

Development and Demonstration of Mercury Control by Adsorption Processes (MerCAP™)

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ABSTRACT

Over the last several years, EPRI has been developing a promising mercury control technology known as MerCAP™ (Mercury Control Adsorption Processes). For this process, a rigid, mercury adsorbing sorbent-coated structure is placed in the duct. Mercury is removed from the flue gas as it flows past the rigid structure. When the plates and tubes are saturated with mercury, they can then be removed as a cartridge or regenerated in-situ. The mercury can be recovered and isolated.

The attractiveness of this approach is that the process can be retrofitted into existing ductwork, baghouse or ESP casing, or the stack, and no waste is generated (mercury is recovered). Testing to-date has been conducted with structures coated with a thin layer of gold and with structures containing activated carbon. This paper describes several field test programs conducted to test prototype bench-scale MerCAP™ systems on units firing subbituminous Powder River Basin (PRB) coal and North Dakota lignites. These tests were conducted with gold-coated MerCAP™ plates.

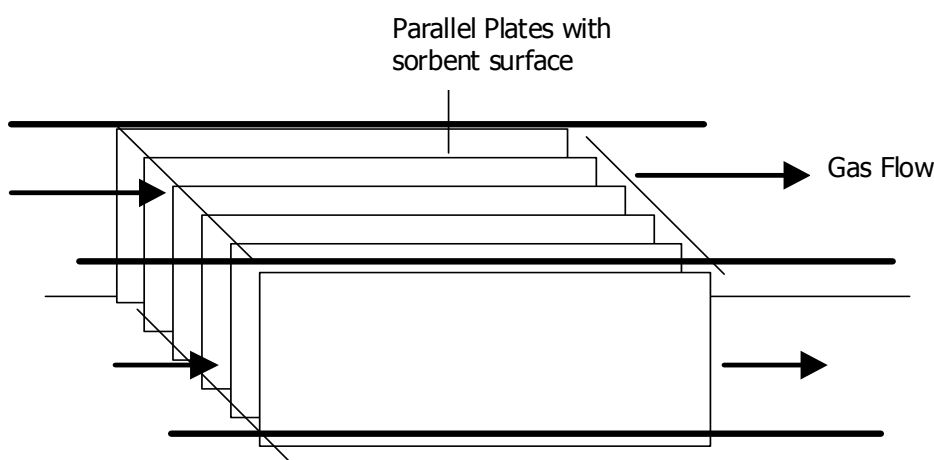
BACKGROUND

The U.S. Environmental Protection Agency (EPA) has submitted a Mercury Study Report to Congress that states that 52 of the 158 tons of anthropogenic Hg emissions in the United States are from coal-fired utility boilers. On December 14th 2000, EPA announced that it would regulate mercury emissions from coal-fired boilers under Title III of the 1990 Clean Air Act Amendments. EPA plans to issue final regulations by December 15th 2004 and is expected to require compliance by December 2007.

MerCAPTM

One potential novel option for mercury control is EPRI's Mercury Control Adsorption Process (MerCAPTM) technology. The general concept for the MerCAPTM is to place fixed structures into the flue gas stream to adsorb mercury and then periodically regenerate them and recover the mercury. The plates are placed at suitable locations in the ductwork downstream of the air heater where temperatures are normally <400°F. The fixed structures can be made of a sorbent or coated with a sorbent material such as activated carbon or metals which can amalgamate with mercury such as gold and silver. As the surfaces of the sorbent structure become saturated, the structure can be heated electrically or with other means such as passing hot gas over them. One example of such a structure is parallel gold-coated plates as shown in Figure 1.

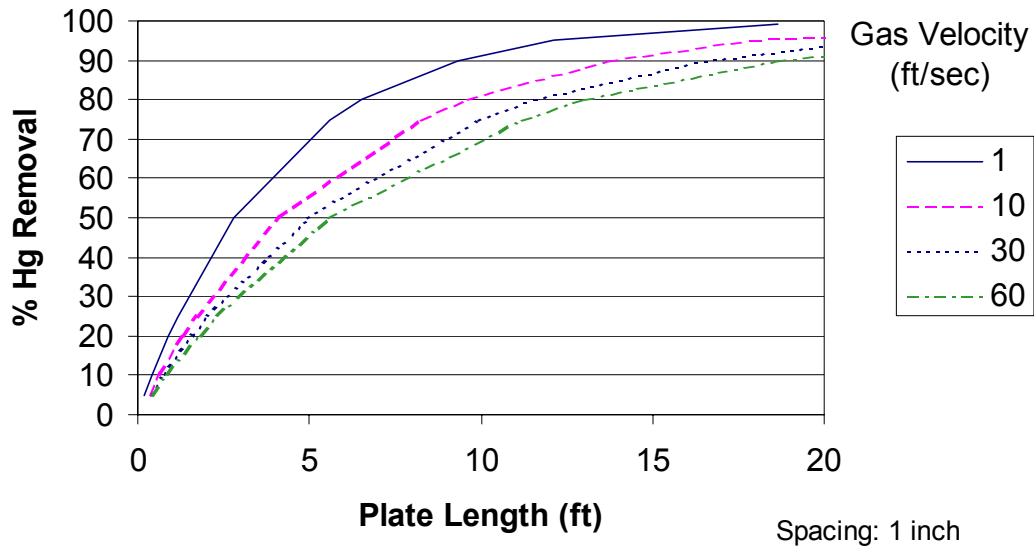
Figure 1. MerCAPTM Schematic



Model Predictions: Mercury Removal and Pressure Drop

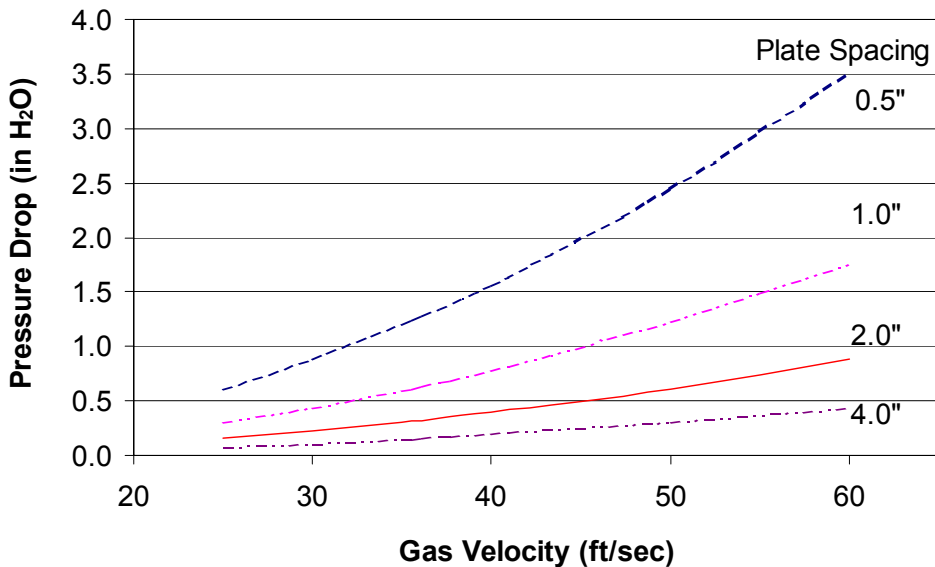
A mass transfer analysis was performed to predict potential removal with the MerCAPTM design. Figure 2 indicates the projected mercury removal for gas velocities from 1 to 60 ft/sec at a plate-to-plate spacing of 1-inch. As shown, 80% mercury removal is projected for an installation that is operating at 60 ft/sec with 15-foot long plates. At gas velocities of 10 to 15 ft/sec, similar to those present in an SCR installation, the model predicts > 90% mercury removal with 15-foot long plates.

Figure 2. Effect of Gas Velocity on Mercury Removal with Rigid Sorbent-Coated Plates



Pressure drop across the system begins to be of concern at narrower plate spacing and higher velocity. The projected pressure drop for plate-to-plate spacing from 0.5 to 4 inches is presented in Figure 3. As shown, for the case discussed in the previous paragraph, < 2.0 inches of additional pressure drop would be expected at a plate-to-plate spacing of 1-inch and a gas velocity of 60 ft/s.

Figure 3. Projected Pressure Drop Across Sorbent Plates



Early Field and Laboratory Test Results

Most of the tests to date have been focused on gold as the sorbent since it has been shown to be fairly inert and can amalgamate mercury readily. Initial proof-of-concept testing was conducted

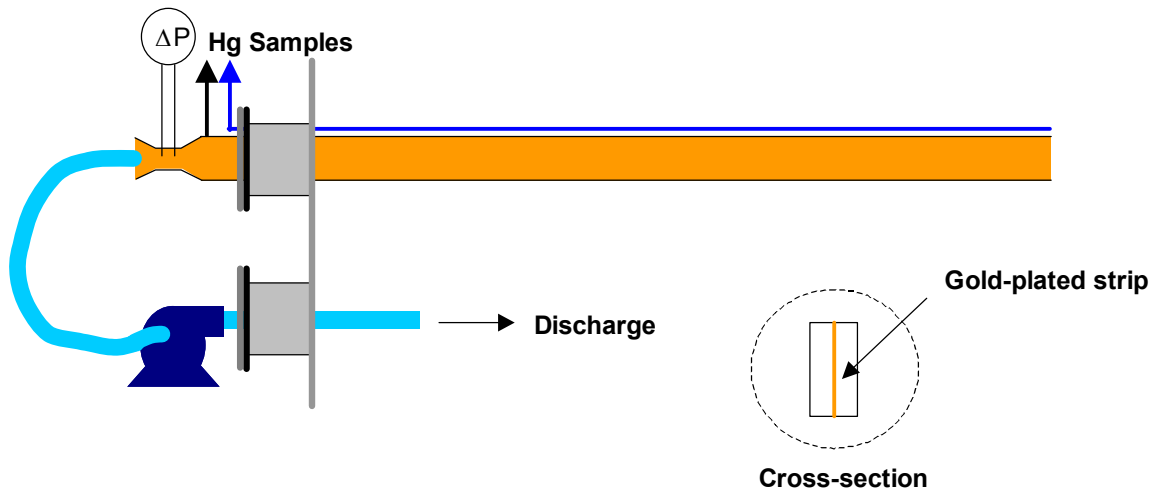
on a variety of coal-fired sites (western subbituminous, low-sulfur bituminous, and lignite coals). Gold-coated coupons were exposed in the gas stream for selected periods of time, and the performance was checked periodically by removing the coupons and testing them in the laboratory using simulated flue gas. The results indicated that the mercury removal of the samples exposed to flue gas for up to 2160 hours at temperatures up to 375°F continued to remain close to theoretical predictions in the follow-up laboratory tests and the initial mercury removal could be fully recovered by thermal regeneration.

DESCRIPTION OF EQUIPMENT

MerCAP™ Probes

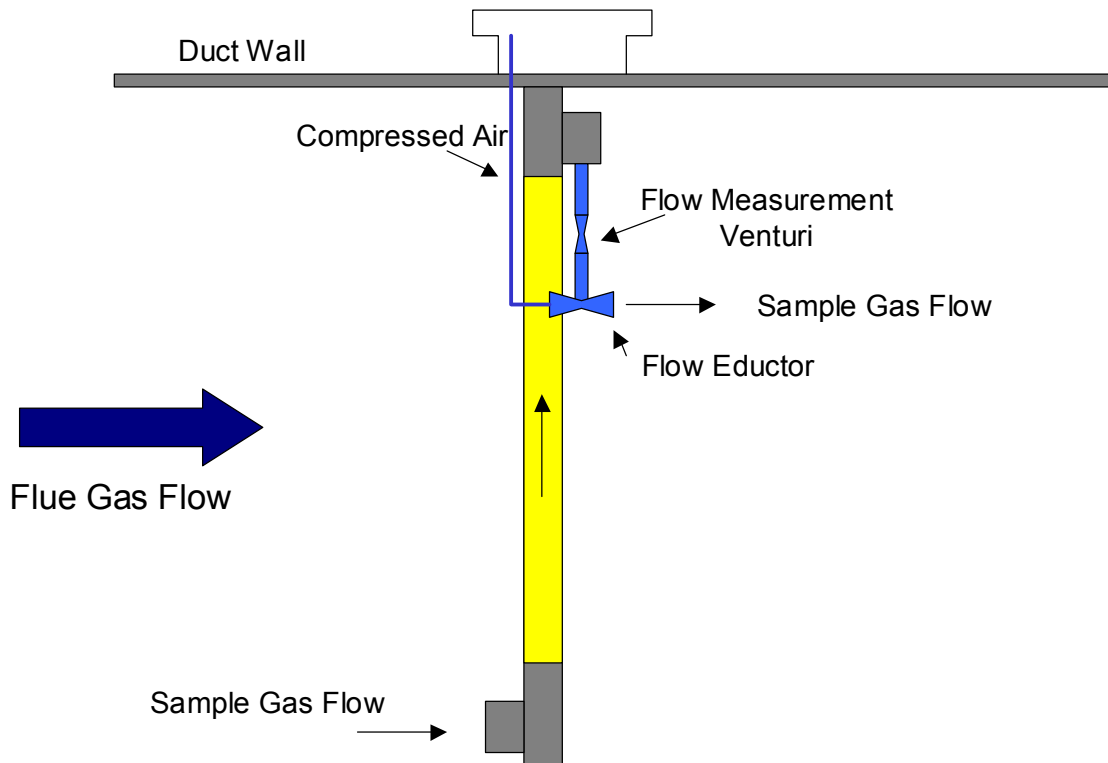
Two bench-scale test systems have been fabricated to facilitate field installation and testing at conditions (temperature and face velocity) representative of full-scale installations. The Mini-MerCAP™ test system consists of a 10-foot probe inserted into a standard 4-inch test port at a plant and is designed for a range of gas flow rates from 40 to 50 acfm. The probe incorporates an inlet and outlet sample manifold, a flow measurement venturi, and a fan. A sketch of this system is shown in Figure 4. The test section consists of a 10-foot long chamber. A single, 2-inch high plate was installed in the chamber and the wall spacing is set to simulate 1-inch plate-to-plate spacing. Flue gas is drawn across the plates and the mercury is measured at the inlet and outlet of the chamber.

Figure 4. Sketch of Mini-MerCAP™ Probe



The large MerCAP™ probe was designed and fabricated to allow testing at flow rates of 150 acfm and full-length plates. A sketch of this system is shown in Figure 5. As indicated the probe is placed inside the duct and gas is drawn across plates installed inside the probe. The plate spacing and flow rate are variable. The gold plates installed in the large MerCap™ probe are 14 inches long and 8.4 inches wide. The size of the prototype plates was limited by bath size for the small batch plating process. Therefore, 17 plate sections were required for the large probe. A custom bath could be fabricated for larger batches.

Figure 5. Large MerCAP (150 acfm) Field Evaluation Probe



Another small swatch test fixture (2 slpm) has also been used at several sites to evaluate the effectiveness of gold-coated screens. In this arrangement, two circular screens were placed in a standard 47 mm filter holder with an open diameter of 35 mm. The holder is heated and flue gas is drawn across the screens at a face velocity similar to the velocity in a standard baghouse used for particulate control. Mercury measurements are made upstream and downstream of the screens.

Mercury Monitors

Continuous measurement of mercury at the inlet and outlet of the bench-scale control device is a critical component of a field test system where mercury levels fluctuate with boiler operation (temperature, load, etc.). The analyzers used for these tests consisted of a cold vapor atomic absorption spectrometer (CVAAS) coupled with a gold amalgamation system (Au-CVAAS). The system is calibrated using vapor phase elemental mercury. The semi-continuous mercury

emissions monitors (S-CEMs) were configured to automatically switch from measuring total vapor phase mercury to vapor phase elemental mercury during these tests. Oxidized mercury can then be calculated by difference.

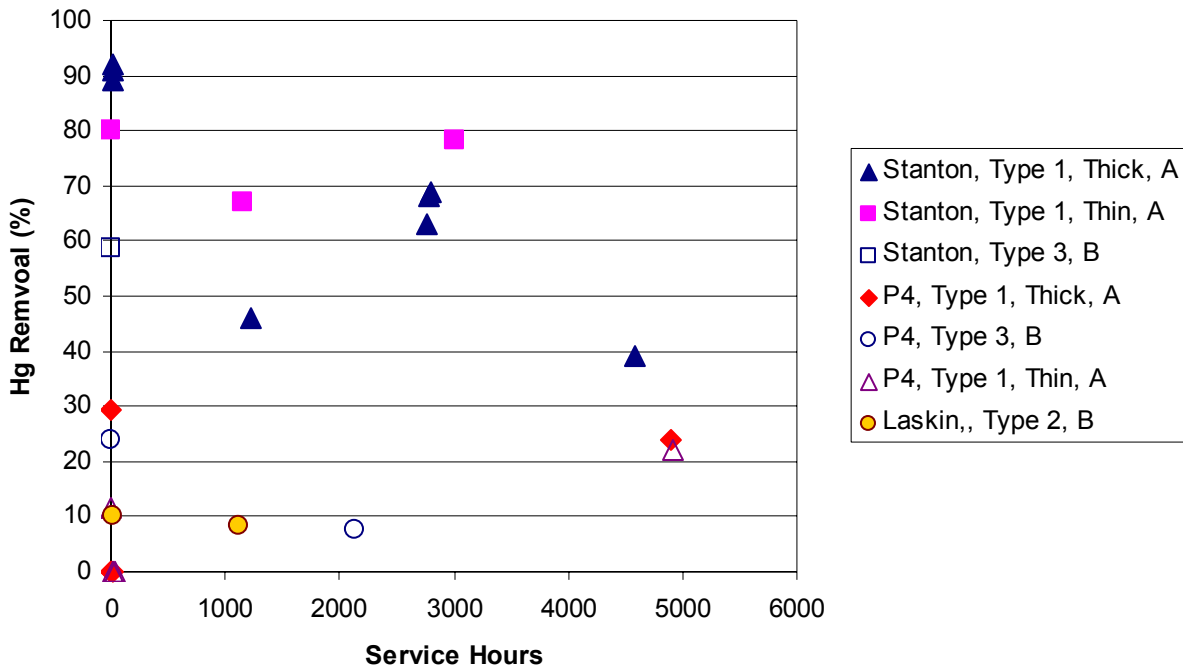
MERCAP™ SLIPSTREAM TESTS

Field tests were conducted at four different sites with the in-situ probes with various spacing and gold coatings (different thickness and support plates). The in-situ probes were designed and fabricated to allow testing of full-length (10-foot long) plates. Table 1 summarizes the test conditions at the four sites. The sites included two PRB units, one equipped with an ESP (probe located downstream of the ESP) and one with a wet particulate scrubber (WPS) (probe located upstream of the WPS in full dust loading) and two ND lignite units, one equipped with an ESP (probe located downstream of ESP) and one with a spray dryer-baghouse (downstream of SD-BH). The results of these in-situ exposure tests are summarized in Figure 6.

Table 1. Summary of MerCAP™ Field Sites

Site ID	Plant	Coal Type	Fuel Composition		Test Location	HCl at Test Loc (est. ppm)	SO ₂ at Test Loc (ppm)
			S (%)	Cl (ppm)			
S2	Pleasant Prairie (P4)	Sub-bituminous	0.5	14	ESP Outlet	< 10	280-340
S9	Laskin	Sub-bituminous	0.4	<50	WPS Inlet	0.7	200-400
L1	Coal Creek	ND Lignite	1	20	ESP Outlet	<10	1000
L2	Stanton	ND Lignite	0.06	30	SD Outlet	<10	100

Figure 6. MerCAP™ Gold plates Removal Effectiveness With Time of Exposure



A= 0.5 inch plate spacing, B= 1 inch plate spacing, plates are 10 ft long, gas velocities over plate 30 to 50 ft/s

Stanton Station

Slipstream MerCAP™ evaluation tests were begun at Great River Energy’s Stanton Station, Unit 10 in October 2001. Stanton Station burns a North Dakota lignite coal and is configured with a spray dryer and baghouse (SD-BH) for SO₂ and particulate control. One large MerCAP™ probe was installed downstream of the baghouse and a Mini-MerCAP™ probe was tested both upstream of the spray dryer and downstream of the baghouse.

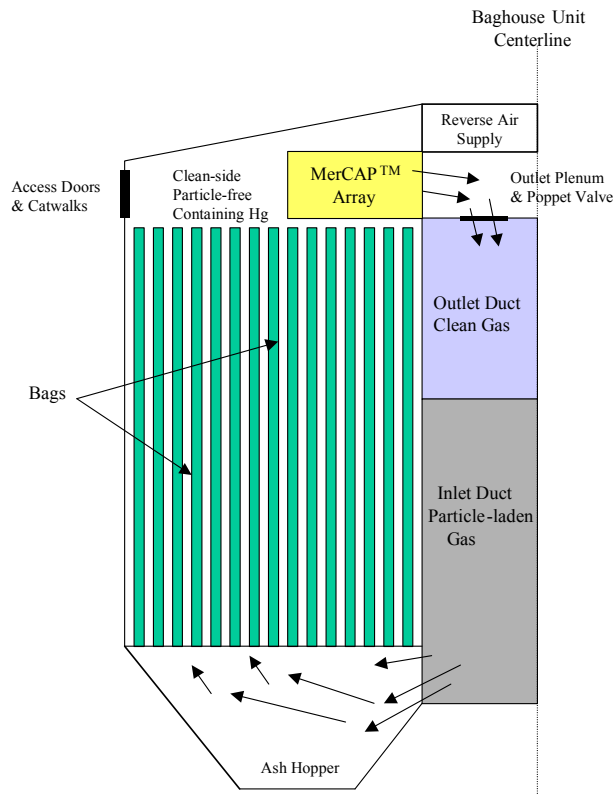
At Stanton Station, one set of 10-foot long MerCAP™ plates with half inch plate spacing placed downstream of the SD-BH and exposed to flue gas for 4582 hours. The initial mercury removal was 89% (theoretical removal for these conditions is 95%) and the removal at the end of testing was 39% at gas velocities ranging from 16 to 40 ft/sec. A second set of MerCAP™ plates using the same type of substrate and coated with nominally half the gold than what was applied to the first set of plates was operated for 3030 hrs. Initial removal was 80%. The mercury removal across the set of plates with the thicker coating of gold after 2800 hours was 69% at a gas velocity of 32 ft/sec as compared to 70% removal at a gas velocity of 30 ft/sec (3030 hours) for the thinner coating of gold. Pressure drop across the plates was <3-inches of water at flue gas velocities of >40ft/sec. It is difficult to determine from the data if additional gold would improve the long-term effectiveness of the gold-coated plates between thermal desorption periods. Ash buildup was observed on the plates when removed from service.

Three types of stainless steel substrates were evaluated at Stanton for variations in mercury removal effectiveness. A Mini-MerCAP™ probe was installed and operated alongside the existing large MerCAP™ probe and used for these evaluations. The plates in the Mini-MerCAP™ probe were spaced 1-inch apart as compared to the large MerCAP™ probe with a plate spacing of 0.5 inches. Initial results indicate that the mercury removal in the mini-probe with a single 10-foot long plate and a gas velocity of 40 ft/sec was 55%. The predicted removal based upon the model is 60%. The substrate material tested during this Mini-MerCAP™ test was the same material used in the initial evaluations in the large probe. This material was removed from the Mini-MerCAP™ probe and replaced with a lower-cost material. The mercury removal measured across the new, Type 2, material at the same operating conditions was 93%, suggesting that the new, lower cost substrate may be more effective at promoting surface layer mixing.

A variation of the Type 2 material, identified in this paper as Type 3 material, was installed in the large probe. Initial mercury measurements across one plate of the new material indicated 50 to 60 % removal at velocities from 9 to 31 ft/sec. Model predictions suggest that 60% mercury removal should be achieved across 10-foot long plates with 1-inch spacing at a gas velocity of 34 ft/sec.

The extractive Mini-MerCAP™ probe was also installed upstream of the Unit 10 spray dryer. The second gold-coated stainless steel material from the same batch of Type 3 material installed in the large probe was installed in the mini-probe for testing. The data suggests that insignificant mercury removal was achieved across one 10-foot long plate during tests at this location. The range of test conditions included temperatures from 200 to 300°F and gas velocities from 10 to 60 ft/sec. This data suggests that installation downstream of scrubbed gases such as a SD-BH may be needed for effective mercury removal performance of gold-coated MerCAP™ probes. The data with mercury removal downstream of the SD-BH at Stanton was sufficiently promising that full-scale retrofit of MerCAP™ plates within one of the baghouse compartments (Figure 7) is being considered for scaled-up evaluation.

Figure 7. Schematic of MerCAP™ Technology Installed in a Baghouse Compartment



Pleasant Prairie Power Plant

Slipstream MerCAP™ evaluation tests were begun at We Energies' Pleasant Prairie Power Plant in February 2002. Pleasant Prairie burns a western subbituminous PRB coal and is configured with a cold-side ESP for particulate control.

Initial tests were conducted with two 10-foot long MerCAP™ probes using Type 1 substrate material and 0.5-inch plate spacing tested downstream of the ESP, where most of the fly ash has been removed. The mercury removal across both probes was low from the beginning and varied between 0 and 20% over about 5000 hours of exposure. At this site, only 2 sets of measurements were made for each probe and there is no information on mercury capture during the exposure period. This data is another indicator that flue gas from unscrubbed low-rank coals may result in lower mercury removal than from scrubbed gas.

Following testing with the Type 1 substrate, the plates were removed and replaced with a single section of gold-coated Type 3 substrate. The cross-sectional geometry for the later tests represents 1-inch plate spacing, as compared to 0.5-inch plate spacing for the initial tests. Model predictions suggest that 60% mercury removal should be achieved across the 10-foot probe at a gas velocity of 40 ft/sec and 1-inch plate spacing. The initial mercury removal for the later tests

was 24% at a velocity of 40 ft/sec, and the fraction of oxidized mercury was 35% at the inlet to probe and 78% at the outlet of probe. This data suggests that the gold may be effective as an oxidation catalyst in PRB flue gas.

Laskin Energy Center

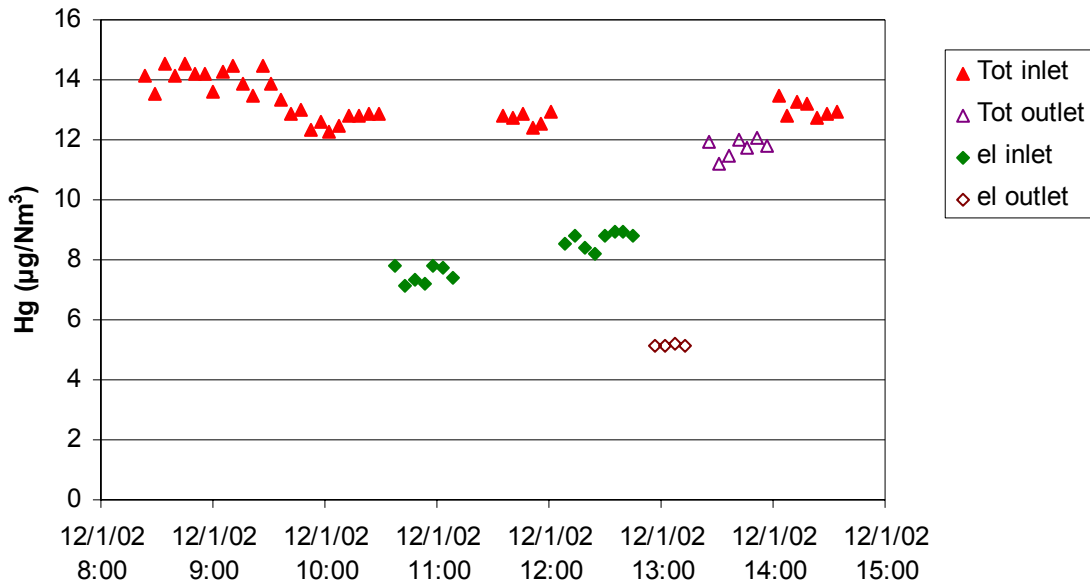
MerCAPTM testing began at Minnesota Power's Laskin Energy Center Unit 2 in August 2002. Unit 2 consists of a 55 MW Combustion Engineering PC-tangential-fired boiler firing PRB coal. A ten-foot long MerCAPTM probe with Type 2 substrate material at 1-inch plate spacing was installed into one of the vertical test ports at the inlet of the WPS at Laskin. Theoretical predictions suggest that 60% mercury removal should be achieved across the 10-foot probe at a gas velocity of 34 ft/sec. Initial mercury measurements showed only 20% removal. After 1120 hours, the probe was partially plugged with fly ash. Mercury measurements made at the highest flow achievable through the plugged probe (14 ft/sec) indicated 9% mercury removal. This data supports the earlier results indicating lower effectiveness on unscrubbed low-rank coal flue gas.

The total vapor phase mercury removal across the probe measured prior to probe removal was 9%. The fraction of oxidized mercury at the inlet to the probe was 11% and the fraction of oxidized mercury at the outlet was 26%. The fraction of oxidized mercury measured at Laskin was much lower than what was measured at Pleasant Prairie. Additional testing is required to determine the oxidation potential of gold-coated stainless steel in various flue gas matrixes.

Coal Creek Station

Great Rivier Energy's Coal Creek Station burns a North Dakota lignite coal and is configured with a cold-side ESP followed by a wet scrubber for combined particulate and SO₂ removal. A ten-foot long Mini-MerCAPTM probe with Type 2 substrate material was installed at the outlet of the ESP in the scrubber bypass ducting on Coal Creek Unit 1 December 1, 2002. Flue gas was drawn across a single Type 2 plate installed in the probe. The cross-sectional geometry for this test represented 1-inch plate spacing. Model predictions suggest that 60% mercury removal should be achieved across the 10-foot probe at a gas velocity of 40 ft/sec. Initial mercury measurements indicated 10% removal at 43 ft/sec. Speciation measurements indicated that the concentration of oxidized mercury was significantly higher at the outlet of the probe than at the inlet. A trend graph of MerCAPTM performance is shown in Figure 8, indicating the potential of gold-coated stainless steel to oxidize mercury.

Figure 8. MerCAP™ Performance at Coal Creek ESP Outlet (10-ft probe, 1-in spacing, 40 ft/sec)



ECONOMIC ANALYSIS

A preliminary engineering economic evaluation of MerCAP™ was conducted to project capital and O&M costs for a full-scale 250 MWe coal-fired power plant. The primary unit design parameters that affect the MerCAP™ system cost and their assumed values for this study follow in Table 2. The purpose of this evaluation was to estimate the potential costs of this technology to ensure it is competitive with other options and, therefore, suitable for further development. For this reason, the design is purposely conservative and no attempt has been made to develop the least cost design.

Table 2. General Design Parameters

Boiler Type	Pulverized Coal
Unit Size	250 MW net
Location	Kenosha, WI
Flue Gas Volume	950,000 acfm
Flue Gas Temperature	282 °F
Hg loading to MerCAP	125 lb/yr
Fly ash Loading to MerCAP	<0.03 lb/Mbtu

Two 100% capacity MerCAP™ sorption vessels were included to allow for isolation of one compartment for change out of sorption media and off-site regeneration while the other compartment remains on line for mercury removal. For this preliminary analysis, the vessels are based on a vertical flow design similar to a low-dust, SCR design configuration. The downward flow design minimizes the possibility of fly ash plugging the spaces between media plates.

The MerCAP™ sorption media must be regenerated periodically with the frequency depending on the amount of gold or other sorbent material applied to the media and the desired mercury collection efficiency. Regeneration could be conducted in situ by isolating a compartment and heating the media to the temperature required to desorb the mercury for recovery using an absorber and/or condenser. However, to simplify this analysis, we assumed removal of the spent media for regeneration off-site at a facility such as one used for recycling of fluorescent light tubes.

The cross sectional area of each MerCAP™ vessel was selected to maintain the Design Linear Gas Velocity between the media panels at 50 ft/sec. This velocity is consistent with design practice for SCR vessels installed in a cleaned-gas environment downstream of a particulate collector. Also, pilot testing of the MerCAP™ concept evaluated downstream of the spray dryer at Stanton Station demonstrated feasibility at a 50-ft/sec velocity.

Bench-scale testing and model predictions indicated that a 15-foot media/sorbent depth (in the direction of gas flow) was required for an initial mercury collection efficiency of 90%. The MerCAP™ conceptual design included a media depth of 8 layers of media panels with 2-foot depths for a total of 16 feet of treatment depth.

To provide a range of possible costs, four cases were selected and summarized in Table 3. Two base cases were considered along with two cost sensitivity cases. Base Case A considers a mercury uptake of 15% (i.e., 0.15 lbs of mercury per 1 lb of gold sorbent) and 90% mercury collection efficiency; both parameters have been demonstrated in testing. Base case B investigates the effects of a reduced mercury uptake of only 10% and, as a contingency to account for possible deterioration in gold reactivity, the application of 10% more gold to collect the needed amounts of mercury. A 3-month and a 1-year regeneration frequency were assumed for each base case.

Table 3. MerCAP™ Cases Considered

	Design Premises for 90% Collection Efficiency	Sorbent Regeneration Frequency	Case	Description	Cost of Gold
Case A	15 % Hg Uptake	3 months	A1-G	Base case A	\$330/oz t
		1 year	A2-G	1-yr Regeneration	\$330/oz t
Case B	• 10 % Hg Uptake • 10% extra gold	3 months	B1-G	Base case B	\$330/oz t
		1 year	B2-G	1-yr Regeneration	\$330/oz t

The results of the preliminary projections for capital and O&M costs based on these cases are summarized in Figures 9 and 10. Figure 9 summarizes the capital costs developed for this study. The most significant is the sorbent media cost. For the cases considered here, the sorption media accounts for 48% to 84% of the total capital invested in a MerCAP™ installation. Based on the relatively conservative design described, the capital costs for a MerCAP™ system with 90% mercury control, 3-month regeneration, and 100% redundancy is estimated at \$4.7 million for a 250 MW unit (\$18.8/kW). \$2.3 million of the capital cost is the gold media and its substrate. For 1-year regeneration and lower mercury capacity (10% compared to 15% of the weight of gold), the costs are \$14.9 million for a 250 MW unit (\$59/kW) with \$12.6 million in gold media and substrate cost.

A ten percent increase in gold pricing was also studied but not presented here, as there was only a minimal affect on the total capital required when compared to the other variables considered.

Figure 9. MerCAP™ System Capital Cost – \$/kW

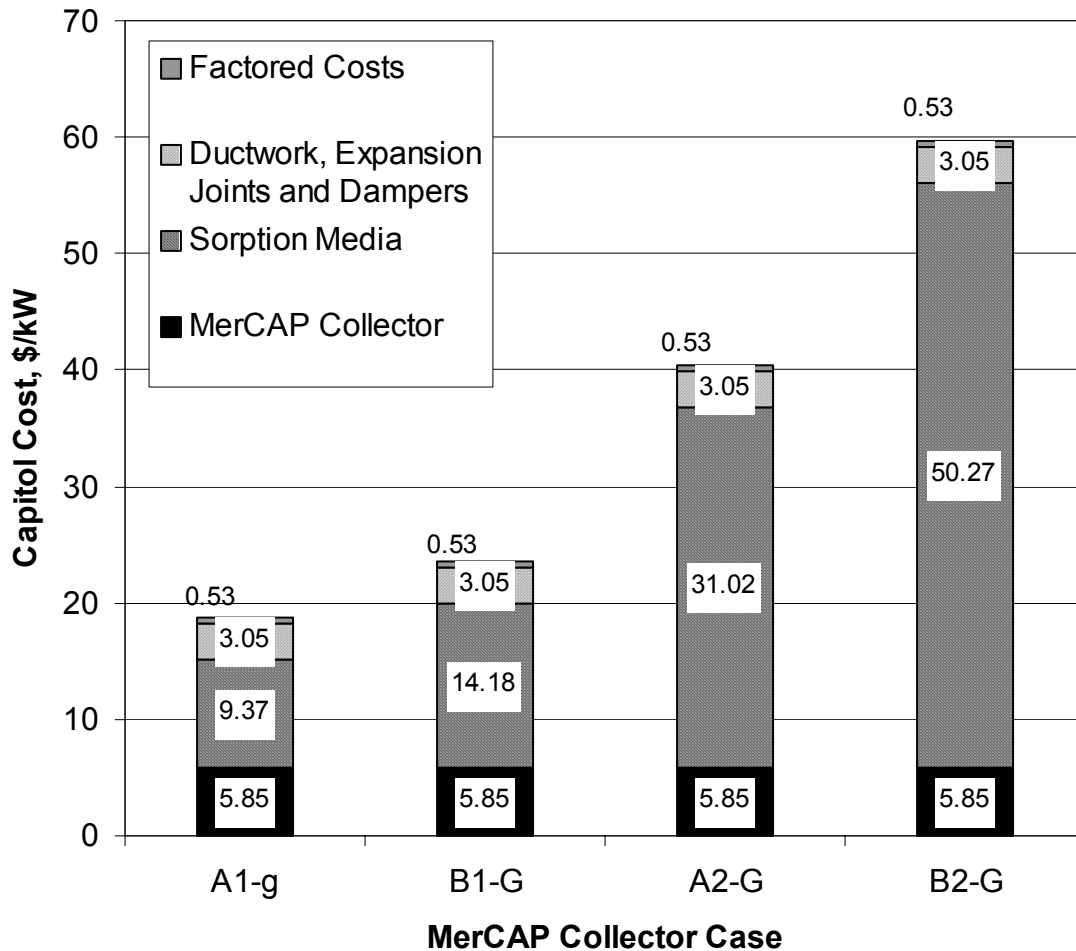
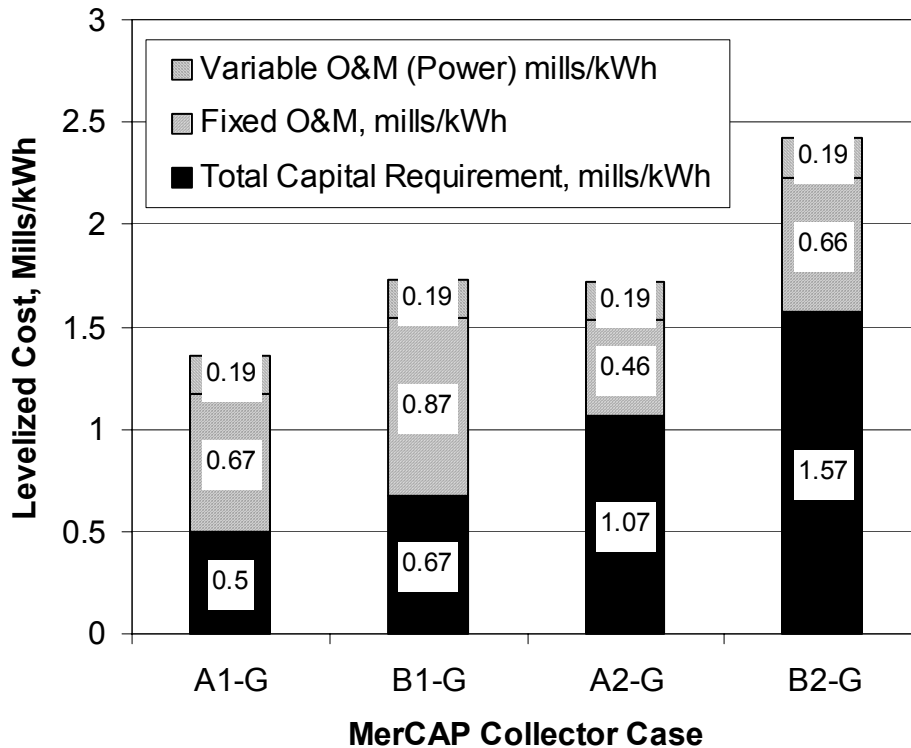


Figure 10. MerCAP™ System Levelized Cost – Mills/kWh



This preliminary engineering economic study shows that MerCAP™ costs can be attractive relative to the use of COHPAC™ ACI for mercury control. The total levelized costs for 90% mercury control (Figure 10) ranged from 1.4 to 2.9 mills/kWh for MerCAP™ versus 2 to 3.5 mills/kWh for COHPAC™ ACI. This does not take into account the elimination of activated carbon use (e.g., ACI costs, impacts on ash sales, etc.) and the potential to recycle or isolate the mercury for MerCAP™.

The amount and cost of the sorbent media is the major cost component for a MerCAP™ installation. The amount of the media needed is dependent on the sorbent capacity, regeneration frequency, and sorbent life expectancy. The analysis shows that it would be cheaper to regenerate more frequently (several times a year) than have enough sorbent to last a very long time (1 year). This is partly a result of assuming the need for two 100% capacity MerCAP™ sorption vessels to allow for isolation of one compartment for change out of sorption media and off-site regeneration while the other compartment remains on line for mercury removal. An alternate lower cost design may be to frequently regenerate the sorbent media in-situ by using a multi-compartment sorption vessel. This would eliminate the need for a 100% redundant vessel. For a 5-compartment system, only about 20% redundant media would be required. An example is a multi-compartment baghouse that periodically isolates one out of six or eight compartments for cleaning (regeneration).

Another factor that may reduce cost is the use of sorbent material that is cheaper and/or has higher mercury capacities than gold. Significant development work is needed to evaluate these potential options to reduce costs as well as to establish a realistic sorbent capacity, regeneration frequency, and sorbent life expectancy for the range of power plant configurations and coal burned.

SUMMARY AND IMPLICATIONS

The tests to date indicate that given the right flue gas conditions, MerCAP™ with gold coated plates around 10 ft long and spaced 0.5 inches apart can remove >80% mercury. In the tests conducted to date in flue gas derived from low rank fuels, this performance was achieved downstream of a SD-BH. Similar results have recently been obtained in other EPRI MerCAP™ tests conducted downstream of a wet absorber in bituminous-derived flue gas. Higher removals (>90%) for the short term should be achievable by increasing plate length, decreasing plate spacing, or reducing gas velocities.

MerCAP™ with gold as the sorbent surface did not perform well in non-scrubbed flue gas. There is no indication of poisoning, as the exposed plates appear to remove mercury well in the laboratory following long periods of exposure in flue gas. MerCAP™ effectiveness, although low in non-scrubbed gases, also did not appear to degrade over time in flue gas. It is uncertain at this point whether the low effectiveness is due to specific flue gas components which reduced the gold capacity for mercury in the gases tested, to an effect of temperature, or to a combination of both. Further tests are being conducted to determine the factors.

Other sorbent materials are also being tested as alternate coatings to gold. Some of the materials may be more effective or offer a cost-effective alternative to gold for specific flue gas conditions.

REFERENCES

1. Sjostrom, S., and R. Chang, *Apparatus and Method of the Removal of Contaminants in Gases*, U.S. Patent 5,948,143, 1999 and U.S. Patent 6,136,072, 2000.