to be a problem. Due to induced draft (ID) fan limitations, it was necessary for the plant to take a number of derates. The first derate occurred on January 8, 2003. The derates reached a level as high as 55 MWe which is well in excess of 10 percent of plant capacity. The 9,000 acfm pilot unit was started up on February 3rd to attempt baseline testing and to compare performance. In analyzing the data from these tests, it was determined that the dust loading to the bags was 3 to 5 times higher than in the pilot unit. This indicated that the ESP portion of the Advanced Hybrid™ was not removing as much particulate as expected. Big Stone personnel felt that the most likely reason for the high dust loading was poor distribution of gas flow due to differences in configuration between the pilot unit and the full-size unit and some gas bypassing the

ESP components and flowing directly to the bags from below. Furthermore, an excessive upward gas velocity component around the bags would inhibit the PM from falling into the hopper when the bags were pulsed.

Several ways to improve performance were considered, including power-off rapping, improvements to the old ESP field and off-line bag cleaning. Power-off rapping did not result in significant improvement, and off-line bag cleaning caused higher pressure differential when a compartment was off-line. During the first two months of 2003, an unusually large amount of soybeans (over 17,000 tons) was burned which caused fouling of the boiler. Since the soybean ash could also have caused bag problems, bag washing was considered.

Early in the third quarter of operation (April 2003), project personnel met to review the status of the project and decided on a list of options for improving performance to be evaluated:

- Filter bag washing to reduce residual drag
- Pulse cleaning system modifications
- Flue gas conditioning
- Reduction of gas volume in-leakage
- Installation of pressure relief valves
- Removal of ID fan outlet dampers
- Use of other bag types

The plant was derated to allow inspection of the first field to determine how much work would be required to bring it to full effectiveness. During the derate, one bag was removed to be washed outside the boiler. Washing seemed to be effective in removing the residual dust cake, and the decision was made to develop a procedure to carry out a mass bag washing with the bags left in place. Shortly after the derate, the boiler experienced an outage unrelated to the Advanced Hybrid™. During the outage, several types of test bags were installed.

By late April 2003, a procedure was developed, and three spray booms were fabricated to allow all three compartments in one chamber to be washed simultaneously. One chamber was washed in late April, and this allowed the plant to gain around 10 MWe. The other chambers were subsequently washed. Also during this period, Gore decided on several types of bags that warranted testing.

During a scheduled outage in June, all 4,833 bags were replaced, and repairs were made to the first field of the ESP. Three types of bags were installed:

- Conductive Gore-Tex Membrane/Conductive Gore-Tex Felt
- Conductive Gore-Tex Membrane/Conductive polyphenylene sulfide (PPS) Felt
- Gore-Tex Membrane/ PPS Felt
- Test bags - PPS bags with PPS scrim

The plant came back on line on June 11, 2003. Differential pressure was controllable. Tests with the first field energized and de-energized were initiated and continued into the next quarter.

During the fourth quarter (July through September 2003), the Advanced Hybrid™ system performed significantly better than in previous quarters, although the system was still not performing as required for commercial acceptability. The excellent performance seen immediately after the outage in June was not maintained. The differential pressure rose from 7 to 8.5 inches of water at the highest flue gas flow rates. The inlet ESP field remained energized to reduce the ash loading to the Advanced Hybrid™ filter bags.

A series of performance tests were conducted to measure performance:

- A/C ratio range testing with the inlet field not energized
- Power off/plate rapper testing (POPR)
- Humidification testing
- Pitot testing as a basis for computational fluid dynamic modeling

The results of these tests led to a decision to focus on the ESP portion of the Advanced Hybrid™ to improve performance.

In the fifth quarter of operation (October through December of 2003), more problems developed. In early October, opacity spikes occurred during periods of pulsing. These spikes were due to bag failures. None of the failed bags were of the type initially installed, but rather were test bags (PPS bags with PPS scrim). The failures were attributed to the fibers being weakened by high temperatures and high energy pulsing. Plant data confirmed that the bags were exposed to temperatures above their rated values.

It was then decided to test additional bag types. Due to the failures, some bag replacement was necessary during a scheduled outage in early December 2003. One chamber was equipped with P-84 bags, one with NOMEX bags, and one with original bags that had been removed and washed. Also during this quarter, preliminary results were obtained for modeling of flue gas dynamics. These results indicated that as much as 15 percent of the flue gas was bypassing the ESP zone. This led to the decision to test baffles to direct the gas into the ESP zone.

In the original installation, one blowpipe would pulse only half the bags in a row (10 bags). This resulted in a stacked arrangement in the clean gas plenum. It was decided to install a single blowpipe to pulse an entire twenty-bag bag row at once, thus simplifying bag replacement and cutting pulsing time in half. There was also evidence that the bags were being over-cleaned, as indicated by increasing bag failures.

During the sixth quarter of operation (January through March 2004), operation of the Advanced Hybrid™ remained stable, and no derates were necessary. However, aggressive cleaning was still required. Modeling indicated that the flow patterns were generally as described earlier, with a significant quantity of gas entering the second and third hybrid fields from below and also from the back in the third field. Modeling also showed unexpectedly high vertical velocities in some areas and a generally non-uniform flow pattern, as shown in Figure 6 and Figure 7 [Madsen, 2004]. As expected (Figure 7), the highest velocity is at the top, inside the bags.

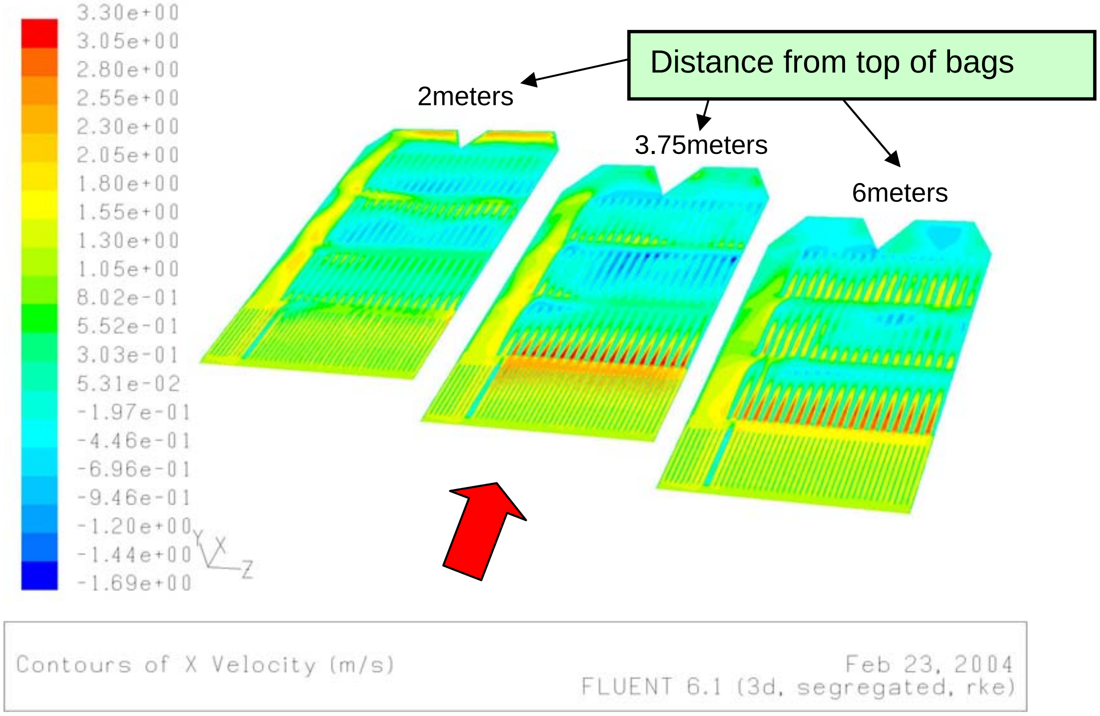


Figure 6. Horizontal Cuts Through Chamber - Horizontal Velocity (front-to-back)

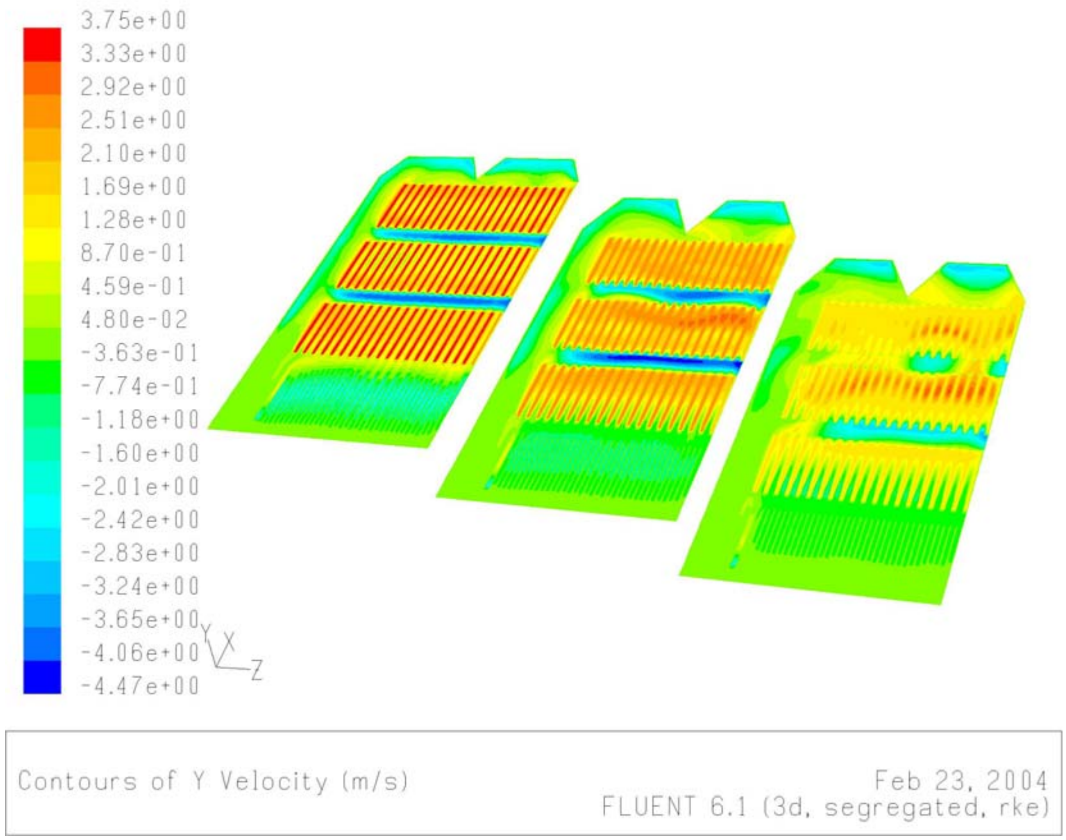


Figure 7. Horizontal Cuts Through Chamber - Vertical Velocity Contours

The P-84 and NOMEX bags were inspected during a February, 2004 derate, and no bag damage was observed. The single blowpipe appeared to clean as efficiently as the dual arrangement, and the baffles performed satisfactorily. It was decided to install baffles in all three compartments of one chamber.

During this period OTPC, EERC, Gore, and ELEX decided that the technology could be competitive at a face velocity of 8 fpm and that long term satisfactory operation could not be maintained at the then current 10.5 fpm. They decided to resize the unit by replacing the existing first field ESP with additional Advanced Hybrid™ components.

During the seventh quarter (April through June 2004), operation of the Advanced Hybrid™ was stable, and there were no significant derates due to the Advanced Hybrid™

system. However, the remaining PPS bags began to fail at an unacceptable rate. The major activities of this quarter were:

- Replacement of 1,928 PPS filter bags with P-84/BHATex filter bags
- Installation of one complete chamber of baffles
- Modification of one compartment of blowpipes to the single pipe design
- Removal of ten filter bags and transfer to an independent laboratory for analysis
- Review of proposed design for installation of Advanced Hybrid™ components in the inlet field
- Review of bag testing data

The new Advanced Hybrid™ field design included the following changes:

- Decreasing the plate-to-plate spacing from 12 in. to 10 in. to allow for more rows of bags. The total number of new bags was 1,974.
- Extending the length and increasing the number of the electrodes and plates. The rigid electrodes and collecting plates were lengthened from 25 feet to 37 feet, creating an ESP collecting zone below the fabric filter components.
- Below the level of the bag row baffles, the perforated collecting plates were replaced with solid plates.
- There were no discharge electrodes in the gas passages below the filter bags.
- The area below the pulse headers was filled from the hot roof to the top of the hoppers with new discharge electrodes and solid collecting plates.
- Electromagnetic rappers were used instead of tumbling hammers for the discharge electrodes.
- New compartments included bag row baffles and the modified (single) blowpipe design.

The results of the bag analyses indicated that the following were acceptable: polytetrafluoroethylene (PTFE), Superflex, Fiberglas, P-84, and NOMEX. All would include a PTFE membrane.

In the eighth quarter (July through September 2004), the operation of the Advanced Hybrid™ system was stable. The plant was not as heavily loaded due to cool summer temperatures. However, there were some derates and uncontrollable pressure drop issues during the warmest period of the summer.

During this quarter, OTPC decided to move ahead with the inlet field modification. A letter of intent and a purchase order were issued to Southern Environmental, Inc. (SEI) from OTPC to install additional Advanced Hybrid™ components. This was done to lower the face velocity of the existing system to levels that had been demonstrated as successful. The then current system operated at up to 12 fpm. The planned installation of four more compartments would reduce this to approximately 9 fpm. Also during this period one full chamber was equipped with baffles to minimize the amount of flue gas that bypasses the ESP portion of the Advanced Hybrid™. The chamber was also converted to the one blowpipe per bag row arrangement.

A bag analysis, done by an independent laboratory, was used to project bag life for several types of bags. The NOMEX bags had undergone significant deterioration and were deemed unsuitable for service in the Big Stone Advanced Hybrid™. The Fiberglas bags were projected to last four to five years, the P-84 bags had a projected life of five to six years, and the PTFE bags had a projected life of 8 to 9 years. As might be expected, the plant was already experiencing a high failure rate with the NOMEX bags. Unexpectedly, the P-84 bags were also failing at an unacceptable rate.

During the ninth and final quarter (October through December 2004), operation of the Advanced Hybrid™ system was fairly stable. The most significant accomplishments were:

- Replacement of one compartment of NOMEX bags with Fiberglas bags (with membrane)
- Replacement of half a compartment of P-84 Bags with Superflex™ bags
- Independent analysis of the failed P-84 bags

An independent analysis of the failed P-84 bags indicated that the primary factor for failure was acid attack on the bags from moisture in the pulse air system.

During the project extension (January through December 2005), the major focus was on the design, fabrication, construction and operation of additional Advanced Hybrid™ components in the existing inlet field. The main goals of this modification were to:

- Lower the A/C ratio to a level where acceptable performance had been demonstrated
- Improve ESP design and performance
- Improve pulse cleaning design
- Optimize bag placement and space consideration
- Return the Big Stone Power Plant to full load and stable operation

The Advanced Hybrid™ components were installed in the first field during a planned outage ending in June 2005. After the outage, the Big Stone Plant became a load-following unit due to fluctuations of the energy market system.

When the Advanced Hybrid™ was first installed, all twelve compartments were equipped with Gore-Tex bags and membranes. After the first field was equipped with Advanced Hybrid™ components the bag types were:

- Fiberglass/PTFE Membrane
- PTFE/PTFE Membrane
- Superflex/PTFE Membrane

The four fundamental performance parameters of the Advanced Hybrid™ system are opacity, A/C ratio, tubesheet pressure drop, and compressed air flow. Opacity during the project extension remained a problem after installation of the inlet fields. Initially the opacity was in the 5 percent range. However, in four to five months, the opacity rose to 10-12 percent due to bag failures. The failed bags were replaced in December 2005. The primary bag type that had failed was the Fiberglas™ bags.

The A/C ratio after the installation of the Advanced Hybrid™ components in the first ESP field dropped to 7-8 fpm compared the original design value of 10-12 fpm. It should be noted that prior to the first field modification, the operation of the Advanced Hybrid™ was acceptable at an A/C ratio of 8 fpm.

The tubesheet pressure drop for the system did not decrease, as expected. Due to the switch to the load-following operation, there is greater variation in the graphical data presented in the appendix for both the tubesheet and flange-to-flange pressure drops.

The compressed air usage shows an increase from 2,000 acfm to approximately 2,400 – 2,750 acfm. This is consistent with the installation of additional bags and pulse valves associated with the inlet field upgrade. The increase above 3,000 acfm at the end of the graph in the appendix was due to a modification in piping at the plant and not related to an increased demand to the Advanced Hybrid™ system.

It was also reported that the ESP components in the first field became misaligned and that the second field did not operate properly, causing the full particulate loading to reach the bags. This essentially reduced the system to a PJFF operating at an A/C ratio of 8 fpm compared to a typical value in the range of 3.5 to 4 fpm.

In late 2005, OTPC decided to replace the Advanced Hybrid™ technology with a proven particulate control technology.

IV. DISCUSSION OF RESULTS

The Advanced Hybrid™ was developed to provide a technology that would provide highly efficient particulate removal that is at least one order of magnitude better than existing technologies – 99.99 percent or better and would be applicable to new applications or could be retrofitted into most existing ESP casings. It was intended to be cost competitive with less capable existing technologies with respect to both capital and operating costs. For reasons discussed below, this project did not establish the commercial readiness of the Advanced Hybrid™.

After correcting some startup problems not related to the technology (e.g., sticking valves), the Advanced Hybrid™ operated at acceptable pressure drop and exhibited outstanding particulate removal capability. The graphs showing opacity readings in the appendix indicate that there were a number of periods, often after shutdown/bag replacement or cleaning, when opacity readings were quite low. Unfortunately, these periods were always followed by increasing pressure drop problems and higher opacities, usually related to failing bags. OTPC, in its final report, attributes the bulk of the problems to high dust loading in the flue gas to the bags. High dust loading results in high pressure drop which leads to high cleaning rates which, in turn, exacerbates any problems that may exist with bag materials. High dust loading is believed to be due to several interrelated factors.

The relatively high entrance velocity makes it more difficult to collect the dust, and the unusual velocity profile makes it harder to get the dust into the hoppers. Modeling results indicate that there are some vertical velocities that approach or exceed particle settling velocities. The high energy pulse used to clean the bags tends to ‘blast’ the dust cake, destroying any clumps that would otherwise easily settle into the hoppers. Additionally, some portion of the gas completely bypassed the ESP zone and approached the bags from below with no particulate removal. All of the above problems were further exacerbated by the fact that this first demonstration unit was installed on a cyclone boiler burning western coal, a difficult application for any ESP.

After modification, problems with collecting plate alignment made it difficult to energize the discharge grid to its full potential, thus reducing the effectiveness of the ESP for an ash that is difficult to collect in the best of circumstances. The Final Report [Hrdlicka and Swanson, 2006] states, "…the reasons for this lack of performance improvement are due to the inability of the AHPC to precollect any flyash on the perforated collecting plates prior to the fabric filters. Main reasons for the lack of ESP collection are (1) high gas velocities, (2) high ash resistivity, and (3) inability to maintain design clearances between the plates and electrodes. Without the benefit of ESP precollection on the perforated collecting plates, the AHPC operates just as a conventional PJFF does. In essence, we replaced a working inlet field ESP with a PJFF compartment operating at an A/C of 8:1."

A number of different bag types were tested, and some would undoubtedly have given satisfactory service if the issue with pressure drop could have been solved. When the bags were essentially all intact, opacity was low. The November 2002 stack tests demonstrate that the Advanced Hybrid™ has the potential to clean stack gas better than either conventional baghouses or ESPs.

Table 7 shows the derate history of the project. As discussed above, derates were a major problem and contributed significantly to the failure to demonstrate commercial viability. In short, the technology showed great promise for its ability to remove particulate matter in all size ranges. However, this demonstration showed that there are significant issues with the technology that, unless satisfactorily resolved, make it unlikely for the technology to have any success in the market place.

Table 7. MWh Derate Comparison

	ESP Opacity Derates	ESP Repair Derates		Advanced Hybrid™ Opacity Derates	Advanced Hybrid™ Repair & Operational Derates
1999	7,786	16,004			
2000	6,859	16,676			
Average MWH/Year	**7,323**	**16,340**			
2003				0	99,324
2004				706	29,108
Average MWH/Year				**353**	**64,216**
Difference by Category				**-6,970**	**+47,876**
Total Derate Difference					**+40,906**

V. MARKET ANALYSIS

A. Potential Market

If the operating and economic potential of this technology can be successfully demonstrated, the market for this particulate control device could be substantial. Based on an internal NETL study, the projected sales for retrofit and new installations are estimated to be in excess of 35,000 and 11,000 MW, respectively. This market analysis assumes that resolution of the issues discussed above would result in achieving the goals initially set forth. The primary market is viewed as retrofitting ESPs that have sufficiently large casings (SCA of about 350 ft^2/kacfm) and are approaching the point where rebuilding or replacement is necessary. New coal-fired power plants are also considered a viable market. A Parson's report [Parsons E&C, 2005] indicates that there are nearly 300 units (total capacity of approximately 68 GW) in the United States with an SCA greater than 400. There are another 230 boilers (combined capacity of approximately 86 GW) with ESPs in the 300 to 400 range. While a precise projection on future construction is difficult, the current trend is toward substantial installation of coal-fired capacity, both domestically and overseas. According to the EIA's Annual Energy Outlook 2006:

- New coal additions through 2015: 10 GW
- New coal additions through 2025: 80.7 GW
- New coal additions through 2030: 148.1 GW

The above numbers are relative to 2004 capacity.

B. Capital Costs

Little data are available on the capital cost of AHPC other than that obtained from the OTPC project. Parsons [Parsons E&C, 2005] estimates the cost of the original installation at approximately $30/kW and the final cost of the installation at approximately $42/kW.

As stated in Reference 4, “It should also be pointed out that the costs for the AHPC are based on the installation at Otter Tail’s Big Stone Plant. This unit (and the associated costs) is a first-of-a-kind installation. First-of-a-kind installations are typically more expensive than the ‘nth’ installation.” In addition, the installation at Big Stone was done in two phases, and both phases required that the installation be done during shutdowns for other purposes, which required that all work be done quickly. Both of these factors tend to increase costs. Based on the above discussion for an nth installation and taking into account lessons learned, capital cost is estimated to be about $30/kW.

C. Operating and Maintenance Costs

Table 8 [Hrdlicka and Swanson, 2006] provides a comparison of electrical energy usage between the Advance Hybrid™ and the original ESP. Table 9 presents a cost comparison, while Table 10 summarizes costs. These are actual incurred costs, resulting from the problems discussed above. Based on these figures, the Advanced Hybrid™ system is significantly more expensive to maintain than the previous ESP system. However, it should be noted that the high costs for the Advanced Hybrid™ are due primarily to high bag replacement costs, power consumption, and derates due to high pressure drop. As stated earlier, it is believed that these problems all relate to the high dust loading to the bags which resulted in high power requirements, short bag life, and derates. If these factors are removed, which seems possible with further development, operating and maintenance costs should be reduced. As stated by OTPC personnel, “Other than the ongoing bag concerns, the maintenance for operation is at acceptable levels.”

Table 8. Electrical Energy Comparison

		ESP Only		Advanced Hybrid™
Precipitator 1A	KW	188.8		110.1
Precipitator 1B	KW	190.4		93.4
Precipitator 2A	KW	172.3		130.4
Precipitator 2B	KW	133.0		98.3
Total ESP Usage	**KW**	**684.5**		**432.2**
ID Fan A	KW	1,552.0		1,888.5
ID Fan B	KW	1,567.6		1,835.7
ID Fan C	KW	1,541.7		1,835.0
ID Fan D	KW	1,573.9		1,851.1
Total ID Fan Power	**KW**	**6,235.2**		**7,410.4**
Air Compressor D	KW	105.5		173.6
Air Compressor E	KW	87.2		181.5
Air Compressor F	KW	127.9		174.9
Total	**KW**	**320.6**		**529.9**
Total Electrical Energy	**KW**	**7,240.3**		**8,372.5**
Difference	KW			**+ 1,132.2**

Table 9. Cost Comparison

		ESP Only		Advanced Hybrid™
Labor & Materials	$/month	$5,741		$35,670
Humidification Chemical	$/month	$7,022		NA
Bag Replacement Cost	$/month	NA		$174,028
Average	**$/Month**	**$12,762**		**$209,698**
Sum of Monthly Average	**$/Year**	**$153,144**		**$2,516,376**
Difference	**$/Year**			**+ $2,363,232**

Notes on the table above:
The Advanced Hybrid™ costs are derived from the spreadsheet AHPC Work Plan. The labor and materials are are taken from the operators and other union personnel time. The material cost is derived from the OTP costs with the bags removed.

Table 10. Comparison Summary

		ESP Only		**Advanced Hybrid™**
Collection Efficiency	**Gr/acf**	**99.29%**		**99.996%**
Cost Difference	**$/Year**			**+ $2,363,232**
Electrical Energy Usage Difference	**KW**			**+ 1,132.2**
Opacity Derate Difference	**MWH/year**			**-6,970**
Operational & Repair Derate Difference	**MWH/year**			**+47,876**

VI. CONCLUSIONS

The Advanced Hybrid™ demonstrated extremely high particulate removal for all size ranges of particulate as long as the filter bags remained intact. Problems arose when the tubesheet pressure drop could not be stabilized within the design limits of 8 inches of water column and the solution was to replace the original filter bags with lower flow resistance but less durable materials. If the effectiveness of the ESP portion of the device, the flow dynamics, and the synergy of the membrane filter bags with the ESP can be perfected and optimized, then this technology may have a huge market potential. The technology needs a major original equipment manufacturer (OEM) to work through the remaining issues with EERC to overcome the problems experienced with this full-scale demonstration. This demonstration was conducted on a cyclone boiler that burns western coal and several alternate fuels which added to the normal challenges for a first-of-a-kind installation. The pilot plant tests that formed the basis for the decision to install a full-size unit did not completely represent the full-size configuration. Given these factors, the inability to meet the project objectives does not necessarily indicate that the Advanced Hybrid™ concept is fatally flawed. If the problems encountered at Big Stone can be resolved, as seems probable, this technology can be a viable option if more stringent emission standards are placed on primary respirable particulate matter.

REFERENCES

1. Hrdlicka, Tom and William Swanson, "Demonstration of a Full-Scale Retrofit of the Advanced Hybrid Particulate Collector Technology – Public Design Report", Otter Tail Power Company, October, 2002

2. Hrdlicka, Tom and William Swanson, "Demonstration of a Full-Scale Retrofit of the Advanced Hybrid Particulate Collector Technology – Final Report", Otter Tail Power Company, 2006

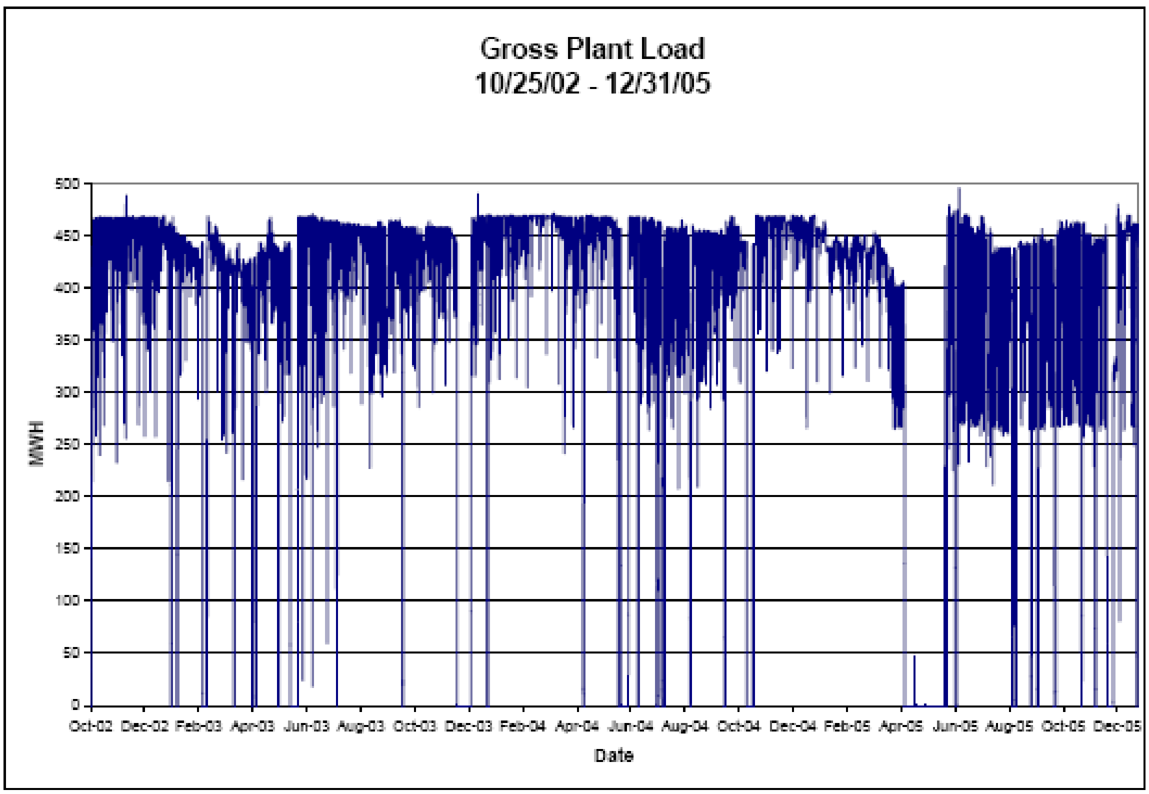
3. Madsen, Jens I., "Big Stone AHPC Simulations - A Brief Summary", Presentation to NETL, Morgantown, WV, May 28, 2004

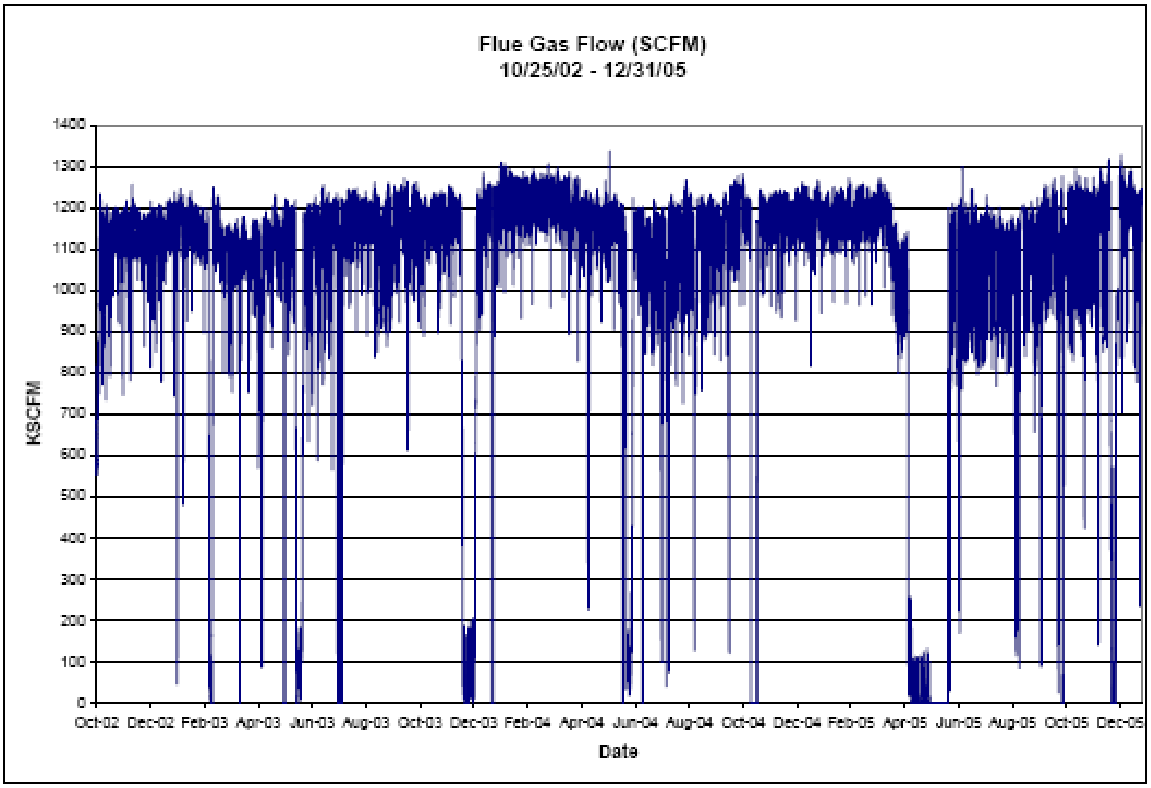
4. Parsons E&C, "Demonstration of a Full-Scale Retrofit of the Advanced Hybrid Particulate Collector Technology, ESP Retrofit Options Evaluation - Final Report", June 23, 2005

APPENDIX

Operating Data

Due to the switch to load-following operation after June of 2005, there is greater variation in the graphical data presented in the appendix for both the tubesheet and flange-to-flange pressure drops.

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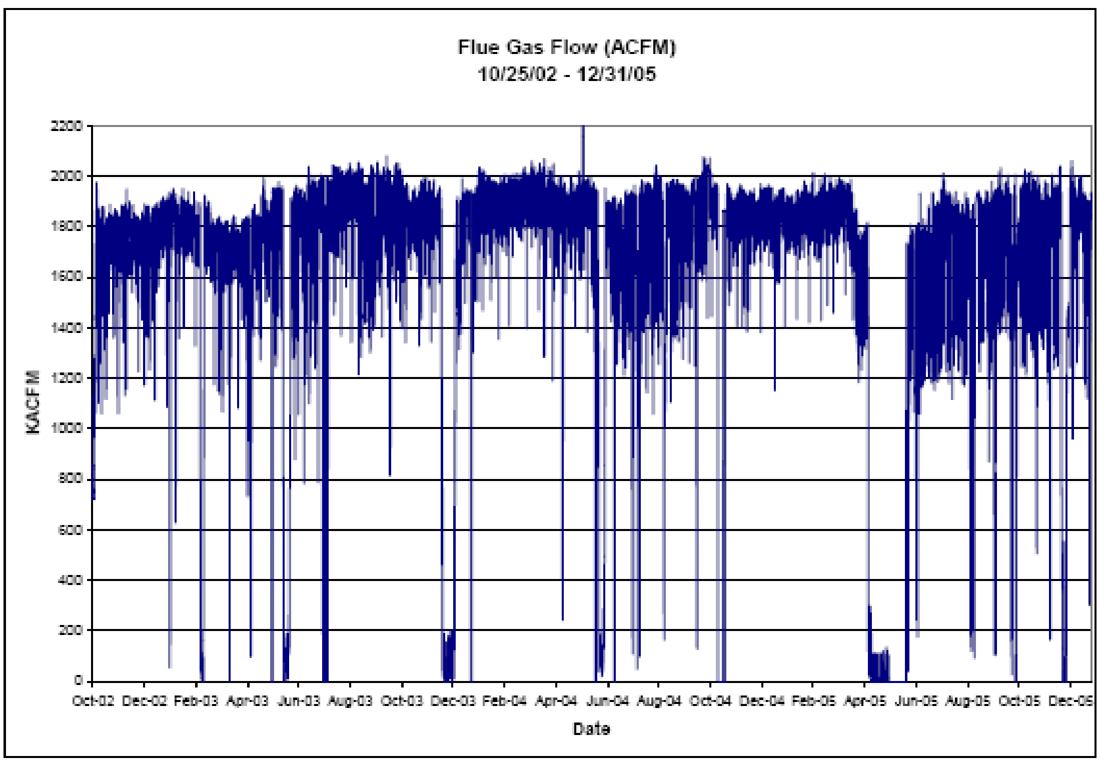
KSCFM
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
Oct-02 Dec-02 Feb-03 Apr-03 Jun-03 Aug-03 Oct-03 Dec-03 Feb-04 Apr-04 Jun-04 Aug-04 Oct-04 Dec-04 Feb-05 Apr-05 Jun-05 Aug-05 Oct-05 Dec-05
Date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KACFM
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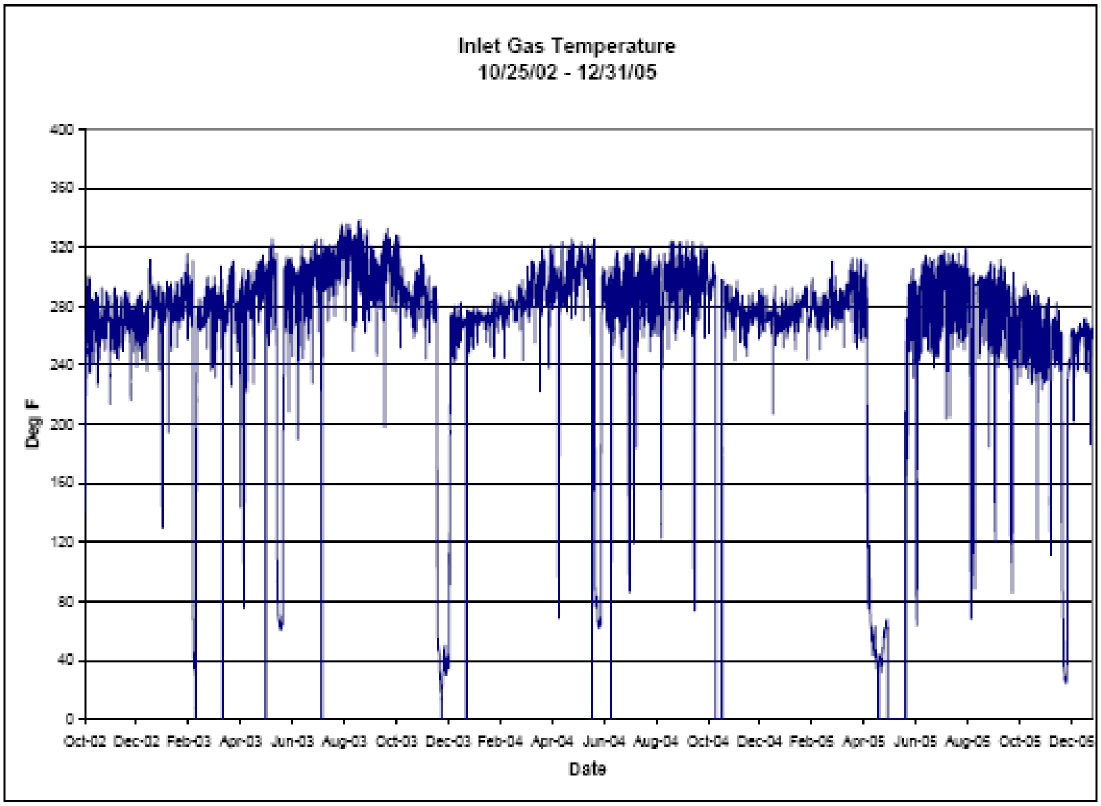
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Oct-02 Dec-02 Feb-03 Apr-03 Jun-03 Aug-03 Oct-03 Dec-03 Feb-04 Apr-04 Jun-04 Aug-04 Oct-04 Dec-04 Feb-05 Apr-05 Jun-05 Aug-05 Oct-05 Dec-05
Date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10/25/02 - 12/31/05
Deg F
Date
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80
120
160
200
240
280
320
360
400
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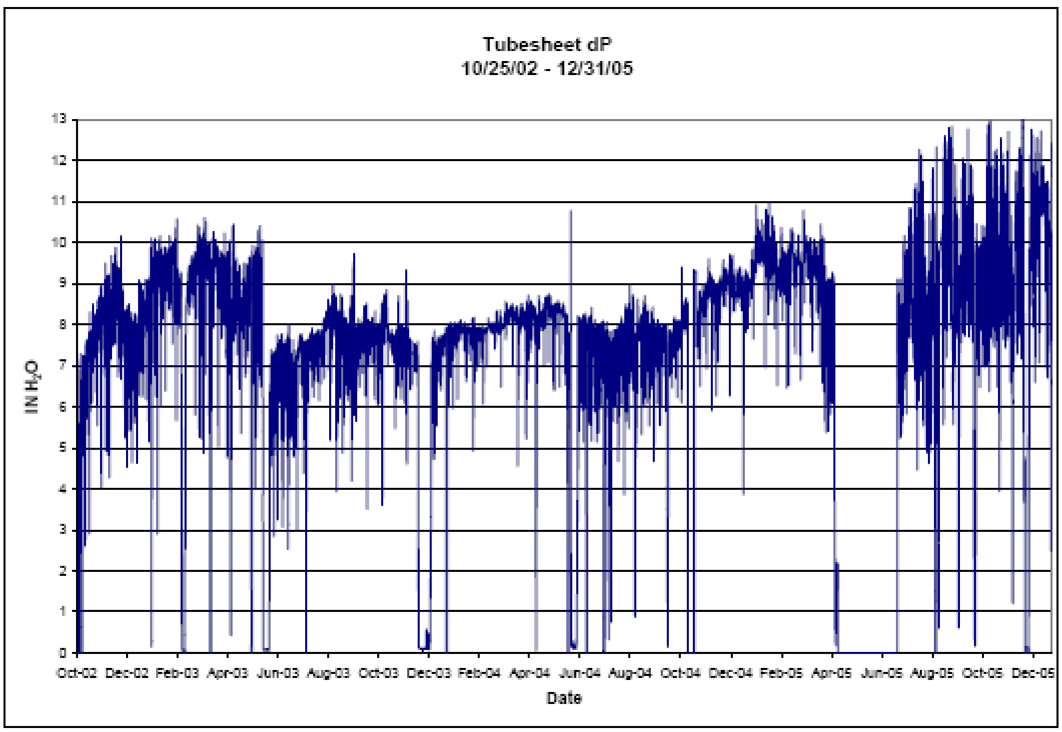
Tubesheet dP
10/25/02 - 12/31/05
IN H_2O
Date
0
1
2
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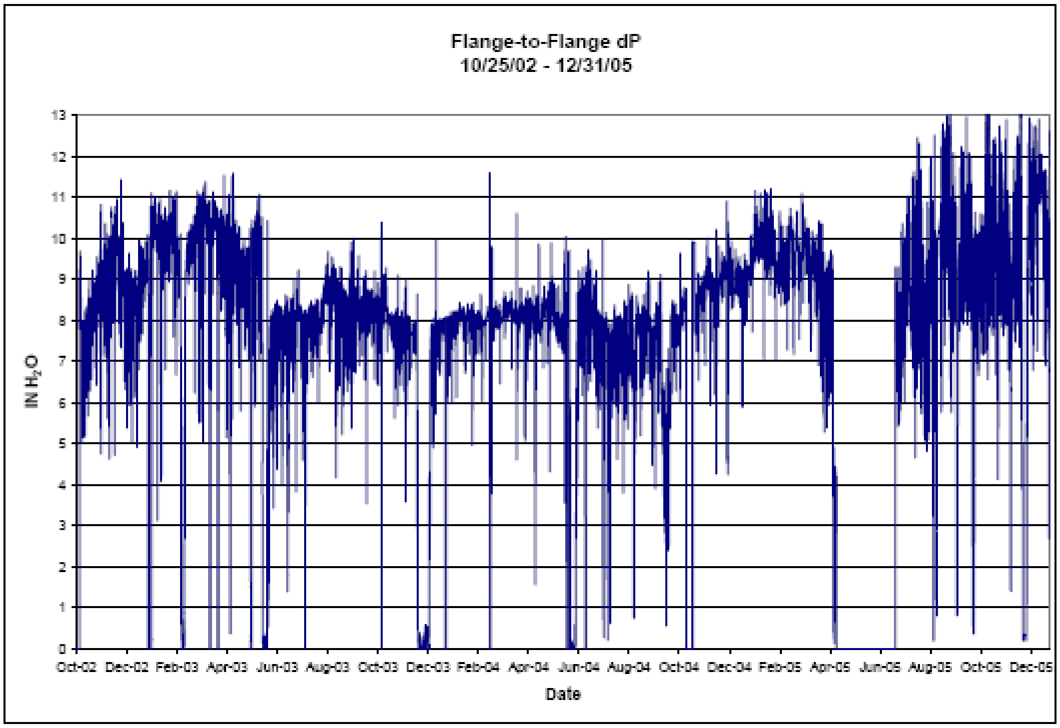
6
7
8
9
10
11
12
13
Oct-02 Dec-02 Feb-03 Apr-03 Jun-03 Aug-03 Oct-03 Dec-03 Feb-04 Apr-04 Jun-04 Aug-04 Oct-04 Dec-04 Feb-05 Apr-05 Jun-05 Aug-05 Oct-05 Dec-05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4
3
2
1
0
Oct-02 Dec-02 Feb-03 Apr-03 Jun-03 Aug-03 Oct-03 Dec-03 Feb-04 Apr-04 Jun-04 Aug-04 Oct-04 Dec-04 Feb-05 Apr-05 Jun-05 Aug-05 Oct-05 Dec-05
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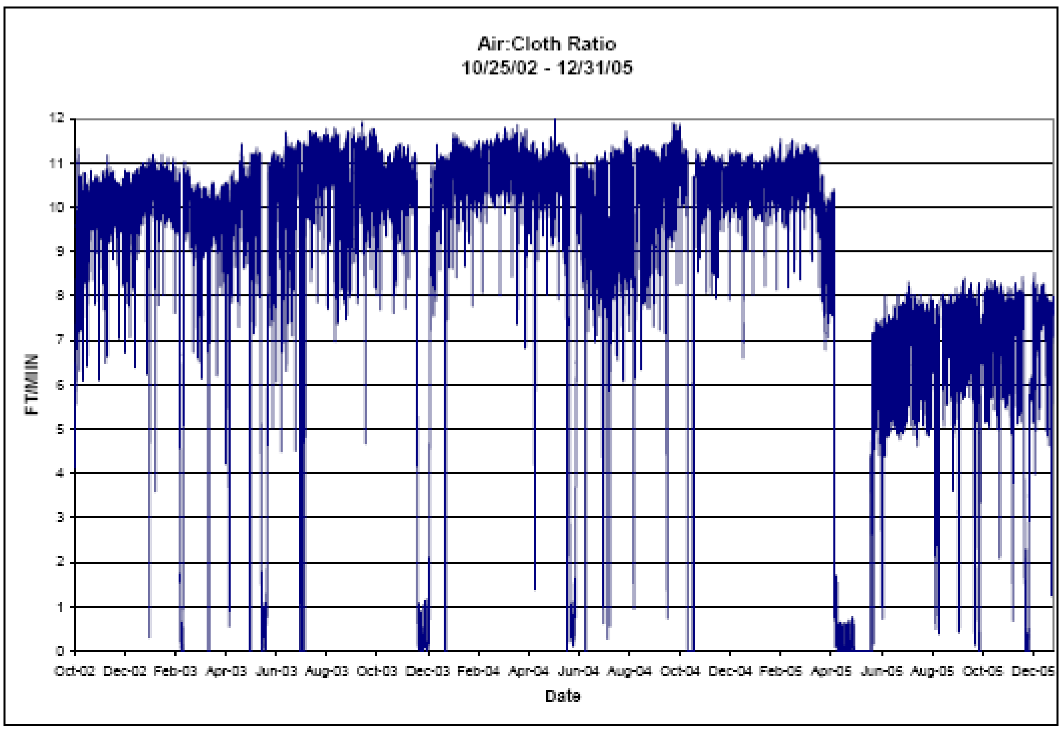
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Oct-02 Dec-02 Feb-03 Apr-03 Jun-03 Aug-03 Oct-03 Dec-03 Feb-04 Apr-04 Jun-04 Aug-04 Oct-04 Dec-04 Feb-05 Apr-05 Jun-05 Aug-05 Oct-05 Dec-05
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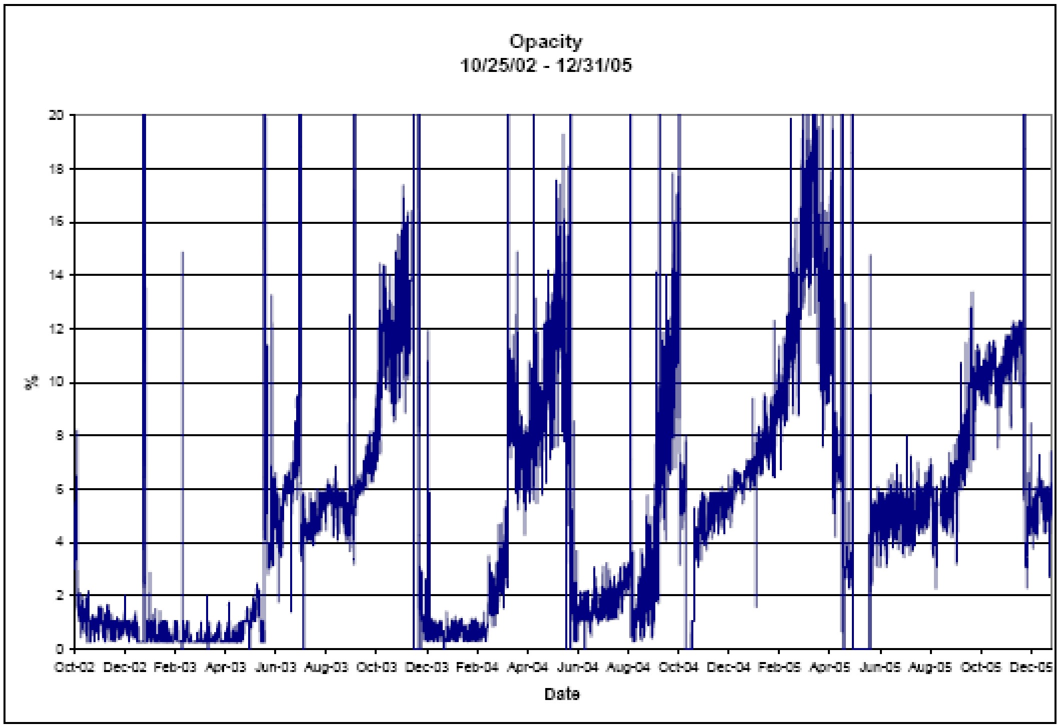
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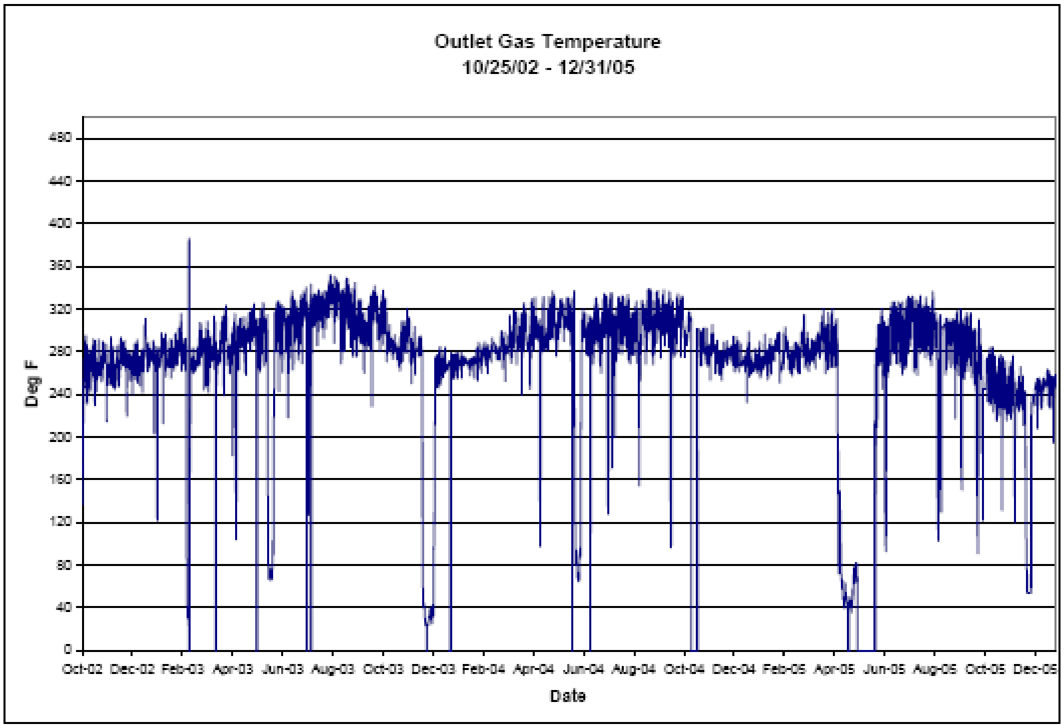
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10/25/02 - 12/31/05
Deg F
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200
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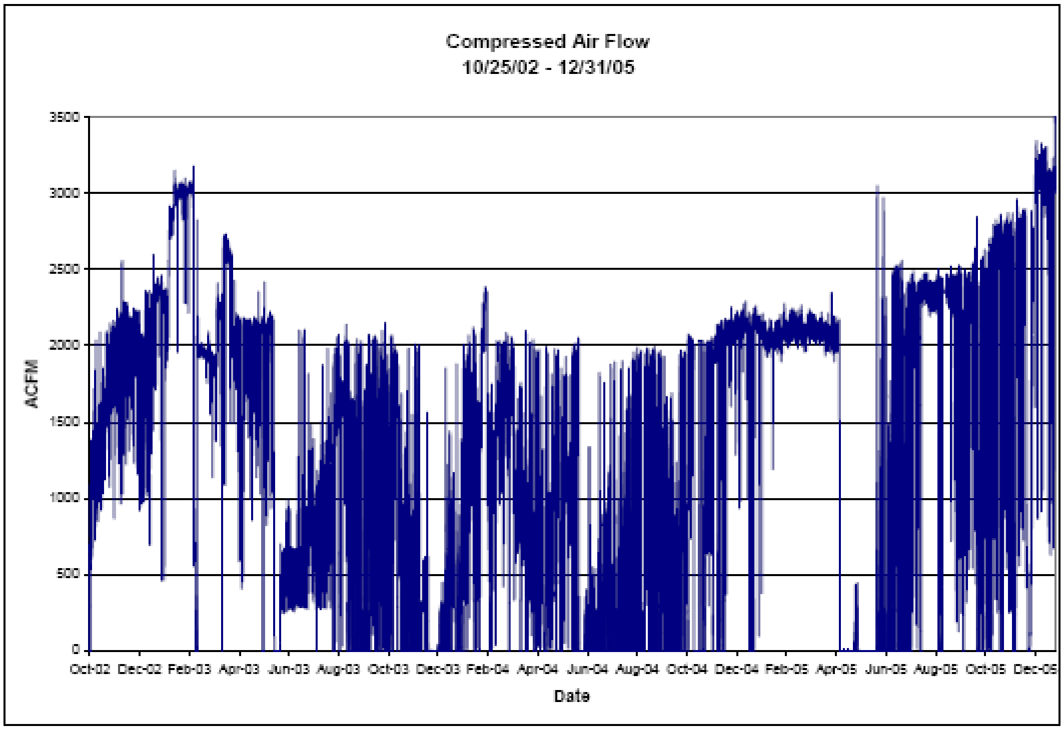
Oct-02 Dec-02 Feb-03 Apr-03 Jun-03 Aug-03 Oct-03 Dec-03 Feb-04 Apr-04 Jun-04 Aug-04 Oct-04 Dec-04 Feb-05 Apr-05 Jun-05 Aug-05 Oct-05 Dec-05
Date


Compressed Air Flow
10/25/02 - 12/31/05
ACFM
Date
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1500
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2500
3000
3500
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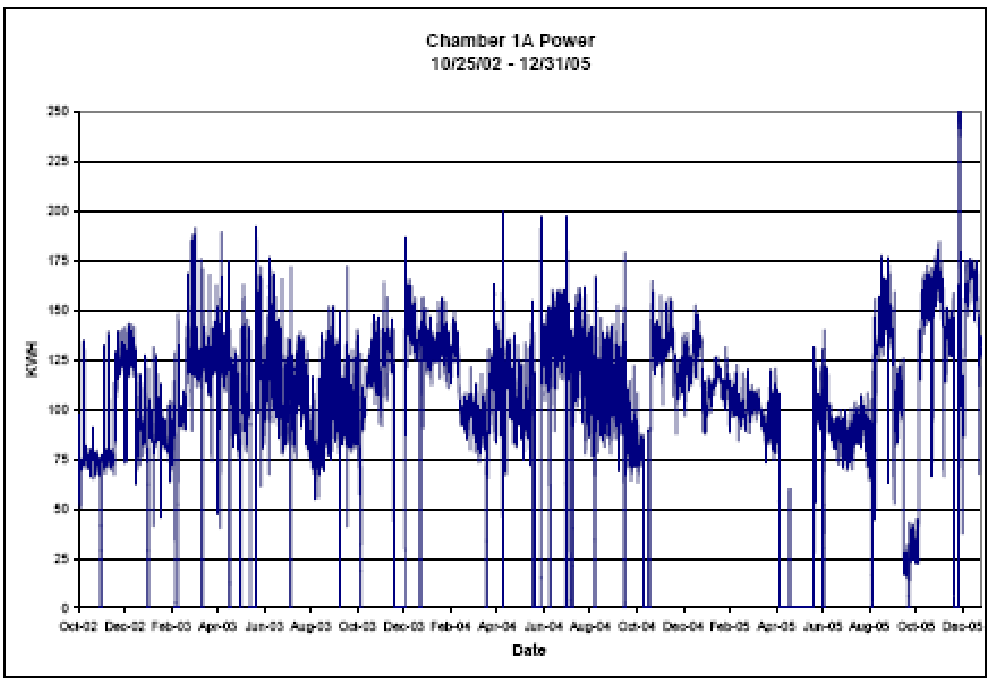
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10/25/02 - 12/31/05
KWH
Date
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25
50
75
100
125
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175
200
225
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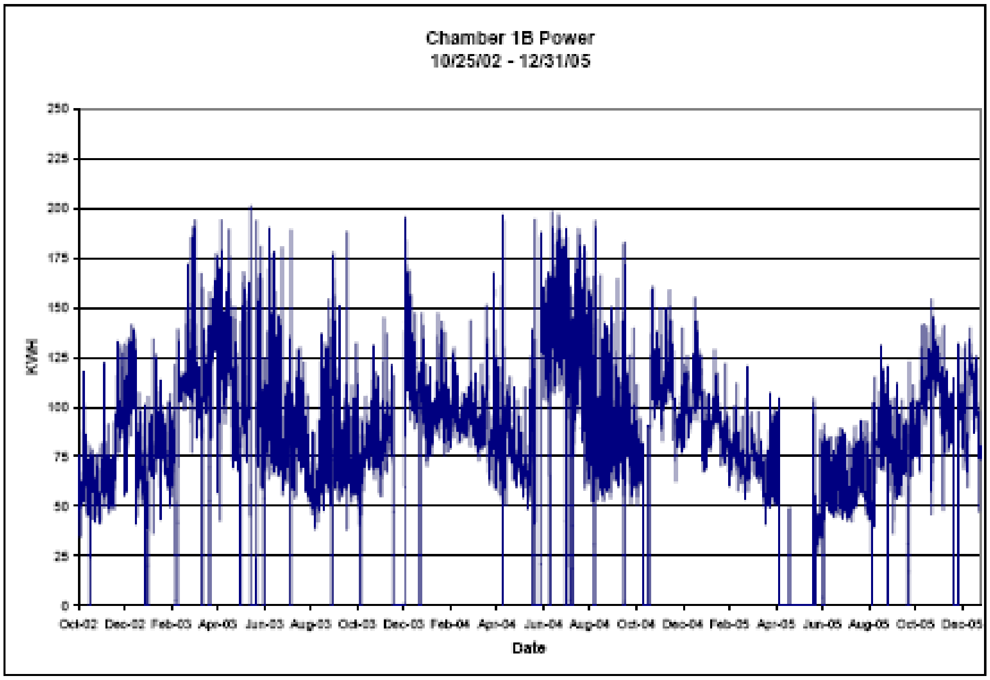
Chamber 1B Power
10/25/02 - 12/31/05
KWH
250
225
200
175
150
125
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75
50
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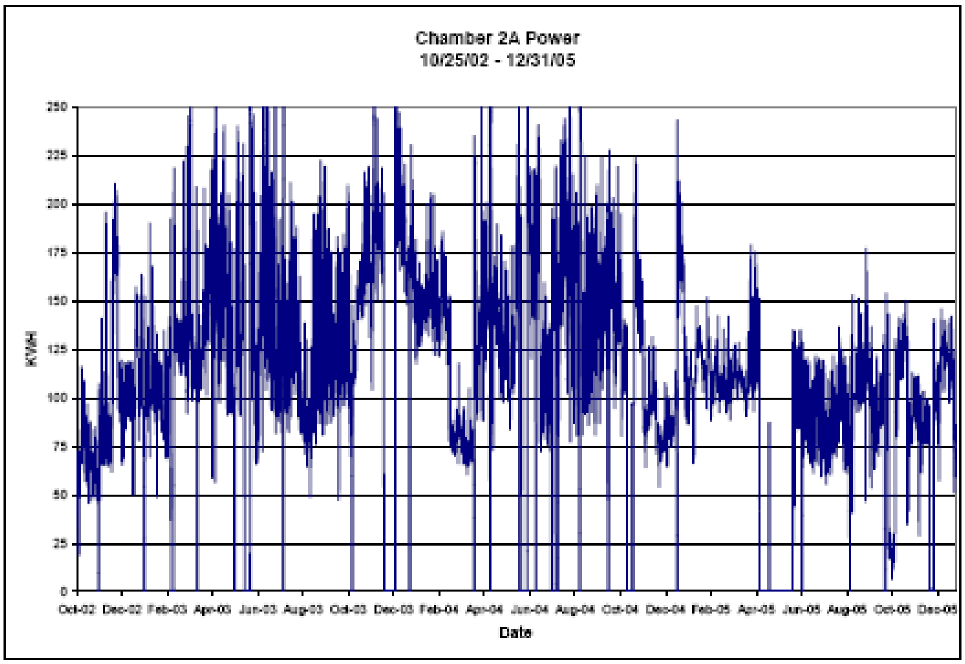
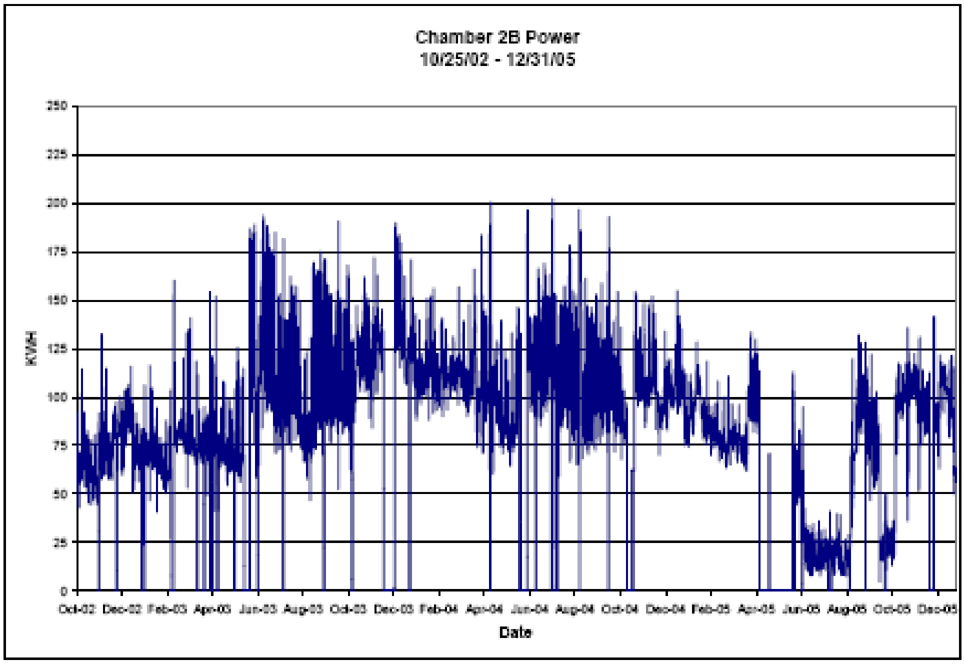
Oct-02 Dec-02 Feb-03 Apr-03 Jun-03 Aug-03 Oct-03 Dec-03 Feb-04 Apr-04 Jun-04 Aug-04 Oct-04 Dec-04 Feb-05 Apr-05 Jun-05 Aug-05 Oct-05 Dec-05
Date


Chamber 2A Power
10/25/02 - 12/31/05
KWH
250
225
200
175
150
125
100
75
50
25
0
Oct-02 Dec-02 Feb-03 Apr-03 Jun-03 Aug-03 Oct-03 Dec-03 Feb-04 Apr-04 Jun-04 Aug-04 Oct-04 Dec-04 Feb-05 Apr-05 Jun-05 Aug-05 Oct-05 Dec-05
Date


Chamber 2B Power
10/25/02 - 12/31/05
KWH
250
225
200
175
150
125
100
75
50
25
0
Oct-02 Dec-02 Feb-03 Apr-03 Jun-03 Aug-03 Oct-03 Dec-03 Feb-04 Apr-04 Jun-04 Aug-04 Oct-04 Dec-04 Feb-05 Apr-05 Jun-05 Aug-05 Oct-05 Dec-05
Date