

MERCURY CONTROL WITH ADVANCED HYBRID PARTICULATE COLLECTOR

Final Technical Report

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MERCURY CONTROL WITH THE ADVANCED HYBRID PARTICULATE COLLECTOR

ABSTRACT

This project was awarded under U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) Program Solicitation DE-PS26-00NT40769 and specifically addressed Technical Topical Area 4 – Testing Novel and Less Mature Control Technologies on Actual Flue Gas at the Pilot Scale. The project team included the Energy & Environmental Research Center (EERC) as the main contractor; W.L. Gore & Associates, Inc., as a technical and financial partner; and the Big Stone Power Plant operated by Otter Tail Power Company, host for the field-testing portion of the research.

Since 1995, DOE has supported development of a new concept in particulate control called the advanced hybrid particulate collector (AHPC). The AHPC has been licensed to W.L. Gore & Associates, Inc., and has been marketed as the *Advanced Hybrid*TM filter by Gore. The *Advanced Hybrid*TM filter combines the best features of electrostatic precipitators (ESPs) and baghouses in a unique configuration, 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*TM filter provides ultrahigh collection efficiency, overcoming the problem of excessive fine-particle emissions with conventional ESPs, and it solves the problem of reentrainment and re-collection of dust in conventional baghouses. The *Advanced Hybrid*TM filter also appears to have unique advantages for mercury control over baghouses or ESPs as an excellent gas–solid contactor.

The objective of the project was to demonstrate 90% total mercury control in the *Advanced Hybrid*TM filter at a lower cost than current mercury control estimates. The approach included bench-scale batch tests, larger-scale pilot testing with real flue gas on a coal-fired combustion system, and field demonstration at the 2.5-MW (9000-acfm) scale at a utility power plant to prove scale-up and demonstrate longer-term mercury control.

An additional task was included in this project to evaluate mercury oxidation upstream of a dry scrubber by using mercury oxidants.

This project demonstrated at the pilot-scale level a technology that provides a cost-effective technique to control mercury and, at the same time, greatly enhances fine particulate collection efficiency. The technology can be used to retrofit systems currently employing

inefficient ESP technology as well as for new construction, thereby providing a solution for improved fine particulate control combined with effective mercury control for a large segment of the U.S. utility industry as well as other industries.

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MERCURY CONTROL WITH THE ADVANCED HYBRID PARTICULATE COLLECTOR

EXECUTIVE SUMMARY

Since 1995, the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) has supported development of a new concept in particulate control called the advanced hybrid particulate collector (AHPC). The AHPC, licensed to W.L. Gore & Associates, Inc., has been marketed as the *Advanced Hybrid*TM filter by Gore. The *Advanced Hybrid*TM filter combines the best features of electrostatic precipitators (ESPs) and baghouses in a unique configuration, providing major synergism between the two collection methods, both in the particulate collection step and in the transfer of dust to the hopper.

The Energy & Environmental Research Center's (EERC's) objective for this project was to demonstrate 90% total mercury control with commercially available sorbents in the *Advanced Hybrid*TM filter at a lower cost than current mercury control estimates. The approach included three levels of testing: 1) bench-scale batch testing that tied the new work to previous results and linked results with larger-scale pilot testing with real flue gas on a coal-fired combustion system, 2) pilot-scale testing on a previously proven combustion system, and 3) field demonstration testing at the 2.5-MW (9000-acfm) scale at a utility power plant to prove scale-up and demonstrate longer-term mercury control.

Initial bench-scale results were in good agreement with previous data. Results showed that the SO₂ and NO₂ concentration effects are additive and have a significant effect on sorbent performance. This finding should facilitate predicting sorbent performance in real systems when the SO₂ and NO₂ concentrations are known. Further finding from the bench-scale tests was that the fixed-bed sorbent-screening tests using simulated flue gas were in good agreement with similar tests sampling real flue gas. This suggests that as long as the main flue gas components are duplicated, the bench-scale fixed-bed tests can be utilized to indicate sorbent performance in larger-scale systems.

An initial field test of the 2.5-MW (9000-acfm) *Advanced Hybrid*TM filter at the Big Stone Power Plant was completed the first week of November 2001. Results showed that the average inlet mercury speciation for seven samples was 55.4% particulate bound, 38.1% oxidized, and

6.4% elemental. A carbon injection rate of 24 mg/m³ (1.5 lb/Macf) resulted in 91% total mercury collection efficiency, compared to 49% removal for the baseline case.

Following the initial field test, the first planned pilot-scale tests were completed. In the pilot-scale tests, a baseline comparison was made between the *Advanced Hybrid*TM filter and a pulse-jet baghouse (PJBH) in terms of the mercury speciation change across the device and the amount of mercury retained by the fly ash. Results showed that for both devices there was very little capture of mercury by the fly ash. There was some increase in oxidized mercury, but no significant differences were noted between the *Advanced Hybrid*TM filter and pulse-jet modes of operation.

Even though the same coal was used in the pilot-scale and initial field tests, there was a significant difference in inlet mercury speciation. For the pilot-scale tests, results were more similar to what is typically expected for Powder River Basin (PRB) coals in that most of the mercury was elemental, with little mercury capture by the fly ash. In contrast, for the November 2001 field test, there was much more oxidized than elemental mercury and significant mercury capture by the fly ash. Possible reasons for the difference include higher carbon in the field ash, somewhat higher HCl in the field flue gas due to the cofiring of tire-derived fuel (TDF), possible variation in the coal, cyclone firing for the field compared to pulverized coal firing for the pilot tests, longer residence time for the field tests, and a finer particle size for the field test.

During April–June 2002, a number of baseline and carbon injection pilot-scale tests were completed with Belle Ayr PRB subbituminous coal, one of the coals burned at Big Stone. For the baseline case, approximately 70% of the inlet mercury was elemental, approximately 23% oxidized, and 2% or less was associated with particulate matter. Very little natural mercury was captured across the *Advanced Hybrid*TM filter for the baseline tests, and the level of oxidized mercury increased only slightly across the *Advanced Hybrid*TM filter during baseline operation.

With carbon injection, a comparison of short and long residence time in the *Advanced Hybrid*TM filter showed that somewhat better mercury removal was achieved with longer residence time. No evidence of desorption of mercury from the carbon was seen upon continued exposure to flue gases up to 24 hr. This suggests that desorption of captured mercury from the carbon sorbent is not a significant problem under these flue gas conditions with the low-sulfur subbituminous coal.

At a carbon-to-mercury ratio of 3000:1, from 50% to 71% total mercury removal was achieved. When the ratio was increased to 6000:1, the removal range increased to 65%–87%, even for the difficult case with predominantly elemental mercury and very little natural capture of mercury by the fly ash.

A longer-term field test was completed with the 2.5-MW (9000-acfm) field *Advanced Hybrid*TM filter August 6 through September 6, 2002. Carbon injection and CMM (continuous mercury monitor) measurements were continuous (24 hr a day) for the entire month, except for an unplanned plant outage from August 29 to September 2. The primary goal of the work was to demonstrate longer-term mercury control with the *Advanced Hybrid*TM filter and evaluate the effect of carbon injection on *Advanced Hybrid*TM filter operational performance. Another goal of the test was to evaluate the effect of supplemental TDF burning on the level of mercury capture for comparison with results from the previous test completed in November 2001.

The inlet mercury speciation during the August 2002 tests averaged 17% particulate bound, 32% oxidized, and 51% elemental. The significant difference in mercury speciation between the August and November 2001 field data is likely the effect of a higher rate of cofiring of TDF with the coal during the November test.

In the November 2001 tests, 49% mercury capture was seen for the baseline conditions without carbon injection. The August tests indicated only 0%–10% mercury capture with no carbon injection. Again, the most likely explanation is the much higher TDF cofiring rate and higher HCl in the flue gas for the November test.

Addition of activated carbon at a rate of 24 mg/m³ (1.5 lb/Macf) resulted in an average of 63% mercury removal in the August tests without any TDF cofiring. A small TDF cofiring rate of about 23 tons a day resulted in an increase in mercury collection to 68%. At the highest TDF rate seen in the August tests of 150–177 tons a day, mercury removal of up to 88% was achieved. This compares with 91% removal seen during the November tests when the TDF feed rate was in the range from 90 to 250 tons a day. These results indicate that TDF cofiring has the effect of increasing the level of mercury control that can be achieved with a low carbon addition rate.

One of the main objectives of the August tests was to assess the effect of carbon injection on longer-term *Advanced Hybrid*TM filter performance. When the carbon was started on August 7, there was no perceptible change in pressure drop or bag-cleaning interval. Similarly, there was no change in the K_2C_i value that relates to how well the ESP portion of the *Advanced Hybrid*TM

filter is working. These results indicate that low addition rates of carbon will have no perceptible effect on the operational performance of the *Advanced Hybrid*TM filter.

Another short field test was completed with the 2.5-MW (9000-acfm) *Advanced Hybrid*TM filter at the Big Stone Plant November 19–22, 2002, to coincide with the first test conducted at the inlet and stack of the full-scale *Advanced Hybrid*TM filter after it came online October 26, 2002. The primary purpose of the test was to evaluate the effect of injecting a small amount of HCl into the flue gas along with the activated carbon. Results showed that without supplemental HCl injection and a low carbon injection rate of 24 kg of carbon sorbent/million m³ of flue gas (1.5 lb of carbon sorbent/million acf), from 65% to over 90% total mercury removal was achieved. This is somewhat better than the results seen in the monthlong continuous test in August 2002. Part of the reason could be the higher temperatures in the *Advanced Hybrid*TM filter during August, which typically were in the range of 132°–143°C (270°–290°F) compared to 121°C (250°F) for the November 2002 tests.

Little or no effect was seen with the supplemental HCl injection. This is somewhat surprising because an extensive amount of bench-scale sorbent work has demonstrated the benefit of HCl for capturing elemental mercury in a simulated flue gas over the temperature range of 107°–188°C (225°–370°F). However, the benefit of additional HCl may be marginal in cases where there is already a sufficient amount of HCl present to achieve good mercury control.

During October–December 2002, a 5.7-m³/min (200-acfm) pilot-scale test was also completed with Springfield bituminous coal. The purpose of this test was to evaluate mercury control with the *Advanced Hybrid*TM filter with a high-sulfur bituminous coal. The Springfield bituminous coal produced a flue gas that was high in all of the acid gases including SO₃, and most of the inlet mercury was in an oxidized form. A number of short- and longer-term tests with the NORIT Americas DARCO[®] FGD carbon at temperatures ranging from 135° to 160°C (275° to 320°F) showed that this sorbent is completely ineffective at mercury control under these conditions. This is in contrast to the extensive testing conducted previously with the *Advanced Hybrid*TM filter and subbituminous coal, where up to 90% mercury capture was seen at a low carbon addition rate. The data are consistent with previous bench-scale testing that has shown that flue gas conditions are critical to the mercury capture ability of an activated carbon.

The previous field studies performed in November 2001 and August 2002 showed there was a correlation between Hg^{2+} concentration in the flue gas and the amount of TDF fed into the boiler. However, because of the variability of the TDF feed rate, it was difficult to quantify the TDF effect on mercury removal. A 1-week pilot-scale test was conducted on the 55-kW (200-acfm) EERC *Advanced Hybrid*TM filter where the coal feed rate and the TDF feed rate were precisely controlled.

Cofiring of TDF with the subbituminous coal had a significant effect on mercury speciation at the inlet to the *Advanced Hybrid*TM filter. Firing 100% coal resulted in only 19% oxidized mercury at the inlet compared to 47% cofiring 5% TDF (mass basis) and 85% cofiring 10% TDF. The significant increase in oxidized mercury may be partly the result of increased HCl in the flue gas with the TDF. However, since the actual increase of measured HCl was only a few parts per million, other changes in combustion conditions or flue gas components may also be responsible for the increase in oxidized mercury.

The TDF not only enhances mercury oxidation in flue gas but also improves mercury capture when combined with FGD carbon injection. With 100% coal, test results have shown from 48% to 78% mercury removal at a relatively low FGD carbon addition rate of 24 kg of carbon/million m^3 (1.5 lb of carbon/million acf). Results showed from 88% to 95% total mercury removal with the same carbon addition rate while 5%–10% TDF was cofired. These results are consistent with previously reported results from the 2.5-MW (9000-acfm) pilot-scale *Advanced Hybrid*TM filter.

W.L. Gore & Associates, Inc., initiated an innovative concept for control of mercury emissions in flue gas streams. Specifically, the configuration involves a mercury control filter placed inside the existing particulate control filter bag, essentially a bag-within-a-bag. This concept is attractive for use the *Advanced Hybrid*TM filter, because of the much fewer number of bags required compared to conventional baghouses.

A week of testing was completed with two different cartridge filters on the 55-kW (200-acfm) pilot-scale *Advanced Hybrid*TM filter in March 2003. The filters were installed inside of the four cylindrical all-polytetrafluoroethylene (PTFE) bags in the *Advanced Hybrid*TM filter unit. Operationally, the mercury filter elements did not appear to impair the pulse cleaning of the bags. Initial tests with these cartridges showed that nearly 100% mercury capture could be achieved, but early breakthrough results were observed.

Another 1-month field test was completed during May–June 2003 with the 2.5-MW (9000-acfm) *Advanced Hybrid*TM filter unit at the Big Stone Plant to demonstrate long-term mercury control with the *Advanced Hybrid*TM filter and evaluate the impacts of various operating parameters such as filtration velocity, carbon feed rate, and carbon in-flight time on mercury control.

The inlet mercury vapor concentration in the flue gas during the May 2003 test ranged from 4.98 to 10.6 $\mu\text{g}/\text{m}^3$ with 20%–70% Hg^0 . The variation in mercury speciation was likely caused by varying coal as well as the intermittent cofiring of TDF and waste seeds. The May 2003 test indicated 0%–30% mercury inherent capture with no carbon addition, typical for western subbituminous coal. At low carbon feed concentrations ranging from 1 to 3 lb/Macf, the *Advanced Hybrid*TM filter demonstrated high overall mercury collection efficiencies from 65% to 95%. When compared with other research results, the *Advanced Hybrid*TM filter clearly demonstrated higher mercury removal efficiency than an ESP under the same carbon feed rate. The overall Hg removal with the *Advanced Hybrid*TM filter was similar to a baghouse or COHPAC (compact hybrid particulate collector).

An additional sixth task was added to the project, initiated in April 2003. The planned objectives for this task were to evaluate mercury capture enhancement by using elemental mercury oxidation additives with a spray dryer absorber and test the novel Gore baghouse inserts downstream of the *Advanced Hybrid*TM filter or a fabric filter. The planned additional tests included 1) Hg oxidation upstream of a lime-based spray dryer fabric filter or *Advanced Hybrid*TM filter combination in order to control mercury emissions using dry scrubbers and 2) field testing of mercury sorbent technology at a North Dakota power plant using a slipstream baghouse. However, planned field testing of the Gore mercury inserts was not completed because Gore discontinued their development.

A pilot-scale Niro spray dryer system was installed on the EERC particulate test combustor (PTC) upstream of a PJFF (pulse-jet fabric filter) or *Advanced Hybrid*TM filter. Several additives and sorbent combinations were tested for mercury control while a Center, North Dakota, lignite was fired. Results showed that 95% mercury removal was seen with NORIT FGD activated carbon when a sorbent enhancement additive was injected into the furnace, compared to only 37% control with the FGD sorbent alone or 54% removal with the additive alone.

The last planned experimental work for the project was a test completed during July–September 2004 to measure the amount of mercury collected by the perforated plates in the *Advanced Hybrid*TM filter apart from any mercury control on the filter bags. To address this question, the 55-kW (200-acfm) pilot-scale *Advanced Hybrid*TM filter was modified so that it included perforated plates totally surrounding the normal bag area, but with the filter bags removed. Mercury removal with this configuration using the NORIT FGD carbon injected at 36 kg of carbon sorbent/million m³ of flue gas (2 lb of carbon sorbent/million acf) was 66%, which was similar to previous results with the *Advanced Hybrid*TM filter. However, using an EERC proprietary sorbent at the same carbon addition rate improved the mercury collection efficiency to 90%. For both tests, the particulate collection efficiency of the perforated plates alone was 98%. These are important results, because they prove that good gas–solid contact leading to excellent mercury removal can be achieved by collection of the activated carbon on the perforated plates alone, without a significant fraction of the carbon reaching the bags.

MERCURY CONTROL WITH THE ADVANCED HYBRID PARTICULATE COLLECTOR

1.0 INTRODUCTION AND BACKGROUND

1.1 Introduction

This project was awarded under U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) Program Solicitation DE-PS26-00NT40769 and specifically addressed Technical Topic Area 4 – Testing Novel and Less Mature Control Technologies on Actual Flue Gas at the Pilot Scale. The project team included the Energy & Environmental Research Center (EERC) as the main contractor; W.L. Gore & Associates, Inc., as a technical and financial partner; and the Big Stone Power Plant operated by Otter Tail Power Company, which hosted the field-testing portion of the research.

Since 1995, DOE has supported development of a new concept in particulate control called the advanced hybrid particulate collector (AHPC). The AHPC has been licensed to W.L. Gore & Associates, Inc., and has been marketed as the *Advanced Hybrid*TM filter by Gore. The *Advanced Hybrid*TM filter combines the best features of electrostatic precipitators (ESPs) and baghouses in a unique configuration, 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*TM filter provides ultrahigh collection efficiency, overcoming the problem of excessive fine-particle emissions with conventional ESPs, and it solves the problem of reentrainment and re-collection of dust in conventional baghouses. The *Advanced Hybrid*TM filter also appears to have unique advantages for mercury control over baghouses or ESPs as an excellent gas–solid contactor. Mercury control with the *Advanced Hybrid*TM filter was the focus of this project.

1.2 History of Development

The *Advanced Hybrid*TM filter concept was first proposed to DOE in September 1994 in response to a major solicitation addressing air toxics. DOE has been the primary funder of the *Advanced Hybrid*TM filter development since that time, along with significant cost sharing from industrial cosponsors. Details of all of the results have been reported in DOE quarterly technical reports, final technical reports for completed phases, and numerous conference papers (1–7). A chronology of the significant development steps for the *Advanced Hybrid*TM filter is shown below.

- September 1994 – *Advanced Hybrid™* filter concept proposed to DOE
- October 1995–September 1997 – Phase I – *Advanced Hybrid™* filter successfully demonstrated at 55-kW (200-acfm) scale
- March 1998–February 2000 – Phase II – *Advanced Hybrid™* filter successfully demonstrated at 2.5-MW (9000-acfm) scale at Big Stone Power Plant
- September 1999–August 2001 – Phase III – *Advanced Hybrid™* filter commercial components tested and proven at 2.5-MW (9000-acfm) scale at Big Stone Power Plant
- Summer 2000 – Minor electrical damage to the bags observed
- January–June 2001 – To prevent electrical damage, the *Advanced Hybrid™* filter perforated plate configuration was developed, tested, and proven to be superior to the original design.
- July 2001–March 2005 – Project to evaluate Mercury Control with the *Advanced Hybrid™* filter – Results are the focus of this final technical report.
- Fall 2002–March 2005 – Full-scale commercial *Advanced Hybrid™* filter demonstration at the 470-MW Big Stone Power Station

1.3 Concept of the *Advanced Hybrid™* Filter for Particulate Control

The goals for the *Advanced Hybrid™* filter are as follows: > 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 *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 re-collection 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 membrane fabric to collect the particles that reach the filtration surface. Charge on the particles also enhances collection and minimizes pressure drop, since charged particles tend to form a more porous dust cake. The goal is to employ only

enough ESP plate area to precollect approximately 90% of the dust. ESP models predict that 90%–95% collection efficiency can be achieved with full-scale precipitators with a specific collection area (SCA) of less than 20 m² collection area/m³/s (100 ft² of collection area/1000 acfm) (8). Fabric filter (FF) models predict that face velocities greater than 3.7 m/min (12 ft/min) are possible if some of the dust is precollected and the bags can be adequately cleaned. The challenge is to operate at high air-to-cloth (A/C) ratios 2.4–4.3 m/min (8–14 ft/min) for economic benefits while achieving ultrahigh collection efficiency and controlling pressure drop. The combination of GORE-TEX[®] membrane filter media (or similar membrane filters from other manufacturers), small SCA, high A/C ratio, and unique geometry meets this challenge.

Studies have shown that FF collection efficiency is likely to deteriorate significantly when the face velocity is increased (9, 10). For high collection efficiency, the pores in the filter media must be effectively bridged (assuming they are larger than the average particle size). 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 solution is to employ a sophisticated fabric that can ensure ultrahigh collection efficiency and endure frequent high-energy cleaning. In addition, the fabric should be reliable under the most severe chemical environment likely to be encountered (such as high SO₃).

Assuming that low particulate emissions can be maintained through the use of advanced filter materials and that 90% of the dust is precollected, operation at face velocities in the range of 2.4–4.3 m/min (8–14 ft/min) should be possible, as long as the dust can be effectively removed from the bags and transferred to the hopper without significant redispersion and re-collection. With pulse-jet cleaning, heavy residual dust cakes are not typically a problem because of the fairly high cleaning energy that can be employed. However, the high cleaning energy can lead to significant redispersion of the dust and subsequent re-collection on the bags. The combination of a very high-energy pulse and a very light dust cake tends to make the problem of redispersion much worse. The barrier that limits operation at high A/C ratios is not so much the dislodging of dust from the bags as it is the transferring of the dislodged dust to the hopper. The *Advanced Hybrid*[™] filter achieves enhanced bag cleaning by employing electrostatic effects to

precollect a significant portion of the dust and by trapping the redispersed dust that comes off the bags following pulsing in the electrostatic zone.

An *Advanced Hybrid*TM filter incorporating the perforated plate configuration was designed and installed on the 2.5-MW (9000-acfm) slipstream pilot unit at the Big Stone Power Plant. Figure 1.3.1 is a simplified top view of the 2.5-MW (9000-acfm) *Advanced Hybrid*TM filter configuration. The perforated plates serve two very important functions: as the primary collection surface and as a protective grid for the bags. With approximately 45% open area, there is adequate collection area on the plates to collect the precipitated dust while not restricting the flow of flue gas toward the bags during normal filtration. During pulse cleaning of the bags, most of the reentrained dust from the bags is forced back through the perforated plates into the ESP zone where it is collected on the plates. Excellent ESP collection efficiency is the result of forcing all of the flue gas through the perforated plate holes before it reaches the bags. This ensures that all of the charged dust particles pass within a maximum of one-half of the hole diameter distance of a grounded surface. In the presence of the electric field, the particles then have a high likelihood of being collected on the plates. Test results with and without the electric

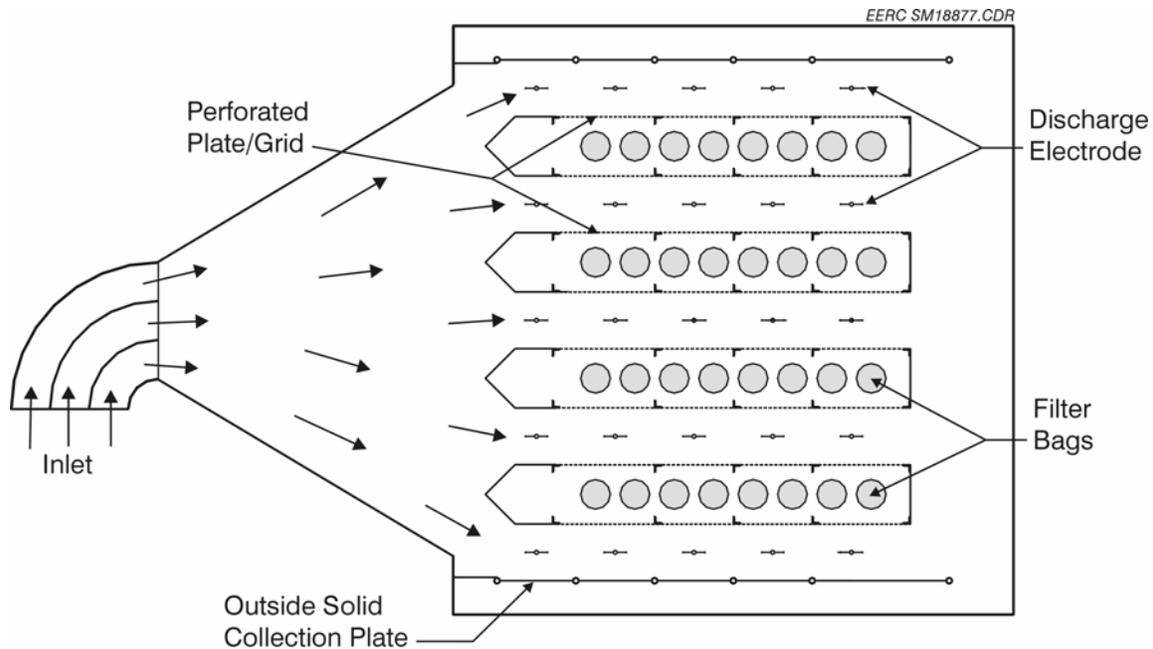


Figure 1.3.1. Top view of the perforated plate configuration for the 2.5-MW (9000-acfm) *Advanced Hybrid*TM filter.

field energized have shown that about 95% of the dust is collected before the flue gas reaches the bags.

1.4 Pressure Drop Theory and Performance Evaluation Criteria

Pressure drop across the bags is one of the main operational parameters that defines overall performance. It must be within capacity limits of the boiler fans at the maximum system flow rate. Since acceptable pressure drop is so critical to successful operation, a detailed discussion of the theory and factors that control pressure drop follows.

For viscous flow, pressure drop across a FF is dependent on three components:

$$dP = K_f V + K_2 W_R V + \frac{K_2 C_i V^2 t}{7000} \quad [\text{Eq. 1}]$$

where:

dP = differential pressure across baghouse tube sheet kPa (in. W.C.)

K_f = fabric resistance coefficient kPa-min/m (in. W.C.-min/ft)

V = face velocity or A/C ratio m/min (ft/min)

K_2 = specific dust cake resistance coefficient kPa-m-min/kg (in. W.C.-ft-min/lb)

W_R = residual dust cake weight kg/m^2 (lb/ft^2)

C_i = inlet dust loading g/m^3 (grains/acf)

t = filtration time between bag cleaning (min)

The first term in Eq. 1 accounts for the pressure drop across the fabric. For conventional fabrics, the pore size is quite large, and the corresponding fabric permeability is high, so the pressure drop across the fabric alone is negligible. To achieve better collection efficiency, the pore size can be significantly reduced, without making fabric resistance a significant contributor to pressure drop. The GORE-TEX[®] membrane filter media allows for this optimization by providing a microfine pore structure while maintaining sufficient fabric permeability to permit operation at high A/C ratios. A measure of the new fabric permeability is the Frazier number which is the volume of gas that will pass through a square foot of fabric sample at a pressure drop of 0.12 kPa (0.5 in. W.C.). The Frazier number for new GORE-TEX[®] bags is in the range from 1.2 to 2.4 m/min (4 to 8 ft/min). Through the filter, viscous (laminar) flow conditions exist, so the pressure drop varies directly with flow velocity. Assuming a new fabric Frazier number of

1.8 m/min (6 ft/min), the pressure drop across the fabric alone would be 0.25 kPa (1.0 in. W.C.) at an A/C ratio (filtration velocity) of 3.7 m/min (12 ft/min).

The second term in Eq. 1 accounts for the pressure drop contribution from the permanent residual dust cake that exists on the surface of the fabric. For operation at high A/C ratios, the bag cleaning must be sufficient to maintain a very light residual dust cake and ensure that the pressure drop contribution from this term is reasonable. The contribution to pressure drop from this term is one of the most important indicators of longer-term bag cleanability.

The third term in Eq. 1 accounts for the pressure drop contribution from the dust accumulated on the bags since the last bag cleaning. K_2 is determined primarily by the fly ash particle-size distribution and the porosity of the dust cake. Typical K_2 values for a full dust loading of pulverized coal (pc)-fired fly ash range from about 0.5 to 2.5 kPa-m-min/kg (4 to 20 in. W.C.-ft-min/lb) but may, in extreme cases, cover a wider range. Within this term, the bag-cleaning interval, t , is the key performance indicator. The goal is to operate with as long of a bag-cleaning interval as possible, since more frequent bag pulsing can lead to premature bag failure and require more energy consumption from compressed air usage. An earlier goal for the pilot-scale tests was to operate with a pulse interval of at least 10 min while operating at an A/C ratio of 3.7 m/min (12 ft/min). While this goal was exceeded in the pilot-scale tests, a pulse interval of only 10 min is now considered too short to demonstrate good *Advanced Hybrid*TM filter performance over a longer period. With a shorter pulse interval, the *Advanced Hybrid*TM filter does not appear to make the best use of the electric field, because of the reentrainment that occurs just after pulsing. Current thought is that a pulse interval of at least 60 min is needed to demonstrate the best long-term performance.

Total tube sheet pressure drop is another key indicator of overall performance of the *Advanced Hybrid*TM filter. Here, the goal was to operate with a tube sheet pressure drop of 2.0 kPa (8 in. W.C.) at an A/C ratio of 3.7 m/min (12 ft/min). Note that the average pressure drop is not the same as the pulse-cleaning trigger point. For many of the previous and current tests, the pulse trigger point was set at 2.0 kPa (8 in. W.C.), but the average pressure drop was significantly lower.

To help analyze filter performance, the terms in Eq. 1 can be normalized to the more general case by dividing by velocity. The dP/V term is commonly referred to as drag or total tube sheet drag, D_T :

$$\frac{dP}{V} = D_T = K_f + K_2 W_R + \frac{K_2 C_i V t}{7000} \quad [\text{Eq. 2}]$$

The new fabric drag and the residual dust cake drag are typically combined into a single term called residual drag, D_R :

$$D_T = D_R + \frac{K_2 C_i V t}{7000} \quad [\text{Eq. 3}]$$

The residual drag term then is the key indicator of how well the bags are cleaning over a range of A/C ratios, but may still be somewhat dependent on A/C ratio. For example, it may be more difficult to overcome a dP of 2.5 kPa (10 in. W.C.) to clean the bags than cleaning at a dP of 1.3 kPa (5 in. W.C.) For most baghouses, the residual drag typically climbs somewhat over time and must be monitored carefully to evaluate the longer-term performance. Current thought is that excellent *Advanced Hybrid*TM filter performance can be demonstrated with a residual drag value of 0.6 or lower.

Between bag cleanings, from the second term in Eq. 3, the drag increases linearly with K_2 (dust cake resistance coefficient), C_i (inlet dust concentration), V (filtration velocity), and t (filtration time). For conventional baghouses, the C_i term is easily determined from an inlet dust loading measurement, and approximate K_2 values can be determined from the literature or by direct measurement. However, for the *Advanced Hybrid*TM filter, the concentration of the dust that reaches the bags is generally not known and would be very difficult to measure experimentally. Early in the development of the *Advanced Hybrid*TM filter, results indicated approximately 90% of the dust was precollected and did not reach the fabric. However, subsequent development work showed that the amount of precollected dust is likely to fluctuate significantly with changes to the electrical field and the dust resistivity. Since C_i is not known, for evaluation of *Advanced Hybrid*TM filter performance, the K_2 and C_i can be considered together:

$$K_2 C_i = \frac{(D_T - D_R) 7000}{V t} \quad [\text{Eq. 4}]$$

Evaluation of $K_2 C_i$ can help in assessing how well the ESP portion of the *Advanced Hybrid*TM filter is functioning, especially by comparing with the $K_2 C_i$ during short test periods in which the ESP power was shut off. For the Big Stone ash, the $K_2 C_i$ value has typically been about 20 without the ESP field. For the 2.5-MW (9000-acfm) pilot *Advanced Hybrid*TM filter, longer-term $K_2 C_i$ values of 1.0 have been demonstrated with the ESP field on, which is

equivalent to 95% precollection of the dust by the ESP. Again, the goal is to achieve as low of a K_2C_i value as possible; however, good *Advanced Hybrid*TM filter performance can be demonstrated with K_2C_i values up to 4, but this is interdependent on the residual drag and filtration velocity.

Eq. 4 can be solved for the bag-cleaning interval, t , as shown in Eq. 5. The bag-cleaning interval is inversely proportional to the face velocity, V , and the K_2C_i term and directly proportional to the change in drag before and after cleaning (delta drag). The delta drag term is dependent on the cleaning set point or maximum pressure drop as well as the residual drag. The face velocity, delta drag, and K_2C_i terms are relatively independent of each other and should all be considered when the bag-cleaning interval is evaluated. However, as mentioned above, the drag may be somewhat dependent on velocity if the dust does not clean off the bags as well at high velocity as at low velocity. Similarly, the K_2C_i is somewhat dependent on velocity for a constant plate collection area. At the greater flow rates, the SCA of the precipitator is reduced, which will result in a greater dust concentration, C_i , reaching the bags.

$$t = \frac{(D_T - D_R)7000}{VK_2C_i} \quad [\text{Eq. 5}]$$

By evaluating these performance indicators, the range in possible A/C ratios can be calculated by using Eq. 1. For example, using the acceptable performance values of a 60-min pulse interval and a residual drag of 0.6, Eq. 1 predicts that a K_2C_i value of 2.33 would be needed when operating at an A/C ratio of 3.0 m/min (10 ft/min) and a pulse trigger of 2.0 kPa (8 in. W.C.). Obviously, deterioration in the performance of one indicator can be offset by improvement in another. Results to date show that performance is highly sensitive to the A/C ratio and that excellent *Advanced Hybrid*TM filter performance can be achieved as long as a critical A/C ratio is not exceeded. If the A/C ratio is pushed too high, system response is to pulse the bags more rapidly. However, too rapid pulsing tends to make the residual drag increase faster and causes the K_2C_i to also increase, both of which lead to poorer performance. The design challenge is to operate the *Advanced Hybrid*TM filter at the appropriate A/C ratio for a given set of conditions.

2.0 GOALS AND OBJECTIVES

The overall project objective was to demonstrate 90% total mercury control with commercially available sorbents in the *Advanced Hybrid*TM filter at a lower cost than mercury control estimates for conventional technologies.

Test goals included the following:

- Determine if the bench-scale mercury breakthrough results can be duplicated when real flue gas is sampled.
- Compare the level of mercury control between the *Advanced Hybrid*TM filter and a pulse-jet baghouse (PJBH) with sorbents under similar conditions at the 55-kW (200-acfm) pilot scale.
- Demonstrate 90% mercury capture for both a western subbituminous (WSB) and an eastern bituminous (EB) coal.
- Demonstrate mercury capture with the 2.5-MW (9000-acfm) *Advanced Hybrid*TM filter at Big Stone.
- Demonstrate 90% mercury capture over a longer time (3 months) with the 2.5-MW (9000-acfm) *Advanced Hybrid*TM filter at Big Stone.
- Evaluate the mercury capture effectiveness of the *Advanced Hybrid*TM filter when used with elemental mercury oxidation additives and a spray dryer absorber (SDA).

To meet the objectives, the work was organized into six tasks. The first five tasks were included in the original plan, and Task 6 was added midway through the project:

- Task 1: Project Management, Reporting, and Technology Transfer
- Task 2: Bench-Scale Experiments at the EERC
- Task 3: Pilot-Scale Tests on the 55-kW (200-acfm) Unit at the EERC
- Task 4: Field Demonstration on the 2.5-MW (9000-acfm) Unit at the Big Stone Power Plant
- Task 5: Facility Removal and Disposition
- Task 6: Mercury Control Enhancement with Oxidation Additives

Details of the work completed for each task are given in following sections of this report.

3.0 SCOPE OF WORK

3.1 Task 1 – Project Management, Reporting, and Technology Transfer

Task 1 included all of the project management requirements, planning, coordination among team members, supervision of tests, review of results, meeting attendance, and all aspects of reporting.

3.2 Task 2 – Bench-Scale Experiments at the EERC

The bench-scale tests were for the purposes of verifying previous results, expanding on the SO₂ and NO₂ concentration effect, linking the synthetic gas results to the results with real flue gas, and screening sorbents.

The bench-scale tests were divided into three series that follow a logical progression. The purpose of the first series of tests was to ensure that previous results obtained by the EERC and others could be duplicated and, second, to include SO₂ and NO₂ as variables. Series 1 tests were intended to verify the previous bench-scale work and expand on the SO₂ and NO₂ concentration effect. In previous work, no tests were completed in which both the SO₂ and NO₂ were varied at the same time. In all of these tests, the inlet Hg⁰ concentration was typically 15 µg/m³, and each test was run for approximately 4 hr. The 150 mg of NORIT FGD activated carbon sorbent is equivalent to a sorbent-to-mercury ratio of 3700 after 3 hr of exposure. This concentration has been shown to provide consistent results in previous testing and is sufficient to accurately measure the amount of mercury in the spent sorbent for mass balance closure.

The second series of bench-scale tests was for the purpose of comparing the bench-scale fixed-bed results sampling real flue gas to those obtained with simulated flue gas for both a WSB and an EB coal. The simulated flue gas concentrations were based on the actual concentrations measured in the combustion tests. The real flue gas tests were part of the pilot-scale tests in Task 3, using a slipstream bench-scale system sampling flue gas from the particulate test combustor (PTC).

Series 2 tests were completed to compare NORIT FGD performance on mercury capture in real and simulated WSB coal flue gases. Similar tests with a bituminous coal were planned but not completed because the pilot-scale tests with the bituminous coal showed that the FGD carbon was ineffective at mercury control for the flue gas conditions produced from combustion of this specific bituminous coal.

A third series of bench-scale tests was planned for the purpose of screening alternative sorbents, such as an iodine-impregnated activated carbon (IAC). However, since IAC is more costly than FGD, it must be effective at lower concentrations than FGD. The plan was to evaluate the IAC for both a subbituminous and a bituminous coal at two concentration levels and two temperatures. However, since available pilot-scale results indicated no improvement in mercury removal over the FGD carbon, there was no basis for running bench-scale IAC tests.

The plan was to conduct additional screening tests on other promising alternative sorbents to be selected based on new information and availability and then, depending on initial results, further evaluate them in pilot-scale testing in Task 3. Several versions of a non-carbon-based sorbents developed outside the EERC were tested, but results showed poor mercury removal, so there was no advantage over the FGD carbon. Late in the project, an EERC-developed sorbent was testing in the pilot-scale tests. However, this was based on promising results from other research, so no specific bench-scale tests on this sorbent were completed under Task 2.

3.3 Task 3 – Pilot-Scale Tests on the 55-kW (200-acfm) Unit at the EERC

A total of 8 weeks of testing on the EERC 55-kW (200-acfm) particulate test combustor (PTC) was completed under Task 3. A week of testing includes an 8-hr heatup period on gas and then 50–100 hr of steady-state operation firing coal. This allows multiple longer-term test periods where the PTC is operated around the clock.

The first 2 weeks were for the purpose of generating baseline data without carbon injection for a bituminous and a subbituminous coal in both the PJBH and the *Advanced Hybrid*TM filter models. These tests were for the purpose of establishing the amount of mercury capture by fly ash and determining whether the amount of mercury capture is different between the PJBH and the *Advanced Hybrid*TM filter. Another purpose was to establish the inlet and outlet speciated mercury concentrations and whether there was a change in mercury speciation across both devices. A third purpose for these baseline tests was to provide flue gas to support the bench-scale testing with real flue gas under Task 2.

Weeks 3 and 4 were conducted to prove the ability of the technology to control mercury at the 90% level with a WSB coal using NORIT FGD carbon. Both continuous and batch injections were tested at different injection rates to evaluate their effects on mercury emission.

Week 5 was for testing mercury control with NORIT FGD in the *Advanced Hybrid*TM filter with an EB coal.

Week 6 was initially planned for testing alternative sorbents in the *Advanced Hybrid*TM filter. Because no alternative sorbent was identified at that point in the project, Week 6 of testing was completed with the FGD carbon combined with cofiring tire-derived fuel (TDF) to evaluate the beneficial effect of cofiring TDF on mercury removal in *Advanced Hybrid*TM filter.

Week 7 testing consisted of evaluations of a unique mercury sorbent cartridge developed by W.L. Gore.

Week 8 testing was completed near the end of the project to determine the amount of mercury collected on the perforated plates in the *Advanced Hybrid*TM filter compared to the total mercury removal across the *Advanced Hybrid*TM filter. Testing of newly developed EERC sorbent was also conducted in Week 8.

3.4 Task 4 – Field Demonstration on the 2.5-MW (9000-acfm) Unit at the Big Stone Power Plant

The purpose of Task 4 was to demonstrate mercury control with the *Advanced Hybrid*TM filter at a much larger scale by utilizing the 2.5-MW (9000-acfm) *Advanced Hybrid*TM filter, which was previously installed on a slipstream at the Big Stone Power Plant. Over the time from November 2001 through June 2003, four separate periods of testing were completed with the 2.5-MW (9000-acfm) *Advanced Hybrid*TM filter, ranging from 1 week to 2 months in duration.

The first field test at Big Stone was completed the week of November 5–10, 2001, with baseline testing on the first day, followed by carbon injection in both the *Advanced Hybrid*TM filter and pulse-jet operational modes for the remainder of the week.

The second field test consisted of a month of baseline operation followed by a month of carbon injection for mercury control. These tests were completed from June 28–September 6, 2002. Carbon injection along with continuous mercury monitor (CMM) measurements were completed during the entire month from August 6 to September 6, except during an unplanned plant outage during the period from August 29 to September 2. The primary goal of the work was to demonstrate longer-term mercury control with the *Advanced Hybrid*TM filter and evaluate the effect of carbon injection on the *Advanced Hybrid*TM filter operational performance. Another goal of the test was to evaluate the effect of supplemental tire burning on mercury capture.

During November 19–22, 2002, another short-term test was completed with the 2.5-MW (9000-acfm) *Advanced Hybrid*TM filter to coincide with stack mercury testing for the full-scale *Advanced Hybrid*TM filter at the Big Stone Power Plant. The primary purpose of the test was to

evaluate the effect of HCl injection into flue gas along with the activated carbon on mercury control.

The fourth field test was a 1-month field completed from May 6 to June 3, 2003, to further demonstrate long-term mercury control with the *Advanced Hybrid*TM filter unit by carbon injection. Another goal was to evaluate the impacts of various operating parameters such as filtration face velocity, carbon injection rate, and injection location on mercury control with the *Advanced Hybrid*TM filter technology.

Two *Advanced Hybrid*TM filter hopper ashes collected on May 10 and 21, 2003, were evaluated at the EERC for mercury stability as part of another project. The two ash samples were analyzed for their mercury contents, loss on ignition (LOI), and major chemical compositions. A series of tests including 1) synthetic groundwater leaching procedure (SGLP), 2) long-term leaching (LTL), 3) microbiological release, 4) long-term ambient temperature release, and 5) thermal desorption at elevated temperatures were completed to evaluate the stability of mercury on the *Advanced Hybrid*TM filter ashes under different conditions.

3.5 Task 5 – Facility Removal and Disposition

The plan was to dismantle and remove the 2.5-MW (9000-acfm) *Advanced Hybrid*TM filter at the end of this project if no further testing was anticipated in support of subsequent work at the Big Stone Power Plant. However, the 2.5-MW (9000-acfm) *Advanced Hybrid*TM filter has already been used in support of the full-scale *Advanced Hybrid*TM filter at Big Stone, so the decision was made to leave the 2.5-MW (9000-acfm) *Advanced Hybrid*TM filter in place at Big Stone until no further use of it is anticipated.

3.6 Task 6 – Mercury Control Enhancement with Oxidation Additives

Task 6 was added to the project to address the use of mercury oxidation additives to the coal to enhance mercury capture in a North Dakota lignite flue gas. A pilot-scale SDA followed by a PJBH was installed at the EERC 55-kW (200-acfm) combustion facility. Pilot-scale tests were completed to evaluate the effectiveness of NORIT FGD carbon combined with three individual Hg⁰ oxidation and sorbent enhancement additives (NaCl, CaCl₂, and SEA2) to enhance the Hg removal efficiency with an SDA–PJBH pollution control system. The sorbents and additives were selected based on previous pilot-scale testing of ESP Hg removal effectiveness. A Center lignite coal was combusted in the unit while Hg concentrations were almost continuously monitored at the SDA inlet and PJBH outlet to evaluate Hg removal

performance. The Hg sorbents and Hg⁰ oxidation and sorbent enhancement additives were evaluated separately and in combination. The testing occurred during a 4-day period, December 8–11, 2003.

4.0 EXPERIMENTAL SYSTEM

4.1 Bench-Scale System

In previous research, the EERC developed a bench-scale fixed-bed system to screen and evaluate sorbent performance on mercury capture in a simulated flue gas environment. A schematic of the system is shown in Figure 4.1.1, and Figure 4.1.2 shows the system in the EERC mercury testing laboratory. The gas-mixing system is shown in Figure 4.1.3.

The fixed-bed reactor consists of a Teflon-coated, 6.35-cm (2.5 in.)-diameter dust-loading filter holder (Figure 4.1.4). A quartz filter loaded with sorbent makes up the actual fixed bed (Figure 4.1.5). The filters are uniformly coated with the sorbents by pulling a vacuum on the outlet side of the filter holder and feeding the sorbent at the inlet side. Typically, 150 mg (3.3×10^{-4} lb) of sorbent is used for screening tests, but the process is very repeatable for mass loadings down to 10 mg (2.2×10^{-5} lb). The fixed-bed assembly is maintained at the desired temperature inside an oven (Figure 4.1.6) which can be controlled to $\pm 1^\circ\text{C}$ ($\pm 1.8^\circ\text{F}$). A Tekran mercury analyzer continuously measures the elemental mercury concentration (Figure 4.1.7). In order to monitor oxidized forms of mercury, a SnCl_2 reduction cell is used prior to the analyzer

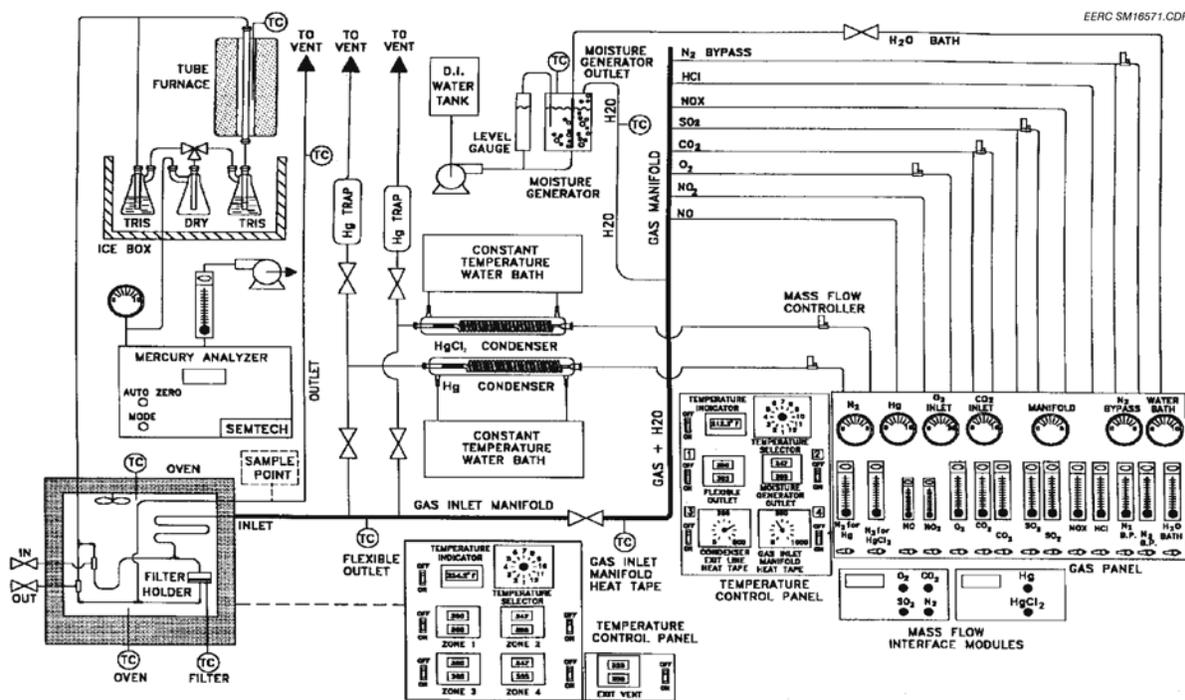


Figure 4.1.1. Schematic diagram of the mercury bench-scale system.



Figure 4.1.2. EERC mercury bench-scale system.



Figure 4.1.3. EERC bench-scale gas delivery system.



Figure 4.14. Fixed-bed filter holder.



Figure 4.1.5. Carbon fixed bed.



Figure 4.1.6. Fixed-bed oven.



Figure 4.1.7. Tekran mercury instrument.

to convert all forms of mercury for analysis. The spent sorbent is analyzed for mercury to determine a mass balance, and typically, good mass balance closures in the range from 80 to 120% are achieved.

The bench-scale results helped us to understand the interactions between sorbent and flue gas constituents, evaluate sorbent performance in different coal combustion flue gases, and link the synthetic gas results to the result with real flue gas.

4.2 55-kW (200-acfm) Pilot-Scale *Advanced Hybrid*TM Filter Unit at the EERC

Figure 4.2.1 shows the schematic diagram of the pilot-scale system. A 55-kW (200-acfm) pc-fired combustor was used to produce flue gas from coal combustion. The combustor is oriented vertically to minimize wall deposits. A refractory lining helps to ensure adequate combustion zone temperature for complete combustion of fuel and prevents rapid quenching of the coalescing or condensing fly ash. Based on the superficial gas velocity, the mean residence time of a particle in the combustor is approximately 3 sec. The coal nozzle of the unit fires axially upward from the bottom of the combustor, and secondary air is introduced concentrically to the primary air with turbulent mixing. Coal is introduced to the primary air stream via a screw feeder and ejector. An electric air preheater is used for precise control of the combustion air temperature. The temperature in the combustion zone may be over 1500°C (2750°F) depending

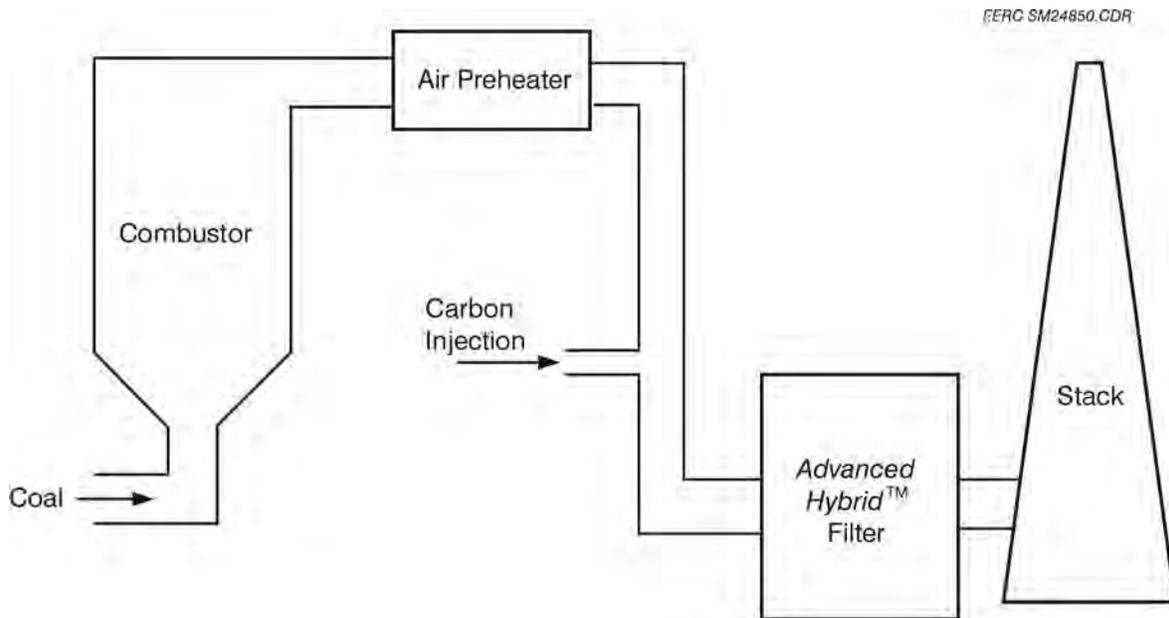


Figure 4.2.1. Schematic drawing of the pilot-scale system.

on fuel type, but flue gas temperature at the combustor outlet cools to approximately 1000°C (1832°F). The unit was designed to generate fly ash and flue gas representative of that produced in a full-scale utility boiler. The coal combustion flue gas exiting the combustor was further cooled to a temperature of approximately 135°C (275°F) and then introduced into the pilot-scale *Advanced Hybrid*TM filter.

As shown in Figure 4.2.2, the 55-kW (200-acfm) combustor has one row of four bags inside the chamber, and perforated plates are placed on each side of the bags to separate the bags from the discharge electrodes. The perforated plates serve as a collection area to capture most of the particulate matter entering the *Advanced Hybrid*TM filter unit, and the FF collects the remaining particulate matter when the flue gas flows through the bags. Instrumentation enables the continuous monitoring of system temperature, pressure, flow rates, flue gas constituent concentrations, and particle control device operating data.

A dry powder feeder (TSI 3410 or Palas RBG 2000) was installed at the *Advanced Hybrid*TM filter inlet to continuously inject sorbents into the flue gas entering the *Advanced Hybrid*TM filter chamber. Two CMMs monitored mercury vapor concentrations at the *Advanced Hybrid*TM filter chamber. Two CMMs monitored mercury vapor concentrations at the *Advanced Hybrid*TM filter chamber.

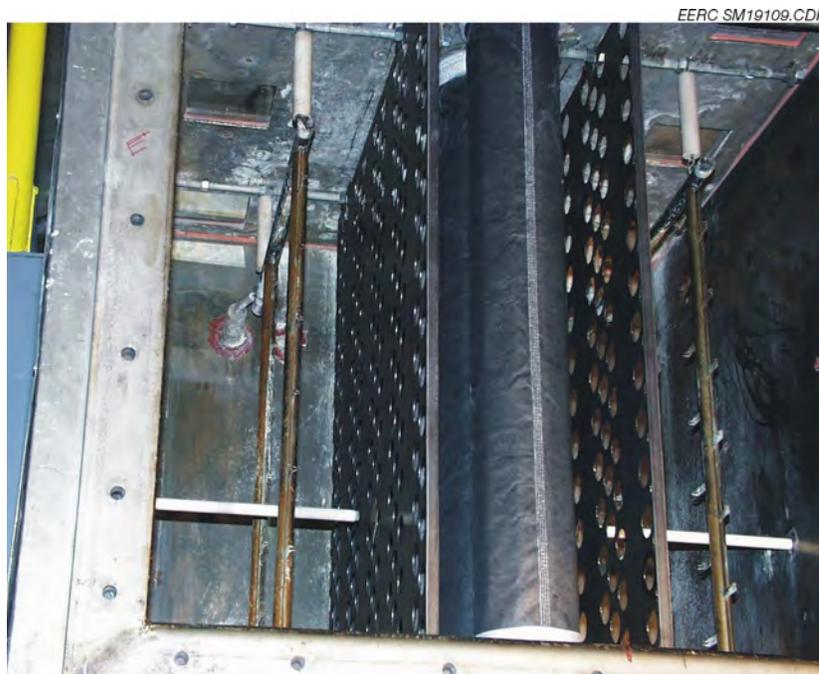


Figure 4.2.2. Front view of the 55-kW (200-acfm) *Advanced Hybrid*TM filter at the EERC.

*Hybrid*TM filter inlet and outlet during the testing period. The Ontario Hydro method was also employed to verify the CMM data.

4.3 2.5-MW (9000-acfm) Field Demonstration of the Advanced HybridTM Filter Unit at the Big Stone Power Plant

Funded by a previous DOE project, the EERC designed and installed a 2.5-MW (9000-acfm) slipstream *Advanced Hybrid*TM filter unit at the Big Stone Power Plant (Figure 4.3.1). Figure 4.3.2 shows a top-view schematic diagram of the perforated plate *Advanced Hybrid*TM filter at the Big Stone Power Plant. Perforated plates with approximately 45% open area are placed in front of the filter bags to serve as the primary collection surface and as a protective grid for the bags. The perforated plates provide enough collection area for fly ash precipitation while not restricting the flue gas flow through the filter bags. During the pulse cleaning of the bags, most of the re-entrained dust from the bags is forced back through the perforated plates into the ESP zone. Figure 4.3.3 shows a top view of the *Advanced Hybrid*TM filter at the Big Stone Power Plant during installation, without the tube sheet or filter bags.

A K-Tron dual-screw feeder was used to continuously inject sorbents into the flue gas entering the *Advanced Hybrid*TM filter chamber. The carbon feeder was located in the enclosed area of the *Advanced Hybrid*TM filter below the hopper (Figures 4.3.4 and 4.3.5). From the feeder, the sorbent was introduced into an Air-Vac eductor that was driven by compressed air. From the outlet of the eductor, the sorbent was then transported approximately 6.1 m (20.0 ft) through 0.019 m (0.062 ft) stainless steel tubing to the elbow location of the inlet piping (Figure 4.3.6). Approximately 0.9 m (3.0 ft) of straight tubing extended inside the duct, so that the carbon was injected directly upstream at a single point in the center of the 0.61-m (2.0-ft)-diameter inlet pipe.

Two CMMs monitored mercury vapor concentrations at the *Advanced Hybrid*TM filter inlet and outlet during the testing periods. The Ontario Hydro method was also performed to verify the CMM data.

4.4 Experimental Setup of Mercury Stability Tests

4.4.1 Synthetic Groundwater Leaching Procedure and Long-Term Leaching

The SGLP batch-leaching procedure is a relatively simple test that follows many of the conditions of the toxicity characteristic leaching procedure (TCLP). The test utilizes a 20:1



Figure 4.3.1. Demonstration-scale *Advanced Hybrid*TM filter at the Big Stone Power Plant.

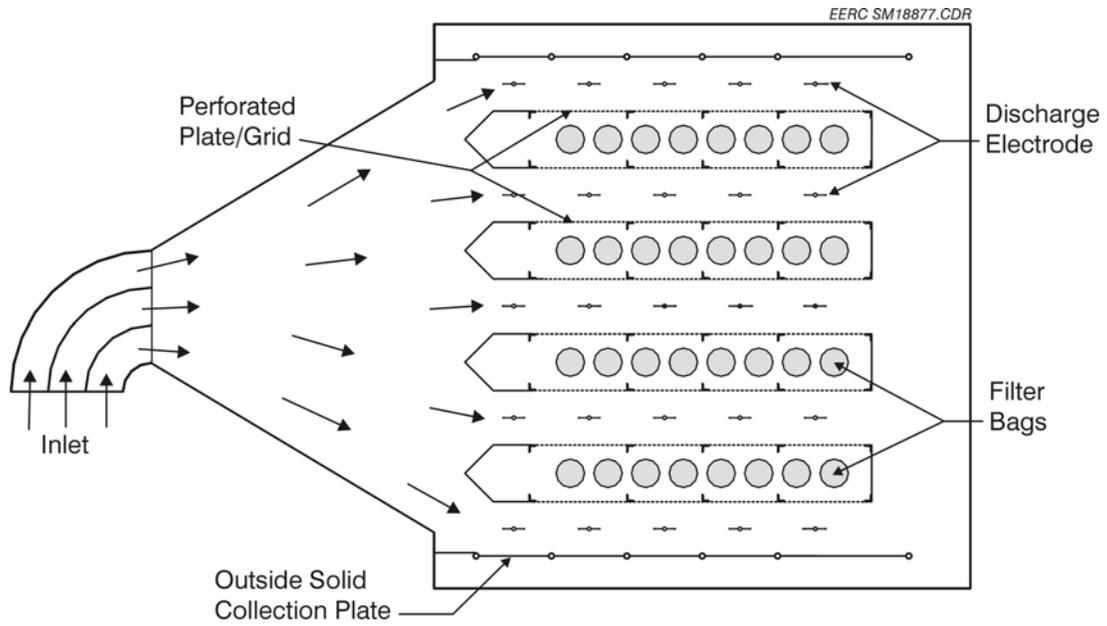


Figure 4.3.2. Top-view schematic diagram of the perforated plate 2.5-MW (9000-acfm) *Advanced Hybrid™* filter.



Figure 4.3.3. Top view of the 2.5-MW (9000-acfm) *Advanced Hybrid™* filter at the Big Stone Power Plant during installation.



Figure 4.3.4. Overview of the carbon injection system.



Figure 4.3.5. Air-Vac eductor of the carbon injection system.



Figure 4.3.6. Carbon-injecting location.

liquid-to-solid ratio, end-over-end agitation at approximately 30 rpm, an 18-hr equilibration time, and usually employs a leaching solution consisting of water from the site, water that has been prepared in the lab similar to water likely to contact the ash, or distilled deionized water. Distilled deionized water was used in this effort. For the long-term component of this procedure, multiple bottles are set up and analyzed at different time intervals. A typical SGLP and LTL test might consist of 18-hr, 30-day, and 60-day equilibration times. Although 60 days is often not long enough to have achieved complete equilibrium, it is generally long enough to determine the concentration evolution of individual parameters. The most important factor when performing LTL is to have at least three equilibration times to determine a true trend.

Leachates were filtered through 0.45- μm filter paper and analyzed for total mercury. Mercury leachate concentrations were determined using cold-vapor atomic absorption (CVAAS) and cold-vapor atomic fluorescence spectrometry (CVAFS) techniques.

4.4.2 Microbiological Releases

The apparatus used to conduct microbiologically mediated vapor-phase mercury release testing is shown in Figure 4.4.1. A 250-mL Erlenmeyer flask was fitted with an impinger inlet/outlet tube with the inlet center shortened to 6 cm below the standard taper. Cylinder gas

was passed through several sets of gold-coated quartz traps for mercury removal and admitted to each of the flasks through a gas distribution manifold that routed the gas through 0.23-mm gas chromatography (GC) capillary tubing to each of the individual flasks. A GC capillary length of approximately 60 cm, when pressurized to between 1 and 2 psig through a gas distribution manifold, provided a convenient means of regulating gas flow to approximately 2 cm³/min. The gas passed mercury vapor from the headspace of the flasks to a mercury vapor collection system at the outlet of the flasks, consisting of two traps. The nearest trap contained Supelco Carbotrap™, which collected organomercury compounds, followed by a gold-coated quartz trap, which collected elemental mercury.

The flasks were placed on a 16-flask wrist-action shaker. The experimental matrix consisted of eight flasks under anaerobic conditions (using argon) and eight flasks under aerobic conditions (using breathing-quality air). In each set of eight flasks, two contained only buffer, three contained the fly ash with buffer (starved), and three contained the fly ash with buffer and glucose (fed). An 80-gram aliquot of fly ash was placed in the flasks, and 100 mL of a phosphate buffer (with or without glucose as appropriate) was added to create a neutral pH. The fly ash-



Figure 4.4.1. Microbiologically mediated mercury vapor-phase collection apparatus.

containing flasks also had 100 μL of mixed bacterial culture added. The source of bacteria was a mixed bacterial inoculum from a brackish wetland.

Mercury vapor was collected for 35 days. The gold-coated quartz collection traps were desorbed for analysis by heating to approximately 500°C (932°F), and the mass of mercury released was determined using atomic fluorescence (AF). The CarbotrapTM collection traps were analyzed for total mercury by heating the trap to approximately 300°C (572°F), passing the released organomercury through a tube at about 800°C (1472°F), and collecting the mercury vapor on a gold-coated quartz trap, which was analyzed as described above.

Bacterial counts were performed upon completion of the 35-day period. A 1-mL aliquot of solution was taken from each flask. The aqueous supernate was serially diluted in 0.1% sodium pyrophosphate buffer (pH 7.0) and then used to inoculate a series of tubes containing 1% PTYG (peptone, tryptone, yeast extract, glucose) broth. The tubes were incubated at 30°C (86°F) and growth, as turbidity, was monitored over a 3-week period.

4.4.3 Long-Term Ambient Temperature Release

A 150-gram aliquot of ash was placed into 250-mL tall wide-mouth bottles with bonded Teflon liner caps. The caps were drilled with two holes to accommodate a silicone tube for gas inlet and a Teflon outlet bulkhead fitting. Two samples of each ash were set up for duplicate analyses. Breathing-quality air from a cylinder was passed through several sets of gold-coated quartz traps for mercury removal and admitted to each of the bottles through a gas distribution manifold that routed the gas through 0.23-mm-ID GC capillary tubing to each of the individual bottles. The pressure drop across the GC capillary tubing allowed for the regulation of air flow through each bottle by simply adjusting the length of tubing to each bottle. The length of tubing was a nominal 65 cm. This length of tubing, when pressurized to between 1 and 2 psig through a gas distribution manifold, provided a convenient means of regulating gas flow to approximately $2\text{ cm}^3/\text{min}$. Because of the variability of particle sizes between different ash samples, the sample with the initial highest gas flow was left with a 65-cm length of GC tubing, and other samples had their tubing lengths shortened until all samples had approximately the same flow rate. The air exiting the GC tubing was given a final scrubbing to remove mercury vapor using gold-coated quartz just prior to entering the bottle containing the ashes. After entering the bottles, the air passed through the ash and exited to a central mercury collection tube containing two separate gold-coated quartz traps. The gold-coated quartz nearest the exit bulkhead fitting was analyzed

after one 7-day period and two 90-day periods to determine the mass of mercury vapor released from the ashes while the top trap, in the same tube, was present to prevent mercury contamination from atmospheric mercury. This setup is illustrated in Figure 4.4.2.

Mercury collection was carried out for a total of 187 days in this experiment. The gold-coated quartz collection tubes were desorbed for analysis by heating to approximately 500°C (932°F). The mass of mercury released was determined using AF.

4.4.4 Thermal Desorption at Elevated Temperatures

A schematic for the controlled thermal desorption of mercury and mercury compounds was assembled and is shown schematically in Figure 4.4.3. The apparatus was constructed using an atomic absorption (AA) spectrophotometer for mercury detection and included a small tube furnace and temperature controller for thermal desorption. A Hewlett Packard 3395 integrator was used for data collection. Detection of thermally desorbed mercury and mercury compounds was done in an electrically heated quartz cell operated at 800°C (1472°F). The use of a heated

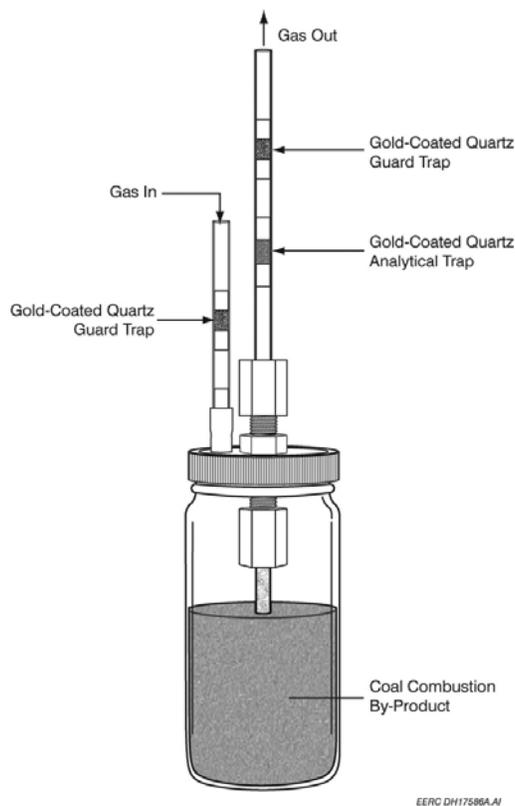


Figure 4.4.2. Mercury vapor release collection apparatus.

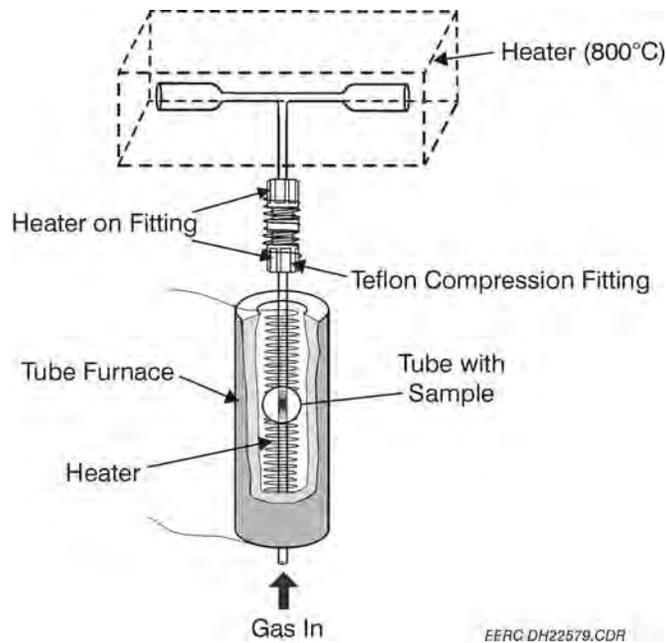


Figure 4.4.3. Mercury thermal desorption apparatus.

cell allowed detection of mercury compounds by thermally decomposing compounds to form elemental mercury, which can be detected by AA. Gas flow was 10 cm³/min of nitrogen. The temperature controller was ramped from ambient temperature to 750°C (1382°F) at a rate of 25°C (45°F) per minute.

4.5 55-kW (200-acfm) Pilot-Scale SDA/PJBH at the EERC

Figure 4.5.1 is a schematic diagram of the pilot-scale SDA/PJBH configuration. The selected additives were blended with coal and cofired in the combustion unit. The generated flue gas passed through the SDA and PJBH and NORIT FGD carbon was injected into the flue gas upstream of the SDA. Mercury samples were taken both at the SDA inlet and PJBH outlet to determine mercury capture efficiency across the system.

The SDA, Model I provided by Niro Inc., is shown schematically in Figure 4.5.2. The drying chamber is 1.2 m (3.9 ft) in diameter, with a 0.75-m (2.5-ft) cylindrical height and a 60° conical bottom. The inner shell is constructed of 2-mm stainless steel, Type AISI 316, with a 220-grit finish. A Niro Inc. Type FS-1 rotary atomizer, capable of speeds ranging from 10,500 to 30,000 rpm, was used for atomizing lime slurry. An air disperser, supplied with the rotary atomizer, was used to introduce the proper heated (149°C, 300°F) airflow pattern throughout the

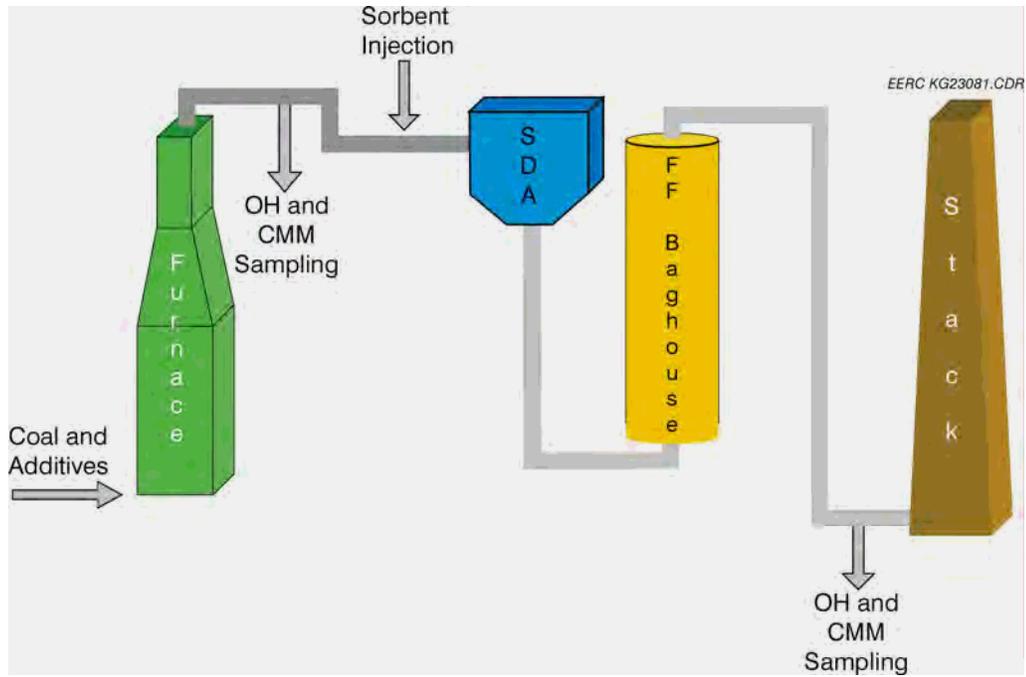


Figure 4.5.1. Schematic diagram of pilot-scale SDA/PJBH configuration.

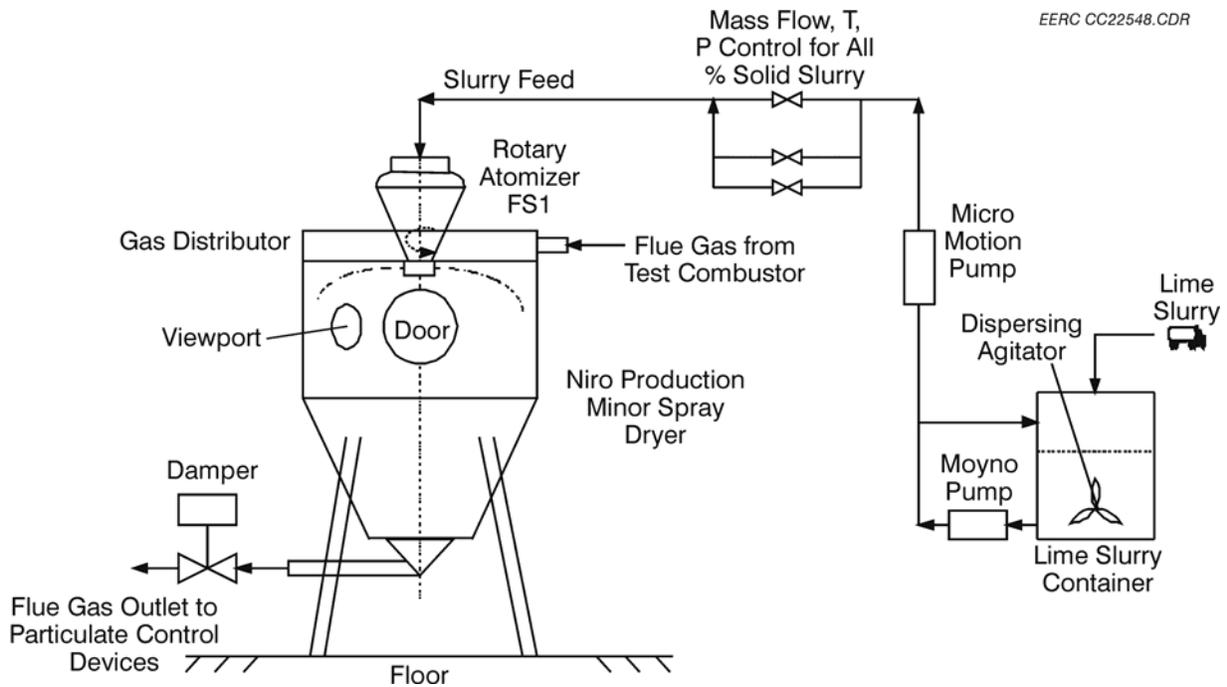


Figure 4.5.2. The SDA, Model I provided by Niro Inc.

chamber. The lime slurry for the SDA was prepared by adding deionized distilled water to slaked lime and fly ash obtained from the Antelope Valley Station in North Dakota. High-purity water was used to avoid the unintended introduction of chlorine into the system via a chlorinated water supply. Lime slurry compositions are presented in Table 4.5.1. The solid contents of the prepared slurries averaged 38 wt% on December 8 and 9 and 33 wt% on December 10 and 11.

Table 4.5.1. Lime Slurry Compositions, wt%

Component	December 8 and 9, 2003	December 10 and 11, 2003
Ca(OH) ₂	4	4
Fly Ash	34	29
Distilled Water	62	67

5.0 MERCURY MEASUREMENT

5.1 Description of Ontario Hydro Method

ASTM Method D6784-02 (Ontario Hydro method) was extensively used in this project to measure directly Hg^0 , Hg^{2+} , $\text{Hg}(\text{p})$, and $\text{Hg}(\text{g})$ in coal combustion flue gas. For this method, a sample is withdrawn from the flue gas stream isokinetically through a filter, which is followed by a series of impingers in an ice bath. A schematic of the sample train is shown in Figure 5.1.1, and Table 5.1.1 presents a list of sample train components. Particulate-bound mercury is collected on the front filter; oxidized mercury is collected in impingers containing 1 N potassium chloride solution; and elemental mercury is collected in one impinger containing a 5% nitric acid and 10% peroxide solution and in three impingers containing a solution of 10% sulfuric acid and 4% potassium permanganate. An impinger containing silica gel collects any remaining moisture. Quartz fiber filters were used as the filter media for the testing, and the filter holder was glass. A heated Teflon line was used between the probe and impinger train.

Figure 5.1.2 is a schematic of the sample recovery procedure for the impinger train. The samples were recovered into precleaned glass bottles with vented Teflon-lined lids for submission to the laboratory. The following sample fractions were recovered (specific rinse solutions are contained in the method):

- Container 1 – sample filter
- Container 2 – front-half rinse (includes all surfaces upstream of the filter)
- Container 3 – Impingers 1 through 3 (KCl impingers) and rinses
- Container 4 – Impinger 4 (HNO_3 – H_2O_2 impinger) and rinses
- Container 5 – Impingers 5 through 7 (H_2SO_4 – KMnO_4 impingers) and rinse
- Silica Gel – Impinger 8 (silica gel impinger) (note that this sample is weighed for moisture determination and is not included in the mercury analysis)

The sample fractions were prepared and analyzed as specified in the method and summarized as follows:

- *Ash Sample (Containers 1 and 2)* – The particulate catch was digested and analyzed using EPA Method 3051 with subsequent analysis using EPA Method 7471A.
- *KCl Impingers (Container 3)* – The impingers were prepared using H_2SO_4 , HNO_3 , and KMnO_4 solutions as specified in the method.

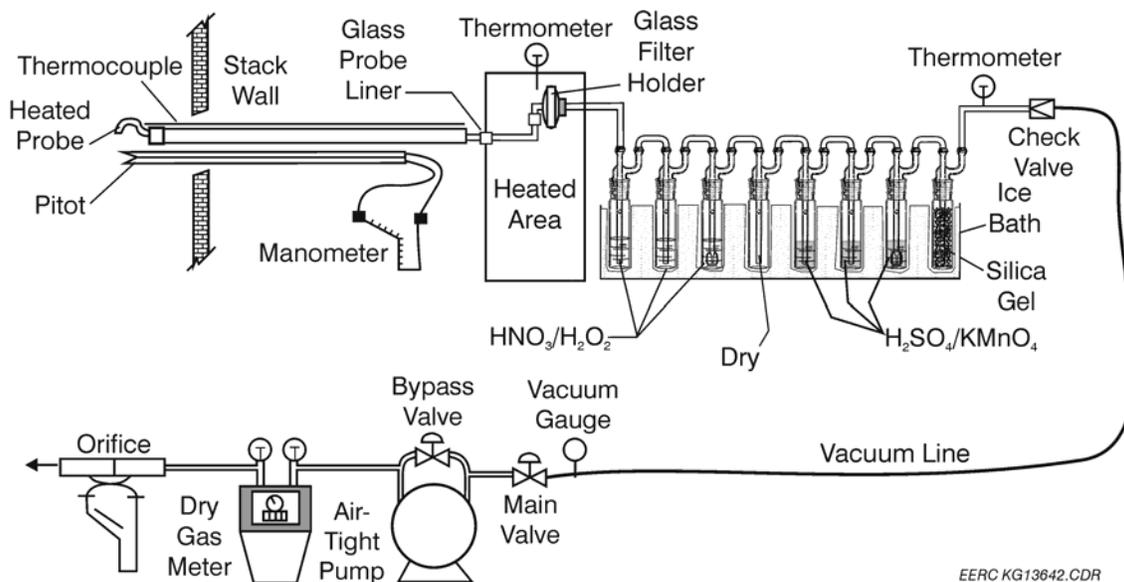


Figure 5.1.1. Schematic of the sample train.

- $HNO_3-H_2O_2$ (Container 4) – The impinger solution was prepared using HCl and $KMnO_4$ solutions as specified in the method.
- $H_2SO_4-KMnO_4$ Impingers (Container 5) – The impinger solution was prepared using hydroxylamine sulfate as specified in the method.

Table 5.1.1. Sample Train Components–EPA Method 17 Configuration

Component	Details
Nozzle	Quartz
Filter	Quartz in glass
Probe	Quartz heated to a minimum temperature of 120°C (338°F)
Connector Line	Teflon line used to connect from probe to impingers – heated to a minimum of 120°C (338°F)
Impingers 1 and 2	1 N KCl solution; modified Smith Greenburg (SG) impinger
Impinger 3	1 N KCl solution; standard SG impinger
Impinger 4	5% nitric acid–10% hydrogen peroxide; modified SG impinger
Impingers 5 and 6	10% sulfuric acid–4% potassium permanganate; modified SG impinger
Impinger 7	10% sulfuric acid–4% potassium permanganate; standard SG impinger
Impinger 8	Silica gel; modified SG impinger

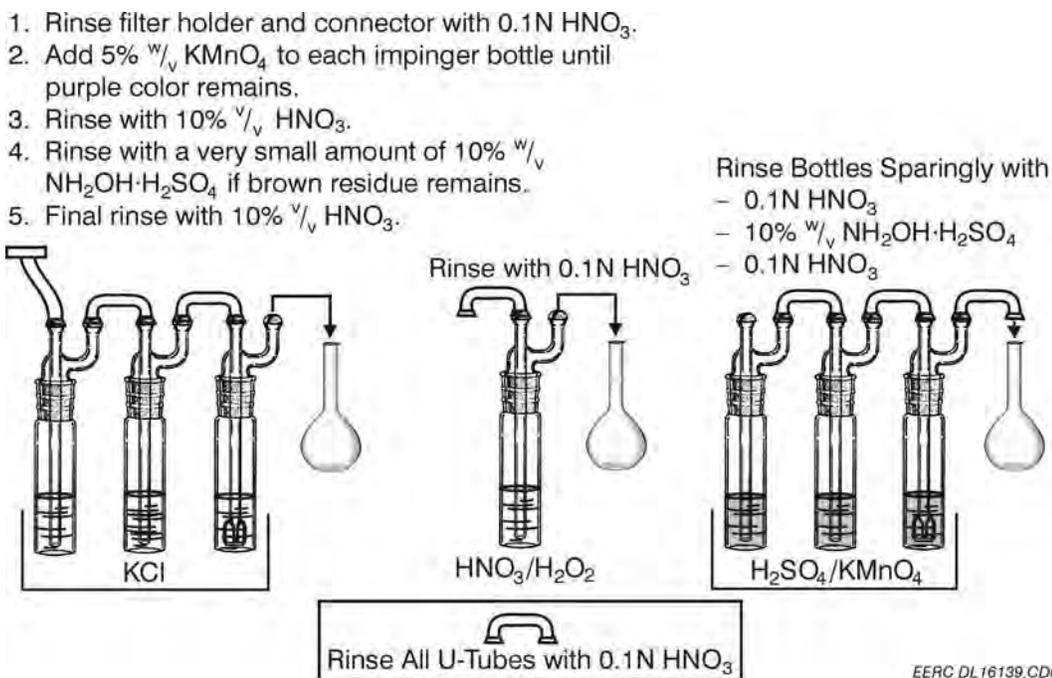


Figure 5.1.2. Sample recovery scheme for the mercury speciation sampling train.

Each prepared fraction was analyzed for total mercury by CVAAS, a method based on the absorption of radiation at 253.7 nm by mercury vapor. The mercury is reduced to the elemental state and aerated from solution in a closed system. The mercury vapor passes through a cell positioned in the light path of an atomic absorption spectrometer. Mercury concentration is proportional to the indicated absorbance. A soda-lime trap and a magnesium perchlorate trap were used to precondition the gas before it entered the absorption cell.

5.2 Description of Continuous Mercury Monitor

CMMs were also widely used in this project to provide continuous gaseous mercury species measurement in coal combustion flue gas, and they are based on the principle of either AA or AF, which provides an inherently more sensitive signal than AA.

Tekran mercury vapor analyzer (2537A) is one of the typical CMMs used in the tests. The instrument samples and traps mercury vapor into a cartridge containing an ultrapure gold adsorbent. The amalgamated mercury is thermally desorbed and detected using CVAFS. A dual-cartridge design allows alternate sampling and desorption, resulting in continuous mercury measurement.

Sir Galahad is another typical CMM used, requiring a four-step process to obtain flue gas mercury measurement. In the first step, 2 L of flue gas is pumped through a gold trap, which is maintained at a constant temperature. Before the mercury is desorbed from the gold trap, a flushing step is initiated to remove any flue gas that may be present because it has a damping effect on the mercury fluorescence. When this is completed, the analysis step begins. The heating coil is activated, and the gold trap is heated to approximately 500°C (932°F). This desorbs the mercury from the trap, and the mercury is carried into the fluorescence detector. The gold trap is rapidly cooled by pumping argon over it, in preparation for the next sample. The total time for the entire process is about 5 min per sample.

All of the CMMs were calibrated using Hg^0 as the primary standard. The Hg^0 is contained in a closed vial which is held in a thermostatic bath. The temperature of the mercury is monitored, and the amount of mercury is calculated using vapor pressure calculations. Typically, the calibration of the unit has proven stable over a 24-hour period.

Whether the CMM uses AA or AF to measure mercury, some form of gas pretreatment is necessary before accurate measurement of total mercury (or speciated mercury) can be accomplished. For the AA-type systems, only Hg^0 can be directly analyzed. Therefore, all mercury forms in the flue gas must be converted to Hg^0 . For the AF CMMs, a pretreatment/conversion system is also needed, but for a different reason. Both Hg^+ and Hg^0 collect on the gold trap; however, if HCl and NO_2 are present in the flue gas, the gold trap is permanently poisoned. To prevent this, since the HCl is much easier to remove than NO_2 , the HCl is removed prior to the flue gas passing through the gold trap. Also, if the instrument is to be used to provide mercury speciation data, then the Hg^+ must be removed from the gas stream so that the Hg^0 concentration can be measured.

For several years, the EERC has been working on the development of pretreatment–conversion systems for both AA- and AF-type mercury CMMs. The system that is currently used by the EERC consists of three primary parts:

1. An acid gas trap that removes the SO_2 and HCl without removing any of the mercury
2. A SnCl_2 gas–liquid separator to convert all Hg^+ to Hg^0
3. A gas–liquid separator that removes Hg^+ without removing Hg^0

Depending on which side of the pretreatment system the flue gas is passed through, either only Hg^0 or total mercury is measured.

The reliability of CMM measurements were evaluated using the Ontario Hydro method. All measurements of mercury in flue gas streams that are reflected in this report have been normalized and corrected to dry conditioning at 3% O₂ and 20°C (68°F).

6.0 RESULTS AND DISCUSSION

6.1 Bench-Scale Experimental Results

The bench-scale tests were for the purpose of verifying previous results, expanding on the SO₂ and NO₂ concentration effect, linking the synthetic gas results to the results with real flue gas, and screening sorbents.

6.1.1 Series 1 Bench-Scale Tests

The purpose of the first series of tests was to ensure that results obtained by the EERC and others could be duplicated and, second, to include SO₂ and NO₂ as variables. Table 6.1.1.1 lists the test matrix completed in Series 1. SO₂ and NO₂ concentrations were varied to establish their individual and combined effects on mercury capture with NORIT FGD carbon in a fixed bed reactor.

The flue gas concentrations for the Series 1 bench-scale tests are given in Table 6.1.1.2. Both SO₂ and NO₂ were varied as part of the tests.

Table 6.1.1.1. Bench-Scale Series 1 – SO₂ and NO₂ Concentration

Test No.	Sorbent Type	Temp., °C (°F)	Sorbent Concentration, mg	Flue Gas	SO ₂ , ppm	HCl, ppm	NO, ppm	NO ₂ , ppm
1	FGD	135 (275)	150	Simulated	1600	50	400	20
2	FGD	135 (275)	150	Simulated	500	50	400	20
3	FGD	135 (275)	150	Simulated	200	50	400	20
4	FGD	135 (275)	150	Simulated	1600	50	400	10
5	FGD	135 (275)	150	Simulated	500	50	400	10
6	FGD	135 (275)	150	Simulated	200	50	400	10
7	FGD	135 (275)	150	Simulated	1600	50	400	5
8	FGD	135 (275)	150	Simulated	500	50	400	5
9	FGD	135 (275)	150	Simulated	200	50	400	5

Table 6.1.1.2. Baseline Flue Gas Concentrations

Hg ⁰	15 µg/m ³
O ₂	6%
CO ₂	12%
H ₂ O	8%
N ₂	Balance
HCl	50 ppm
NO	400 ppm
NO ₂	Varied
SO ₂	Varied

The nine breakthrough curves for these tests are presented at constant SO_2 concentration with varying NO_2 and at constant NO_2 concentration with varying SO_2 concentration in Figures 6.1.1.1–6.1.1.6. For comparison, all nine are shown in Figure 6.1.1.7.

The breakthrough graphs show several effects of SO_2 and NO_2 concentration. First, the time until initial breakthrough decreased significantly with increasing SO_2 and NO_2 concentrations. At the higher concentrations, breakthrough occurred after about 30 min, and at the lower concentrations, breakthrough occurred after about 2.5 hr. This implies that a sorbent at the lower concentrations would have five times the mercury capacity of a sorbent exposed to the higher concentrations. This range is significant enough that it might dictate whether mercury control with carbon is practical for a given set of conditions. Since these are fixed-bed tests, the cumulative carbon-to-mercury ratio was infinite at the start of the test and decreased with exposure time. After 3 hr of exposure, the calculated ratio was approximately 3700, which is considered a reasonable value for control. However, after only 30 min, the cumulative ratio was 22,200, which is likely too high to be considered for economical mercury control. If these data can be shown to be indicative of sorbent performance in real systems, they would appear to be valuable for initial screening of potential sorbents for a known set of flue gas conditions. At high

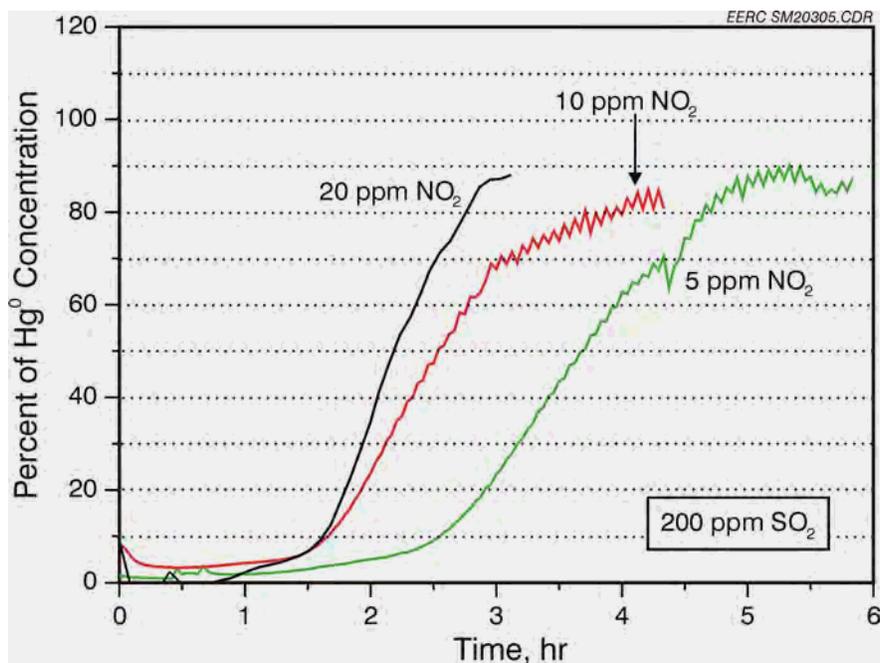


Figure 6.1.1.1. Mercury breakthrough curves at 200 ppm SO_2 with varied NO_2 : 5, 10, 20 ppm.

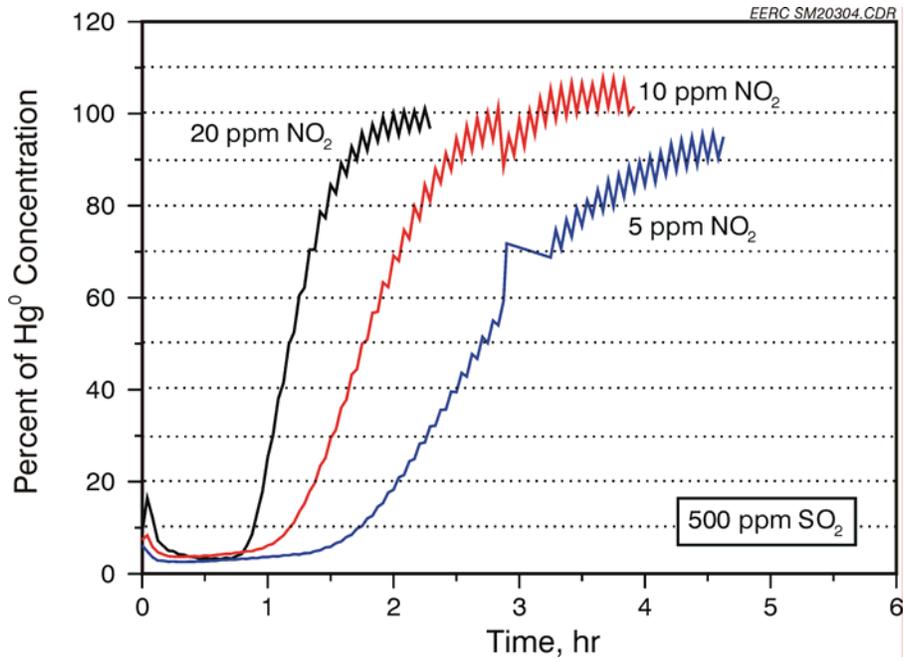


Figure 6.1.1.2. Mercury breakthrough curves at 500 ppm SO₂ with varied NO₂: 5, 10, 20 ppm.

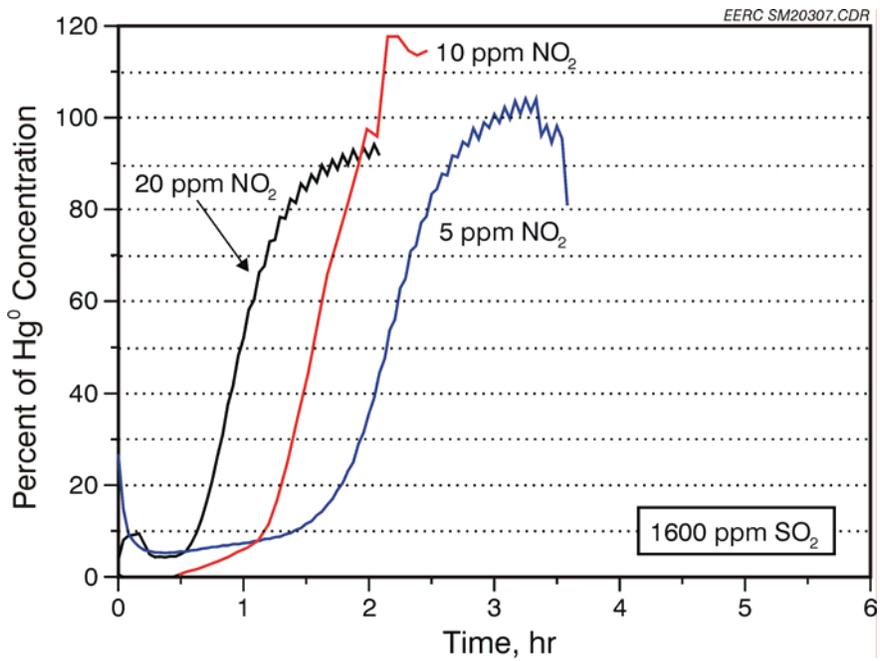


Figure 6.1.1.3. Mercury breakthrough curves at 1600 ppm SO₂ with varied NO₂: 5, 10, 20 ppm.

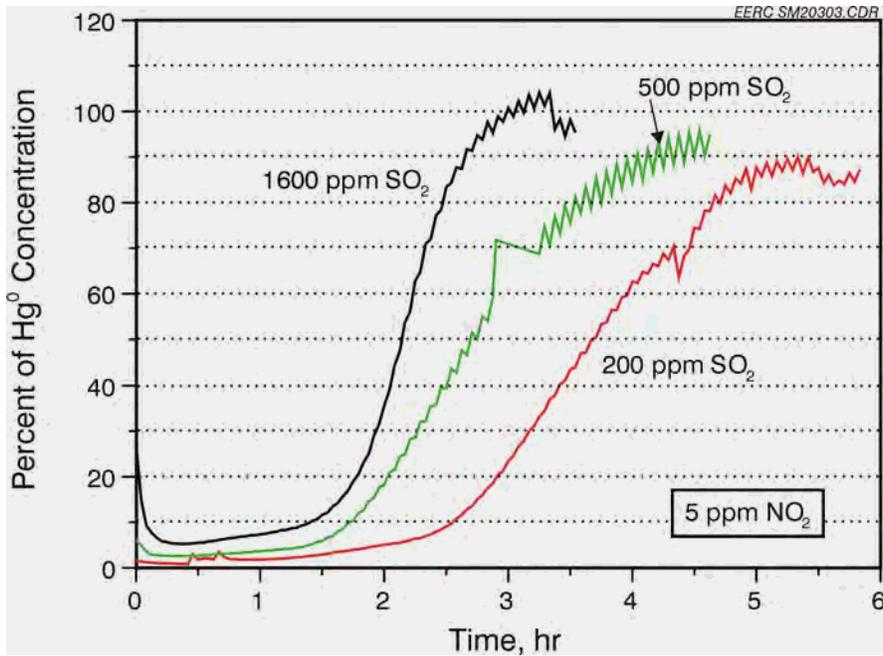


Figure 6.1.1.4. Mercury breakthrough curves at 5 ppm NO₂ with varied SO₂: 200, 500, 1600 ppm.

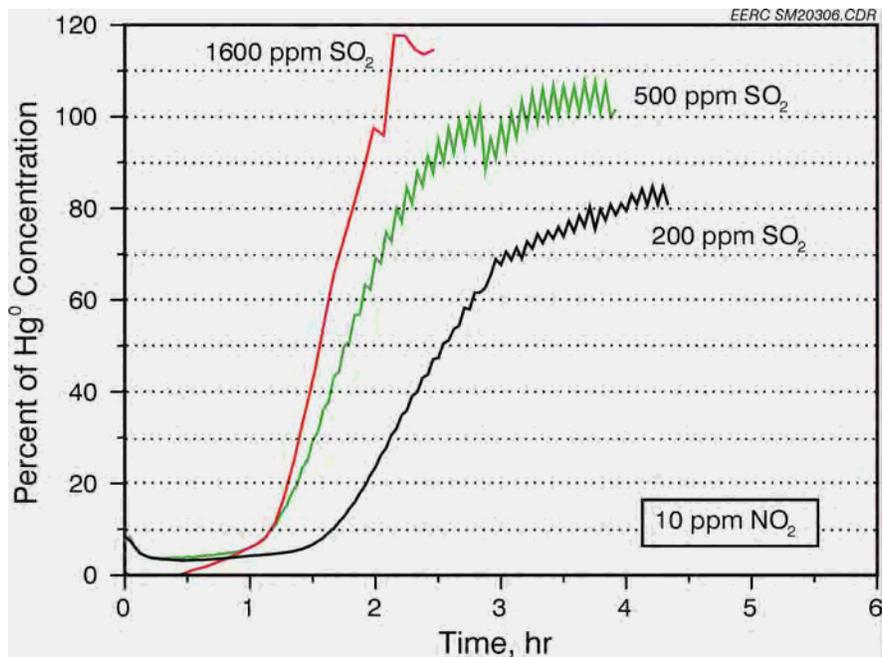


Figure 6.1.1.5. Mercury breakthrough curves at 10 ppm NO₂ with varied SO₂: 200, 500, 1600 ppm.

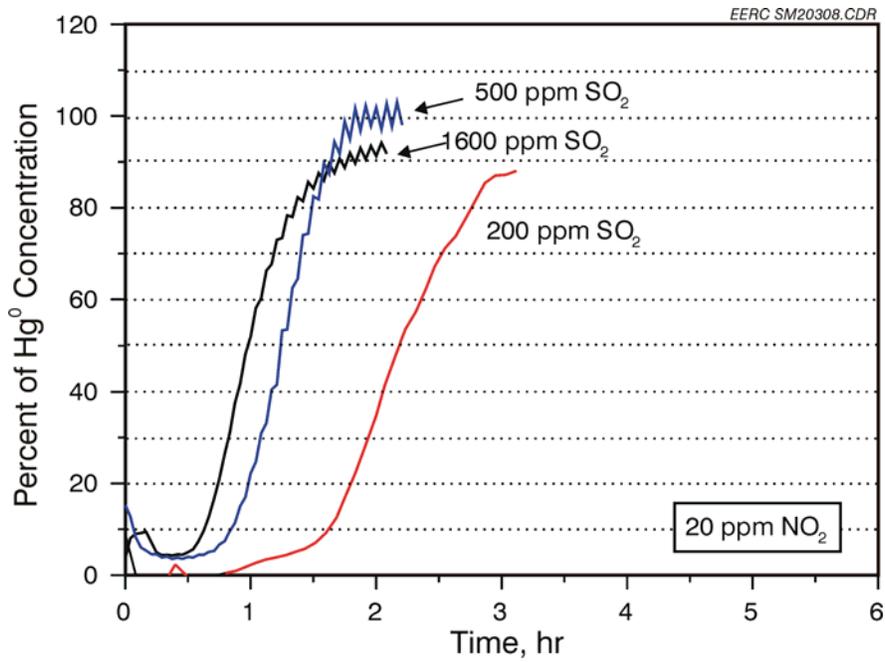


Figure 6.1.1.6. Mercury breakthrough curves at 20 ppm NO₂ with varied SO₂: 200, 500, 1600 ppm.

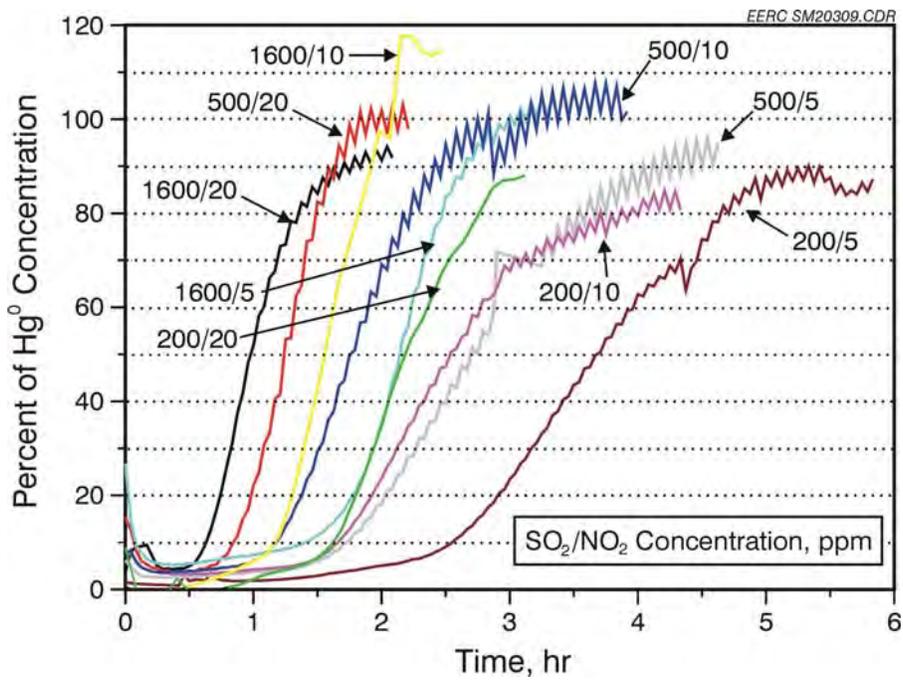


Figure 6.1.1.7. Summary of Hg breakthrough curves at varied NO₂ and SO₂.

SO₂ and NO₂ concentrations, the data suggest that effective elemental mercury control would be difficult to achieve at a reasonable carbon-to-mercury ratio.

The second obvious SO₂ and NO₂ concentration effect is that at lower concentrations the slope of the breakthrough curves is more gradual. This suggests that there is some additional sorbent capacity available for the lower SO₂ and NO₂ concentrations. However, even at the very lowest concentrations tested, the time from initial breakthrough until 50% breakthrough was extended by only about 1 hr, which upon integration yielded only about a 20% increase in sorbent capacity.

A third conclusion from these tests is that both SO₂ and NO₂ concentration have a significant effect on breakthrough capacity and that the combined effect of both of these gases is additive, at least within the range of concentrations tested. These breakthrough tests are highly repeatable and appear to be quantitative to the extent that all of the midpoint tests fell between the respective low- and high-concentration test results.

These Series 1 tests are in agreement with previous bench-scale work conducted for other projects that shows the significance of SO₂ and NO₂ concentration on the elemental mercury capture ability of various sorbents (11). Most of the previous tests were completed with either a HCl concentration of 50 ppm, which would match a medium-chlorine bituminous coal, or with no HCl. The effect of NO₂ and SO₂ concentration at much lower HCl levels of 1–5 ppm, which are more typical of WSB coals, has not previously been tested. While previous results have shown that higher NO₂ and SO₂ concentrations lead to poorer sorbent performance, the presence of 50 ppm HCl was shown to be beneficial to mercury capture. Even though low SO₂ and NO₂ concentrations with a subbituminous coal would be expected to result in good sorbent performance, the lower HCl may lead to poorer performance.

6.1.2 Series 2 Bench-Scale Tests

The second series of bench-scale tests was completed to evaluate FGD performance on mercury capture in a fixed-bed reactor using real coal combustion flue gases to compare to those obtained with simulated flue gases. The simulated flue gas concentrations were based on the actual concentrations measured in the combustion tests. The real flue gas tests were part of the pilot-scale tests in Task 3, using a slipstream bench-scale system sampling flue gas from the PTC.

Table 6.1.2.1 lists a summary test matrix including the concentrations of key acid gases. A total of three bench-scale breakthrough tests were completed on three different days of operation using the real flue gas from a combustion of WSB coal with the 55-kW unit at the EERC. The simulated flue gas concentrations were set according to the actual measured concentrations from the coal-fired test. Table 6.1.2.2 lists the flue gas concentrations (in addition to the acid gases) for the breakthrough test. The real flue gas testing results are shown in Figure 6.1.2.1 along with the simulated flue gas testing data.

From Figure 6.1.2.1, the simulated flue gas testing data are in good agreement with the results upon exposure to real flue gas since the simulated flue gas curve is within the range of the three actual flue gas curves. The results are also in reasonable agreement with the case of nearest SO₂ and NO₂ concentrations (500 ppm SO₂ and 5 ppm NO₂) from the Series 1 tests, even though the mercury concentration and speciation were somewhat different. For the Series 1 bench-scale tests, the mercury concentration was 15 µg/m³ of elemental mercury. The inlet mercury concentration from the pilot-scale tests averaged 11 µg/m³, with about 75% elemental mercury. For the comparative simulated bench-scale test from Series 2, the mercury was set at 10 µg/m³ but included only elemental mercury. Decreasing the mercury from 15 to 10 µg/m³ would be expected to extend the time until breakthrough by 50%. For the Series 1 test at 500 ppm SO₂ and 5 ppm NO₂, breakthrough occurred after about 1.75 hr (see Figure 6.1.1.4), and for the simulated Series 2 test, breakthrough occurred at about 2.25 hr. The 2.25 hr is somewhat less than the 50% increase expected, but the lower HCl value for the Series 2 test may be the reason. Considering all of these effects, the simulated flue gas breakthrough curves appear to be in good agreement with results from real flue gas.

Table 6.1.2.1. Bench-Scale Series 2 – Real Flue Gas Comparison

Test No.	Sorbent Type	Temp., °C (°F)	Sorbent Concentration, mg	Flue Gas	SO ₂ , ppm	HCl, ppm	NO, ppm	NO ₂ , ppm
10	FGD	135 (275)	150	Real	Flue gas from western coal			
11	FGD	135 (275)	150	Real	Duplicate test of western coal			
12	FGD	135 (275)	150	Real	Duplicate test of western coal			
13	FGD	135 (275)	150	Simulated	267	3	598	5

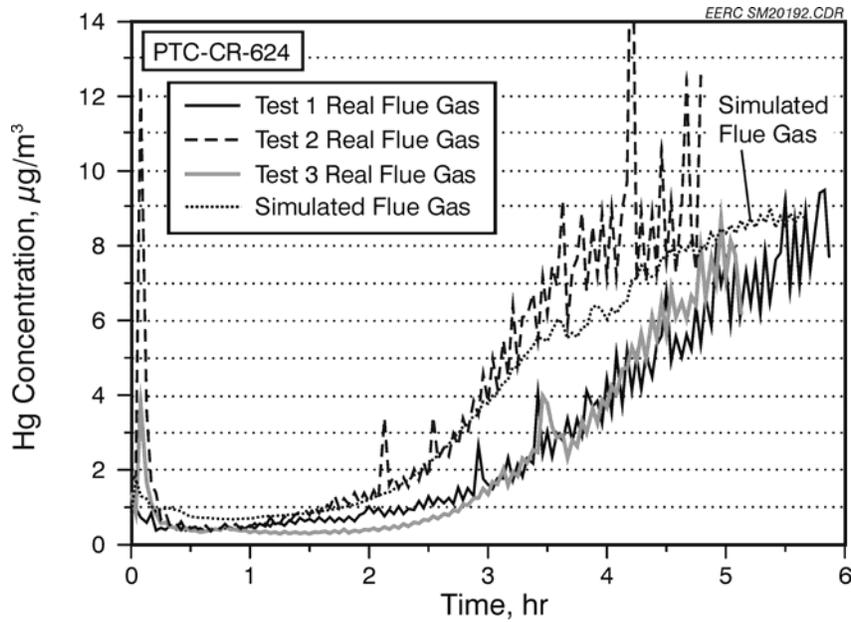


Figure 6.1.2.1. Real flue gas testing results.

Table 6.1.2.2. Flue Gas Concentrations for Bench-Scale Breakthrough Tests

Hg (total)	10 µg/m ³
O ₂	5%
CO ₂	12%
H ₂ O	10%
N ₂	Balance

6.2 Experimental Results of the Pilot-Scale 55-kW (200-acfm) *Advanced Hybrid*TM Filter Unit at the EERC

6.2.1 Summary of the Pilot-Scale Testing with the 55-kW (200-acfm) *Advanced Hybrid*TM Unit

Eight weeks of tests were completed with the 55-kW *Advanced Hybrid*TM filter pilot-scale unit at the EERC in this project. The primary goal was to evaluate the effectiveness of carbon injection on mercury control with the *Advanced Hybrid*TM filter for both bituminous and subbituminous coal flue gases and compare the *Advanced Hybrid*TM filter performance with a PJBH. Operating parameters such as injection rate, injection mode, sorbent residence time, and corona current were evaluated to understand their impacts on mercury removal. Several alternate mercury control technologies including amended silicate developed by ADA, iodine-impregnated carbon by Barneby & Sutcliffe, and pleated cartridge filter developed by W.L. Gore

were tested in real coal combustion flue gases to determine their mercury removal efficiencies with the *Advanced Hybrid*TM filter. Cofiring TDF and coal along with FGD carbon injection was tested to evaluate the beneficial effect of TDF cofiring on mercury control with the *Advanced Hybrid*TM filter. At the end of this project, an added pilot-scale test was completed to evaluate mercury capture on the perforated plates of the *Advanced Hybrid*TM filter. Table 6.2.1 summarizes the 8 weeks of testing at the EERC.

6.2.2 PTC-CR-624

6.2.2.1 Test Conditions

A 4-day test was completed January 7–10, 2002, with the EERC PTC and pilot-scale 55-kW (200-acfm) *Advanced Hybrid*TM filter. The run was designated as PTC-CR-624, where CR refers to the Cordero Rojo Complex Powder River Basin (PRB) subbituminous coal burned in this test, which was the same coal burned at the Big Stone Power Plant during November 2001. The system was continuously operated during the 4-day test to provide baseline mercury speciation data for WSB flue gas with both the *Advanced Hybrid*TM filter and a PJBH, with several different cleaning cycle configurations. The test also provided real flue gas for some of the bench-scale tests.

In the Day 1 test, the *Advanced Hybrid*TM filter was set at 4.0-mA corona current with a 30-min bag-cleaning interval. During this time period, the perforated plates, electrodes, and outside wall collection surface were rapped every 30 min, and the hopper ash was also emptied once per 30 min to maintain the ash at a constant residence time level.

The unit was switched to pulsing upon reaching a pressure drop of 2.0 kPa (8.0 in. W.C.) in Days 2 and 3, while the current level was still kept at 4.00 mA. The bag-cleaning intervals increased to 4–6 hr as the result of pulse cleaning at 2.0 kPa (8.0 in. W.C.) of pressure drop across the filter bags. During the test period, the hopper ash was emptied twice, providing approximately 17–22 hr of residence time of ash in the system.

The unit was next operated in a pulse-jet mode with a pulse trigger pressure of 2.0 kPa (8.0 in. W.C.). Because of the high A/C ratio of 3.7 m/min (12 ft/min) and no electric field to precollect any of the dust, the bag-cleaning interval was only 3 min. The hopper ash was emptied once every 30 min.

Table 6.2.1. Pilot-Scale Testing

Week/ Test	Purpose	Coal	Collection Device	Sorbent Type	C:Hg Ratio	Injection Method
1-1	Baseline	WSB	PJBH	None	NA ¹	NA
1-2	Baseline	WSB	<i>Advanced Hybrid™ filter</i>	None	NA	NA
2-1	Baseline	EB	PJBH	None	NA	NA
2-2	Baseline	EB	<i>Advanced Hybrid™ filter</i>	None	NA	NA
3-1	Hg capture, collection device	WSB	PJBH	FGD	3000 ²	Continuous
3-2	Hg capture, collection device	WSB	<i>Advanced Hybrid™ filter</i>	FGD	3000 ²	Continuous
4-1	Hg capture, residence time	WSB	<i>Advanced Hybrid™ filter</i>	FGD	3000 ²	Continuous
4-2	Hg capture, residence time	WSB	<i>Advanced Hybrid™ filter</i>	FGD	3000 ²	Batch
5-1	Hg capture, residence time	EB	<i>Advanced Hybrid™ filter</i>	FGD	3000 ²	Continuous
5-2	Hg capture, residence time	EB	<i>Advanced Hybrid™ filter</i>	FGD	3000 ²	Batch
6-1	Sorbent type and concentration	WSB	<i>Advanced Hybrid™ filter</i>	TDF cofiring /FGD	3000 ²	Continuous
6-2	Sorbent type and concentration	WSB	<i>Advanced Hybrid™ filter</i>	IAC	3000 ²	Continuous
7	Sorbent type and concentration	WSB	<i>Advanced Hybrid™ filter</i>	Gore ³	NA	NA
8 ⁴	Plate capture vs. total capture	WSB	<i>Advanced Hybrid™ filter</i>	FGD	3000 ²	Continuous

¹ Not applicable.² Nominal concentrations; actual concentrations were varied for specific tests.³ Bag insert within the *Advanced Hybrid™* filter.⁴ Newly added test.

Table 6.2.2.1. Summary of Mercury, Gas, and Solids Samples Taken

Ontario Hydro	Day 1 – One pair of simultaneous inlet and outlet Days 2–4 – Two pairs of simultaneous inlet and outlet
Method 101A	Day 1 – One pair of simultaneous inlet and outlet
HCl	Two Method 26A inlet samples on Days 2 and 4
SO ₂ , NO, NO ₂ , CO, CO ₂ , O ₂	Sampling at both inlet and outlet with portable Ecom gas analyzer Days 2 and 4
Coal	One sample a day
<i>Advanced Hybrid</i> TM filter hopper ash	One sample a day

Table 6.2.2.1 summarizes the sampling schedule for mercury, hopper ash, and flue gases. During the Day 1 test, one pair of Method 101A and one pair of Ontario Hydro measurements were completed at the *Advanced Hybrid*TM filter inlet and outlet. A total of four Ontario Hydro mercury measurements were taken for each day during the rest of the test.

6.2.2.2 Coal and Flue Gas Analyses

Approximate 2485 kg (5478 lb) of Cordero Rojo Complex was burned during the 4-day test. Table 6.2.2.2 shows the proximate and ultimate analysis results of the coal samples collected during the test. The mercury content in the raw coal samples (also listed in Table 6.2.2.2) had a mean value of 0.108 µg/g. From a combustion calculation based on the proximate and ultimate analysis results, the coal should produce 2.74 scm (96.8 acf) of dry flue gas per lb normalized to 3.0% oxygen, which corresponds to a theoretical inlet mercury concentration of 13.4 µg/m³ of dry flue gas at 3.0% O₂. The theoretical inlet mercury value is somewhat higher than the 9.2 to 12.1 µg/m³ inlet total mercury concentrations measured by the Ontario Hydro method. Possible reasons for the small difference are discussed later in this report.

Table 6.2.2.3 lists daily averaged flue gas compositions of O₂, CO₂, CO, NO, NO₂, and SO₂. Because of the low-sulfur Cordero Rojo coal, the SO₂ concentration in the flue gas was at a low level, ranging from 260 to 330 ppm. The NO and NO₂ concentrations in the flue gas were 549–695 ppm for NO and only 4–7 ppm for NO₂, respectively. The O₂ concentration was slightly increased from the inlet to the outlet because of minor air leakage in the system. Two EPA Method 26 samples were collected at the *Advanced Hybrid*TM filter inlet at Days 2 and 4 to determine HCl concentration in flue gas, and the results are shown in Table 6.2.2.3.

Table 6.2.2.2. Coal Analysis for the PTC-CR-624 Test

	As Sampled	Moisture-Free
Proximate Analysis, wt%		
Moisture Content	23.1	NA
Volatile Matter	36.43	47.37
Fixed Carbon	35.42	46.06
Ash	5.05	6.57
Ultimate Analysis, wt%		
Hydrogen	6.12	4.62
Carbon	52.53	68.31
Nitrogen	0.78	1.02
Sulfur	0.24	0.31
Oxygen	35.27	19.17
Ash	5.05	6.57
Heating Value, Btu/lb	9023	11,733
Chlorine in Coal, dry basis, µg/g		14.7
Mercury in Coal, dry basis, µg/g		
Days 1–3		0.114
Day 4		0.103
Mean		0.108

6.2.2.3 *Mercury Species in Cordero Rojo Complex Flue Gas and Mercury Transformation Across the Advanced Hybrid™ filter/PJBH Unit*

Mercury concentrations in the flue gas were normalized to a moisture-free basis and 3% O₂ level. Figure 6.2.2.1 shows speciated mercury concentrations in the flue gas at the *Advanced Hybrid™* filter inlet and outlet when the unit was operated under *Advanced Hybrid™* filter mode, with a 30-min bag-cleaning interval. The collection plates and electrodes were rapped every 30 min, and the hopper ash was also emptied every half hour during the testing period to keep the residence time of the fly ash in the chamber to a maximum of 30 min. At the *Advanced*

Table 6.2.2.3. Summary of Flue Gas Compositions During PTC-CR-624 Sampling, dry basis

		O ₂ , %	CO ₂ , %	CO, ppm	NO, ppm	NO ₂ , ppm	SO ₂ , ppm	HCl, ppm
Day 1	In	4.5	13.4	7.0	653	–	299	–
	Out	5.2	–	–	601	–	269	–
Day 2	In	4.4	14.7	6.6	693	4	306	3.4
	Out	5.2	–	–	614	3	267	–
Day 3	In	4.6	15.1	37.1	695	–	293	–
	Out	5.3	–	–	624	–	260	–
Day 4	In	4.4	15.1	43.5	630	5	331	2.4
	Out	5.1	–	–	549	7	271	–

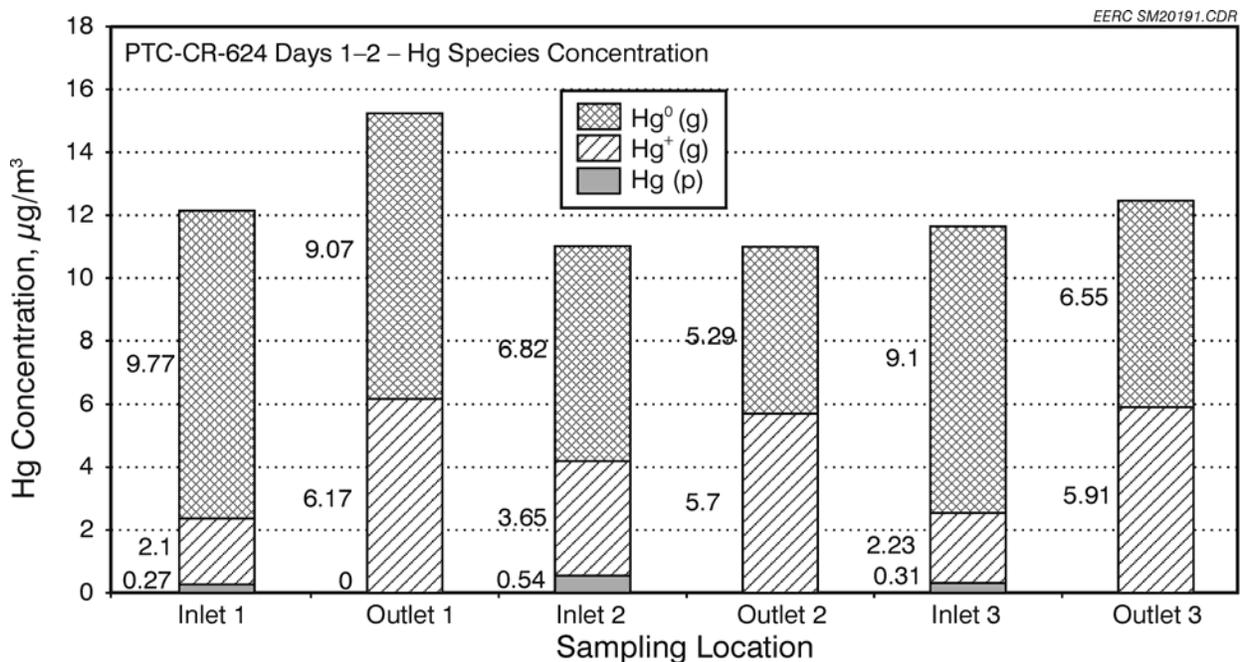


Figure 6.2.2.1. Speciated mercury concentrations in flue gas at the *Advanced Hybrid*TM filter inlet and outlet.

*Hybrid*TM filter inlet, oxidized mercury vapor varied from 2.1 to 3.7 µg/m³, while the elemental mercury vapor was in the range of 6.8–9.8 µg/m³. Mercury species associated with particulate was at a low level, ranging from 0.3–0.5 µg/m³. There was no particulate-associated mercury at the *Advanced Hybrid*TM filter outlet flue gas because of the excellent fly ash capture efficiency of the *Advanced Hybrid*TM filter. The total gas-phase mercury was the same for both the *Advanced Hybrid*TM filter inlet and outlet. However, the oxidized mercury vapor concentration at the *Advanced Hybrid*TM filter outlet was higher than the corresponding oxidized mercury at the *Advanced Hybrid*TM filter inlet, indicating additional mercury oxidation across the *Advanced Hybrid*TM filter unit.

To better clarify the transformation of mercury species across the *Advanced Hybrid*TM filter unit, the average normalized mercury species concentrations at the *Advanced Hybrid*TM filter inlet are plotted in Figure 6.2.2.2, showing 75.3% of elemental mercury, 21.7% of oxidized mercury vapor, and only 3.0% of fly ash-associated mercury. Since the particulate collection efficiency of the *Advanced Hybrid*TM filter was 99.99%, the mercury associated with the inlet fly

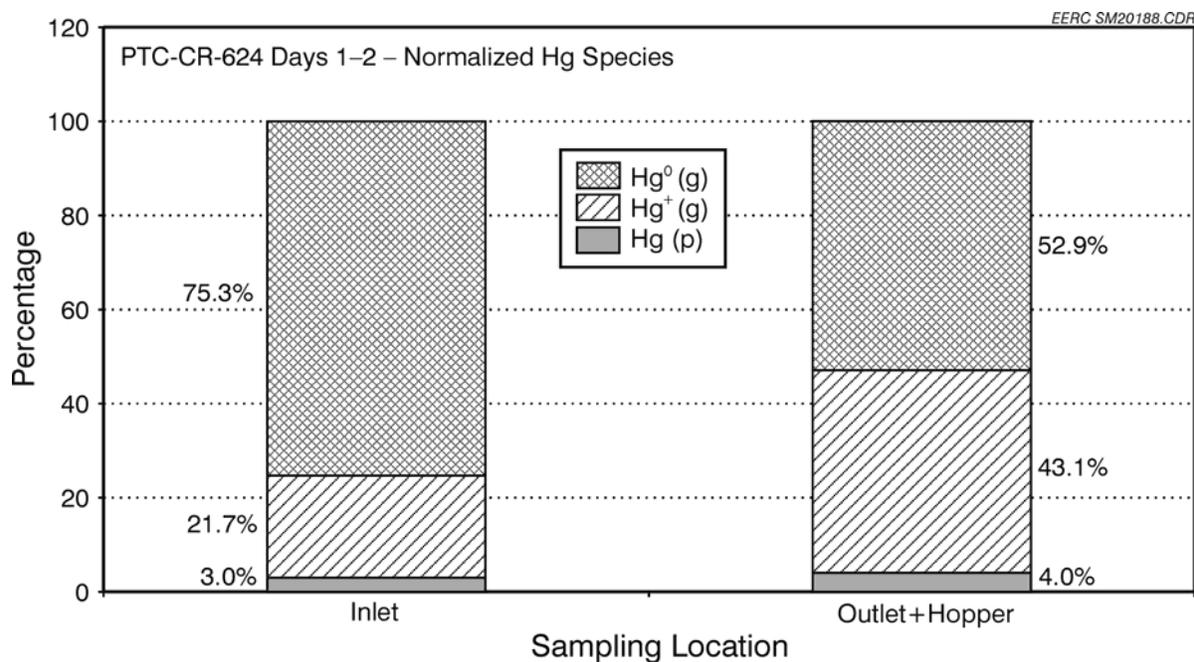


Figure 6.2.2.2. Normalized mercury species at the *Advanced Hybrid™* filter inlet and outlet.

ash was all collected in the hopper. The mercury in the hopper ash was analyzed for comparison with mercury concentration on the Ontario Hydro inlet sampling filters (Table 6.2.2.4). The hopper ash mercury was added to the outlet vapor species and normalized to 100% for comparison with the inlet (Figure 6.2.2.2). Results show there was an increase in oxidized mercury from 21.7% to 43.1% across the *Advanced Hybrid™* filter, while there was a

Table 6.2.2.4. Mercury Concentration in Fly Ash

Test Day	Sample Type	Time of Sampling	Hg Concentration, $\mu\text{g/g}$
Day 1	Inlet filter	15:05–16:05	0.0595
Day 1	Inlet filter	16:37–17:37	0.0581
Day 2	Inlet filter	11:00–13:00	0.109
Day 2	Inlet filter	15:00–17:00	0.0653
Day 2	Hopper ash	17:00	0.102
Day 3	Inlet filter	9:10–11:10	0.0311
Day 3	Inlet filter	12:17–14:17	0.148
Day 3	Hopper ash	15:06	0.182
Day 4	Inlet filter	10:17–12:17	0.396
Day 4	Inlet filter	14:00–16:00	0.025
Day 4	Hopper ash	19:30	0.337
Day 4	Outlet filter	10:17–12:17	0.944
Day 4	Outlet filter	14:00–16:00	0.233

corresponding decrease in elemental mercury from 75.3% at the inlet to 52.9% at the outlet. The results clearly demonstrate that elemental mercury vapor was oxidized across the *Advanced Hybrid*TM filter, but very little was captured by the fly ash.

For the Day 3 sampling test, the unit was operated in *Advanced Hybrid*TM filter mode with a 2.0-kPa (8.0-in. W.C.) pulse trigger pressure, resulting in longer bag-cleaning intervals ranging from 4 to 6 hr. The hopper ash was emptied twice during the testing period, providing approximately 17–22 hr of residence time of fly ash in the system. Results of two pairs of Ontario Hydro samples collected at the *Advanced Hybrid*TM filter inlet and outlet are plotted in Figure 6.2.2.3. The total mercury vapor concentrations at the *Advanced Hybrid*TM filter inlet and outlet were at the same level, showing no capture of mercury vapor across the *Advanced Hybrid*TM filter unit and a complete removal of mercury associated with fly ash. Again, mercury oxidation occurred across the *Advanced Hybrid*TM filter unit.

Figure 6.2.2.4 plots normalized mercury species distributions across the *Advanced Hybrid*TM filter unit. The inlet mercury species were 75.4% elemental mercury, 20.8% oxidized mercury vapor, and 3.8% fly ash-associated mercury. The inlet mercury species distribution for the Day 3 test agrees very well with the results obtained for the Day 1–2 test. In the flue gas out

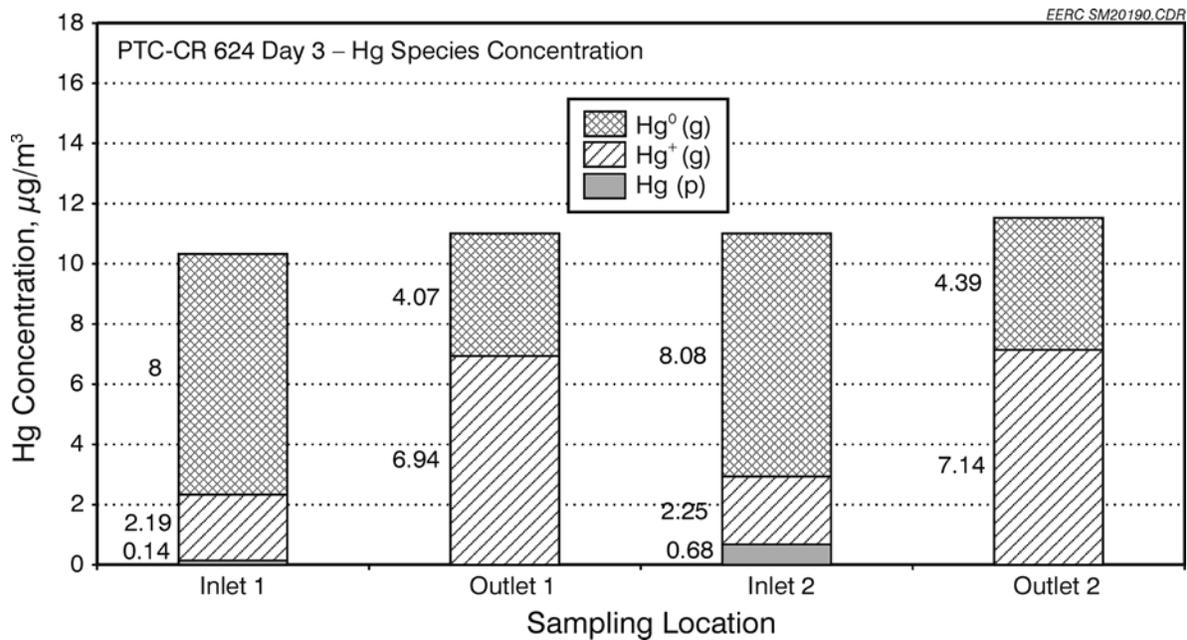


Figure 6.2.2.3. Speciated mercury concentration at the *Advanced Hybrid*TM filter inlet and outlet in longer residence time test.

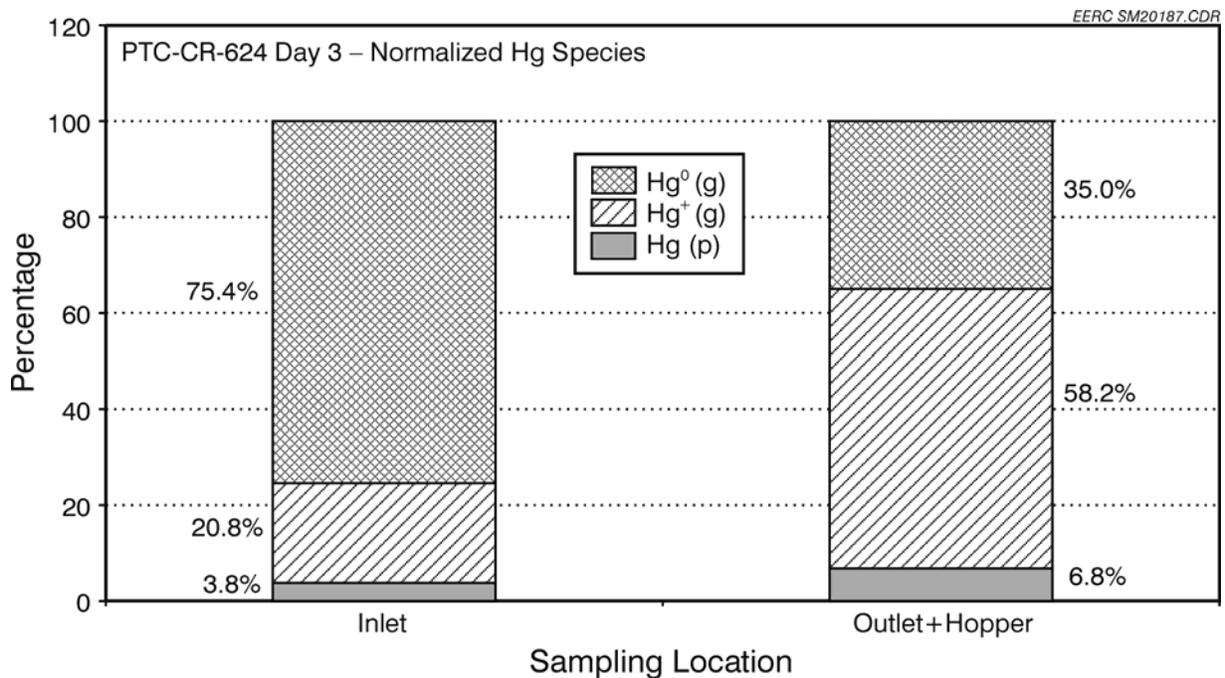


Figure 6.2.2.4. Normalized mercury species distributions across the *Advanced Hybrid*TM filter unit in longer residence time test.

of the *Advanced Hybrid*TM filter unit, only 35.0% of the total mercury vapor was in the elemental state, compared to the 52.9% measured for the Day 1–2 test. The oxidized mercury, on the other hand, increased to 58.2%. The mercury concentration associated with fly ash also increased slightly from 3.8% at the inlet to 6.8%. The accumulated hopper ash along with the extended residence time of fly ash in the *Advanced Hybrid*TM filter unit may have promoted the increased mercury vapor oxidation compared to the Day 1–2 test, where the residence time was limited to 30 min.

The *Advanced Hybrid*TM filter unit was then operated as a PJBH (no high-voltage power) for the Day 4 test. The high A/C ratio of 3.7 m/min (12 ft/min) resulted in frequent bag pulse cleaning every 3 min caused by the high dust loading to the filter bags and severe fly ash reentrainment. The hopper ash was also emptied every half hour to keep a 30-min maximum residence time of fly ash in the system. The measured mercury species concentrations at the *Advanced Hybrid*TM filter inlet and outlet are plotted in Figure 6.2.2.5. The mercury species concentrations at the *Advanced Hybrid*TM filter inlet during this testing period showed more

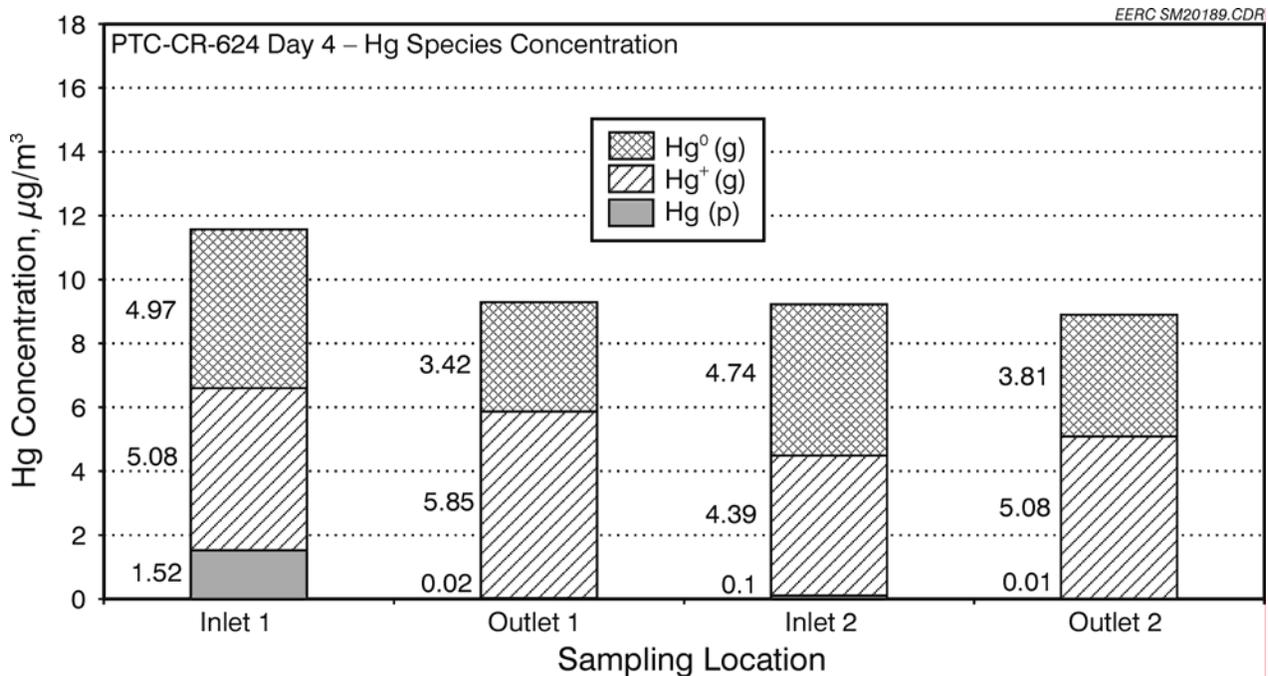


Figure 6.2.2.5. Speciated mercury concentrations at the PJBH inlet and outlet.

oxidized mercury than the previous tests. Because of the frequent bag-cleaning pulsing, a fraction of ultrafine fly ash was measured at the *Advanced Hybrid*TM filter outlet. The ultrafine ash was also analyzed for mercury. However, based on the measured dust loading at the *Advanced Hybrid*TM filter outlet, mercury associated with fly ash was only 0.01–0.1 µg/m³, indicating a very low emission level of particulate mercury.

The normalized mercury distributions at the inlet and outlet plotted in Figure 6.2.2.6 show an increase of oxidized mercury across the PJBH, but not to the extent of the increase noted in either the short-residence-time *Advanced Hybrid*TM filter test (Figure 6.2.2.2) or the long-residence-time *Advanced Hybrid*TM filter test (Figure 6.2.2.4). However, since the inlet oxidized mercury fraction was higher for the pulse-jet test, no conclusion can be drawn as to the reason. Some variation in inlet speciation is typically seen with the Ontario Hydro method, and the differences seen may simply be the effect of that variability. The data indicate no significant difference between the PJBH and the *Advanced Hybrid*TM filter in the level of oxidation of mercury across the device or in the amount of mercury retained by the fly ash.

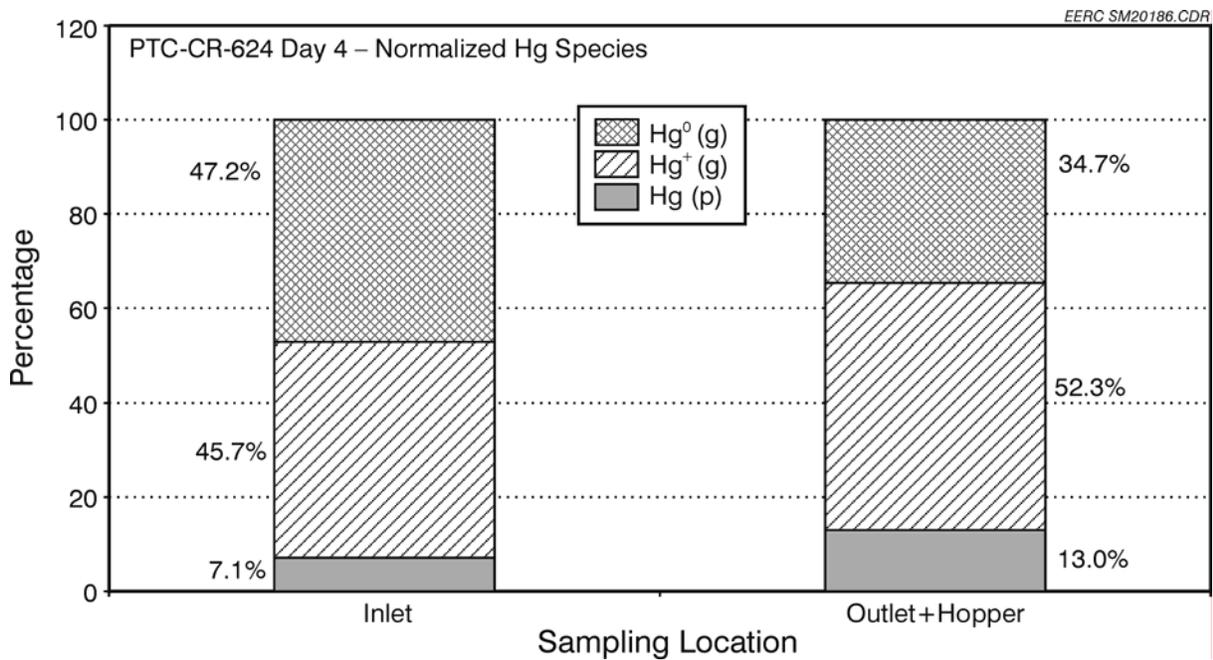


Figure 6.2.2.6. Normalized mercury species distribution across the PJBH.

A summary of Ontario Hydro method mercury analysis results during the 4-day test is listed in Table 6.2.2.5. The total mercury concentration in the flue gas (present as total mercury concentration at the *Advanced Hybrid*TM filter inlet) varied from 9.2 to 12.1 $\mu\text{g}/\text{m}^3$, which is close to a theoretical value of 13.4 $\mu\text{g}/\text{m}^3$ obtained from the coal combustion calculation based on the coal analysis. The slight difference may be the result of uncertainty in the mercury coal analysis as well as additional process variability.

A pair of Method 101A samples was taken at both the *Advanced Hybrid*TM filter inlet and outlet simultaneously in the Day 1 test. The goal was to compare Method 101A with the results from the Ontario Hydro method being performed on the same day. Method 101A provides information on mercury associated with fly ash and total concentration of mercury vapor in flue gas but cannot differentiate mercury species in the vapor phase. As shown in Table 6.2.2.6, mercury species were 11.3 $\mu\text{g}/\text{m}^3$ of total mercury vapor and 0.3 $\mu\text{g}/\text{m}^3$ of particulate mercury at the *Advanced Hybrid*TM filter inlet and 10.5 $\mu\text{g}/\text{m}^3$ of mercury vapor at the outlet. The results agree with the data obtained from the Ontario Hydro method.

Table 6.2.2.5. Summary of Ontario Hydro Mercury Results, dry flue gas at 3.0% O₂ (µg/Nm³)

		Hg ⁰	Hg ⁺	Hg (particulate)	Hg (total)
Day 1	Inlet	9.8	2.1	0.3	12.1
	Outlet	9.1	6.2	0.0	15.2
Day 2	Inlet	6.8	3.7	0.5	11.0
		9.1	2.2	0.3	11.6
	Outlet	5.3	5.7	0.0	11.0
		6.6	5.9	0.0	12.5
Day 3	Inlet	8.0	2.2	0.1	10.3
		8.1	2.3	0.7	11.0
	Outlet	4.1	6.9	0.0	11.0
		4.4	7.1	0.0	11.5
Day 4	Inlet	5.0	5.1	1.5	11.6
		4.7	4.4	0.1	9.2
	Outlet	3.4	5.9	0.0	9.3
		3.8	5.1	0.0	8.9

Day 1 – *Advanced Hybrid*TM filter mode, 30-min bag-cleaning interval.

Day 2 – *Advanced Hybrid*TM filter mode, 30-min bag-cleaning interval.

Day 3 – *Advanced Hybrid*TM filter mode, 8.0-in. W.C. (2.0-kPa) pulse trigger pressure.

Day 4 – Pulse-jet mode, 8.0-in. W.C. (2.0-kPa) pulse trigger pressure.

6.2.2.4 Particulate Matter Collection Efficiencies for the *Advanced Hybrid*TM Filter and PJBH

Since the Ontario Hydro method uses isokinetic sampling to measure mercury concentration in fly ash particles, it also provides information on the dust loading in the flue gas. Table 6.2.2.7 lists the measured dust loadings at the *Advanced Hybrid*TM filter inlet and outlet and the calculated particle collection efficiencies across the system. The overall particle collection efficiency varied from 99.984% to 99.996% during the first 3 days, showing excellent capture of fly ash particles in the *Advanced Hybrid*TM filter mode for both a short bag-cleaning interval (30 min) and a long bag-cleaning interval (4–6 hr). When the unit was operated in pulse-jet mode for the Day 4 test, the overall particle collection efficiency was reduced to 99.0%–99.52%. The reason is that the unit was experiencing frequent pulsing (every 3 min), which caused a high particle penetration through the filter bags as a result of a short particle emission spike after each pulse. The results confirm the *Advanced Hybrid*TM filter technology is superior

Table 6.2.2.6. Summary of Method 101A Results, dry flue gas at 3.0% O₂

		Hg, g	Hg (particulate)	Hg (total)
Day 1	Inlet	11.3	0.3	11.5
	Outlet	10.5	0	10.5

Table 6.2.2.7. Dust Loading at the *Advanced Hybrid*TM Filter Inlet and Outlet and the Calculated Collection Efficiency

		Inlet, g/m ³ (gr/dscf)	Outlet, g/m ³ (gr/dscf)	Collection Efficiency, %
<i>Advanced Hybrid</i> TM Filter	Day 1-1	3.25 (1.42)	1.33×10^{-4} (5.80×10^{-5})	99.996
	Day 1-2	3.52 (1.54)	1.81×10^{-4} (7.90×10^{-5})	99.995
	Day 2-1	3.82 (1.67)	4.28×10^{-4} (1.87×10^{-4})	99.989
	Day 2-2	3.64 (1.59)	5.70×10^{-4} (2.49×10^{-4})	99.984
	Day 3-1	3.46 (1.51)	2.56×10^{-4} (1.12×10^{-4})	99.993
	Day 3-2	3.56 (1.56)	4.26×10^{-4} (1.86×10^{-4})	99.988
PJBH	Day 4-1	3.24 (1.42)	1.56×10^{-2} (6.80×10^{-3})	99.520
	Day 4-2	3.49 (1.52)	3.48×10^{-2} (1.52×10^{-2})	99.000

to a conventional baghouse and demonstrate that longer bag-cleaning intervals benefit particle emission reduction.

6.2.2.5 Mercury Species Comparison Between the PTC-CR-624 Test and Big Stone Field Test (November 2001)

Figure 6.2.2.7 shows averaged mercury speciation in *Advanced Hybrid*TM filter inlet flue gas measured in Big Stone field test (completed in November 2001) and the baseline pilot-scale testing results, and Figure 6.2.2.8 plots corresponding normalized Hg distributions. Detailed results of the field testing are given later in this report. The total values are similar within the margin of error, but the field results showed 56% of the mercury was retained by the fly ash, much higher than the 5% particle-associated mercury in the pilot-scale tests. A second significant difference is that only 6% of the total mercury was elemental mercury in the field result compared to 67% elemental mercury in the pilot-scale tests.

A number of differences in conditions between the two tests could be responsible for the significant speciation difference. Big Stone Power Plant cofired a small percentage of waste tires with coal during the November 2001 test, while the pilot-scale coal did not include waste tires. The cofiring of tires may change mercury–flue gas chemistry. For example, the HCl for the pilot-scale tests was measured by Method 26A to be 3 ppm in the flue gas compared to 9 ppm for the field test. However, 9 ppm HCl is still a fairly low concentration compared to the 50–100 ppm level that is typically seen for bituminous coals.

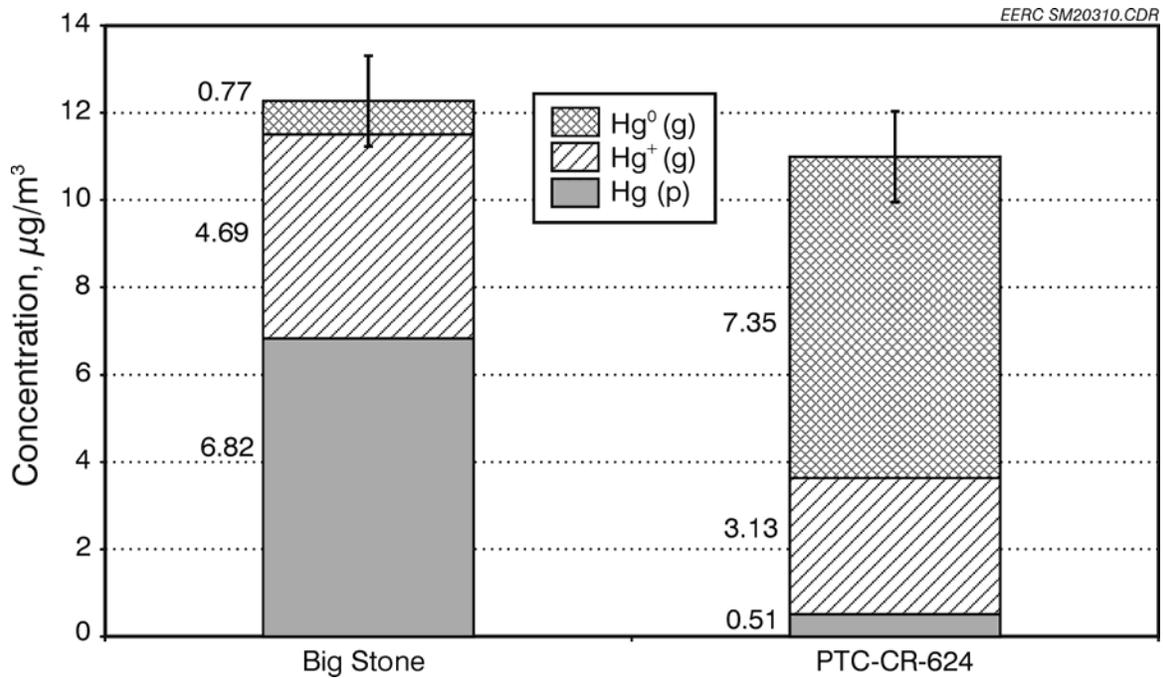


Figure 6.2.2.7. Averaged mercury speciation in *Advanced Hybrid*TM filter inlet flue gas measured in Big Stone field test (completed in November 2001) and pilot-scale test.

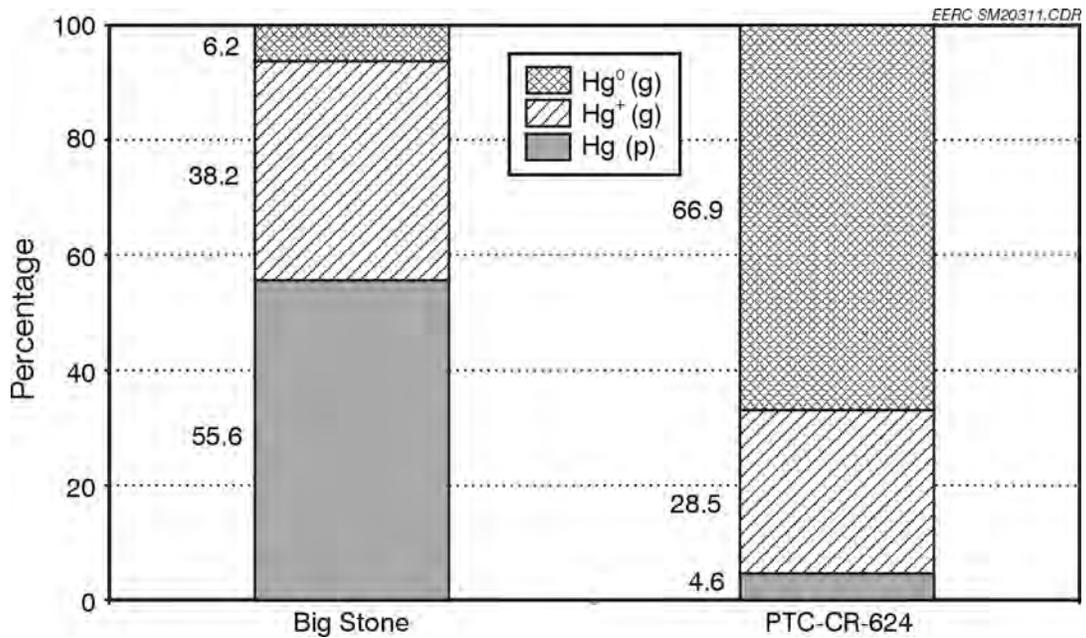


Figure 6.2.2.8. Normalized Hg species distribution in flue gas of Big Stone field test and pilot-scale test.

Another possible reason for the difference is the amount of unburned carbon in the ash, which for the Big Stone baseline tests ranged from 0.5% to 1.9% (without carbon injection) compared to only 0.16% for the pilot-scale tests. Under some conditions, carbon in the ash can be responsible for mercury retention as well as oxidation.

Cyclone firing is known to produce a finer fly ash particle size than pulverized-coal firing, which could also lead to more mercury retention as well as oxidation. Other work has shown that mercury concentration is typically higher in the smaller fly ash fraction, and the higher surface area of the finer particles may also promote more oxidation.

Still further possible contributors to the differences are the longer residence time and exposure of the flue gas to the fly ash for a full-scale boiler and possible differences in the coal. The coal burned in the pilot-scale unit was from the Big Stone Power Plant and was from the same mine, but it was obtained over a month prior to the field test. Further discussion of the effects of cofiring waste tires is given later in this report.

6.2.2.6 *Conclusions from the PTC-CR-624 Testing Results*

In the pilot-scale tests, a baseline comparison was made between the *Advanced Hybrid*TM filter and a PJBH in terms of the mercury speciation change across the device and the amount of mercury retained by the fly ash. Results showed that for both devices there was very little capture of mercury by the fly ash, but there was some increase in oxidized mercury across the device. No significant differences were noted between the *Advanced Hybrid*TM filter and the PJBH modes of operation.

The extended residence time of fly ash in the *Advanced Hybrid*TM filter chamber may promote slightly more mercury oxidation with the Cordero Rojo complex flue gas.

Even though the same coal was used in the pilot-scale tests and the November 2001 field tests at the Big Stone Power Plant, there was a significant difference in inlet mercury speciation. For the pilot-scale tests, results were more similar to what is typically expected for PRB coals in that most of the mercury was elemental with little mercury capture by the fly ash. In contrast, the field test results show high levels of oxidized and particle-bound mercury. Possible reasons for the difference include higher carbon in the field ash, somewhat higher HCl in the field flue gas, possible variation in the coal, cyclone firing for the field tests compared to pulverized coal firing for the pilot tests, longer residence time for the field tests, and a finer particle size for the field tests.

6.2.3 PTC-BA-628

6.2.3.1 Test Conditions

Big Stone Power Plant switched coal from Cordero Rojo Complex to Belle Ayr coal, which is another WSB coal from the PRB. This was the coal currently being burned at the Big Stone Power Plant and was the expected coal to be burned at Big Stone during the *Advanced Hybrid*TM filter field tests planned for August 2002. Note that this was a different PRB fuel than was burned at the plant during the first field test and the PTC-CR-624 pilot-scale tests. The EERC, therefore, decided to burn the Belle Ayr coal in the pilot-scale test, designated as PTC-BA-628. A dry powder disperser system (TSI Model 3410) installed 30 feet upstream of the *Advanced Hybrid*TM filter continuously injected NORIT FGD sorbent into the Belle Ayr flue gas entering the *Advanced Hybrid*TM filter. Ontario Hydro samples were collected both at the *Advanced Hybrid*TM filter inlet and outlet to measure mercury concentrations in the Belle Ayr flue gas across the *Advanced Hybrid*TM filter unit.

Table 6.2.3.1 lists five tests that were completed in this testing period. The residence time of the injected sorbent in the unit was either 60 min or 24 hr, controlled by the time interval to empty ash from the hopper. By using the TSI dry powder disperser, the activated carbon was continuously injected into the system at injection rates of 19 mg/m³ (1.2 lb/Macf) and 38 mg/m³(2.4 lb/Macf), corresponding to carbon-to-mercury ratios of 3000:1 and 6000:1,

Table 6.2.3.1. Pilot-Scale Testing Plan for Run PTC-BA-628

Test No.	Operating Mode	Residence Time	C:Hg Ratio	Carbon Injection Rate, mg/m ³ (lb/Macf)	Injection Method
1	<i>Advanced Hybrid</i> TM filter, 4.0 mA	60 min	None	None	NA
2	<i>Advanced Hybrid</i> TM filter, 4.0 mA	60 min	3000:1	19 (1.2)	Continuous
3	PJBH	60 min	3000:1	19 (1.2)	Continuous
4	<i>Advanced Hybrid</i> TM filter, 0.5 mA	60 min	3000:1	19 (1.2)	Continuous
5	<i>Advanced Hybrid</i> TM filter, 4.0 mA	24 hr	6000:1	38 (2.4)	Continuous

respectively. The pilot-scale unit was operated either as the *Advanced Hybrid*TM filter or a PJBH by shutting off the ESP power.

The purposes of this pilot-scale test were to evaluate NORIT FGD ACI on mercury emission control in the *Advanced Hybrid*TM filter, understand the impacts of corona current and residence time of sorbent in the *Advanced Hybrid*TM filter, and compare mercury control of the *Advanced Hybrid*TM filter with a PJBH for Belle Ayr, a WSB coal.

6.2.3.2 Coal and Flue Gas Analyses

Table 6.2.3.2 lists proximate and ultimate analysis data for the Belle Ayr coal and mercury content from the testing of the Belle Ayr coal. The analysis data show mercury concentrations of 0.077–0.089 µg/g (dry basis), with a mean value of 0.083 µg/g in the raw coal, slightly lower than the Cordero Rojo complex tested in PTC-CR-624. Based on the proximate and ultimate analysis data, 1 lb of Belle Ayr coal would produce 3.04 m³ (107.3 scf) of dry flue gas normalized to 3.0% oxygen level. Combining the mercury content in raw coal and combustion calculations, the total mercury concentration in the flue gas was expected to be 12.4 µg/m³ of dry flue gas (at 3% oxygen level).

Table 6.2.3.3 summarizes daily average flue gas concentrations of O₂, CO₂, CO, NO, NO₂, SO₂, both at the *Advanced Hybrid*TM filter inlet and outlet during the testing period. The

Table 6.2.3.2. Coal Analysis for Run PTC-BA-628

Proximate Analysis, wt%	As Sampled	Moisture Free
Moisture Content	24.8	NA
Volatile Matter	35.94	47.83
Fixed Carbon	34.42	45.74
Ash	4.83	6.43
Ultimate Analysis, wt%		
Hydrogen	6.29	4.69
Carbon	51.42	68.42
Nitrogen	0.8	1.07
Sulfur	0.29	0.38
Oxygen	36.37	19.01
Ash	4.83	6.43
Heating Value, Btu/lb	8999	11,975
Chlorine in coal, µg/g, dry basis		22.5
Mercury in coal, µg/g, dry basis		
Sample 1		0.077
Sample 2		0.089
Mean		0.083

Table 6.2.3.3. Summary of the Flue Gas Compositions During Run PTC-BA-628, dry basis

		O ₂ , %	CO ₂ , %	CO, ppm	NO, ppm	NO ₂ , ppm	SO ₂ , ppm	HCl, ppm
Day 1	In	4.8	14.3	3.9	590	–	314	–
	Out	5.13	13.5	–	537	–	307	–
Day 2	In	4.5	14.3	4.5	559	4	306	2.7
	Out	5.2	–	–	540	3	266	–
Day 3	In	4.6	14.8	3.6	558	–	316	3.7
	Out	5.9	–	–	533	–	289	–
Day 4	In	4.6	14.2	3.4	571	–	312	3
	Out	4.8	–	–	547	–	289	–
Day 5	In	4.4	14.9	3.51	580	5	331	–
	Out	5.1	–	–	571	7	291	–

CO concentration was in the range of 3–5 ppm, indicating complete coal combustion. The low-sulfur Belle Ayr coal produced SO₂ in the flue gas ranging from 306 to 331 ppm. The NO and NO₂ concentrations in the flue gas were 571–590 ppm for NO and only 4–7 ppm for NO₂. The O₂ concentration was slightly increased from the inlet to the outlet because of the air leakage in the system. Three U.S. Environmental Protection Agency (EPA) Method 26 samples were collected at the *Advanced Hybrid*TM filter inlet, and the results (also listed in Table 6.2.3.3) show low levels of chlorine concentration in the Belle Ayr flue gas. Because of the low levels of CO, SO₂, NO, NO₂, and HCl in flue gas, most mercury in the flue gas was expected to be in the elemental vapor phase.

6.2.3.3 Mercury Results for PTC-BA-628

Test 1 – Baseline

Because this was a different coal than that evaluated in PTC-CR-624 baseline test, Test 1 (listed in Table 6.2.3.1) from this run was designated as a baseline to establish the inlet and outlet mercury species concentrations and determine whether there was a change in mercury speciation across the *Advanced Hybrid*TM filter unit. In Test 1, the system was operated in *Advanced Hybrid*TM filter mode with a corona current of 4.0 mA. The collection plates and electrodes were rapped every 60 minutes followed by a pulse-jet bag cleaning. The hopper ash was then emptied to maintain the residence time of the fly ash in the chamber at approximately 60 min. No activated carbon was injected into the system during the testing period, and a total of three pairs of Ontario Hydro samples were taken out at both the *Advanced Hybrid*TM filter inlet and outlet.

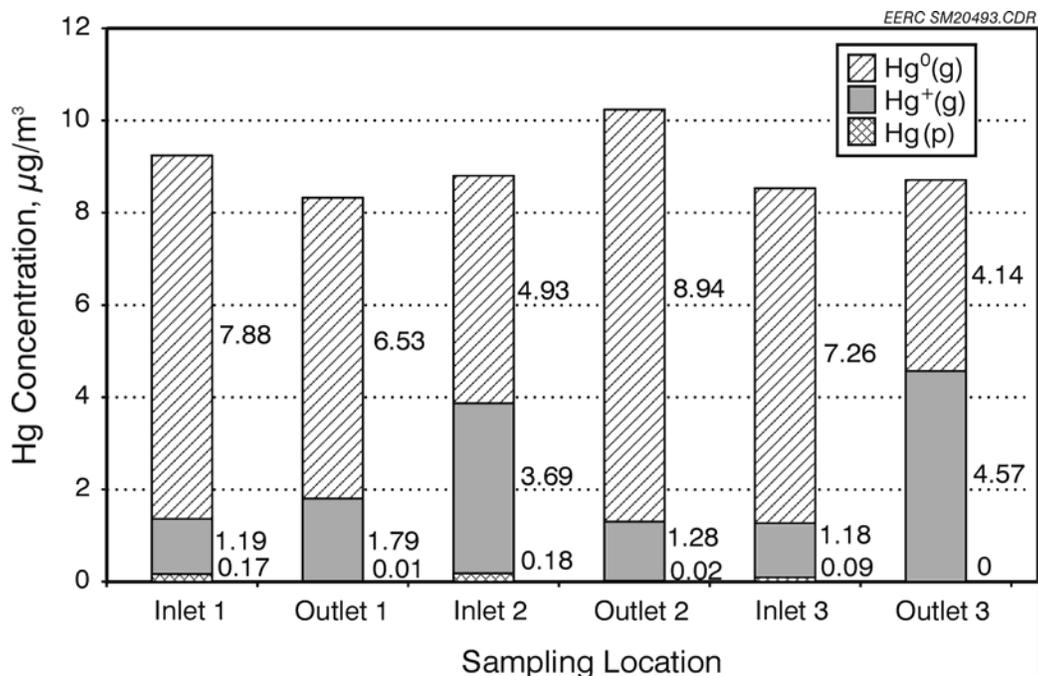


Figure 6.2.3.1. Mercury species concentrations in the Belle Ayr flue gas across the *Advanced Hybrid*TM filter in baseline test.

Plotted in Figure 6.2.3.1 are mercury species concentrations in the Belle Ayr flue gas across the *Advanced Hybrid*TM filter in baseline test. At the *Advanced Hybrid*TM filter inlet, oxidized mercury vapor varied from 1.18 to 3.69 µg/m³, while the elemental mercury vapor was dominant, in the range of 4.93–7.88 µg/m³. Mercury associated with the particulate was at a very low level, ranging from 0.09 to 0.17 µg/m³, showing little capture of mercury by fly ash particles. The total mercury concentration in the flue gas entering the *Advanced Hybrid*TM filter varied from 8.83 to 9.24 µg/m³, slightly lower than the theoretical value of 12.4 µg/m³ obtained from the coal combustion calculation based on the coal analysis. The slight difference may be the result of uncertainty in the mercury analysis as well as additional process variability. Because of the excellent fly ash capture efficiency of the *Advanced Hybrid*TM filter, particulate-associated mercury was completely removed from the flue gas. The total mercury in the outlet flue gas (also shown in Figure 6.2.3.1) was about the same as the *Advanced Hybrid*TM filter inlet, showing virtually no capture of mercury vapor (including both elemental and oxidized mercury vapor) across the *Advanced Hybrid*TM filter.

To better clarify the transformation of mercury species across the *Advanced Hybrid*TM filter unit in the baseline test, the average normalized mercury species distribution at the *Advanced Hybrid*TM filter inlet is shown in Figure 6.2.3.2. At the *Advanced Hybrid*TM filter inlet, 75.5% of mercury was in the elemental state, 22.9% was oxidized mercury vapor, and only 1.6% of total mercury was associated with fly ash particles. Because of the excellent capture of fly ash by the *Advanced Hybrid*TM filter, the mercury associated with fly ash was all collected in the hopper. The mercury in the hopper ash was analyzed, added to the outlet mercury species, and normalized to 100% for comparison with the inlet. The results show a slight increase in oxidized mercury from 22.9% to 28.8% across the *Advanced Hybrid*TM filter unit while there was a corresponding decrease in elemental mercury from 75.5% at the inlet to 71.7% at the outlet.

Test 2 – 19 mg/m³ (1.2 lb/Macf) Continuous NORIT FGD Injection – *Advanced Hybrid*TM Filter with 60-min Residence Time and 4-mA Current

Figure 6.2.3.3 shows the effect of NORIT FGD carbon injection on mercury emission for the *Advanced Hybrid*TM filter (Test 2 in Table 6.2.3.1). The unit was operated in *Advanced Hybrid*TM filter mode (Test 2) with a 4.0-mA corona current and a pulse trigger pressure of 2.0 kPa (8.0 in. W.C.). The fly ash and NORIT FGD carbon collected in the hopper were

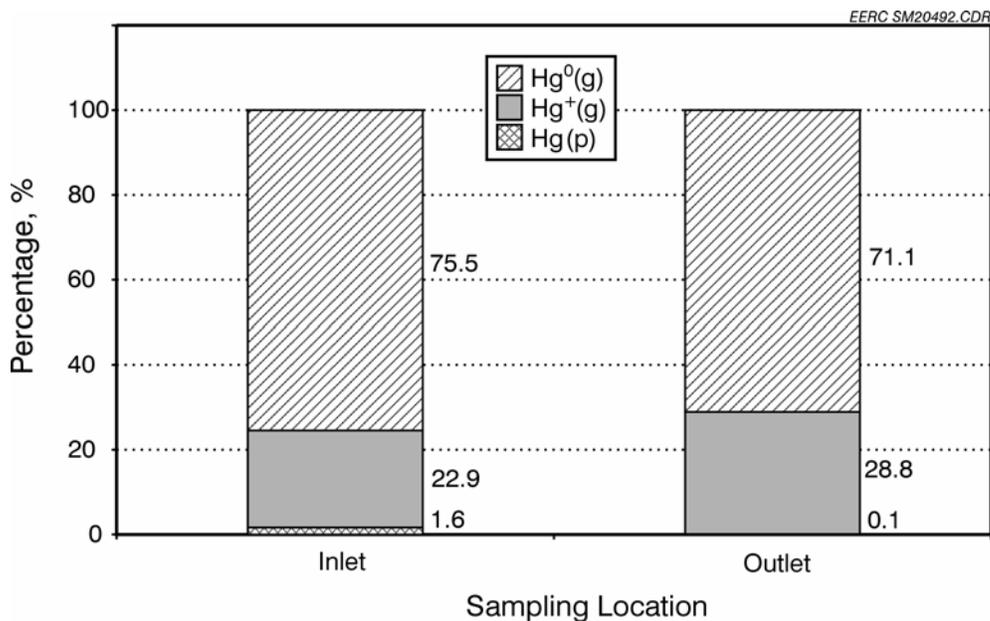


Figure 6.2.3.2. Normalized mercury species distributions across the *Advanced Hybrid*TM filter in Belle Ayr coal baseline test.

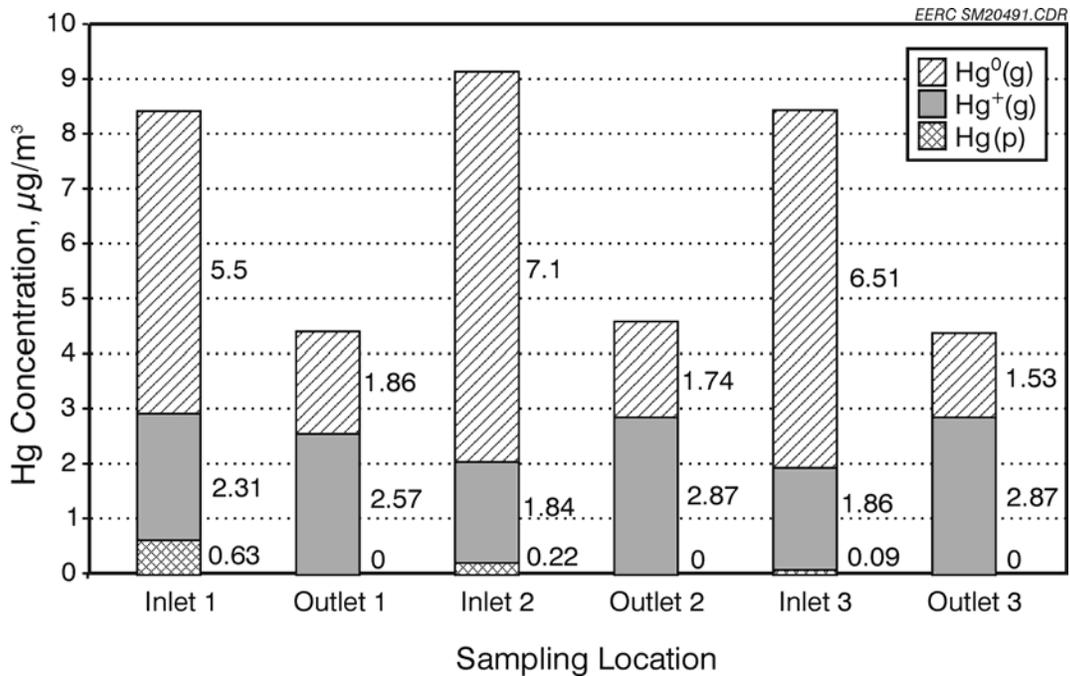


Figure 6.2.3.3. Effect of 19 mg/m³ (1.2 lb/Macf) NORIT FGD carbon injection on mercury emission in the *Advanced Hybrid*TM filter.

emptied once every hour to maintain the 1-hr residence time in the system. With continuous 19 mg/m³ (1.2 lb/Macf) FGD injection into the *Advanced Hybrid*TM filter, the mercury outlet emission reduced to approximately 4.48 µg/m³ with 38% of elemental mercury, 62% of oxidized mercury, and 0% of particle-bound mercury. Compared to average inlet mercury concentrations of 8.44–9.16 µg/m³ with 73.2% elemental mercury, 23.1% oxidized mercury, and 3.6% particulate associated mercury, 19 mg/m³ (1.2 lb/Macf) NORIT FGD injection resulted in an overall 48.4% mercury removal in the *Advanced Hybrid*TM filter, while there was virtually no inherent mercury capture in the baseline test. The FGD carbon efficiently oxidized mercury: 73% of the elemental mercury at the *Advanced Hybrid*TM filter inlet vs. 38% of the elemental mercury at the *Advanced Hybrid*TM filter outlet. However, the 48.4% overall mercury removal is lower than expected based on the bench-scale results, likely because some of the activated carbon deposited on the outside walls rather than the perforated plates or the filtration bags, and consequently, some of the carbon was not in full contact with the flue gas. To help minimize this effect, Test 4 was completed later with a reduced corona current. The lower current was still high enough for good operation, but could improve the gas–sorbent contact.

Test 3 – 19 mg/m³ (1.2 lb/Macf) Continuous NORIT FGD Injection – PJBH with 60-min Residence Time

In Test 3, the unit was operated in a PJBH mode (without high-voltage power) with a 2.0-kPa (8.0-in. W.C.) pulse trigger pressure. The filter bags were pulse cleaned every 5–7 min because of the high A/C ratio of 3.7 m/m (12 ft/min), high dust loading to the filter bags, and severe fly ash reentrainment. Figure 6.2.3.4 shows measured mercury species concentrations at the *Advanced Hybrid*TM filter inlet and outlet during the test. The mercury species concentrations at the *Advanced Hybrid*TM filter inlet during this test were somewhat different from the previous tests in that more mercury vapor was already in the oxidized state at the *Advanced Hybrid*TM filter inlet: 1.82–4.7 µg/m³ of Hg⁰, 1.65–5.03 µg/m³ of Hg⁺, and 0.76–1.09 µg/m³ of Hg(p). The total outlet mercury concentration was reduced to 2–2.17 µg/m³ under 19 mg/m³ (1.2 lb/Macf) NORIT FGD injection into the system, reaching a total mercury collection efficiency of 72.7%. Compared to the 48.4% mercury capture in *Advanced Hybrid*TM filter mode, the PJBH mode appeared to provide a higher mercury collection efficiency with the same carbon-to-mercury ratio. However, because of the high levels of oxidized and particle-bound mercury in the inlet flue gas during the test, which are typically easier to capture than

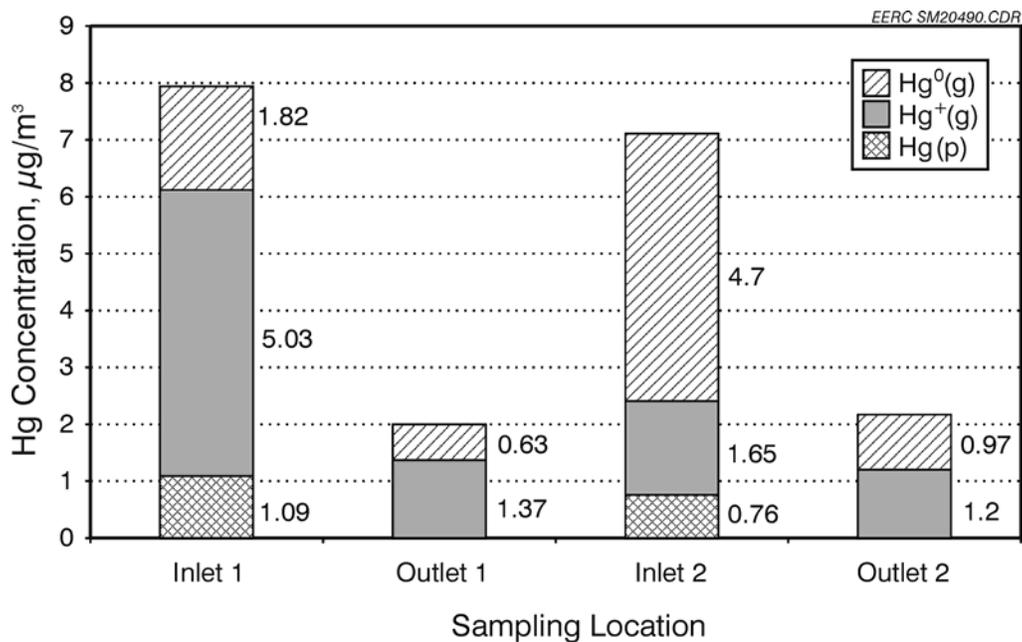


Figure 6.2.3.4. Effect of 19 mg/m³ (1.2-lb/Macf) NORIT FGD injection on mercury emission of PJBH.

elemental mercury, more tests are needed. So far, both the *Advanced Hybrid*TM filter and the PJBH show they can produce good mercury control in a WSB flue gas with low FGD addition.

Test 4 – 19 mg/m³ (1.2 lb/Macf) Continuous NORIT FGD Injection – *Advanced Hybrid*TM Filter with 60-min Residence Time and 0.5-mA Current

In Test 4, the system was returned to the *Advanced Hybrid*TM filter mode with a reduced 0.5-mA corona current, while the carbon injection rate and residence time of the sorbent were the same as in Test 2. As a result of the reduced corona current, we expected more activated carbon would deposit on the perforated plates and the bag surface instead of the outside wall. The good contact between the flue gas stream and the activated carbons on the perforated plates and filter bags should improve overall mercury capture in the *Advanced Hybrid*TM filter. Plotted in Figure 6.2.3.5 are the Ontario Hydro sampling results for the test. Mercury concentration in the inlet flue gas was 7.55 µg/m³ (2.58 µg/m³ elemental mercury, 4.11 µg/m³ oxidized mercury, and 1.06 µg/m³ particulate mercury) and was reduced to 3.46 µg/m³ in the outlet flue gas. The overall mercury collection efficiency of the *Advanced Hybrid*TM filter increased to 54.2% compared to the 48.4% obtained in Test 2, indicating that the reduced corona current appeared to somewhat improve mercury capture, but there was still considerable dust capture on the outside walls.

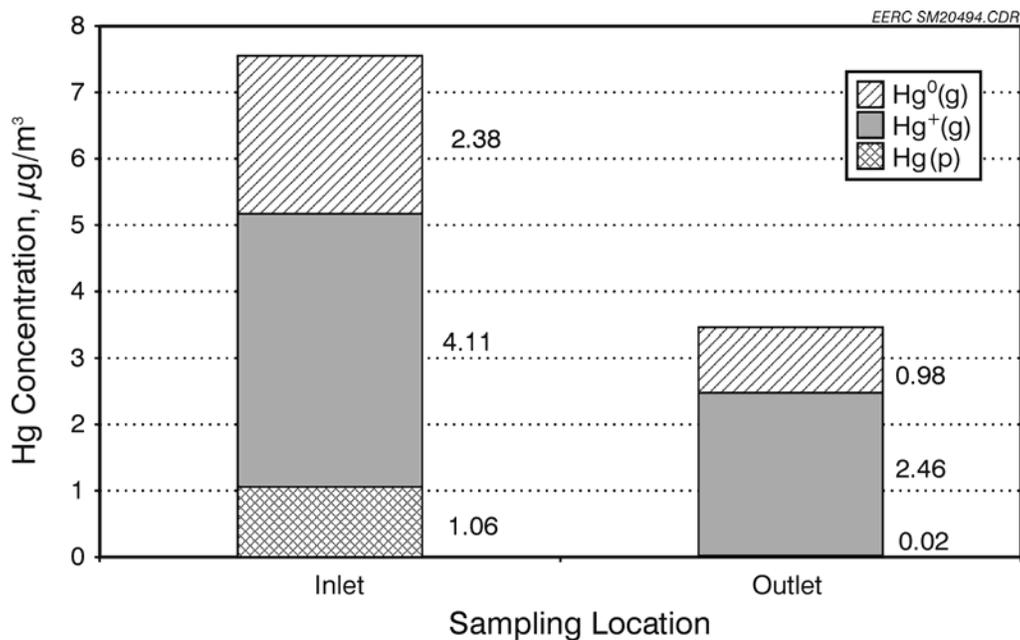


Figure 6.2.3.5. Effect of 19 mg/m³ (1.2-lb/Macf) NORIT FGD injection on Hg emission of the *Advanced Hybrid*TM filter at reduced current.

Test 5 – 38 mg/m³ (2.4 lb/Macf) Continuous NORIT FGD Injection – Advanced Hybrid™ Filter with 2-hr Residence Time and 4-mA Current

In order to achieve a higher mercury capture, the carbon injection rate was doubled to 38 mg/m³ (2.4 lb/Macf) in Test 5, corresponding to a carbon-to-mercury ratio of 6000:1. The unit was in *Advanced Hybrid™* filter mode with a 0.5-mA corona current. The residence time of the sorbent in the *Advanced Hybrid™* filter chamber was extended to 24 hr. The Ontario Hydro sampling results are shown in Figure 6.2.3.6. Again, all the particulate mercury was removed from the flue gas because of the excellent particle collection efficiency. Most of the elemental mercury vapor (>80%) in the flue gas was removed either by direct absorption on the activated carbons or oxidation followed by absorption. The elemental mercury vapor at the outlet was in the range of 0.6–0.97 µg/m³, while the oxidized mercury was 0.83–1.76 µg/m³. Early in the test, the first pair of Ontario Hydro samples indicated 68% removal, but the second pair of samples near the end of the test indicated 83% removal, possibly because of the accumulated sorbent in the *Advanced Hybrid™* filter chamber with extended residence time. However, concern is that if the exposure time is too long, the sorbent may desorb mercury. The bench-scale results indicate this will mostly likely occur in cases with very high SO₂ and NO₂ concentrations. Even though

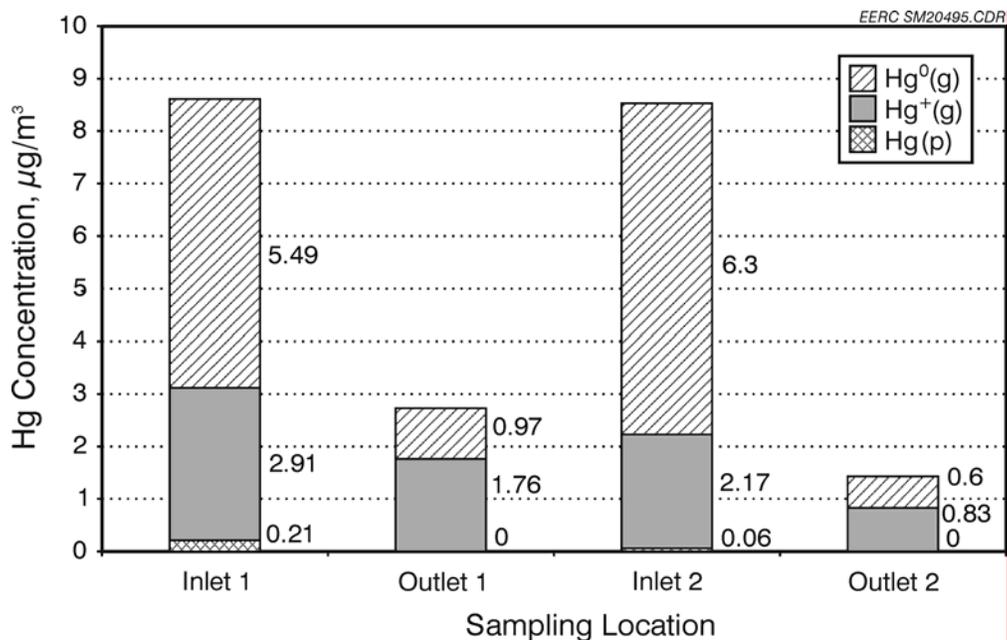


Figure 6.2.3.6. Effect of 38 mg/m³ (2.4-lb/Macf) FGD injection on Hg emission of the *Advanced Hybrid™* filter.

the sorbent particles were kept in the *Advanced Hybrid*TM filter chamber for 24 hr, there was no obvious desorption of mercury from the sorbent. These results are highly encouraging because they are for the difficult scenario with mostly elemental mercury and low levels of particulate-bound mercury.

A summary of *Advanced Hybrid*TM filter mercury collection efficiency under the different operating conditions is plotted in Figure 6.2.3.7. Without carbon injection, the Belle Ayr coal shows virtually no capture of mercury. At the 3000:1 carbon-to-mercury injection ratio, the *Advanced Hybrid*TM filter overall mercury collection efficiency ranged from 48.4% to 54.2%, depending on the corona current. When the carbon-to-mercury ratio increased from 3000:1 to 6000:1 with the same 0.5-mA corona current and with extended 24-hr residence time, the mercury capture efficiency reached 83% at the end of the test.

6.2.3.4 Particulate Matter Collection Efficiency of *Advanced Hybrid*TM Filter and PJBH in PTC-BA-628

While the focus of these tests was mercury control, the Ontario Hydro samples also provide the particulate collection efficiency as shown in Table 6.2.3.4. The data indicate the

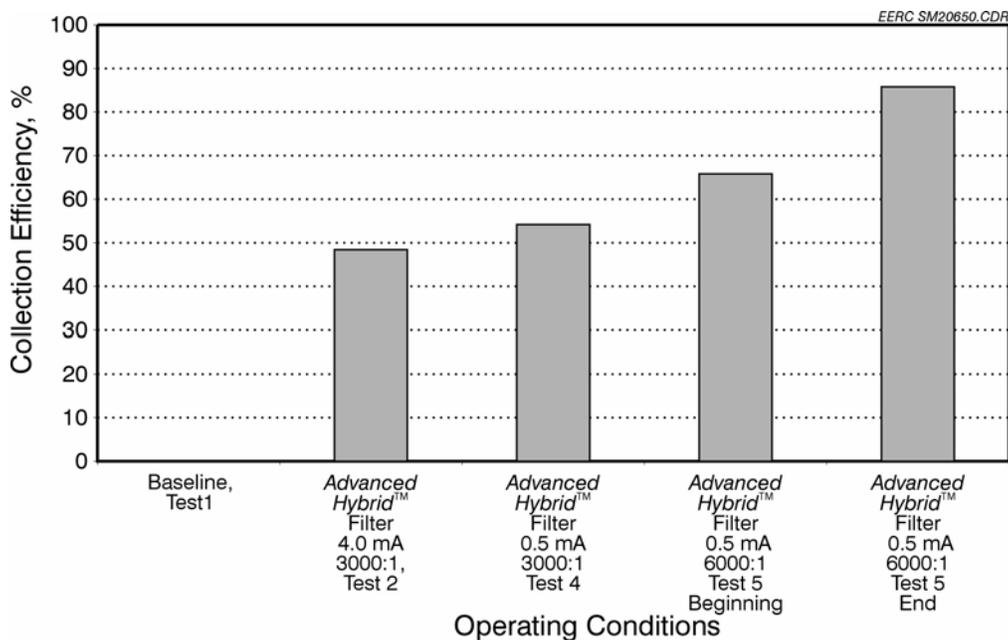


Figure 6.2.3.7. Summary of *Advanced Hybrid*TM filter mercury collection efficiency with carbon injection under the different operating conditions.

Table 6.2.3.4. PTC-BA-628 – Dust Loading at the *Advanced Hybrid*TM Filter Inlet and Outlet and the Calculated Collection Efficiency

	Inlet, g/m ³ (gr/dscf)	Outlet, g/m ³ (gr/dscf)	Collection Efficiency, %
Day 1-1	3.09 (1.35)	4.58×10^{-3} (2.0×10^{-4})	99.985
Day 1-2	3.27 (1.43)	1.60×10^{-5} (7.0×10^{-6})	99.999
Day 2-1	3.02 (1.32)	2.29×10^{-4} (1.0×10^{-3})	99.992
Day 2-2	3.48 (1.52)	1.60×10^{-5} (7.0×10^{-6})	99.999
Day 2-2	3.64 (1.59)	3.89×10^{-5} (1.7×10^{-5})	99.998
Day 3-1	2.84 (1.24)	0 (0)	100.000
Day 3-2 (pulse jet)	3.39 (1.48)	1.83×10^{-3} (8.0×10^{-4})	99.945
Day 3-3 (pulse jet)	3.34 (1.46)	1.83×10^{-3} (8.0×10^{-4})	99.945
Day 4-1	3.43 (1.50)	6.86×10^{-5} (3.0×10^{-5})	99.998
Day 4-2	3.39 (1.48)	2.29×10^{-4} (1.0×10^{-4})	99.993
Day 4-3	3.29 (1.44)	0 (0)	100.000
Day 5-1	3.36 (1.47)	4.58×10^{-5} (2.0×10^{-5})	99.999

*Advanced Hybrid*TM filter consistently had an overall 99.99% particle collection efficiency, while the PJBH clearly showed some loss in collection efficiency due to no precollection of dust, no enhanced bag cleaning, and much more frequent pulsing than the *Advanced Hybrid*TM filter. Even though the bags were the same for all of the tests, the much higher collection efficiency for the *Advanced Hybrid*TM filter shows the benefit of the *Advanced Hybrid*TM filter for reduced fine-particle emissions.

6.2.3.5 Conclusions from the PTC-BA-628 Testing Results

A number of baseline and carbon injection tests were completed with Belle Ayr PRB sub-bituminous coal. For the baseline case, approximately 70% of the inlet mercury was elemental, approximately 23% oxidized, and 2% or less was associated with particulate matter. There was very little natural mercury capture across the *Advanced Hybrid*TM filter for the baseline tests and only a slight increase in the level of oxidized mercury across the *Advanced Hybrid*TM filter during baseline operation.

With carbon injection, a comparison of short and long residence time in the *Advanced Hybrid*TM filter showed that somewhat better mercury removal was achieved with longer residence time. No evidence of desorption of mercury from the carbon was seen upon continued exposure to flue gases up to 24 hr. This suggests that desorption of captured mercury from the carbon sorbent is not a significant problem under these flue gas conditions with the low-sulfur subbituminous coal.

At a carbon-to-mercury ratio of 3000:1, approximately 50% total mercury removal was achieved. When the ratio was increased to 6000:1, the removal increased to the range from 65% to 87%. These results are highly encouraging because this level of control was achieved for the very difficult case with predominantly elemental mercury and very little natural capture of mercury by the fly ash.

Observation of the flow patterns within the pilot-scale *Advanced Hybrid*TM filter showed that a significant fraction of the sorbent was collected on the outside walls of the vessel rather than the perforated collection plates and filter bags, resulting in a situation where a fraction of the sorbent was directed away from the main gas flow region. Reducing the corona current somewhat improved the collection efficiency, but collection on the outside walls was still evident. This problem is unique to the small-scale pilot unit with a single row of bags and is not likely to be significant in a larger-scale *Advanced Hybrid*TM filter.

6.2.4 PTC-BA-629

6.2.4.1 Test Conditions

Another 1-week pilot-scale *Advanced Hybrid*TM filter test was completed in May 2002 to further expand on the *Advanced Hybrid*TM filter mercury control tests from the previous tests with the same Belle Ayr subbituminous coal. Results from PTC-BA-628 test indicated the carbons were not fully utilized in the *Advanced Hybrid*TM filter since some carbon deposited on the outside wall instead of on the perforated plates and filter bags. Therefore, to improve the contact between the injected carbon and the flue gas in the *Advanced Hybrid*TM filter, we switched from continuous injection to a batch injection mode, where an amount of carbon is injected every few hours. It is expected that more activated carbon would be on the perforated plates and filter bags, and the longer exposure time of the sorbent to the flue gas may provide better mercury removal than continuous injection. Table 6.2.4.1 lists the seven tests that were completed, including an initial baseline test without carbon injection, three continuous injection tests, and three batch injection tests. The applied corona current was in the range of 0.5–4 mA, and the hopper ash was emptied every 2 hr. The carbon injection rates were 19 mg/m³ (1.2 lb/Macf) and 38 mg/m³ (2.4 lb/Macf), corresponding to carbon-to-mercury ratios of 3000:1 and 6000:1, respectively.

Table 6.2.4.1. PTC-BA-629 – Summary of the Test Scenarios

Test No.	<i>Advanced Hybrid™</i>				
	<i>Filter Current, mA</i>	<i>Residence Time, min</i>	<i>Carbon:Hg Ratio</i>	<i>Injection Mode</i>	
1	4.0	120	None		
2	0.5	120	6000:1	Continuous	
3	3.0	120	6000:1	Continuous	
4	3.0	120	3000:1	Batch power off	
5	3.0	120	6000:1	Batch power off	
6	3.0	120	6000:1	Batch power on	
7	3.0	120	3000:1	Continuous	

In addition to Ontario Hydro sampling, CMMs were used at the *Advanced Hybrid™* filter inlet and outlet during the test to track the mercury concentration variations in near-real time. This was especially useful for the batch injection tests, because initially upon injection the mercury quickly dropped to its lowest level and then gradually increased with time.

6.2.4.2 Coal and Flue Gas Analyses

Table 6.2.4.2 summarizes the average flue gas compositions in the Belle Ayr coal flue gas for the tests. Since the coal used in this test is the same as that used in the PTC-BA-628, no proximate and ultimate coal analyses were completed for this test.

6.2.4.3 Mercury Results for PTC-BA-629

Test 1 – Baseline

Test 1 is a baseline test without carbon injection to establish mercury species in the Belle Ayr coal flue gas. Plotted in Figure 6.2.4.1, the Ontario Hydro results for this test show the inlet flue gas had 11.2 µg/Nm³ of total mercury with a dominant 83% elemental mercury, 13.7% oxidized mercury, and a low level of 3.2% particle-bound mercury. Mercury concentration in the outlet flue gas was reduced to 8.8 µg/Nm³ of total mercury, indicating approximately 21% inherent mercury removal across the *Advanced Hybrid™* filter. Figure 6.2.4.2 depicts the temporal variation of mercury species across the system based on the CMM measurements during the baseline test and indicates that there was very low inherent mercury capture with the *Advanced Hybrid™* filter for the Belle Ayr coal flue gas.

Table 6.2.4.2. PTC-BA-629 – Summary of the Flue Gas Compositions During the Pilot-Scale Test, dry basis

	O ₂ , %	CO ₂ , %	CO, ppm	NO, ppm	NO ₂ , ppm	SO ₂ , ppm	HCl, ppm
Average Inlet	4.5	14.9	4.4	637	8.5	310	2.05

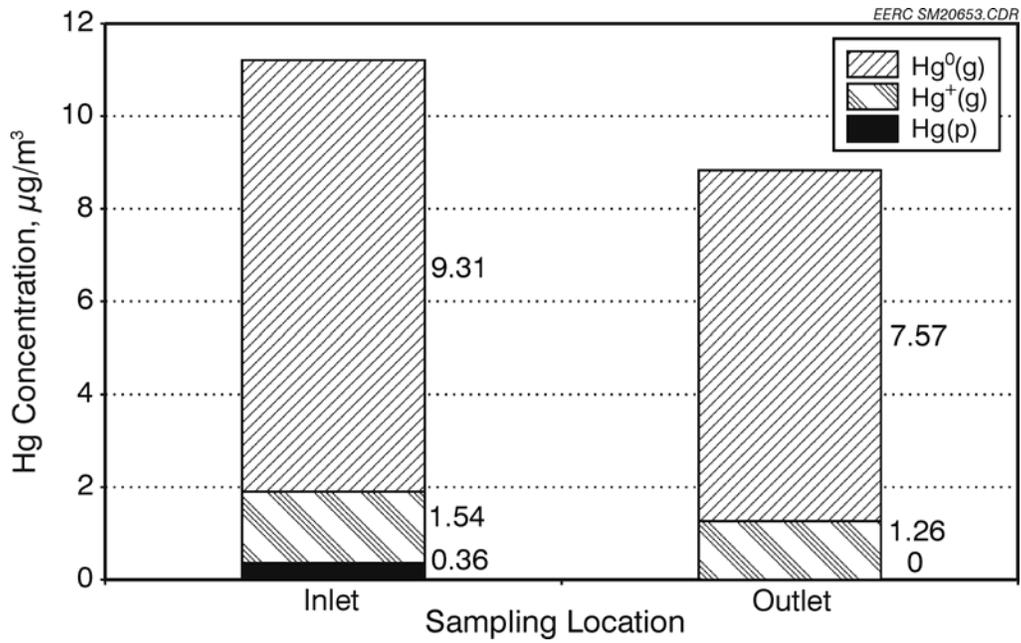


Figure 6.2.4.1. Mercury species across the *Advanced Hybrid*TM filter for the baseline test.

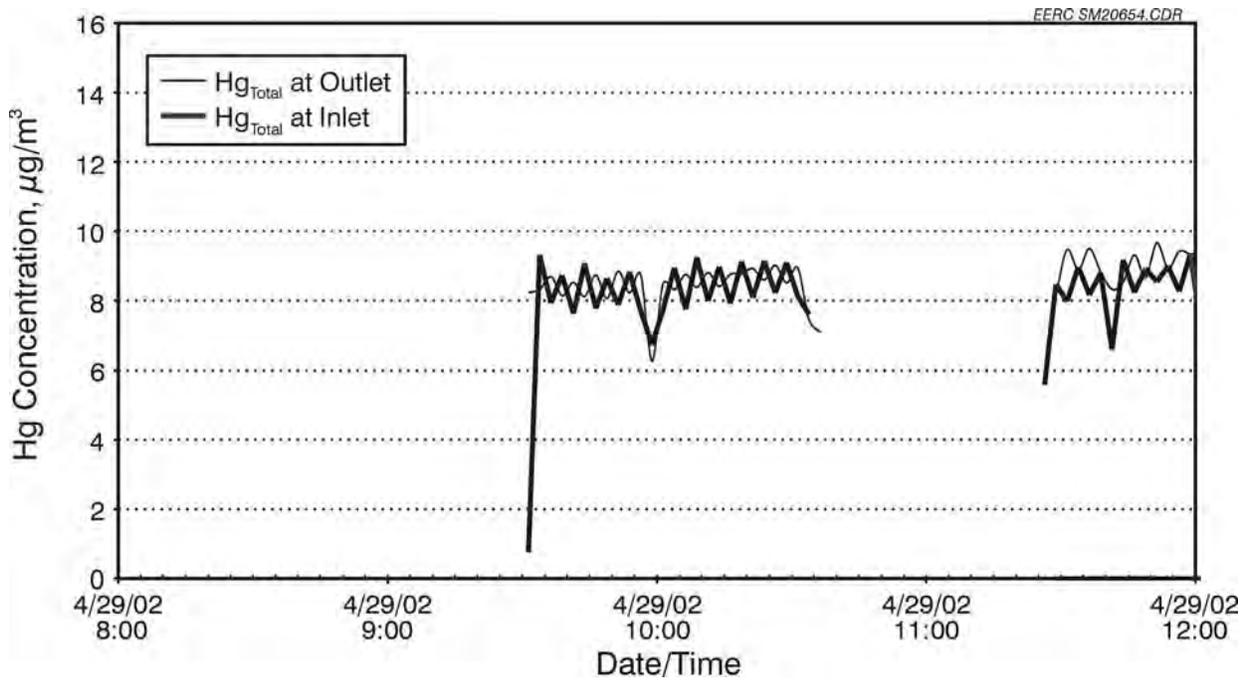


Figure 6.2.4.2. Temporal variation of mercury species across the system based on the CMM measurements during the baseline test.

Figure 6.2.4.3 plots the six inlet Ontario Hydro sampling results obtained for the PTC-BA-629 test along with the average of the six tests. The experimental data show a consistent low level of particle-bound mercury in the inlet flue gas, averaging only $0.2 \mu\text{g}/\text{m}^3$, while the average oxidized mercury was $2.8 \mu\text{g}/\text{m}^3$ and the average elemental mercury was $6.9 \mu\text{g}/\text{m}^3$ for a total average inlet mercury concentration of $9.9 \mu\text{g}/\text{m}^3$. The mercury removals were calculated based on the average inlet mercury concentration from all six inlet measurements.

Test 2 – $38 \text{ mg}/\text{m}^3$ (2.4 lb/Macf) Continuous NORIT FGD Injection – Advanced Hybrid™ Filter with 120-min Residence Time and 0.5-mA Current

To verify the mercury removal obtained in the PTC-BA-628 test, the *Advanced Hybrid™* filter was operated at 0.5-mA corona current and 2-hr residence time with $38 \text{ mg}/\text{m}^3$ (2.4 lb/Macf) continuous NORIT FGD carbon injection. Mercury measurements for Ontario Hydro sampling and CMMs are plotted in Figures 6.2.4.4 and 6.2.4.5. The CMM data indicate approximately 70% mercury removal when the system reached equilibrium, which is in reasonable agreement with the 76.3% mercury capture based on the Ontario Hydro measurement. The mercury removal efficiency under the present operating condition agrees well with the results of PTC-BA-628.

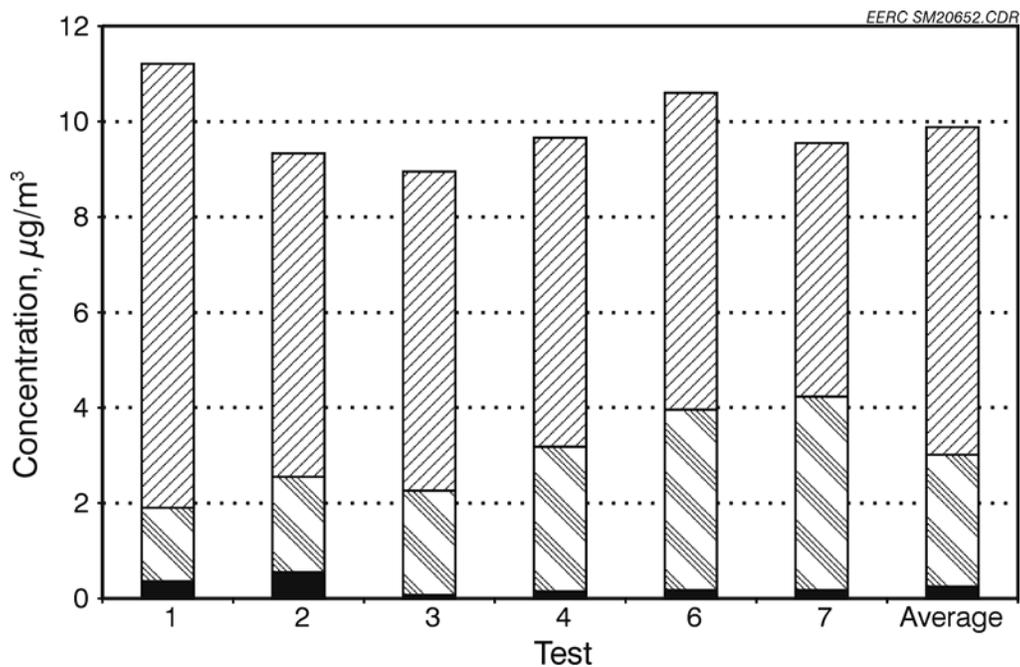


Figure 6.2.4.3. Summary of mercury species in Belle Ayr flue gas for PTC-BA-629 tests.

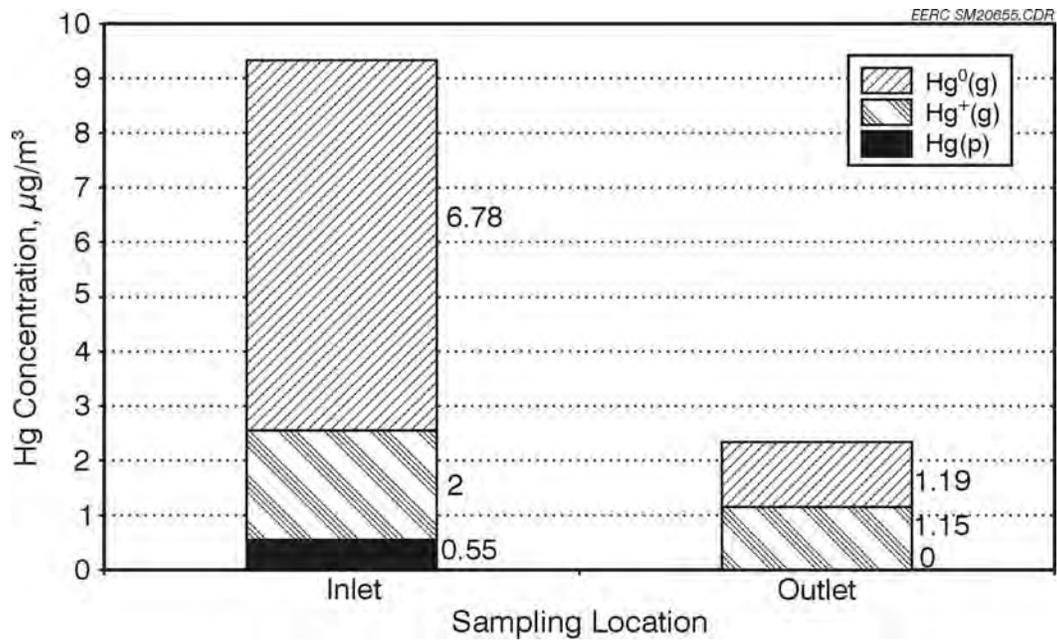


Figure 6.2.4.4. Mercury species across the *Advanced Hybrid*TM filter (0.5 mA) under 38 mg/m³ (2.4-lb/Macf) continuous FGD injection – Ontario Hydro results.

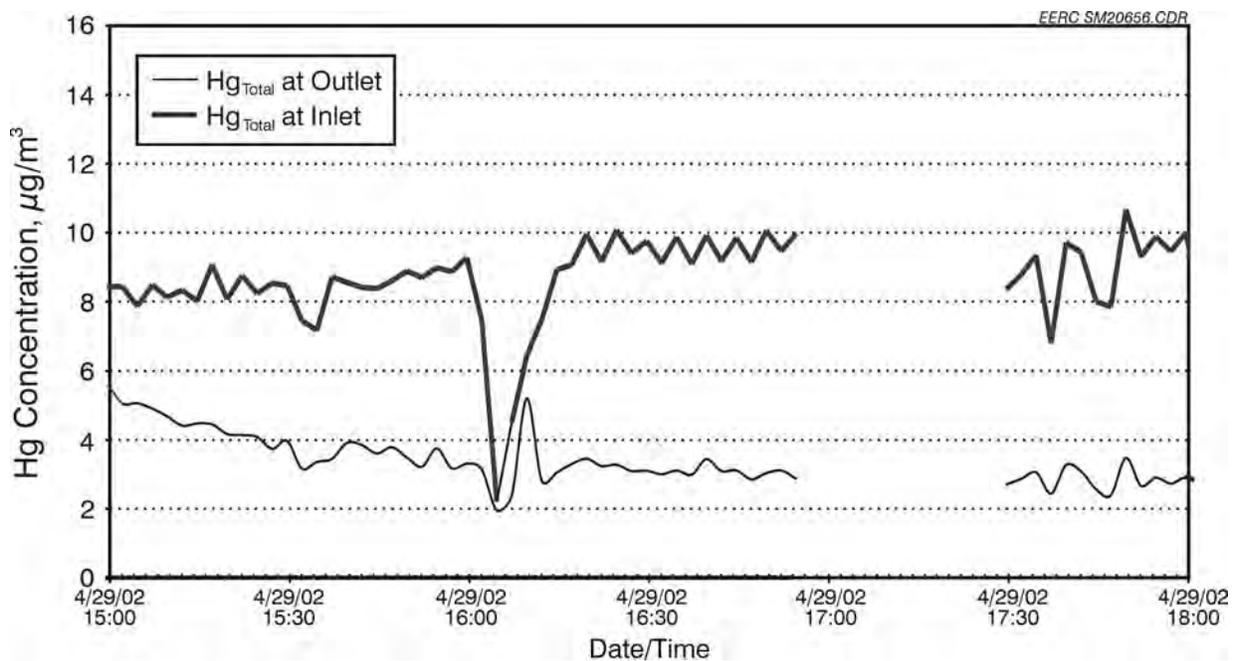


Figure 6.2.4.5. Mercury species across the *Advanced Hybrid*TM filter (0.5 mA) under 38 mg/m³ (2.4-lb/Macf) continuous FGD injection – CMM data.

Test 3 – 38 mg/m³ (2.4 lb/Macf) Continuous NORIT FGD Injection – Advanced Hybrid™ Filter with 120-min Residence Time and 3-mA Current

The *Advanced Hybrid™* filter current was increased from 0.5 to 3 mA to see if the mercury removal would decrease significantly. Results shown in Figures 6.2.4.6 and 6.2.4.7 indicate a slight increase in mercury emissions at the higher current setting. Based the Ontario Hydro data, the removal decreased to 71.5% at the 3.0-mA corona current compared to 76.3% at 0.5-mA current, while the CMM data also indicate a small decrease in mercury capture at the higher current level. Since the *Advanced Hybrid™* filter performed much better in terms of pulse interval and pressure drop control at the higher current, subsequent tests were completed at the higher current setting.

Test 4 – 19 mg/m³ (1.2 lb/Macf) Power-Off Batch NORIT FGD Injection – Advanced Hybrid™ Filter with 120-min Residence Time and 3-mA Current

A total of 13.3 g of the NORIT FGD activated carbon was batch-injected into the flue gas entering the *Advanced Hybrid™* filter at a time interval of every 2 hr, which corresponds to 19 mg/m³ (1.2 lb/Macf) carbon injection rate and an average carbon:mercury ratio of 3000:1.

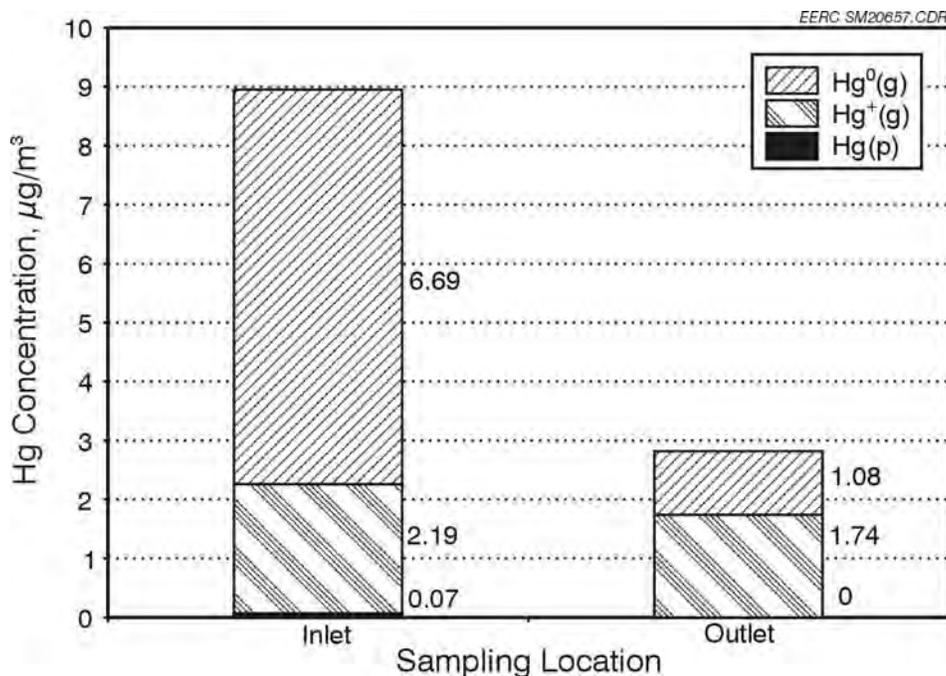


Figure 6.2.4.6. Mercury species across the *Advanced Hybrid™* filter (3 mA) under 38 mg/m³ (2.4-lb/Macf) FGD continuous injection – Ontario Hydro results.

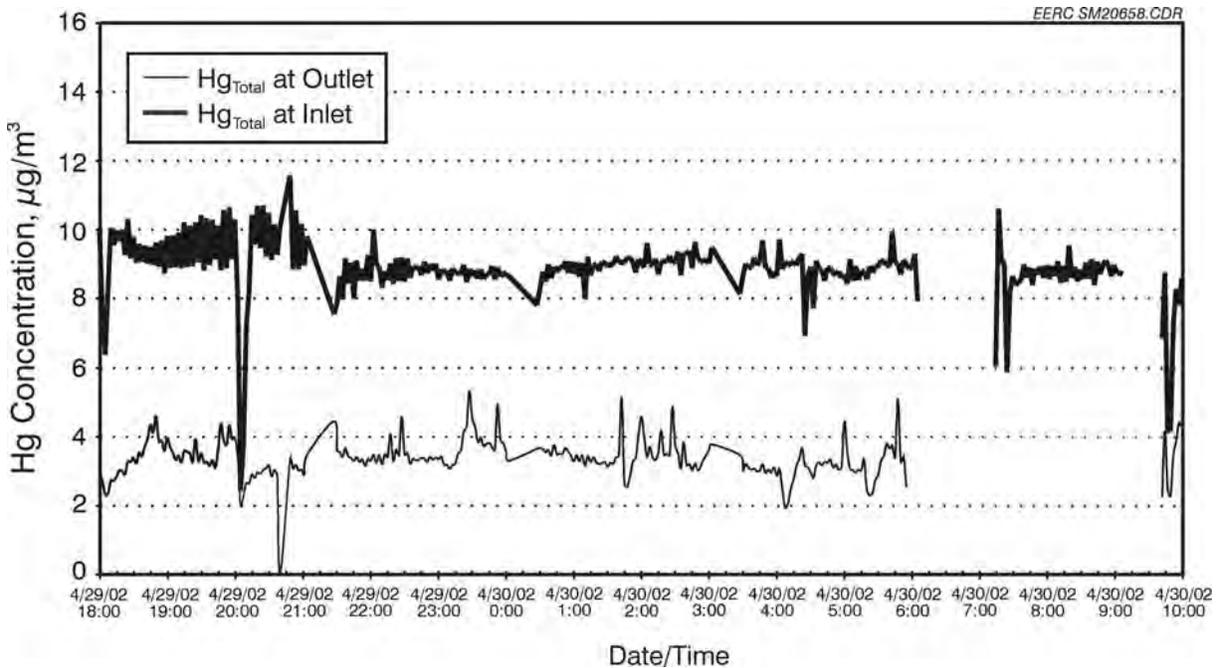


Figure 6.2.4.7. Mercury species across the *Advanced Hybrid*TM filter (3 mA) under 38 mg/m³ (2.4-lb/Macf) FGD continuous injection – CMM data.

During the batch injection, the *Advanced Hybrid*TM filter power was momentarily shut off to facilitate the carbon reaching the bags. The pressure drop across the system increased to 0.5 kPa (2 in. W.C.) during the power-off batch injection, indicating that most of the carbon deposited on the filter bags where the carbon had good contact with the flue gas.

The CMM data (Figure 6.2.4.8) indicate that, within a few minutes of the power-off batch injection, the outlet mercury level dropped to near zero for approximately 30 min. During this time, total mercury removal was well above 90%. However, after this time, the emission slowly increased until at the end of 2 hr it was close to the inlet level. Two Ontario Hydro samples (Figure 6.2.4.9) were collected at the *Advanced Hybrid*TM filter inlet and outlet over a single 2-hr cycle, and the outlet sampling result should represent the average mercury emission during the 2-hr time period. Based on both inlet and outlet Ontario Hydro sampling results, the overall mercury removal was 71.2% for the 19-mg/m³ (1.2-lb/Macf) power-off batch carbon injection. This represents an improvement in mercury control compared to 48.4% to 54.2% of mercury capture under the same carbon injection rate in continuous mode (PTC-BA-628), but it is still

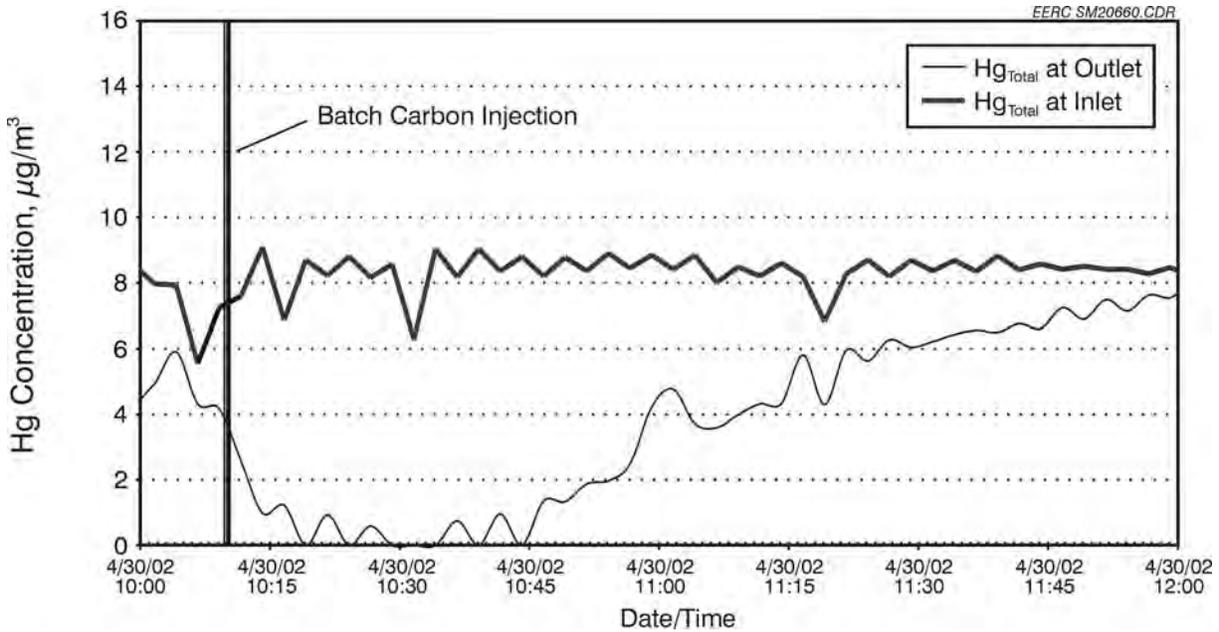


Figure 6.2.4.8. Temporal variation of mercury emission of mercury species across the *Advanced Hybrid*TM filter (3 mA) under 38 mg/m³ (2.4-lb/Macf) FGD continuous injection – Ontario Hydro results during the 19 mg/m³ (1.2-lb/Macf) FGD power-off batch injection test.

lower than the goal of 90% removal. Mercury speciation in the outlet flue gas shows the NORIT FGD carbon efficiently oxidized mercury but could not capture all of it.

Test 5 – 38 mg/m³ (2.4 lb/Macf) Power-Off Batch NORIT FGD Injection – *Advanced Hybrid*TM Filter with 120-min Residence Time and 3-mA Current

In Test 5, the amount of carbon injected every 2 hr was increased to 26.6 g (0.059 lb), equivalent to 38-mg/m³ (2.4-lb/Macf) carbon injection and an average carbon-to-mercury ratio of 6000:1. The Ontario Hydro data (Figure 6.2.4.10) indicate the mercury removal improved to 86.8%, very close to the 90% removal goal. The CMM data (Figure 6.2.4.11) also show that the time of over 90% removal increased to about 1 hr after injection. By the end of the 2-hr interval, the mercury level reached only about 50% of the inlet level. Again, NORIT FGD carbon demonstrated efficient mercury oxidation, as well as capture.

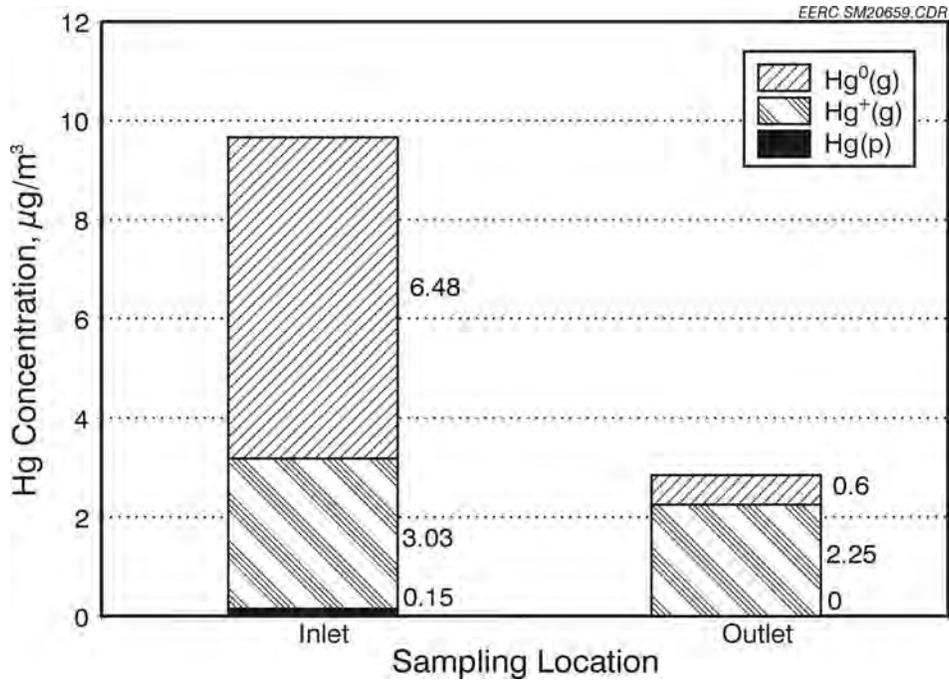


Figure 6.2.4.9. Mercury species across the *Advanced Hybrid*TM filter with 19 mg/m³ (1.2-lb/Macf) FGD power-off batch injection.

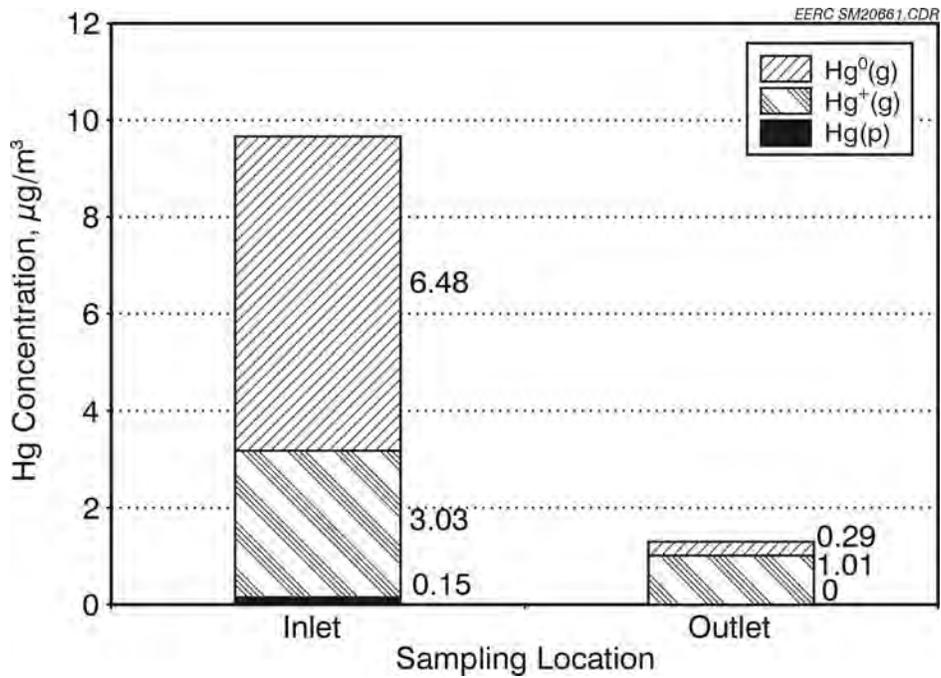


Figure 6.2.4.10. Mercury species across the *Advanced Hybrid*TM filter under 38 mg/m³ (2.4-lb/Macf) FGD power-off batch injection.

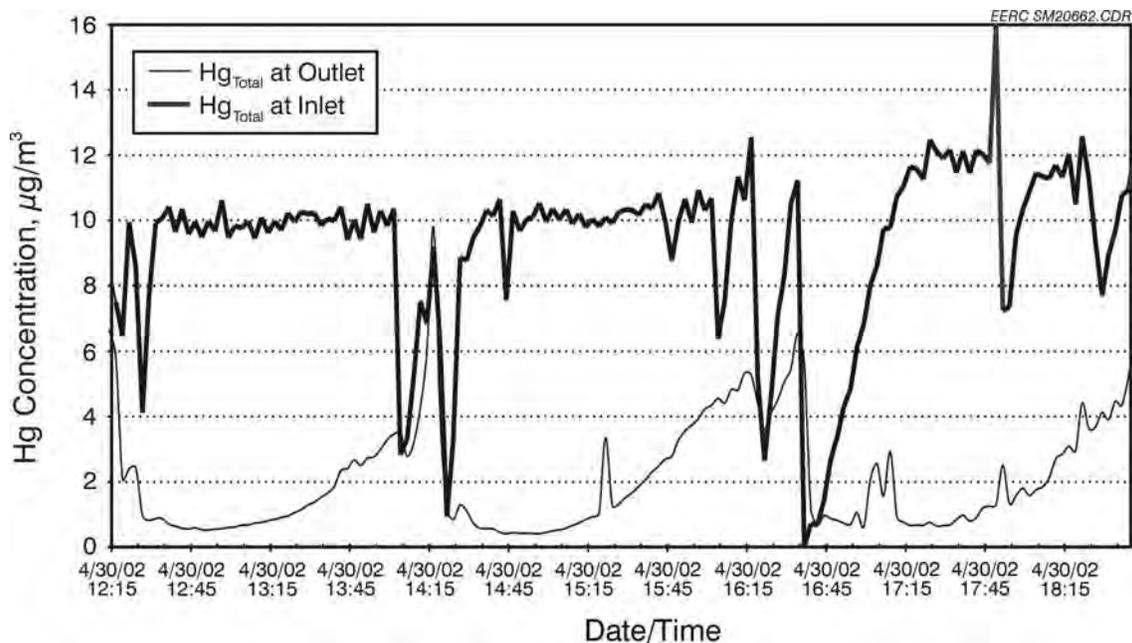


Figure 6.2.4.11. Temporal variations of mercury emission of the *Advanced Hybrid*TM filter under 38 mg/m³ (2.4-lb/Macf) FGD power-off batch injection test.

Test 6 – 38 mg/m³ (2.4 lb/Macf) Power-On Batch NORIT FGD Injection – *Advanced Hybrid*TM Filter with 120-min Residence Time and 3-mA Current

The previous two tests clearly showed improved mercury capture with power-off batch injection, but that approach may not be as practical as batch injection while maintaining the *Advanced Hybrid*TM filter power. Test 6 was similar to Test 5 except the power remained on during the batch injection. The calculated removal efficiency based on the Ontario Hydro data (Figure 6.2.4.12) was reduced to 75.5%, but was still somewhat better than the 71.5% removal seen with continuous injection in Test 3 under otherwise similar conditions.

The CMM data (Figure 6.2.4.13) show mercury temporal variation over multiple injection cycles and indicate some differences compared to the power-off batch injection test. After each injection, the mercury emission did not drop as low as in the previous power-off batch injection test, and it started to increase immediately. This suggests that the carbon was not as well exposed to the flue gas as with the power-off batch injection. From inspection through sight ports of the flow patterns and dust deposition in the *Advanced Hybrid*TM filter, a significant fraction of the dust deposited on the outside walls away from the main gas flow region. Altering the inlet

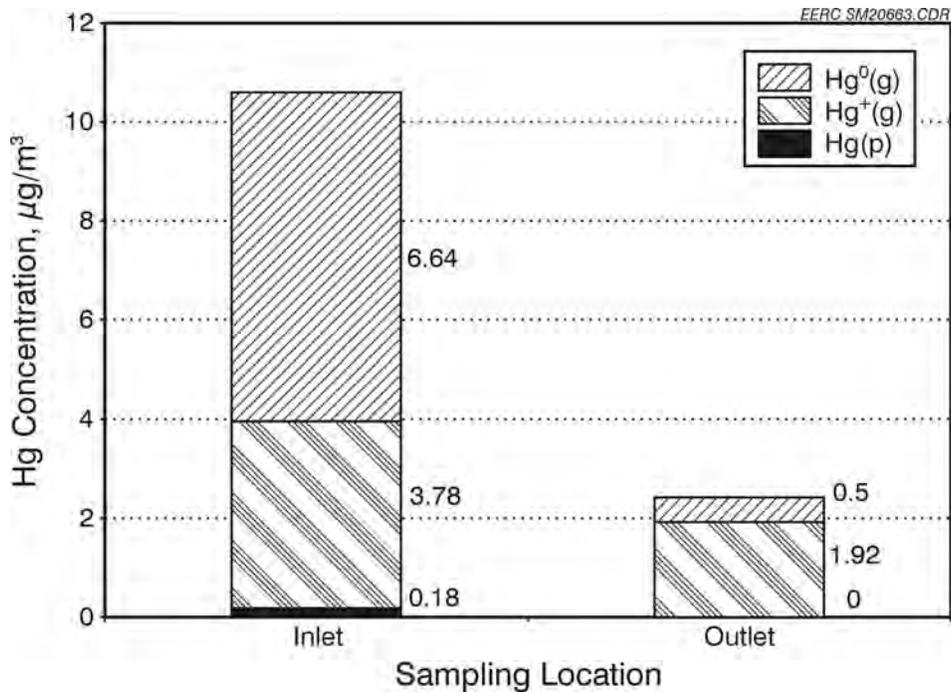


Figure 6.2.4.12. Mercury species across the *Advanced Hybrid*TM filter under $38 \text{ mg}/\text{m}^3$ ($2.4\text{-lb}/\text{Macf}$) FGD power-on batch injection.

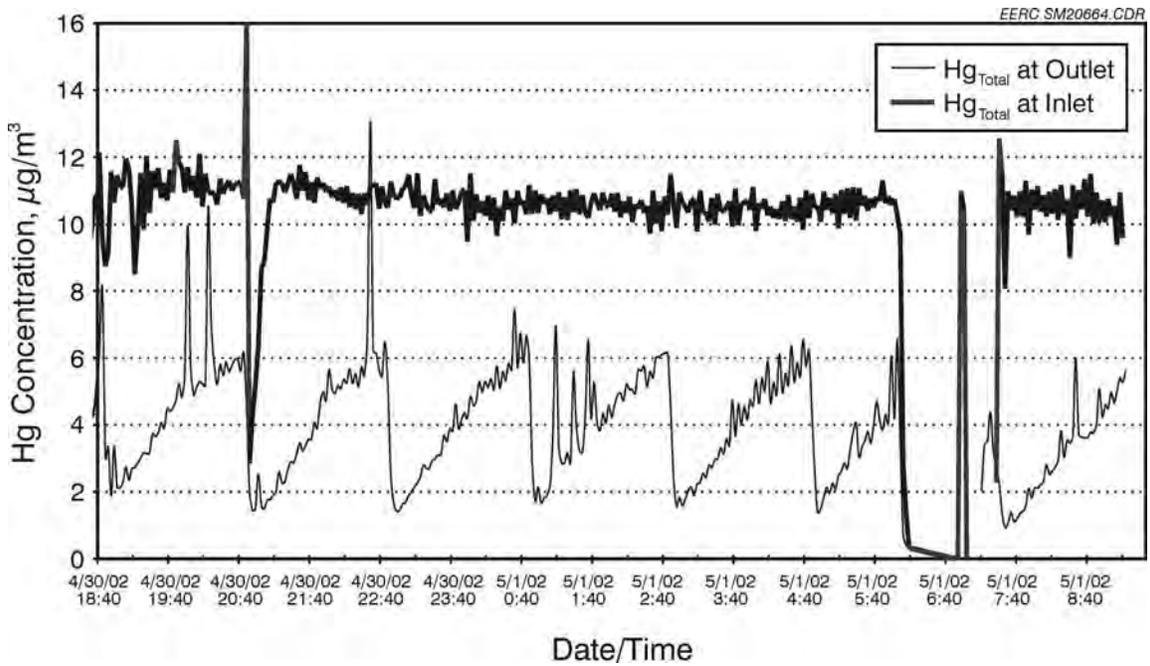


Figure 6.2.4.13. Temporal variations of mercury emission of the *Advanced Hybrid*TM filter under $38 \text{ mg}/\text{m}^3$ ($2.4\text{-lb}/\text{Macf}$) FGD power-on batch injection.

configuration to force the gas flow between the discharge electrodes and perforated plates would likely improve the carbon–flue gas contact.

Test 7 – 19 mg/m³ (1.2 lb/Macf) Continuous NORIT FGD Injection – Advanced Hybrid™ Filter with 120-min Residence Time and 3-mA Current

Another test was completed with a continuous 19-mg/m³ (1.2-lb/Macf) NORIT FGD injection, corresponding to carbon-to-mercury ratio of 3000:1, to verify the previous results and to determine if extended operational time might result in a gradual increase in mercury removal as a result of carbon buildup in the system. The Ontario Hydro results (Figure 6.2.4.14) indicate only a 41.7% removal, which is somewhat lower than the results from the previous run (PTC-BA-628) under the same carbon injection rate. However, the mercury monitor data (Figure 6.2.4.15) indicate about 60% removal over an extended time and show the very steady level of control that is maintained with continuous injection.

6.2.4.4 Conclusions from the PTC-BA-629 Testing Results

Figure 6.2.4.16 summarizes mercury removal efficiencies for the seven tests completed in PTC-BA-629. From these data, the removal efficiency of the *Advanced Hybrid™* filter is not only dependent on the carbon addition rate, but can be improved by batch injection. Over 70%

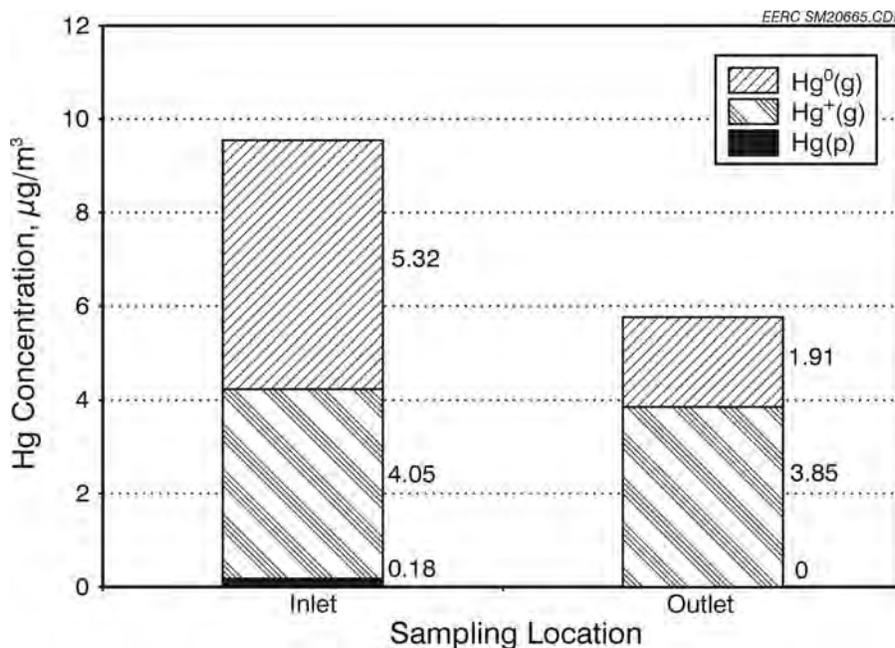


Figure 6.2.4.14. Mercury species across the *Advanced Hybrid™* filter under 19 mg/m³ (1.2-lb/Macf) FGD continuous injection.

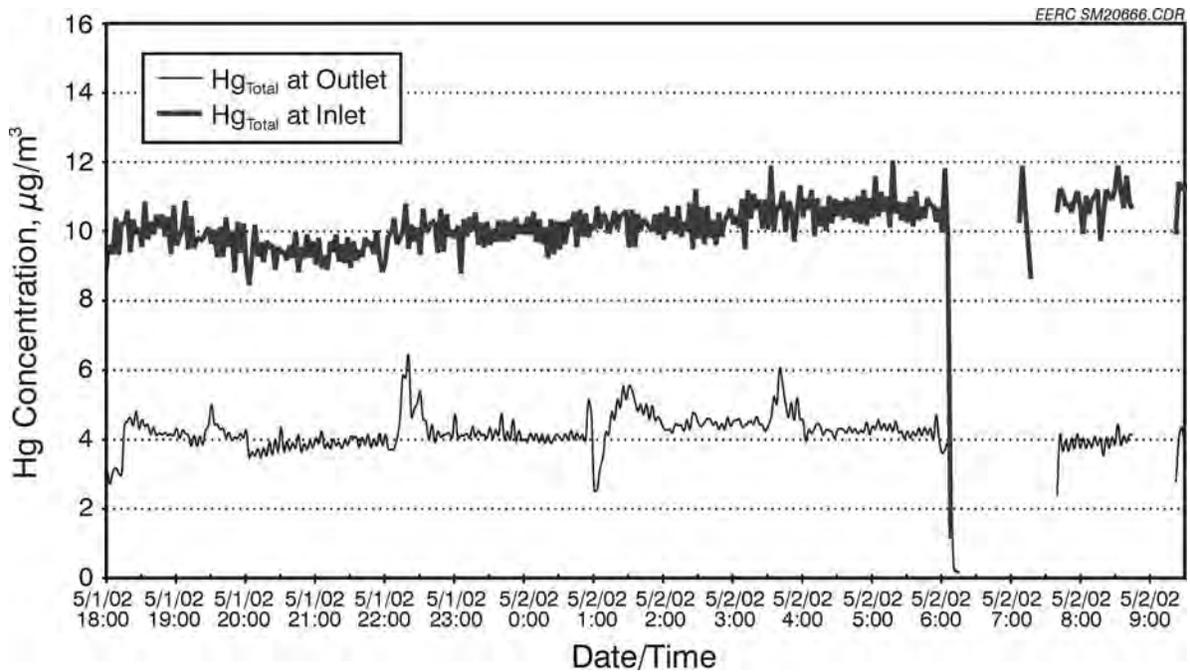


Figure 6.2.4.15. Temporal variations of mercury emission of the *Advanced Hybrid*TM filter under 19 mg/m³ (1.2-lb/Macf) FGD continuous injection.

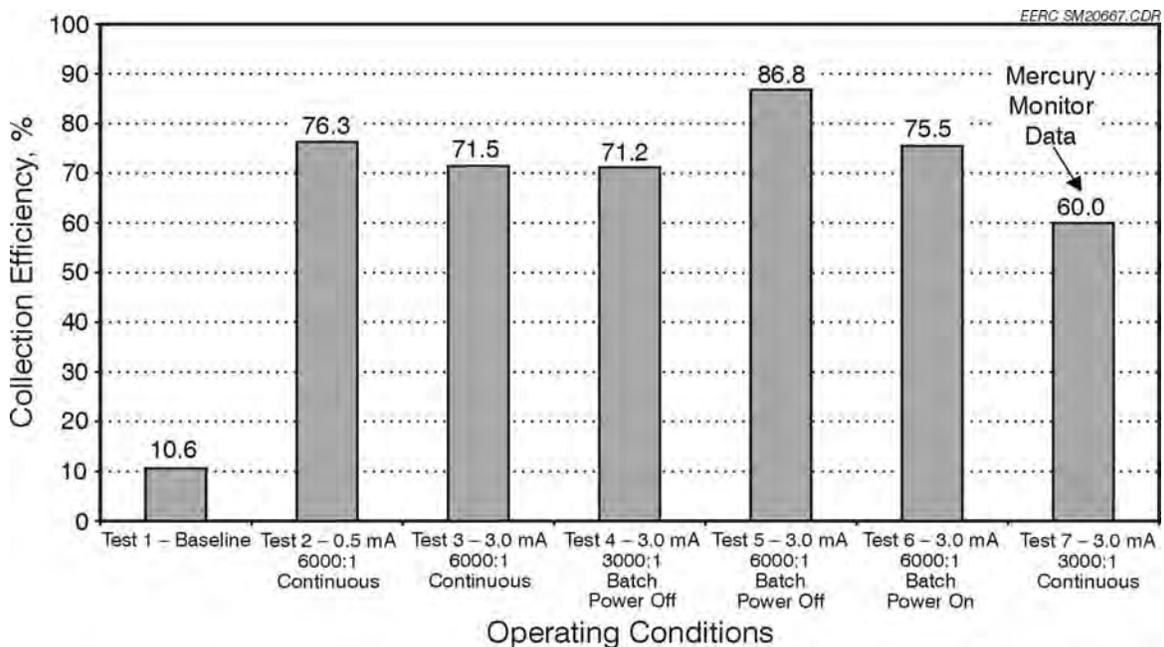


Figure 6.2.4.16. Comparisons of mercury removal with *Advanced Hybrid*TM filter under both continuous and batch carbon injection.

removal was seen for all of the injection tests except for the last test. This suggests that excellent mercury removal can be achieved with the *Advanced Hybrid*TM filter, even for the difficult case seen here with very little natural capture of mercury by the fly ash and primarily elemental mercury at the inlet. To increase the capture above the 90% level will require further optimization of the *Advanced Hybrid*TM filter and injection mode and may require a higher carbon addition rate or a more effective sorbent. Modification of the pilot-scale *Advanced Hybrid*TM filter inlet configuration is expected to improve mercury capture by keeping more of the carbon in the main flow region within the *Advanced Hybrid*TM filter housing.

A comparison of batch injection of sorbent with continuous injection showed that mercury removal was improved with the batch injection. Tests with power-off batch injection compared to power-on injection showed 87% removal was seen when the power was momentarily shut off during injection, compared to 75% removal with power-on batch injection. The power-off injection should result in most of the sorbent reaching the filter bag surface where the best gas–solid contact occurs. However, during the power-on injection, a fraction of the sorbent collected on the outside walls. With a modified inlet configuration, the benefit of power-off injection may be negligible.

During the power-off batch injection cycles, the mercury removal was well over 90% for the first half of each cycle. This is encouraging because it indicates that over 90% removal is possible with the low-cost FGD sorbent and that with further optimization, 90% control should be achievable, even for a coal that produces mostly elemental mercury and with little natural mercury capture in the fly ash.

6.2.5 PTC-SC-632

6.2.5.1 Test Conditions

The primary purpose of this 1-week test was to establish the mercury species baseline across the *Advanced Hybrid*TM filter with a bituminous coal flue gas. For this test, Shade Creek bituminous coal was selected and burned in the pilot-scale unit. The run was designated as PTC-SC-632, where “SC” refers to the Shade Creek coal burned in this test, Table 6.2.5.1 lists the three tests that were completed. The pilot-scale unit was continuously operated to provide baseline mercury speciation data with the Shade Creek coal flue gas with both the *Advanced Hybrid*TM filter and a PJBH. In the *Advanced Hybrid*TM filter mode, the corona current was

Table 6.2.5.1. PTC-SC-632 – Test Parameters

Test No.	Mode	Residence Time
1	<i>Advanced Hybrid</i> TM Filter 2 mA	30 min
2	<i>Advanced Hybrid</i> TM Filter 2 mA	>24 hr
3	Pulse jet	30 min

2 mA, while the fly ash residence time in the hopper was 30 min and > 24 hour, respectively, to evaluate the residence time effect on mercury species. Having finished Tests 1 and 2, we switched to the PJBH to compare mercury species between the *Advanced Hybrid*TM filter and the PJBH. The PJBH was pulse-cleaned under a trigger pressure of 2.0 kPa (8.0 in. W.C.), and the hopper ash was emptied every 30 min. Ontario Hydro samples were collected at the unit inlet and outlet for each test to determine the mercury species in the flue gas.

6.2.5.2 Coal Analysis

Table 6.2.5.2 lists the analysis results for Shade Creek coal, including proximate and ultimate data, and the mercury and chlorine concentrations in the raw coal. Compared to low levels of chlorine and sulfur in the Cordero Rojo complex (0.31% of sulfur and 14.7 ppm of chlorine) and Belle Ayr (0.38% of sulfur and 22.5 ppm of chlorine), Shade Creek coal has 1.48% sulfur and 314 ppm of chlorine in raw coal. Based upon the averaged 0.173 µg/g mercury in coal and data from proximate and ultimate analyses, the Shade Creek coal is expected to have 17.6 µg/m³ (dry flue gas, 3% O₂) of mercury in the flue gas.

6.2.5.3 Mercury Results for PTC-SC-632

Plotted in Figure 6.2.5.1 are one Ontario Hydro result at the unit inlet and two Ontario Hydro results at the unit outlet when the unit was operated in the *Advanced Hybrid*TM filter mode with 2.0-mA corona current and 30-min fly ash residence time. The inlet data indicate 15.1 µg/m³ oxidized mercury, 1.3 µg/m³ elemental mercury, and 2.9 µg/m³ particulate mercury. The two outlet samples indicate the mercury was primarily oxidized with only 1.1 to 1.9 µg/m³ of elemental mercury. The 2.9 µg/m³ particle-bound mercury for the inlet sample and the evidence that no mercury removal occurred across the *Advanced Hybrid*TM filter suggest that some desorption occurred across the *Advanced Hybrid*TM filter. However, the 2.9 µg/m³ particle-bound mercury may be caused by the additional mercury adsorption on the inlet sampling filter.

Table 6.2.5.2. PTC-SC-632 – Coal Analysis

Proximate Analysis, wt%	As Sampled	Moisture-Free
Moisture Content	2.1	NA
Volatile Matter	23.22	23.72
Fixed Carbon	63.1	64.46
Ash	11.57	11.82
Ultimate Analysis, wt%		
Hydrogen	4.46	4.32
Carbon	75.94	77.56
Nitrogen	1.64	1.68
Sulfur	1.45	1.48
Oxygen	4.93	3.14
Ash	11.57	11.82
Heating Value, Btu/lb	12,855	13,129
Chloride Concentration, dry coal basis, $\mu\text{g/g}$		314
Hg Concentration, dry coal basis, $\mu\text{g/g}$		
Day 1		0.175
Day 2		0.18
Day 3		0.165
Mean		0.173

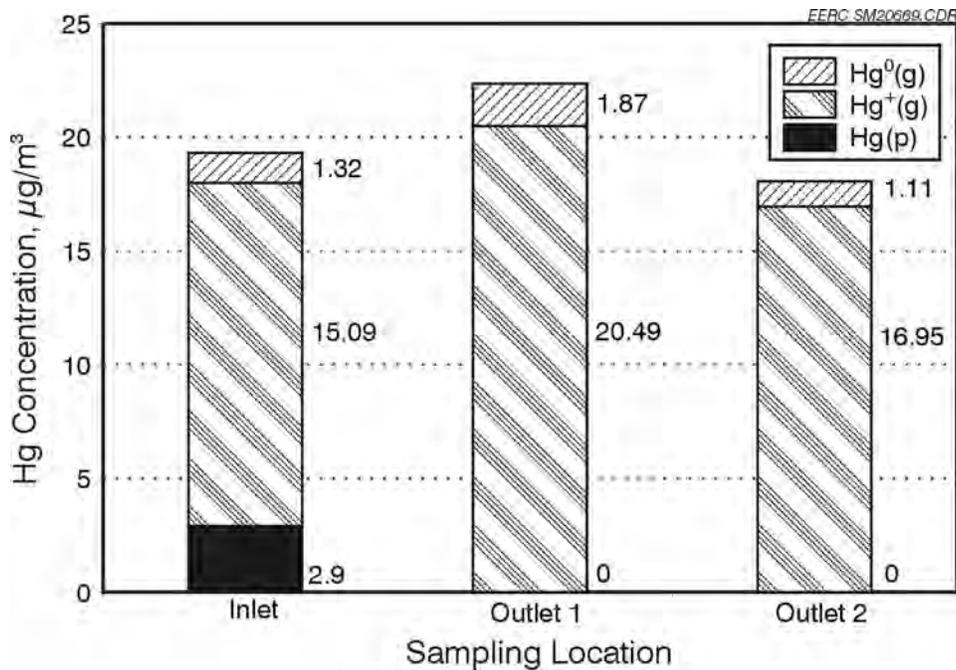


Figure 6.2.5.1. Mercury species across the *Advanced Hybrid*™ filter in Shade Creek flue gas – 30-min residence time.

For Test 2, the *Advanced Hybrid*TM filter was operated in a similar mode, except the hopper was not emptied for 24 hr. The Ontario Hydro data in Figure 6.2.5.2 indicate very different results compared to Test 1. At the inlet, almost all of the mercury was in particulate form, and there was about 75% removal of mercury across the *Advanced Hybrid*TM filter. If all of the inlet mercury was associated with particulate, it would be expected to be captured in the *Advanced Hybrid*TM filter. The 3.8–5.0 $\mu\text{g}/\text{m}^3$ of mercury emission at the *Advanced Hybrid*TM filter unit outlet suggests, again, there may have been desorption of mercury from the inlet ash upon the long exposure to the flue gas, or there was a fair fraction of oxidized mercury in the inlet flue gas, which was adsorbed on the inlet filter.

For Test 3, the unit was operated in pulse-jet mode, and the hopper was emptied every 30 min to maintain a constant half-hour residence time of fly ash in contact with flue gas. The inlet Ontario Hydro data in Figure 6.2.5.3 again show a high level of particulate mercury of 13.7 $\mu\text{g}/\text{m}^3$, with 2.8 $\mu\text{g}/\text{m}^3$ of oxidized mercury. The outlet mercury emission was 4.3 $\mu\text{g}/\text{m}^3$ of

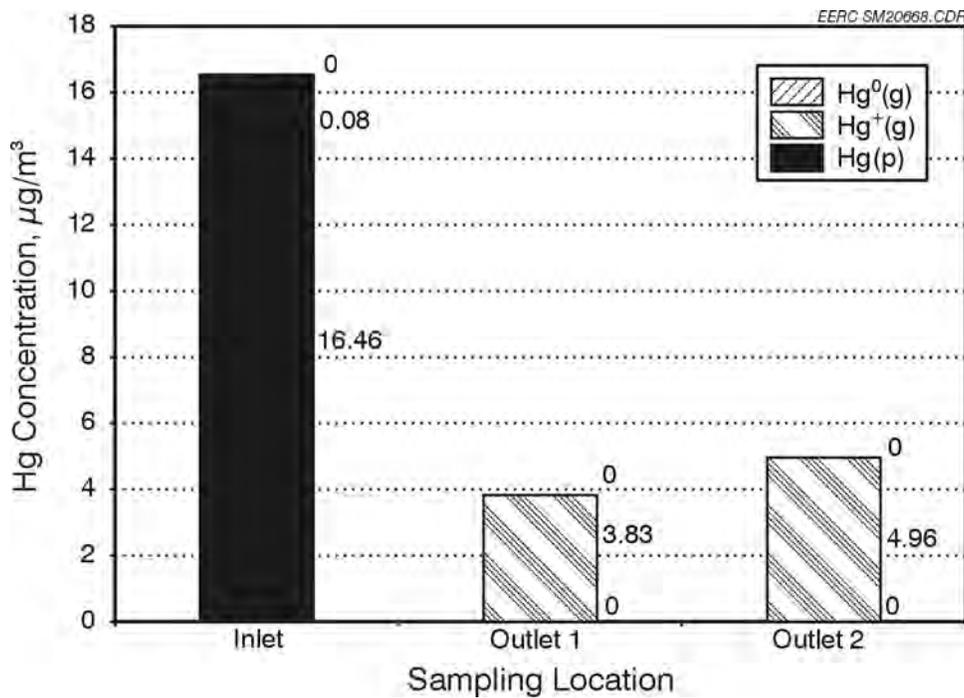


Figure 6.2.5.2. Mercury species across the *Advanced Hybrid*TM filter in Shade Creek flue gas – 24-hr residence time.

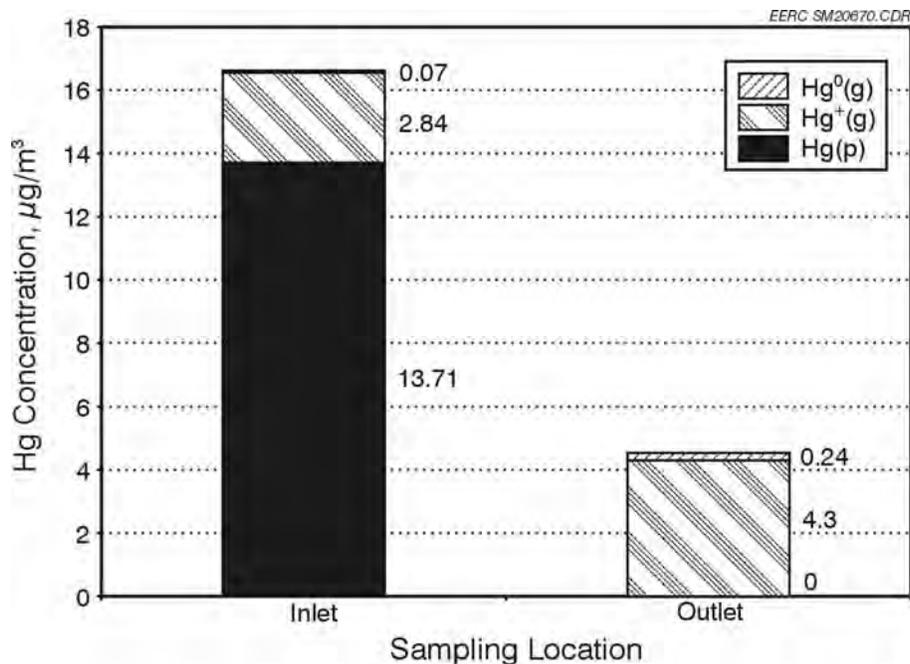


Figure 6.2.5.3. Mercury species across the PJBH in Shade Creek flue gas – 30-min residence time.

oxidized mercury and 0.24 µg/m³ of elemental mercury, indicating about 75% mercury capture across the PJBH.

To further understand the reason for the differences between Test 1 and Tests 2 and 3, the selected hopper ash and inlet filter ash were analyzed for mercury content and LOI, and Table 6.2.5.3 summarizes the analysis results. It became apparent that the differences of mercury species among the inlet Ontario Hydro samples were related to the amount of carbon in the ash. For Test 1, the first inlet filter and hopper ash had similar mercury concentrations of about 0.35 µg/g, and the LOI of the hopper ash was 10.85% (Table 6.2.5.3). However, the second hopper ash sample had almost five times more mercury, which corresponded to an LOI of 20.33%. For Test 2, again, the inlet filter and hopper samples had high mercury levels corresponding to 20.66% LOI. For Test 3, the results were similar, with a high ash mercury level and high LOI in the ash. An interesting result from these tests is the relationship between the carbon content of the ash and the mercury retention. The significant increase of mercury retention in ash when the fly ash LOI increased from 10% to 20% suggests that the characteristics of the carbon may be as important as the amount of carbon.

Table 6.2.5.3. PTC-SC-632 – Mercury Concentration in Fly Ash

Test No.	Sample Type	Time Sample Taken	Hg Concentration, $\mu\text{g/g}$	LOI, %
1	Inlet filter	6/03/02 14:00–16:00	0.362	
	Hopper ash	6/03/02 16:00	0.344	10.85
	Hopper ash	6/04/02 7:00	1.64	20.33
2	Inlet filter	6/05/02 8:27–10:27	2.19	
	Hopper ash	6/05/02 11:00	1.48-1.63	20.66
3	Inlet filter	6/05/02 14:00–16:00	1.55	
	Hopper ash	6/05/02 16:00		21.59

The above experimental data indicate that the pilot-scale combustion unit cannot combust the Shade Creek coal completely because of the high carbon and low volatile matter with this coal, resulting in a high 10%–20% LOI in ash instead of 1%–5% LOI in a typical bituminous coal flue gas. Good combustion for this coal in the pilot-scale unit to produce low LOI may be difficult without burner modification.

One purpose of this run was to serve as the source of flue gas for a bench-scale breakthrough test, but because of the high carbon in the ash and varied mercury concentrations at the *Advanced Hybrid*TM filter outlet, the fixed-bed tests could not be completed.

6.2.5.4 – Conclusions from PTC-SC-632 Testing Results

A baseline test with an EB Shade Creek coal was completed. Fly ash analysis show high levels of LOI from 10% to 20% because of incomplete coal combustion.

At the 10% LOI level, there was minimal capture of mercury by the fly ash, but at 20% LOI, most of the mercury was retained by the fly ash. This suggests that the relationship between the amount of carbon in the ash and the level of mercury capture is complex and may depend more on critical carbon characteristics than on the amount of carbon present.

6.2.6 PTC-SF-635

6.2.6.1 Test Conditions

Results from the previous bituminous coal test (PTC-SC-632) indicate that the pilot-scale combustor cannot completely combust Shade Creek coal because of its high carbon level and low level of volatile matter. Therefore, we switched to Springfield coal, another bituminous coal, and evaluated mercury control technology with the *Advanced Hybrid*TM filter with this high-sulfur EB coal flue gas. Care was taken to maintain good combustion conditions to avoid generating significant amounts of CO and to minimize the amount of unburned carbon in the ash.

The planned variables to be evaluated included residence time of the ash in the *Advanced Hybrid*TM filter chamber, activated carbon feed rate, and carbon injection method. Amended silicate developed by ADA, referred to as Sorbent X in this test, was an alternative sorbent tested for its effectiveness on mercury removal in the *Advanced Hybrid*TM filter. An additional unplanned variable tested included the *Advanced Hybrid*TM filter temperature. Because of the very poor mercury removal results seen at 135°C (275°F), additional tests were completed at 160°C (320°F). At the measured SO₃ level of 31.7 ppm, 135°C (275°F) is below the acid dew point. There was concern that operation below the acid dew point might be the cause of the poor mercury removal, so some tests were repeated at 160°C (320°F), which is well above the acid dew point for 31.7 ppm SO₃. At the end of the testing period, limestone mixed with NORIT FGD was injected into the *Advanced Hybrid*TM filter to determine the combined effect on mercury removal. Table 6.2.6.1 is a summary of the tests completed.

Two CMMs monitored mercury species in flue gas at the *Advanced Hybrid*TM filter inlet and outlet continuously over the entire testing period. Ontario Hydro samples were collected for the selected tests to verify CMM measurements. The mercury sampling schedule is also listed in Table 6.2.6.1.

6.2.6.2 Coal and Flue Gas Analyses

Table 6.2.6.2 lists coal analysis data including proximate–ultimate analysis and concentrations of mercury and chlorine for the Springfield coal. The Springfield coal has 3.1% of sulfur, 350 ppm of chlorine, and 0.11 µg/g mercury. Combining a combustion calculation based on proximate and ultimate analysis results with mercury content in the raw coal, mercury concentration in the Springfield coal flue gas is expected to be 13.9 µg/m³ (dry flue gas, at 3.0% O₂). Also included in Table 6.2.6.2 are the concentrations of the major and minor elements in the Springfield ashed coal as measured by x-ray fluorescence (XRF). Average flue gas concentrations for the test are shown in Table 6.2.6.3. The Springfield coal flue gas had a higher level of NO_x than might be seen in full-scale boilers, especially with the implementation of low-NO_x burners. The high NO_x level of >1300 ppm seen here is the result of trying to maintain very hot flame conditions with sufficient excess air to ensure good carbon burnout. Compared to the lower levels of chlorine and sulfur in WSB coal flue gases measured in previous pilot-scale tests,

Table 6.2.6.1. Summary of the Test Scenarios for PTC-SF-635

Test	Description	Test Time	Mode	Temp, °C (°F)	Ontario Hydro Sample Times	
					Inlet	Outlet
1	Baseline, 30-min residence time	Dec. 9, 8:42–16:40	<i>Advanced</i> <i>Hybrid™ Filter</i>	135 (275)	11:05–13:05	11:05–13:05 13:45–15:15
2	Baseline, 24-hr residence time	Dec. 9, 16:40–Dec.10, 17:04	<i>Advanced</i> <i>Hybrid™ Filter</i>	135 (275)	8:36–10:16	8:36–10:16 13:25– 14:55
3	FGD, 7.5 g/hr	Dec. 10, 17:04–18:20	<i>Advanced</i> <i>Hybrid™ Filter</i>	135 (275)	9:46–10:30	9:46–10:30
4	FGD, 37.5 g/hr	Dec. 10, 19:12–Dec.11 12:41 Dec. 10, 18:20–18:32	<i>Advanced</i> <i>Hybrid™ Filter</i>	135 (275)		
5	FGD 37.5 g/hr	Dec. 10, 18:32–18:57	PJBH	135 (275)		
6	FGD 15 g power-off batch	Dec. 10, 18:57–19:12	<i>Advanced</i> <i>Hybrid™ Filter</i>	135 (275)		
7	FGD 22.5 g power-off batch	Dec. 11, 12:41–13:25	<i>Advanced</i> <i>Hybrid™ Filter</i>	135 (275)		
8	FGD, 7.5 g/hr	Dec. 11, 19:51–20:42	<i>Advanced</i> <i>Hybrid™ Filter</i>	160 (320)	9:45–10:45	9:45–10:45
9	FGD, 30 g/hr	Dec. 11, 22:12–Dec.12 10:30 Dec. 11, 20:42–22:12	<i>Advanced</i> <i>Hybrid™ Filter</i>	160 (320)		
10	FGD, 7.5 g/hr	Dec. 12, 10:30–10:45	PJBH	160 (320)		
11	FGD 30 g/hr	Dec. 12, 10:45–11:05	PJBH	160 (320)		
12	Sorbent X 15 g/hr	Dec. 12, 13:23–14:27	<i>Advanced</i> <i>Hybrid™ Filter</i>	160 (320)		
13	Sorbent X 15 g power-off batch	Dec. 12, 14:37–15:01	<i>Advanced</i> <i>Hybrid™ Filter</i>	160 (320)		
14	Limestone 15 g power-off batch	Dec. 12, 15:01–5:30	<i>Advanced</i> <i>Hybrid™ Filter</i>	160 (320)		
15	15 g limestone + 15 g FGD, power-off batch	Dec. 12, 15:30–6:09	<i>Advanced</i> <i>Hybrid™ Filter</i>	160 (320)		

Table 6.2.6.2. Coal Analysis for the PTC-SF-635 Test*

	As-Received, wt%
Proximate Analysis	
Moisture Content	5.40 ± 0.27
Volatile Matter	39.2 ± 0.6
Fixed Carbon	45.8 ± 0.8
Ash	9.56 ± 0.15
Ultimate Analysis	
Hydrogen	4.64 ± 0.03
Carbon	67.0 ± 0.2
Nitrogen	2.22 ± 0.05
Sulfur	3.1 ± 0.07
Oxygen	8.11 ± 0.31
Ash	9.56 ± 0.15
Hg Concentration in Raw Coal, µg/g, as-received	0.111
Cl Concentration in Raw Coal, µg/g, as-received	350

PTC-SF-635 Coal Ash – Major and Minor Element Oxide Compositions, wt%*

SiO ₂	46.2
Al ₂ O ₃	20.9
Fe ₂ O ₃	23.6
MnO	ND**
TiO ₂	1.00
BaO	ND
P ₂ O ₅	0.10
CaO	1.73
MgO	1.50
Na ₂ O	0.40
K ₂ O	2.20
SO ₃	2.28
Total	99.8

* Results from Final Topical Report for Task 28, “Pilot-Scale Evaluation of the Impact of Selective Catalytic Reduction for NO_x on Mercury Speciation” (DE-FC26-98FT40321).

** Not detectable.

Table 6.2.6.3. Characteristics of Flue Gas for the PTC-SF-635 Test, dry basis

O ₂ , %	4.6
CO ₂ , %	14.3
CO, ppm	5.3
NO, ppm	1334
NO ₂ , ppm	8.5
SO ₂ , ppm	2000–2300
HCl, ppm	32.0–42.9
SO ₃ , ppm	31.7

the EB Springfield coal flue gas has much higher concentrations of SO₂ (2000–2300 ppm) and HCl (32.4–42.9 ppm). The high concentration of SO₂ (2000–2300 ppm) may have a negative impact on carbon sorbent performance for mercury capture, while HCl would benefit mercury oxidation and possibly enhance carbon reactivity with mercury. Note that the SO₃ level was also fairly high at 31.7 ppm.

6.2.6.3 Mercury Results for PTC-SF-635

Tests 1 and 2 – Baseline Comparison for 30-min and 24-hr Residence Time

Since this coal was not previously tested in the pilot-scale *Advanced Hybrid*TM filter unit, Tests 1 and 2 were completed to establish mercury baselines across the *Advanced Hybrid*TM filter and to evaluate whether the residence time of the ash in the *Advanced Hybrid*TM filter chamber had any effect on mercury retention by the fly ash or oxidation of mercury across the *Advanced Hybrid*TM filter. For Test 1, there was no carbon injection, and the *Advanced Hybrid*TM filter was operated with a timed-pulse interval of 30 min. The plates were also rapped every 30 min to remove the deposited fly ash, and the hopper was emptied every hour. For Test 2, the pulse pressure set point was 2.0 kPa (8 in. W.C.), which resulted in a pulse interval of about 1 hr, and the plates were rapped every 3 hr. Ash was allowed to accumulate in the hopper for 24 hr before it was emptied.

Figure 6.2.6.1 plots Ontario Hydro results of mercury species across the *Advanced Hybrid*TM filter unit during Tests 1 and 2 and indicates no significant mercury capture for the baseline condition. The inlet flue gas of Test 1 had a high level of 12.5 µg/m³ oxidized mercury, 0.87 µg/m³ elemental mercury, and a very low level of particle-bound mercury of 0.02 µg/m³. With the 30-min fly ash residence time in the *Advanced Hybrid*TM filter hopper, the outlet flue gas of Test 1 had almost the same level of total mercury as the inlet, but it did show a slight increase of oxidized mercury at the *Advanced Hybrid*TM filter outlet.

For Test 2, there was a significant increase in oxidized mercury across the *Advanced Hybrid*TM filter. However, since the amount of elemental mercury at the outlet is similar to Test 1, this increase in oxidation cannot be attributed to residence time alone. The Test 2 Ontario Hydro data indicate somewhat higher total outlet mercury than the inlet. This difference may be within the normal variability of the measurements, but the CMM data also show higher outlet than inlet mercury concentrations near the end of the 24-hr residence time (Figure 6.2.6.2).

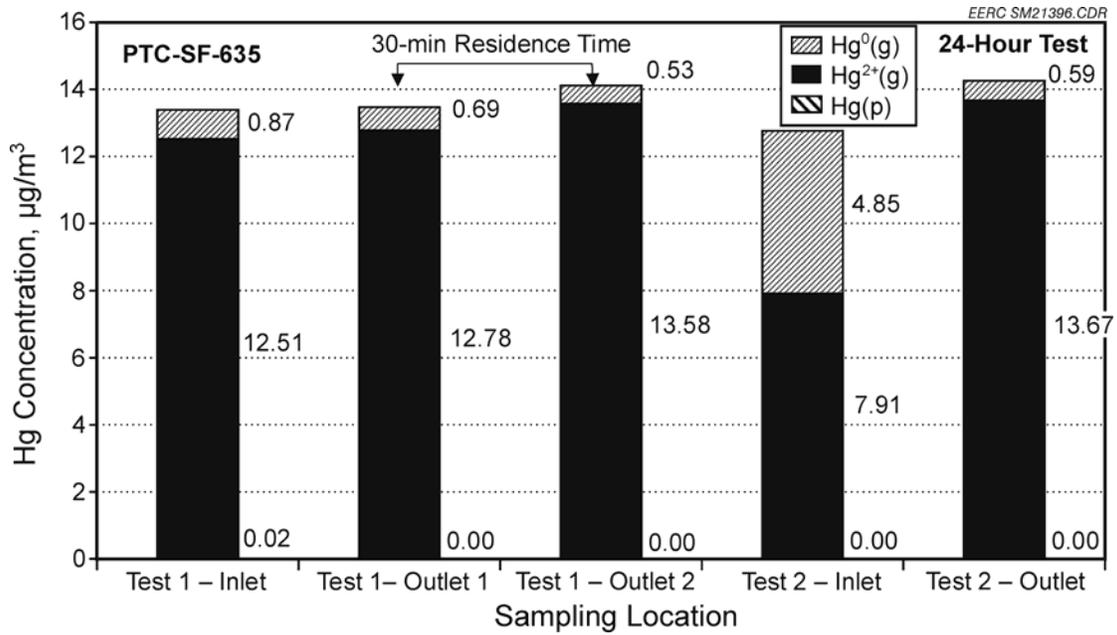


Figure 6.2.6.1. Ontario Hydro results of mercury species across the *Advanced Hybrid*TM filter unit during Tests 1 and 2.

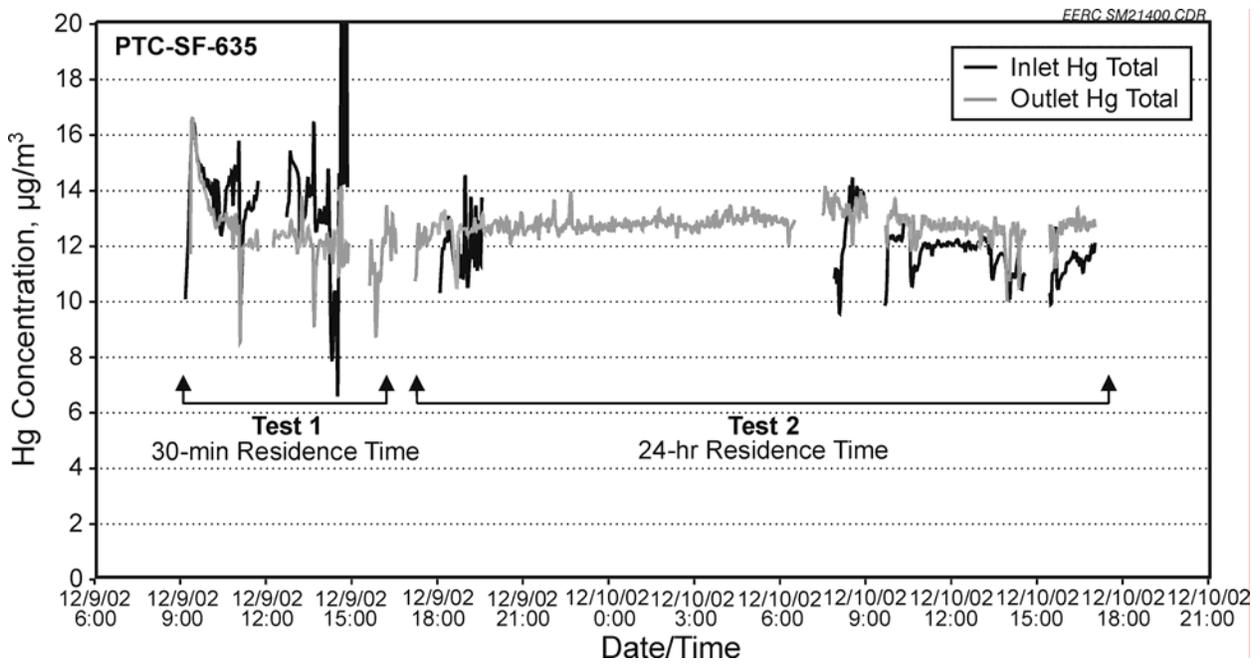


Figure 6.2.6.2. Temporal variations of gaseous mercury across the *Advanced Hybrid*TM filter in Springfield coal baseline test.

Again, the difference could be within the variability of the instruments, but a comparison of the mercury in the hopper ash shows that the mercury concentration after 24 hr of exposure to flue gas was 7 times lower ($0.00490 \mu\text{g/g}$ compared to $0.34 \mu\text{g/g}$ for the 30-min residence time sample). From previous bench-scale work, high SO_2 and NO_x concentrations led to the most significant desorption of mercury from activated carbon, so the same mechanism could be responsible for desorption of mercury from fly ash. The Test 3 data also indicate that desorption may be occurring with the activated carbon.

Figure 6.2.6.3 summarizes four Ontario Hydro inlet mercury samples completed during the entire PTC-SF-635 testing period, showing predominantly oxidized mercury and almost an undetectable amount of particulate mercury in the Springfield coal flue gas. Interestingly, even though the Springfield coal flue gas has very high concentrations of all of the acid gases, including SO_2 , NO_x , and HCl , there is still some elemental mercury present. The total average inlet mercury is in good agreement with the CMM inlet data, which typically was in the range from 12 to $14 \mu\text{g}/\text{m}^3$. In cases with little particulate mercury, it is usually possible to get good agreement between the CMM and Ontario Hydro measurements.

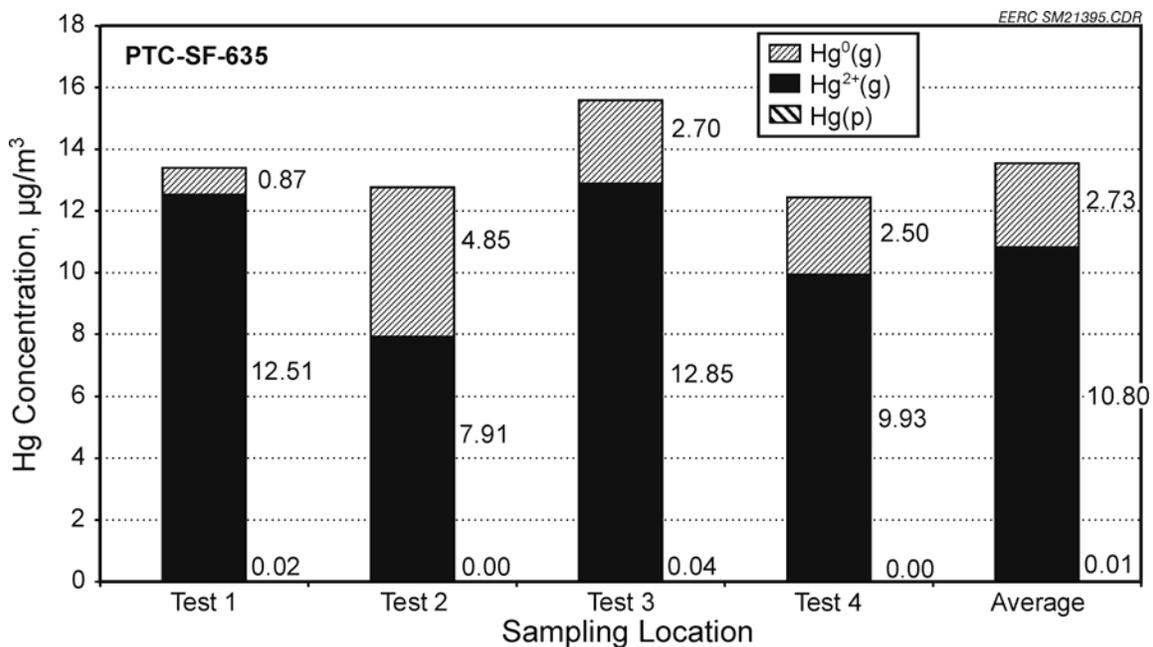


Figure 6.2.6.3. Four Ontario Hydro inlet mercury samples completed during the PTC-SF-635 testing period.

Tests 3–7 NORIT FGD Activated Carbon Injection at 135°C (275°F)

Two CMMs monitored the mercury species in flue gas across the *Advanced Hybrid*TM filter during the short-term activated carbon injection tests, and the measurements are plotted in Figure 6.2.6.4. With an activated carbon injection of 7.5 g/hr (1.5 lb/Macf), which was equivalent to a carbon-to-mercury ratio of about 3000:1, there was no detectable reduction in mercury emissions. The inlet and outlet Ontario Hydro data (Figure 6.2.6.5) also indicate less than 10% mercury removal in the *Advanced Hybrid*TM filter with the 7.5 g/hr (1.5 lb/Macf) NORIT FGD carbon injection. The predominant oxidized mercury in the Springfield flue gas is thought to be easily captured with activated carbon, but both CMM and Ontario Hydro data indicate otherwise. One possible reason is that the overwhelmingly high SO₂ in flue gas poisons the activated carbon sites, either to prevent mercury adsorption on the carbon or to form a volatile mercury compound that reenters the flue gas. The carbon feed rate was increased to 37.5 g/hr (7.5 lb/Macf) to see if better mercury capture would occur. CMM data in Figure 6.2.6.4 indicate only a 15% mercury removal at the higher carbon feed rate. The high-voltage power to the *Advanced Hybrid*TM filter was then turned off to determine mercury removal in the PJBH when all of the carbon reached

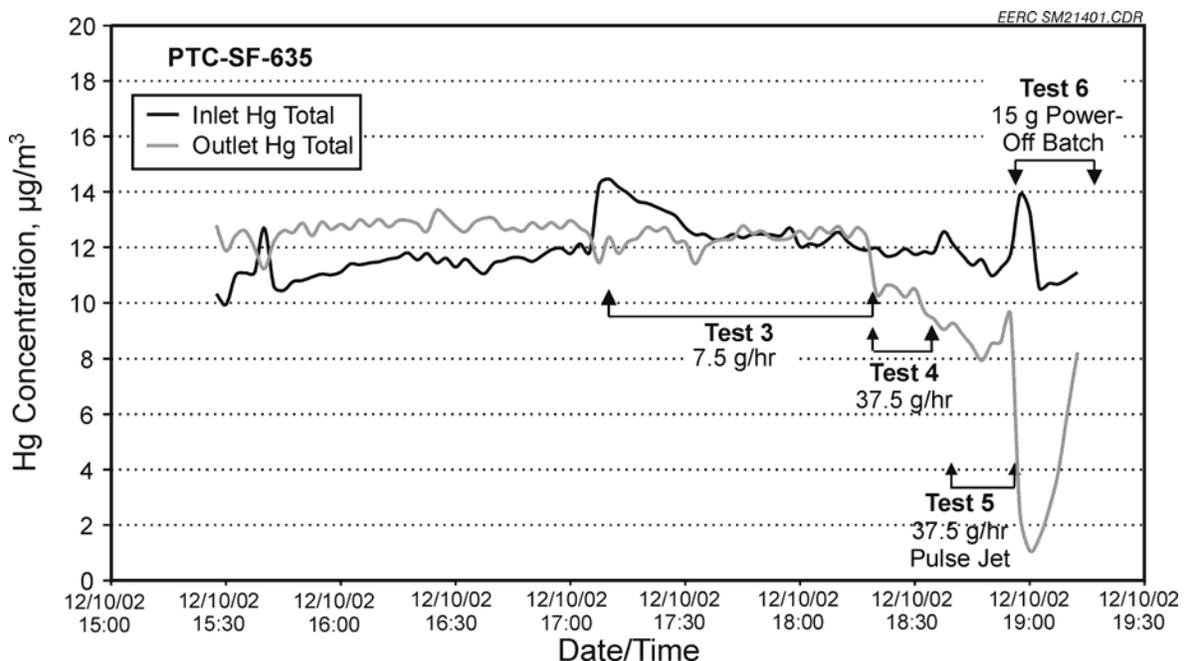


Figure 6.2.6.4. Temporal variations of gaseous mercury in the *Advanced Hybrid*TM filter inlet and outlet flue gas with FGD injection at 135°C (275°F).

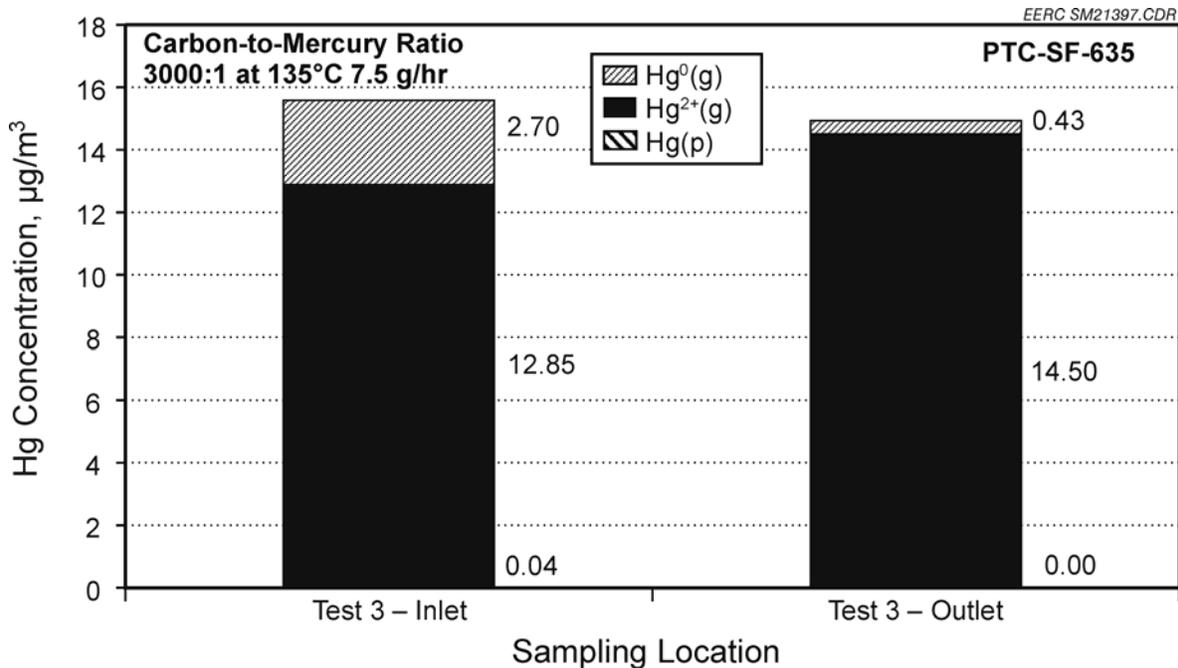


Figure 6.2.6.5. Inlet and outlet Ontario Hydro results with FGD injection at 135°C (275°F).

the bags. The mercury removal with PJBH under the same carbon feed rate of 37.5 g/hr (7.5 lb/Macf) was still marginal based on mercury emission data measured by the outlet CMM. A power-off batch of 15 g of NORIT FGD was then added to see if the mercury level would drop. The outlet CMM data show that the additional batch of carbon did briefly result in a mercury dropping down to 1 µg/m³, but it quickly climbed again. These tests all indicated that the FGD carbon was not effective at removing mercury in the Springfield flue gas with either the *Advanced Hybrid*TM filter or the PJBH. To further verify the above experimental results, the carbon injection rate was then set back to 7.5 g/hr (1.5 lb/Macf) and operated overnight until noon the next day. The CMM data during this time (Figure 6.2.6.6) showed no mercury removal, which provides further proof of the ineffectiveness of the FGD carbon. One additional power-off batch test was completed by injecting a batch of 22.5 g of carbon within a minute. This resulted in a brief drop in mercury, but after only 15 min, the mercury rapidly started increasing again. Figure 6.2.6.7 provides more detailed information of this batch injection test. Since the outlet mercury rises above the inlet level after breakthrough, this may indicate desorption of some of

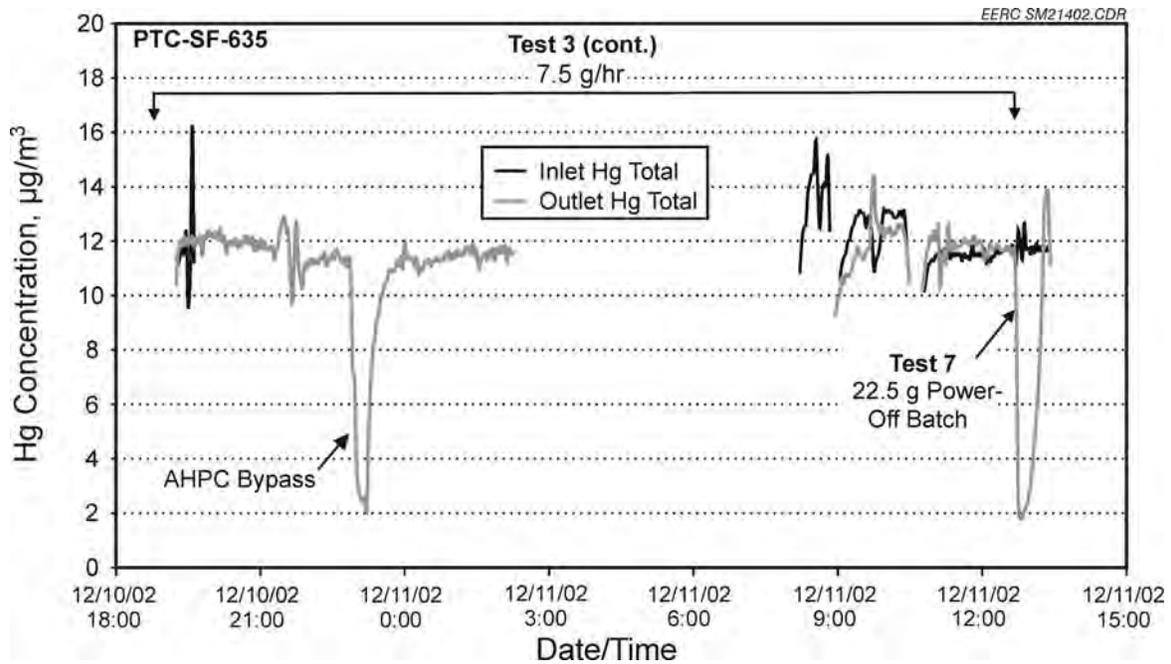


Figure 6.2.6.6. Temporal variations of gaseous mercury in *Advanced Hybrid™* filter inlet and outlet flue gases with FGD injection at 135°C (275°F).

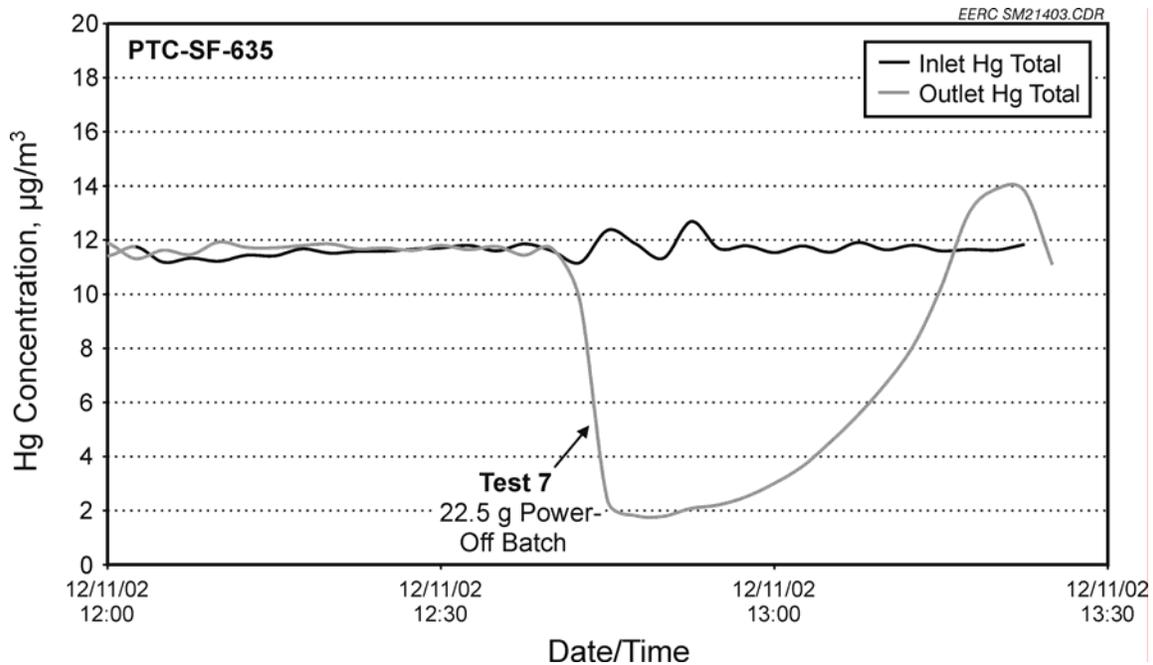


Figure 6.2.6.7. Test 7 – Detailed information of mercury emission of the *Advanced Hybrid™* filter under this batch injection test.

the previously captured mercury. In previous bench-scale breakthrough tests with a thin fixed bed of carbon, desorption was commonly seen for cases where the flue gas was high in both NO_x and SO₂.

The poor mercury capture by the activated carbon is consistent with previous bench-scale tests, but those bench-scale tests were completed without SO₃. These tests were all conducted at a temperature of 135°C (275°F), which is below the acid dew point for the measured SO₃ level of 31.7 ppm. The possibility was raised that SO₃ condensation on the activated carbon might impair mercury capture. To address this concern, further testing was completed after increasing the *Advanced Hybrid*TM filter temperature to 160°C (320°F).

Tests 8–11 NORIT FGD Activated Carbon Injection at 160°C (320°F)

With the *Advanced Hybrid*TM filter temperature raised to 160°C (320°F), carbon injection was started at a rate of 7.5 g/hr, increasing to 30 g/hr later. CMM outlet data (Figure 6.2.6.8) showed no mercury removal at the 7.5 g/hr injection and less than 10% mercury removal across the *Advanced Hybrid*TM filter at the increased rate of 30 g/hr. The carbon injection was

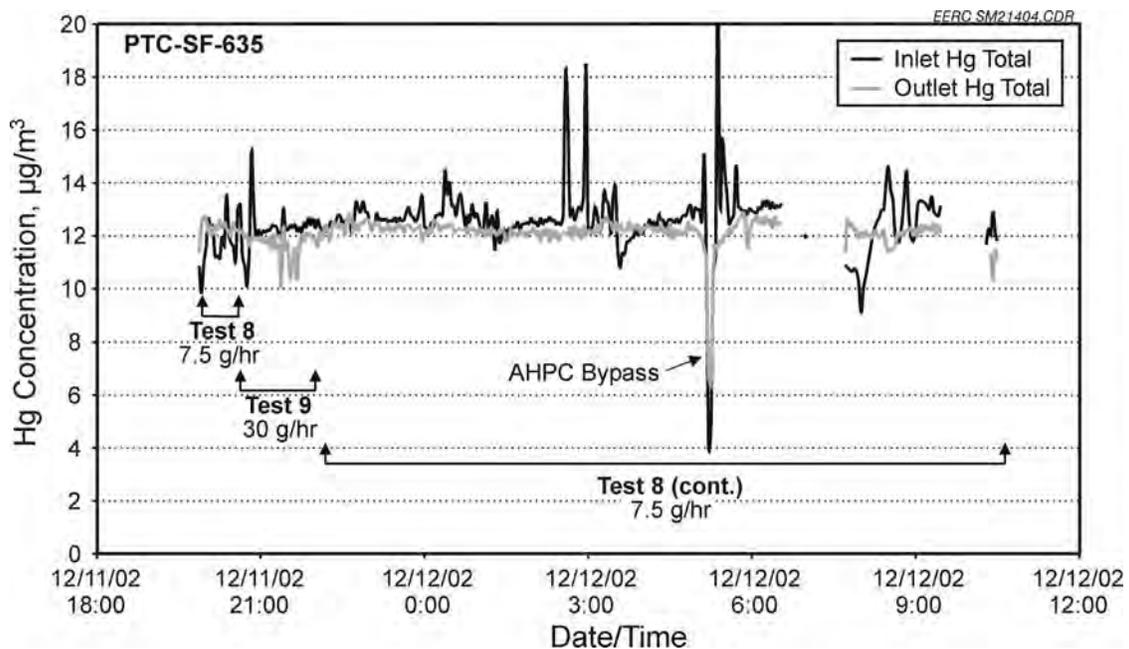


Figure 6.2.6.8. Tests 8 and 9 – Temporal variations of gaseous mercury in the *Advanced Hybrid*TM filter inlet and outlet flue gas with FGD injection at 160°C (320°F).

then scaled back to 7.5 g/hr for a longer-term test overnight. The inlet and outlet CMM data in Figure 6.2.6.8 and the Ontario Hydro measurements (Figure 6.2.6.9) showed no mercury removal during this time.

To provide final proof that the poor mercury removal was due to the carbon sorbent rather than a limitation of the *Advanced Hybrid*TM filter, the high-voltage power was again shut off, and short-term tests were completed with the PJBH at a carbon injection of 7.5 and 30 g/hr, respectively. CMM outlet data in Figure 6.2.6.10 showed that even with no high-voltage power and the high carbon addition rate, mercury removal was in the range from 0% to 10%.

Since very poor mercury capture was seen at 160°C (320°F) as well as at 135°C (275°F), the reason appeared to be something other than an acid dew point problem. Apparently, in the temperature range from 135° to 160°C (275° to 320°F) with these flue gas concentrations, the FGD sorbent is ineffective at mercury capture.

Tests 12–15 Alternative Sorbent Injection at 160°C

Before Tests 12–15 were begun, all of the carbon-laden ash was removed from the *Advanced Hybrid*TM filter hopper, and the system was allowed to return to baseline conditions.

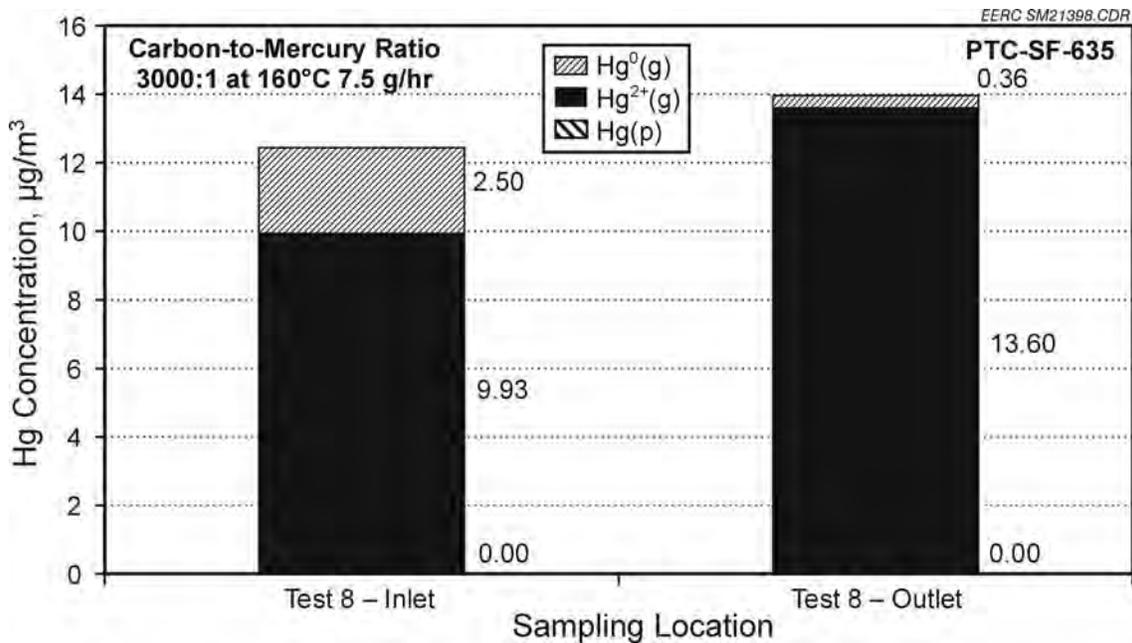


Figure 6.2.6.9. *Advanced Hybrid*TM filter inlet and outlet Ontario Hydro results with FGD injection at 160°C (320°F).

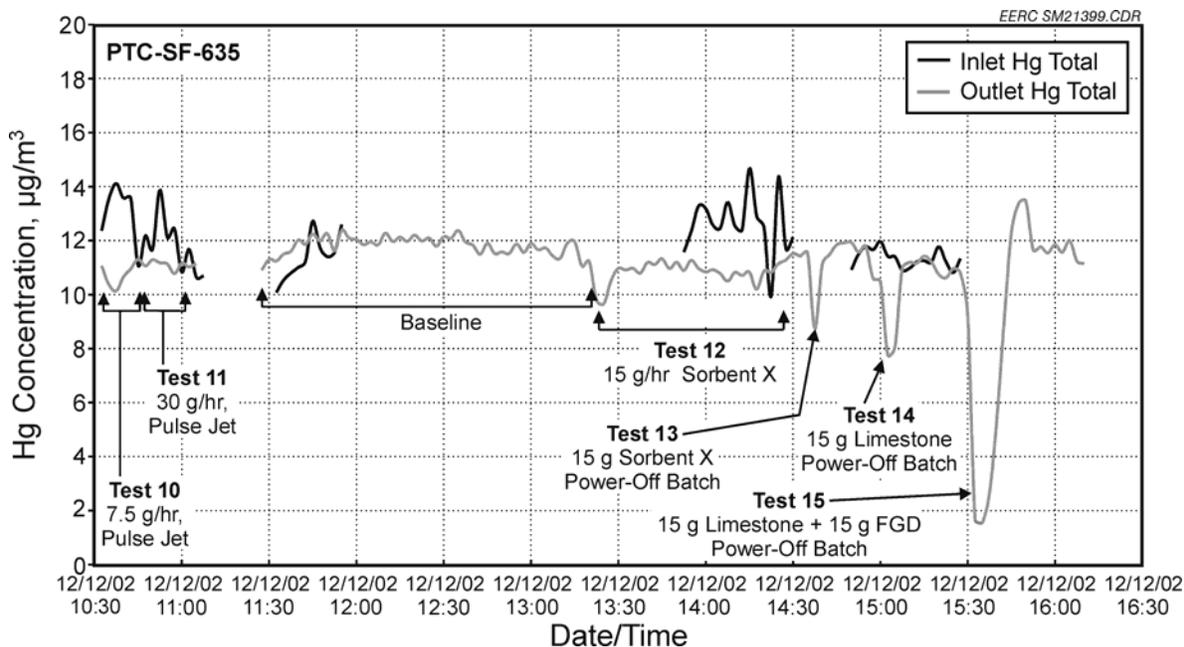


Figure 6.2.6.10. Tests 10–15 – Temporal variations of gaseous mercury in the *Advanced Hybrid*[™] filter inlet and outlet flue gas with FGD injection at 160°C (320°F).

Next, a non-carbon-based alternative sorbent (Sorbent X) was injected, first continuously at 15 g/hr and then in a power-off batch mode. This sorbent also was ineffective at mercury capture (Figure 6.2.6.10). Two additional short-term batch injection tests were completed, first with straight limestone powder followed by a combination of 15 g of limestone and 15 g of the NORIT FGD carbon. As seen in the Figure 6.2.6.10 data, these tests were marginal in mercury removal effectiveness, and the combination of limestone and FGD carbon was no better than the previous batch FGD carbon injection tests.

6.2.6.4 Conclusions from PTC-SF-635 Testing Results

The Springfield bituminous coal flue gas has high levels of the acid gases, and most of the inlet mercury was in oxidized form.

A number of short- and longer-term tests with NORIT FGD carbon injection at both 135° and 160°C (275° and 320°F) with both the *Advanced Hybrid*[™] filter and the PJBH showed that this sorbent was completely ineffective at mercury control for the Springfield coal flue gas. The data are consistent with previous bench-scale testing showing that flue gas conditions are critical to the mercury capture ability of an activated carbon.

The amended silicate developed by ADA also showed ineffectiveness in mercury capture for this Springfield coal flue gas.

6.2.7 PTC-BA-636

6.2.7.1 Test Conditions

The November 2001 field test at Big Stone Power Plant demonstrated over 90% mercury removal with the *Advanced Hybrid*TM filter with injection of 0.29 kg/hr (1.2 lb/Macf) NORIT FGD combined with 90–250 tons/day of TDF cofiring. During the start of the August 2002 field test at the Big Stone Power Plant, the tire feed was deliberately stopped to evaluate mercury control with TDF cofiring, showing an overall 63% mercury removal across the *Advanced Hybrid*TM filter field unit with 0.26 kg/hr (1.1 lb/Macf) FGD carbon injection. When TDF cofiring was started August 12, 2002, at 23 ton/day, much lower than the 90–250-ton/day rate during the November 2001 test, 68% mercury capture was achieved.

All the field demonstrations showed there was a correlation between oxidized mercury concentration in the flue gas and the amount of TDF fed into the boilers, suggesting that the low rate of TDF cofiring resulted in some improvement in mercury collection with the *Advanced Hybrid*TM filter. However, because of the variability of the TDF feed rate, it was difficult to quantify the TDF effect on mercury removal. Subsequently, a 1-week pilot-scale test was designed and conducted on the 55-kW (200-acfm) pilot-scale *Advanced Hybrid*TM filter where the coal feed rate and the TDF feed rate were precisely controlled.

Belle Ayr coal was used in this test. The *Advanced Hybrid*TM filter unit was operated at 2–4-mA corona current, pulse-cleaned at trigger pressures of 2.0–2.5 kPa (8–10 in. W.C.), and kept at approximately 135°C (275°F) across the *Advanced Hybrid*TM filter. To confirm and clarify the TDF effect on mercury species in flue gas, TDF was used as a supplemental fuel to cofire with the Belle Ayr coal. The TDF was preshredded by the supplier to –20 mesh. This material was then screened to –40 mesh at the EERC. The TDF was then fed with a separate feeder directly into the pneumatic coal feed line at rates of 1.4 and 2.7 kg/hr, corresponding to 5% and 10% of the feed coal (mass-based), respectively. The NORIT FGD injection rate was set at 24 mg/m³ (1.5 lb/Macf), corresponding to 3000:1 carbon-to-mercury ratio. By combining cofiring TDF with NORIT FGD injection, a series of tests were completed to evaluate the beneficial effect of TDF cofiring on mercury removal with the *Advanced Hybrid*TM filter. At the end of this 1-week

test, an iodine-treated carbon was also tested for its effectiveness on mercury capture in the *Advanced Hybrid*TM filter. Table 6.2.7.1 lists the nine tests completed during this period.

Two CMMs monitored the mercury species across the *Advanced Hybrid*TM filter, and Ontario Hydro samples were collected at *Advanced Hybrid*TM filter inlet and outlet to verify mercury species in the flue gas. EPA Method 26 sampling was conducted to determine the increase of HCl in the flue gas with TDF cofiring. The sampling schedule is also included in Table 6.2.7.1.

6.2.7.2 Coal and Flue Gas Analyses

Since the Belle Ayr coal used in this test was the same as in previous tests (PTC-BA-628 and 629) and the general information on this coal was known, no additional coal analysis was performed. Listed in Table 6.2.7.2 are the analysis results of the TDF, including proximate–ultimate data and chlorine content, indicating a high carbon content and heating value. The

Table 6.2.7.1. Summary of the Test Conditions for PTC-BA

Test	Time	Test Conditions	OH and HCl Sampling
1	Feb. 10, 10:24–16:20	Baseline	OH (13:31–14:31) M26 (15:07–16:07)
2	Feb. 10, 16:20–Feb.11, 11:35	1.4 kg/hr (3 lb/hr) TDF	OH ¹ (17:44–19:44) OH ² (9:05–10:05) M26 (10:30–11:30)
3	Feb. 11, 11:47–15:34; 15:49 – Feb. 12, 1:08; 1:18–7:13, 7:21– 11:14	1.4 kg/hr (3 lb/hr) TDF + 3000:1 FGD carbon	OH (13:27–15:29) OH (8:57–9:58) M26 (10:20–11:14)
4	Feb. 12, 12:15–13:28, 14:11– 17:10	3000:1 FGD carbon	OH (14:28–15:29) M26 (16:00–17:00)
5	Feb. 12, 17:12–18:30, 19:15– 23:08, 23:18–Feb. 13, 0:23, 0:43–3:25	2.7 kg/hr (6 lb/hr) TDF + 3000:1 FGD carbon	
6	Feb. 13, 10:16–14:34	2.7 kg/hr (6 lb/hr) TDF, bigger size	OH (11:11–12:11) M26 (12:33–13:33)
7	Feb. 13, 14:35–18:07	2.7 kg/lb (6 lb/hr) TDF + 3000:1 FGD carbon	OH (17:01–18:01)
8	Feb. 13, 18:36–Feb. 14, 8:45	Baseline	
9	Feb. 14, 8:45–13:33	4700:1 IAC carbon	OH (10:01–11:01) M26 (11:26–12:40)

Table 6.2.7.2. Analysis for the TDF

	As-Received, wt%
Proximate Analysis	
Moisture Content	0.6
Volatile Matter	66.22
Fixed Carbon	28.06
Ash	5.12
Ultimate Analysis	
Hydrogen	7.58
Carbon	83.23
Nitrogen	0.80
Sulfur	2.69
Oxygen	0.58
Ash	5.12
Heating Value, Btu/lb	16,485
Cl Concentration in TDF, µg/g, as received	598

598 µg/g of chlorine in the TDF is much higher than the 22.5 µg/g of chlorine in the Belle Ayr coal, which may enhance mercury oxidation in the coal flue gas.

6.2.7.3 Mercury Results for PTC-BA-636

Test 1 – Baseline Test

A short-term 6-hr baseline test was completed without any carbon or TDF to establish mercury species in the Belle Ayr coal flue gas. One pair of OH samples was collected at the *Advanced Hybrid*TM filter inlet and outlet to determine whether there was a change in mercury speciation across the *Advanced Hybrid*TM filter unit. The results are plotted in Figure 6.2.7.1. Based on Ontario Hydro results, the flue gas entering the *Advanced Hybrid*TM filter contained 13.1 µg/m³ of elemental mercury, 3.07 µg/m³ of oxidized mercury, and a very low level of 0.04 µg/m³ of particle-bound mercury. Since all of the particulate-associated mercury was captured in the *Advanced Hybrid*TM filter, the outlet flue gas had 8.1 µg/m³ of elemental mercury and 4.6 µg/m³ of oxidized mercury. The total mercury concentration of 16.2 µg/m³ in the inlet flue gas was reduced to 12.6 µg/m³ at the *Advanced Hybrid*TM filter outlet, showing 22.2% mercury capture across the *Advanced Hybrid*TM filter. Compared in Figure 6.2.7.2 are normalized mercury species distributions in Belle Ayr coal flue gas obtained in the current and previous tests. The results show very consistent mercury species distributions for the Belle Ayr coal flue gas during the three individual tests: 75.5%–83.1% Hg⁰, 13.7%–22.8% Hg²⁺, and 0.24%–3.21%

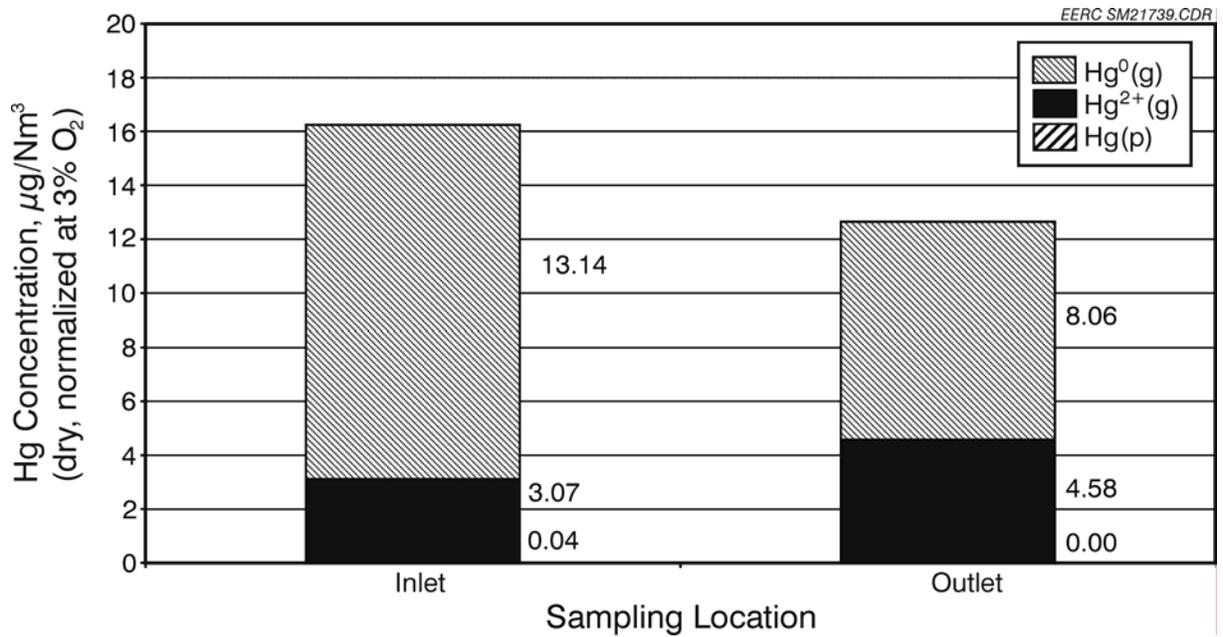


Figure 6.2.7.1. Mercury species across the *Advanced Hybrid*TM filter in the Belle Ayr baseline test.

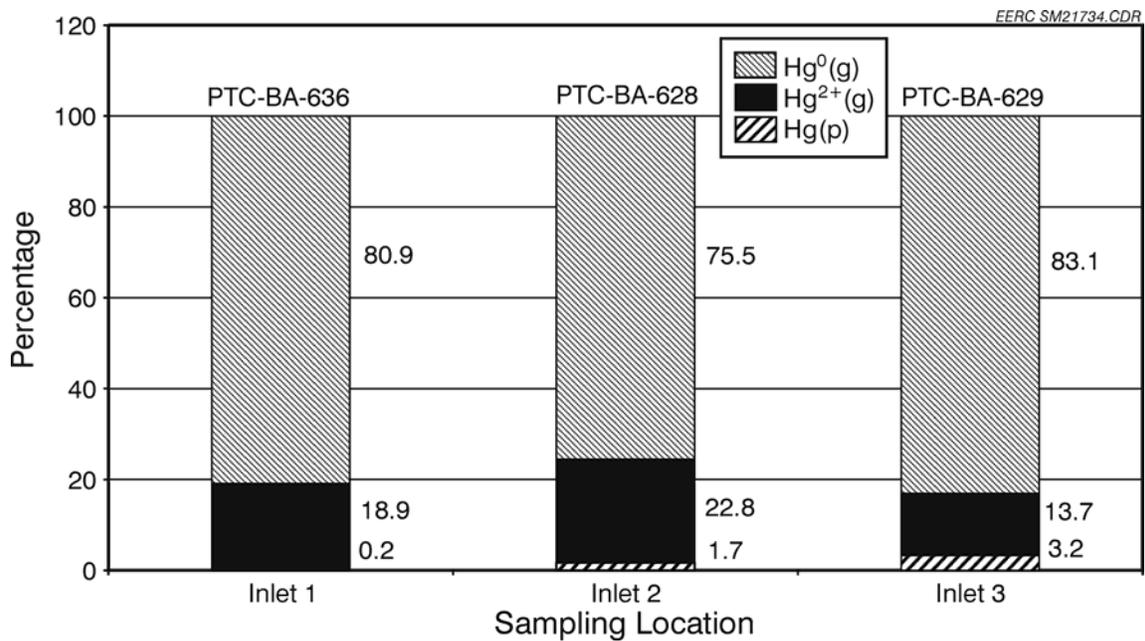


Figure 6.2.7.2. Comparison of normalized mercury species distributions in Belle Ayr coal flue gas obtained in the current and previous tests.

Hg(p), indicating a representative and repeatable coal combustion performance for the pilot-scale *Advanced Hybrid*TM filter system. At the same time, two CMMs monitored temporal variations of mercury vapor species in the flue gas across the *Advanced Hybrid*TM filter, and the data (Figure 6.2.7.3) showed almost the same level of mercury in the inlet and outlet flue gases during the baseline test. Both Ontario Hydro and CMM data showed that a 33% Hg⁰ to Hg²⁺ and Hg(p) conversion occurred across the filter bags.

Test 2 – 1.4-kg/hr (3-lb/hr) TDF Cofiring

The TDF is suspected to be the reason for the high levels of particulate-bound and oxidized mercury observed in the November 2001 and August 2002 field demonstrations. The mechanisms, however, are not quite understood and may be attributed to the additional chlorine or other substance in the TDF, the unburned carbon from the TDF combustion, or other unknown factors. Therefore, to further confirm and clarify the TDF effect on mercury species in flue gas, Test 2 included the TDF as a supplemental fuel at a feed rate of 1.4 kg/hr (3 lb/hr) (corresponding to 5% coal mass-based) to cofire with the Belle Ayr coal. Two pairs of Ontario Hydro samples were taken at the *Advanced Hybrid*TM filter inlet and outlet, and the mercury vapor species across the *Advanced Hybrid*TM filter unit were monitored by two CMMs. The inlet

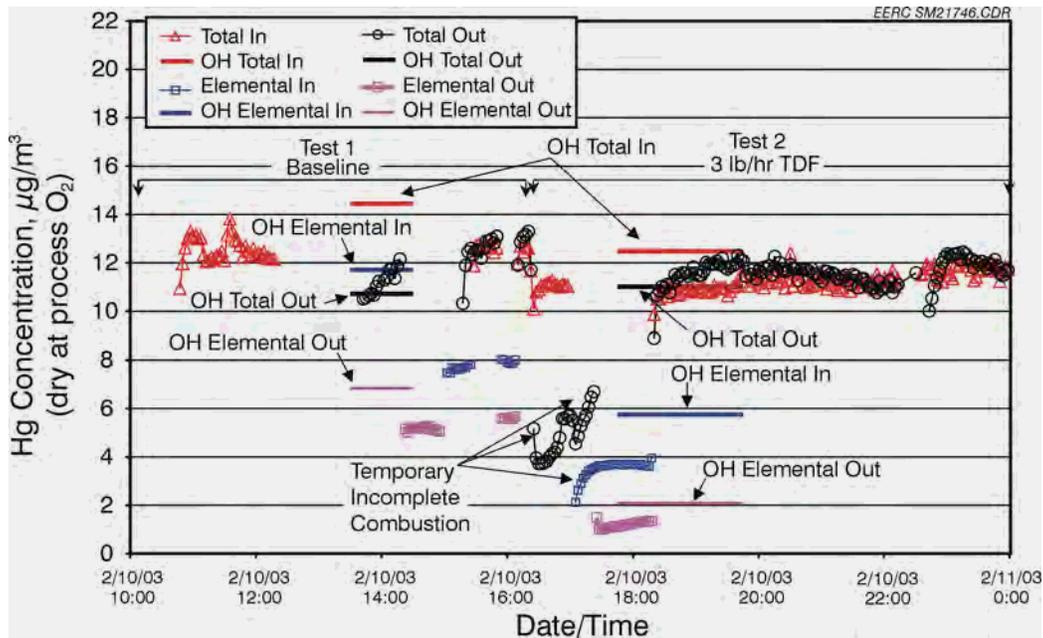


Figure 6.2.7.3. Temporal variations of gaseous mercury across the *Advanced Hybrid*TM filter in the Belle Ayr baseline test.

Ontario Hydro results indicate 13–14 $\mu\text{g}/\text{m}^3$ of total mercury in the flue gas (shown in Figure 6.2.7.4, slightly lower than the 16.2 $\mu\text{g}/\text{m}^3$ without TDF cofiring. Part of the reason for lower inlet mercury could be the reduced coal feed rate with supplemental TDF.

The CMM data (Figure 6.2.7.3) were quite consistent with the Ontario Hydro results, and they both showed more oxidized mercury in the flue gas while cofiring TDF and Belle Ayr coal than firing Belle Ayr coal alone: 47.5% of oxidized mercury with TDF cofiring flue gas compared to 18.9% without TDF cofiring, indicating additional oxidation occurred upstream of the *Advanced Hybrid*TM filter inlet sampling port. In the *Advanced Hybrid*TM filter outlet flue gas, 79.2% of the total mercury emission was oxidized mercury, and only 20.8% was elemental mercury. The conversion of Hg^0 to Hg^{2+} and $\text{Hg}(\text{p})$ across the *Advanced Hybrid*TM filter was 65%, compared to 33% in the baseline test. The mercury emission, nevertheless, was around 12 $\mu\text{g}/\text{m}^3$: only a 10%–20% capture efficiency.

The above experimental data indicate that TDF enhances mercury oxidation, which may start in the combustion zone and continue in the *Advanced Hybrid*TM filter unit. One hypothesis

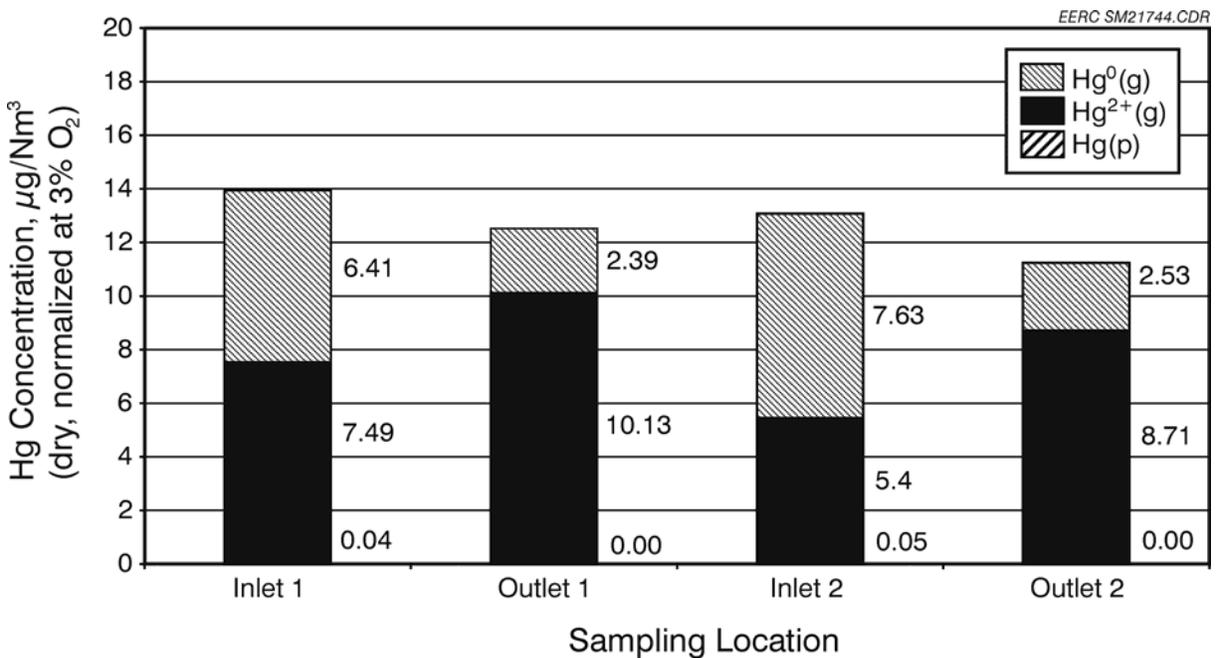


Figure 6.2.7.4. Test 2 – Ontario Hydro results in the *Advanced Hybrid*TM filter inlet and outlet flue gas with 1.4-kg/hr (3-lb/hr) TDF cofiring.

is that the additional chlorine from the TDF caused the enhanced oxidation. A Method 26 sample collected in the inlet flue gas showed a HCl concentration in flue gas of 2.54 ppm with TDF cofiring compared to 0.75 ppm measured in the baseline test (listed in Table 6.2.7.3). The 2.54-ppm HCl in flue gas is still low, but the TDF combustion may enhance the formation of atomic chlorine, which is considered the chlorine species responsible for oxidation.

The CMM data in Figure 6.2.7.3 indicated a dramatic decrease of mercury emission in the outlet flue gas when TDF cofiring started: the total mercury concentration in the *Advanced Hybrid™* filter outlet flue gas decreased to less than 4 µg/m³. It took nearly 3 hr to return to the same level as at the inlet concentration. The flue gas concentrations of O₂, CO, CO₂, NO_x, and SO₂ during this period are shown in Figure 6.2.7.5. The O₂ concentration was momentarily decreased to 3.5% during 16:20–16:30, with a corresponding CO₂ spike at the combustor outlet, indicating temporary incomplete fuel combustion when TDF addition was started. Possibly, unburned carbon was generated and attached to the filter bags, where mercury was subsequently captured.

At the end of the test, the hopper ash with a residence time of 18 hr was collected for LOI analysis. Table 6.2.7.4 lists the analysis result with a comparison to the LOI level in the baseline ash. The LOI levels in both ash samples are very close: 0.16% and 0.14% for the baseline and 1.4 kg/hr (3 lb/hr) for the tire addition test, respectively, indicating, in general, good combustion and no significant carbon residue in the ash.

Test 3 – 1.4-kg/hr (3-lb/hr) TDF Cofiring Combined with 1.5-lb/Macf NORIT FGD Carbon Injection

With TDF cofiring, FGD carbon injection was started at a rate of 24 mg/m³ (1.5 lb/Macf), corresponding to a carbon-to-mercury ratio of 3000:1. The CMM data (Figures 6.2.7.6 and 6.2.7.7) indicated the temporal variations of mercury species in the flue gas under TDF cofiring combined with NORIT FGD injection. Upon the injection of 24 mg/m³ (1.5 lb/Macf) NORIT FGD into the system, the mercury emissions in the *Advanced Hybrid™* filter outlet dropped from 10 to 1.1–1.9 µg/m³ with only 0.07–0.25 µg/m³ elemental mercury. CMM data in Figure 6.2.7.7

Table 6.2.7.3. Chloride Concentrations in Flue Gas, ppmv, dry basis, 3%

Baseline	1.4-kg/hr (3-lb/hr) TDF	3000:1 Carbon	2.7-kg/hr (6-lb/hr) TDF	1.4-kg/hr (3-lb/hr) TDF + 3000:1 Carbon
0–0.75	2.54	0	2.47	2.47

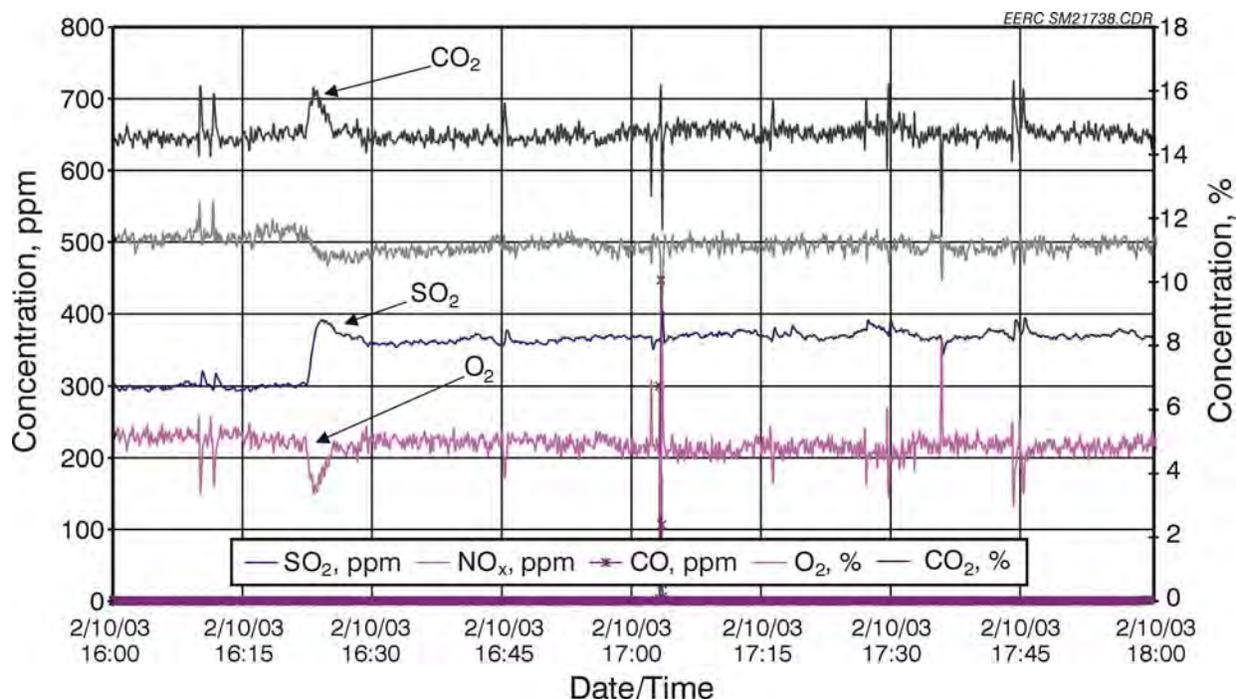


Figure 6.2.7.5. Flue gas concentrations for PTC-BA-636.

Table 6.2.7.4. LOI in the *Advanced Hybrid*TM Filter Hopper Ash, %

	1.4 kg/hr (3 lb/hr)	1.4 kg/hr (3 lb/hr) TDF + 3000:1 Carbon	3000:1 Carbon	2.7 kg/hr (6 lb/hr) TDF + 3000:1 Carbon	2.7 kg/hr (6 lb/hr) TDF	4400:1 IAC
Baseline	0.16	0.14	0.58	0.68	0.77	0.48
						1.31

show a quick recovery of mercury emission when carbon injection was accidentally shut down, which further confirms the fact that TDF cofiring results in oxidation rather than capture of the mercury.

Plotted in Figure 6.2.7.8 are the Ontario Hydro results during this test. The total mercury (44.7%–67.4%) in the inlet flue gas, based on the Ontario Hydro data shown in Figure 6.2.7.4, had already been oxidized as a result of TDF cofiring. After contacting the FGD carbon, the total mercury emission at the *Advanced Hybrid*TM filter outlet was dramatically decreased to 1.72–1.90 µg/Nm³ with only 1.43–1.61 µg/Nm³ of oxidized mercury vapor and virtually no elemental mercury. Total mercury collection efficiency in this test was about 88%. Both CMM and Ontario Hydro data were in good agreement with total mercury vapor concentration. The

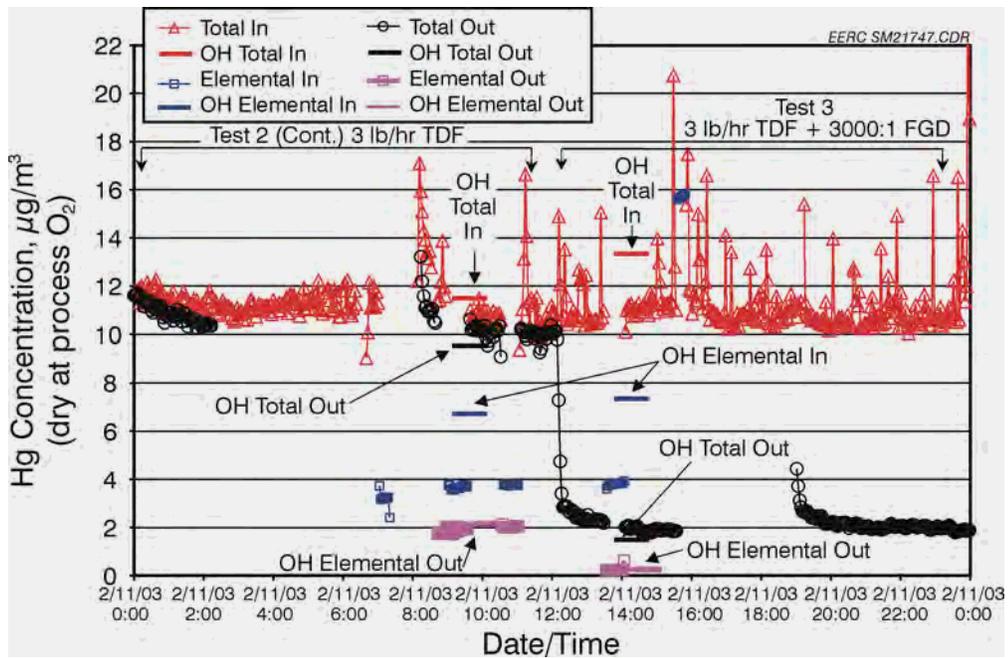


Figure 6.2.7.6. Temporal variations of gaseous mercury across the *Advanced Hybrid™* filter in Day 2 test.

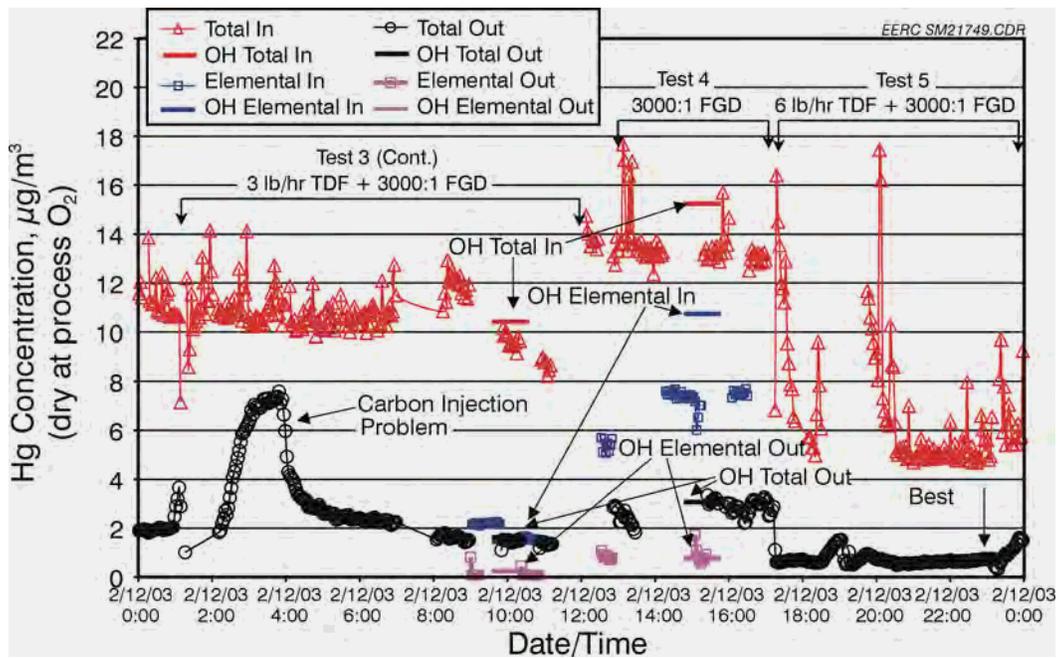


Figure 6.2.7.7. Temporal variations of gaseous mercury across the *Advanced Hybrid™* filter in Day 3 test.

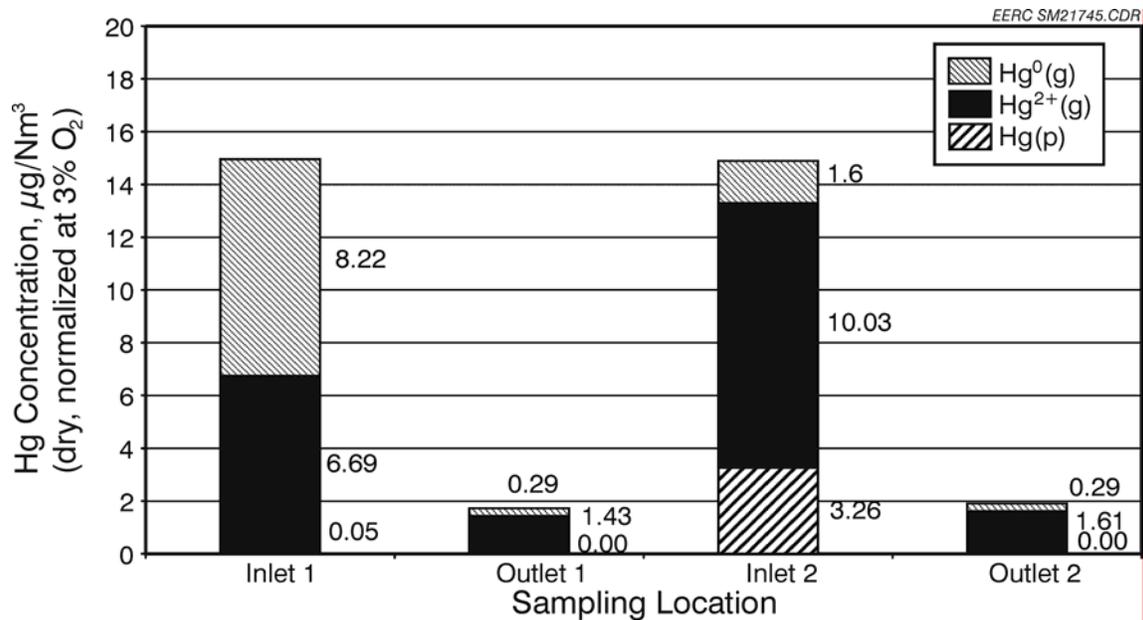


Figure 6.2.7.8. Ontario Hydro results in the *Advanced Hybrid*TM filter inlet and outlet flue gas under 3-lb/hr TDF cofiring combined with 1.5-lb/Macf FGD injection.

inlet elemental mercury measured by CMM was slightly lower than the corresponding Ontario Hydro data, which may be the result of some mercury capture on the sampling filter before the flue gas entered the CMM.

The 0.58% LOI in hopper ash was higher than that in Tests 1 and 2, which is expected because of FGD carbon injection. The chlorine concentration was 2.47 ppm, the same as the 2.54 ppm in Test 2 since the TDF injection rate was maintained at 1.4 kg/hr (3 lb/hr).

Test 4 – 24 mg/m³ (1.5 lb/Macf) NORIT FGD Carbon Injection

To confirm the improved mercury removal efficiency by TDF cofiring combined with NORIT FGD injection, the TDF feeder was shut off while carbon injection was maintained into the *Advanced Hybrid*TM filter. CMM data in Figure 6.2.7.7 indicated the temporal variation of mercury species across the *Advanced Hybrid*TM filter during the test. Once the TDF feeding was stopped, the gaseous mercury in the inlet flue gas was around 13–14 µg/m³, while the elemental mercury in the inlet flue gas gradually increased and reached 7.5 µg/m³, accounting for approximately 60% of the total mercury in the inlet flue gas. Without TDF cofiring, the mercury species in the Belle Ayr coal flue gas were almost at the same level as in the baseline test. Total

mercury emission at the *Advanced Hybrid*TM filter outlet recovered to approximately 3.0 µg/m³ with 1.2 µg/m³ of elemental mercury under NORIT FGD injection alone.

The corresponding mercury removal efficiency was 78%, somewhat higher than the previous data in PTC-BA-628 and-629 tests, although the operating conditions were the same. One pair of Ontario Hydro samples was collected at the inlet and outlet to verify the CMM measurement, and the analysis results (Figure 6.2.7.9) indicated the same level of mercury removal.

The flue gas compositions, including SO₂, NO_x, O₂, CO, and CO₂, were very similar among the three tests; the only obvious difference was the 17.3 µg/m³ of total mercury present in the flue gas compared to 10 µg/m³ from previous PTC-BA-628 and 629 tests. The higher mercury concentration in the flue gas resulted in a greater concentration difference between the mercury vapor in the bulk gas phase and the mercury on the FGD carbon. This imposed a greater driving force from bulk phase to carbon surface, and might lead to a higher percentage of mercury capture. The conversion of Hg⁰ to Hg²⁺ and Hg(p) across the *Advanced Hybrid*TM filter

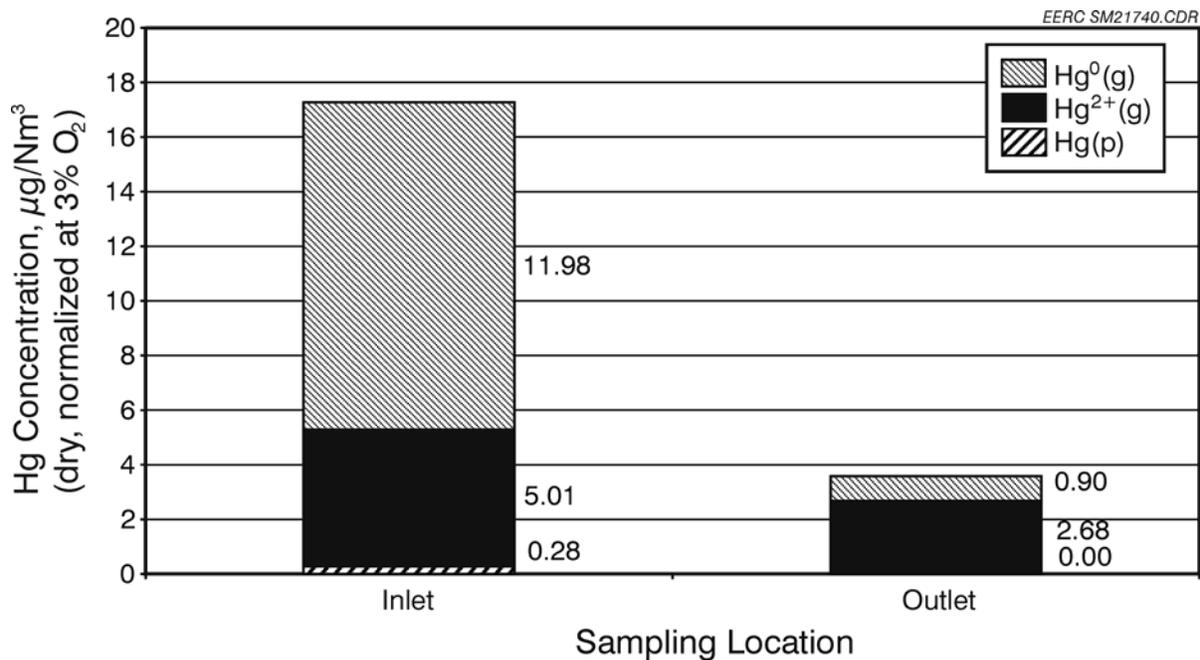


Figure. 6.2.7.9. Ontario Hydro sample collected at the *Advanced Hybrid*TM filter inlet and outlet with 24-mg/m³ (1.5-lb/Macf) FGD injection.

was 93% in this test, almost the same level as that in Test 3 and higher than the 60%–75% in the PTC-BA-628 and -629 tests. It is possible that there was a residual effect from TDF cofiring which caused both higher mercury oxidation and capture. Nevertheless, FGD carbon combined with TDF cofiring provided better mercury capture than FGD alone.

Analysis results from Method 26 (listed in Table 6.2.7.3) indicate that chloride concentration in the flue gas during this time was virtually zero without TDF injection. The LOI in the hopper ash was 0.68%, the same level as in Test 3, since they both had the same carbon injection rate.

Test 5 – 2.7-kg/hr (6-lb/hr) TDF Cofiring Combined with 24-mg/m³ (1.5-lb/Macf) NORIT FGD Carbon Injection

To enhance the carbon reactivity with mercury species in the coal flue gas, TDF cofiring was restarted and the feed rate increased from 1.4 to 2.7 kg/hr (3 to 6 lb/hr). The CMM data (Figures 6.2.7.7 and 6.2.7.10) showed that total mercury vapor at the *Advanced Hybrid*TM filter inlet during this test temporarily dropped to 5 µg/Nm³ while the coal feed rate was stable and

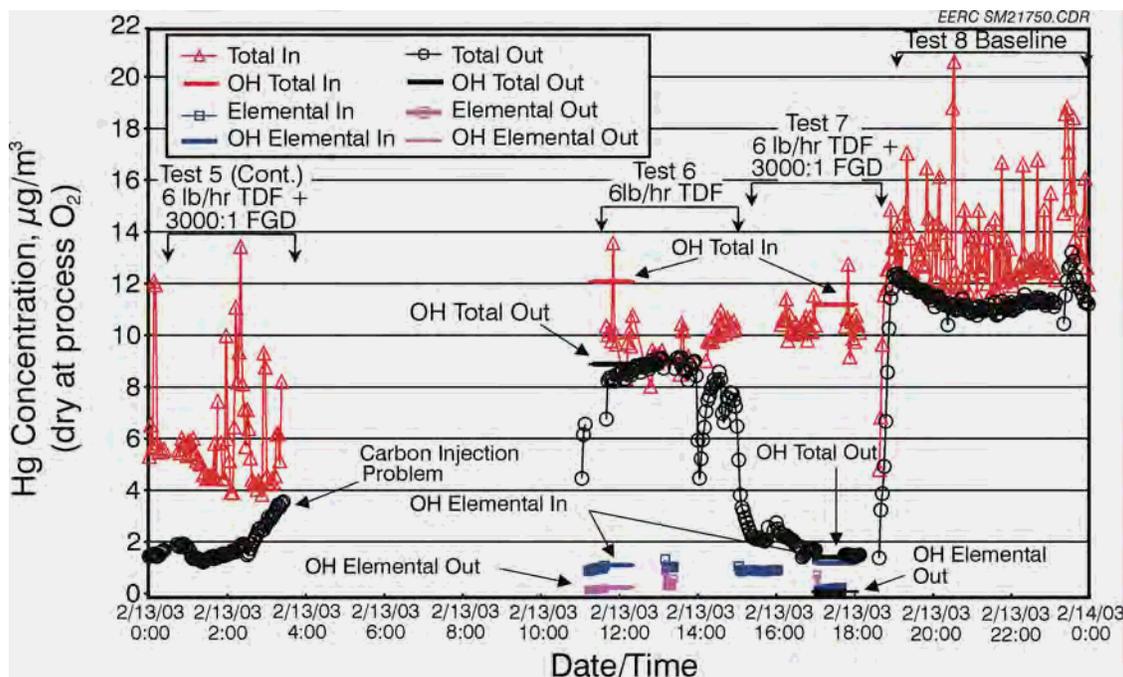


Figure 6.2.7.10. Temporal variations of gaseous mercury across the *Advanced Hybrid*TM filter in Day 4 tests.

consistent. The possible reason is that some of the mercury vapor was captured in the inlet filter as a result of the higher TDF feed rate. At the same time, the total mercury emission level at the *Advanced Hybrid*TM filter outlet was around 0.6 µg/Nm³. Since no Ontario Hydro sampling was completed at that time, a total mercury concentration of 12 µg/Nm³ in flue gas is assumed, corresponding to a capture efficiency of 95%, which was the best achieved so far.

Test 6 – 2.7-kg/hr Larger-Sized TDF Cofiring

To clarify the benefit from the 2.7-kg/hr TDF cofiring on mercury oxidation and capture across the *Advanced Hybrid*TM filter unit, the NORIT FGD carbon was stopped during this test, while the TDF was still fed into the furnace. However, the TDF included larger (-20-mesh) material rather than the -40-mesh size TDF for the previous tests. The chloride concentration in the flue gas was 2.48 ppmv compared to zero without TDF cofiring.

The CMM data (Figure 6.2.7.10) showed that the gaseous mercury concentrations in the *Advanced Hybrid*TM filter inlet and outlet flue gases were the same at 8–9 µg/Nm³, and most of the mercury vapor (85%) had already been oxidized because of the TDF cofiring before it entered the *Advanced Hybrid*TM filter. The total mercury concentration including the particulate-associated mercury (Figure 6.2.7.11) in the inlet flue gas, measured by the Ontario Hydro method, was 14.7 µg/Nm³, higher than the CMM measured gaseous mercury concentration value because of the particle-bound mercury in flue gas. The mercury capture efficiency was 29.4%, slightly higher than the inherent capture efficiency of 22.1% in the baseline test, showing that cofiring TDF not only enhances mercury vapor oxidation, but also somewhat improves gaseous mercury conversion to the particulate phase. The low LOI of 0.48% obtained in this test indicates that the larger-size TDF burned as well as the smaller-size TDF.

Test 7 – 2.7-kg/hr TDF Cofiring Combined with 1.5-lb/Macf FGD Carbon Injection

This test is a repeat of Test 5 to verify mercury collection efficiency with the *Advanced Hybrid*TM filter with 2.7-kg/hr TDF cofiring combined with 24 mg/m³ (1.5 lb/Macf) NORIT FGD carbon injection. One pair of Ontario Hydro samples was collected in the *Advanced Hybrid*TM filter inlet and outlet flue gases, and Figure 6.2.7.12 plots the analysis results. In the inlet flue gas, there was only approximately 1 µg/m³ of elemental mercury vapor due to the 2.7-kg/hr TDF cofiring compared to 4–8 µg/Nm³ of elemental mercury under 1.4-kg/hr TDF

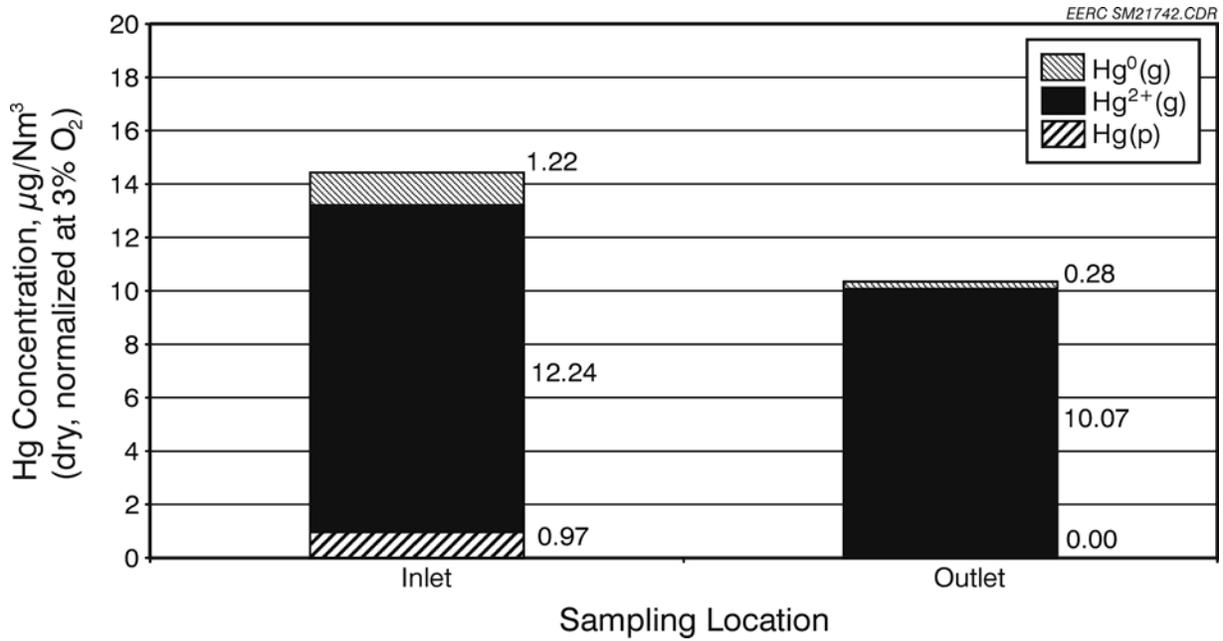


Figure 6.2.7.11. Ontario Hydro results in the *Advanced Hybrid*TM filter inlet and outlet flue gases under 2.7-kg/hr (6-lb/hr) TDF cofiring.

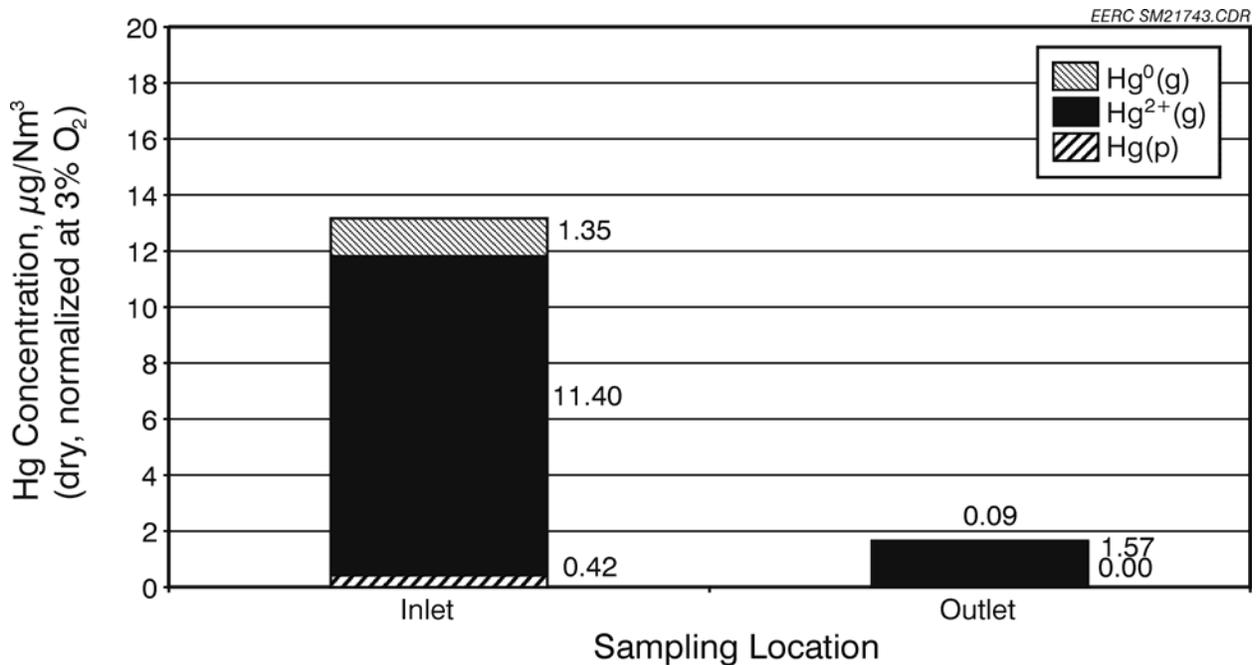


Figure 6.2.7.12. Ontario Hydro result from the *Advanced Hybrid*TM filter inlet and outlet flue gases with 2.7-kg/hr (6-lb/hr) TDF cofiring and 24-mg/m³ (1.5-lb/Macf) FGD injection.

cofiring. Most mercury was oxidized, accounting for around 86.5% of the total mercury in the flue gas. The total mercury concentration in the flue gas was around $13.2 \mu\text{g}/\text{m}^3$, partly because of the decreased coal feed rate. Mercury emission in the *Advanced Hybrid*TM filter outlet flue gas was $1.66 \mu\text{g}/\text{m}^3$ (Ontario Hydro results) with $1.57 \mu\text{g}/\text{m}^3$ of oxidized mercury and virtually no elemental mercury. The CMM data during this testing period (plotted in Figure 6.2.7.10) matched very well with Ontario Hydro results.

The mercury capture efficiency with the *Advanced Hybrid*TM filter, based on Ontario Hydro results, was 87.4%, very close to the 95% mercury removal in Test 5 under the same rates of TDF cofiring and NORIT FGD injection. Compared to 88% of mercury capture at 1.4-kg/hr (3-lb/hr) TDF cofiring combined with $24\text{-mg}/\text{m}^3$ (1.5-lb/Macf) NORIT FGD injection, there is no significant improvement in mercury removal by increasing the TDF cofiring rate. More carbon is needed to further improve mercury capture.

Test 8 – Baseline Reestablishment

Both NORIT FGD and TDF were off during this testing period to reestablish baseline conditions. The CMM data (Figures 6.2.7.10 and 6.2.7.13) showed that the total mercury vapor

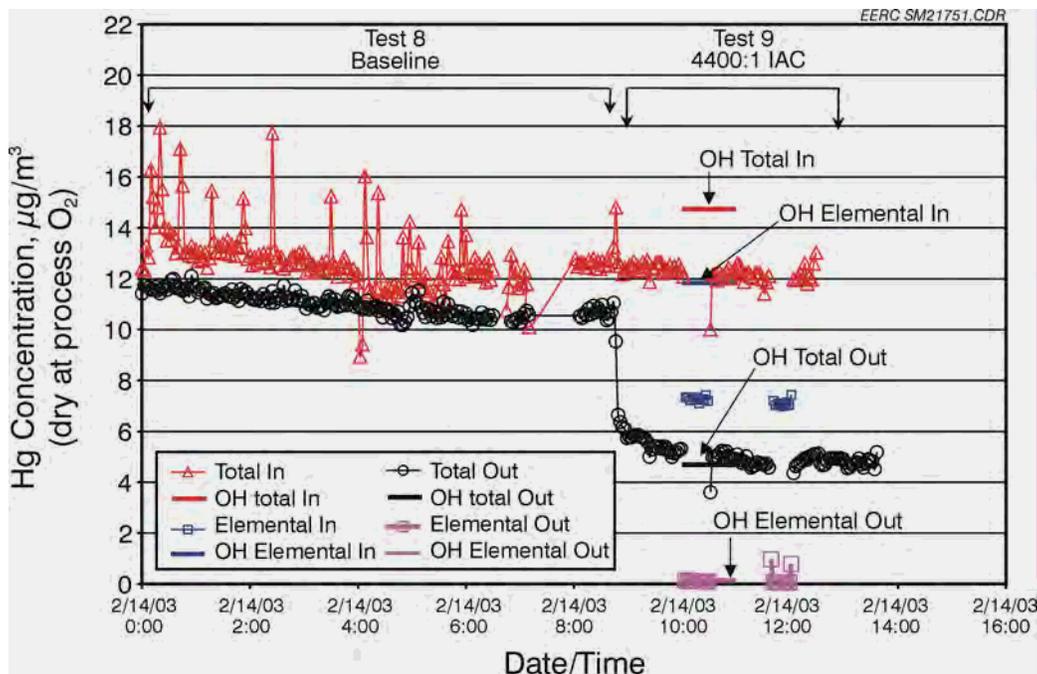


Figure 6.2.7.13. Temporal variations of gaseous mercury across the *Advanced Hybrid*TM filter in Day 5 tests.

concentration at the outlet was returned to the same level as the inlet mercury concentration, indicating a fully recovered baseline condition.

Test 9 – 41.6-mg/m³ (2.6-lb/Macf) Iodine-Treated Carbon Injection

After reestablishing the baseline, an IAC, commercially available from Barnebey and Sutcliffe, was tested to examine its ability to remove mercury with the *Advanced Hybrid*TM filter in the Belle Ayr coal flue gas. Because of the bulk density difference between the FGD carbon and IAC, the actual IAC injection rate was 41.6 mg/m³ (2.6 lb/Macf), corresponding to a carbon-to-mercury mass ratio of 4400:1.

The mercury species in the inlet flue gas (Figure 6.2.7.14) were 13.2 µg/Nm³ of Hg⁰, 3.23µg/Nm³ of Hg²⁺, and 0.04 µg/Nm³ of Hg(p), almost the same as in the baseline tests. At the *Advanced Hybrid*TM filter outlet, both the CMM and Ontario Hydro experimental data (Figure 6.2.7.13 and 6.2.7.14) showed the IAC completely oxidized the mercury. Virtually no elemental mercury exited the *Advanced Hybrid*TM filter unit when 7–11 µg/Nm³ of elemental mercury, accounting for 60%–80% of the total mercury, entered the *Advanced Hybrid*TM filter unit. The

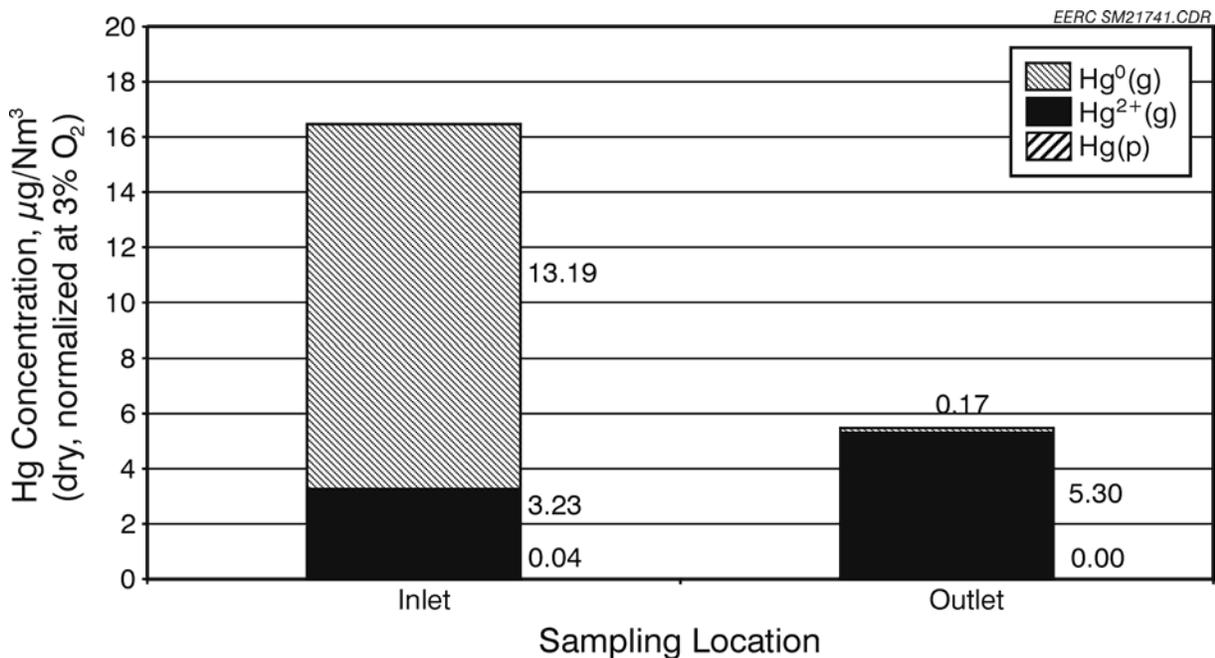


Figure 6.2.7.14. Ontario Hydro results in the *Advanced Hybrid*TM filter inlet and outlet flue gases under 42 mg/m³ (2.6-lb/Macf) IAC injection.

total mercury emission at the *Advanced Hybrid*TM filter outlet was still maintained at a relatively high level of 5 µg/Nm³, mainly in the oxidized form, which indicates the IAC may face a capacity limit for mercury capture rather than oxidation with the Belle Ayr coal flue gas.

The overall mercury capture efficiency was 66.8% based on the Ontario Hydro data, similar to what has previously been achieved with the NORIT FGD carbon.

Effect of TDF Cofiring on Carbon Performance for Mercury Oxidation and Capture

Figure 6.2.7.15 summarizes mercury capture with the *Advanced Hybrid*TM filter in Belle Ayr coal flue gas under TDF cofiring combined with carbon injection. With 1.4-kg/hr TDF cofiring with Belle coal, there was no significant improvement on mercury removal compared to the inherent mercury removal with the *Advanced Hybrid*TM filter in the baseline test, although the TDF cofiring effectively enhanced mercury oxidation in the flue gas. Only 28.9% mercury removal was obtained at the 2.7-kg/h (6-lb/hr) TDF addition test compared to 0%–22% inherent mercury capture for baseline tests.

For the 24-mg/m³ (1.5-lb/Macf) NORIT FGD carbon injection test, since the 78% mercury capture efficiency is suspected to be overestimated, 48.4%–71.2% Hg capture efficiency in PTC-

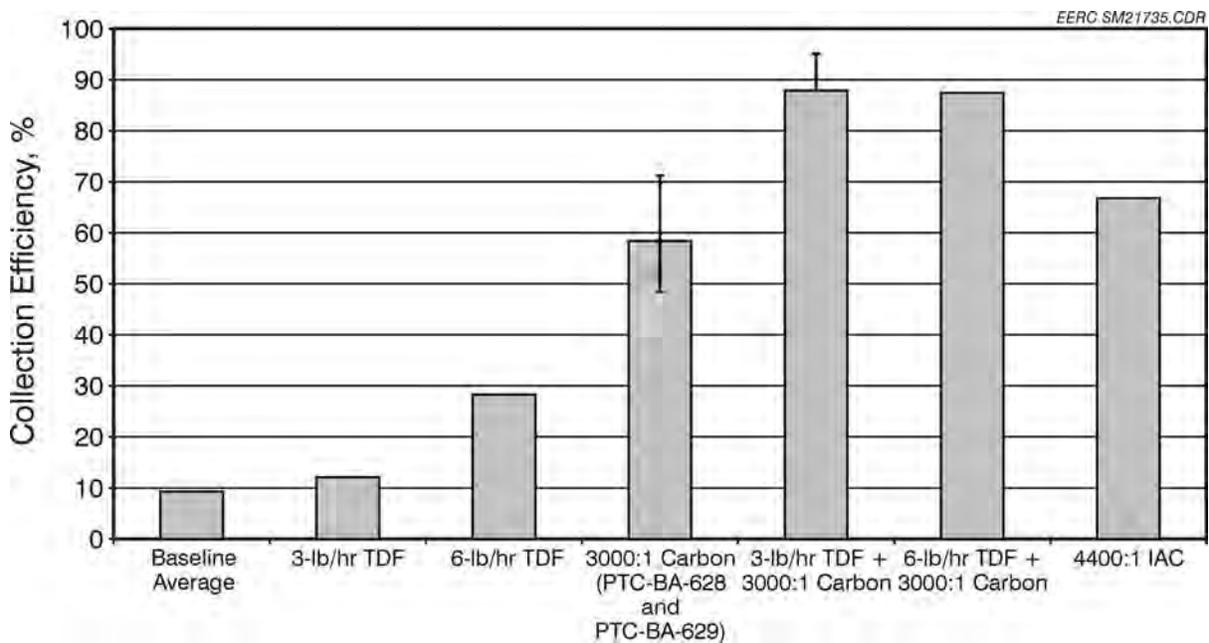


Figure 6.2.7.15. Summary of mercury capture with the *Advanced Hybrid*TM filter in Belle Ayr coal flue gas under TDF cofiring combined with carbon injection.

BA-628 and -629 tests is plotted in Figure 6.2.7.15. When 24-mg/m³ (1.5-lb/Macf) NORIT FGD and 1.4-kg/hr TDF were injected simultaneously, the overall mercury removal efficiency was increased to 88%–95%, showing TDF cofiring does benefit mercury capture in the *Advanced Hybrid*TM filter because of more Hg²⁺ in the flue gas. The FGD has a better ability to capture Hg²⁺ than Hg⁰ because the capture process only involves adsorption instead of oxidation and adsorption. There was no further improvement in mercury capture by increasing the TDF cofiring rate.

Table 6.2.7.5 lists the calculated capacity of NORIT FGD carbon for different conditions. With NORIT FGD carbon injection alone, the capacity of NORIT FGD was 125 µg Hg/g carbon in the pilot-scale test, very close to the 161 µg Hg/g carbon obtained in the bench-scale test under the same condition, indicating that the carbon was efficiently utilized in the *Advanced Hybrid*TM filter unit.

With the added TDF, much higher capacity was seen compared to the NORIT FGD carbon injection alone test. The TDF not only promotes mercury oxidation but also enhances mercury reactivity with activated carbon, resulting in improved carbon capacity.

Plotted in Figure 6.2.7.16 are normalized mercury species distributions in the *Advanced Hybrid*TM filter inlet flue gas for the baseline and TDF cofiring tests. The data clearly show a significant effect of TDF cofiring on mercury oxidation upstream of the *Advanced Hybrid*TM filter. The outlet mercury speciation data (Figure 6.2.7.17) showed that additional oxidation occurred across the *Advanced Hybrid*TM filter with the TDF cofiring. Almost complete mercury oxidation in the *Advanced Hybrid*TM filter outlet flue gas was also seen with the IAC injection test.

6.2.7.4 – Conclusions from PTC-BA-636 Testing Results

Cofiring of TDF with the subbituminous coal had a significant effect on mercury speciation in the flue gas. When 100% coal was fired, there was only 19% oxidized mercury in the flue gas compared to 47% when cofiring 5% TDF (mass basis) and 85% when cofiring 10%

Table 6.2.7.5. Capacity of FGD Carbon, µg Hg/g

3000:1 Carbon Injection ¹	3000:1 Carbon + 1.4-kg/hr (3-lb/hr) TDF ²	3000:1 Carbon + 2.7-kg/hr (6-lb/hr) TDF ²	Capacity from Bench Scale
125	236	206	161

¹ Results from PTC-BA-628.

² 22% inherent mercury capture is considered in calculation.

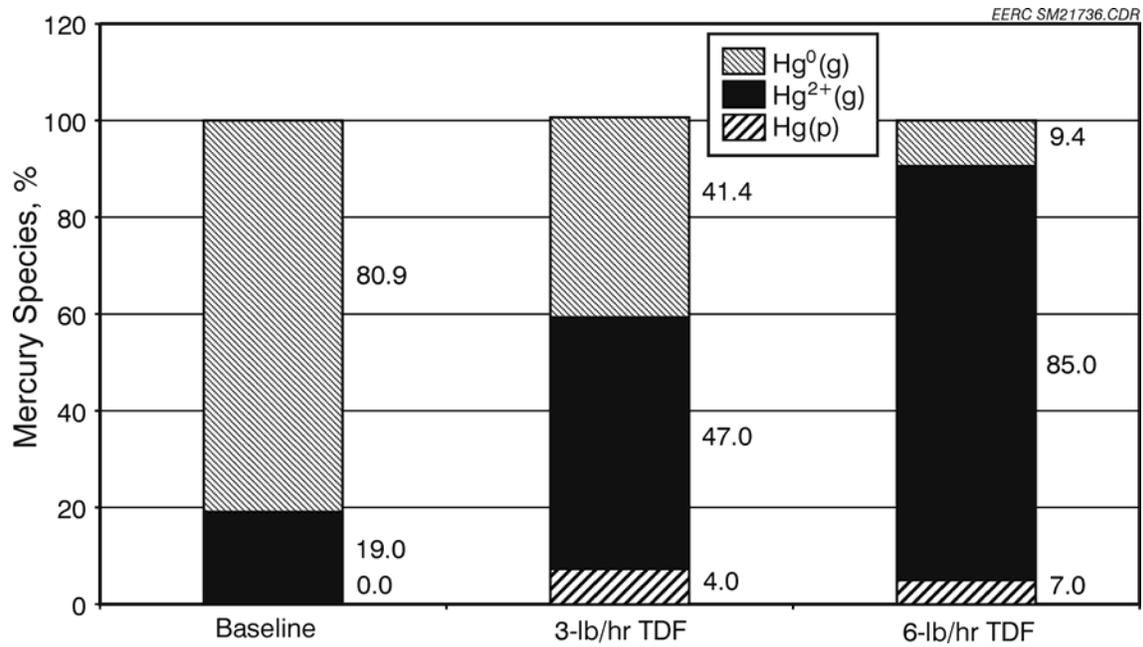


Figure 6.2.7.16. Effect of TDF cofiring on mercury species distributions in the *Advanced Hybrid*TM filter inlet flue gases for the baseline and TDF cofiring tests.

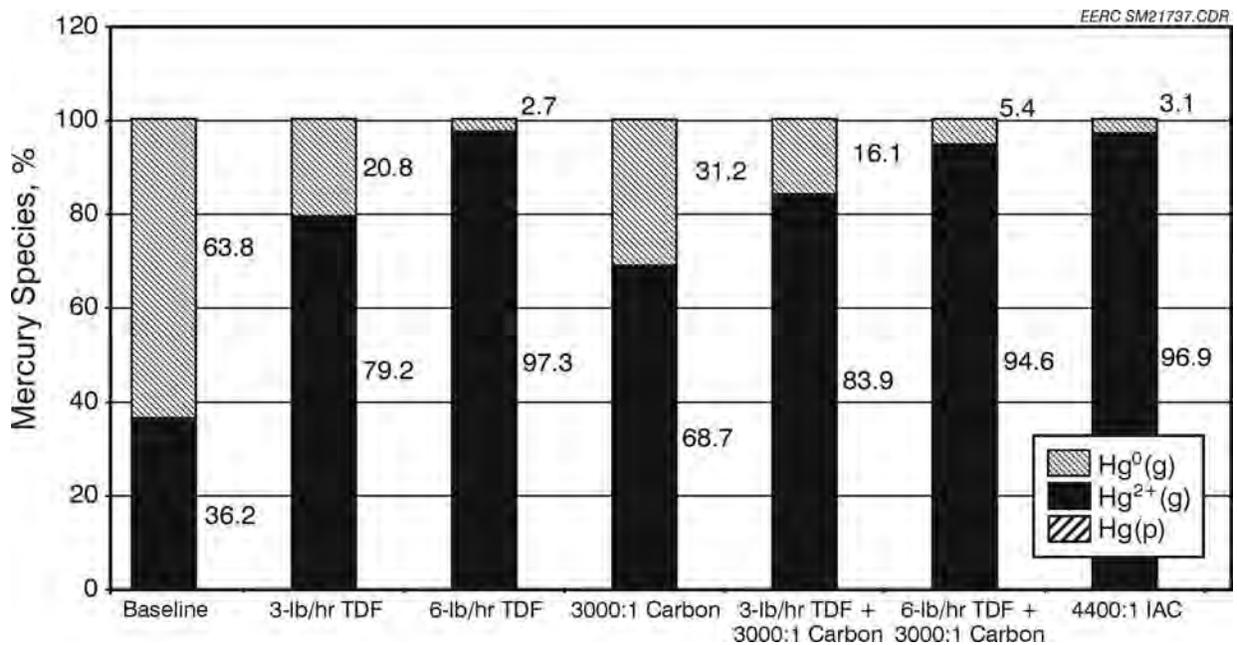


Figure 6.2.7.17. Effects of TDF cofiring combined with carbon injects on mercury oxidation in the *Advanced Hybrid*TM filter outlet flue gas.

TDF. The significant increase in oxidized mercury may be partly the result of increased HCl in the flue gas with the TDF. However, since the actual increase of measured HCl was only a few ppm, other changes in combustion conditions or flue gas components may also be responsible for the increase in oxidized mercury.

TDF not only enhanced mercury oxidation in the flue gas but also improved mercury capture when it was combined with FGD carbon injection. With 100% coal, test results have shown from 48% to 78% mercury removal at a relatively low FGD carbon addition rate of 24 mg/m³ (1.5 lb/Macf). With 5%–10% TDF cofiring, results showed from 88% to 95% total mercury removal with the same carbon addition rate. These results are consistent with results from the 2.5-MW (9000-acfm) *Advanced Hybrid*TM filter presented later in this report.

The IAC provided no better mercury removal than the FGD carbon. However, with the IAC, a larger fraction of mercury was oxidized across the *Advanced Hybrid*TM filter. This suggests that the IAC effectiveness is also highly dependent on flue gas conditions, similar to the FGD. The mechanisms of oxidation and capture for the two carbons may be different, but the exact conditions where the IAC may provide better mercury control than the FGD carbon are not known.

6.2.8 PTC-BA-637

6.2.8.1 Test Conditions

W.L. Gore has developed a cartridge filter for mercury emission control designed to fit inside the cage of a conventional filter bag. Two different cartridge filters (Inserts A and B) were tested separately with the EERC 55-kW (200-acfm) *Advanced Hybrid*TM filter unit with Belle Ayr coal flue gas. The cartridge filters were installed inside of the four cylindrical all-PTFE bags of the pilot-scale *Advanced Hybrid*TM filter unit. The four all-PTFE bags would remove all the fly ash, and the cartridge filter would capture the gaseous mercury that penetrates the all-PTFE bags in a fly ash-free environment.

The unit was operated as a PJBH with varied A/C ratios of 0.015 m/s (3 ft/min) and 0.03 m/s (6 ft/min). The flue gas temperature across the unit was varied at 124°C (255°F), 149°C (300°F), and 193°C (380°F) to evaluate the temperature dependence of the cartridge filter on mercury removal with the subbituminous coal flue gas. The filter bags were pulse-cleaned under a trigger pressure of 2.0 kPa (8.0 in. W.C.) and had a bag-cleaning interval of 20–30 min during the test.

One CMM was used to monitor the mercury concentrations in the inlet and outlet flue gases. Pairs of Ontario Hydro samples were collected at the inlet and outlet to verify the CMM measurement and determine the overall mercury removal with the cartridge filters with the Belle Ayr coal flue gas.

6.2.8.2 *Coal and Flue Gas Analyses*

The Belle Ayr coal used in this testing period was well characterized in previous tests. Therefore, no proximate and ultimate analyses were performed, but a mercury content analysis of the testing coal was done showing 0.115 µg/g of mercury content, which agrees with previous analytical data.

6.2.8.3 *Mercury Results for PTC-BA-637*

Test 1 – Cartridge A in PJBH at 0.03 m/s (6 ft/min) Face Velocity and 149°C (300°F)

For this test, four Cartridge A filters were installed inside of the four PTFE membrane bags, and the pilot-scale unit was operated as a PJBH with an A/C ratio of 0.03 m/s (6 ft/min). With the flue gas flowing through the system, the temperature across the unit stabilized around 149°C (300°F). CMM data in Figures 6.2.8.1 and 6.2.8.2 show the gaseous mercury concentrations in the inlet flue gas and mercury emissions of the PJBH installed with Cartridge A for the 149°C (300°F) Belle Ayr coal flue gas. In the inlet flue gas, the total gaseous mercury was in the range of 10.8–13.5 µg/m³ with approximately 8 µg/m³ of elemental mercury, indicating a very representative mercury species partition for the Belle Ayr coal flue gas. Mercury emission at the PJBH outlet started at 1.1 µg/m³ with 0.5 µg/m³ Hg⁰ and gradually increased to 3.0 µg/m³ after 8 hr of operation, indicating approximately 30% breakthrough.

To confirm the outlet CMM measurement, natural gas was temporarily fired instead of the Belle Ayr coal to determine if the mercury emission would drop to zero. With natural gas combustion, the gaseous mercury concentration in the inlet flue gas (Figure 6.2.8.1) decreased to 0.2 µg/m³ immediately, while the mercury emission at the outlet gradually decreased to 0.6 µg/m³ after 2 hr, meaning mercury desorbed either from the cartridge filters or the residual ash in the pipe. The results from the natural gas combustion test indicate the CMM responded to mercury variation in the flue gas promptly and accurately.

The pilot-scale unit was returned to Belle Ayr coal firing, and the CMM data (Figures 6.2.8.1 and 6.2.8.2) showed a continuous increase of mercury emission. After approximately

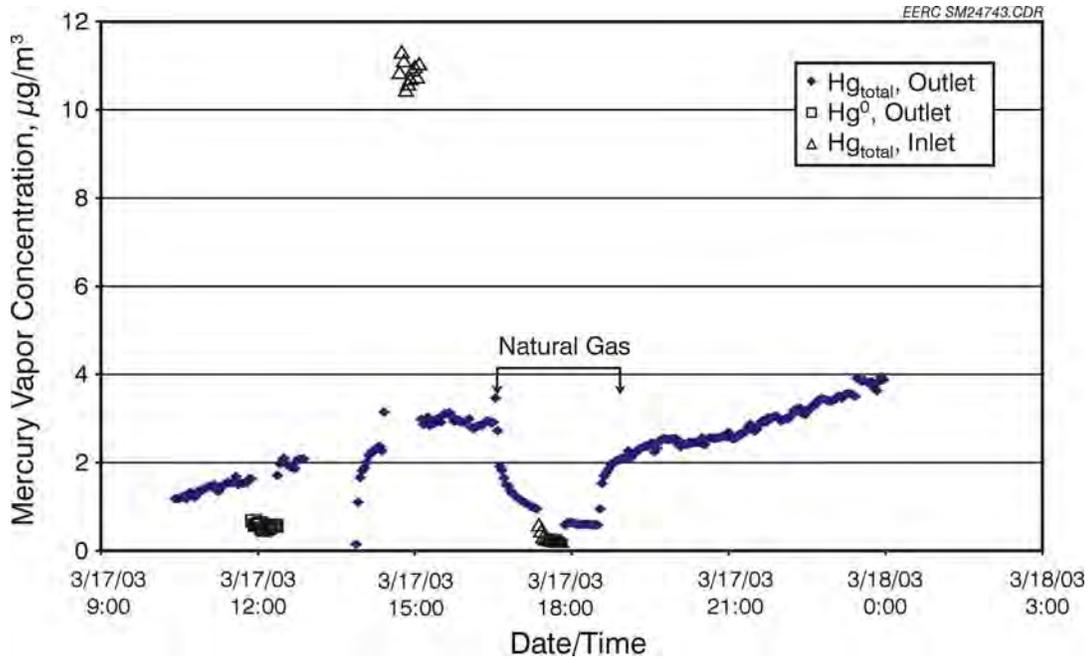


Figure 6.2.8.1. Gaseous mercury across PJBH equipped with Cartridge A filters – 149°C (300°F) test.

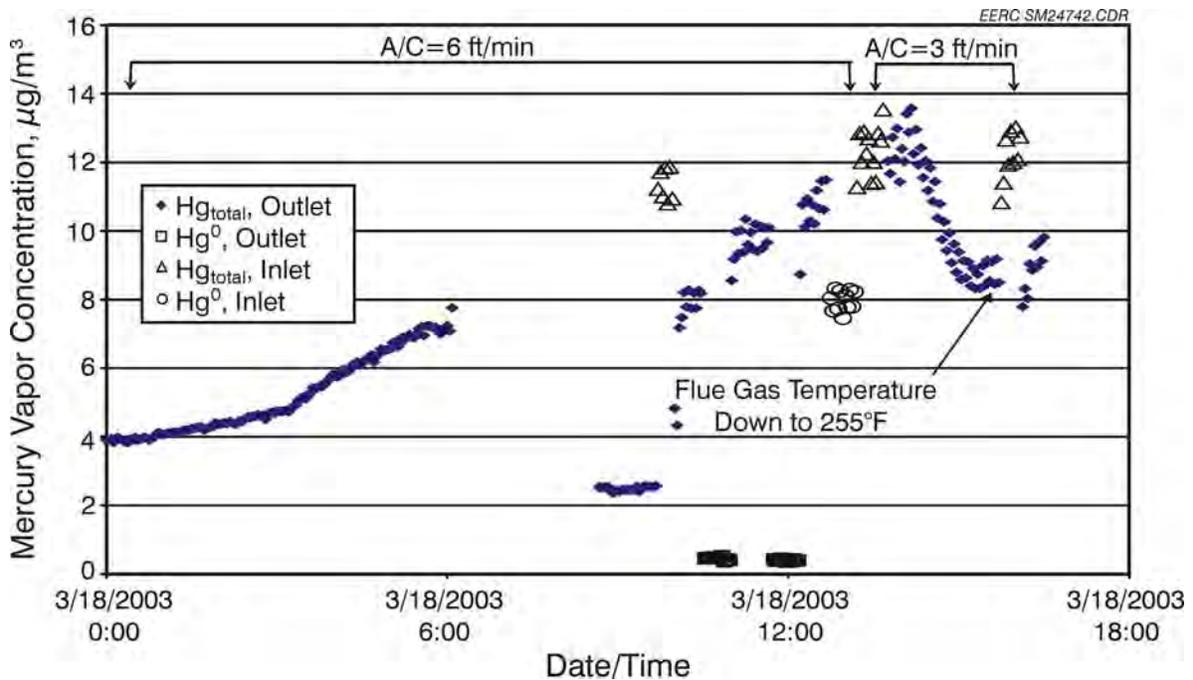


Figure 6.2.8.2. Gaseous mercury across the PJBH equipped with Cartridge A filters – 149°C (300°F) and 124°C (255°F) tests.

26 hr of operation with Cartridge A, the gaseous mercury concentration in the outlet flue gas reached 10.1–11.5 $\mu\text{g}/\text{m}^3$, and most of the mercury was in an oxidized state, with only 0.45 $\mu\text{g}/\text{m}^3$ of elemental mercury. One pair of Ontario Hydro samples was taken at the inlet and outlet at the end of this test to verify the complete breakthrough based on CMM data, and Figure 6.2.8.3 plots the analysis results.

Mercury in the flue gas was primarily elemental mercury at 11.3 $\mu\text{g}/\text{m}^3$, Hg^{2+} at 2.1 $\mu\text{g}/\text{m}^3$, and $\text{Hg}(\text{p})$ virtually undetectable. The total mercury emission at the outlet was 13 $\mu\text{g}/\text{m}^3$, very close to the 13.6 $\mu\text{g}/\text{m}^3$ measured at the inlet. In the outlet flue gas, almost all of the mercury was in oxidized form.

The Ontario Hydro results agree very well with the corresponding CMM measurements. They both indicate that the Cartridge A was capable of oxidizing mercury efficiently but had a 100% breakthrough after 26 hr of operation with the Belle Ayr coal flue gas. The overall mercury capture was initially 91.8% but dropped to almost zero after 26 hr of operation.

Test 2 – Cartridge A in PJBH at 0.015 m/s (3 ft/min) Face Velocity and 124°C (255°F)

In this test, the performance of Cartridge A for mercury removal was evaluated for a reduced face velocity of 0.015 m/s (3 ft/min) and operating temperature of 124°C (255°F).

Plotted CMM data (Figure 6.2.8.2) shows that although the gaseous mercury in the inlet flue gas stayed around 11–13 $\mu\text{g}/\text{m}^3$, the same as in Test 1, the mercury emissions at the outlet gradually decreased from the 100% percent mercury breakthrough with the reducing operating temperature. The gaseous mercury concentration in the outlet flue gas decreased with decreasing temperature and stabilized around 8.8 $\mu\text{g}/\text{m}^3$ when the operating temperature leveled off at 124°C (255°F). The short-term testing data indicate better mercury capture as a result of the reduced operating temperature and lower A/C ratio.

Test 3 – Cartridge B with a PJBH at 0.03 m/s (6 ft/min) Face Velocity and 149°C (300°F)

Since Cartridge A did not demonstrate efficient long-term mercury removal in the above tests, a different cartridge filter, referred to as Cartridge B, was installed and tested with the PJBH at a 0.03 m/s (6ft/min) A/C ratio and 149°C (300°F) operating temperature.

The outlet CMM data (Figure 6.2.8.4) showed, initially, a very low gaseous mercury concentration of 0.4 $\mu\text{g}/\text{m}^3$ with virtually no elemental mercury, while gaseous mercury in the inlet flue gas was 9–10 $\mu\text{g}/\text{m}^3$ with 7–8 $\mu\text{g}/\text{m}^3$ of elemental mercury.

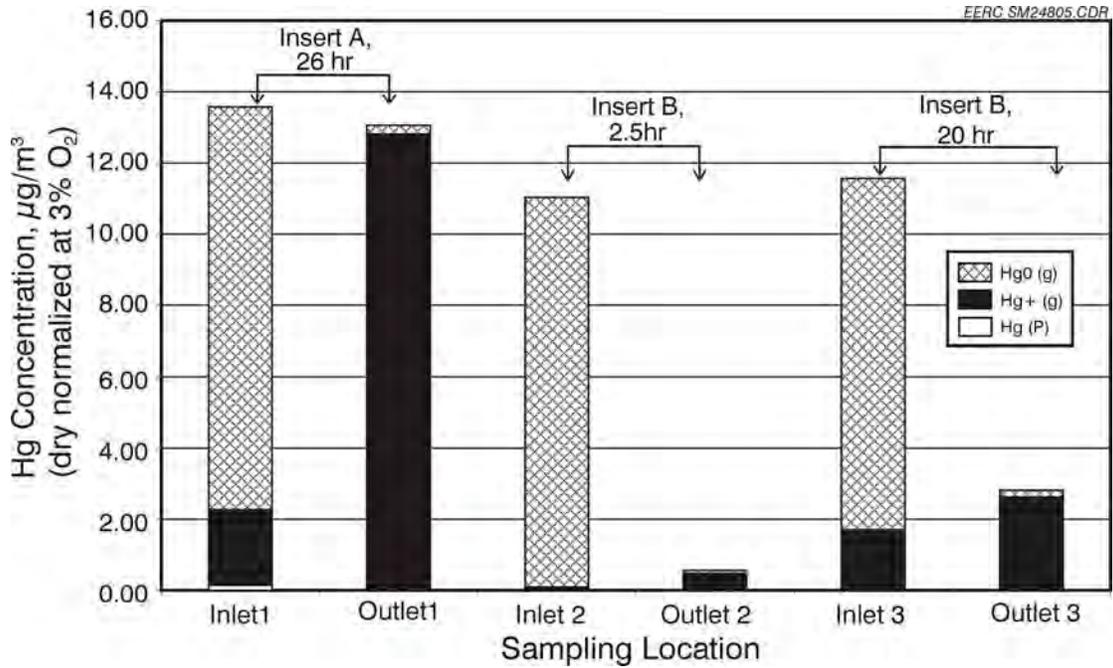


Figure 6.2.8.3. Ontario Hydro results in the inlet and outlet flue gas during PTC-BA-637.

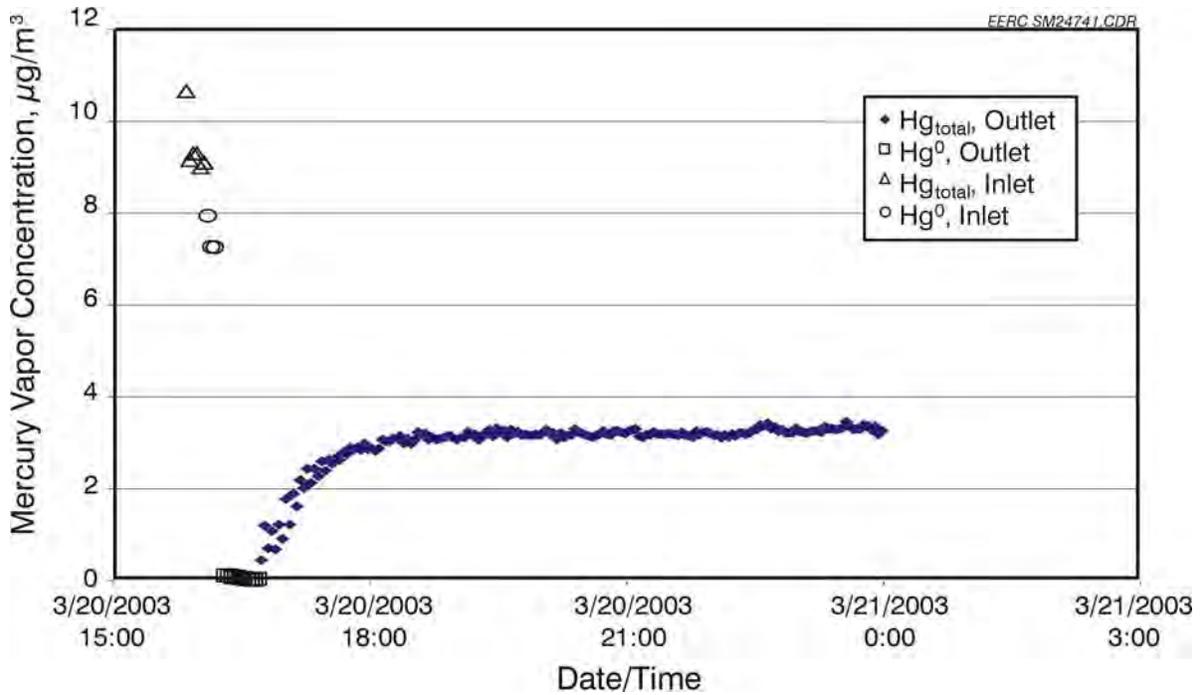


Figure 6.2.8.4. Gaseous mercury across the PJBH equipped with Cartridge B filter – 149°C (300°F) test.

One pair of Ontario Hydro samples was taken at the inlet and outlet to verify CMM measurement and determine overall mercury collection efficiency with Cartridge B after the 2.5-hr testing, and analysis results are plotted in Figure 6.2.8.3. The mercury in the inlet flue gas was $10.9 \mu\text{g}/\text{m}^3$ of elemental mercury, $0.1 \mu\text{g}/\text{m}^3$ of oxidized mercury, and $0.04 \mu\text{g}/\text{m}^3$ of particle-bound mercury, and the total mercury emission in the outlet flue gas was only $0.6 \mu\text{g}/\text{m}^3$. Both the CMM data and Ontario Hydro result are in good agreement, and the overall mercury capture efficiency with Cartridge B was 94.5% after 2.5 hr of operation.

With extended exposure time, the CMM data (Figures 6.2.8.4 and 6.2.8.5) indicated a gradual increase of mercury concentration in the outlet flue gas. The mercury emission reached $5.7 \mu\text{g}/\text{m}^3$ after approximately 20 hr of operation with no elemental mercury in the flue gas. The results of the second pair of Ontario Hydro samples (Figure 6.2.8.3) confirm the CMM measurement, showing a total of $2.8 \mu\text{g}/\text{m}^3$ mercury emission after 20 hr of operation of Cartridge B with only $2.6 \mu\text{g}/\text{m}^3$ of oxidized mercury and $0.2 \mu\text{g}/\text{m}^3$ of elemental mercury. The overall mercury collection efficiency of Cartridge B was 75% after 20 hr of operation, which was much better than Cartridge A.

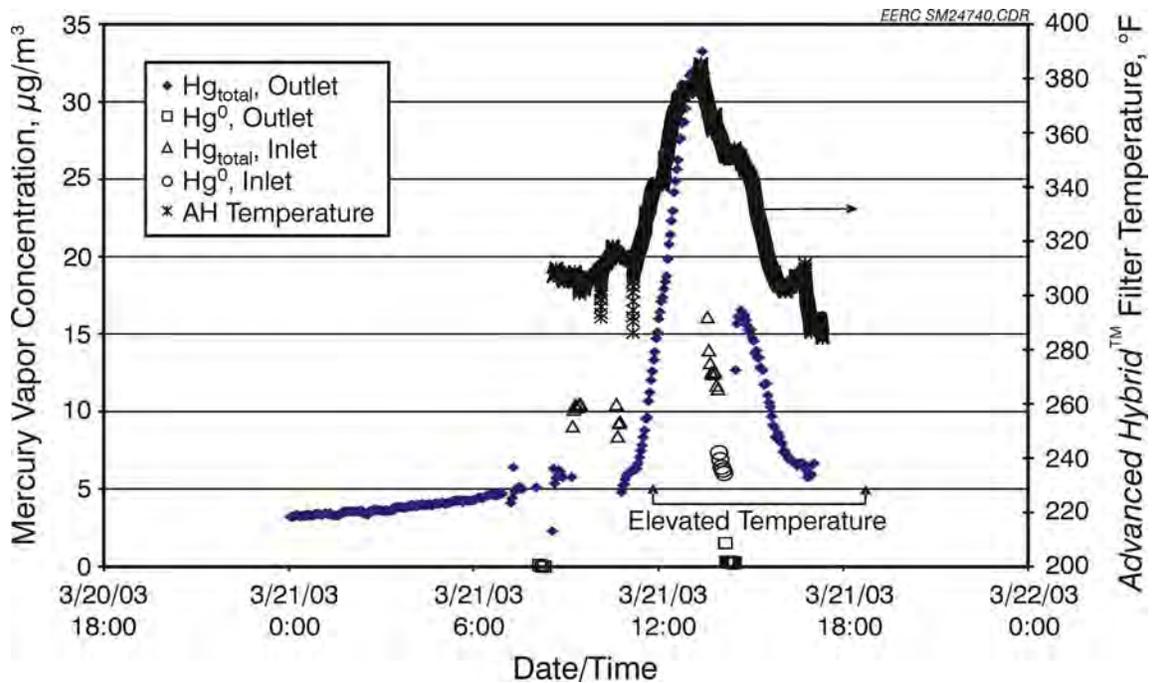


Figure 6.2.8.5. Gaseous mercury across the PJBH equipped with Cartridge B filter – 149°C (300°F) and 193°C (380°F) tests.

The mercury emission response of Cartridge B was different from Cartridge A, which showed continuously and steadily increasing mercury emission as a function of operating time. For Cartridge B, an initial transition zone existed where the mercury emission increased very fast. Mercury emission then reached the second phase where the mercury concentration at the outlet slowly increased until the flue gas chemistry changed. It is hypothesized that the capacity limit is the controlling factor for Cartridge A, while reactivity is the limit for Cartridge B.

Test 4 – Cartridge B with PJBH at 0.03 m/s (6 ft/min) Face Velocity and 193°C (380°F)

Near the end of testing, the flue gas temperature was increased to 193°C (380°F) to examine mercury removal with Cartridge B at an elevated temperature. The outlet CMM data (Figure 6.2.8.5) indicate that, upon increasing the flue gas temperature, mercury concentration in the outlet flue gas increased significantly. A mercury vapor concentration of 32 $\mu\text{g}/\text{m}^3$ was measured in the outlet flue gas when flue gas temperature reached 193°C (380°F). Compared to the 10~12 $\mu\text{g}/\text{m}^3$ of total mercury vapor concentration in the inlet flue gas, the much higher mercury emission indicates significant mercury desorption from the cartridge filters at the elevated temperature.

Also plotted in Figure 6.2.8.5 is the average flue gas temperature across the filter during the testing period as a function of time. The desorption took place once the flue gas temperature was higher than 159°C (318°F). After the flue gas temperature cooled, mercury emissions also decreased. The total mercury emission was back to 5.9 $\mu\text{g}/\text{Nm}^3$ when the flue gas temperature was returned to 141°C (285°F). The experimental data demonstrate that Cartridge B is very temperature-dependent for mercury capture.

6.2.8.4 Conclusions from PTC-BA-637 Testing Results

Cartridges A and B showed excellent (over 98%) mercury oxidation, and Cartridge B attained 75% overall mercury removal efficiency with the Belle Ayr coal flue gas after 20 hr of operation.

The mercury capture performance of the cartridge filter was highly temperature-dependent. The best operating temperature is in the range of 124°~149°C (255°~300°F).

6.2.9 PTC-BA-650

6.2.9.1 Test Conditions

Previous results with both the 55-kW (200-acfm) pilot-scale *Advanced Hybrid*TM filter and the 2.5-MW (9000-acfm) field *Advanced Hybrid*TM filter showed that, over a range of conditions, from 50% to 95% mercury control could be achieved. Based on the rate of pressure drop increase in comparative tests without high-voltage power, the particulate collection efficiency of the perforated-plate ESP portion of the *Advanced Hybrid*TM filter was calculated to be about 95%. If the injected carbon is collected at the same efficiency as the fly ash, then it can be assumed that most of the carbon was also collected on the plates rather than on the bags. It is important to show that good mercury control can be achieved by collection of the carbon on the perforated plates, because then the carbon addition rate can be adjusted as necessary to achieve the target mercury control level without concern of the effect of carbon injection on pressure drop. While it could be inferred from previous tests that most of the mercury capture occurred before the flue gas reached the bags, the uncertainty over the exact amount of fly ash and injected carbon collected on the perforated plates made the conclusion tentative. The primary purpose of this pilot-scale test with the modified 55-kW (200-acfm) *Advanced Hybrid*TM filter unit was to determine the amount of mercury control across the perforated plates alone.

The 55-kW (200-acfm) pilot-scale *Advanced Hybrid*TM filter was set up with perforated plates surrounding the bag area. The plates had approximately 50% open area with 0.019-m (0.75-in.)-diameter holes. Directional discharge electrodes pointing toward the perforated plates were used to minimize any unwanted collection on the outside walls of the *Advanced Hybrid*TM filter housing. To further facilitate collection of the dust on the plates rather than the housing walls, the distance from the discharge electrodes to the plates was set at 0.13 m (5.25 in.), while the distance from the discharge points to the outside housing walls was 0.21 m (8.25 in.). Flue gas was introduced into the *Advanced Hybrid*TM filter housing in the area between the discharge electrodes and the outside walls to make sure that all of the gas would pass through the plane of the discharge electrodes before reaching the perforated plates (see Figures 6.2.9.1 and 6.2.9.2).

To minimize collection of any ash or carbon downstream from the perforated plates, the bags were removed. After the gas passed through the perforated plates, it exited through the open holes in the tube sheet into the clean air plenum and then out of the *Advanced Hybrid*TM filter housing.

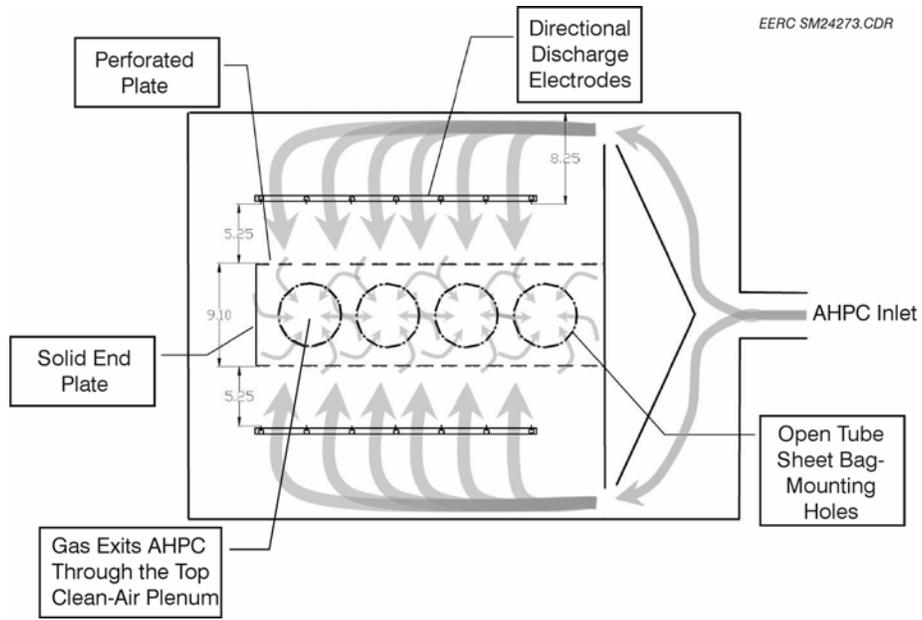


Figure 6.2.9.1. Top-view schematic of the *Advanced Hybrid™* filter (perforated plate only).

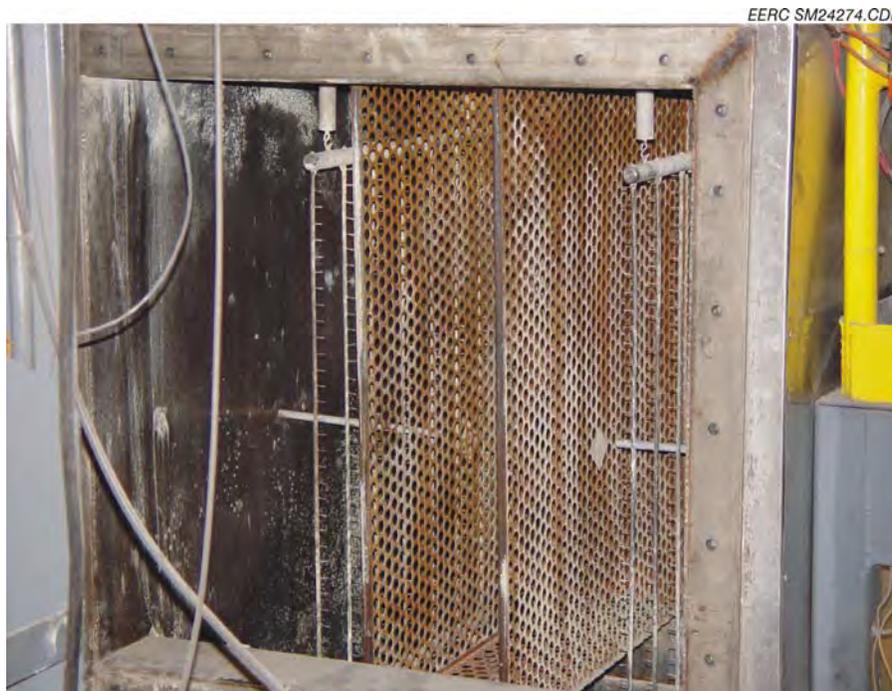


Figure 6.2.9.2. Front view of the *Advanced Hybrid™* filter (perforated plate only) with inlet cover removed.

Three test conditions were evaluated with this configuration: 1) baseline tests before each of the carbon injection tests, 2) the NORIT FGD carbon injection test, and 3) the treated-NORIT FGD carbon injection test. The coal for the tests was Belle Ayr, which is one of the PRB subbituminous coals burned at the Big Stone Power Plant and which was used for previous pilot-scale tests. Gaseous mercury was measured with two PS Analytical CMMs: one at the inlet upstream of the point of carbon injection and one at the *Advanced Hybrid*TM filter outlet. Outlet particulate dust loadings were determined with EPA Method 5 during each of the two carbon injection tests.

6.2.9.2 Coal and Flue Gas Analyses

Since the Belle Ayr coal used in this test is the same as in previous tests (PTC-BA-628, 629, 636, and 637) and the general information on this coal was known, no additional coal analysis was completed.

6.2.9.3 Mercury Results for PTC-BA-650

Plotted in Figure 6.2.9.3 are the mercury emissions from the perforated plate-only *Advanced Hybrid*TM filter unit during the testing period. Mercury concentration in the outlet flue gas in the baseline test was around 10–11 $\mu\text{g}/\text{m}^3$ (dry gas corrected to 3% O_2), which is the expected inlet concentration based on previous tests with this coal. When the NORIT FGD carbon was injected just upstream of the *Advanced Hybrid*TM filter at a rate of 32 mg/m^3 (2 lb/Macf), the outlet mercury concentration quickly dropped to 3–4 $\mu\text{g}/\text{m}^3$, corresponding to an average of 66% removal compared to 0.95% inherent mercury capture in the baseline test (Figure 6.2.9.4).

This level of removal was similar to previous results with the *Advanced Hybrid*TM filter and higher than the ESP configuration using the NORIT FGD carbon at the same injection rate, which indicates that reasonably good mercury control can be achieved with carbon collected on the perforated plates alone. However, there was still the question of whether the mercury control was limited by the gas–solid contact geometry or by the mercury sorption ability of the injected carbon. During this test, the outlet dust loading measurement showed that the total particulate control removal across the perforated plates was 98.3%, so very little carbon bypassed the perforated plates (Figure 6.2.9.5).

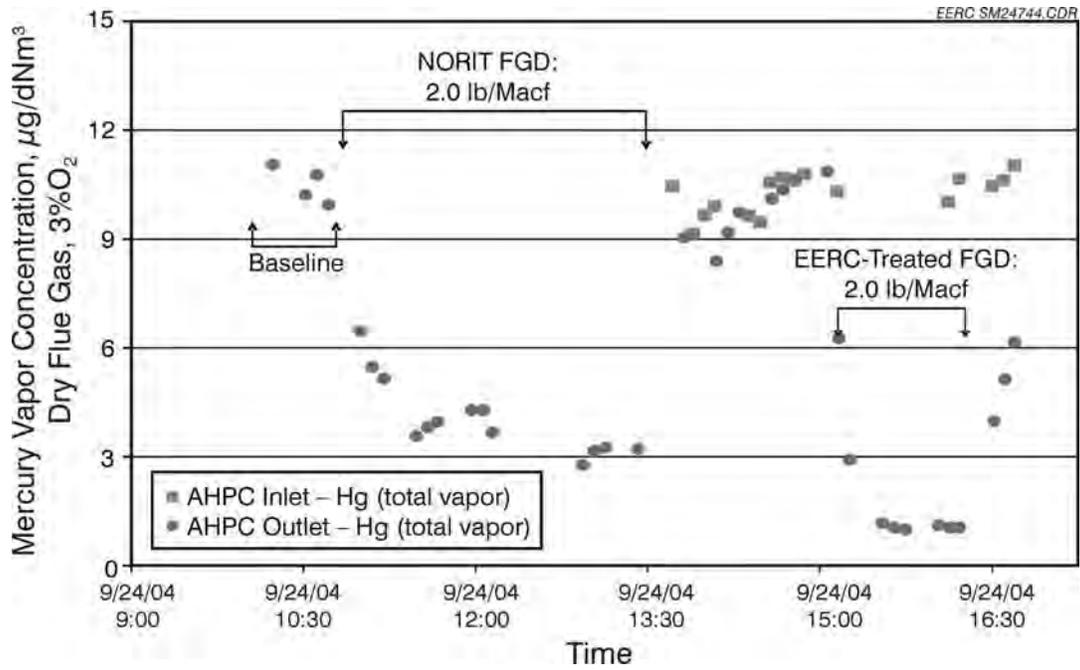


Figure 6.2.9.3. Mercury emissions from the perforated plate-only *Advanced Hybrid*TM filter unit under carbon injection.

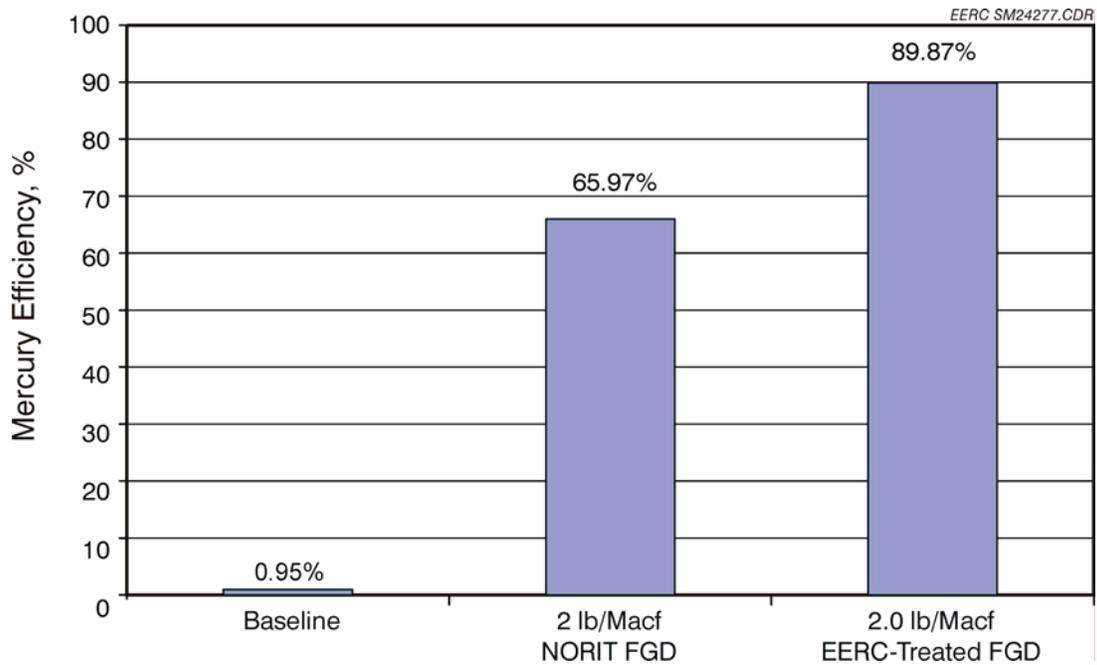


Figure 6.2.9.4. Average gaseous mercury removals for baseline and carbon injection tests.

To further evaluate the level of mercury control across the perforated plates, a second carbon injection test was conducted using a treated NORIT FGD carbon developed by the EERC. After reestablishing the baseline, the treated carbon was injected upstream of the *Advanced Hybrid*TM filter at the same carbon injection rate as in the FGD test. Immediately after starting injection, the outlet mercury dropped to about 1 µg/m³, corresponding to an average mercury removal of 89.9% (Figures 6.2.9.3 and 6.2.9.4). Since the carbon injection rate and the particulate collection efficiency (Figure 6.2.9.5) were the same for both tests, the better mercury removal for the treated carbon is attributed to superior mercury capture ability of the carbon rather than any difference in gas–solid contact exposure. These results provide convincing evidence that the geometry of the *Advanced Hybrid*TM filter allows sufficient gas–solid contact for achieving excellent mercury control when most of the carbon is collected on the perforated plates. The data represent the minimum level of mercury control that would be expected. Any carbon that reaches the bags would only enhance the gas–solid contact and further improve total mercury capture.

6.2.9.4 Conclusions from PTC-BA-650 Testing Results

The last planned experimental work for the project was a test to measure the amount of mercury collected by the perforated plates in the *Advanced Hybrid*TM filter apart from any mercury control on the filter bags. To address this question, the 55-kW (200-acfm) pilot-scale

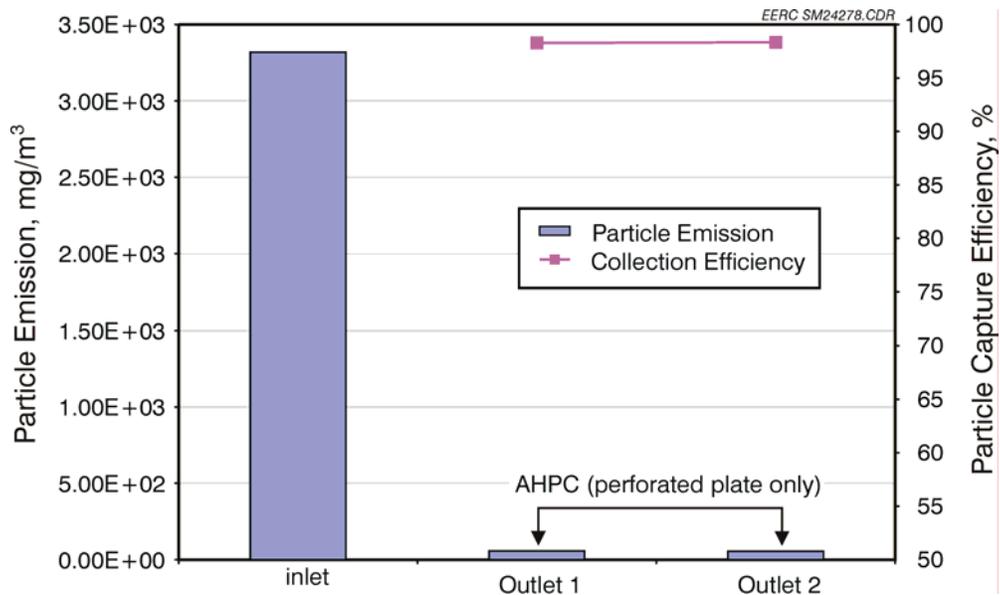


Figure 6.2.9.5. Particle emissions from the *Advanced Hybrid*TM filter – perforated plate only.

*Advanced Hybrid*TM filter was modified so that it included perforated plates totally surrounding the normal bag area, but with the filter bags removed. Mercury removal with this configuration using NORIT FGD carbon injected at 32 mg/m³ (2 lb/Macf) was similar to previous results with the *Advanced Hybrid*TM filter when filter bags were installed. These results indicate that good mercury control can be achieved with carbon collected on the perforated plates alone. However, using an EERC proprietary sorbent at the same carbon addition rate, the mercury collection efficiency improved to 90%. For both tests, the particulate collection efficiency of the perforated plates alone was 98%. These results are even more convincing because they prove that good gas–solid contact leading to excellent mercury removal can be achieved by collection of the activated carbon on the perforated plates alone, without a significant fraction of the carbon reaching the bags. It is important to show that good mercury control can be achieved by collection of the carbon on the perforated plates, because then the carbon addition rate can be adjusted as necessary to achieve the target mercury control level without concern of the effect of carbon injection on pressure drop. These results are consistent with previous pilot-scale and field data that have consistently shown that carbon injected upstream of the *Advanced Hybrid*TM filter for mercury control has little or no effect on pressure drop.

6.3 Field Demonstration at the 2.5-MW (9000-acfm) *Advanced Hybrid*TM Filter Unit at the Big Stone Power Plant

6.3.1 Short-Term Field Test During November 5–10, 2001

6.3.1.1 Test Conditions

According to the planned work, testing with the 2.5-MW (9000-acfm) *Advanced Hybrid*TM filter at the Big Stone Power Plant was not scheduled to begin until early 2002 after completion of the first pilot-scale tests. However, the project team decided to conduct an initial field test the first week of November 2001 prior to the pilot-scale tests at the EERC. There were several reasons for performing an initial early test:

- Delay in implementing the overall program by 5 months resulted in moving the whole schedule back by 5 months. With the original proposed work, the field testing would have begun in the summer. This would have prevented some of the weather problems associated with mercury sampling in the winter. By doing initial testing in November, we avoided beginning the mercury sampling in the worst part of the winter. It was expected that the mercury control testing at Big Stone would then resume in the spring

of 2002, and the completion of the field testing within the planned schedule would still be possible.

- A full-scale retrofit of an *Advanced Hybrid*TM filter at Big Stone was announced by DOE as one of the projects selected under the DOE Power Plant Improvement Initiative. Because design of this project needed to begin immediately, it was imperative to have as much information available as possible. By completing this initial field test early, additional information on *Advanced Hybrid*TM filter performance with carbon injection would facilitate final design of the full-scale Big Stone *Advanced Hybrid*TM filter.
- Since no mercury sampling was previously completed at the Big Stone Power Plant, early baseline data on the actual inlet mercury concentration and speciation would help in finalizing the EERC pilot plant testing. For example, if higher-than-expected fly ash capture of mercury were seen at Big Stone, that would have to be considered in planning the pilot plant tests.

The field test at Big Stone was completed the week of November 5–10, 2001, with baseline testing on the first day, followed by NORIT FGD carbon injection in both *Advanced Hybrid*TM filter and pulse-jet operational modes for the remainder of the week. The starting carbon addition rate was set at 24 mg/m³ (1.5 lb/Macf).

During the baseline test, the *Advanced Hybrid*TM filter was operated at a constant A/C ratio of 3.0 m/min (10 ft/min), the bags were cleaned on a constant timed 20-min interval, and the ash hopper was emptied once an hour.

For the second day, conditions were identical except for carbon addition at a rate of 24 mg/m³ (1.5 lb/Macf). The DARCO FGD carbon used was obtained from NORIT Americas and is commercially available. The carbon addition was controlled with a K-Tron powder feeder and was injected pneumatically at a single point into the center of the 0.610-m (24-in)-diameter inlet duct.

For the third day, the *Advanced Hybrid*TM filter was operated as a PJBH at an A/C ratio of 1.5 m/min (5 ft/min) with carbon injection. To keep the same carbon-to-flue gas ratio of 24 mg/m³ (1.5 lb/Macf), the carbon feed rate was set to half the previous level.

The fourth day was a repeat of Day 2, where the unit was again operated in *Advanced Hybrid*TM filter mode with carbon injection at 24 mg/m³ (1.5 lb/Macf).

For the fifth day of testing, the unit was operated with carbon injection in both *Advanced Hybrid*TM filter and PJBH modes, but with both at an A/C ratio of 1.5 m/min (5 ft/min). This test was completed to allow for a valid comparison between the *Advanced Hybrid*TM filter and pulse-jet modes without changing the residence time or temperature.

For all of the tests with carbon, the sorbent was injected only during the day, and after the mercury sampling was completed, the carbon was shut off overnight to allow the unit to return to baseline conditions prior to starting carbon injection the next day.

A total of four Ontario Hydro samples were taken for each day, including both at the inlet and outlet of the *Advanced Hybrid*TM filter. Two mercury CMMs provided gaseous mercury species for both inlet and outlet flue gases during the last 3 days of testing. A summary of the mercury, solids, and flue gas sampling is given in Table 6.3.1.1.

6.3.1.2 Big Stone Fuel Records and Analyses

Table 6.3.1.2 lists the fuel burn record of the Big Stone Power Plant November 5–10, 2001. During the testing period, the plant mainly fired coals from either Cordero or Caballo Mines in the PRB with supplemental fuels of TDF and waste seeds.

Table 6.3.1.1. Summary of Mercury, Gas, and Solids Samples Taken

Ontario Hydro
Day 1 – Two Pairs of Simultaneous Inlet and Outlets
Days 2–4 – One Inlet and Three Outlets
Day 5 – Two Pairs of Simultaneous Inlet and Outlets
CMM
Continuous Sampling with Two PS Analytical Mercury CMMs on Days 3–5
SO ₃
Three Inlets Total
HCl
Three Inlets Total
SO ₂ , NO, NO ₂ , CO, CO ₂ , O ₂
Select Sampling Each Day at Both Inlet and Outlet with Portable Ecom Gas Analyzer
Coal
One Sample a Day
<i>Advanced Hybrid</i> TM Filter Hopper Ash
Day 1 – Three Total
Days 2–4 – One Baseline Before Starting Carbon Injection and Three Corresponding to the End of Each Outlet Ontario Hydro Sample
Day 5 – One Baseline Before Starting Carbon Injection and Two Corresponding to the End of Each Outlet OH Sample

Table 6.3.1.2. Big Stone Fuel Record November 5–10, 2001

Date	Coal Mine	Coal, tons	TDF, tons	Waste Seeds, tons
November 5, 2001	Cordero	4695	140	100
November 6, 2001	Cordero	6117	200	100
November 7, 2001	Caballo	6104	150	120
November 8, 2001	Caballo	6296	90	100
November 9, 2001	Caballo	6024	250	80
November 10, 2001	Caballo	5344	200	30

A 4-L (1-gallon) grab sample of coal was collected each day from the coal feed conveyor by Big Stone Power Plant personnel. Table 6.3.1.3 lists proximate and ultimate analysis results of the testing coal, showing a low level of sulfur in the raw coal. Mercury analysis for the five coal samples (Table 6.3.1.3) indicates a consistent mercury content in the range of 0.105–0.149 µg/g with a mean value of 0.126 µg/g, while a single analysis of the waste corn seed indicates almost no mercury originated from the corn. The chlorine analyses show the coal had a

Table 6.3.1.3. Coal Analysis for the Big Stone Power Plant

Proximate Analysis	% As-Sampled	% Moisture-Free
Moisture Content	29.3	NA
Volatile Matter	33.92	47.96
Fixed Carbon	31.57	44.67
Ash	5.21	7.37
Ultimate Analysis		
Hydrogen	6.48	4.57
Carbon	49.46	69.93
Nitrogen	0.77	1.09
Sulfur	0.38	0.54
Oxygen	37.69	16.50
Ash	5.21	7.37
Heating Value, Btu/lb	8607	12,174
Mercury Analysis, µg/g		
Coal Day 1 Sample		0.127
Coal Day 2 Sample		0.122
Coal Day 3 Sample		0.105
Coal Day 4 Sample		0.149
Coal Day 5 Sample		0.125
Mean		0.126
Corn Screened from Feed Coal		<0.001
Chlorine Analysis, µg/g		
Coal		8.72
Corn		577
TDF		741

very low level of 8.7 µg/g of chlorine; in contrast, the corn and TDF had quite a high chlorine level of 577 and 741 µg/g, respectively. Although the feed rates of corn and TDF were approximately only 1.5% and 3% of the coal feed rate, the high chlorine contents may alter mercury–flue gas chemistry.

From the combustion calculation based on proximate–ultimate analyses and mercury content in raw coal, the test coal is expected to produce 15.1 µg/m³ (dry basis, 3% O₂) of mercury in flue gas.

6.3.1.3 Flue Gas Analysis

Flue gas composition was measured each day both at the *Advanced Hybrid*TM filter inlet and outlet by using a portable Ecom gas analyzer which provides the concentrations of O₂, CO₂, CO, NO, NO₂, and SO₂ in the flue gas on a dry basis. The results of the 5-day test are listed in Table 6.3.1.4. Because of the use of the low-sulfur coal, the SO₂ concentration in the flue gas was low, ranging from 165 to 299 ppm. The NO and NO₂ concentrations in the flue gas were 499–575 ppm for NO and only 1–4 ppm for NO₂. Three SO₃ samples (by using selective condensation method) and three HCl samples (using EPA Method 26) were collected at the *Advanced Hybrid*TM filter inlet during the 5-day test. The analysis results were normalized to 3% O₂ dry flue gas and are summarized in Table 6.3.1.5. The coal flue gas had low levels of HCl and SO₃ during the testing period.

Table 6.3.1.4. Summary of the Flue Gas Compositions During the 5-day Sampling, dry basis

		O ₂ , %	CO ₂ , %	CO, ppm	NO, ppm	NO ₂ , ppm	SO ₂ , ppm
Day 1	In	6.2	13.1	1	509	4	165
	Out	5.1	14.1	1	543	3	238
Day 2	In	4.9	14.3	–	545	2	252
	Out	5.0	14.2	10	531	2	247
Day 3	In	5.3	13.9	2	575	2	251
	Out	5.3	13.9	1	514	3	248
Day 4	In	5.2	–	–	545	2	260
	Out	5.3	–	4	499	1	299
Day 5	In	5.1	14.1	2	541	2	226
	Out	5.5	13.8	1	523	3	201

Table 6.3.1.5. HCl and SO₃ Analysis in the Flue Gas, ppm dry at 3% O₂

Gas, ppm	Sample 1	Sample 2	Sample 3
HCl	9.12	10.12	9.95
SO ₃	0.41	0.61	0.65

6.3.1.4 – Mercury Results for November 5–10, 2001, Field Test

Ontario Hydro sampling trains were set up at the *Advanced Hybrid*TM filter inlet and outlet to measure mercury species concentrations in the flue gas. Figure 6.3.1.1 shows the inlet sampling location which was 6.1 m (20 ft) upstream of the carbon injection location, and Figure 6.3.1.2 shows the outlet sampling location that was just before the flue gas entered the fan. The Ontario Hydro method provides mercury species information in flue gas as elemental mercury vapor, oxidized mercury, and mercury associated with particulate matter. All of the results are presented in the form of $\mu\text{g}/\text{m}^3$ based on the CVAA analysis results of the impinger solutions, sampled flue gas volume, and dust loading. All of the measured mercury concentrations in the flue gas were corrected to a moisture-free 3% O_2 level to allow a valid comparison at varying O_2 levels.

During the Day 1 baseline test, the *Advanced Hybrid*TM filter unit was operated at an A/C ratio of 3.0 m/min (10 ft/min) without carbon injection. Plotted in Figure 6.3.1.3 are mercury species in the *Advanced Hybrid*TM filter inlet and outlet flue gas. At the *Advanced Hybrid*TM filter inlet, the mercury associated with particulate was 5.91–7.12 $\mu\text{g}/\text{m}^3$, and the oxidized mercury was 5.2–6.55 $\mu\text{g}/\text{m}^3$, while the elemental mercury vapor was at a surprisingly low level of

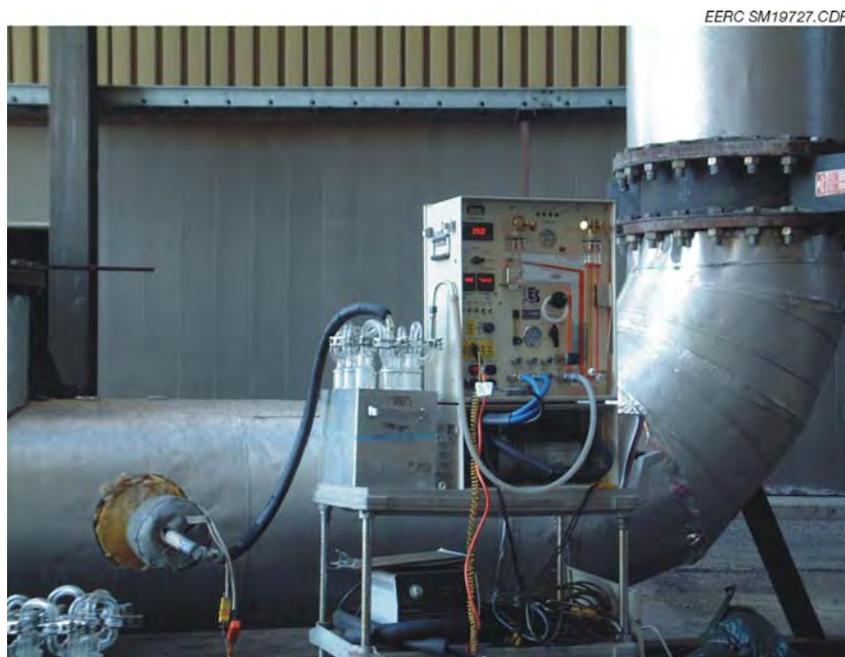


Figure 6.3.1.1. Inlet sampling location.



Figure 6.3.1.2. Outlet sampling location just before flue gas entered the fan.

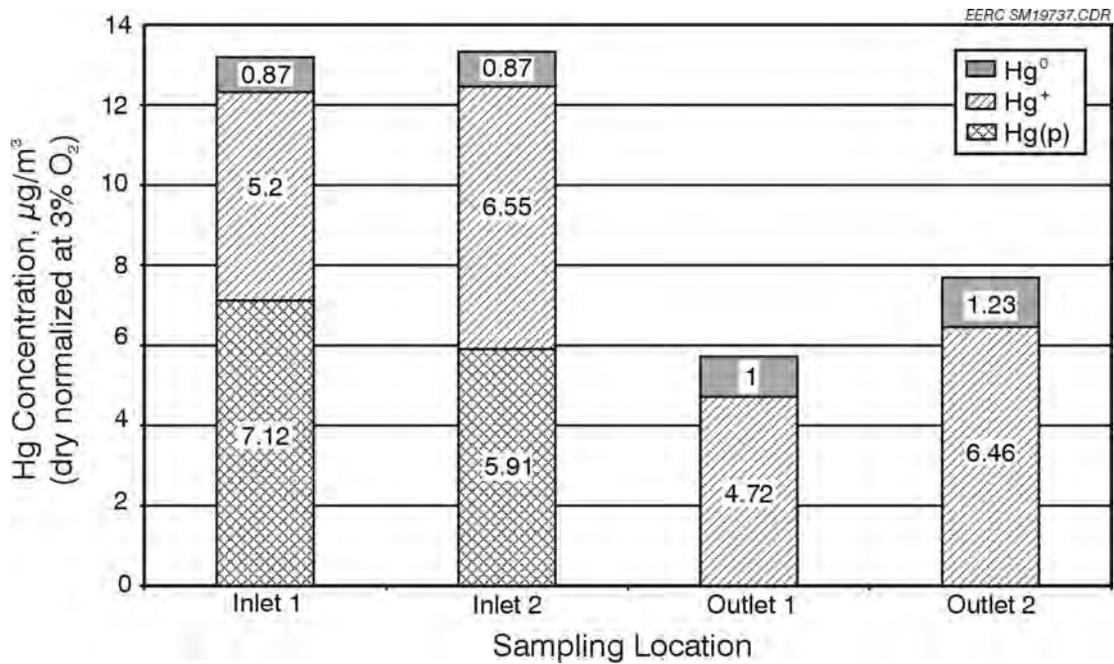


Figure 6.3.1.3. Baseline mercury species in the *Advanced Hybrid*TM filter inlet and outlet flue gas.

0.87 $\mu\text{g}/\text{Nm}^3$. Mercury concentration at the *Advanced Hybrid*TM filter outlet was 1–1.23 $\mu\text{g}/\text{m}^3$, of elemental mercury, 4.72–6.46 $\mu\text{g}/\text{m}^3$ of oxidized mercury, no particle-bound mercury. The sampling data indicate an excellent removal of particle-associated mercury and virtually no additional capture of gaseous mercury (including elemental and oxidized mercury) across the *Advanced Hybrid*TM filter unit under the baseline testing conditions.

Mercury species in the inlet and outlet flue gases are normalized and replotted in Figure 6.3.1.4 to further clarify mercury transformation across the *Advanced Hybrid*TM filter system. In the inlet flue gas, around 50% of total mercury had already been associated with fly ash, another 43% of total mercury was in the oxidized state, and only about 7% was in the elemental state. At the *Advanced Hybrid*TM filter outlet, only elemental (16–17.5%) and oxidized (82.5–84%) mercury were in the flue gas since all the particle-bound mercury had been captured with the *Advanced Hybrid*TM filter. The overall mercury removal with *Advanced Hybrid*TM filter under the baseline test was approximately 49.4%, mainly due to the capture of particle-bound mercury in the coal flue gas.

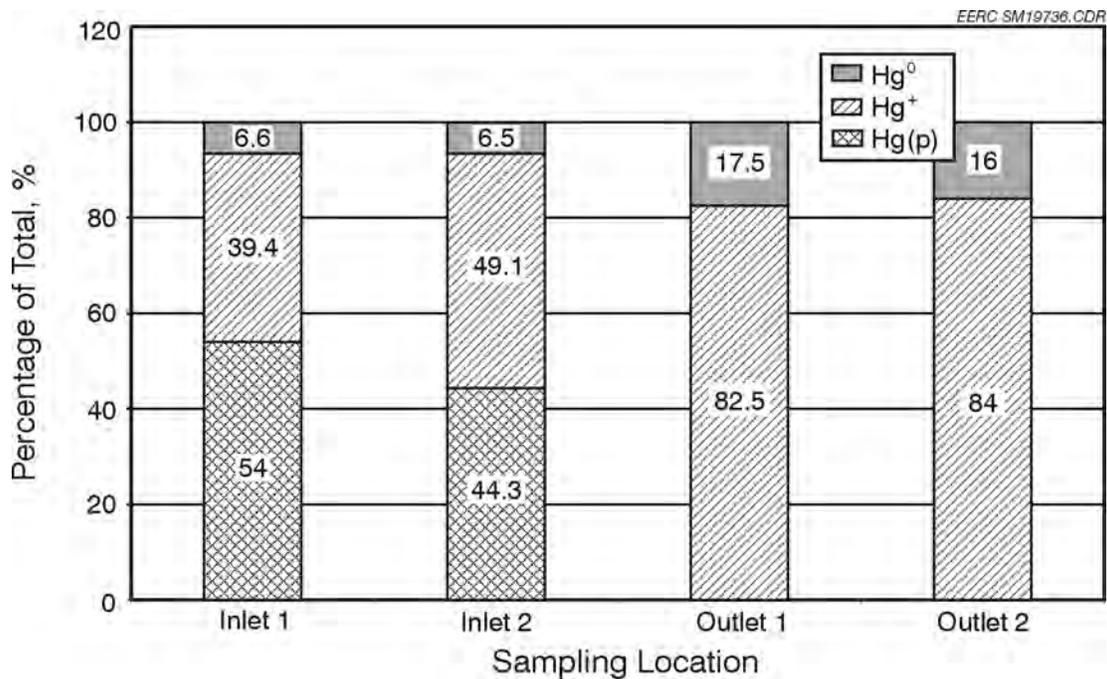


Figure 6.3.1.4. Normalized baseline mercury species distributions in the inlet and outlet flue gases.

On Day 2 (November 7, 2001), the *Advanced Hybrid*TM filter was operated at 3.0 m/min (10 ft/min) A/C ratio, 70 mA, 58 kV, and 0.29 kg/hr (0.64 lb/hr) carbon injection rate, corresponding to 24 mg/m³ (1.5 lb/Macf). One inlet Ontario Hydro sample and three outlet Ontario Hydro samples were collected during the test, and the results are plotted in Figure 6.3.1.5. In the inlet flue gas, there was high level of particle-bound mercury of 6.5 µg/m³, 3.0 µg/m³ of oxidized mercury, and only 1.04 µg/m³ of elemental mercury. With the carbon injection, mercury emission in the outlet flue gas decreased to 0.75–1.42 µg/m³ with 0–0.55 µg/m³ oxidized mercury and 0.74–0.85 µg/m³ elemental mercury. The overall mercury removal with the *Advanced Hybrid*TM filter at the carbon injection rate of 24 mg/m³ (1.5 lb/Macf) was 90.6% compared to 49% without carbon injection. The injected carbon efficiently adsorbed oxidized mercury vapor and part of the elemental mercury in the flue gas and then was removed from the flue gas by the injected carbon.

Figure 6.3.1.6 plots the Ontario Hydro results of the Day 3 test where the *Advanced Hybrid*TM filter was operated as a PJBH with a 20-min bag-cleaning interval (BCI). In order to keep the pressure drop across the system at a reasonable level, the A/C ratio was reduced to

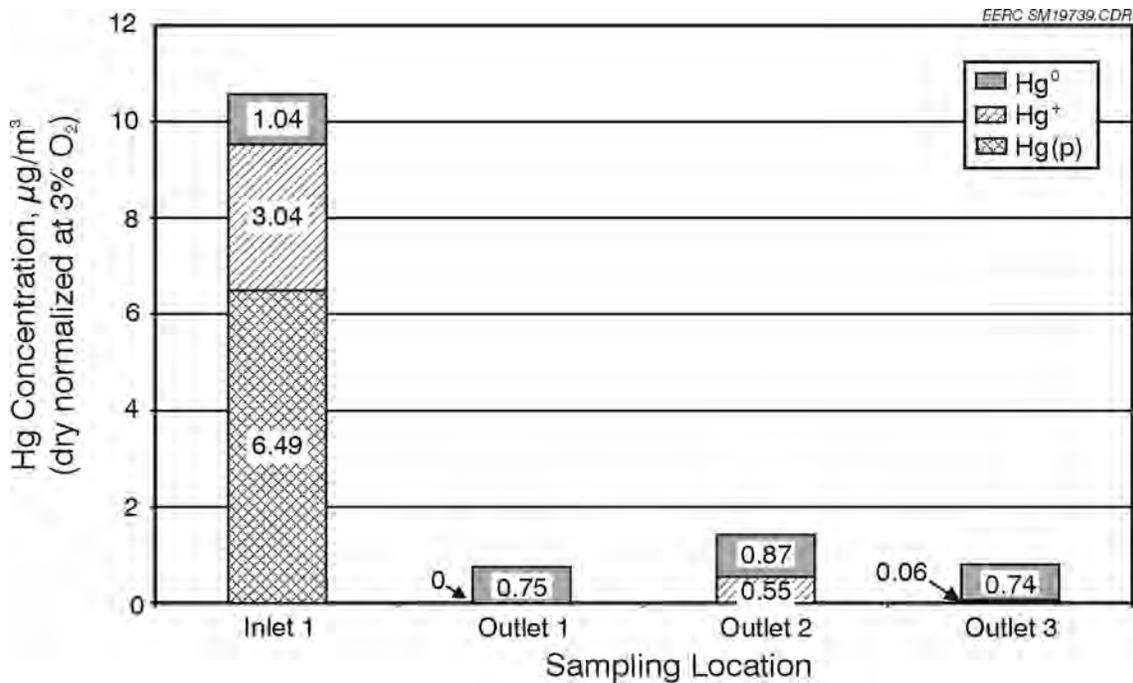


Figure 6.3.1.5. Ontario Hydro results in the *Advanced Hybrid*TM filter inlet and outlet flue gas at 24-mg/m³ (1.5-lb/Macf) FGD injection.

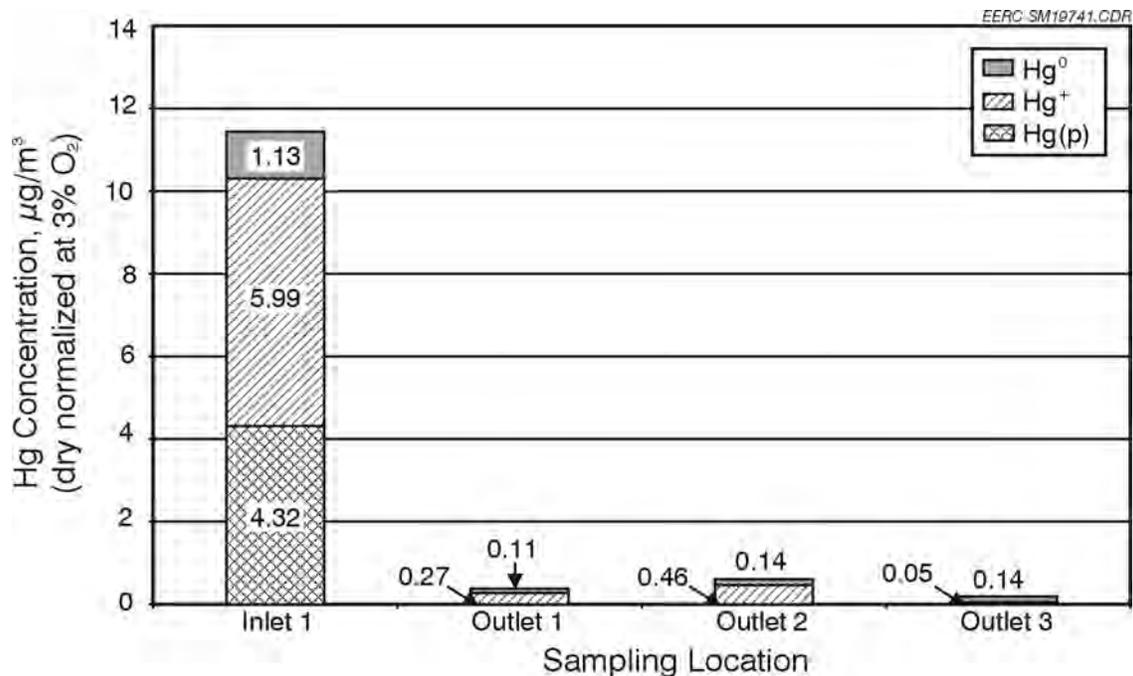


Figure 6.3.1.6. Ontario Hydro results in the PJBH inlet and outlet flue gas under 24-mg/m³ (1.5-lb/Macf) FGD injection.

1.5 m/min (5 ft/min), and the carbon injection rate was correspondingly reduced to 0.15 kg/hr (0.33 lb/hr) to keep the same carbon-to-flue gas ratio of 24 mg/m³ (1.5 lb/Macf). The inlet mercury species distribution was similar to the previous 2 days. The outlet mercury emission with carbon injection was 0 µg/m³ particle-associated mercury, 0.07–0.46 µg/m³ oxidized mercury, and 0.11–0.14 µg/m³ elemental mercury vapor.

Two CMMs monitored elemental and total mercury concentrations in the inlet and outlet flue gases during the test. Figure 6.3.1.7 plots the temporal variation of mercury species in flue gas in the testing period. The inlet elemental mercury was around 0.39 µg/m³, only accounting for 8.4% of the 4.62 µg/m³ gaseous mercury, which agreed with the Ontario Hydro results. With NORIT FGD carbon injection into the *Advanced Hybrid*TM filter chamber, the total mercury concentration at the outlet reduced to 0.54 µg/m³, and the elemental mercury concentration in the flue gas was below the CMM detection limit. Having the carbon injection shut down, the outlet mercury emission gradually increased and reached the same level as that of the inlet. The

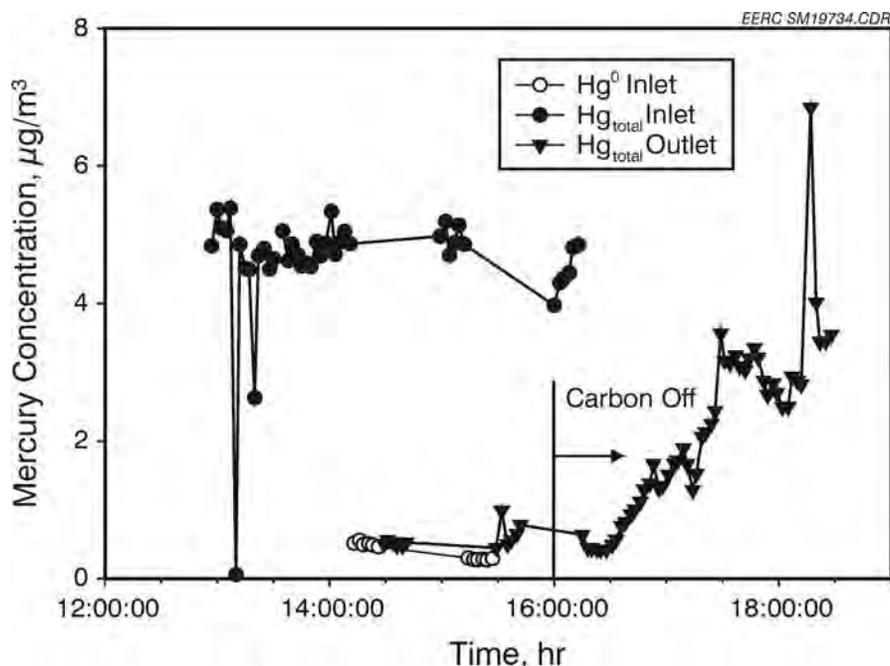


Figure 6.3.1.7. Temporal variation of mercury species in flue gas across the PJBH with $24\text{-mg}/\text{m}^3$ (1.5-lb/Macf) FGD injection.

observed slow increase of mercury concentration at the outlet was likely caused by the residual activated carbon in the *Advanced Hybrid*TM filter chamber.

Both Ontario Hydro results and CMM data showed that most of the inlet mercury vapor in the flue gas was in the oxidized state and there was excellent mercury capture with the PJBH at $24\text{ mg}/\text{m}^3$ (1.5 lb/Macf) of carbon injection. The corresponding overall mercury collection efficiency of PJBH was 96.6%, which is somewhat better than the 90.6% of the *Advanced Hybrid*TM filter achieved in the Day 2 sampling test. Longer residence time at the reduced A/C ratio of 1.5 m/min (5 ft/min) and a lower temperature may have contributed to the somewhat lower mercury emissions compared to Day 2.

The Day 4 sampling test was a repeat of the Day 2 test (*Advanced Hybrid*TM filter mode, 20-min BCI, 3.0 m/min [10 ft/min] A/C ratio, and 0.29 kg/hr [0.65 lb/hr] carbon injection rate). Plotted in Figures 6.3.1.8 and 6.3.1.9 are the Ontario Hydro results and CMM data, respectively. The CMM data (Figure 6.3.1.9) show the total inlet mercury vapor concentration varied from 2.78 to 3.54 $\mu\text{g}/\text{m}^3$, with an average value of 3.09 $\mu\text{g}/\text{m}^3$, which was very close to the

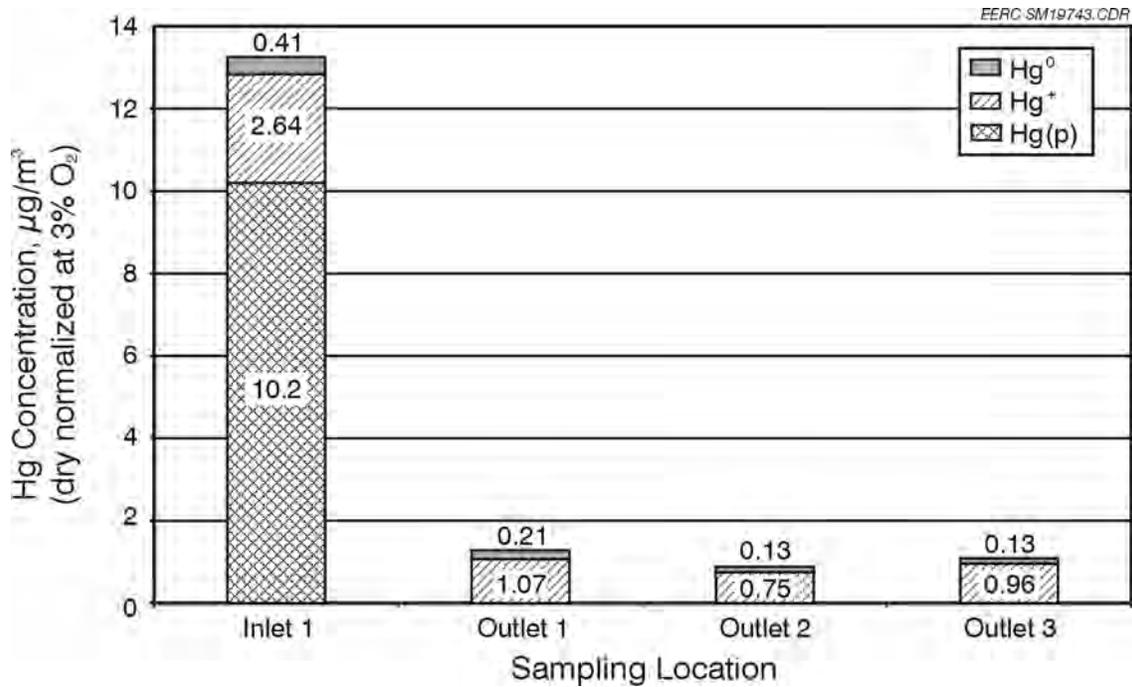


Figure 6.3.1.8. Ontario Hydro results in the *Advanced Hybrid*TM filter inlet and outlet flue gases with 24-mg/m³ (1.5-lb/Macf) FGD injection for Day 4.

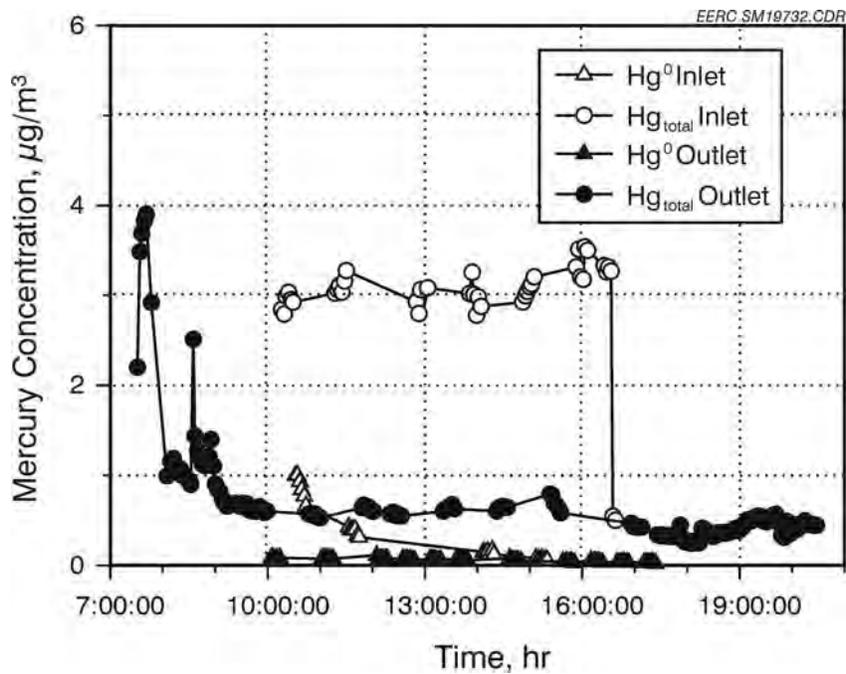


Figure 6.3.1.9. Temporal variations of gaseous mercury across the *Advanced Hybrid*TM filter with 24-mg/m³ (1.5-lb/Macf) FGD injection for Day 4.

3.05 $\mu\text{g}/\text{Nm}^3$ from Ontario Hydro analysis (Figure 6.3.1.8). Again, a very low percentage of elemental mercury was observed at the *Advanced Hybrid*TM filter inlet. Both Ontario Hydro and CMM data indicated mercury emission in the outlet flue gas was in the range of 0.6–1.28 $\mu\text{g}/\text{m}^3$.

For Day 5, the unit was operated as both an *Advanced Hybrid*TM filter and a PJBH at the same A/C ratio of 1.5 m/min (5 ft/min) with the same carbon injection rate of 24 mg/m³ (1.5 lb/Macf) to compare mercury removals. The tests provided a better comparison between the two operating modes because the residence time and temperature were constant. The measured mercury species concentrations in flue gas for the two operating modes are plotted in Figure 6.3.1.10 (Ontario Hydro results) and Figure 6.3.1.11 (CMM data).

The total inlet mercury concentration was 11.98 $\mu\text{g}/\text{m}^3$ in the *Advanced Hybrid*TM filter mode and 12.13 $\mu\text{g}/\text{m}^3$ in the PJBH, indicating constant inlet conditions. Both Ontario Hydro and CMM data confirmed the same levels of outlet mercury emissions for the *Advanced Hybrid*TM filter and the PJBH operating modes. The total mercury collection efficiency was 93.8% for the *Advanced Hybrid*TM filter and 94.8% for the PJBH. Since each test only lasted for 2 hr, more long-term experiments are necessary to verify these results.

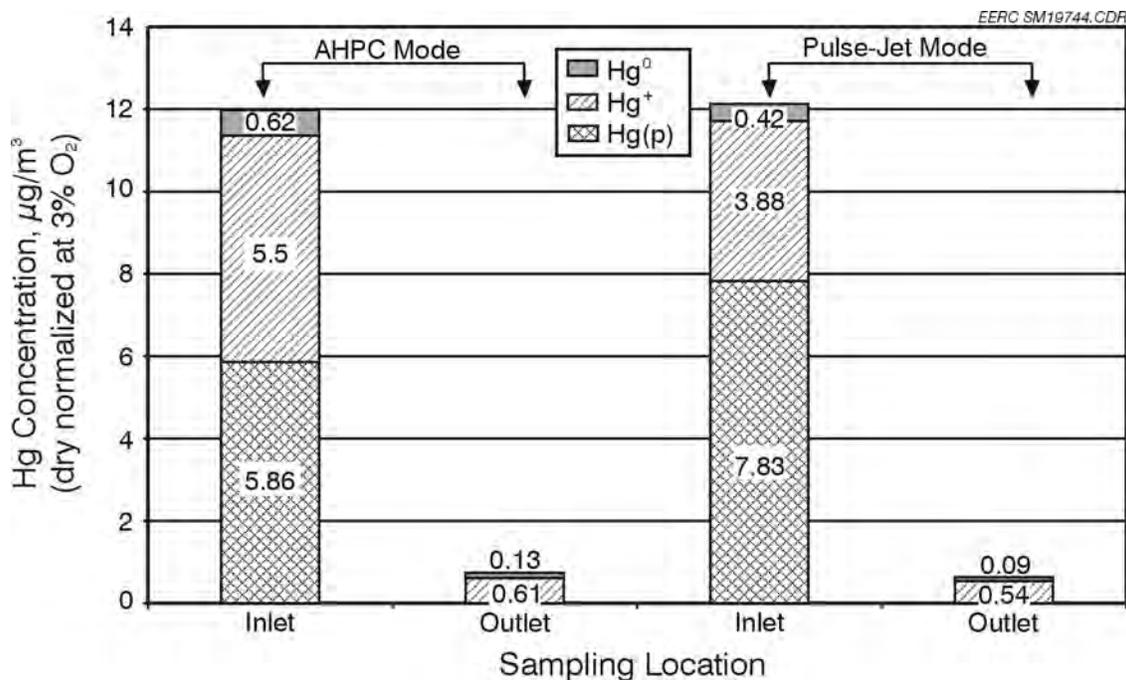


Figure 6.3.1.10. Comparison of mercury species concentration in both the *Advanced Hybrid*TM filter and PJBH inlet and outlet flue gas with 24-mg/m³ (1.5-lb/Macf) FGD injection for Day 5.

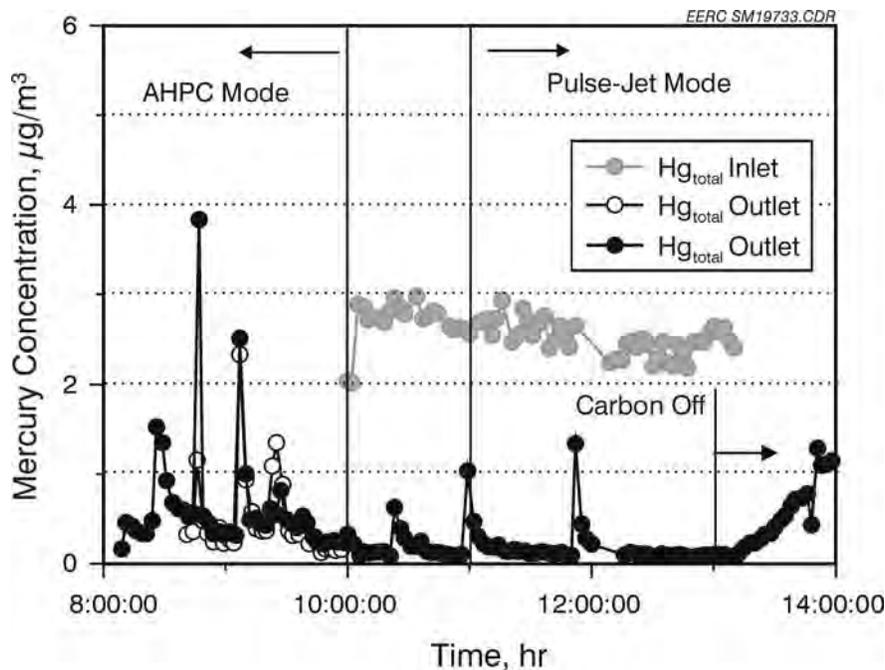


Figure 6.3.1.11. Temporal variations of gaseous mercury across the *Advanced Hybrid*TM filter or PJBH with 24-mg/m³ (1.5-lb/Macf) FGD injection for Day 5.

Table 6.3.1.6 summarizes the Ontario Hydro results collected during the entire 5-day test. The total mercury concentration in the flue gas (present as total mercury concentration at the *Advanced Hybrid*TM filter inlet) ranged from 10.6 to 13.2 µg/Nm³, which is slightly lower than the theoretical value of 15.1 µg/Nm³ obtained from the coal combustion calculation based on the coal analysis. A possible reason is the underestimated inlet dust loading. However, considering the complexity of mercury analysis, the measured mercury results are close to the theoretical value.

During the week, the sorbent was injected only during the day, and after the mercury sampling was completed, the carbon injection was shut off overnight to allow the unit to return to baseline conditions. Four hopper ash samples were collected each day except for the first and the fifth day when two samples and three samples were collected, respectively. The first sample usually was regarded as baseline ash, and the rest represented ash samples from the carbon injection tests. The hopper ash samplers were then acid-digested and measured for mercury concentration. The results are presented in Table 6.3.1.7. For comparison, the filter ash mercury

Table 6.3.1.6. Summary of Ontario Hydro Mercury Results, dry flue gas at 3.0% O₂ (µg/Nm³)

		Hg ⁰	Hg ⁺	Hg (particulate)	Hg (total)
Day 1	Inlet	0.87	5.2	7.12	13.19
		0.87	6.55	5.91	13.33
	Outlet	1.0	4.72	0	5.72
		1.23	6.46	0	7.69
Day 2	Inlet	1.04	3.04	6.49	10.57
		0.75	0	0	0.75
	Outlet	0.87	0.55	0	1.42
		0.74	0.06	0	0.80
Day 3	Inlet	1.13	5.99	4.32	11.44
		0.11	0.27	0	0.38
	Outlet	0.14	0.46	0	0.6
		0.14	0.05	0	0.19
Day 4	Inlet	0.41	2.64	10.2	13.25
		0.21	1.07	0	1.28
	Outlet	0.13	0.75	0	0.88
		0.13	0.96	0	1.09
Day 5	Inlet	0.62	5.5	5.86	11.98
		0.13	0.61	0	0.74
Day 5	Inlet	0.42	3.88	7.83	12.13
		0.09	0.54	0	0.63

Day 1 – No carbon injection, *Advanced Hybrid*TM filter, 3.0 m/min (10 ft/min).

Day 2 – Carbon: 0.65 lb/hr, *Advanced Hybrid*TM filter, 3.0 m/min (10 ft/min).

Day 3 – Carbon: 0.33 lb/hr, pulse jet, 1.5 m/min (5 ft/min).

Day 4 – Carbon: 0.65 lb/hr, *Advanced Hybrid*TM filter, 3.0 m/min (10 ft/min).

Day 5 – Carbon: 0.33 lb/hr, *Advanced Hybrid*TM filter, 1.5 m/min (5 ft/min).

Day 5 – Carbon: 0.33 lb/hr, pulse jet, 1.5 m/min (5 ft/min).

from the inlet Ontario Hydro samples is also reported in Table 6.3.1.7. For the Day 1 baseline test, both the inlet filter ash and hopper ash had almost the same mercury concentration at approximately the same operating time. With carbon injection, the mercury concentration in the hopper ash gradually increased, showing the mercury vapor was absorbed on the activated carbon and removed from the flue gas by the *Advanced Hybrid*TM filter. A fly ash sample collected in the thimble filter used in CMM sampling at the inlet location was also analyzed for mercury concentration and is shown in Table 6.3.1.7. The mercury concentration of 8.22 µg/Nm³ on the CMM filter fly ash was much higher than that of the hopper ash. One possible reason could be that the sampling nozzle was pointing downstream so the fine fly ash collected in the filter by nonisokinetic sampling had a greater enrichment of mercury compared to that of larger-

Table 6.3.1.7. Mercury Concentration and LOI in Fly Ash

Test Day	Sample Type	Time Sample Taken	Hg Concentration, $\mu\text{g/g}$	% LOI
Day 1	Hopper ash baseline	11:01	1.84	
Day 1	Hopper ash baseline	14:00	1.53	0.48
Day 1	Inlet filter	9:20–11:20	1.98	
Day 1	Inlet filter	12:05–14:05	1.58	
Day 2	Hopper ash baseline	7:10	1.34	0.79
Day 2	Carbon injection	10:02	2.58	
Day 2	<i>Advanced Hybrid</i> TM filter			
Day 2	Carbon injection	12:01	2.74	
Day 2	<i>Advanced Hybrid</i> TM filter			
Day 2	Carbon injection	14:00	3.06	1.56
Day 2	<i>Advanced Hybrid</i> TM filter			
Day 2	Inlet filter	8:00–10:00	1.67	
Day 3	Hopper ash baseline	7:18	1.67	1.86
Day 3	Carbon injection pulse jet	11:00	3.58	
Day 3	Carbon injection pulse jet	14:04	3.94	
Day 3	Carbon injection pulse jet	16:01	3.62	2.15
Day 3	Inlet filter	10:23–12:23	1.59	
Day 4	Hopper ash baseline	7:20	1.64	0.71
Day 4	Carbon injection	11:01	2.71	
Day 4	<i>Advanced Hybrid</i> TM filter			
Day 4	Carbon injection	13:04	2.80	
Day 4	<i>Advanced Hybrid</i> TM filter			
Day 4	Carbon injection	16:01	3.36	1.90
Day 4	<i>Advanced Hybrid</i> TM filter			
Day 4	Inlet filter	9:00–11:00	2.89	
Day 5	Hopper ash baseline	7:18	3.09	1.67
Day 5	Carbon injection	10:01	3.46	
Day 5	<i>Advanced Hybrid</i> TM filter			
Day 5	Carbon injection pulse jet	13:01	3.90	2.45
Day 5	Inlet filter	8:00–10:00	2.18	
Day 5	Inlet filter	11:00–13:00	2.89	
Day 4	Inlet filter from CMM	8:00–19:00	8.22	

sized fly ash particles. Another factor could be that this filter was continually used over a whole day, so the extended exposure time may lead to higher mercury adsorption.

The mercury concentrations for the *Advanced Hybrid*TM filter hopper ash samples along with percent LOI shown in Table 6.3.1.7 indicate a general trend of increasing values with carbon injection, as would be expected. However, because of the varying baseline values, it is not possible to complete a good mass balance. For the measured inlet dust loading, the expected increase in carbon in the fly ash (for the given carbon injection rate) is about 1.6%. The LOI data

from Days 4 and 5 are in reasonable agreement with this level of increase. The varying baseline LOI levels and the short-term tests do not allow for a better mass balance closure. The morning baseline ash samples were collected after a time without carbon injection, but no attempt was made to clean the *Advanced Hybrid™* filter hopper of residual ash between tests, so some mixing of the hopper ash from different tests could have occurred.

6.3.1.5 Summary of *Advanced Hybrid™* Filter Performance for the First Field Test

During the 5-day sampling test, the *Advanced Hybrid™* filter unit was set up at a fixed 20-min BCI with an A/C ratio of either 1.5 m/min (5 ft/min) or 3.0 m/min (10 ft/min). The carbon injection rate of 24 mg/m³ (1.5 lb/Macf) is equivalent to a dust inlet loading of 0.023 g/actual m³ or 0.034 g/standard m³ (0.01 gr/acf or 0.015 gr/scf). Compared to the average inlet fly ash dust loading of 2.2 g/standard m³ (0.96 gr/scf), this represents 1.6% of the dust loading and would not be expected to affect the *Advanced Hybrid™* filter pressure drop. From the pressure drop and drag data with and without carbon injection, there was no effect of the carbon injection on *Advanced Hybrid™* filter operation.

The dust loadings in the inlet and outlet flue gases (obtained from the Ontario Hydro method) are listed in Table 6.3.1.8, and the corresponding particle collection efficiencies are also calculated and presented in Table 6.3.1.8. The particle collection efficiency ranged from 99.972% to 100%, which represents the level of accuracy that can be achieved by this method with a 2-hr sample. Earlier tests on the Big Stone *Advanced Hybrid™* filter where the outlet was sampled for over 15 hr indicated dust loadings in the range of 0.00009 to 0.0002 g/m³ (0.00004 to 0.00009 gr/dscf). Independent measurements with real-time particle analyzers have also proven the collection efficiency to be better than 99.99%.

6.3.1.6 – Conclusions from the First Field Test

The average inlet total mercury concentration was 12.3 µg/Nm³ with 55.4% particulate-bound, 38.1% oxidized, and 6.4% elemental mercury. The high level of particulate-bound mercury and oxidized mercury was somewhat surprising because for western PRB coals lower levels of particulate-bound mercury and oxidized mercury are more typical. Possible factors that determine the level of particulate-bound and oxidized mercury include coal type, boiler type, HCl (as well as other flue gases), temperature, and amount of carbon in the fly ash. For this test, the supplemental TDF was suspected to be reason for the high levels of particulate-bound and oxidized mercury.

Table 6.3.1.8. Dust Loadings at the *Advanced Hybrid*TM Filter Inlet and Outlet and the Calculated Collection Efficiency

	Inlet, gr/dscf	Outlet, gr/dscf	Collection Efficiency, %
Day 1-1	1.169	0.000250	99.978
Day 1-2	1.235	0.000191	99.984
Day 2-1	1.324	0.000363	99.972
Day 4-1	1.189	1.760E-06	99.999
Day 5-1	0.909	0	100.000

With 1.5 lb/Macf carbon injection rate, total mercury removal with the *Advanced Hybrid*TM filter was 91%–97% compared to 49% removal for the baseline case. Even though the carbon addition rate was low, the carbon was highly effective at removing mercury. The data show that the carbon was effective at removing both elemental and oxidized mercury.

Mercury removal with carbon injection in the *Advanced Hybrid*TM filter mode was 91% and 92% on Days 2 and 4 compared to 97% on Day 4 PJBH test. The difference in mercury removals was possibly caused by the longer residence time and lower flue gas temperature in PJBH. On Day 5, the unit was operated in both modes at the same flow rate, which resulted in 94% capture in the *Advanced Hybrid*TM filter mode and 95% capture in PJBH. It can be concluded that there was no significant difference in mercury capture between the *Advanced Hybrid*TM filter and the PJBH during this testing period.

These short-term tests are highly encouraging because they prove that excellent mercury removal can be achieved with very low addition rates of carbon injected upstream of the *Advanced Hybrid*TM filter. Further testing is needed to demonstrate that the high level of mercury removal can be maintained over the longer term and that the carbon injection will not have any adverse effect on the longer-term operation of the *Advanced Hybrid*TM filter. Since the conditions that lead to good mercury capture with carbon are not well known, at this point the results should not be generalized to other coals or plants.

6.3.2 Long-Term Field Test June 28–September 6, 2002

6.3.2.1 Test Conditions

A 2-month field test was completed with the 2.5-MW (9000-acfm) field *Advanced Hybrid*TM filter from June 28 through September 6, 2002. From June 28 to August 6, the *Advanced Hybrid*TM filter was operated without carbon injection to establish baseline conditions. Carbon injection and CMM measurements were continuous (24 hr a day) from August 6 to September 6, except during an unplanned plant outage from August 29 to September 2. The

primary goal of the work was to demonstrate longer-term mercury control with the *Advanced Hybrid*TM filter and evaluate the effect of carbon injection on the *Advanced Hybrid*TM filter operational performance.

During the November 2001 test, the Big Stone Power Plant was burning approximately 3%–5% waste tires, which was suspected to be the reason for the unexpectedly high levels of particle-bound and oxidized mercury in the flue gas. Therefore, another goal of this test was to evaluate the effect of supplemental TDF cofiring on the level of mercury capture for comparison with results from the previous test completed in November 2001. During the start of the August test, the TDF feed was deliberately stopped to evaluate mercury control without tire feed. The plan was then to start the tire feed again during the monthlong test. However, because of an unsteady supply of the waste tires, the tire feed rate was lower and more intermittent than the amount burned previously.

During the week of testing from August 5 to 9 and on August 26 and 27, Ontario Hydro samples were collected at both the *Advanced Hybrid*TM filter inlet and outlet. Several Method 26A samples were also taken during those days to determine HCl concentrations in flue gas. The inlet and outlet mercury concentrations were also monitored by a CMM. For the majority of the time, the mercury monitor sampled at the outlet, but several times a day it was switched to the inlet for a short time to document the inlet concentration. On the days when Ontario Hydro samples were not taken, the CMM was operated continuously for 24 hr a day. The CMM was normally set up to measure the outlet total vapor-phase mercury, but during the day for several hours, it was manually switched to measure both the total and elemental vapor-phase mercury at the inlet as well as the elemental mercury at the outlet.

6.3.2.2 *Big Stone Fuel Record*

The fuel burn record from the plant data for the field test last November and the August 5–September 6, 2002, test is shown in Table 6.3.2.1. In November 2001, the coal was from either the Cordero or Caballo Mines in the PRB. For the August 5–September 6 test, the coal was from the Belle Ayr and Eagle Butte Mines. Both coals are similar low-sulfur subbituminous fuels from the PRB. The amounts of TDF and waste seed fuel burned during this time are also listed in Table 6.3.2.1. Waste tires are known to be a source of chlorine and thought to be the reason for the higher HCl seen in the flue gas last November. Waste corn seed may also be a source of

Table 6.3.2.1. Big Stone Fuel Record

Date	Coal Mine	Coal, tons	TDF, tons	Waste Seeds, tons
November 5, 2001	Cordero	4695	140	100
November 6, 2001	Cordero	6117	200	100
November 7, 2001	Caballo	6104	150	120
November 8, 2001	Caballo	6296	90	100
November 9, 2001	Caballo	6024	250	80
August 5, 2002	Belle Ayr	5947	0	18
August 6, 2002	Belle Ayr	5945	0	0
August 7, 2002	Belle Ayr	6096	0	46
August 8, 2002	Belle Ayr	6312	0	0
August 9, 2002	Belle Ayr	6135	16	157
August 10, 2002	Belle Ayr	6473	0	0
August 11, 2002	Belle Ayr	6242	0	0
August 12, 2002	Belle Ayr	6418	23	92
August 13, 2002	Belle Ayr	5531	23	88
August 14, 2002	Belle Ayr	5525	22	64
August 15, 2002	Eagle Butte	5793	25	50
August 16, 2002	Eagle Butte	5867	0	69
August 17, 2002	Eagle Butte	5344	0	0
August 18, 2002	Eagle Butte	5278	0	0
August 19, 2002	Eagle Butte	5121	20	24
August 20, 2002	Eagle Butte	5895	51	33
August 21, 2002	Eagle Butte	5951	177	0
August 22, 2002	Eagle Butte	5771	150	0
August 23, 2002	Eagle Butte	5827	0	169
August 24, 2002	Belle Ayr	6100	0	0
August 25, 2002	Belle Ayr	5878	0	0
August 26, 2002	Belle Ayr	6040	0	92
August 27, 2002	Belle Ayr	5862	24	116
August 28, 2002	Belle Ayr	2488	0	0
September 3, 2002	Eagle Butte	5996	23	0
September 4, 2002	Belle Ayr	6298	0	0
September 5, 2002	Belle Ayr	6336	0	0
September 6, 2002	Eagle Butte	6186	45	24

some additional chlorine, but the amount of inorganic material in the corn is expected to be less than in TDF.

6.3.2.3 Mercury Results for August 6–September 6, 2002, Field Test

Mercury Species in the Inlet Flue Gas

Figures 6.3.2.1 and 6.3.2.2 summarize mercury species in the Big Stone Power Plant flue gas based on Ontario Hydro samples collected in August 5–9 and August 26–27, respectively.

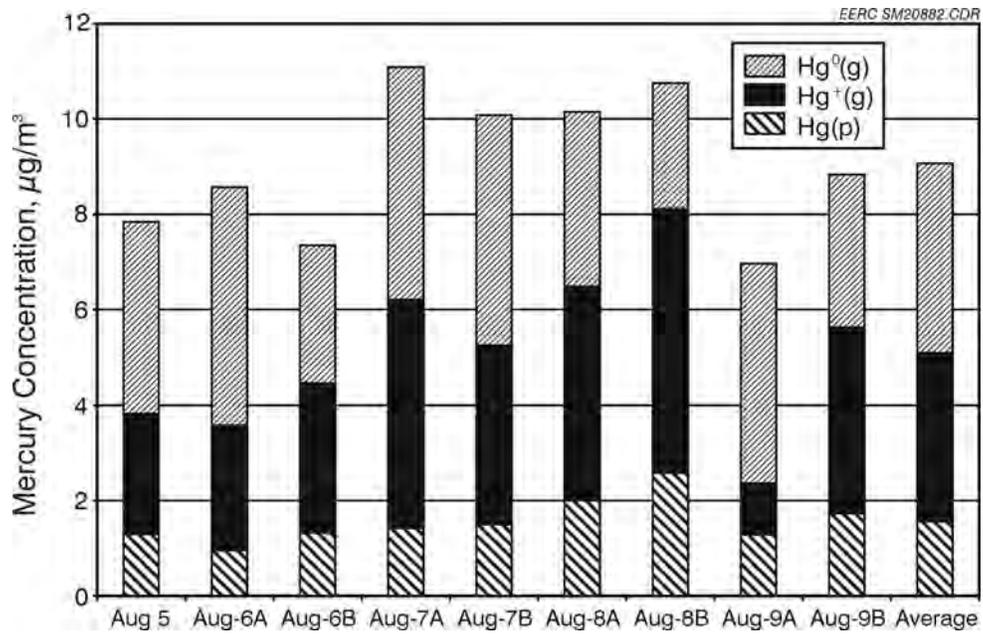


Figure 6.3.2.1. Mercury species in the Big Stone Power Plant flue gas based on Ontario Hydro samples collected August 5–9, 2002.

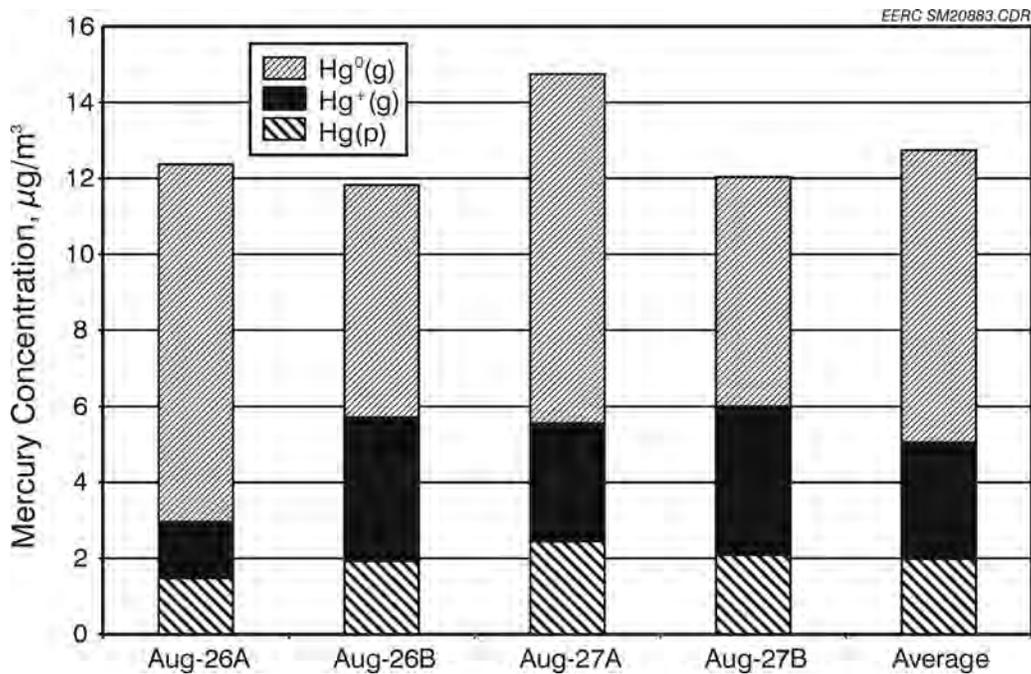


Figure 6.3.2.2. Mercury species in the Big Stone Power Plant flue gas based on Ontario Hydro samples collected in August 26–27, 2002.

During most of the sampling time period, the Big Stone Power Plant burned Belle Ayr coal, except on August 9 and 27 when the plant cofired small amounts of TDF and waste seeds. While there is some variability in the coal as well as analytical uncertainty, the data indicate fairly consistent mercury speciation. The averaged mercury concentration in the coal combustion flue gas was $9.1 \mu\text{g}/\text{m}^3$ during August 5–9 and $12.7 \mu\text{g}/\text{m}^3$ for August 26–27, respectively, showing approximately 16.4% $\text{Hg}(\text{p})$, 31.6% Hg^{++} , and 52% Hg^0 .

Compared in Figure 6.3.2.3 are the Ontario Hydro results with CMM data collected during the same sampling time. No particulate mercury for the CMM is shown because the gas is sampled through a filter with a probe pointed downstream to minimize any gas–particulate contact. In contrast, the Ontario Hydro samples are collected isokinetically, and the particulate fraction is captured on a filter. The particulate mercury may have existed in the duct or could have been absorbed on the particulate during sampling. Some of the particulate mercury in the Ontario Hydro method may be measured as vapor-phase mercury with the CMM. In spite of this difference, the CMM data, in most cases, are in good agreement with the Ontario Hydro data.

Figure 6.3.2.4 plots the daily average of gaseous mercury (CMM data) in the flue gas over the 1-month testing period. The total gaseous mercury varied from 8 to $14 \mu\text{g}/\text{m}^3$, and the

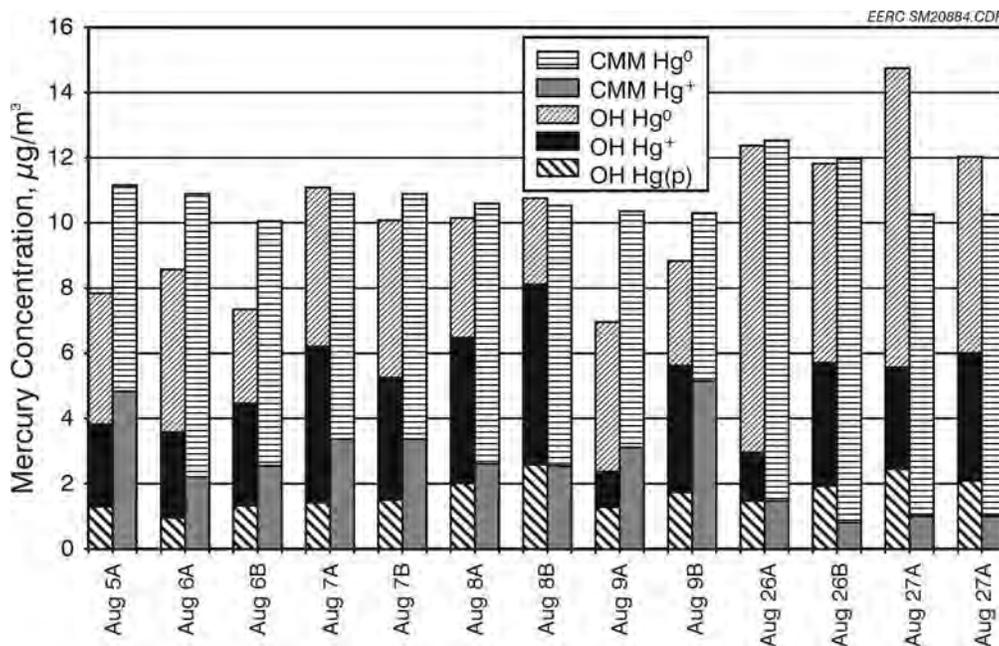


Figure 6.3.2.3. Comparison of Ontario Hydro results with CMM data.

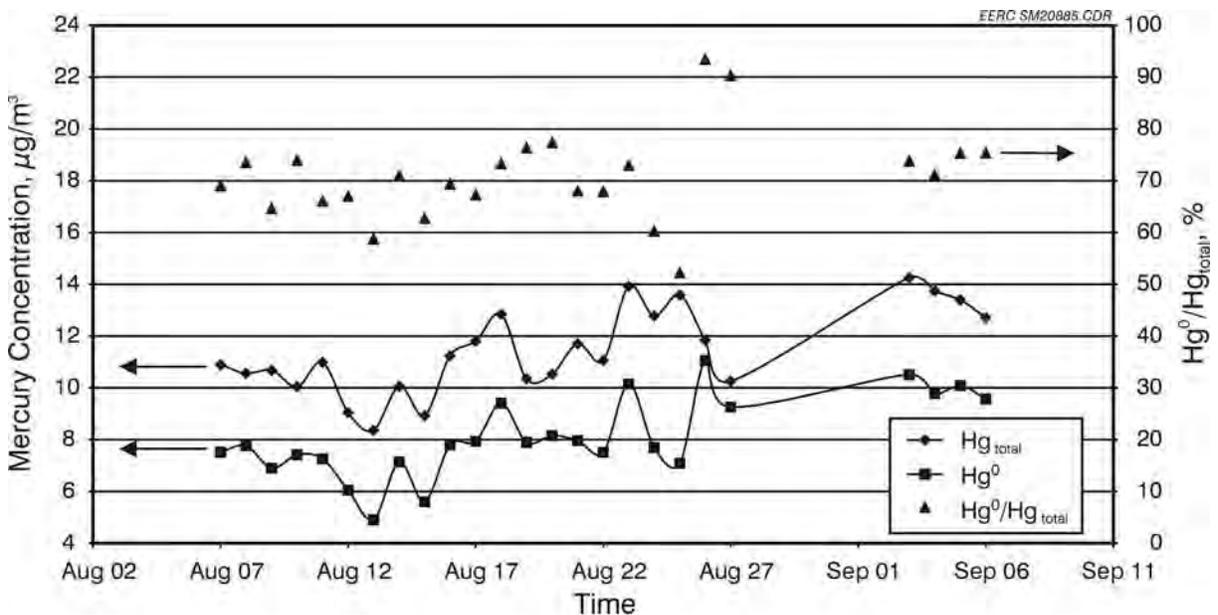


Figure 6.3.2.4. Daily average of gaseous mercury (CMM data) in the flue gas over the 1-month testing period.

elemental mercury tracked with the total gaseous mercury consistently between 60% and 80%. Comparing the mercury concentration when the two coals were burned (see Figure 6.3.2.4 and Table 6.3.2.1) does not indicate any clear effect of coal type beyond the day-to-day variability in the data.

The inlet mercury speciation may depend on a number of factors such as the amount of carbon in the fly ash, chlorine level in the coal, firing mode, contact with fly ash, and residence time. However, the current level of understanding of how these variables affect mercury speciation does not allow accurate prediction. In general, high-chlorine EB fuels tend to produce flue gas with more oxidized mercury and low-chlorine WSB coals tend to produce more elemental mercury. Data also show that contact between the fly ash and flue gas promotes mercury oxidation for some coals.

Compared in Figure 6.3.2.5 are the inlet Ontario Hydro mercury speciation data for the November 2001 field test, January 2002 EERC pilot-scale data burning the same fuel, EERC pilot-scale data burning the Belle Ayr coal from April to May, 2002, and August 5–9 and August 26–27, 2002, field test data with the Belle Ayr fuel. The error bars represent plus and minus one standard deviation.

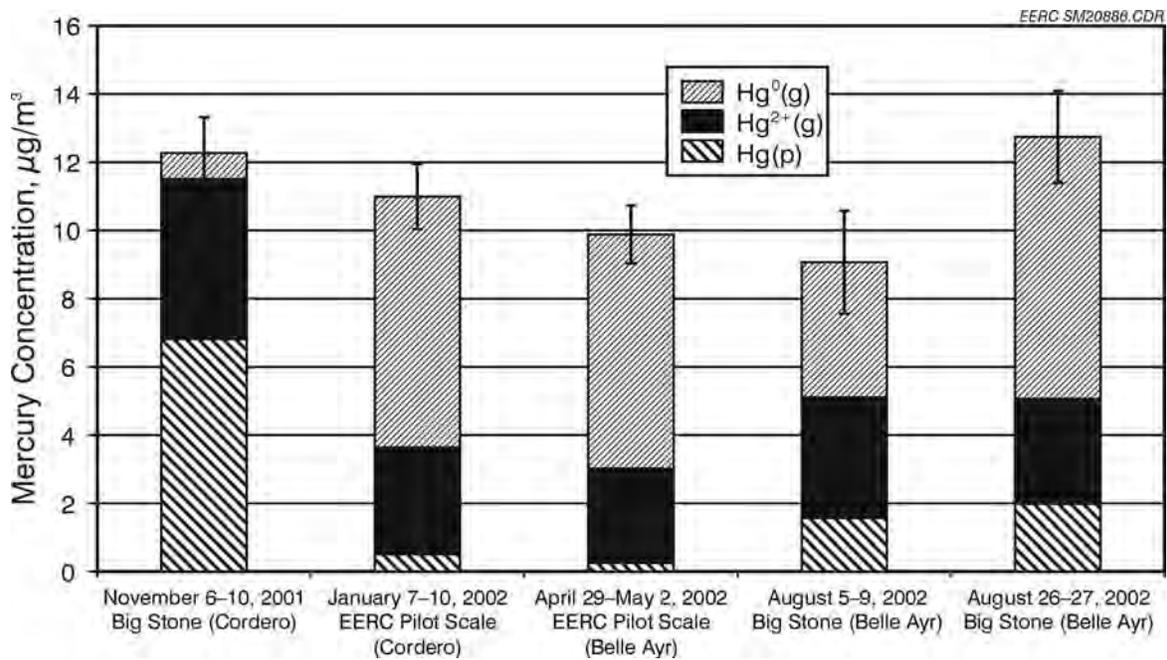


Figure 6.3.2.5. Comparisons of mercury species distribution in the *Advanced Hybrid*TM filter Big Stone field tests and EERC pilot-scale tests.

For the November 2001 field test and the January 2002 pilot-scale baseline test, the mercury speciation in flue gas revealed two significant differences although they both burned the same Cordero complex coal. For the field results, an average of 56% of the mercury was retained by the fly ash compared to only 5% for the pilot-scale tests. A second significant difference is the vapor-phase speciation. There was 38% of the total mercury as oxidized mercury and only 6% as elemental mercury, compared to 29% oxidized and 67% elemental for the pilot-scale tests.

A number of differences in conditions between the two tests could be responsible for the significant speciation difference. The HCl for the pilot-scale tests measured by Method 26A was 1–2 ppm in the flue gas compared to about 10 ppm for the November 2001 field test (Table 6.3.2.2). The additional HCl in the field tests is likely the result of the small percentage of waste tires that were cofired with coal at the Big Stone Power Plant during the November test. However, 10 ppm HCl is still a fairly low concentration compared to the 50–100 ppm level that is typically seen for bituminous coals.

Table 6.3.2.2. Chlorine Concentration in Flue Gas at Big Stone Power Plant

Date	HCl, ppm
November 7, 2001	9.1
November 8, 2001	10.1
November 9, 2001	10.0
August 5, 2002	1.0
August 7, 2002	0.9
August 8, 2002	1.2
August 26, 2002	0.5
August 27, 2002	1.4
August 28, 2002	1.2

Another possible reason for the difference is the amount of unburned carbon in the ash, which for the Big Stone baseline tests ranged from 0.5% to 1.9% (without carbon injection) compared to only 0.16% for the pilot-scale tests. Under some conditions, carbon in the ash can be responsible for mercury retention and for promoting oxidation.

Cyclone firing is known to produce a finer fly ash particle size than pulverized-coal firing, which could also lead to more mercury retention as well as oxidation. Other work has shown that mercury concentration is typically higher in the smaller fly ash fraction, and the higher surface area of the finer particles may also promote more oxidation.

Comparison of the EERC pilot-scale data between the Cordero and Belle Ayr coals (shown in Figure 6.3.2.5) suggests that there was no significant difference in mercury species as a result of coal type. The mercury speciation data for the EERC pilot-scale tests with the Belle Ayr coal are also similar to the Big Stone field data with the same coal when TDF was not being cofired. However, the Big Stone data do show somewhat more particulate-bound mercury than the pilot-scale data. A possible reason for this difference is the slightly higher carbon content in the Big Stone ash.

The higher August 26–27 total mercury than the August 5–9 data is consistent with the CMM data and is likely due to somewhat higher mercury in the coal. The significant difference in mercury speciation between the August field data and the November field data, however, is likely the effect of cofiring the coal and TDF, since the pilot-scale data indicated no difference between the two coals when they were burned without TDF.

Baseline Test

Three pairs of Ontario Hydro samples were collected at the inlet and outlet of the field *Advanced Hybrid*TM filter unit during August 5–6, 2002, to establish mercury species under

baseline conditions without carbon injection and TDF cofiring. The Ontario Hydro results (Figure 6.3.2.6) show the same levels of total mercury in the inlet and outlet flue gases, indicating no mercury capture. It does appear, however, that there is an increase in the fraction of oxidized mercury across the *Advanced Hybrid™* filter. Another baseline test was conducted August 19–20 while the plant was burning the Eagle Butte coal with a small amount of TDF. The CMM data for those tests indicated from 5% to 10% mercury capture without any carbon injection. Both of these baseline results are significantly different than the November tests with a much higher TDF cofiring rate, where 49% mercury capture was seen for the baseline conditions. Again, the most likely explanation is the much higher TDF cofiring rate and higher HCl in the flue gas for the November test.

NORIT FGD Carbon Continuous Injection Without Cofiring TDF

During the testing period, a K-Tron dual-screw feeder continuously fed NORIT FGD carbon at a starting rate of 24 mg/m³ (1.5-lb/Macf), which corresponds to 0.29 kg/hr (0.65 lb/hr) at an A/C ratio of 3.0 m/min (10 ft/min). This is equivalent to a carbon-to-mercury ratio of 3000:1 for an inlet mercury concentration of 14 µg/m³. The carbon feeder was located in the

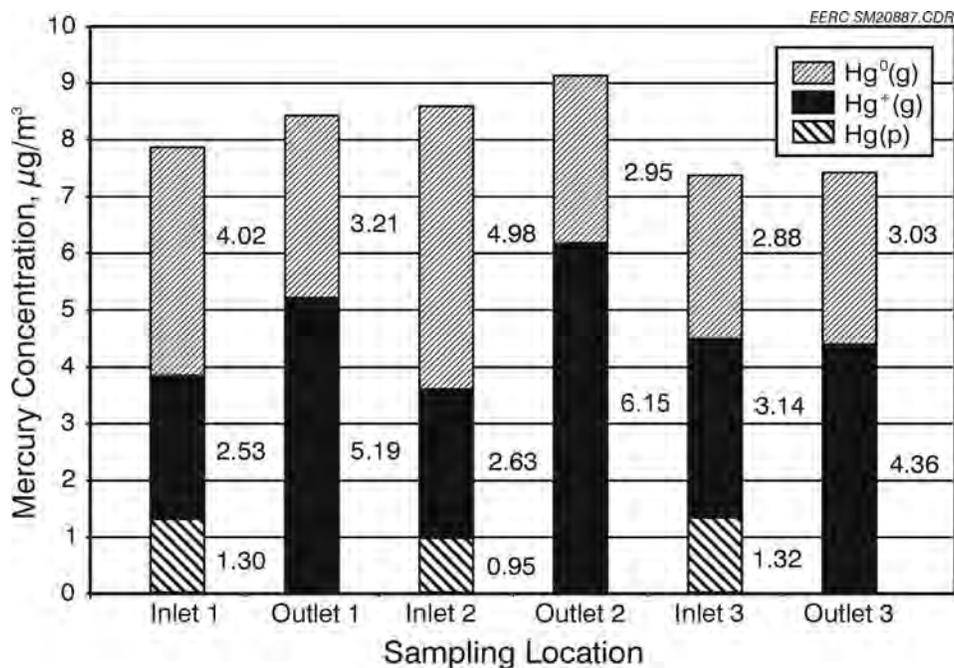


Figure 6.3.2.6. Inlet and outlet Ontario Hydro mercury speciation for the *Advanced Hybrid™* filter baseline test at Big Stone, August 5–6, 2002.

enclosed area of the *Advanced Hybrid*TM filter below the hopper. From the screw feeder, the carbon was introduced into an Air-Vac eductor that was driven by compressed air. From the outlet of the eductor, the carbon was then transported approximately 6.1 m (20 ft) through 0.019-m (0.75-in.) stainless steel tubing to the elbow location of the inlet piping. Approximately 0.9 m (3 ft) of straight tubing extended inside the duct so that the carbon was injected directly upstream at a single point in the center of the 0.610-m (24-in.)-diameter inlet pipe.

The feeder was calibrated prior to the start of carbon injection. In addition, the weight of carbon added during a day was divided by the time of injection to provide an average feed rate. According to the calibration data and weight-of-added-carbon data, the feeder appeared to provide a very steady and consistent feed rate within a few percent of the target rate. The carbon feed and injection system worked very well, and there were no problems with inconsistent feeding or plugging of the feeder or injection system. Other *Advanced Hybrid*TM filter operating conditions are given in Table 6.3.2.3.

With no TDF cofiring on August 7, two sorbent injection tests with feed rates of 0.29 kg/hr (0.65 lb/hr) and 0.58 kg/hr (1.28 lb/hr) were completed. Figure 6.3.2.7 plots both the Ontario Hydro results and CMM data during the tests, and the two methods provided very consistent mercury species in the inlet and outlet flue gases. Most of the mercury in the inlet flue gas was gaseous mercury with a fair fraction of elemental mercury. At the lower feed rate of 0.29 kg/hr (0.65 lb/hr), mercury removal was 54% with 5 $\mu\text{g}/\text{m}^3$ mercury emission, and at doubled the feed rate, it increased marginally to 61%. The outlet mercury emission was slightly down to 4.8 $\mu\text{g}/\text{m}^3$. Since doubling the carbon feed rate did not significantly improve mercury capture, the decision was made to do further testing at the lower carbon feed rate. Two additional Ontario Hydro tests were completed at 0.29 kg/hr (0.65 lb/hr) on August 8 (Figure 6.3.2.8). Again, the Ontario Hydro and CMM results were in good agreement and indicated 63%–68% removal, slightly better than the August 7 test. On August 9 and 26, tests were repeated at the same carbon injection rate of 24 mg/m^3 (1.5lb/Macf), and four pairs of Ontario Hydro samples were taken to determine the overall mercury removal in the *Advanced Hybrid*TM filter. Figure 6.3.2.9 summarizes the mercury collection efficiencies with the *Advanced Hybrid*TM filter at the

Table 6.3.2.3. Standard Operating Conditions During August 5–September 6, 2002

A/C Ratio	10 ft/min (3 m/min)
Pulse Pressure	70 psi (482 kPa)
Pulse Duration	200 ms
Pulse Sequence	87654321 (multibank)
Pulse Trigger	8.0 in. W.C. (2.0 kPa)
Pulse Interval	260–400 min
Temperature	127°–160°C (260°–320°F)
Rapping Interval	15–20 min
Voltage	58–62 kV
Current	55 mA

24 mg/m³ (1.5 lb/Macf) carbon injection during the August 2002 field test. From these results, it appears that a fairly low carbon addition rate of 24 mg/m³ (1.5 lb/Macf) can provide from 60% to 70% mercury control with the *Advanced Hybrid*TM filter in subbituminous coal flue gas. This is lower than the 91% removal seen last November but similar to the 50%–60% removal seen with EERC pilot-scale tests completed earlier 2002. This suggests that the higher removal seen November 2001 was because of the much higher TDF feed rate and higher HCl in the flue gas.

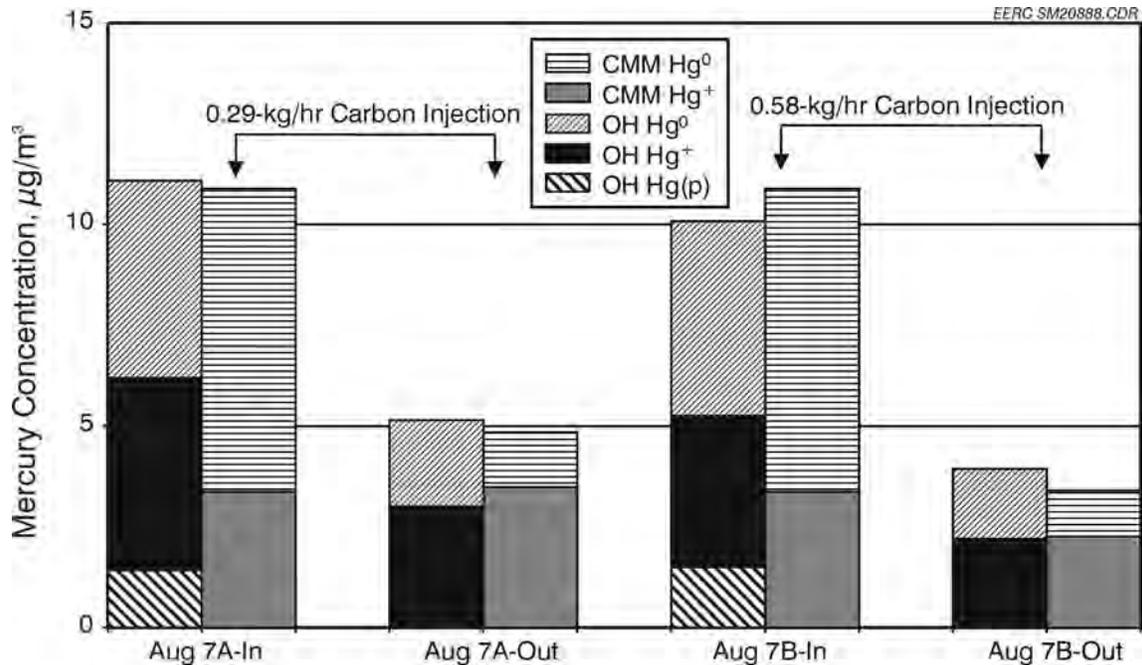


Figure 6.3.2.7. Mercury species concentration in flue gas at the *Advanced Hybrid*TM filter inlet and outlet under two FGD injection rates.

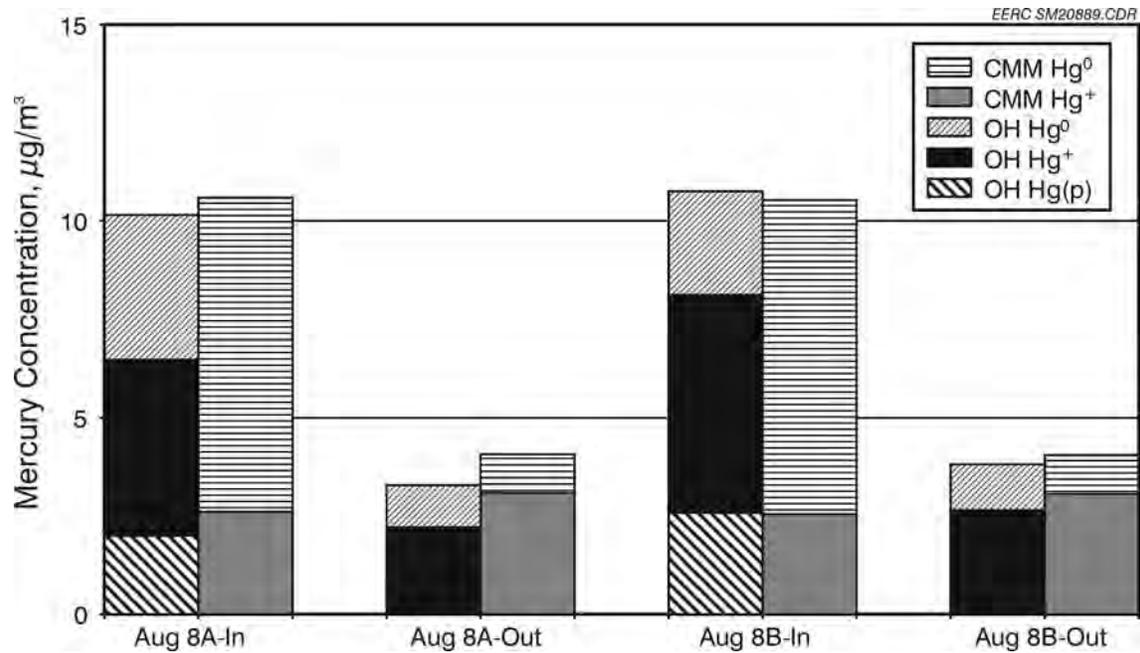


Figure 6.3.2.8. *Advanced Hybrid*TM filter inlet and outlet mercury species at 24-mg/m³ (1.5-lb/Macf) FGD injection.

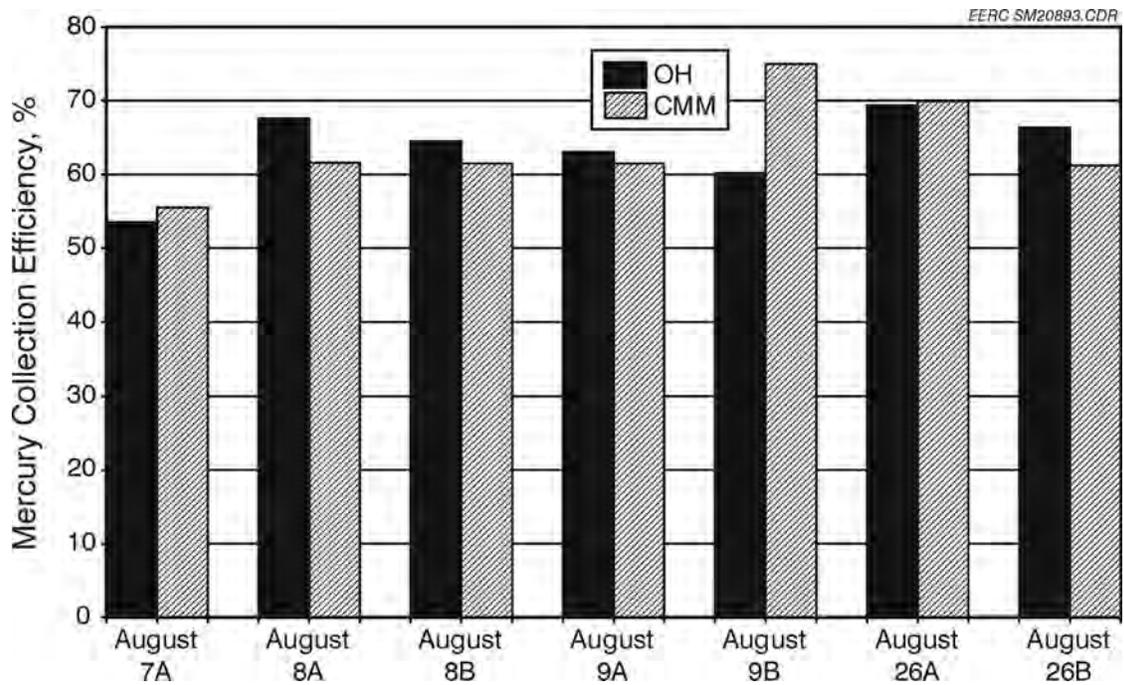


Figure 6.3.2.9. Mercury collection efficiencies with the *Advanced Hybrid*TM filter at 24-mg/m³ (1.5-lb/Macf) carbon injection.

Also included in Figure 6.3.2.9 are the mercury removals based on the CMM data. With the exception of the August 9 data, the Ontario Hydro and CMM data are in excellent agreement. This provides confidence that the CMM data for the rest of the month are reliable even though Ontario Hydro samples were not taken.

Batch NORIT FGD Carbon Injection Tests

On August 27, a batch injection test was completed with high-voltage power on and another where the high voltage was briefly shut off during injection. For both tests, 0.91 kg (2.0 lb) of carbon was injected in about 1 min. The Ontario Hydro sampling was then started a half hour after injection for a period of 2 hr. The outlet Ontario Hydro results represented averaged mercury emission during the 2.5-hr period after the carbon was batched into the system. Plotted in Figure 6.3.2.10 are the inlet and outlet mercury speciation results of the batch injection tests along with the continuous injection tests completed the previous day at 0.29 kg/hr (0.65 lb/hr). The calculated mercury removal efficiencies are shown in Figure 6.3.2.11. The data indicate that the batch power-on removal was comparable to the continuous injection results, but the power-off batch injection improved the collection efficiency to 82.5%. This suggests that it might be possible to optimize the overall collection efficiency by modifying the injection approach.

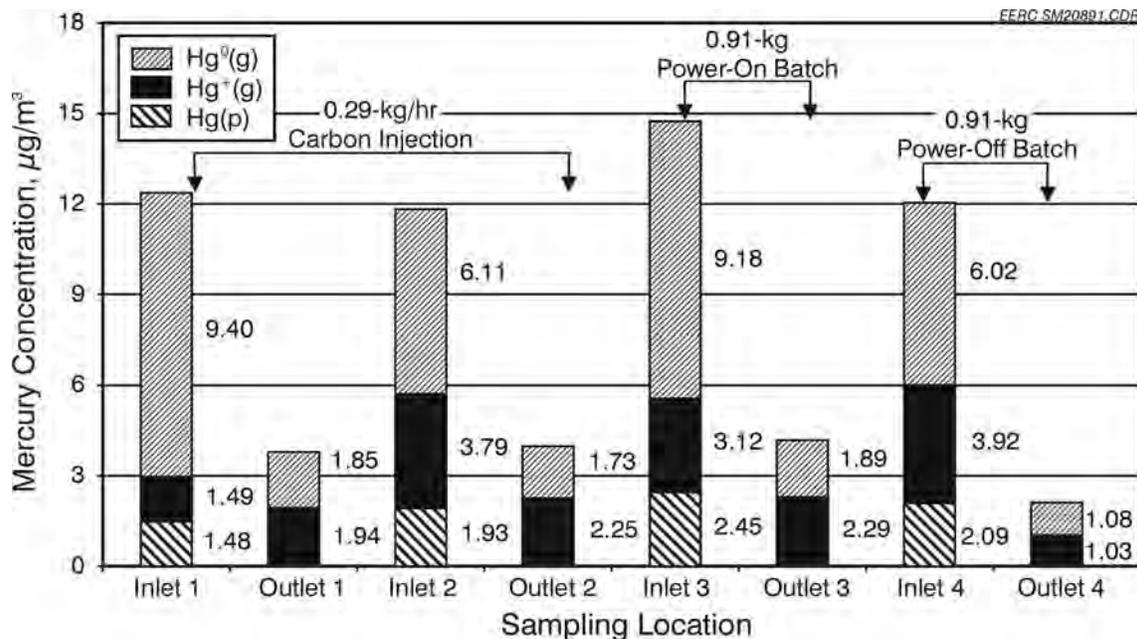


Figure 6.3.2.10. Inlet and outlet mercury speciation results of the batch injection tests.

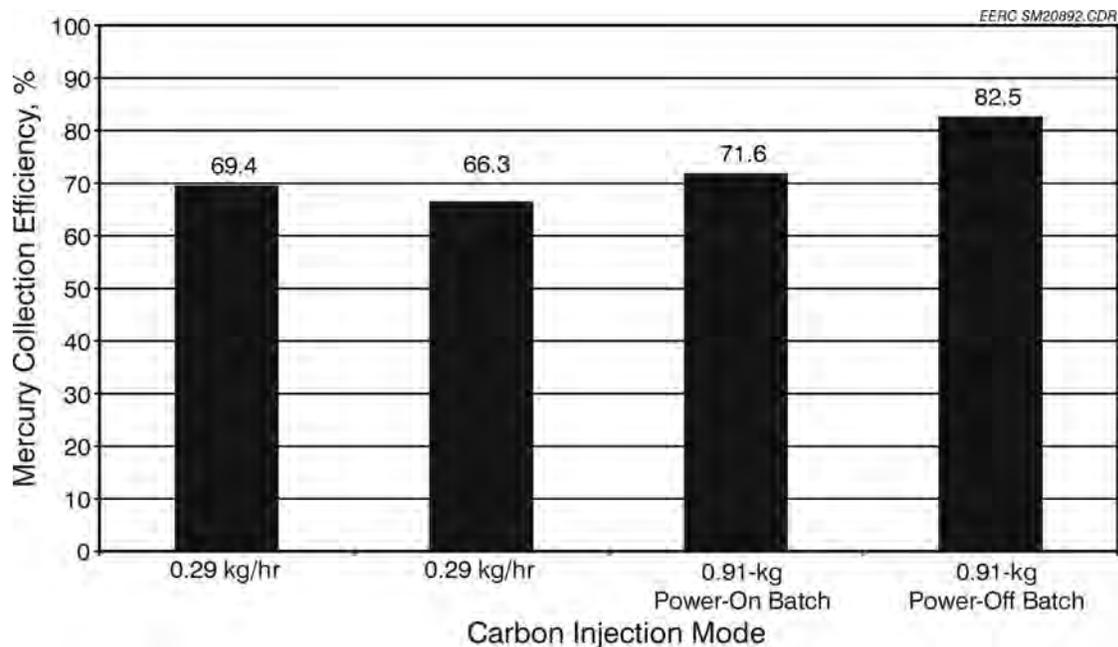


Figure 6.3.2.11. Mercury removal efficiencies for continuous and batch FGD injection tests.

However, on a larger scale, power-off batch injection would likely not be as practical as continuous injection. Another batch injection test was completed where the batch amount was increased to 1.82 kg (4.0 lb) with only the CMM measurement. In this case, the outlet mercury was near zero for over 2 hr before it slowly started to increase, and even after 3 hr, the integrated average removal was over 90%. This implies that all of the flue gas was effectively treated and that with a reactive sorbent, it should be possible to achieve over 90% mercury removal.

Effect of TDF Cofiring on Mercury Removal

TDF cofiring was started August 12, but at a much lower rate than the 90–250 ton/day rate during the November 2001 test (see Table 6.3.2.1). Subsequently, the effect on mercury removal was small. From the daily averages of the CMM data plotted in Figure 6.3.2.12, it did appear that mercury removal improved from about 63% on August 9–11 to about 68% on August 12–13 as a result of the TDF cofiring. On August 14 and part of the day on August 15, the carbon feed rate was doubled to 0.58 kg/hr (1.28 lb/hr). At the higher rate on August 14, the removal increased to 77%, and on August 15, it reached 89%. However, the 89% removal corresponded to a time of lower plant load where the temperature was about 11°C (20°F) lower than normal. Later on August 15, the carbon feed rate was reduced back to 0.29 kg/hr (0.65 lb/hr), and with a

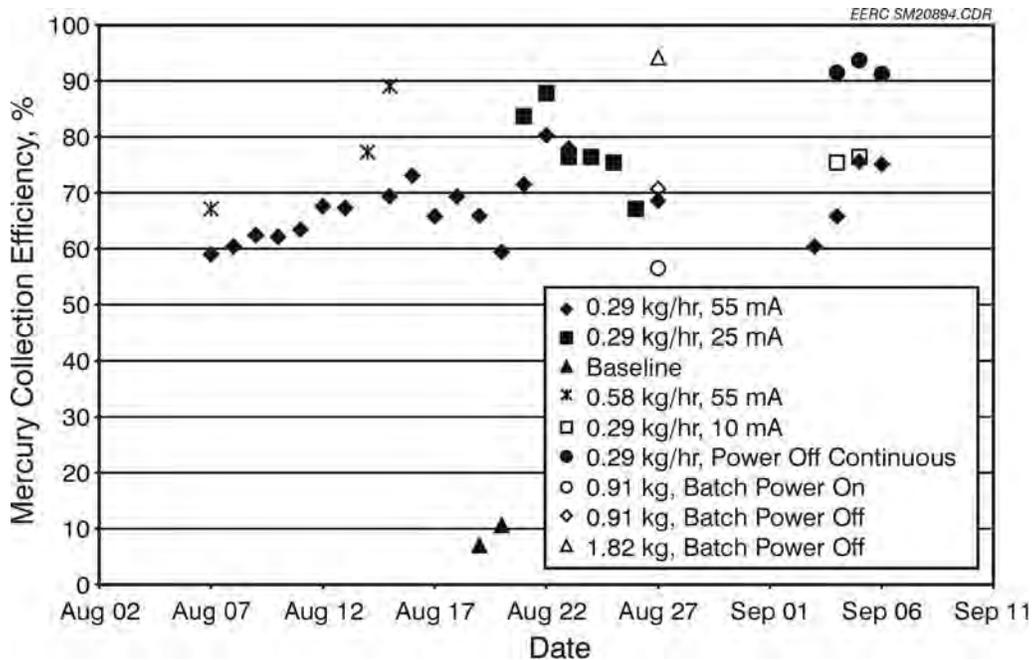


Figure 6.3.2.12. Gaseous mercury capture efficiency at Big Stone field unit during August–September 2002 (CMM data).

temperature increase, the removal dropped to 69%. This is consistent with the data from August 12–13 and suggests that the small rate of TDF cofiring resulted in some improvement in mercury collection.

The power plant switched to Eagle Butte fuel during August 16–22, 2002, and stopped the TDF cofiring from August 16 to 18, 2002. The coal switch may have also affected the mercury species in flue gas and the capture efficiency with carbon injection. Without TDF cofiring and carbon injection, there was only 5%–10% mercury capture across the *Advanced Hybrid*TM filter in the Eagle Butte flue gas. By injecting 0.29 kg/hr (0.65 lb/hr) NORIT FGD without TDF cofiring, the overall removal was 66%–73%.

On August 20–22, there was a high TDF cofiring rate (Table 6.3.2.1), and the high-voltage power supply current was decreased to 25 mA from the standard condition of 55 mA. The data from Figure 6.3.2.12 indicated the mercury removal improved to 84%–88% during this time which corresponded to the 2 days when the TDF was high. The next day on August 23 when the TDF was stopped, the mercury removal dropped to 76%. This indicated that the 84%–88% removal seen the previous 2 days was partly due to the higher TDF cofiring rate.

Effect of Corona Current on Mercury Removal

Reducing the current of the *Advanced Hybrid*TM filter unit will increase the amount of carbon that reaches the bags and subsequently produce better gas-sorbent contact. A closer examination of the immediate effect of a change in current is shown in Figure 6.3.2.13 during August 21–23 based on CMM measurements. During this time, whenever the current was changed, there was an immediate effect. On August 21 at 12:00, the reduce in current from 55 to 25 mA resulted in an immediate decrease in outlet mercury emission from 2.3 to 1.7 $\mu\text{g}/\text{m}^3$; on August 22 at noon, a current increase from 25 to 55 mA resulted in an increase in mercury emission from 1.2 to 1.7 $\mu\text{g}/\text{m}^3$; and on August 23 at noon, a current change back to 25 mA brought a decrease of mercury in outlet flue gas from 2.9 to 2.0 $\mu\text{g}/\text{m}^3$. These data indicate better mercury removals under the reduced current condition. Operational data indicate that there would be some compromise in *Advanced Hybrid*TM filter performance, because the bag pulse cleaning interval was 150 min at the 25 mA compared to about 300 min at 55 mA. However, in both cases, the *Advanced Hybrid*TM filter pressure drop was readily controlled at about 1.5 kPa (6 in. W.C.).

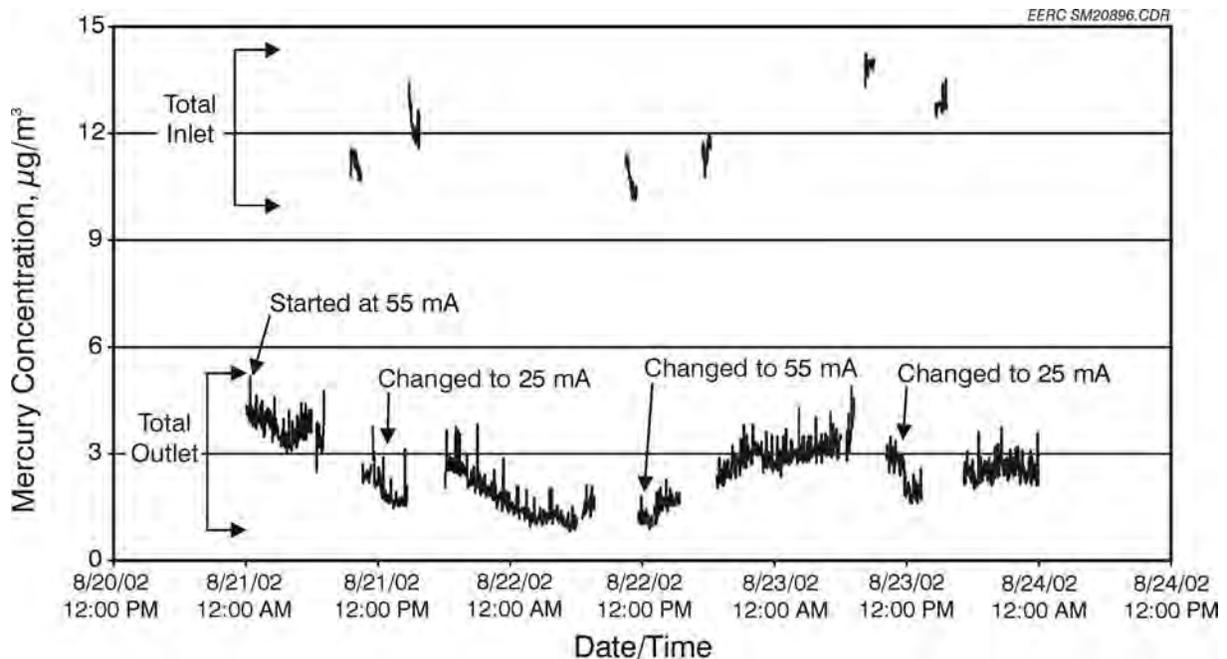


Figure 6.3.2.13. Effect of change in current on mercury emission from the *Advanced Hybrid*TM filter field unit.

6.3.2.4 Comparison of Mercury Removals of the Advanced Hybrid™ Filter and the PJBH

On September 5–6, several additional tests were completed where the current was reduced to 10 mA, and in the extreme case, the high-voltage power was shut off completely, switching into a PJBH. The data show that the best removal was seen in short-term tests where the power was off (Figure 6.3.2.12). However, the BCI dramatically reduced to 10 min for the PJBH compared to 300 min at 55 mA with the *Advanced Hybrid™* filter, and the average pressure drop across the filter bags increased. From past experience, pressure drop would not be controlled for long at these operating conditions. However, these CMM data indicate that, in the *Advanced Hybrid™* filter mode, the sorbent–gas contact may not be sufficient to achieve 90% removal at a low carbon addition rate with the FGD carbon.

Figure 6.3.2.14 shows individual bag flows for one row of the bags over several bag-cleaning cycles. Individual bag flow monitors were installed in the 1, 3, 5, 7, and 8 bag positions for one of the rows. The bags are numbered from the back of the unit to the front, so Bag No. 8 is at the entrance of the *Advanced Hybrid™* filter where the dust loading is highest and No. 1 is at the back where the dust loading is lowest. The data indicate that shortly after a pulse, the flows

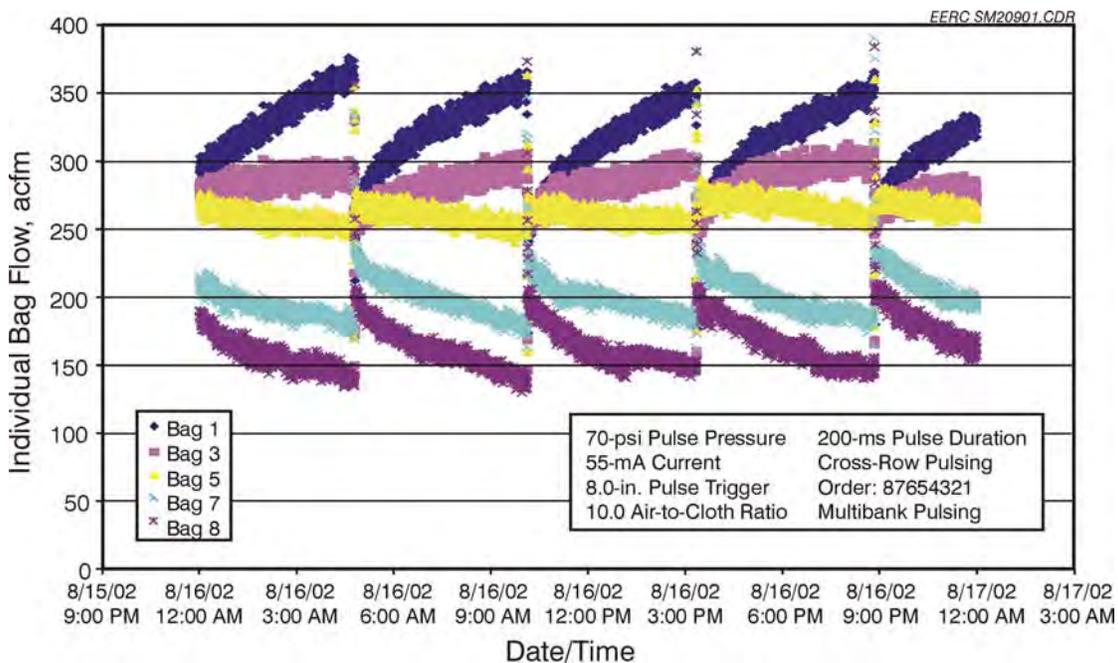


Figure 6.3.2.14. Individual bag flows for one row of the bags over several bag-cleaning cycles.

through the bags are similar, or with power off, the flows are similar. However, in the operating mode when all of the bags are pulsed when the pressure drop reaches 2.0 kPa (8 in. W.C.), a larger fraction of the flow goes through the last bags with increasing time from cleaning. Pulsing the bags more often or in a different sequence could significantly change the flow distribution, possibly resulting in better mercury capture.

6.3.2.5 Mercury and Particulate Matter Emissions at Big Stone Stack

Two Ontario Hydro samples were taken at the middle level of the Big Stone stack on August 6–7, 2002. Figure 6.3.2.15 shows the Ontario Hydro results at the stack. Also included in Figure 6.3.2.15 are the Ontario Hydro data collected at the *Advanced Hybrid*TM filter inlet, which are equivalent to the Big Stone ESP inlet. The data indicate little or no change in mercury species or removal across the ESP.

As part of the Ontario Hydro measurements, the measured particulate level at the stack is given in Table 6.3.2.4. Based on inlet measurements from the *Advanced Hybrid*TM filter inlet on the same day, the Big Stone ESP collection efficiency was in the range from 99.75% to 99.77%, which is well within compliance. However, because of the concentration of fine particles exiting the ESP, even at this level of control, a visible plume can frequently be seen at an opacity much less than the 20% opacity compliance requirement. These particulate emission values served as a

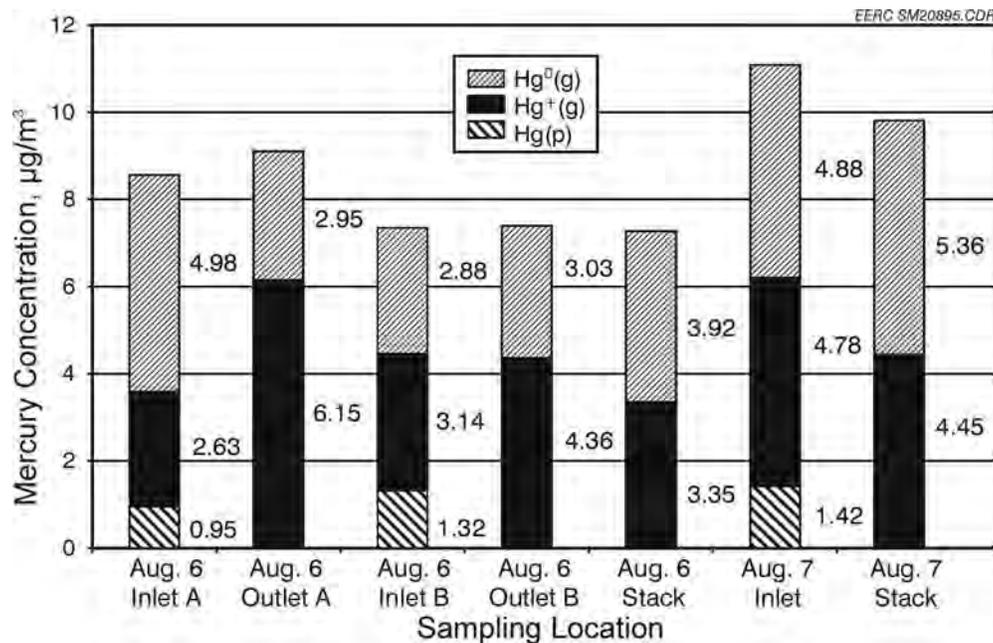


Figure 6.3.2.15. Ontario Hydro results at the Big Stone stack.

Table 6.3.2.4. Big Stone Power Plant Stack Emissions

Date		<i>Advanced Hybrid</i> TM Filter Inlet Dust Loading, mg/m ³ (gr/scf)	Big Stone Stack Dust Loading, mg/m ³ (gr/scf)	Big Stone ESP Collection Efficiency, %
8-6-02	Sample 1	0.0021 (0.9077)		
	Sample 2	0.0026 (1.1308)		
	Average	0.0023 (1.0193)	0.0000 (0.0023*)	99.774
8-7-02	Sample 1	0.0027 (1.1981)		
	Sample 2	0.0026 (1.1255)		
	Average	0.0027 (1.1618)	0.0000 (0.0029*)	99.750

* Single stack sample each day.

baseline for comparison with emissions after the Big Stone Power Plant completed installation of a full-scale *Advanced Hybrid*TM filter.

6.2.3.6 *Advanced Hybrid*TM Filter Performance with Carbon Injection

One of the main objectives of these tests was to evaluate the impact of carbon injection on longer-term *Advanced Hybrid*TM filter performance. The *Advanced Hybrid*TM filter was started with new bags on June 28 and operated continuously through the entire tests. Figures 6.3.2.16–6.3.2.19 plot the pressure drop, BCI, K_2C_i , and residual drag from June 28 to September 3 to see if carbon injection affected the *Advanced Hybrid*TM filter operation. The daily average pressure drop data increased slightly with time as would be expected after starting with new bags. When the carbon was started on August 7, there was no perceptible change in pressure drop. The BCI was somewhat variable as a result of temperature and load swings, but, again, there was no increase when the carbon feed was started. The K_2C_i values are an indication of the amount of dust that reaches the bags and subsequently relate to how well the ESP portion of the *Advanced Hybrid*TM filter is working. Again, there was no perceptible change when the carbon was started. The residual drag data indicate how well the bags clean and also did not show any change as a result of the carbon.

Of interest is the effect on these performance parameters with the lower current setting of 25 mA (see Figures 6.3.2.16–6.3.2.19). At 25 mA, the bag-cleaning interval dropped to about one-half, and the K_2C_i value approximately doubled. Both of these indicate that about twice as much dust reached the bags at 25 mA compared to 55 mA. However, almost no effect on

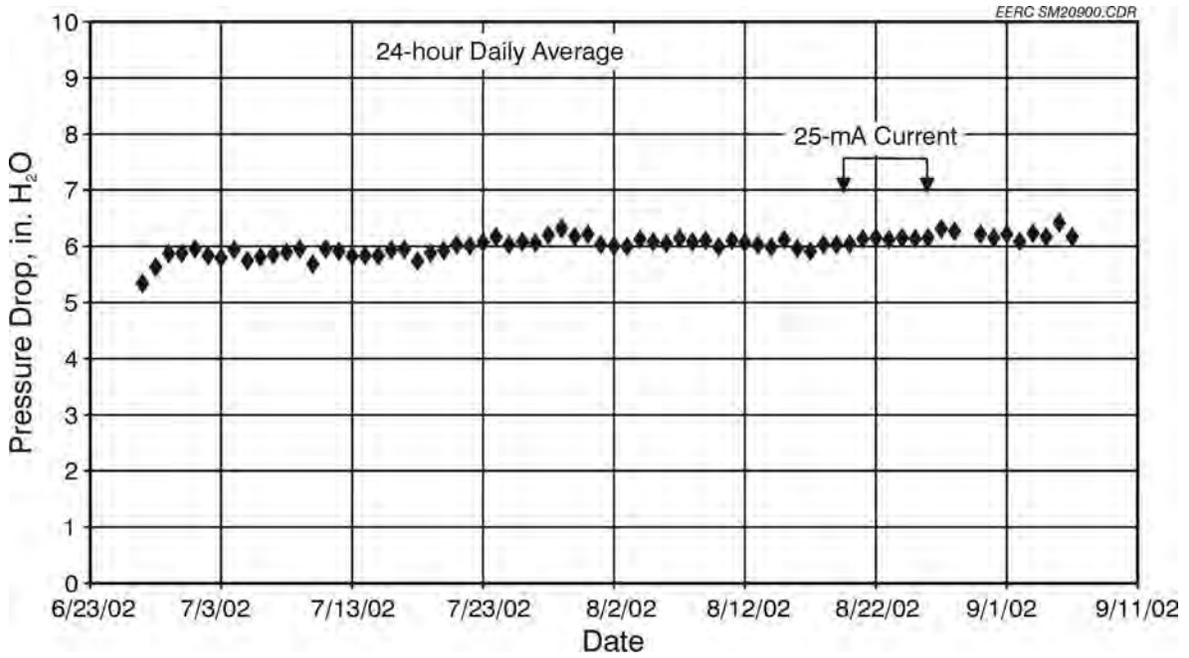


Figure 6.3.2.16. Average daily pressure drop for June 28–September 3, 2002.

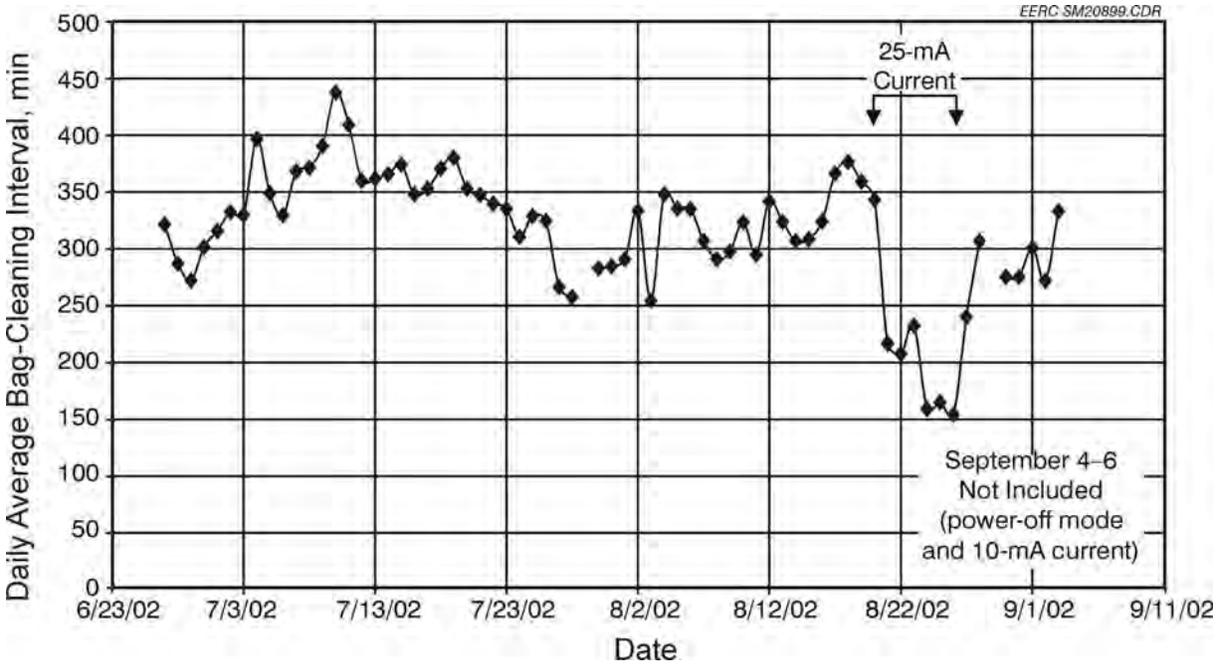


Figure 6.3.2.17. Daily average BCI for June 28–September 3, 2002.

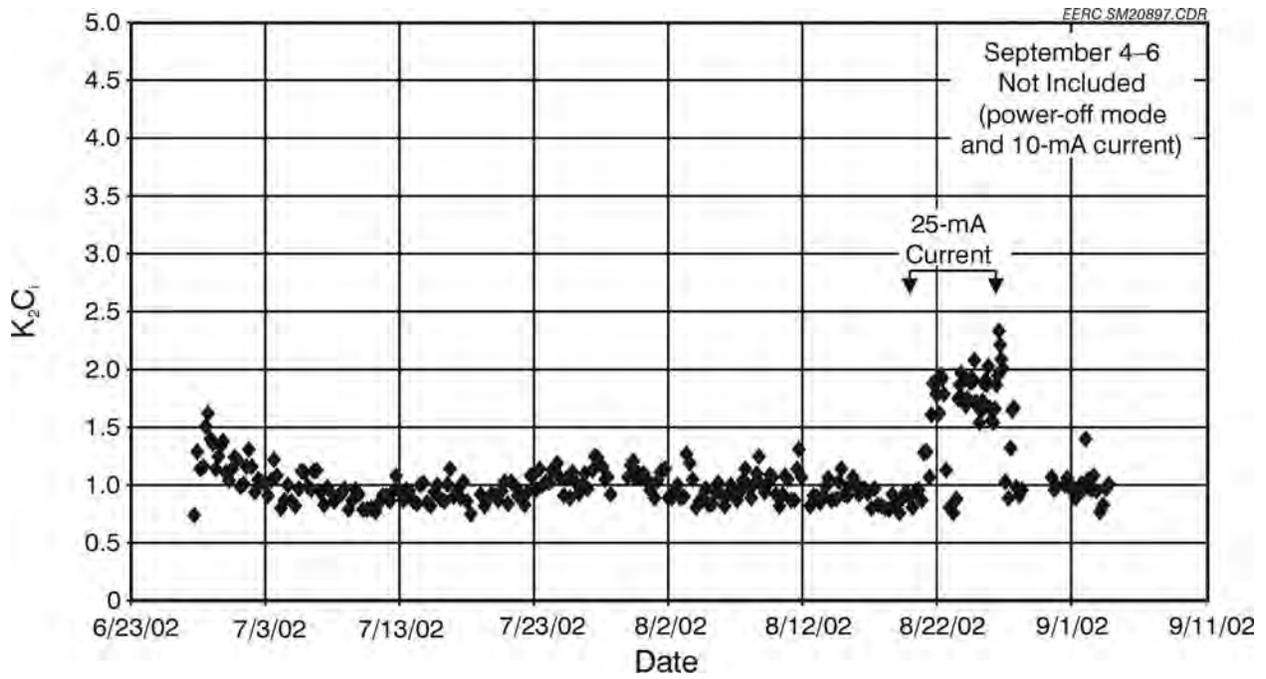


Figure 6.3.2.18. K_2C_i for June 28–September 3, 2002.

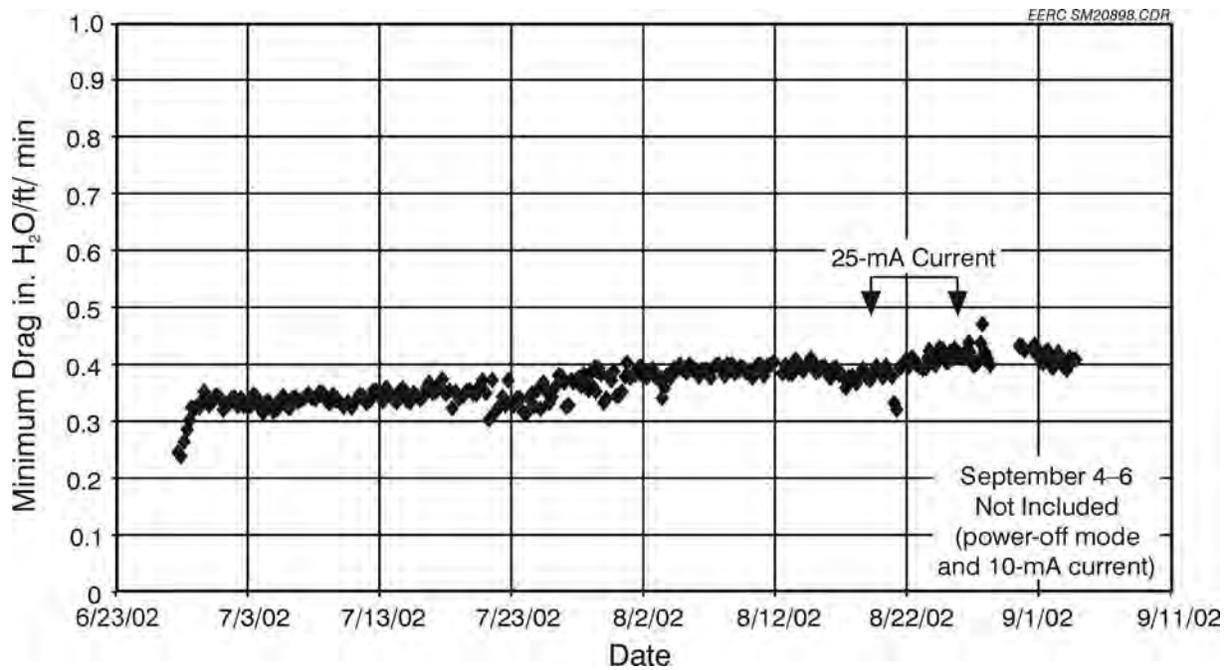


Figure 6.3.2.19. Residual drag for June 28–September 3, 2002.

pressure drop or residual drag was seen. This implies that it should be possible to optimize *Advanced Hybrid*TM filter operational parameters to get the best overall mercury removal while maintaining good *Advanced Hybrid*TM filter performance.

6.2.3.7 Conclusions

The average inlet mercury speciation values during the August 2002 tests were 17% particulate-bound, 32% oxidized, and 51% elemental, and the corresponding inherent mercury capture efficiency across the *Advanced Hybrid*TM filter was 0%–10%. The significant differences of mercury species in flue gas as well as inherent removal between the August 2002 test and November 2001 test are likely caused by high TDF cofiring rates during the November 2001 test.

1.5 lb/Macf NORIT FGD carbon injection resulted in an average of 63% mercury removal with the *Advanced Hybrid*TM filter in the August tests without any TDF cofiring. A small TDF cofiring rate of about 23 tons per day improved mercury capture to 68%. At the highest TDF rate seen in the August tests of 150–177 tons per day, mercury removal up to 88% was achieved. Comparing with 91% removal seen during the November tests when the TDF feed rate was in the range from 90 to 250 tons per day, the field testing results indicate that TDF cofiring benefits mercury control with a low carbon addition rate in the *Advanced Hybrid*TM filter.

Possible approaches to improve mercury capture include batch injection of the carbon or reducing the *Advanced Hybrid*TM filter current density. At 25-mA current, mercury emissions were from 0.5 to 0.9 $\mu\text{g}/\text{m}^3$ lower than at the standard current setting of 55 mA. The short-term power-off tests also showed improved mercury capture. These results suggest that modifying the pulsing sequence or interval could change the flow distribution to enhance the gas–solid contact and improve mercury removal.

Based on measured pressure drop across the *Advanced Hybrid*TM filter, BCI, K_2C_i , and residual drag, there was no perceptible effect of the carbon injection on the performance of the *Advanced Hybrid*TM filter.

6.3.3 Short-Term Field Test During November 19–22, 2002

6.3.3.1 Test Conditions

A short field test was completed with the 2.5-MW (9000-acfm) *Advanced Hybrid*TM filter at the Big Stone Power Plant from November 19–22, 2002. This test period was planned to coincide with the first test conducted at the inlet and stack of the full-scale *Advanced Hybrid*TM filter after it came online October 26, 2002. From earlier testing results with the 2.5-MW (9000-

acfm) *Advanced Hybrid*TM filter at the Big Stone Power Plant, when the plant was cofiring a small amount of TDF, there was an increase in HCl in the flue gas and a higher fraction of oxidized mercury. In addition, improved mercury control was seen with the addition of activated carbon when the plant cofired TDF. It is not know whether the better mercury control was the result of more oxidized mercury, higher HCl in the flue gas, more unburned carbon in the ash or, possibly, a combination of these factors. The primary purpose of the test was to evaluate the effect of injecting a small amount of HCl into the flue gas along with the activated carbon. Table 6.3.3.1 lists 11 tests completed with the 2.5-MW (9000-acfm) *Advanced Hybrid*TM filter during this

Table 6.3.3.1. Summary of Test Matrix for the November 2002 Big Stone Power Plant Field Sampling

Test	Mode	Carbon Injection	HCl Injection	Time Frame
1	8.0 in. W.C. (2.0 kPa) Pulse trigger	NA	NA	Nov. 19, 8:00–Nov. 20, 13:00
2	8.0 in. W.C. (2.0 kPa) Pulse trigger	0.3 kg/hr (0.66 lb/hr)	NA	Nov. 20, 13:00–15:02
3	8.0 in. W.C. (2.0 kPa) Pulse trigger	0.3 kg/hr (0.66 lb/hr)	10 ppm HCl at feeder	Nov. 20, 15:02–17:00
4	8.0 in. W.C. (2.0 kPa) Pulse trigger	0.29 kg (2 lb) power-off batch	NA	Nov. 20, 17:11
5	8.0 in. W.C. (2.0 kPa) Pulse trigger	0.3 kg/hr (0.65 lb/hr)	NA	Nov. 20, 20:00–Nov. 21, 11:00
6	8.0 in. W.C. (2.0 kPa) Pulse trigger	0.3 kg/hr (0.65 lb/hr)	10 ppm HCl at feeder	Nov. 21, 11:00–13:00
7	8.0 in. W.C. (2.0 kPa) Pulse trigger	0.3 kg/hr (0.65 lb/hr)	NA	Nov. 21, 13:00–15:00
8	8.0 in. W.C. (2.0 kPa) Pulse trigger	0.09 kg/hr (0.2 lb/hr) due to plug at feeder	16 ppm HCl at feeder	Nov. 21, 15:00–17:00
9	20-min interval	0.3 kg/hr (0.65 lb/hr)	NA	Nov. 21, 17:12–Nov. 22, 9:30
10	20-min interval	0.3 kg/hr (0.65 lb/hr)	10 ppm HCl at <i>Advanced Hybrid</i> TM filter inlet pipe	Nov. 22, 9:30–11:00
11	20-min interval	0.6 kg/hr (1.3 lb/hr)	NA	Nov. 22, 11:30–13:30

testing period. For the first eight tests, the *Advanced Hybrid*TM filter was set to pulse when the pressure drop reached 2.0 kPa (8 in. W.C.), which resulted in a pulse interval of about 3 hr and an average pressure drop of 1.6 kPa (6.5 in. W.C.). Conversely, the remaining three tests had a constant 20-min BCI with an average pressure drop of 1.2 kPa (5.0 in. W.C.).

Since the inlet and stack mercury measurements were being completed for the full-scale *Advanced Hybrid*TM filter, no Ontario Hydro samples were taken on the 2.5-MW (9000-acfm) *Advanced Hybrid*TM filter. However, two mercury CMMs monitored gaseous mercury concentrations at the inlet and outlet of the 2.5-MW (9000-acfm) *Advanced Hybrid*TM filter. Method 29 instead of the Ontario Hydro method was used in the full-scale *Advanced Hybrid*TM filter because of the need to measure a number of trace elements in addition to mercury.

6.3.3.2 *Big Stone Fuel Record for November 2002*

During the test period, the Big Stone Power Plant burned coal from the Belle Ayr Mine. The plant fuel burn record (Table 6.3.3.2) shows that some supplemental TDF and waste seed were cofired on two of the test days, November 19 and 22.

6.3.3.3 *Mercury Results for November 19–22, 2002, Field Test*

Mercury Stack Emission at Big Stone Flue-Scale *Advanced Hybrid*TM Filter November 2002

Mercury results from three pairs of Method 29 sample collected at plant inlet and stack are shown in Figure 6.3.3.1. Since Method 29 can provide an accurate split between the particulate and vapor-phase mercury but not between oxidized and elemental mercury, the data shown are only with particulate and vapor-phase fractions. The total mercury concentrations in the flue gas were within the range of previously measured inlet values for the 2.5-MW (9000-acfm) *Advanced Hybrid*TM filter, but appeared to vary significantly, especially in the particulate-bound fraction. Because of this variability the exact total inlet mercury for specific tests in the 2.5-MW (9000-acfm) *Advanced Hybrid*TM filter is somewhat uncertain.

Test 1 – Baseline test

The 2.5-MW (9000-acfm) *Advanced Hybrid*TM filter was operated under baseline conditions without any carbon or HCl injection from noon on November 19 until 13:00 on November 20. The inlet and outlet mercury CMM data for this time (Figure 6.3.3.2) indicated no vapor-phase mercury capture across the *Advanced Hybrid*TM filter unit. For the later part of Test

Table 6.3.3.2. Big Stone Fuel Record for November 2002

Date	Coal Mine	Coal, tons	TDF, tons	Waste Seeds, tons
November 1, 2002	Eagle Butte	5988	22	189
November 2, 2002	Eagle Butte	6001	0	0
November 3, 2002	Caballo Rojo	5641	0	0
November 4, 2002	Caballo Rojo	4601	90	980
November 5, 2002	Eagle Butte	5871	23	36
November 6, 2002	Eagle Butte	6182	45	48
November 7, 2002	Cordero	6062	0	0
November 8, 2002	Cordero	5519	250	98
November 9, 2002	Eagle Butte	5418	0	0
November 10, 2002	Eagle Butte	6080	0	0
November 11, 2002	Belle Ayr	6316	0	0
November 12, 2002	Belle Ayr	6170	45	24
November 13, 2002	Belle Ayr	6140	92	23
November 14, 2002	Belle Ayr	6306	117	49
November 15, 2002	Belle Ayr	6202	46	85
November 16, 2002	Belle Ayr	6511	0	0
November 17, 2002	Belle Ayr	6185	0	0
November 18, 2002	Belle Ayr	5797	44	160
November 19, 2002	Belle Ayr	6013	23	195
November 20, 2002	Belle Ayr	6290	0	0
November 21, 2002	Belle Ayr	6365	0	0
November 22, 2002	Belle Ayr	6037	139	180
November 23, 2002	Belle Ayr	4781	0	0
November 24, 2002	Belle Ayr	6276	0	0
November 25, 2002	Belle Ayr	6342	23	0
November 26, 2002	Belle Ayr	6249	0	0
November 27, 2002	Belle Ayr	6152	0	78
November 28, 2002	Eagle Butte	5913	0	0
November 29, 2002	Eagle Butte	5652	46	0
November 30, 2002	Caballo Rojo	6338	0	0

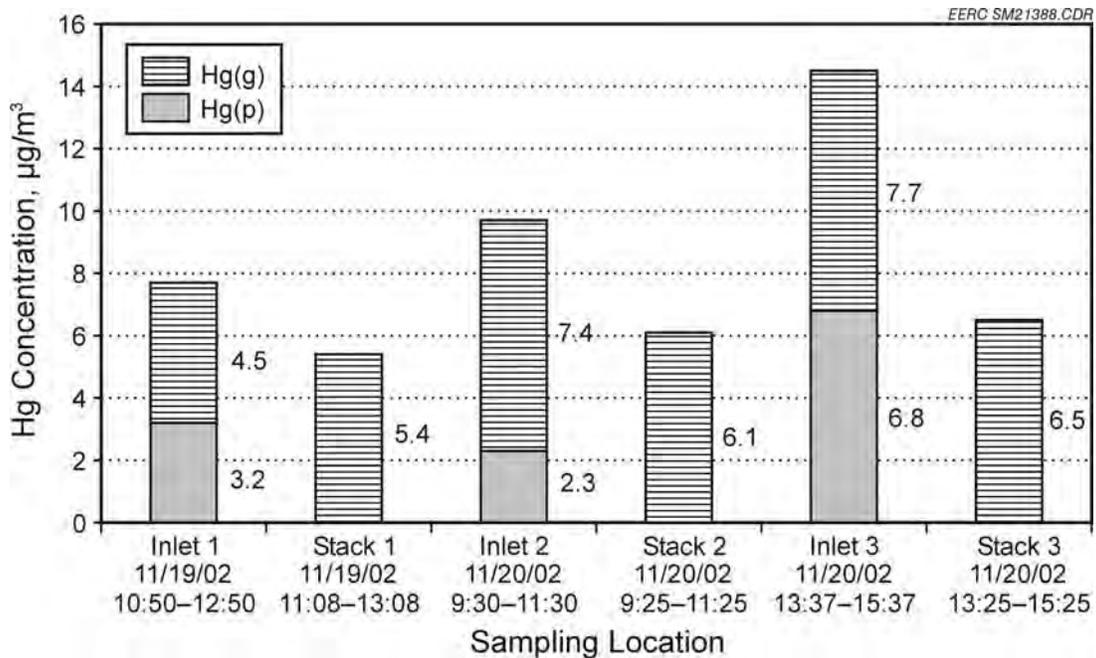


Figure 6.3.3.1. Mercury species concentration at the full-scale *Advanced Hybrid*TM filter inlet and stack.

1 (Figure 6.3.3.2), the outlet CMM data were higher than the measured inlet values. From previous work, we know that this can be caused by accumulation of dust on the inlet sampling filter. In cases where the fly ash has a tendency to capture some of the mercury, this causes a low bias to the measured inlet mercury. Because of this effect, only the outlet CMM data are shown for the remaining tests.

Tests 2–3 0.3-kg/hr (0.65-lb/hr) NORIT FGD Carbon Injection with and Without HCl Addition

From 13:00 to 15:00 on November 20, at a carbon injection rate of 0.3 kg/hr (0.65 lb/hr), equivalent to a 24 mg/m³ (1.5 lb/Macf), the outlet mercury emissions dropped to 3.7 µg/m³, which corresponds to 65% total mercury removal (based on the average inlet total value of 10.6 µg/m³) (see Figure 6.3.3.3).

While carbon injection was continued, 10 ppm HCl was injected directly into the carbon feed line just downstream from the carbon feeder. Over the 2-hr test from 15:00 to 17:00 (Figure 6.3.3.3), there was only a slight decrease in outlet mercury to about 3.1 µg/m³, corresponding to a 71% total mercury control. The lower mercury emissions may be attributable to the added HCl.

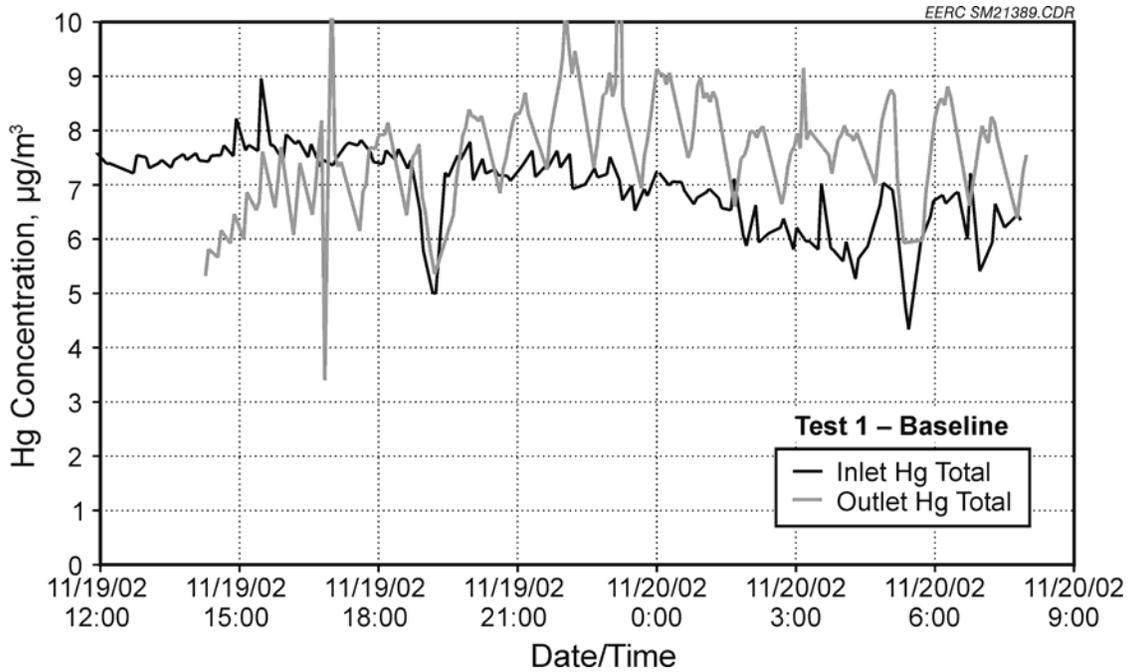


Figure 6.3.3.2. Test 1 Baseline inlet and outlet mercury CMM data for the 2.5-MW (9000-acfm) *Advanced Hybrid™* filter.

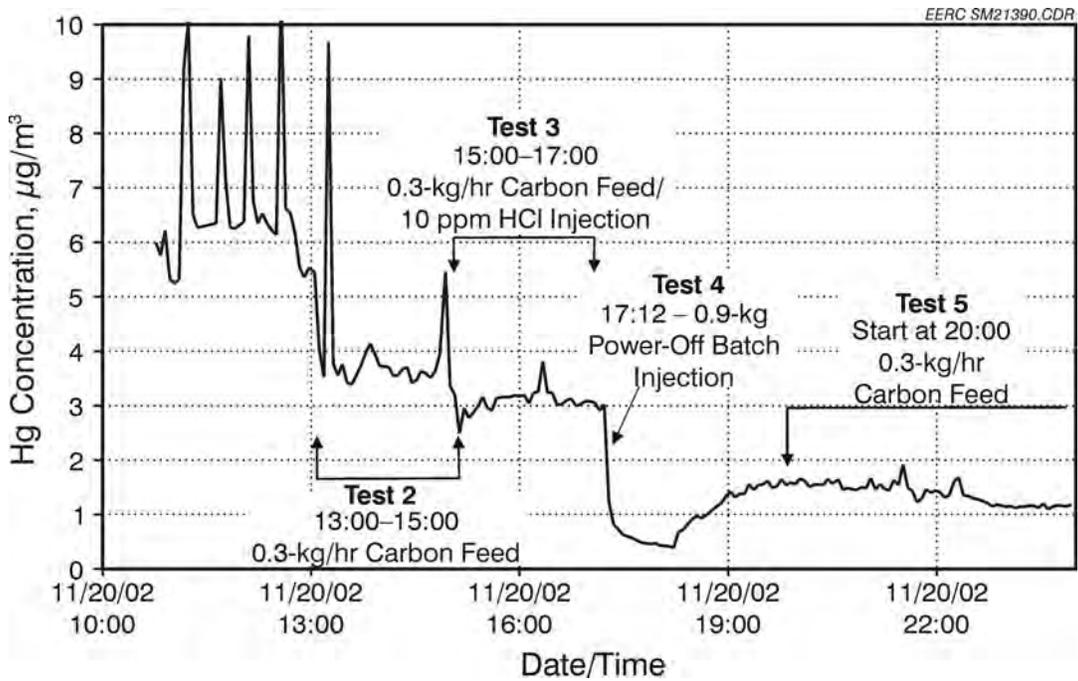


Figure 6.3.3.3. Tests 2–5 – outlet mercury emission for the 2.5-MW (9000-acfm) *Advanced Hybrid™* filter.

Test 4 – NORIT FGD Power-Off Batch Injection, No HCl

There was a concern that the mercury monitor might be biased high. So, at 17:12, 0.9 kg (2 lb) of carbon was injected into the flue gas within about a minute with the high-voltage power off to verify CMM performance. Based on previous testing data, the outlet mercury concentration would drop to near zero, at least for a short time. From the data in Figure 6.3.3.3, the outlet mercury concentration dropped as low as $0.4 \mu\text{g}/\text{m}^3$, which indicated that the mercury monitor was providing valid readings. After 1 hr, the mercury started increasing again. During this time, the carbon feeder was at a rate of 0.3 kg/hr (0.65 lb/hr).

Tests 5–8 0.3-kg/hr NORIT FGD Carbon Injection with and Without HCl Additions

For Test 5, the carbon remained at a constant 0.3-kg/hr (0.65-lb/hr) feed rate while the CMMs monitored mercury emissions overnight to establish mercury removal with 0.3-kg/hr (0.65-lb/hr) carbon injection alone. After recovering from the batch carbon injection, the CMM data in Figures 6.3.3.3 and 6.3.3.4 showed the outlet mercury increased only to $1.7 \mu\text{g}/\text{m}^3$ and then slowly dropped to $1.0 \mu\text{g}/\text{m}^3$ by 01:00 on the next day where it remained until 05:30. This corresponds to a total mercury removal of 91% without any supplemental HCl injection.

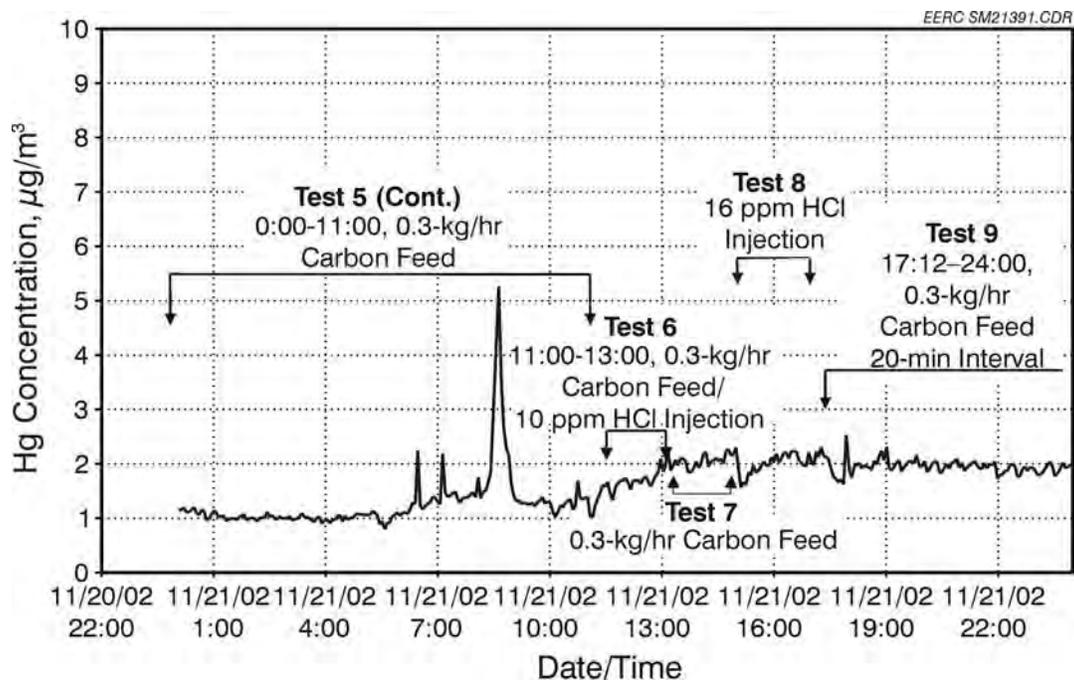


Figure 6.3.3.4. Tests 5–9 – Outlet mercury emission for the 2.5-MW (9000-acfm) *Advanced Hybrid™* filter.

Interestingly, during this time there was also no cofiring of TDF. The plant load (Figure 6.3.3.5) was reduced slightly from midnight until 06:00 on November 21, but the drop in mercury emission already started before the drop in plant load. The *Advanced Hybrid*TM filter inlet and outlet temperatures (Figure 6.3.3.6) did decrease slightly from midnight until 06:00, which may have benefited the mercury retention. It is also expected that with longer-term carbon injection some additional capture of mercury might occur until all of the carbon retained in the unit has reached its maximum capacity. From the time of starting carbon injection on November 20 until 05:30 on November 21, it is possible that some additional carbon buildup would occur and this could account for the gradual drop in mercury emissions. At 05:30, the mercury started to increase again, corresponding to a return to full plant load and a gradual increase in temperature. This suggests that the level of mercury control may be sensitive to even small changes in plant conditions.

Test 6 was a repeat of Test 3 to determine the effect of HCl combined with carbon injection on mercury removal with the *Advanced Hybrid*TM filter. After the outlet mercury was

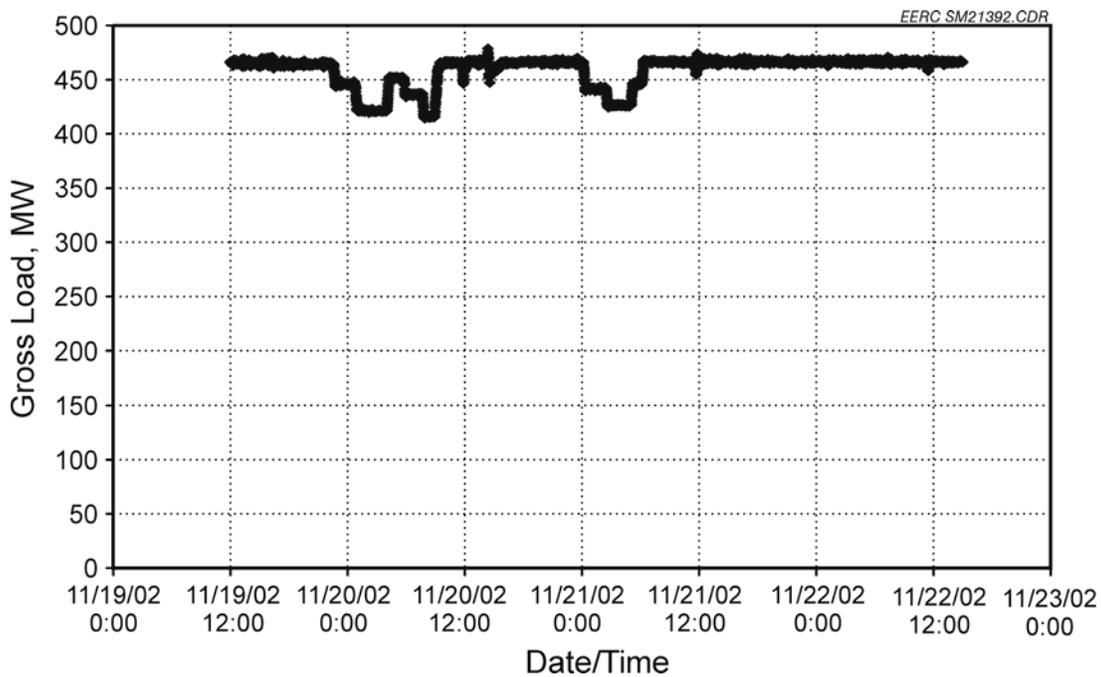


Figure 6.3.3.5. Big Stone Power Plant load during field sampling at the 2.5-MW (9000-acfm) *Advanced Hybrid*TM filter.

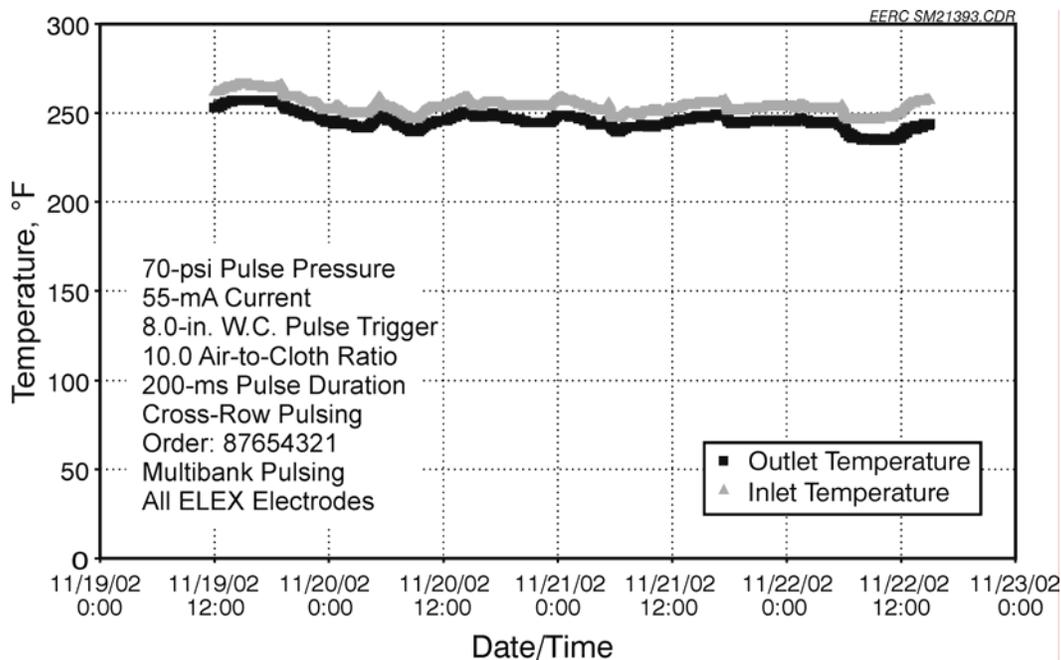


Figure 6.3.3.6. The *Advanced Hybrid*TM filter inlet and outlet temperatures.

shown to be fairly steady at about $1.5 \mu\text{g}/\text{m}^3$, 10 ppm of HCl was again injected into the carbon feed line from 11:00 to 13:00. However, from the results shown in Figure 6.3.3.4, the outlet mercury actually increased from 1.5 to $2.0 \mu\text{g}/\text{m}^3$. During this time, the *Advanced Hybrid*TM filter temperature was also increasing somewhat so the increase in mercury is more likely associated with the temperature increase rather than the injected HCl. Another possible reason is that the injected HCl mobilized mercury captured on carbon which reentered the flue gas. Results from Tests 3 and 6 indicated little or no benefit of adding 10 ppm HCl directly into the flue gas.

The HCl was shut off from 13:00 to 15:00, and the mercury emission remained at $2.0 \mu\text{g}/\text{m}^3$, which corresponded to a total mercury removal of 81% (Test 7).

For Test 8, HCl was started again from 15:00 to 17:00 and increased to the maximum controller setting which allowed up to 16 ppm HCl. During this time, there was a short-term plug in the carbon feeder which may have contributed to some variability in the outlet mercury, but comparing the mercury concentration while injecting the HCl with the times before and after the test without HCl injection indicates little or no effect of the HCl.

Tests 9–11 Carbon and/or HCl Injections with a 20-min Timed Pulsed Interval

From 17:12 on November 21 until 09:30 on November 22, the carbon feed was held constant at 0.3 kg/hr (1.5 lb/Macf), but the bag pulse controller was set to a 20-min timed interval (Test 9) rather than the 2.0 kPa (8 in. W.C.) trigger for all of the previous tests. At the 2.0 kPa (8 in. W.C.) pulse trigger pressure, the bags typically pulsed about every 3 hr, which allowed for a fairly long carbon residence time in the *Advanced Hybrid™* filter chamber. A 20-min timed pulse interval possibly could limit the carbon residence time and result in lower mercury capture. However, much of the carbon was likely deposited on the perforated collection plates which were rapped at a constant 40-min interval for all of the tests. CMM data in Figures 6.3.3.4 and 6.3.3.7 indicated no immediate change in the outlet mercury concentration after starting the 20-min timed bag pulsing. The outlet mercury emissions were very steady at about $1.9 \mu\text{g}/\text{m}^3$ from 19:00 November 21 to 03:00 November 22 and dropped to $0.9 \mu\text{g}/\text{m}^3$ during 03:00–06:00. During this time, the plant was at steady full load, and the *Advanced Hybrid™* filter temperatures did not fluctuate. Inspection of the plant fuel burn record shows that supplemental TDF and waste seed burning were started again on November 22, but the exact

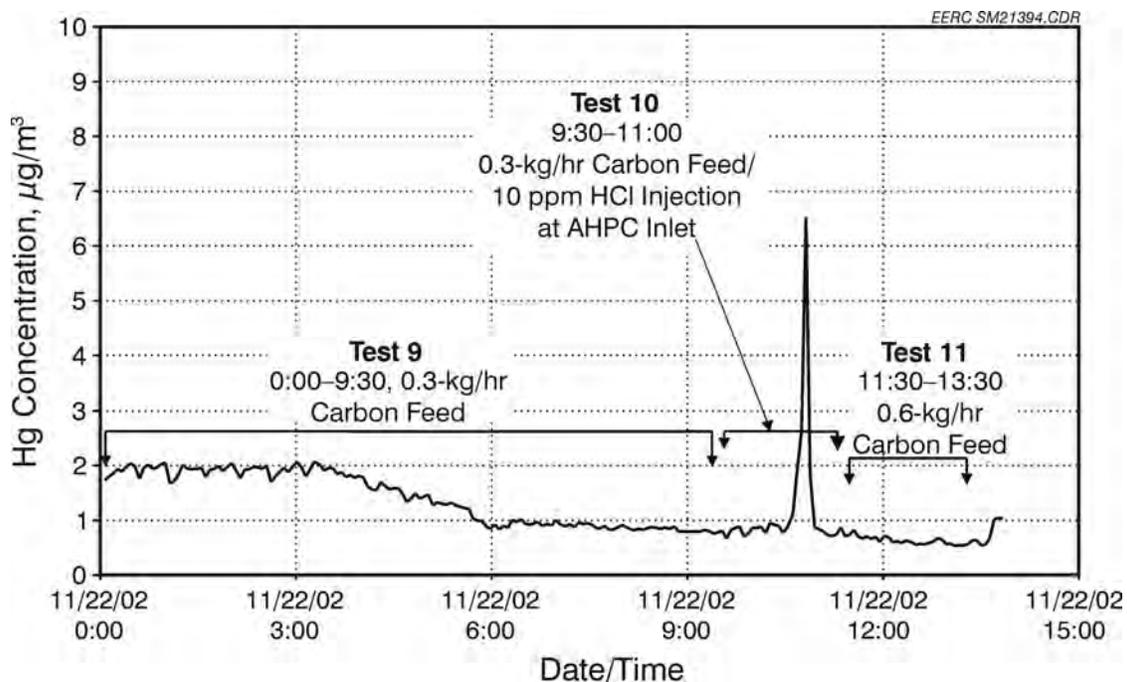


Figure 6.3.3.7. Tests 9–11 – outlet mercury emission for the 2.5-MW (9000-acfm) *Advanced Hybrid™* filter.

time that the fuels reached the boiler is unknown. From previous tests, similar effects were seen when TDF was started, but the drop could also be the result of variation in the inlet mercury concentration or speciation.

Test 10 was another attempt to determine if supplemental injection of HCl along with carbon injection would benefit mercury control. In this case, HCl was injected directly into the *Advanced Hybrid*TM filter inlet duct just upstream of the carbon injection location. From the outlet CMM data plotted in Figure 6.3.3.7, there was, again, no obvious decrease of mercury emission as the result of the HCl injection. However, the mercury removal during the test as well as just before and just after the test was over 90% so there may have already been a sufficient amount of HCl in the flue gas. During Test 10, there was a short-term spike in the mercury emission up to 6 $\mu\text{g}/\text{m}^3$. It is not know whether it was caused by a process upset or some transient condition in the sampling and analytical instrumentation.

Test 11 was completed in which the carbon injection rate was doubled to 1.3 kg/hr (3 lb/million acf). From the results shown in Figure 6.3.3.7, there was not an immediate drop in outlet mercury, but there did appear to be a gradual decrease in mercury. By the end of the 2-hr test, the mercury was only 0.6 $\mu\text{g}/\text{m}^3$ which corresponds to 94% total mercury removal. The excellent mercury removal seen here may have been at least partially due to the burning of TDF on November 22.

6.3.3.4 Conclusions

The November 2002 field testing data show a 24-mg/m³ (1.5-lb/Macf) NORIT FGD carbon injection alone provided 65%– 90% mercury removal with the *Advanced Hybrid*TM filter for the subbituminous coal flue gas, which is somewhat better than the results from the monthlong continuous field test in August 2002. Part of the reason could be the higher temperatures of 132°–143°C (270°–290°F) in the *Advanced Hybrid*TM filter during August 2002 compared to 121°C (250°F) for the November 2002 tests. These results indicate that the exact level of mercury control that can be achieved with a low carbon addition rate is dependent on many factors and is difficult to predict.

High mercury removal was seen both for the 2.0-kPa (8-in. W.C.) pulse trigger tests, which resulted in a 3-hr pulse interval and for the 20-min timed pulse interval tests. This indicates that a long pulse interval is not necessary to achieve good mercury removal.

The small effect (if any) seen with the supplemental HCl injection is somewhat surprising because an extensive amount of bench-scale sorbent work demonstrated the benefit of HCl for capturing elemental mercury in a simulated flue gas over the temperature range from 107°–188°C (225°–370°F). Previous work has also demonstrated that the addition of chlorine compounds into the combustion zone will result in a higher fraction of oxidized mercury. However, the benefit of additional HCl may be marginal in cases where there is already a sufficient amount of HCl present to achieve good mercury control.

6.3.4 Long-Term Field Test During May 6–June 3, 2003

6.3.4.1 Test Conditions

A 1-month field test was completed with the 2.5-MW (9000-acfm) *Advanced Hybrid*TM filter unit from May 6 to June 3, 2003. Carbon injection (NORIT FGD and/or Barneby & Sutcliffe IAC) was continuous (24 hr a day) for the entire month except for a planned plant outage on May 8, 2003, Memorial Day weekend break, and a 1-day shutdown on May 30, 2003. The primary goal of the 1-month test was to demonstrate long-term mercury control with the *Advanced Hybrid*TM filter technology by carbon injection. Another goal was to evaluate the impacts of various operating parameters of filtration face velocity, carbon injection rate, and residence time of carbon on mercury control with the *Advanced Hybrid*TM filter technology. A summary of the testing parameters is listed in Table 6.3.4.1.

Since previous field testing results (August–November 2002) had proved that CMM instruments were able to precisely measure gaseous mercury species in the flue gas two CMMs were used to continuously monitor mercury concentrations in the inlet and outlet flue gas, over the entire testing period, and no Ontario Hydro sampling was completed. The CMMs were normally set up to measure inlet and outlet total mercury vapor concentrations, but during the day for several hours, they were manually switched to also measure the elemental mercury vapor concentrations at the inlet and outlet.

6.3.4.2 Big Stone Fuel Record for May 2003

Table 6.3.4.2 lists the fuel burn record for Big Stone Power Plant from May 6 – June 3, 2003. During the majority of this test, the coals burned were from the Belle Ayr and Eagle Butte Mines, which are both similar low-sulfur subbituminous fuels from the PRB. On May 31, 2003, another PRB coal, Caballo coal, was burned. The amounts of TDF and waste seed fuel burned during this time are also listed in Table 6.3.4.2.

6.3.4.3 Mercury Results for May 6–June 3, 2003, Field Test

Baseline Test

Figure 6.3.4.1 shows daily average mercury vapor concentrations, both total and elemental, in the inlet flue gas for the entire test period. The error bars represent plus and minus one standard deviation. The inlet CMM sampling probe was set up prior to the carbon injection location so that the collected data were reflective of mercury species entering the *Advanced Hybrid™* filter unit. The concentrations of total mercury vapor (Hg_{gas}) in the inlet flue gas varied

Table 6.3.4.1. Testing Parameters During May–June 2003 Test

Carbon	NORIT FGD Activated Carbon, IAC
Filtration Face Velocity, m/min (ft/min)	1.8, 2.4, 3.0, 3.7, 4.3 (6, 8, 10, 12, 14)
Carbon Injection Concentration, mg/m ³ (lb/Macf)	17, 20, 30 40, 48 (1.07, 1.25, 1.88, 2.51, 3.00)
Carbon Injection Location	Inlet elbow, inlet transition

Table 6.3.4.2. Fuel Burn Record for the Big Stone Power Plant for May 2003

Date	Coal Mine	Coal, tons	TDF, tons	Waste Seed, tons
5/6/2003	Belle Ayr	5945	46	0
5/7/2003	Eagle Butte	5759	0	0
5/8/2003	Eagle Butte	4741	0	0
5/9/2002	Belle Ayr	6216	49	46
5/10/2003	Belle Ayr	6429	0	0
5/11/2003	Belle Ayr	6585	0	0
5/12/2003	Eagle Butte	6301	0	0
5/13/2003	Belle Ayr	6073	22	180
5/14/2003	Belle Ayr	6003	46	183
5/15/2003	Belle Ayr	6222	0	0
5/16/2003	Belle Ayr	5882	27	140
5/17/2003	Belle Ayr	6158	0	0
5/18/2003	Belle Ayr	6133	0	0
5/19/2003	Belle Ayr	6011	69	71
5/20/2003	Belle Ayr	6156	70	73
5/21/2003	Belle Ayr	6109	0	94
5/22/2003	Belle Ayr	5943	22	48
5/23/2003	Belle Ayr	5777	45	24
5/27/2003	Belle Ayr	5637	22	24
5/28/2003	Belle Ayr	5847	45	0
5/29/2003	Belle Ayr	6051	0	0
5/31/2003	Caballo	5579	0	0
6/1/2003	Eagle Butte	5439	0	0
6/2/2003	Eagle Butte	5564	111	68
6/3/2003	Eagle Butte	4109	0	0

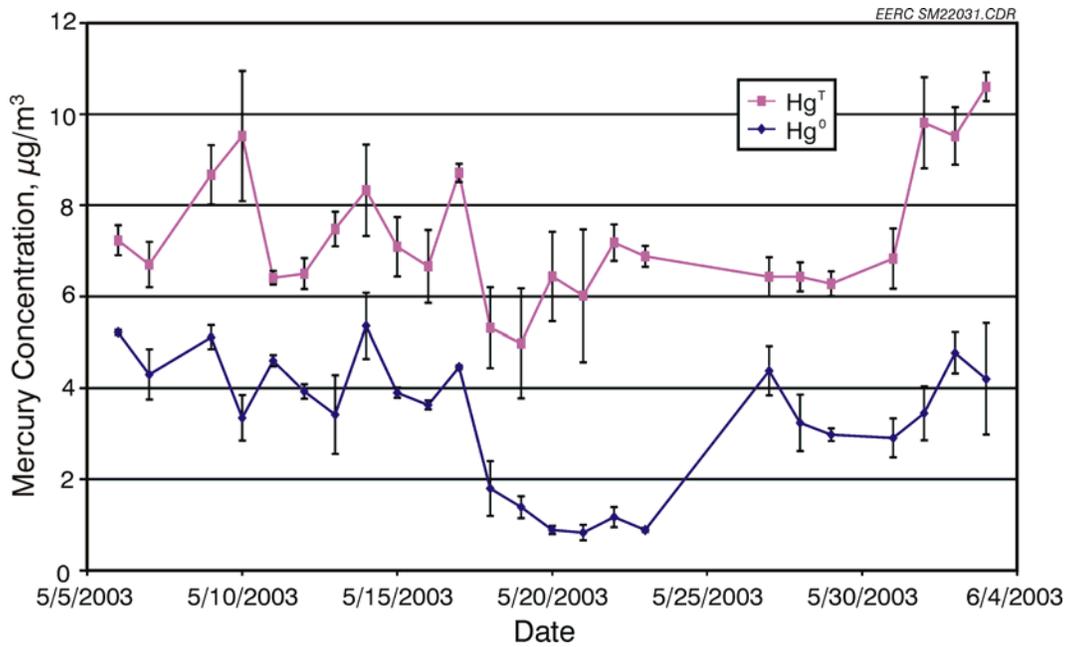


Figure 6.3.4.1. Daily average mercury vapor concentrations, both total and elemental, in the inlet flue gas for the 2.5-MW (9000-acfm) *Advanced Hybrid*TM filter.

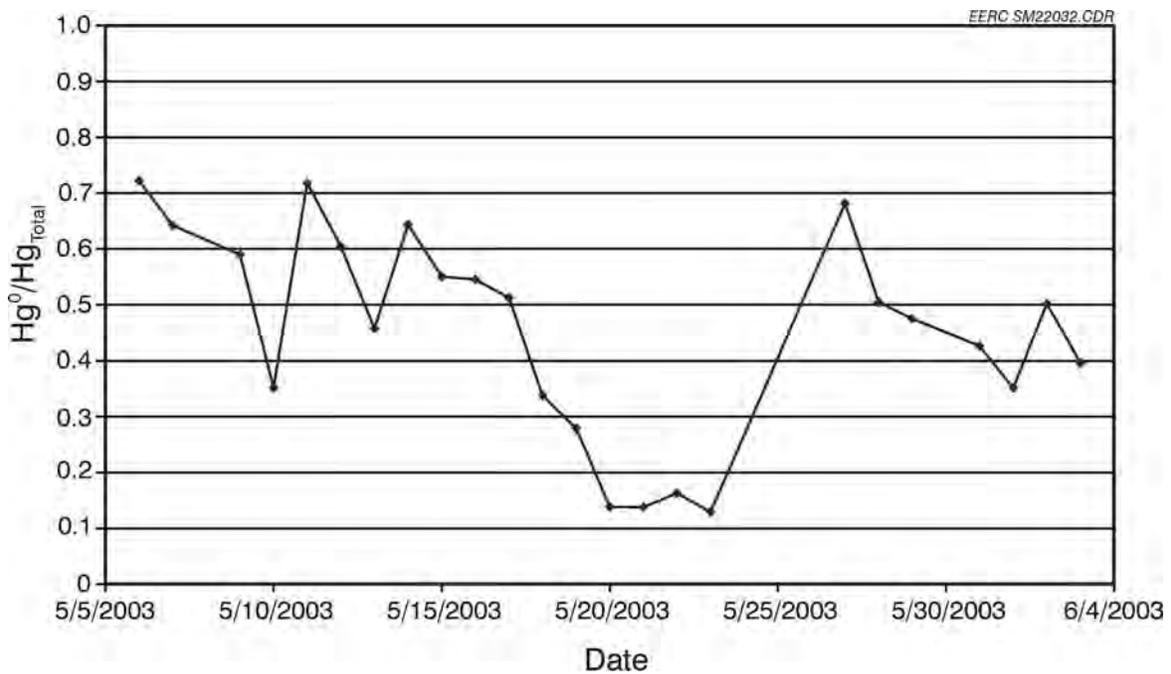


Figure 6.3.4.2. Ratios of Hg^0 -to- Hg_{gas} in the inlet flue gas for the 2.5-MW (9000-acfm) *Advanced Hybrid*TM filter.

from 4.98 to 10.6 $\mu\text{g}/\text{m}^3$ with 0.83 to 5.36 $\mu\text{g}/\text{m}^3$ elemental mercury. Figure 6.3.4.2 plots the daily ratios of Hg^0 -to- Hg_{gas} based on the daily averaged mercury species in the inlet flue gas, which ranged from 12.9% to 72.9%. During the previous field test in August 2002 for the Belle Ayr and Eagle Butte coals, 60%–80% of total mercury vapor in the flue gas was elemental, while 20%–40% was oxidized mercury. The wide variations of Hg^0 -to- Hg_{gas} ratio during this testing period were likely the result of the variation in the coal as well as the intermittent cofiring of TDF and waste seed. By correlating the fuel burn record with mercury species in the flue gas for both field tests, it appeared that the Belle Ayr coal was more sensitive to cofiring TDF and waste seed in that more oxidized mercury in the flue gas was seen under relatively low levels of TDF additions. However, because the TDF and waste seed were fed into the plant intermittently, it is very difficult to precisely estimate the TDF effect on mercury species.

Table 6.3.4.3 lists mercury contents of the three different coals burned during the testing period. Although these coals are from different mines, their mercury contents are quite similar, in the range of 0.0689 to 0.109 $\mu\text{g}/\text{g}$. The predicted mercury concentration in the flue gas is in the range of 7.8 to 12.3 $\mu\text{g}/\text{m}^3$, with an average of 9.85 $\mu\text{g}/\text{m}^3$. Also included in Table 6.3.4.3 are the mercury analysis results of hopper ash samples collected in baseline tests.

During the test on May 20, 2003, the power plant burned Belle Ayr coal along with 1.1% TDF (mass basis) and 1.2% (mass basis) waste seed. The total gaseous mercury in the flue gas during the test was 6.44 $\mu\text{g}/\text{m}^3$. Based on the measured 0.233–0.256 $\mu\text{g}/\text{g}$ mercury in the Belle Ayr hopper ash collected in the baseline test and a typical dust loading of 2.83 g/m^3 (1.2 gr/scf), the particle-bound mercury in the flue gas was in the range of 0.66–0.72 $\mu\text{g}/\text{m}^3$, giving a total mercury concentration of 7.16–7.76 $\mu\text{g}/\text{m}^3$. Compared to the predicted 9.45 $\mu\text{g}/\text{m}^3$ total mercury in the Belle Ayr coal flue gas, the discrepancy between the measured and predicted

Table 6.3.4.3. Mercury Content in the Coals and Hopper Ash

Coal Samples	Date	Coal Mine	Mercury Content, $\mu\text{g}/\text{g}$, dry basis
	5/20/03	Belle Ayr	0.0836
	5/31/03	Caballo	0.0689
	6/02/03	Eagle Butte	0.109
Ash Samples	Date	Mercury Content, $\mu\text{g}/\text{g}$, dry basis	
	5/09/03	0.256	
	5/27/03	0.233	
	5/31/03	0.438	

total mercury concentrations in the flue gas may be the result of analytical uncertainty or could be caused by some mercury collected on the CMM sampling filter, which occurs to greater extent when TDF was cofired.

On the May 31, 2003, baseline test, the power plant burned Caballo coal without any TDF and waste seed added. At the same time, the *Advanced Hybrid*TM filter was operated under baseline conditions without additional carbon injection. The mercury in the raw coal and *Advanced Hybrid*TM filter hopper ash were 0.0689 and 0.438 µg/g, respectively. Assuming a typical dust loading of 2.83 g/m³ (1.2 gr/scf) in the flue gas (based on previous sampling data), the particle-bound mercury was about 1.13 µg/m³ (dry basis). Combined with the averaged gaseous mercury of 6.83 µg/m³ in the inlet flue gas, the total mercury concentration in the flue gas was 7.96 µg/m³, close to the calculated mercury concentration of 7.8 µg/m³ based on the mercury content in the raw coal. This agreement is easier to achieve when no TDF and waste seeds are burned.

The coal burned on June 2, 2003, was Eagle Butte with a mercury concentration of 0.109 µg/g, corresponding to a total mercury concentration of 12.3 µg/m³, which was higher than the measured 9.8 µg/m³. Again, the TDF is a possible reason for the discrepancy.

Since the TDF was added into the plant intermittently during the entire test period, the total mercury vapor concentration measured by the CMM at the *Advanced Hybrid*TM filter inlet may not accurately reflect the real total mercury concentrations in the flue gas. Therefore, the average 9.85 µg/m³ from the combustion calculation was used as a typical inlet total mercury concentration in the flue gas for the mercury removal calculation.

Figure 6.3.4.3 summarizes the inherent mercury captures with the *Advanced Hybrid*TM filter during several different baseline testing periods when the power plant burned Belle Ayr, Eagle Butte, or Caballo with and/or without cofiring of TDF and waste seed. For the Belle Ayr coal, without cofiring TDF and waste seeds (May 10, 2003), there was virtually no inherent mercury capture by fly ash itself. However, when the power plant was cofiring with TDF as well as waste seed (May 6, 9, 27, and 28, 2003), the inherent mercury removal ranged from 2% to 18.9%. The above data indicated again the impacts of added TDF and waste seed on mercury species in the flue gas. Somewhat higher inherent mercury capture was seen with the Eagle Butte coal ranging from 24.7% to 30.5%, but this is somewhat overestimated because the average

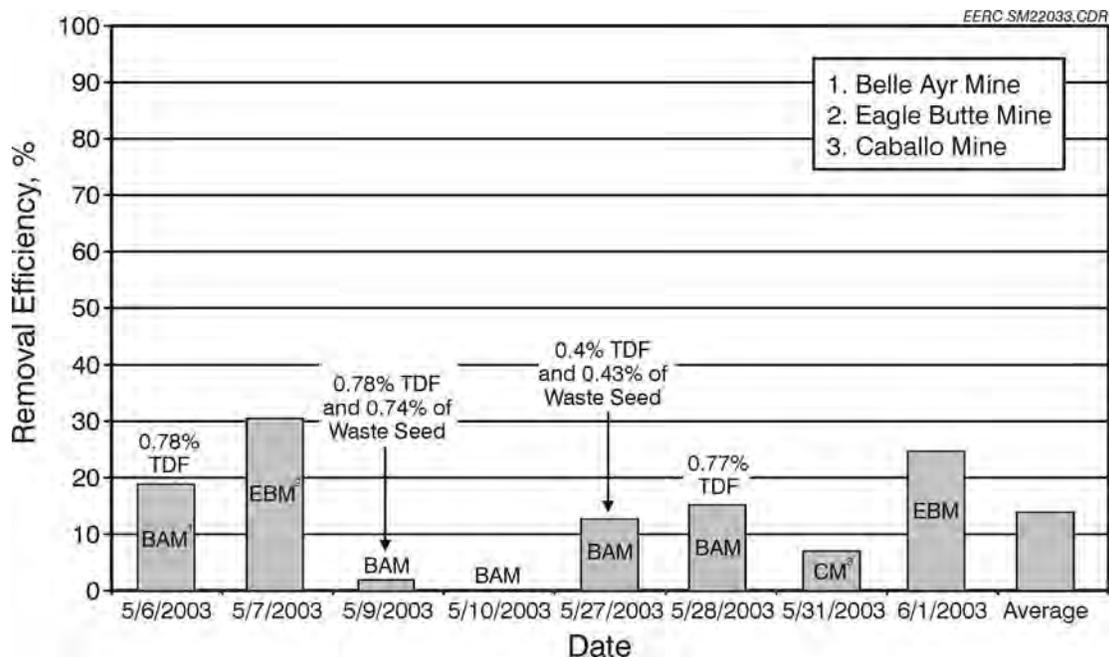


Figure 6.3.4.3. Summary of the inherent mercury captures with the *Advanced Hybrid™* filter during several different baseline testing periods.

9.85 $\mu\text{g}/\text{m}^3$ instead of 12.1 $\mu\text{g}/\text{m}^3$ was used for inherent capture calculation. In summary, the overall inherent mercury removal by the ash was low, with an average of 13.9% during the 1-month test.

Effect of Filtration Velocity on Mercury Removal with Carbon Injection

The goal of this test was to understand the impact of filtration velocity on *Advanced Hybrid™* filter mercury capture with carbon injection. By adjusting the *Advanced Hybrid™* filter flue gas flow rate from 122 to 285 m^3/min (4320 to 10,080 acfm), the filtration velocity through the bags varied from 2 to 4 m/min (6 to 14 ft/min), while the carbon injection rate was maintained at 0.3 kg/hr (0.65 lb/hr) during the testing time. When the flue gas flow rate was increased at a constant 0.3 kg/hr (0.65 lb/hr) carbon feed rate, the in-flight mercury-to-carbon adsorption was impeded as results of the diluted carbon-to-mercury ratio and reduced contact time between mercury and the in-flight carbon. However, at higher flow rates, more carbon deposited on the filter bags where they would have the best contact with mercury vapor. The mercury removals were the results of these competing factors.

The flow rate tests were completed on May 14, 15, and 20, 2003. On May 14, 2003, the *Advanced Hybrid*TM filter was initially operated at 3 m/min (10 ft/min) of filtration velocity with a 24 mg/m³ (1.5 lb/Macf) carbon injection rate. The average mercury collection efficiency (Figure 6.3.4.4) was 55.3%. The flue gas flow rate through the *Advanced Hybrid*TM filter was then reduced to 163 m³/min (5760 acfm) for a few hours and further reduced to 1317 m³/min (4320 acfm) for the rest of the day (8 hr), resulting in decreased filtration velocities of 1.8 and 2.4 m/min (6 and 8 ft/min) and corresponding increased carbon injection concentrations of 30 and 40 mg/m³ (1.88 and 2.51 lb/Macf), respectively. The subsequent overall mercury removal increased to 63.8% at 2.4 m/min (8 ft/min) and further to 81.1% at 1.8 m/min (6 ft/min). The higher mercury removal at the reduced filtration velocity is likely the result of the raised carbon-to-mercury ratio combined with better contact of mercury with the in-flight carbon and the carbon on the perforated plates under extended residence times.

On May 15, 2003, the *Advanced Hybrid*TM filter was operated at filtration velocities of 1.8, 3.0, and 3.7 m/min (6, 10 and 12 ft/min). The overall mercury collection efficiency (Figure 6.3.4.5) increased with decreasing filtration velocity from 65.8% at 3.7 m/min (12 ft/min) to 73.2% at 3 m/min (10 ft/min) and to 83.1% at 1.8 m/min (6 ft/min). The better mercury removals

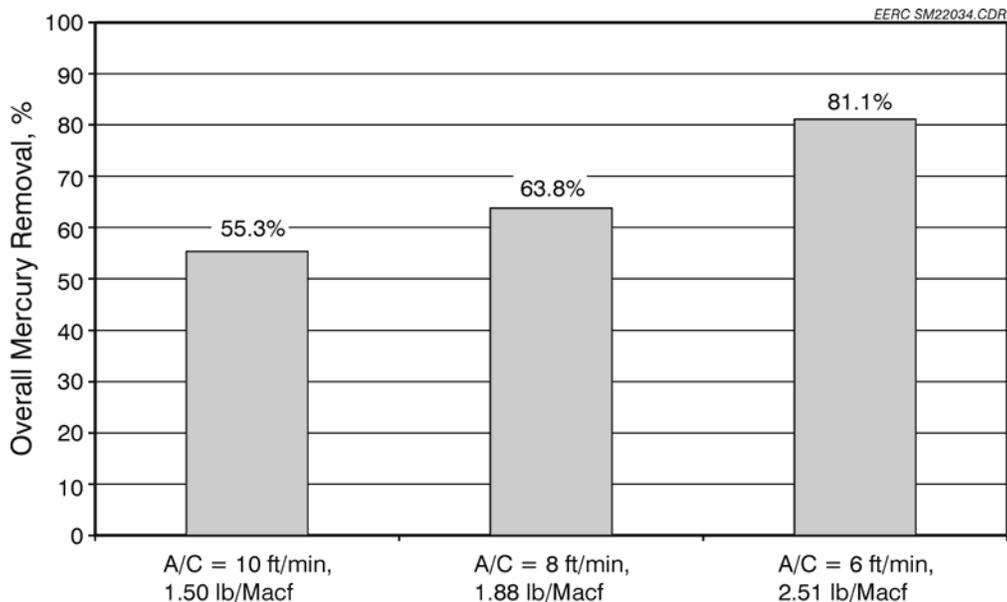


Figure 6.3.4.4. Mercury collection efficiencies under different filtration velocities (May 14, 2003).

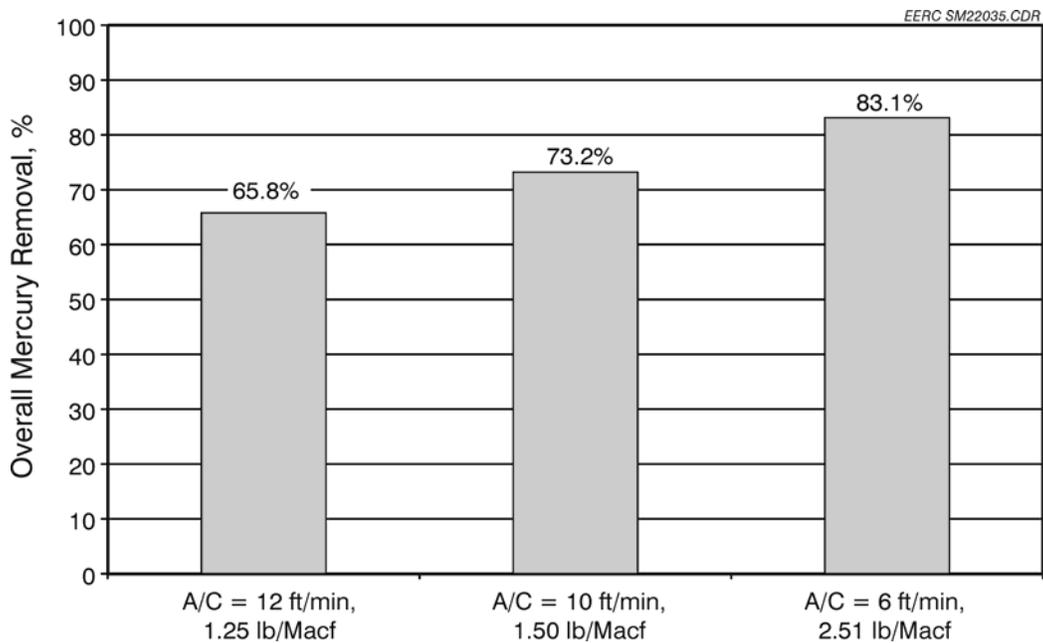


Figure 6.3.4.5. Mercury collection efficiencies under different filtration velocities (May 15, 2003).

at the 3 m/min (10 ft/min) and 1.8 m/min (6 ft/min), compared to May 14, 2003 testing data, may be the result of more oxidized mercury in the flue gas on May 15 (Figures 6.3.4.1 and 6.3.4.2).

To further confirm the filtration velocity effect on mercury removal with carbon injection, another test was conducted on May 20, 2003. Approximately 70 tons of TDF and 70 tons of waste seed (Table 6.3.4.2) were cofiring with the Belle Ayr coal on May 19–20, which resulted in more oxidized mercury in the flue gas. The total mercury collection efficiency (Figure 6.3.4.6) was 76.9% at 4.3 m/min (14 ft/min), increased to 82% at 3 m/min (10 ft/min) and 93.9% at 1.8 m/min (6 ft/min), again showing the beneficial effect of reducing filtration velocity on mercury removal in the *Advanced Hybrid*TM filter. The higher mercury removal in this test compared to the previous two tests was likely because of the high percentage of oxidized mercury and somewhat lower total mercury vapor in the flue gas (Figures 6.3.4.1 and 6.3.4.2).

All three short-term individual tests showed that reducing the filtration velocity at a fixed carbon injection rate of 0.3 kg/hr (0.65 lb/hr) improved mercury removal in the *Advanced Hybrid*TM filter. This improvement is likely the result of both increased carbon-to-mercury ratio and better contact between mercury and carbon.

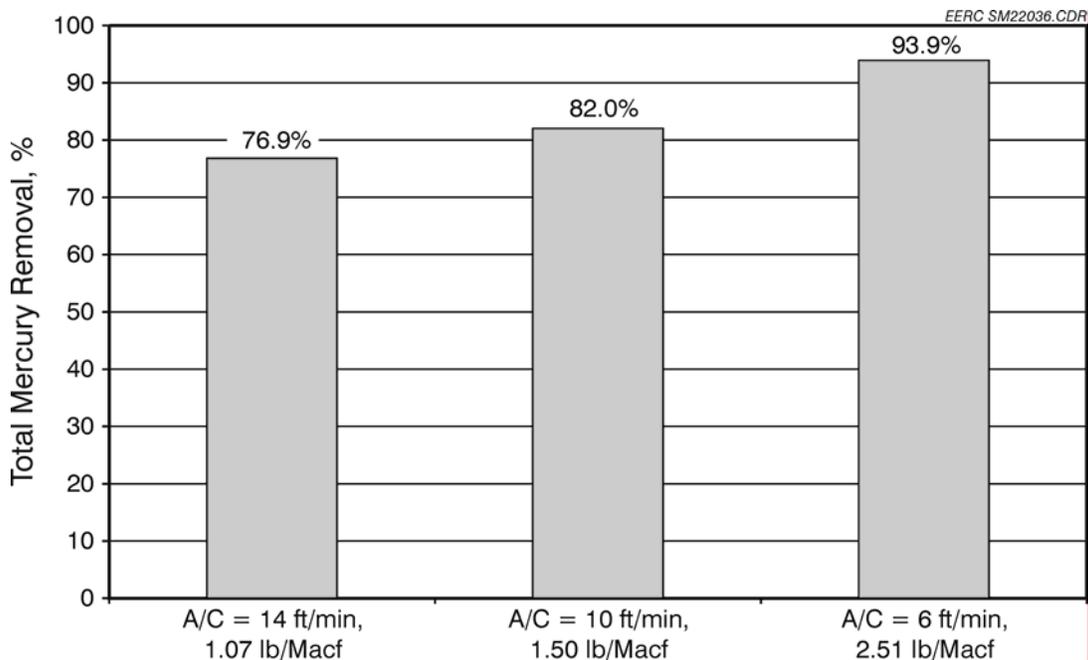


Figure 6.3.4.6. Mercury collection efficiencies under different filtration velocities (May 20, 2003).

Effect of the Sorbent In-Flight Time on Mercury Removal

Mercury removal is divided into three stages in the *Advanced Hybrid™* filter configuration: 1) in-flight adsorption by carbon, 2) adsorption by carbon collected on the perforated plates, and 3) fixed-bed adsorption on the filter bag surface. The in-flight mercury adsorption is limited because of a short contact time between the bulk gas-phase mercury in the flue gas and the in-flight carbon. The mercury capture by carbon collected on the perforated plates may be somewhat greater than the in-flight mercury capture because of 1) longer residence time of activated carbon in the *Advanced Hybrid™* filter unit, approximately 30 min or longer, depending on the plate-rapping and bag-cleaning intervals; 2) extended contact time between mercury in the flue gas and sorbent on the perforated plates due to the local recirculation of the flue gas; and 3) enhanced mass transfer from the bulk gas-phase mercury to the carbon surface since the flue gas flows straight toward the perforated plate instead of in a parallel flow with the plates in a conventional ESP. The fixed-bed adsorption on the filter bags is capacity-limited rather than mass transfer-limited.

To further understand the detailed mercury capture mechanisms in the *Advanced Hybrid*TM filter with carbon injection, the carbon injection location was switched from the normal inlet elbow location to the closer inlet transition zone on June 2–3, 2003, while other operating parameters were the same: 3 m/min (10 ft/min) filtration velocity and 0.3 kg/hr (0.65 lb/hr) FGD carbon injection rate. Subsequently, the in-flight time of activated carbon was reduced by roughly 50%. Figure 6.3.4.7 plots the measured mercury overall collection efficiencies under the two different in-flight times, showing almost the same levels of mercury capture: 58.4% at the inlet elbow vs. 60.9% at the inlet transition. The extended sorbent in-flight time did not benefit mercury capture with the *Advanced Hybrid*TM filter. At the end of this test, the ESP power was shut down when carbon was injected from the inlet transition zone, resulting in a 20% increase of mercury removal. The additional gain was because all of the activated carbon was uniformly collected on the filter bags. This indicates that in-flight mercury capture is not a dominant capture mechanism.

Effect of Carbon Injection Rate on Mercury Removal

On May 12, 2003, when the FGD carbon injection rate was set as 0.3 kg/hr (0.65 lb/hr), corresponding to 24 mg/m³ (1.5 lb/Macf), the mercury removal efficiency was 71.6% (Figure

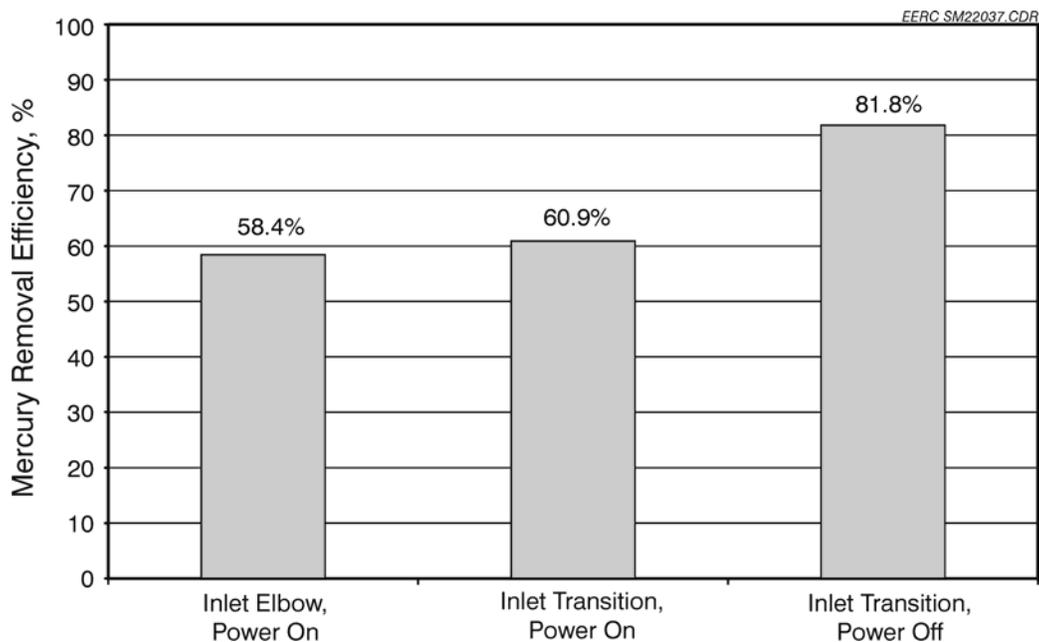


Figure 6.3.4.7. Measured mercury overall collection efficiencies under the two different sorbent in-flight times (June 2–3, 2003).

6.3.4.8). While keeping all other operating parameters the same, the FGD carbon injection rate was doubled to 0.6 kg (1.3 lb/hr), corresponding to 48 mg/m³ (3 lb/Macf). The overall mercury collection efficiency, however, only slightly increased to 74.0% (Figure 6.3.4.8), which was somewhat surprising. A possible reason for the marginal benefit gained from the double carbon injection rate is that the effectiveness of activated carbon to capture mercury may be limited by the amount of HCl in the flue gas.

Effect of ESP Power on Mercury Removal

During the 1-month test, the ESP power was shut down temporarily several times to confirm the maximum mercury capture efficiency of the NORIT FGD carbon at different filtration velocities. With the high-voltage power off, the *Advanced Hybrid*TM filter unit was operated as a PJBH with a BCI of 60 min. Because of the unique geometric configuration of the *Advanced Hybrid*TM filter, the flue gas into the *Advanced Hybrid*TM filter unit is evenly distributed among all of the filter bags when the unit was operated as a PJBH. However, the side inlet of the unit and the larger spacing between bag rows make gas distribution in the *Advanced Hybrid*TM filter without ESP power more ideal than in a conventional PJBH. Therefore, a

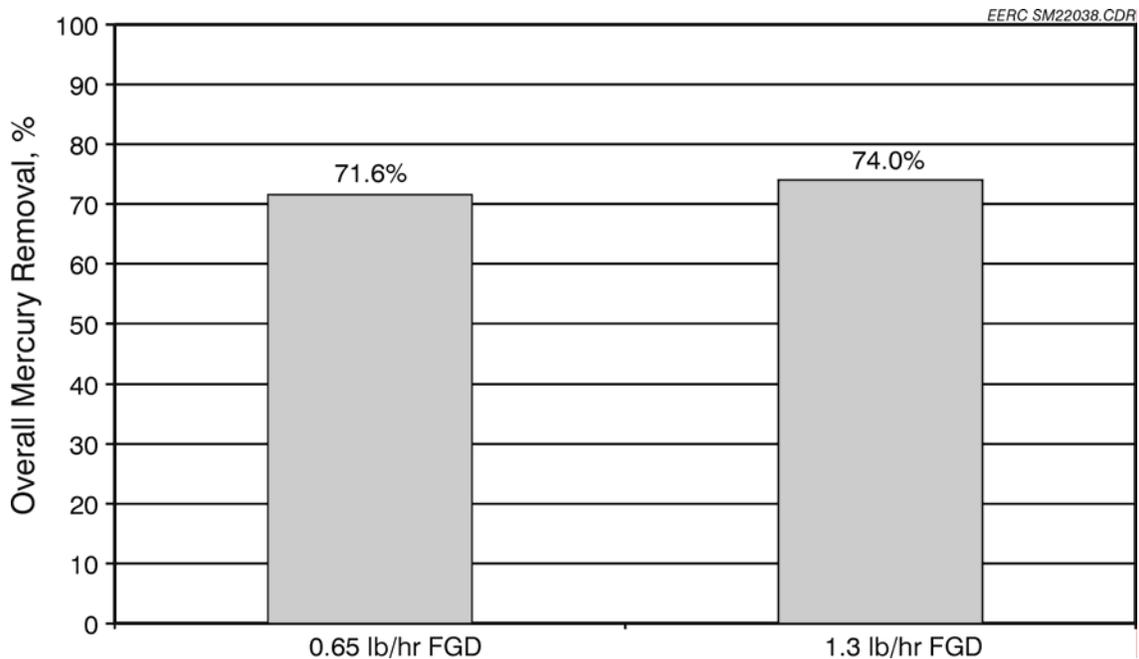


Figure 6.3.4.8. The effect of sorbent injection rate on mercury removal (May 12, 2003).

comparison of mercury removal in the *Advanced Hybrid*TM filter with and without ESP power is not the same as a comparison between the *Advanced Hybrid*TM filter and a conventional PJBH.

A summary of mercury removal efficiencies with the ESP power on and off (Figure 6.3.4.9) shows consistently higher levels of mercury capture when the ESP was shut down, which suggests better or more uniform gas–solid contact. The pressure drop across the *Advanced Hybrid*TM filter unit, however, was dramatically increased when the ESP power was off, reaching as high as 3.3 kPa (13 in. W.C.) depending on filtration velocity.

Effect of Iodine-Impregnated Carbon on Mercury Removal

On May, 17 2003, IAC provided by Barneby & Sutcliffe was tested in the *Advanced Hybrid*TM filter unit at an injection rate of 0.2 kg/hr (0.46 lb/hr), corresponding to 17.6 mg/m³ (1.1 lb/Macf), to evaluate its effectiveness on mercury removal. The overall mercury collection efficiency, however, was only 57.3% (shown in Figure 6.3.4.10), which is lower than expected. A possible reason is that the particle size of the IAC is –200 mesh (less than 74 µm), which is larger than the NORIT FGD carbon whose size is –325 mesh (less than 45 µm), according to supplier information. The larger-sized IAC results in a less efficient usage of the activated

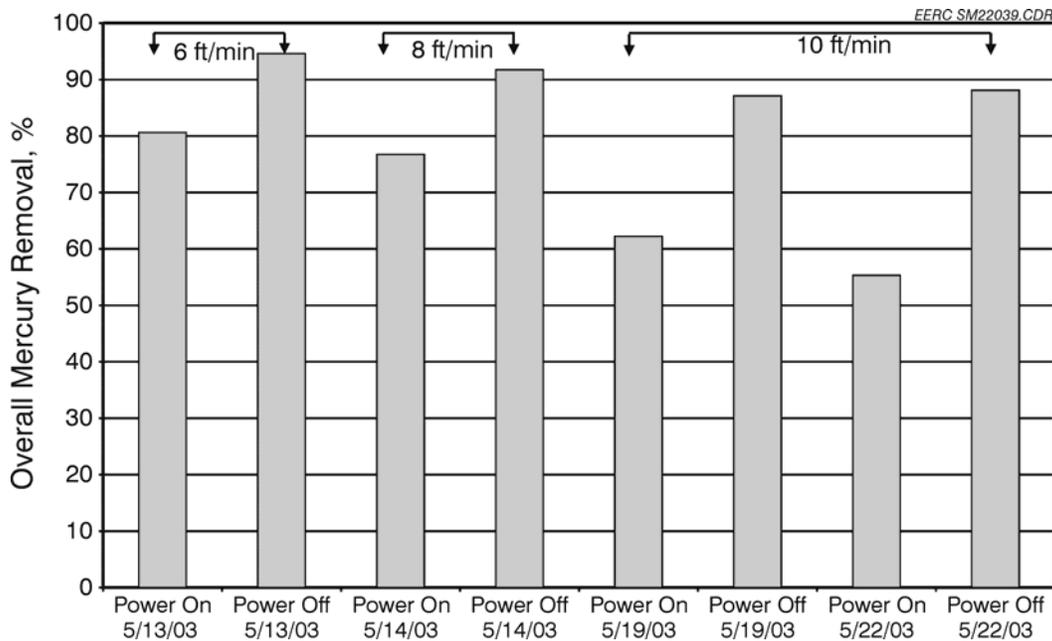


Figure 6.3.4.9. Summary of mercury removal efficiencies with the ESP power on and off.

carbon. The ESP power was shut off for a short time to confirm the maximum mercury removal by IAC, showing only increased to 64.5%, a lower mercury capture than that of the FGD carbon at the same injection rate.

6.3.4.4 Results from Mercury Stability Tests

Two *Advanced Hybrid*TM filter hopper ashes were collected on May 10 and 21, 2003, labeled as 03-061 and 03-060, respectively, and evaluated at the EERC for mercury stability as part of another project. More detailed discussion can be found in the DOE report (12, 13).

Table 6.3.4.4 lists the total mercury contents of the *Advanced Hybrid*TM filter ash samples, showing moderate levels of mercury concentration with both samples in the range typically seen in standard coal combustion fly ash samples produced without mercury emission controls. However, the mercury concentration for Sample 03-060 was approximately three times greater than that for 03-061, indicating improved mercury capture with the addition of a carbon-based sorbent.

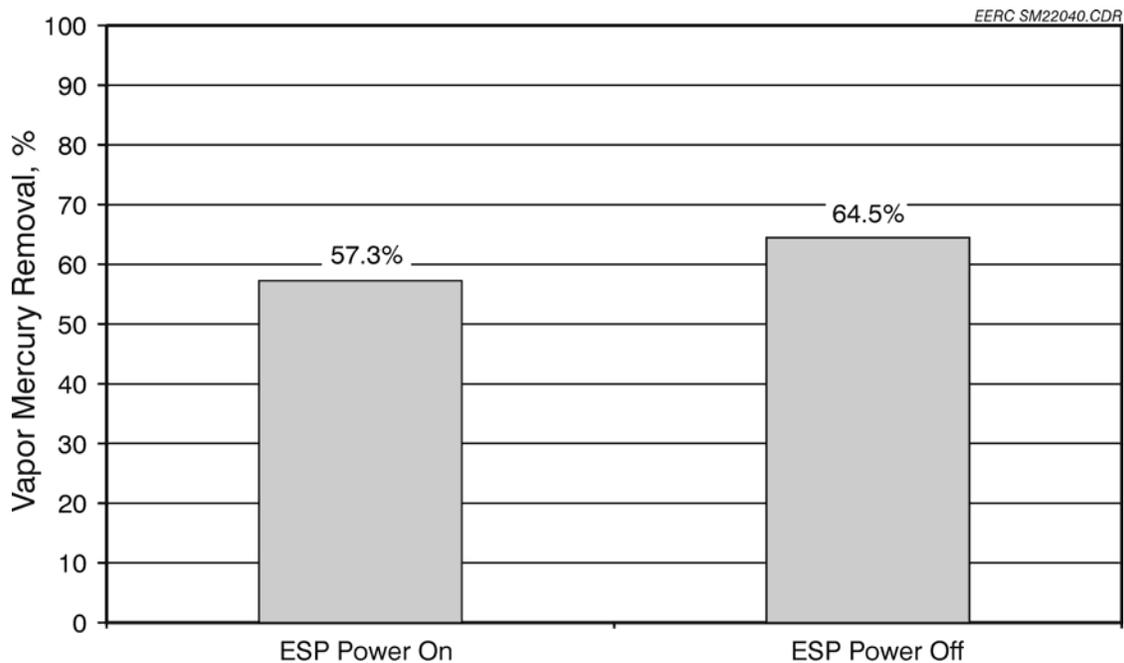


Figure 6.3.4.10. Mercury removals with the 2.5-MW (9000-acfm) *Advanced Hybrid*TM filter under 17.6 mg/m³ (1.1-lb/Macf) IAC injection.

Total major chemical composition is reported as % oxides for the *Advanced Hybrid*TM filter samples is shown in Table 6.3.4.5. Moisture and LOI are also included in Table 6.3.4.5. The dominant carbon form in Sample 03-060 was anisotropic coke, whereas it was isotropic coke in Sample 03-061. These carbon forms have been shown to be present in samples containing activated carbon and to be associated with elevated mercury concentrations in coal combustion fly ash where they are present.

SGLP and LTL Leaching Results

Leaching data, including final leachate pH and mercury concentrations, for the *Advanced Hybrid*TM filter samples using synthetic groundwater leaching procedure (SGLP), 30-day, and 60-day long-term leaching (LTL) tests are shown in Table 6.3.4.6.

Most leaching testing data show the mercury concentrations in the leachate solutions were below detection limit except for the 60-day LTL tests where both 03-060 and 03-061 samples indicated measurable mercury concentrations of 0.034 µg/L and 0.33 µg/L, respectively, in the leachate solutions.

Table 6.3.4.4. Total Mercury Content of *Advanced Hybrid*TM Filter Samples, µg/g

ID No.	Hg
03-060	1.86
03-061	0.578

Table 6.3.4.5. Bulk Oxide Data for *Advanced Hybrid*TM Filter Samples (%)

ID No.	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	Na ₂ O	K ₂ O	TiO ₂	MnO ₂	P ₂ O ₅	SrO	BaO	SO ₃	LOI	Moisture, as received
03-060	30.07	17.63	5.87	27.50	6.11	2.42	0.68	1.35	0.02	2.31	0.44	0.84	2.54	2.22	0.09
03-061	22.64	17.25	6.87	31.56	8.48	2.99	0.49	1.21	0.03	1.24	0.19	0.87	4.73	1.15	0.11

Table 6.3.4.6. Leaching Data on *Advanced Hybrid*TM Filter Samples, µg/L

ID No.	Test	Hg	pH
03-060	SGLP	<0.01	12.15
03-060	30 LTL	<0.01	12.46
03-060	60 LTL	0.034	12.38
03-061	SGLP	<0.01	12.40
03-061	30 LTL	<0.01	12.63
03-061	60 LTL	0.33	12.58

Microbiological Releases

Microbiological leaching tests were completed for Sample 03-060, and the results are shown in Table 6.3.4.7. These results show that more elemental mercury is being released from the flasks than organomercury. The mass of elemental mercury released from the flasks in the aerobic environment was much higher than in the anaerobic environment. All mercury releases and final bacterial counts were greater in the glucose-fed flasks than in the starved flasks.

Long-Term Ambient Temperature Release

Long-term ambient temperature mercury release results obtained from individual sample containers for this effort are shown in Figure 6.3.4.11, including the *Advanced Hybrid*TM filter samples. Over the duration of the entire 187 days of the experiment, five samples showed overall mercury release, including the *Advanced Hybrid*TM filter samples, and seven samples showed overall mercury sorption. The release of mercury, expressed as pg/g/day, was less for most samples in the final 90-day collection period than for the previous 90-day collection period. As evident in Figure 6.3.4.11, the variability of the data is relatively high, averaging -0.0002 pg/g/day. In part, the variability can be attributed to the variability inherent in the analysis of the extremely low concentrations of mercury captured by and desorbed from the gold-coated analytical traps.

Thermal Desorption at Elevated Temperatures

Thermal desorption results for the *Advanced Hybrid*TM filter sample are shown in Figures 6.3.4.12 and 6.3.4.13. The thermal curves generated for each of these samples show one peak of mercury release. The peak mercury release was at 395°C (743°F) for Sample 03-060 and 383°C (721°F) for Sample 03-061.

6.3.4.5 Conclusions

The gaseous mercury concentration in the flue gas during the May 2003 test ranged from 4.98–10.6 $\mu\text{g}/\text{m}^3$ with 20% to 70% Hg^0 . The variation in mercury speciation is likely caused by varying coal as well as cofiring TDF and waste seeds.

At low carbon feed concentrations, in the range of 17–48 mg/m^3 (1–3 lb/Macf), the *Advanced Hybrid*TM filter demonstrated overall mercury collection efficiencies, from 65% to 95%. On further increasing carbon concentration in the flue gas, however, only a marginal

Table 6.3.4.7. Microbiologically Mediated Release of Vapor-Phase Mercury and Total Bacterial Count Data for Sample 03-060

Condition	Elemental Mercury, pg/g (pg/g/day)	Organomercury, pg/g (pg/g/day)	Bacterial Count, #/mL	Condition	Elemental Mercury, pg/g (pg/g/day)	Organomercury, pg/g (pg/g/day)	Bacterial Count, #/mL
Anaerobic-Fed	2.42 (0.0691)	0.28 (0.0080)	>24,000,000	Aerobic-fed	57.9 (1.65)	0.36 (0.0103)	>24,000,000
Anaerobic-Fed	3.21 (0.0917)	0.26 (0.0074)	1,500,000	Aerobic-fed	22.8 (0.651)	0.62 (0.0177)	>24,000,000
Anaerobic-Fed	1.15 (0.0329)	0.07 (0.0020)	930,000	Aerobic-fed	45.7 (1.31)	0.25 (0.0071)	>24,000,000
aerobic-Starved	0.87 (0.0249)	0.04 (0.0011)	<30	Aerobic-starved	0.85 (0.0243)	0.09 (0.0026)	4300
Anaerobic-Starved	0.75 (0.0214)	0.03 (0.0009)	40	Aerobic-starved	0.71 (0.0203)	0.07 (0.0020)	430
Anaerobic-Starved	1.72 (0.0491)	0.07 (0.0020)	40	Aerobic-starved	1.34 (0.0383)	0.06 (0.0017)	<30

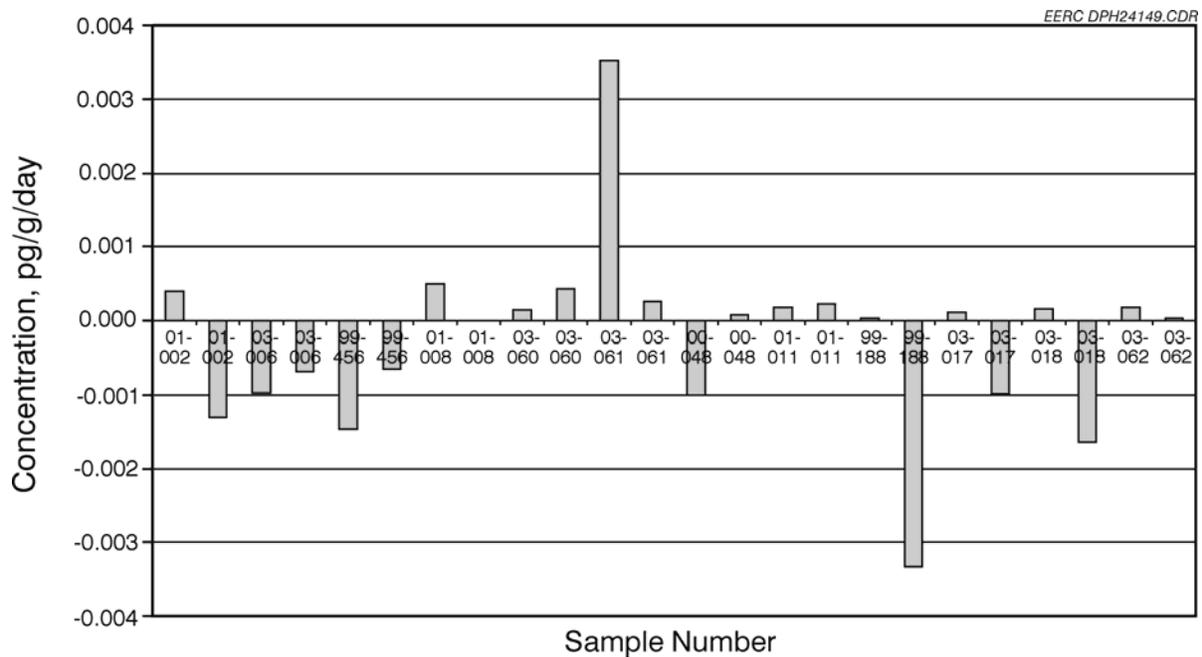


Figure 6.3.4.11. Average total long-term ambient-temperature mercury release or sorption as related to blank values, pg/g/day. Positive values indicate release and negative values indicate sorption of mercury.

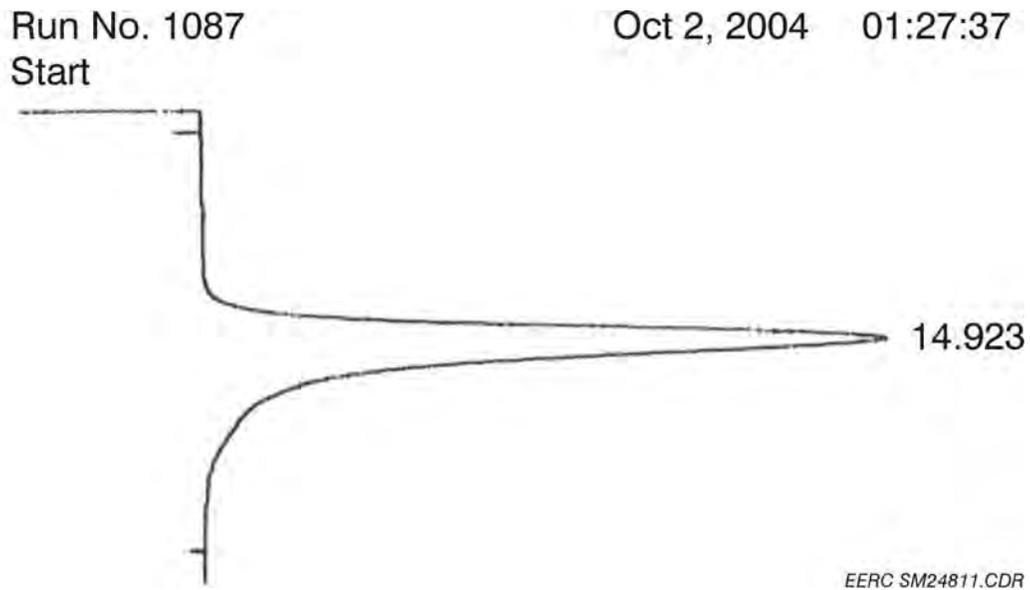


Figure 6.3.4.12. Thermal desorption curve for Sample 03-060.

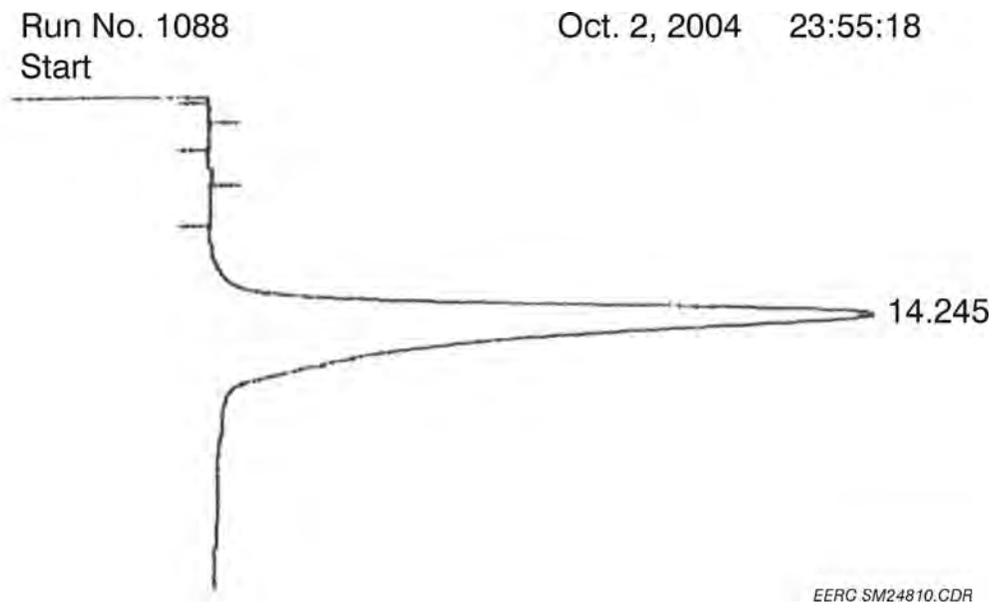


Figure 6.3.4.13. Thermal desorption curve for Sample 03-061

benefit was seen on mercury removal, possibly due to the low level of HCl in the WSB coal flue gas.

Extending the in-flight time of sorbent did not benefit mercury capture in the *Advanced Hybrid*TM filter significantly.

The leaching experiments indicated that the mercury present was not readily leached from the ash samples. There is no observable correlation between total mercury and leachable mercury.

Organomercury compounds were present in leachates from microbiological experiments, but the data reported on microbiological rerelease of mercury are too preliminary for reliable comparisons to be drawn at this time.

The *Advanced Hybrid*TM filter samples appeared to release a small amount of mercury in the long-term ambient temperature release experiments. Most other samples evaluated act as mercury sinks in ambient-temperature vapor-phase release experiments.

The *Advanced Hybrid*TM filter samples released mercury in the elevated temperature release experiments, and both samples released mercury at similar temperatures. This indicated that the mercury forms present are likely similar. Most samples evaluated exhibit a single- or

double- peak mercury release profile, and mercury is generally released at temperatures greater than 200°C (392°F).

6.4 Pilot-Scale Testing of Mercury Oxidation Upstream of Dry Scrubber

6.4.1 Test Conditions

A brief summary of the results of this work are provided in this section. Further details of the mercury oxidation work are provided in a separate report (14).

A North Dakota lignite from Center Mine was burned in the pilot-scale combustion system to test various Hg control strategies. The coal combustion flue gas was cooled to approximately 149°C (300°F) before entering the SDA and PJBH. Seven tests were completed to evaluate the effectiveness of potential Hg sorbents (NORIT FGD) and Hg⁰ oxidation and sorbent enhancement additives (NaCl, SEA2, and CaCl₂) to remove Hg using an SDA and PJBH. The test matrix is presented in Table 6.4.1. Potential Hg⁰ oxidation and sorbent enhancement additives were metered into the coal using a screw feeder prior to combustion, whereas the Hg sorbents were metered with a K-Tron dual-screw feeder upstream of the SDA.

Two CMMs were used to measure Hg⁰ and Hg(g) concentrations simultaneously at the SDA inlet and FF outlet locations to determine the Hg(g) removal efficiency of various control strategies designed to improve the mercury capture of the SDA–PJBH pollutant control system.

Table 6.4.1 Mercury Control Test Matrix

Coal Additive	Feed Rate, mg/m ³ (lb/Macf)	Sorbent	Injection Rate, mg/m ³ (lb/Macf)
None	NA	None	NA
None	NA	NORIT FGD	29.44, 58.72, 117.6, and 176.0 (1.84, 3.67, 7.35, and 11.0)
NaCl	58.72, 117.6, and 176.0 (3.67, 7.35, and 11.0)	None	NA
NaCl	58.72, 117.6, and 176.0 (3.67, 7.35, and 11.0)	NORIT FGD	58.72 (3.67)
SEA2	29.44 and 58.72 (1.84 and 3.67)	None	NA
SEA2	29.44 and 58.72 (1.84 and 3.67)	NORIT FGD	29.44 (1.84)
CaCl ₂	58.72, 117.6, and 176.0 (3.67, 7.35, and 11.0)	None	NA
CaCl ₂	58.72, 117.6, and 176.0 (3.67, 7.35, and 11.0)	NORIT FGD	58.72 (3.67)

During tests involving the addition of Cl-containing compounds, infrared spectroscopy (Model 15°C HCl analyzer) combined with a Perma Pure GASS™ drying system was used to measure HCl concentrations at the SDA inlet.

6.4.2 Coal and Flue Gas Analyses

Proximate and ultimate analysis results for the North Dakota Center Mine lignite are presented in Tables 6.4.2 and 6.4.3, respectively. The Hg and Cl contents of the Center lignite are presented in Table 6.4.4. Based on the proximate and ultimate analysis data, theoretically, the Hg (total) and HCl concentrations of the Center lignite combustion flue gas should be 13.8 µg/Nm³ and 1.59 ppmv, respectively (on a dry flue gas at 3.0% O₂ basis).

Table 6.4.4 summarizes the representative flue gas compositions in the North Dakota lignite flue gas entering the SDA. CO concentrations ranged from <50 to 145 ppmv, which is

Table 6.4.2 Center Lignite Coal Proximate Analysis Results

Analysis Parameters	Concentration, as-received, wt%
Moisture	30.5
Volatile Matter	33.4
Fixed Carbon	29
Ash	7.19
Heating Value, Btu/lb	7330

Table 6.4.3 Center Lignite Coal Ultimate Analysis Results

Analysis Parameters	Concentration, as-received,
Carbon	43.8
Hydrogen ¹	2.82
Nitrogen	0.83
Sulfur	0.84
Ash	7.19
Oxygen (by difference) ¹	14
Total Moisture	30.5

¹Hydrogen and oxygen do not include H and O in sample moisture.

Table 6.4.4 Major Flue Gas Compositions of Center Lignite Flue Gas

O ₂ , %	CO ₂ , %	CO, ppm	NO _x , ppm	SO ₂ , ppm
4–6	14–16	<50–145	560–0710	438–854

indicative of efficient coal combustion and thus very low concentrations of unburned carbon in the fly ash. SDA inlet SO₂ concentrations ranged from 438 to 854 ppm, which is similar to the calculated SO₂ concentration, based on proximate and ultimate coal analysis. The concentration of NO_x was in the range of 560–710 ppm.

6.4.3 Discussion of Mercury Results

Baseline Test

Compared in Figure 6.4.1 are mercury results that were obtained simultaneously using the Ontario Hydro method and CMMs during the combustion of Center coal at the SDA and PJBH inlet and outlet showing little mercury removal.

NORIT FGD Carbon Injection Tests

During this test, the NORIT FGD carbon was continuously injected into the SDA at four different rates in the range of 29.44 mg/m³ (1.84 lb/Macf) to 176.0 mg/m³ (11 lb/Macf). Table 6.4.5 summarizes the overall mercury capture efficiency across the SDA–PJBH in the carbon injection tests. Compared to the very low 2.5% inherent mercury capture in the baseline test, with carbon injection, the Hg(g) removal efficiency of the SDA–PJBH improved immediately

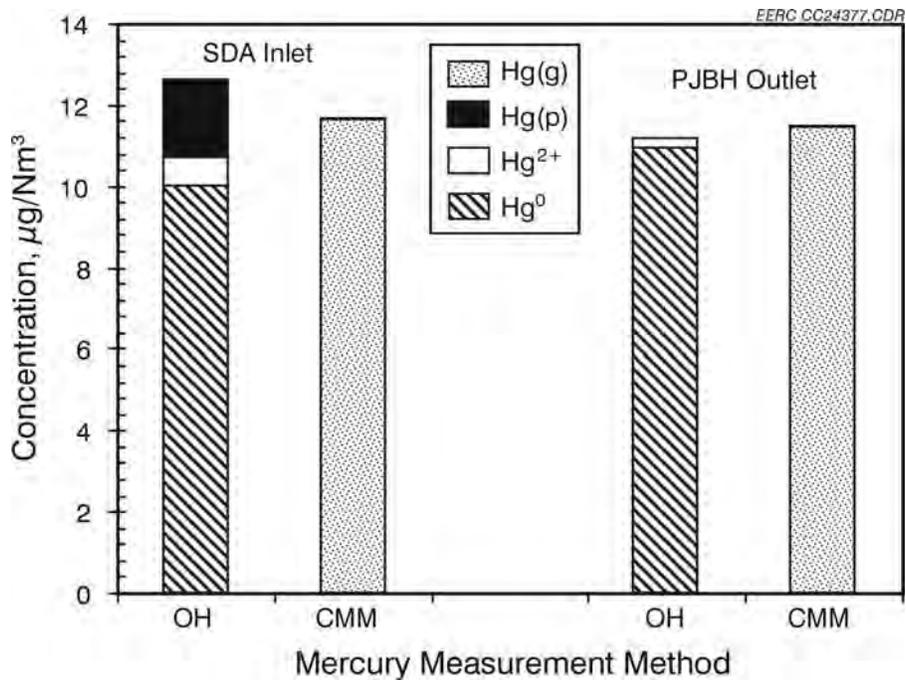


Figure 6.4.1. SDA inlet and PJBH outlet mercury results in the SDA and PJBH baseline test.

Table 6.4.5 SDA–PJBH Hg(g) Removal Efficiencies (%) with NORIT FGD Injection

Injection Rate, mg/m ³ (lb/Macf)	0.0 (0.0)	29.44 (1.84)	58.72 (3.67)	117.6 (7.35)	176.0 (11)
Average	40.0 (2.5)	584.0 (36.5)	691.2 (43.2)	888.0 (55.5)	948.8 (59.3)
95% Confidence Limit	±13.12 (±0.82)	±40.0 (±2.5)	±20.8 (±1.3)	±35.2 (±2.2)	±54.4 (±3.4)

and continued to improve with increasing injection rates until it approached about 60% at an injection rate of 117.6 mg/m³ (7.35 lb/Macf).

Mercury Oxidation and Sorbent Enhancement Additive Performance

Three mercury oxidation and sorbent enhancement additives including NaCl, CaCl₂, and SEA2 were tested separately for their effectiveness of mercury oxidation and capture across the SDA–PJBH in the North Dakota lignite flue gas. Additional tests were also completed to evaluate the beneficial effects of these additives on mercury sorbent injection technology.

Figure 6.4.2 and Table 6.4.6 summarize and compare the average SDA–FF Hg(g) removal efficiencies when NaCl, CaCl₂, and SEA2 additives were used with and without NORIT FGD injection. The combination of SEA2 addition and NORIT FGD injection provided the best SDA–FF Hg(g) removal efficiency, even at the lowest addition and injection rates of 1.84 lb/Macf. NaCl and CaCl₂ addition combined with NORIT FGD injection provided similar high levels of SDA–FF Hg(g) removal, 70%–90%, although the lone addition of SEA2 at 58.72 mg/m³ (3.67 lb/Macf) also provided a similar level of efficient Hg(g) removal.

6.4.4 Conclusions

NORIT FGD and three Hg⁰ oxidation and sorbent enhancement additives NaCl, CaCl₂, SEA2 were evaluated in the PTC equipped with an SDA–PJBH. A Center lignite coal was burned in the unit while Hg(g) concentrations were measured using CMMs at the SDA inlet and PJBH outlet to evaluate Hg removal performance. The inlet center lignite flue gas had 12–13 µg/Nm³ mercury, and there was only 2.5% inherent mercury capture across the SDA–PJBH

The Hg(g) removal efficiency when activated carbon was injected upstream of the SDA improved with increasing injection rates until it approached about 60% at an injection rate of 117.6 mg/m³ (7.35 lb/Macf).

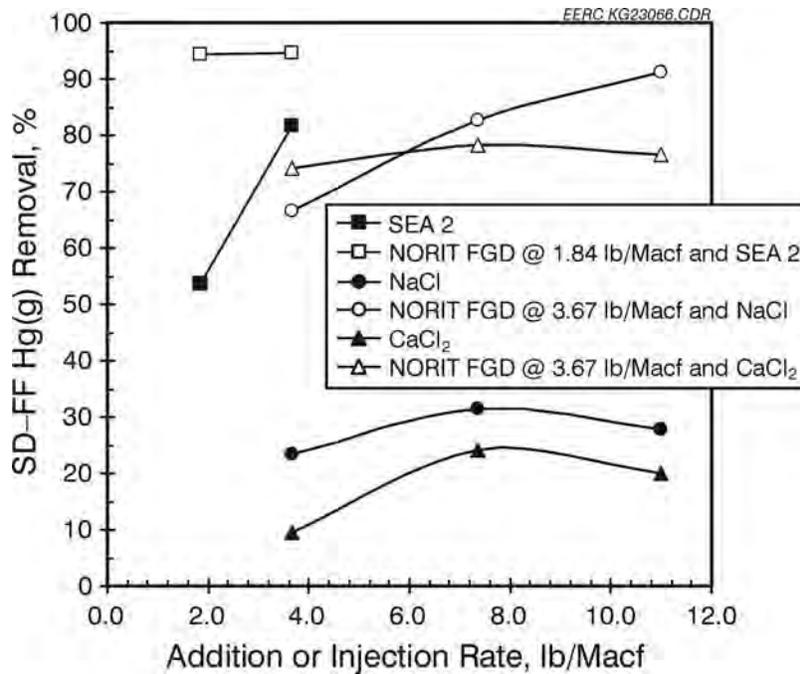


Figure 6.4.2. Comparisons of mercury removals in SDA-PJBH with additive alone and in combination with FGD injection.

Table 6.4.6 Average ($\pm 95\%$ confidence limit) SDA-FF Hg(g) Removal Efficiencies for Sorbents and Additives, %

Sorbent and/or Additive	Injection or Addition Rate, mg/m ³ (lb/Macf)			
	29.44 (1.84)	58.72 (3.67)	117.6 (7.35)	176.0 (11)
NORIT FGD	584.0 \pm 40.0 (36.5 \pm 2.5)	691.2 \pm 20.8 (43.2 \pm 1.3)	888.0 \pm 35.2 (55.5 \pm 2.2)	948.8 \pm 54.4 (59.3 \pm 3.4)
NaCl	NT	376.0 \pm 57.6 (23.5 \pm 3.6)	504.0 \pm 36.8 (31.5 \pm 2.3)	444.8 \pm 6.4 (27.8 \pm 0.4)
CaCl ₂	NT	152.0 \pm 12.8 (9.5 \pm 0.8)	387.2 \pm 22.4 (24.2 \pm 1.4)	320.0 \pm 44.8 (20.0 \pm 2.8)
SEA2	859.2 \pm 84.8 (53.7 \pm 5.3)	1308.8 \pm 19.0 (81.8 \pm 1.2)	NT	NT
NORIT FGD @ 58.72 mg/m ³ (3.67 lb/Macf) and NaCl	NT	1065.6 \pm 38.4 (66.6 \pm 2.4)	1321.6 \pm 38.4 (82.6 \pm 2.4)	1459.2 \pm 8.0 (91.2 \pm 0.5)
NORIT FGD @ 58.72 mg/m ³ (3.67 lb/Macf) and CaCl ₂	NT	1187.2 \pm 27.2 (74.2 \pm 1.7)	1254.4 \pm 33.6 (78.4 \pm 2.1)	1224.0 \pm 72.0 (76.5 \pm 4.5)
NORIT FGD @ 29.44 mg/m ³ (1.84 lb/Macf) and SEA2	1513.6 \pm 14.4 (94.6 \pm 0.9)	1508.8 \pm 41.6 (94.3 \pm 2.6)	NT	NT

The addition of NaCl or CaCl₂ to the Center lignite did not significantly increase the level of oxidized mercury, but the combination of the additive and NORIT FGD injection was very effective in capturing Hg(g) in the SDA–PJBH pollution control devices. 176.0 mg/m³ (11 lb/Macf) NaCl in conjunction with 58.72 mg/m³ (3.67 lb/Macf) NORIT FGD provided 90% overall mercury removal with the SDA–PJBH. Injection of NORIT FGD at a rate of 58.72 mg/m³ (3.67 lb/Macf) with 176.0 mg/m³ (11 lb/Macf) CaCl₂ addition to the coal resulted in 80% Hg(g) removal across the SDA–PJBH.

The addition of SEA2 alone to the coal at a rate of 58.72 mg/m³ (3.67 lb/Macf) resulted in about 80% removal across the SDA–PJBH. The combination of NORIT FGD injection at 29.44 mg/m³ (1.84 lb/Macf) and SEA2 addition provided exceptional SDA–FF Hg(g) capture, >90%, even at the lower addition rate of 29.44 mg/m³ (1.84 lb/Macf).

These tests were not conducted with an *Advanced Hybrid*[™] filter, but they addressed specifically a possible application for the *Advanced Hybrid*[™] filter: the case where it would be installed downstream of a spray dryer scrubber. The testing proved that the Hg oxidant and sorbent enhancement additives, similar to cofiring TDF, formed very reactive species in the combustion zone, which effectively converted elemental mercury to oxidized and/or particle-bound mercury and improved the reactivity between gaseous mercury and injected carbons. As a result, the particle-bound mercury was easily captured on the filter bags. These results apply directly to mercury control with the *Advanced Hybrid*[™] filter and offer additional alternatives to help achieve a very high level of control while minimizing the amount of carbon required.

7.0 CONCLUSIONS

7.1 Bench-Scale Tests at the EERC

Bench-scale results confirmed that the SO₂ and NO₂ concentration effects were additive and had a significant effect on sorbent performance. This finding facilitated predicting sorbent performance in real systems when the SO₂ and NO₂ concentrations were known.

Another key finding from the bench-scale tests was that the fixed-bed sorbent-screening tests using simulated flue gas were in good agreement with similar tests sampling real flue gas. This suggests that as long as the main flue gas components are duplicated, the bench-scale fixed-bed tests can be utilized to indicate sorbent performance in larger-scale systems.

7.2 Pilot-Scale Tests at the EERC

Eight weeks of pilot-scale tests were completed in this project to measure *Advanced Hybrid*TM filter mercury control with NORIT FGD carbon injection for both EB and WSB coal flue gases. Several operating parameters, including carbon injection rate 19 mg/m³–38 mg/m³ (1.2–2.4 lb/Macf), carbon residence time (1 and 24 hr), injection mode (continuous vs. batch), and corona current (0.5–4.0 mA), were varied during the tests to understand their impacts on mercury emissions from the *Advanced Hybrid*TM filter. Alternative mercury control technologies including TDF cofiring by the EERC, treated carbon by the EERC, amendate silicate by ADA, iodine-treated activated carbon from Barneby and Sutcliffe, and a cartridge filter insert by W.L. Gore were tested in this project for mercury removal with the *Advanced Hybrid*TM filter. Additional tests were completed to determine mercury control efficiency in a PJBH compared to the *Advanced Hybrid*TM filter under the same conditions.

The mercury species in the WSB coal flue gas was primarily elemental mercury, 65%–75%; 20%–30% oxidized mercury; and less than 5% particle-bound mercury. The inherent mercury removal across the *Advanced Hybrid*TM filter or PJBH with typical WSB flue gas was at low levels of 0%–20% as a result of low LOI in the fly ash and low levels of particle-bound mercury and acid gases in the flue gas.

With continuous NORIT FGD injection into a typical WSB flue gas entering the *Advanced Hybrid*TM filter, the *Advanced Hybrid*TM filter mercury removal was 50%–60% at an injection rate of 19 mg/m³ (1.2 lb/Macf), and increased to 65%–87% at 38 mg/m³ (2.4 lb/Macf). A comparison of short and long residence time in the *Advanced Hybrid*TM filter indicated no significant mercury desorption from the injected carbon upon continued exposure to the low-

sulfur flue gases up to 24 hr. Reducing corona current improved overall mercury capture in the *Advanced Hybrid*TM filter since more carbon deposited on the perforated plates and filter bags at the reduced corona current. An extreme case was when the unit was operated as a PJBH by completely shutting off the high-voltage power while maintaining continuous carbon injection. At 19-mg/m³ (1.2-lb/Macf) NORIT FGD carbon injection into the PJBH, the overall mercury removal with the PJBH was 72.7% with the WSB coal flue gas. However, the PJBH experienced frequent pulse cleaning and high particulate matter emissions under the high filtration velocity.

Power-off batch injection of the activated carbon provided somewhat better mercury removal than continuous injection in the *Advanced Hybrid*TM filter. A 71.2% overall mercury removal across the *Advanced Hybrid*TM filter was attained with WSB coal flue gas at 19 mg/m³ (1.2 lb/Macf) power-off NORIT FGD batch injection and 87% mercury collection efficiency at 38 mg/m³ (2.4 lb/Macf) power-off NORIT FGD batch injection. A power-on NORIT FGD injection, at 38 mg/m³ (2.4 lb/Macf), provided 75.5% overall mercury capture with the *Advanced Hybrid*TM filter for the typical WSB coal flue gas.

Cofiring TDF with a WSB coal had a significant effect on mercury speciation in the flue gas. 47% of the total mercury was oxidized with 5% (mass basis) TDF cofiring, and the oxidized mercury percentage increased to 87% at 10% TDF cofiring. The inherent mercury removal across the *Advanced Hybrid*TM filter was approximately 30% with 10% TDF cofiring, compared to less than 10% for the baseline tests. The possible reasons could be elevated HCl concentration, activated unburned carbon, or other changes in combustion and flue gas components.

Cofiring TDF also enhanced mercury capture with NORIT FGD carbon for the WSB coal. Cofiring 5%–10% TDF combined with 24 mg/m³ (1.5 lb/Macf) NORIT FGD injection provided 88%–95% overall mercury capture across the *Advanced Hybrid*TM filter with the western subbituminous coal flue gas compared to 48.4%–71.2% Hg capture efficiency with NORIT FGD carbon injection alone.

The proprietary sorbent developed by the EERC demonstrated over 90% mercury removal with the perforated plate only *Advanced Hybrid*TM filter at an injection rate of 32 mg/m³ (2 lb/Macf).

The IAC provided no better mercury removal with the *Advanced Hybrid*TM filter in the WSB coal flue gas than the FGD carbon. However, with the IAC, a larger fraction of mercury was oxidized across the *Advanced Hybrid*TM filter.

The cartridge filters of Insert A and B showed excellent (over 98%) mercury oxidation in the *Advanced Hybrid*TM filter, and Cartridge B attained 75% overall mercury removal efficiency in the WSB coal flue gas after 20-hr operation. The mercury capture performance of the cartridge filter was highly temperature-dependent. The best operating temperature was in the range of 124°~149°C (255°~300°F).

In an EB coal flue gas with high levels of acid gases, most of the mercury was in oxidized form. A number of short- and longer-term tests with NORIT FGD carbon injection at both 135° and 160°C (275° and 320°F) with both the *Advanced Hybrid*TM filter and the PJBH showed that this sorbent was completely ineffective at mercury control for the EB coal flue gas. Amended silicate developed by ADA also showed ineffective mercury capture for this coal flue gas.

7.3 Field Demonstration at the Big Stone Power Plant

Two 1-week short-term and two 1-month long-term field tests were completed with the 2.5-MW (9000-acfm) *Advanced Hybrid*TM filter unit at the Big Stone Power Plant to demonstrate mercury control with the *Advanced Hybrid*TM filter by using carbon injection and to evaluate the corresponding impacts on *Advanced Hybrid*TM filter performance.

Without significant TDF cofiring, the average mercury species was 51% elemental, 32% oxidized, and 17% particle-bound mercury. Inherent mercury capture with the *Advanced Hybrid*TM filter for baseline tests was 0%–10%.

Without any TDF cofiring, 24-mg/m³ (1.5-lb/Macf) continuous NORIT FGD carbon injection into the *Advanced Hybrid*TM filter resulted in 63%–90% overall mercury removal. Part of the reason for the widely varying mercury collection efficiency could be the varying flue gas temperatures. Increasing the carbon injection rates yielded only a marginal benefit on mercury removal.

Short-term tests indicated that power-off batch carbon injection and reducing corona current improved *Advanced Hybrid*TM filter mercury capture, while extending the in-flight time of sorbent did not benefit mercury capture significantly. High mercury removals were seen both for the 2.0-kPa pulse trigger tests, which resulted in a 3-hr pulse interval, and for the 20-min pulse interval tests, indicating that a long pulse interval is not necessary to achieve good mercury capture in the *Advanced Hybrid*TM filter.

A small amount of TDF cofiring, 150–177 tons a day, significantly changed mercury species in the WSB coal flue gas: 6.4% elemental, 38.1% oxidized, and 55.4% particle-bound

mercury. The corresponding inherent mercury capture with *Advanced Hybrid*TM filter was up to 49%, compared to the 0%–10% in the baseline tests without cofiring TDF.

TDF cofiring also enhanced carbon effectiveness on mercury capture by improving the reactivity between mercury and carbon. Depending on the cofiring rate of TDF, 24-mg/m³ (1.5-lb/Macf) NORIT FGD carbon injection attained mercury removals in the *Advanced Hybrid*TM filter of 68% to 97%.

Based on measured pressure drop across the *Advanced Hybrid*TM filter, bag-cleaning interval, K₂C_i, and residual drag, there was no perceptible effect of carbon addition on the performance of the *Advanced Hybrid*TM filter.

The leaching results from the *Advanced Hybrid*TM filter hopper ash, which contained spent carbon sorbent, indicated that the mercury present was not readily leachable. There was no observable correlation between the total mercury in the ash and the leachable mercury.

7.4 Pilot-Scale Testing of Mercury Oxidation Upstream of the Dry Scrubber

NORIT FGD and three Hg⁰ oxidation and sorbent enhancement additives (NaCl, CaCl₂, and SEA2) were evaluated in a Center lignite flue gas under an SDA–PJBH configuration. The inlet Center lignite flue gas had 12–13 µg/Nm³ mercury, and there was only 2.5% inherent mercury capture across the SDA–PJBH.

The Hg(g) removal efficiency when activated carbon was injected upstream of the SDA improved with increasing injection rates until it approached about 60% at an injection rate of 117.6 mg/m³ (7.35 lb/Macf).

The addition of NaCl or CaCl₂ to the Center lignite did not significantly increase the level of oxidized mercury, but the combination of the additive and NORIT FGD injection was very effective in capturing Hg(g) in the SDA–PJBH pollution control devices. 176.0 mg/m³ (11 lb/Macf) NaCl in conjunction with 58.7 mg/m³ (3.67 lb/Macf) NORIT FGD provided 90% overall mercury removal in the SDA–PJBH. Injection of NORIT FGD at a rate of 58.7 mg/m³ (3.67 lb/Macf) with 176.0 mg/m³ (11 lb/Macf) CaCl₂ addition to the coal resulted in 80% Hg(g) removal across the SDA–PJBH.

The addition of SEA2 alone to the coal at a rate of 58.72 mg/m³ (3.67 lb/Macf) resulted in about 80% removal across the SDA–PJBH. The combination of NORIT FGD injection at 29.4 mg/m³ (1.84 lb/Macf) and SEA2 addition provided exceptional SDA–FF Hg(g) capture, >90%, even at the lower addition rate of 29.4 mg/m³ (1.84 lb/Macf).

7.5 Significance of Conclusions

A goal of the project was to demonstrate 90% mercury control with the *Advanced Hybrid*TM filter using low addition rates of carbon. This was demonstrated for WSB coals under some conditions. With supplemental TDF cofiring, results showed that over 90% mercury control is achievable with a small addition rate (24 mg/m³ [1.5 lb/Macf]) of carbon injected upstream of the *Advanced Hybrid*TM filter. Without TDF cofiring, the level of mercury control was typically in the range from 50%–75%. These findings are significant because they indicate that mercury removal is limited more by the flue gas and sorbent chemistry rather than a mass transfer limit of the gas–solid contact within the *Advanced Hybrid*TM filter. This was further proven in perforated plate tests, which showed that 90% mercury control was achieved across the perforated plates alone with a superior sorbent. To achieve high levels of mercury control, the carbon injection rate of the FGD sorbent can be increased, but results indicate that a better approach might be to alter the flue gas chemistry to make the sorbent more effective or to use an alternative advanced sorbent. The oxidation tests with an SDA scrubber also demonstrated that additives can significantly improve mercury capture with a reasonably low carbon addition rate.

Another highly significant result from the research was that the carbon injection had no effect on the pressure drop or bag-cleaning interval of the *Advanced Hybrid*TM filter. This finding is not surprising because the *Advanced Hybrid*TM filter is designed to handle a full dust loading, so a small increase in dust loading from the carbon addition would be expected to have only a minor effect on pressure drop. In addition, since over 90% of the dust is collected on the perforated plates, most of the increased loading from the carbon injection never reaches the bags. This means that the *Advanced Hybrid*TM filter is capable of handling much higher carbon loadings without a significant effect on pressure drop. This is a major advantage of the *Advanced Hybrid*TM filter over a PJBH that is installed as a polishing device downstream of an ESP. In that case, the PJBH is designed to handle only a very low dust loading so that any additional carbon injection would likely significantly affect the pressure drop and/or bag-cleaning interval.

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