SUBTASK 2.13 – *ADVANCED HYBRID*™ PARTICULATE COLLECTOR –FUNDAMENTAL PERFORMANCE

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SUBTASK 2.13 – *ADVANCED HYBRID*™ PARTICULATE COLLECTOR – FUNDAMENTAL PERFORMANCE

ABSTRACT

Under the Power Plant Improvement Initiative Program funded by the U.S. Department of Energy, a full-scale *Advanced Hybrid*™ filter was installed at the Big Stone Plant, with start-up in October 2002. The *Advanced Hybrid*™ filter was retrofitted into Fields 2–4 of the old Big Stone electrostatic precipitator (ESP). While many aspects of the operation were satisfactory, pressure drop was higher than expected. To achieve acceptable pressure drop and successfully demonstrate the *Advanced Hybrid*™ filter technology, the first fields of the ESP were also converted into an *Advanced Hybrid*™ filter in 2005. However, since start-up in June 2005, the first fields have been inoperable for multiple reasons.

The fundamental cause of the dysfunctional performance of the first fields was attributed to spacing and alignment problems, which led to excessive sparking and shutdown of the high-voltage power. In spite of attempts to correct the problems, satisfactory performance of the first fields was never achieved. Because of the uncertainties of how to achieve acceptable performance with a new technology, the Big Stone Plant made the decision to convert the entire *Advanced Hybrid*™ filter housing into a pulse-jet fabric filter.

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SUBTASK 2.13 – *ADVANCED HYBRID*™ PARTICULATE COLLECTOR – FUNDAMENTAL PERFORMANCE

EXECUTIVE SUMMARY

Under the Power Plant Improvement Initiative Program funded by the U.S. Department of Energy, a full-scale *Advanced Hybrid*™ filter was installed at the Big Stone Plant, located near Milbank, South Dakota, with start-up in October 2002. The *Advanced Hybrid*™ filter was retrofitted into Fields 2–4 of the old Big Stone electrostatic precipitator (ESP). While many aspects of the operation were satisfactory, pressure drop was higher than expected. To achieve acceptable pressure drop and successfully demonstrate the *Advanced Hybrid*™ filter technology, the first fields of the ESP were also converted into an *Advanced Hybrid*™ filter in 2005. However, since start-up in June 2005, the first fields have been inoperable for multiple reasons.

A purpose of this subtask was to evaluate the fundamental reasons why the power level input to the first fields has been near zero, which makes the electrostatic portion of the first fields useless. A further purpose was to make recommendations of how to achieve proper operation of the first fields as well as satisfactory performance of the entire *Advanced Hybrid*™ filter.

SUBTASK 2.13 – *ADVANCED HYBRID*™ PARTICULATE COLLECTOR – FUNDAMENTAL PERFORMANCE

INTRODUCTION

The most common particulate control approach employed on coal-fired boilers in the United States is the electrostatic precipitator (ESP). Of the approximately 1100 coal-fired utility boilers in the United States, about 90% are equipped with dry ESPs. Many of the older ESPs were originally designed to collect only 0.1 lb/million Btu of total mass particulate matter. The ESPs constructed since 1977 are typically under the somewhat stricter NSPS (New Source Performance Standards) emission limit of 0.03 lb/million Btu and 20% opacity, but since these ESPs are now aging, many will require upgrades to remain in compliance. Furthermore, since the ambient air quality standard is now based on fine particles (PM_{2.5}), there is interest in controlling PM_{2.5} emissions rather than total mass emissions. Since ESP collection efficiency is much lower for finer particles, existing ESP technology may not be adequate to control PM_{2.5} emissions to the level required. A recent example where much stricter emissions were required for an existing plant is the Craig Station in Colorado, which was required as part of a settlement of a Sierra Club lawsuit to replace the plant's ESPs with baghouses (1) to meet a new emission limit of 0.015 lb/million Btu and 5% opacity. Because of the requirement to completely replace the old ESPs and the required additional fan capacity for the higher pressure drop with the baghouses, the project was very costly compared to a simple upgrade of an existing ESP.

The *Advanced Hybrid*™ filter would be a candidate for applications such as the Craig Station example because it is a superior technology that can achieve much better fine-particle collection efficiency at a lower cost than current approaches. However, for the *Advanced Hybrid*™ filter to be replicated at other plants, it must demonstrate satisfactory long-term performance.

The *Advanced Hybrid*™ filter combines the best features of ESPs and baghouses in a unique approach to develop a compact but highly efficient system. Filtration and electrostatics are employed in the same housing, providing major synergism between the two collection methods, both in the particulate collection step and in the transfer of dust to the hopper. The *Advanced Hybrid*™ filter provides ultrahigh collection efficiency, overcoming the problem of excessive fine-particle emissions with conventional ESPs and solves the problem of reentrainment and recollection of dust in conventional baghouses.

The electrostatic and filtration zones are oriented to maximize fine-particle collection and minimize pressure drop. Ultrahigh fine-particle collection is achieved by removing over 90% of the dust before it reaches the fabric and using a membrane fabric to collect the particles that reach the filtration surface. The goal is to employ only enough ESP plate area to precollect approximately 90% of the dust. The challenge is to operate at high air-to-cloth (A/C) ratios (8–14 ft/min) for economic benefits while achieving ultrahigh collection efficiency and controlling pressure drop. The combination of membrane filter media, small ESP, high A/C ratio, and unique geometry meets this challenge. Details of the development of the *Advanced Hybrid*™ filter have been previously reported (2–18).

OBJECTIVES

The goals for the *Advanced Hybrid*™ filter are >99.99% particulate collection efficiency for particle sizes ranging from 0.01 to 50 µm, applicable for use with all U.S. coals, and cost savings compared to existing technologies.

The specific objectives for this subtask are:

- Evaluate the first fields of the *Advanced Hybrid*™ filter at Big Stone to determine the fundamental causes for the dysfunctional performance
- Make specific recommendations that, when implemented, could lead to fully functional performance of the first fields of the Big Stone *Advanced Hybrid*™ filter
- Achieve overall satisfactory performance with the *Advanced Hybrid*™ filter at the Big Stone plant

SCOPE OF WORK AND EXPERIMENTAL

Activity 1 – Field Inspection and Performance Evaluation of the *Advanced Hybrid*™ Filter at Big Stone Plant

Wallis Harrison of Particulate Control Technologies, Inc., was hired as an independent consultant for Activity 1. The consultant provided an independent evaluation of the performance history of the *Advanced Hybrid*™ filter at Big Stone, located near Milbank, South Dakota, from the perspective of someone who was not previously associated with any of the development steps. The consultant reviewed the operational data from the pilot-scale *Advanced Hybrid*™ filter development work, the full-scale operational results from October 2002 – June 2005, and the operational data since June 2005, after the first fields were retrofit into the *Advanced Hybrid*™ filter configuration. The consultant met with plant personnel, completed an on-site inspection of the unit when it was operating, and also completed an internal inspection.

Activity 2 – Status and Recommendations for Performance Improvement

One of the main components of this subtask is the independent consultant report, which is attached as an Appendix. The report provides the fundamental reasons why the first field has been inoperable along with recommendations of how to improve the performance of the first fields. The coals being burned at Big Stone Plant are from the Powder River Basin, which are known to produce high-resistivity ash that is challenging for conventional ESPs. An additional challenge is the very fine particle size of the ash produced by the cyclone-fired boiler at Big Stone. Cyclone-fired boilers are known to produce a much finer fly ash particle-size distribution than pulverized-coal fired boilers. Considering these challenges, the consultant also recommended options for achieving the best overall performance with the entire *Advanced Hybrid*™ filter at Big Stone. Energy & Environmental Research Center (EERC) personnel

reviewed the consultant findings and, along with other available data, also assessed the performance of the *Advanced Hybrid™* filter at Big Stone.

RESULTS AND DISCUSSION

Subtask 2.13 was implemented approximately 1 year after the conversion of first fields at the Big Stone plant in June 2005 to the *Advanced Hybrid™* filter configuration. The following chronology helps put into perspective where Subtask 2.13 fits in the history of the *Advanced Hybrid™* filter.

History of the Development of the *Advanced Hybrid™* Filter

September 1994 – *Advanced Hybrid™* filter concept proposed to U.S. Department of Energy (DOE).

October 1995 – September 1997 – Phase I – *Advanced Hybrid™* filter successfully demonstrated at 0.06-MW (200-acfm) scale at the EERC.

March 1998 – August 2001 – Phases II and III – *Advanced Hybrid™* filter successfully demonstrated at 2.5-MW (9000-acfm) scale at Big Stone Plant.

April 2001 – Full-scale *Advanced Hybrid™* filter proposed to DOE under Power Plant Improvement Initiative.

November 2001 – June 2003 – Mercury Control with the *Advanced Hybrid™* filter – Extensive additional testing conducted with the 2.5-MW pilot unit at Big Stone.

December 2001 – In the EERC Phase III Final Report, the detrimental effect of high-resistivity ash on *Advanced Hybrid™* filter performance was emphasized. A conclusion was that ash resistivity $>10^{11}$ ohm-cm will limit performance.

October 2002 – Full-Scale *Advanced Hybrid™* filter start-up at Big Stone.

April 2004 – Vendor bid for expanding the *Advanced Hybrid™* filter at Big Stone by converting the first fields from the old ESP configuration into an *Advanced Hybrid™* filter configuration.

August 2004 – EERC first field design review report submitted to Otter Tail Power Company. The importance of alignment and spacing tolerances was emphasized along with the need for adequate time to check out system components and to correct any identified problems prior to start-up.

June 2005 – Start-up after conversion of first field to *Advanced Hybrid™* filter configuration. Major spacing and alignment problems resulted in first fields being inoperable. High-resistivity ash also contributed to marginal performance of the back fields. Big Stone had switched to Black Thunder coal (which produces high-resistivity ash) in January 2005.

August 2005 – Measurements showed ash resistivity with Black Thunder coal is very high, $>10^{12}$ ohm-cm.

May 2006 – Subtask 2.13 was implemented to help evaluate fundamental *Advanced Hybrid*^{TM} filter performance issues.

March 2007 - Big Stone Plant initiated conversion of *Advanced Hybrid*^{TM} filter into a pulse-jet baghouse.

EERC EVALUATION OF FIRST FIELDS OF THE *ADVANCED HYBRID*^{TM} FILTER

Approximately 2 months after start-up with the first fields, EERC personnel had a chance to inspect two of the *Advanced Hybrid*^{TM} filter chambers during a time when the plant was down to fix a hydrogen leak. The *Advanced Hybrid*^{TM} filter at Big Stone consists of four parallel chambers (1A, 2A, 1B, and 2B). Each of the four chambers consists of four fields (compartments) in series for a total of 16 compartments. For the 2B chamber, the inspection included the clean air plenums as well as all four fields of the dirty side of the chamber. For the 1A chamber, the inspection only included the dirty side of the four fields. Following are several observations:

2B Clean Air Plenums

In Field 1, three or four of the blow tubes had come off completely from the connection near the wall and another three or four had loose flanges with a significant gap. Plant personnel were able to fix the problem during the outage. The tube sheet was quite clean, which means there were no significant bag failures or tube sheet leaks. The clean air plenums of Fields 2–4 of Chamber 2B also appeared to be reasonably clean.

2B Field 1 Dirty Side

The 2B Field 1 was inspected at both the front and back sides of the field from the bottom access walkway as well as the midlevel walkway. There were multiple locations where there were severe spacing tolerance problems caused by several mechanical issues including the following:

- The bolt heads and nuts on the tadpole bars at the bottom of the plates protruded out too far and subsequently were too close to the discharge electrodes. Many of them were only 2 to 3 inches from the electrode, which would lead to sparking problems.
- Compounding the problem with the bolt heads, some of the pins holding the tadpole bars had come out so the bars had dropped down and did not return to the proper position after rapping. It appeared that some of the plates had moved forward by several inches, which moves the tadpole bolts more directly across from the discharge electrodes, again causing a spacing problem.

- At least two of the flow passageways had severe plate bowing toward the middle of the field.
- Several of the flow passageways had discharge electrodes that were out of alignment.
- At the back of the field, there was only about a 2-inch distance between some of the tabs on the last electrode to the vertical square stiffener at the end of the plate. This may have been partly caused by some of the plates being pushed forward.
- At the bottom front of the field, for some of the passageways, there was only a 2-inch gap between the sharp side edge of the first discharge electrode and the end guide plates.

2B Fields 2–4

In contrast to the first field, the back fields (which were part of the original *Advanced Hybrid*™ filter installation) were all in good alignment, and there were no obvious spacing problems. However, there was excessive ash buildup on the discharge electrodes and the plates, which indicates they were not being rapped sufficiently. There was also ash piled up on some of the rapper bars, which indicates they had not been on for some time. Just very light tapping on a discharge electrode resulted in almost complete removal of the ash; however, it is expected that the ash will be removed more easily under cold conditions without the field on.

1A Field 1

Even though this field had not had additional warranty work, the plate alignment was actually better than in the 2A chamber. However, there were electrode alignment problems and many of the same spacing issues as in the 2A Field 1 compartment.

INSPECTION SUMMARY

The EERC assessment was that the main reason why it was not possible to get any power into the first fields was the severe mechanical spacing problems that occurred at multiple locations in the first fields. These problems would have to be corrected before any fair evaluation of the performance of the first fields could be made.

The Big Stone Plant worked with the vendor of the first field retrofit as well as outside consultants in an attempt to achieve satisfactory performance of the first fields. In spite of these efforts, the performance of the first fields remained far below expectations. Subsequently, Big Stone made the decision to abandon the *Advanced Hybrid*™ filter technology and convert the whole particulate control system into a conventional pulse-jet baghouse. This conversion is being completed in several steps, which started in March 2007, and is scheduled for completion in the fall of 2007.

FINDINGS OF PARTICULATE CONTROL TECHNOLOGIES, INC.

The consultant report, attached as an Appendix, was written as an interim report with the intent that a formal final version of the report would be completed at a later time. However, since the Big Stone plant made the decision to convert the unit to a pulse-jet baghouse, a final consultant report was not completed.

The consultant report is in agreement with the EERC assessment that the main fundamental problem with the first fields was misalignment of the discharge electrodes leading to excessive sparking and making the first fields essentially useless. The opinion was also expressed that the lack of midspan electrode support led to electrode sway during operation, which would only exacerbate the sparking problems. These alignment problems were unique to the first fields. There were never any significant electrode alignment problems with the back fields, which have operated continuously since start-up in October 2002. The first field spacing problems were likely the result of a combination of factors including a tighter spacing design than the back fields, a different design with longer electrodes, and a failure to meet spacing tolerances.

Another factor that has limited the *Advanced Hybrid*^{TM} filter performance at Big Stone is the high-resistivity fly ash. This is not unique to the first field performance, but affects the performance of all of the fields. The report recommended that an SO₃ conditioning system could be installed to effectively lower the ash resistivity. Numerous measurements by the EERC have shown that the ash resistivity at Big Stone was high enough to significantly impair performance. However, the Big Stone Plant chose not to test this option because of the uncertainty of the level of performance improvement that could be achieved, considering the costs and maintenance of a conditioning system.

SUMMARY AND CONCLUSIONS

An *Advanced Hybrid*^{TM} filter was retrofitted into Fields 2–4 of the old Big Stone ESP with start-up in October 2002. Because the pressure drop across the *Advanced Hybrid*^{TM} filter was unacceptably high, the Big Stone Plant made the decision to expand the *Advanced Hybrid*^{TM} filter by also retrofitting the first fields into an *Advanced Hybrid*^{TM} filter. However, since start-up in June 2005, after the first fields were converted, the first fields have been inoperable for multiple reasons.

The fundamental cause of the dysfunctional performance of the first fields was the spacing and alignment problems, which led to excessive sparking and shutdown of the high-voltage power. This condition has made the ESP portion of the first fields essentially useless. The main recommendation was that these severe spacing problems in the first fields would have to be corrected before an overall satisfactory level of performance of the *Advanced Hybrid*^{TM} filter could be achieved. In spite of attempts by the vendor to correct the problems and the efforts of the outside consultants, satisfactory performance of the first fields was never seen.

A second fundamental factor contributing to the overall marginal performance of the *Advanced Hybrid*™ filter at Big Stone is the very high-resistivity ash. The recommendation was made that to achieve good electrical performance of the *Advanced Hybrid*™ filter an SO₃ conditioning system would need to be installed. However, since the first field spacing problems were never resolved, there was concern that lowering the ash resistivity may not produce enough of an improvement to achieve overall acceptable performance. Because of the uncertainties of how to achieve acceptable performance with a new and unproven technology, the Big Stone Plant made the decision to convert the entire *Advanced Hybrid*™ filter housing into a pulse-jet fabric filter, which is considered to be a more conventional and proven technology. The conversion to a pulse-jet baghouse at Big Stone is expected to be completed in the fall of 2007.

REFERENCES

1. Wolf, D.; Campbell, F.; Gregory, D. Pulse-Jet Fabric Filter Retrofit and Results at Craig Station Units 1 & 2. Presented at The Mega Symposium, Washington, DC, Aug 30 – Sept 2, 2004.
2. Hrdlicka, T.; Swanson, W. *Demonstration of a Full-Scale Retrofit of the Advanced Hybrid™ Particulate Collector Technology*; Final Report (Oct 2002 – Dec 2004). Prepared for the U.S. Department of Energy National Energy Technology Laboratory; DOE Award No. DE-FC26-02NT41420; Otter Tail Power Company: Big Stone City, SD.
3. Miller, S.J.; Zhuang, Y.; Almlie, J.C.; Rinschler, C.; Gebert, R.; Davis, D.; Swanson, W.; Hrdlicka, T. Mercury Control with the *Advanced Hybrid*™ Filter – 2003 Update. In *Proceedings of the Air Quality IV: Mercury, Trace Elements, and Particulate Matter Conference*; Arlington, VA, Sept 22–24, 2003.
4. Gebert, R.; Rinschler, C.; Davis, D.; Leibacher, U.; Studer, P.; Eckert, W.; Swanson, W.; Endrizzi, J.; Hrdlicka, T.; Miller, S.J.; Jones, M.L.; Zhuang, Y.; Collings, M.E. Commercialization of the *Advanced Hybrid*™ Filter Technology. In *Proceedings of the Air Quality III: Mercury, Trace Elements, and Particulate Matter Conference*; Arlington, VA, Sept 10–12, 2002; Energy & Environmental Research Center: Grand Forks, ND, 2002.
5. Miller, S.J.; Zhuang, Y.; Rinschler, C.; Gebert, R.; Davis, D.; Swanson, W. Mercury Control with the *Advanced Hybrid*. In *Proceedings of the Air Quality III: Mercury, Trace Elements, and Particulate Matter Conference*; Washington, DC, Sept 10–12, 2002.
6. Miller, S.J.; Collings, M.E.; Zhuang, Y.; Gebert, R.; Davis, D.; Rinschler, C. The *Advanced Hybrid* Particulate Collector Field-Testing Results. Presented at the Combined Power Plant Air Pollutant Control Symposium: The Mega Symposium, Chicago, IL, Aug 20–23, 2001.
7. Zhuang, Y.; Miller, S.J.; Collings, M.E. *Advanced Hybrid Particulate Collector – Pilot-Scale Testing*; Final Report for U.S. Department of Energy Cooperative Agreement No. DE-FC26-98FT40321; EERC Publication 2001-EERC-09-04; Energy & Environmental Research Center: Grand Forks, ND, Sept 2001.

8. Zhuang, Y.; Miller, S.J.; Olderbak, M.R. *Advanced Hybrid Particulate Collector*; Final Report for Phase III (Sept 30, 1999 – Sept 29, 2001) for U.S. Department of Energy National Energy Technology Laboratory Cooperative Agreement No. DE-FC26-99FT40719; EERC Publication 2001-EERC-12-05; Energy & Environmental Research Center: Grand Forks, ND, Dec 2001.
9. Gebert, R.; Darrow, J.; Miller, S.J.; Feeley, T.J.; Swanson, W. *Advanced Hybrid Particulate Collector: A New Method for Control of Fine Particles*. Presented at the 93rd Air & Waste Management Association Annual Meeting, Salt Lake City, UT, June 18–22, 2000.
10. Gebert, R.; Davis, D.; Rinschler, C.; Miller, S.J.; Jones, M.L.; Collings, M.E.; Swanson, W.; Krigmont, H. *Advanced Hybrid Particulate Collector: Concept, Field Results, and Commercialization Potential*. Presented at the Air Quality II: Mercury Trace Elements, and Particulate Matter, McLean, VA, Sept 19–21, 2000.
11. Miller, S.J.; Jones, M.L.; Walker, K.; Gebert, R.; Darrow, J.; Krigmont, H.; Feeley, T.J.; Swanson, W. Field Testing of the *Advanced Hybrid Particulate Collector*, A New Concept for Fine-Particle Control. Presented at the 2000 American Chemical Society Symposium, San Francisco, CA, March 26–31, 2000.
12. Miller, S.J.; Olderbak, M.R.; Zhuang, Y. *Advanced Hybrid Particulate Collector*, Final Technical Report, Phase I and II, for U.S. Department of Energy Contract No. DE-AC22-95PC95258; Energy & Environmental Research Center: Grand Forks, ND, Dec 2000.
13. Miller, S.J. *Advanced Hybrid Particulate Collector*. Presented at the 1998 International Mechanical Engineering Congress & Exposition, Anaheim, CA, Nov 15–20, 1998.
14. Miller, S.J.; Schelkoph, G.L.; Walker, K.; Gore, W.L.; Feeley, T.J.; Krigmont, H. Ultrahigh Collection of PM_{2.5} with the *Advanced Hybrid Particulate Collector*. Presented at the International Joint Power Generation Conference and Exposition and the International Conference on Power Engineering, San Francisco, CA, July 25–28, 1998.
15. Miller, S.J.; Schelkoph, G.L.; Walker, K.; Krigmont, H. *Advanced Hybrid Particulate Collector, A New Concept for Fine-Particle Control*. In *Preprint of the PARTEC 98 International Congress for Particle Technology, 4th European Symposium Separation of Particles from Gases*; Nürnberg, Germany, March 10–12, 1998; pp 256–265.
16. Miller, S.J.; Schelkoph, G.L.; Dunham, G.E.; Walker, K.; Krigmont, H. *Advanced Hybrid Particulate Collector, A New Concept for Air Toxics and Fine-Particulate Control*. Presented at the EPRI-DOE-EPA Combined Utility Air Pollutant Control Mega Symposium, Washington, DC, Aug 25–29, 1997.
17. Miller, S.J.; Schelkoph, G.L.; Dunham, G.E.; Walker, K.; Krigmont, H. *Advanced Hybrid Particulate Collector, A New Concept for Air Toxics and Fine-Particle Control*. Presented at the Advanced Coal-Based Power and Environmental Systems '97 Conference, Pittsburgh, PA, July 22–24, 1997.
18. Miller, S.J. *Advanced Hybrid Particulate Collector*. Presented at the 1st Joint Power and Fuel Systems Contractors' Conference, Pittsburgh, PA, July 9–11, 1996.

APPENDIX A

WALLIS HARRISON REPORT

Particulate Control Technologies, Inc.

World Wide Technology Information Source

May 9, 2006

Interim Report on the Evaluation of the Big Stone Power Plant, Advanced Hybrid Particulate Collector

**Prepared by Wallis Harrison
President, PCT, Inc.**

This report covers the initial data evaluation, visit to the Energy and Environmental Research Center (EERC) in Grand Forks, North Dakota and a visit to the Big Stone Power Plant, located in Big Stone City, South Dakota during the week of April 10, 2006.

Previous to my visit to EERC, I was provided numerous reports outlining the pilot scale facility, the various modifications to the existing electrostatic precipitator, and the test and operational results from the Advanced Particulate Hybrid Collector (AHPC) installed at Big Stone Power Plant. These reports were reviewed to gain an understanding of the installation and potential problems that exist with the AHPC.

Initially, I visited with Mr. Stan Miller and Mr. Carsten Heide of EERC. During this visit, we discussed the entire case history of the AHPC and its current operating conditions. We also discussed the desire of EERC to assist in some way with the current problems that exists with the Big Stone installation. I also visited the Big Stone Plant and met with plant engineers Mr. Stu Schreurs and Mr. D J Haggerty. Mr. Haggerty provided an excel file with hourly plant operational data from January 1, 2006 until the present. Two bags that were recently removed from the AHPC were also provided for independent analysis if required.

The Big Stone Power Plant consists of one 450 MW generating unit with a cyclone fired boiler burning a variety of Powder River Basin fuels and other fuels such as seeds, tire derived fuel, and plastic chips. Some of the Powder River Basin fuels are known to produce high resistivity ash which is difficult to collect in electrostatic precipitators. Cyclone fired boilers are known to produce fly ash that consist primarily of submicron diameter particles. These submicron particles are difficult to collect in electrostatic precipitator and may cause problems with bag filters, due to blinding of the bag surface. The submicron particles also contribute greatly to high stack opacity readings.

Overview of AHPC and Problems at Big Stone

The AHPC is a novel particulate control device designed to combine an electrostatic precipitator and a pulsejet baghouse in a very compact footprint. Because of the small space requirements of the AHPC, it is suitable for retrofit into an existing electrostatic precipitator.

The existing electrostatic precipitator located at Big Stone Power Plant is relatively large, and suitable for the installation of the AHPC into the existing electrostatic precipitator casing. The existing electrostatic precipitator consisted of four mechanical fields in the direction of gas flow, and four individual electrostatic precipitators that are approximately 45 feet wide and 40 feet tall.

Initially a pilot scale AHPC with a volumetric flow rate of 9000 ft.³ per minute was installed at the Big Stone Plant. EERC operated this pilot scale facility under a variety of conditions for several years. During this test period a variety of mechanical configurations and bag fabrics were tested. The configuration that gave the best performance was selected for the full-scale installation. This configuration consisted of an electrostatic precipitator with perforated collecting plates. The electrostatic precipitator portion of the AHPC is separated from the pulsejet portion by these perforated collecting plates. The perforated collecting plates serve several important purposes in this design.

It had been observed during the pilot scale testing, that spark over from the discharge electrode occurred to the pulsejet bag. This resulted in small holes being melted in the fabric, thus increasing outlet emissions. The installation of perforated collecting plates resulted in a shielding of the electrical field from the pulsejet bag, reducing the spark over to the bag. The reduction in electrical field on the bag surface also prevented the formation of back Corona, which also contributed to sparking between the surface of the bag and the internal cage, causing additional holes in the bags.

The overall performance of the pilot scale unit with the perforated collecting plates was considered to be very good. It operated at relatively high air to cloth ratios and demonstrated very high collection efficiency. Therefore, the perforated collecting plate design was installed in the last three mechanical fields of the Big Stone electrostatic precipitator in 2002. The first field of the electrostatic precipitator remained in its original condition.

However, following start up, a number of problems developed. At low boiler loads the performance of the AHPC was very good. At full load operation, the AHPC began to pulse continuously in an effort to maintain a reasonable pressure drop. The tube sheet pressure drop set point was increased along with pulsed air pressure; however, this did little to correct the problem. The increase in pulse pressure and continuous pulsing has resulted in premature bag failures. Operation of the AHPC at high pressure drop consumes considerable fan horsepower and compressed air. A number of different bag

types were also installed and evaluated. However, the problem of premature bag failure and operation at higher than desired pressure drop remained.

Numerous load reductions were required during this period to maintain ID fan stability. It had been observed that at full load conditions of 450 MW and high pressure drop, the ID fans tended to stall. The stalling of the ID fans will result in a serious and unstable operating condition for the boiler and could force a boiler shutdown.

Testing had demonstrated that having the electrostatic precipitator fields energized improved the overall performance of the AHPC. Therefore, an effort was made to improve this situation by retrofitting the first mechanical field, with additional bags and collecting plates. This design was a modification of the original design installed in the last three fields. The perforated plate design was maintained, however, the plate to plate spacing in this field was decreased in an effort to install more bags within the inlet field increasing the total bag surface area and reducing the air to cloth ratio. There are however, a number of fundamental problems in this new inlet field.

The inlet field retrofit was configured to provide the maximum amount of collecting plate area and the maximum amount of bag surface area. To accomplish this goal, the plate to plate spacing was reduced from 12 inches down to 10 inches. Additional 24 feet long collecting bags were installed adjacent to the perforated collecting plates. Rigid discharge electrodes of approximately 38 feet in length were installed in the electrostatic precipitator sections. The area of the collecting plates below the new pulsejet bags was left solid and not perforated, again in an effort to increase the collecting surface area of the electrostatic precipitator portion.

Two longitudinal baffle plates were installed along the bottom of each pulsejet bag row in an effort to direct more flow into the electrostatic precipitator sections. The longitudinal baffle plates were designed based upon the results of a computational fluid dynamics study off the AHPC. The baffle plates appear to be effective in directing more flow into the electrostatic precipitator section, however, very little if any improvement in the operation of the AHPC was observed following the installation of the baffles.

The new collecting plates in the inlet field are approximately 40 feet in length. They are installed without any mid span alignment device. It is customary, and always recommended, that for collecting plates of this length some form of mid span alignment should be installed. The rigid discharge electrodes that are installed within this inlet field are over 38 feet in length, and only have a weight at the bottom of each electrode to maintain rigidity. A lower alignment rack is installed to maintain the position of the discharge electrodes at the bottom. However, again there is no mid span alignment device installed to maintain adequate alignment of these very long discharge electrodes. The inlet field and remaining fields of the AHPC are powered by only one high-voltage transformer rectifier set for each field. Therefore, one close clearance situation existing anywhere within any of the fields will cause premature sparking and limit the power that can be applied to the fields. The poor electrical sectionalization that is present within the entire AHPC unit contributes to the inability to apply maximum power to the electrostatic precipitator sections.

It was observed during my recent internal inspection of the unit, that the collecting plates and discharge electrodes within the inlet field were too flexible and prone to movement, either from the gas flow or from the electric field. It was possible during the inspection to lightly push upon the discharge electrodes and cause them to start swinging. Observations of the primary and secondary current meters on the inlet fields indicated that the discharge electrodes were swinging back and forth. This movement of the discharge electrodes results in premature spark over at very low voltages and currents preventing the inlet field electrostatic precipitator section from collecting any ash.

One question that remains unanswered: is there significant presence of back Corona in the electrostatic precipitation sections to limit the performance? During the pilot scale testing back Corona was observed on both the collecting surfaces of the precipitator and on the bag surfaces. Voltage, current curves taken in the past (August 2005) and just recently (4-14-2006) by plant personnel, do not show any evidence of back Corona. Analysis of hopper ash samples by EERC (6-15-2005) have shown resistivities that are very high and would be expected to limit the precipitator performance. My computer predicted resistivities of both Black Thunder and Cordero Rojo ash analysis, provided to me by Mr. Scherurs, do not indicate high resistivities. Ash resistivity obviously has an impact upon the operation of the AHPC, but I do not believe it is the overriding factor in the observed performance.

Recommendations for Improving the Performance of the AHPC at Big Stone Power Plant

The main problems at Big Stone Power Plant are:

1. The misalignment of the inlet fields of the AHPC.
2. The electrical sectionalization.
3. The particle size distribution of the ash entering the AHPC.
4. Fly ash resistivity.
5. The internal flow velocity and distribution of flow within the AHPC.
6. The use of membrane bags.

Inlet Field Misalignment

The inlet fields of the AHPC suffer from serious misalignment problems due to the design that was installed. A minimum of one mid span alignment device should be installed at the front and back sides of the existing collecting plates within the inlet fields. At least one level of alignment devices should be installed at the front and back sides of the discharge electrodes within the inlet fields. Installing an alignment device on the existing discharge electrodes within the 10 inch, spaced collecting plates will compromise the clearances to some degree. However, a clearance of 3 to 4 inches is much better than the clearances of zero that presently exist within the inlet fields.

I have prepared an estimate of the man-hours and cost to install the alignment devices on the inlet fields of the electrostatic precipitator. The estimate is based upon South Dakota Union Boiler Maker hourly rates. The estimate does not include the materials needed for the alignment devices. It does include labor, hole watch, supervision, tools, welding and cutting equipment, miscellaneous materials for scaffolding, etc.

The collecting plate alignment device can be made from 2"x 2" angle, and the electrode alignment device can be made from 2"x 0.25" flat bar, and ceramic stand-off insulators.

The estimated man-hours to install the alignment devices per precipitator inlet field are 522, for a total of 2088 man-hours. This total of 2088 is the hours I estimate that men would be inside the precipitator, and does not include the other man-hours reflected in the total estimate.

If the job is worked on straight time, the cost would be \$140900. If time-and-one-half rates are used the cost would be \$196000. Double time rates will increase the cost to \$224800. Details of this estimate are available if needed.

Electrical Sectionalization

Each field of the AHPC is powered by only one transformer rectifier set. Therefore, one close clearance within the entire field will limit performance of that entire field. It is highly recommended, particularly for the inlet fields, to add at least one more high-voltage transformer rectifier set to each field. Because of space and possible weight limitations for a conventional transformer rectifier set, I would recommend the use of the NWL switch mode high frequency transformer rectifier set. These devices are very small and weigh only a few hundred pounds, allowing for placements in areas where conventional transformer rectifier sets could not be placed. Additional transformer rectifier sets will improve the power input into the electrostatic precipitator sections and should improve the overall performance of the AHPC.

Fly Ash Particle Size Distribution

It is known that cyclone boilers produce fly ash that is predominantly submicron in size. The submicron particles have little, if any, inertia and follow the gas stream. Because of the aggressive cleaning frequencies of the existing pulsejet baghouse within the AHPC little, if any, ash cake is allowed to collect on the bag surfaces. Therefore, it is suspected, that no agglomeration of the submicron particles take place on the bag surface. When the bag is pulsed without an ash cake being present, I believe much of the ash that is removed from the bag surface is simply re-entrained upon the bag surface by the gas flow. My calculations of the can velocity within the AHPC show velocities that are at the upper limit or exceed the upper limit for good performance. The performance of the AHPC at low load is very good. The calculated can velocities at low load fall well within the range where good performance of a pulsejet baghouse would be expected. An increase of 60% in the total flow is observed between low load and full load. This increase in flow and corresponding increase in ash loading, places the AHPC in a very unfavorable operating

condition. This is also demonstrated since the AHPC goes into continuous cleaning, as the unit approaches full load and tries to maintain the pressure drop set point.

The continuous cleaning of the bags with high-pressure air is definitely contributing to premature bag failure. It has also been observed that rust is forming on the bag cages. The presence of rust on the cages will contribute to premature cage failure and cause the bag fabric to adhere to the cage. If the bag fabric is stuck to the cage, the fabric cannot flex during pulsing and removal of the ash from the bag surface will be reduced. I believe that the root cause of the formation of rust on the bag cages results from the continuous pulsing of cold ambient air into the baghouse. This problem will increase during the very cold winter months, when ambient temperatures are low.

It is recommended that in-situ particle size distribution measurements be made at the inlet of the AHPC to verify the actual size distribution of the fly ash entering the unit.

Fly Ash Resistivity

As discussed earlier, fly ash resistivity can have a detrimental effect upon the performance of the AHPC. It is recommended that in-situ resistivity measurements be performed at the inlet of the AHPC for each of the major fuels that are burned at Big Stone Plant. These measurements will verify if high resistivity ash is being produced from these fuels. If determined that high resistivity ash (greater than mid 10x11 ohm/cm) is present within the AHPC, it can be expected that back Corona will be present in the electrostatic precipitator sections. There are several methods by which back Corona and its effects can be mitigated.

The most effective method for controlling fly ash resistivity is with the injection of SO₃ (sulfur trioxide). The injection of SO₃ is best accomplished by using a commercially available sulfur burner to produce the required amount of SO₃. The SO₃ can be injected on the hot or cold side of the air pre-heater.

Another method, but somewhat less effective, is the use of intermittent energization (IE). The transform rectifier set automatic voltage control is typically able to produce an IE waveform. The proper application of IE to the electrostatic precipitator will often control back Corona to a manageable level. It is recommended that this be tried with the existing automatic voltage controls to determine if this feature is present. IE can then be evaluated to determine if any improvement in the operation of the AHPC is shown.

Flow Velocity and Distribution

The installation of the flow diversion baffles at the bottom of the pulsejet sections was a result of a previous flow study. It is recommended that additional flow modeling be attempted to gain a better understanding of the flue gas and ash particle distribution within the AHPC. Test of the flow, through individual bags, has demonstrated a large difference in flow through the bag dependent upon the location of the bag. This large

difference in flow is obviously the result of a poor distribution of flue gas and fly ash with in the AHPC chambers.

Membrane Bags

The original concept of the AHPC was to provide to industry, a device with extremely high particulate removal efficiencies. The use of membrane bags was a method to achieve this high efficiency. However, there are no current regulatory incentives for a plant to install such a high efficiency device.

For the AHPC to become a commercially viable product, and for long-term improvements in the operating conditions of the AHPC at Big Stone Plant, I believe that the use of membrane bags should be questioned. Currently, Big Stone is replacing all of the bags in the AHPC on a yearly basis. This is a yearly cost of approximately \$1 million, not inclusive of the cost of the loss in generation.

I believe that the application of high permeability PPS bags should be investigated. Bags of this type have been working very well for a number of years in the Alabama Power Plant Gaston COHPAC units. The high permeability bags will increase outlet opacity by small amount, but should provide significantly better operating conditions of the AHPC. Provided that high temperature events are prevented, the PPS fabric should perform very well. The high permeability bag will allow lower pressure drop set points, decreased cleaning frequency, and allow the presence of a suitable ash cake to form on the bag surface. The presence of this ash cake, when pulsed, should result in much better cleaning and should allow some of the ash to penetrate back through the perforated plates, which will then be collected by the electrostatic precipitator section. To properly evaluate the performance of the high permeability bag, one would have to replace all of the bags in one of the four AHPCs. I believe that Big Stone Plant would be reluctant to undertake this experiment prior to this year's summer run.

I recommend the best way to evaluate the high permeability bag at this time is to use the existing pilot facility that is still present at Big Stone Plant. Testing has demonstrated some differences in the operation of the pilot facility and a full-scale unit. However, now that these differences are known, correlations between the operation of the pilot facility and the full-scale AHPC could be developed. The utilization of the pilot facility would be a much more economical means to evaluate the performance of the high permeability bag.

Final Report

The final report will be submitted following receipt of the in-situ ash resistivity and particle size data. At this time there are no bag samples available that can be used for permeability testing, therefore, no bag analysis will be done at this time. During the June outage bag samples can be obtained for analysis.

The final report will include a discussion of the resistivity and particle size data as related to the AHPC at Big Stone Plant.

A comparison of the various options available to Big Stone will be provided in the final report including some estimated costs.