Evaluation of MerCAP™ for Power Plant Mercury Control

Final Project Report

Project Start Date: 09/29/03
Project End Date: 09/30/08

Principal Author:
Dr. Carl Richardson

May, 2009

Cooperative Agreement Number DE-FC26-03NT41993

URS Group, Inc.
P.O. Box 201088
Austin, TX 78720-1088

Apogee Scientific, Inc.
2895 West Oxford Ave., Suite 1
Englewood, CO 80110

Disclaimer

Acknowledgements

The project team would like to thank and acknowledge the United States Department of Energy-National Energy Technology Laboratory, The Electric Power Research Institute (EPRI), The North Dakota Industrial Commission (NDIC), Great River Energy (GRE), Southern Company Services, Georgia Power [Georgia Power is a subsidiary of The Southern Company], and Alabama Power [Alabama Power is a subsidiary of The Southern Company]for providing the funding and host sites for the research and efforts conducted under this program.

Abstract

This report is submitted to the U.S. Department of Energy National Energy Technology Laboratory (DOE-NETL) as part of Cooperative Agreement DE-FC26-03NT41993, "Evaluation of EPRI's MerCAP™ Technology for Power Plant Mercury Control". This project has investigated the mercury removal performance of EPRI's Mercury Capture by Amalgamation Process (MerCAP™) technology. Test programs were conducted to evaluate gold-based MerCAP™ at Great River Energy's Stanton Station Unit 10 (Site 1), which fired both North Dakota lignite (NDL) and Power River Basin (PRB) coal during the testing period, and at Georgia Power's Plant Yates Unit 1 (Site 2) [Georgia Power is a subsidiary of The Southern Company] which fires a low sulfur Eastern bituminous coal. Additional tests were carried out at Alabama Power's Plant Miller, which fires Powder River Basin Coal, to evaluate a carbon-based MerCAP™ process for removing mercury from flue gas downstream of an electrostatic precipitator [Alabama Power is a subsidiary of The Southern Company].

A full-scale gold-based sorbent array was installed in the clean-air plenum of a single baghouse compartment at GRE's Stanton Station Unit 10, thereby treating 1/10th of the unit's exhaust gas flow. The substrates that were installed were electroplated gold screens oriented parallel to the flue gas flow. The sorbent array was initially installed in late August of 2004, operating continuously until its removal in July 2006, after nearly 23 months. The initial 4 months of operation were conducted while the host unit was burning North Dakota lignite (NDL). In November 2004, the host unit switched fuel to burn Powder River Basin (PRB) subbituminous coal and continued to burn the PRB fuel for the final 19 months of this program. Tests were conducted at Site 1 to evaluate the impacts of flue gas flow rate, sorbent plate spacing, sorbent pre-cleaning and regeneration, and spray dryer operation on MerCAP™ performance.

At Site 2, a pilot-scale array was installed in a horizontal reactor chamber designed to treat approximately 2800 acfm of flue gas obtained from downstream of the plant's flue gas desulfurization (FGD) system. The initial MerCAP™ array was installed at Plant Yates in January 2004, operating continuously for several weeks before a catastrophic system failure resulting from a failed flue gas fan. A second MerCAP™ array was installed in July 2006 and operated for one month before being shut down for a reasons pertaining to system performance and host site scheduling. A longer-term continuous-operation test was then conducted during the summer and fall of 2007. Tests were conducted to evaluate the impacts of flue gas flow rate, sorbent space velocity, and sorbent rinsing frequency on mercury removal performance. Detailed characterization of treated sorbent plates was carried out in an attempt to understand the nature of reactions leading to excessive corrosion of the substrate surfaces.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ACRONYMS

ACI	Activated carbon injection
acfm	Actual cubic feet per minute
Al	Aluminum
APC	Air pollution control (device)
ASTM	American Society for Testing and Materials
Au	Gold
Au-CVAAS	Gold pre-concentration coupled with Cold Vapor Atomic Absorption Spectroscopy
°C	Degrees Celsius
CFD	Computational Flow Dynamics
Cl	Chlorine
CMM	Continuous Mercury Monitor
COR	(DOE) Contracting Officer Representative
Cr	Chromium
Cu	Copper
CVAAS	Cold Vapor Atomic Absorption Spectroscopy
DI	Deionized
DOE	U.S. Department of Energy
dP	Differential pressure
DSCS	Dry sampling conditioning system
EDS	Energy Dispersive X-ray Spectroscopy
EDTA	Ethylenediaminetetraacetic acid
EPA	Environmental Protection Agency
EPRI	Electrical Power Research Institute
ESP	Electrostatic precipitator
EVM	Elemental vapor-phase mercury
°F	Degrees Fahrenheit
Fe	Iron
FGD	Flue gas desulfurization
gpm	Gallons per minute
H_2O	Dihydrogen oxide (water)
HCl	Hydrochloric acid
HF	Hydrofluoric acid
Hg	Mercury
Hg^0	Elemental mercury
Hg^{+2}	Oxidized mercury
ICR	Information Collection Request

ID	Inner diameter
in. H_2O	Inches of water (pressure)
JBR	Jet Bubbling Reactor
KCl	Potassium Chloride
ME	Mist Eliminator
MerCAP™	MERcury Capture Adsorption Process
MercScreen™	EPRI carbon based fixed structure mercury removal technology
Mn	Manganese
MWe	Megawatt
NDL	North Dakota Lignite
NETL	National Energy Technology Laboratory
Nm^3	Normal cubic meters
Ni	Nickel
NO_2	Nitrogen dioxide
NO_X	Nitrogen oxides
O_2	Oxygen
OH	Ontario Hydro
OVM	Oxidized vapor-phase mercury
PRB	Powder River Basin
QA/QC	Quality assurance/quality control
QAPP	Quality Assurance Project Plan
SBS	Sodium bisulfite
SCA	Specific Collection Area
SCEM	Semi-continuous emissions monitor
SDA	Spray Dryer Absorber
SD-BH	Spray dryer – baghouse combination
SD-FF	Spray dryer – fabric filter
SEM	Scanning Electron Microscopy
SO_2	Sulfur dioxide
SO_3	Sulfur trioxide
SO_x	Sulfur oxides
TVM	Total vapor-phase mercury
UV	Ultraviolet

1.0 Introduction

This report is submitted to the U.S. Department of Energy National Energy Technology Laboratory (DOE-NETL) as part of Cooperative Agreement DE-FC26-03NT41993, “Evaluation of EPRI’s MerCAP™ Technology for Power Plant Mercury Control”. This project has evaluated the performance of EPRI’s Mercury Capture by Amalgamation Process (MerCAP™) technology at Great River Energy’s Stanton Station Unit 10 (Site 1), which fired both North Dakota lignite (NDL) and Power River Basin (PRB) coal during the testing period, and at Georgia Power's Plant Yates Unit 1 (Site 2) [Georgia Power is a subsidiary of The Southern Company] which fires a low sulfur Eastern bituminous coal.

1.1 MerCAP™ Technology Background

The emission of vapor-phase mercury from coal-fired utility boilers has come under increasing scrutiny over the past decade leading to a number of proposed and promulgated state and federal regulatory rules. In an effort to enable cost-effective collection of vapor-phase mercury, the Electric Power Research Institute (EPRI) has developed several novel methods to capture mercury from coal exhaust gas. MerCAP™ is an EPRI technology developed as a novel approach to capture and control mercury emissions from the combustion of coal for electric generation. The general concept for MerCAP™ is to place fixed sorbent structures into a flue gas stream to adsorb mercury and then, as the sorbent surfaces becomes saturated, thermally regenerate the sorbent and recover the mercury. The sorbent substrates are comprised of materials possessing high affinities for mercury, such as noble metals or activated carbon. The substrates are designed to contact flue gas for an extended duration during which time mercury is adsorbed and subsequently concentrated at the surface. One example includes parallel gold-coated plates, depicted in Figure 1-1. Mercury forms an amalgam with the gold and is removed from the flue gas flowing past the plates. This program utilized an electroplated layer of gold on a stainless steel screen (substrate). The captured mercury can be subsequently sequestered using a carbon canister or cryogenic trap during thermal or chemical regeneration of the substrates. Recent work has shown that chemical desorption of the mercury from the gold-coated substrates is also a feasible regeneration technology.

The MerCAP™ concept has been tested in actual flue gas since 1999, starting with evaluations of small gold-coated coupons and evolving to long-term tests of probes containing 10-ft substrates. These tests have shown that high mercury removals (>80%) can be achieved at various operating parameters and in different flue gas types. Tests have also indicated that gold-coated substrates can be thermally regenerated without degradation of the initial adsorption capacity. Tests conducted with an in-duct probe in North Dakota Lignite (NDL)-derived flue gas downstream of a spray dryer-baghouse configuration showed >80% mercury removal with a substrate configuration of 10-ft long gold-coated plates spaced 0.5 inches apart at a gas velocity of 40 ft/s. These results were consistent with mass transfer model predictions. Results with a 140-acfm probe showed mercury removals of >70% for six months of continuous flue gas exposure in NDL-derived flue gas.

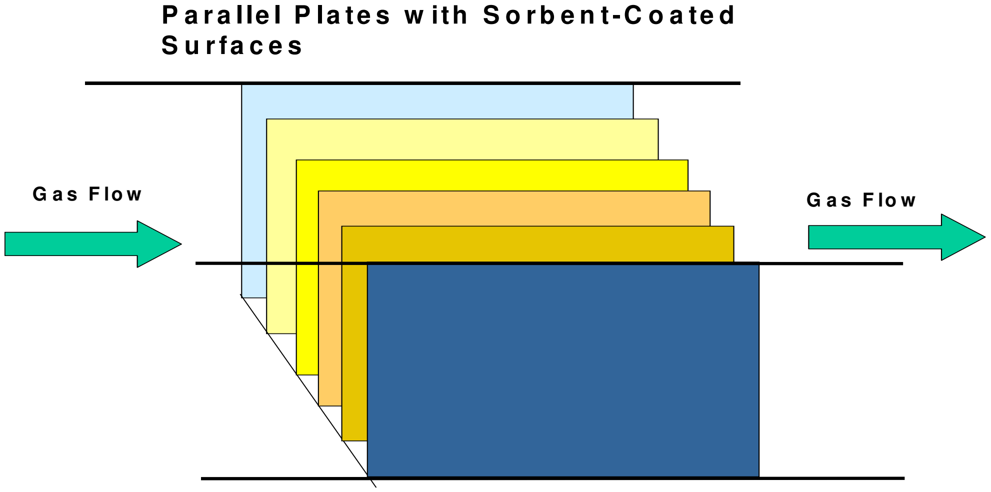


Figure 1-1. Parallel Plate Configuration of a Fixed Sorbent

The most promising MerCAP™ results have been measured in NDL, PRB sub-bituminous, and Eastern bituminous gases that have been scrubbed via lime spray dryers, wet flue gas desulfurization units, or venturi-type wet scrubbers. The mercury removal results in unscrubbed gases downstream of ESP units have typically shown lower mercury removal rates (below 25%) and de-activation of the substrates. Several tests and analyses are continuing to better understand the flue gas chemistries that limit the technology in unscrubbed applications.

1.2 Test Program Description

With funding provided by the U.S. Department of Energy and other participants including EPRI, Great River Energy (GRE), the North Dakota Industrial Commission, Southern Company and its affiliate, Georgia Power, URS Group (URS) and Apogee Scientific Inc. have conducted test programs to evaluate MerCAP™ technology at GRE's Stanton Station Unit 10 (Site 1) and Georgia Power's Plant Yates Unit 1 (Site 2).

Site 1 Tests

A full-scale gold-based sorbent array was installed in the clean-air plenum of a single baghouse compartment at GRE's Stanton Station Unit 10, thereby treating 1/10th of the unit's exhaust gas flow. The substrates that were installed were electroplated gold screens oriented parallel to the flue gas flow. The sorbent array was initially installed in late August of 2004, operating continuously until its removal in July 2006, after nearly 23 months. The initial 4 months of operation were conducted while the host unit was burning North Dakota lignite (NDL). In November 2004, the host unit switched fuel to burn Powder River Basin (PRB) subbituminous coal and continued to burn the PRB fuel for the final 19 months of this program.

A flexible gas sampling system was installed as part of the MerCAP™ array and was used extensively to monitor the mercury removal performance of the system. Parametric evaluations of the effects of variable plant operations on the mercury capture performance of the full-scale array were conducted to include temperature, spray dryer absorber (SDA) operation, and low-temperature in-situ regeneration of the substrates. A single Apogee continuous mercury monitor (CMM) was installed to continuously monitor mercury removal performance of the full-scale installation. Automation of the sampling array and the CMM made remote monitoring and performance of these parametric evaluations possible.

A key consideration to the overall economics of the MerCAP™ technology is the ability to regenerate the sorbent structures many times, thus minimizing or eliminating costs associated with sorbent consumption. Periodically the sorbent substrates would require regeneration to remove the captured vapor-phase mercury. Evaluations to simulate regeneration of the MerCAP™ substrates were conducted on a small slipstream scale apparatus. A single set of substrates was regenerated on six distinct occasions to investigate potential impacts of repeated regeneration cycles on the mercury capture ability of the substrates. Based on the operation of the full-scale array observed during this test program, six regeneration cycles would allow a single set of substrates to operate for nearly 12 years.

In addition to evaluations of the full-scale array, several small-scale investigations were conducted with samples removed from the full-scale MerCAP™ installation. These tests evaluated the effect of temperature, gas composition, and active length on the mercury removal performance. As part of additional efforts funded by EPRI and GRE, laboratory studies were also conducted on promising alternative substrate materials. Materials including charcoal cloth, high-surface area gold "leaf" material, silver sand (platinum substitute), and a gold-coated sand material were evaluated for mercury removal performance and capacity, and pressure drop.

<u>Site 2 Tests</u>

A pilot-scale array was installed in a horizontal reactor chamber designed to treat approximately 2800 acfm of flue gas obtained from downstream of the Plant Yates Unit 1 flue gas desulfurization (FGD) system. The substrates that were installed were electroplated gold screens oriented parallel to the gas flow. The initial MerCAP™ array was installed just after completion of baseline testing at Plant Yates in January 2004, operating continuously for several weeks before a catastrophic system failure resulting from a failed flue gas fan. A second MerCAP™ array was installed in July 2006 and operated for one month before being shut down for a reasons pertaining to system performance and host site scheduling. A longer-term continuous-operation test was then conducted during the summer and fall of 2007 after which the pilot system was shut down and demobilized.

A single EPRI semi-continuous mercury emission monitor (SCEM) system was used extensively to monitor the mercury removal performance of the pilot MerCAP™ system. Parametric evaluations of the effects of flue gas flow rate and wash water rinse frequency were conducted. Additional surface characterization tests were conducted to evaluate the impacts of extended flue gas exposure on the integrity of the gold coated screen substrates.

In addition to evaluations of the full-scale array, several small-scale tests were conducted on MerCAP™ substrate samples prepared from the same lots as the full-scale substrates. An EPRI slipstream reactor was configured at the host site to evaluate performance in similar flue gas as the pilot-scale reactor. Short-term tests were conducted to evaluate the effects of flue gas flow rate and wash water rinsing frequency on performance. Results from the slipstream tests were used to design the operating parameters for the pilot-scale system.

1.3 Key Personnel

Key personnel for the Site 1 test program are listed in Table 1-1; included are key staff from Great River Energy, EPRI, U.S. DOE-NETL, ADA-ES, URS Group, and Apogee Scientific.

Key personnel for the Site 2 test program are listed in Table 1-2; included are key staff from Southern Company, Georgia Power, EPRI, U.S. DOE-NETL, URS Group, and Apogee Scientific.

Table 1-1. Key Personnel for Site 1 Test Program

Contact Name	Responsibility and Organization	Telephone Number	Email Address
Steve Smokey	GRE Stanton Station Site Coordinator	(701) 745-5204	ssmokey@GREnergy.com
Greg Archer	GRE Project Manager		garcher@GREnergy.com
Mark Strohfus	GRE Project Manager		mstrohfu@GREnergy.com
William Aljoe	U.S. DOE Project Manager		
Ramsay Chang	EPRI Program Manager	(650) 855-2535	rchang@epri.com
Sharon Sjostrom	ADA-ES Technical Lead, Lead Consultant	(303) 339-8856	sharons@adaes.com
Carl Richardson	URS Group Project Manager	(512) 419-5966	Carl_Richardson@URSCorp.com
Tom Machalek	URS Group Project Coordinator	(512) 419-5361	Tom_Machalek@URSCorp.com
Tim Ebner	Apogee Project Engineer	(303) 783-9599 ext. 31	tebner@apogee-sci.com
Kevin Fisher	Apogee Field Engineer and CMM Automation Lead	(303) 783-9599 ext. 36	kfisher@apogee-sci.com
Rick Slye	Apogee Field Test Coordinator	(303) 783-9599 ext. 23	rslye@apogee-sci.com

Table 1-2. Key Personnel for Site 2 Test Program

Contact Name	Responsibility and Organization	Telephone Number	Email Address
Ken McBee	Georgia Power Plant Yates Site Coordinator	(770) 252-0515	klmcbee@southernco.com
Brandon Looney	Southern Company Project Manager	(205) 257-6162	mblooney@southernco.com
Pierina Fayish	U.S. DOE Contract Officer's Representative (COR)	(412) 386-5428	Pierina.Fayish@NETL.DOE.gov
Ramsay Chang	EPRI Program Manager	(650) 855-2535	rchang@epri.com
Carl Richardson	URS Group Project Manager	(512) 419-5966	Carl_Richardson@URSCorp.com
Tom Machalek	URS Group Project Coordinator	(512) 419-5361	Tom_Machalek@URSCorp.com
Tim Ebner	Apogee Project Engineer	(303) 783-9599 ext. 31	tebner@apogee-sci.com

2.0 Executive Summary

This report is submitted to the U.S. Department of Energy National Energy Technology Laboratory (DOE-NETL) as part of Cooperative Agreement DE-FC26-03NT41993, “Evaluation of EPRI’s MerCAP™ Technology for Power Plant Mercury Control”. This project has evaluated the performance of EPRI’s Mercury Capture by Amalgamation Process (MerCAP™) technology at Great River Energy’s Stanton Station Unit 10 (Site 1), which fired both North Dakota lignite (NDL) and Power River Basin (PRB) coal during the testing period, and at Georgia Power's Plant Yates Unit 1 (Site 2) [Georgia Power is a subsidiary of The Southern Company] which fires a low sulfur Eastern bituminous coal.

The Mercury Capture by Amalgamation Process (MerCAP™) technology of the Electric Power Research Institute (EPRI) uses fixed sorbent structures placed in flue-gas streams to passively remove vapor-phase mercury compounds. As the sorbent surfaces become saturated, they can be thermally treated to both regenerate the substrate and recover the captured mercury. Previous laboratory and flue gas slipstream tests showed that electroplated gold plates or screens showed good potential as a MerCAP™ sorbent substrate, demonstrating good mercury removal performance and effective thermal regeneration properties. Test data suggested that a MerCAP™ sorbent process could be effective when configured downstream of either a particulate control device or flue gas desulfurization (FGD) unit. Results from the small-scale tests indicated that additional longer-term tests, conducted at larger scale, were warranted to better evaluate the feasibility of this technology. Thus, the objective of this program was to evaluate long-term operational performance of the gold-based MerCAP™ process at a scale appropriate for estimating performance and costs of a full-scale installation.

In this program, tests were conducted at two host sites to evaluate the performance of gold-based MerCAP™. At both sites, parametric tests were conducted to evaluate the impacts of flue gas flow rate and reactor space velocity on performance. Long-term tests, conducted for periods greater than 6 months, were conducted at both sites to evaluate mercury removal performance over extended periods of flue gas exposure. At Site 1, a full-scale installation of the MerCAP™ technology was configured to treat 1/10th of the Unit 10 flue gas. The fixed sorbent structures were installed in the clean-air plenum of a single full-scale compartment of the Unit 10 baghouse. Mercury removal performance was documented over a period of 9 months where the MerCAP™ system operated continuously. At Site 2, a pilot-scale gold-based MerCAP™ system was installed and configured to receive a flue gas slipstream from downstream of the Unit 1 wet flue gas desulfurization (FGD) system. An initial series of small-scale slipstream tests were conducted at Site 2 to provide process information used to design pilot-scale tests. Pilot testing included parametric and long-term evaluations to determine the mercury removal performance of the MerCAP™ process.

This report describes the MerCAP™ evaluation tests conducted and results obtained at the two host sites. In addition, a summary of a pilot-scale test program conducted to evaluate a carbon-based MerCAP™ system at Alabama Power’s Plant Miller [Plant Miller is a subsidiary of The Southern Company] is also provided.

2.1 Site 1

The MerCAP™ substrates evaluated in this program were electroplated gold screens oriented parallel to the flue gas flow. The Site 1 sorbent array was initially installed in late August of 2004 and operated continuously until its removal in July 2006, after nearly 23 months. The initial 4 months of operation were conducted while the host unit was burning NDL. In November 2004, the host unit switched fuel to burn PRB subbituminous coal and continued to burn the PRB fuel for the final 19 months of the program.

Parametric testing of different plant operation variables was conducted to evaluate the effects of temperature, small-scale thermal regeneration, and spray dryer absorber operation on the mercury removal performance of the MerCAP™ technology. In addition, small-scale testing of sorbent substrate samples was conducted to investigate the effect of gas composition, physical installation parameters, and temperature on the MerCAP™ mercury removal performance.

As part of the additional effort funded by EPRI and GRE, alternative substrate materials were investigated for promising mercury removal capabilities. Alternative materials tested included charcoal cloth, alternate forms of gold, and substrates prepared using an electrodeless plating process. Laboratory evaluations have been performed to determine mercury removal performance and pressure drop data.

The data and observations collected during the Site 1 test program support the following conclusions:

- Long term demonstration of the MerCAP™ technology showed its ability to achieve modest mercury removals of 30 to 50% over extended time periods when operated downstream of a spray-dryer fabric filter (SD-FF) unit. A single set of substrates operated for 23 months continuously over the course of this program.
- Mercury capture performance was found to be directly affected by flue gas temperature with removal tracking inversely with gas temperature. At temperatures >200 °F (93°C), mercury removal effectiveness decreased dramatically as temperature increased. In some cases, outlet mercury levels spiked to levels well above those at the inlet with increased operating temperature, indicating possible re-volatilization of captured mercury from the MerCAP™ substrate.
- Operational parameters of the full-scale spray dryer absorber (SDA) were found to directly affect the mercury removal performance of the MerCAP™ substrates. Increased acid gas scrubbing was shown to dramatically increase mercury capture independent of gas temperature. Mercury removal was increased from 20% to 25% with the SDA system off to 40% capture with the absorber operating.
- Tests conducted with a high efficiency lime reagent (i.e., lime with higher surface area, lower density) in the SDA demonstrated the most effective manner of increasing mercury removal performance of the MerCAP™ system. Prior to feeding the high efficiency lime reagent to the SDA, mercury removal was measured at 25 to 30% capture. Following the change in lime product mercury removal increased to 60 to 70% for ducts 1 and 2 for the first 24 hours of

operation and stabilized near 50% capture for the duration of the ‘high efficiency’ period. High levels of sulfur dioxide (SO_2) removal (>95%) were achieved with the enhanced lime reagent suggesting a possible inhibitory impact of the acid gas component on MerCAP™ performance.

- Variation of MerCAP™ plate spacing and active length did not demonstrate a direct correlation to mercury removal, indicating that a mechanism other than mass transfer dominates the mercury capture performance of the gold substrates. Comparison of SDA operation and mercury capture results indicated that temperature and acid gas constituents are the most likely limiting factors.
- Both thermal and chemical regeneration of slipstream-scale MerCAP™ substrates demonstrated no adverse impact to mercury capture performance after six regeneration cycles were performed. In general, mercury capture performance was increased following each regeneration cycle. No degradation in performance was observed as a function of the number of regeneration cycles performed on the substrates. The mercury liberated from the substrates was captured and analyzed from four of the six cycles to verify mercury removal by the small-scale substrates during unmonitored service time.
- Throughout the test program, minimal oxidation of vapor-phase mercury was observed across the MerCAP™ array; most of the vapor-phase mercury exiting the MerCAP™ reactor was present in the elemental form. It is likely that oxidative catalysis of vapor-phase mercury by the MerCAP™ substrates was inhibited due to the lack of acid gases and low halogen levels in the flue gas.
- During the course of this program the cost of commodity gold increased from approximately $280/ounce to > $900/ounce. Original cost estimates to install the MerCAP™ technology to the entire baghouse of Stanton Unit 10 (60 MWe) were roughly 2.0 to 2.5 million dollars. The increased cost of gold used as the substrate for the technology increases the costs of installation dramatically. Furthermore, the extent of mercury removal achieved by the installed MerCAP™ reactor during this program (i.e., ~40% average) was appreciably lower than the reactor design removal and the 55% removal goal of the program. This indicates that a full-scale MerCAP™ installation would require a much larger reactor size than predicted by mass-transfer model predictions. This ultimately results in gold-based MerCAP™ being economically unattractive compared to other options such as activated carbon injection for applications similar to that of Site 2.

2.2 Site 2

A pilot-scale demonstration of the MerCAP™ technology was installed to treat approximately 2800 acfm of flue gas from Georgia Power's Plant Yates Unit 1. The technology was installed in a horizontal reactor configured to obtain flue gas just downstream of the Unit 1 FGD system. Evaluation of the pilot-scale installation was conducted under a Cooperative Agreement with the U.S. Department of Energy/National Energy Technology Laboratory (DOE/NETL) and other participants including EPRI, Southern Company, and Georgia Power. Mercury removal performance was documented over a 16-month period where the MerCAP™ system was run during several shorter periods of continuous operation.

A single EPRI semi-continuous mercury emission monitor (SCEM) was installed to monitor mercury removal performance of the pilot-scale installation. Parametric testing of different system operation variables was conducted to evaluate the effects of flue gas flow rate and system wash frequency on the performance of the technology. In addition, small-scale testing of samples of the sorbent substrates was conducted to investigate the effect of flue gas flow rate and water rinsing process parameters on the MerCAP™ mercury removal performance.

The objective of this program was to evaluate the performance of gold-based MerCAP™ for mercury removal in flue gas downstream of a wet FGD absorber. Testing at Plant Yates included a series of small-scale slipstream tests followed by a pilot-scale test program. The data and observations collected under this program support the following conclusions:

- Results from small-scale slipstream tests showed that mercury removals as high as 90% could be achieved by the gold-coated screen substrates in flue gas obtained downstream of the Plant Yates Unit 1 FGD absorber. Results also indicated the importance of an effective rinse-water process for cleaning the MerCAP™ sorbent screens. Although the best results were obtained when a continuous water wash was used, high levels of removal were still obtained and sustained for over a month of continuous operation using a cycling approach where routine periodic rinses were performed.
- The correlation between rinsing frequency and MerCAP™ performance indicated that some species in the saturated flue gas reacted with the gold surfaces inhibiting their ability to remove mercury. Results showed that even after decreased mercury removal was observed following extended flue gas exposure, the gold screens could be rejuvenated with an intensive water wash. This suggested that the reactions between the gold surfaces and inhibiting species in the flue gas did not permanently alter the gold coating. Inspection of the gold screens after 2 months of continuous flue gas exposure showed no signs of surface degradation or damage.
- MerCAP™ mercury capture performance across the pilot scale system was considerably lower than that observed in slipstream tests and predicted by mass transfer properties. Initial removals observed with fresh or cleaned gold screen substrates were only about one third of what was predicted by mass transfer properties. Specific causes for the lower-than-expected removals are not understood, but may include interactions between the gold surfaces and inhibiting species in the flue gas, inadequate rinsing of the screens, or unexplained poor flow patterns across the MerCAP™ arrays. Results from the pilot tests suggest that a much larger MerCAP™ reactor (than initially thought) would be required to obtain desired mercury removals.
- Parametric tests indicated no strong correlation between flue gas flow rate and mercury removal performance of the MerCAP™ system. In all cases the removal

was considerably lower than predicted by mass transfer properties. Pilot tests confirmed the need for a routine water rinse of the MerCAP™ plates for mercury removal to be achieved. However, after prolonged exposure to flue gas, an intensive water rinse was not sufficient to regenerate the gold screens. Pilot-scale parametric gas flow and water rinsing tests therefore did not correlate well to earlier results obtained using the small-scale slipstream device.

- Pilot test results indicated that the gold MerCAP™ performance decreased with increased exposure to flue gas. Longer-term tests showed rapid declines in performance over the first 1-2 days of operation followed by a slow continual decline thereafter. Results from the second longer-term test showed that removal dropped from just over 30% to 0% in under 5 months of operation. The decline was observed with both the adsorption and oxidation of mercury by the gold sorbent, indicating a general loss of mercury reactivity (over time) with the sorbent. Test results indicated that a full-scale MerCAP™ system would require multiple shut-downs per year for regeneration or sorbent replacement.
- Pilot test results showed that the gold-based sorbents did not adequately withstand the wet flue gas environment to which they were exposed. The failure of the initial test resulted from the very rapid destruction of the substrates when exposed to unscrubbed flue gas (i.e., a condition that would not be expected for an actual installation). Long-term exposure of scrubbed flue gas caused severe corrosion and damage to the MerCAP™ sorbent substrates, ultimately resulting in appreciable loss of gold from the screens. The use of a continuous water rinse of the screens might be expected to increase the sorbent lifetime. However, the low tolerance of the screens to flue gas exposure would create a high-risk situation for sorbent loss regardless of the rinsing process used.
- The relatively poor results observed during this pilot test program, along with an appreciable increase in the price of gold over the past six years, greatly impact the estimated costs for the gold MerCAP™ technology. Pilot results, showing appreciably lower mercury removals than predicted by mass transfer model predictions, suggest that a much larger reactor would be required to achieve over 80% mercury removal than originally thought. Assuming a gold price of $870 per troy ounce, the gold cost (alone) to charge a MerCAP™ reactor required for a 500 MWe power plant would be over $15M. This does not take into account costs associated with sorbent re-charging or regeneration. Pilot-scale results predict that in order to achieve 90% mercury removal, a wet gold MerCAP™ reactor would need to be 60-feet long (for a 20-ft x 75-ft duct). The associated costs for the enlarged reactor structure and resulting pressure drop (i.e., as high as 15 in-H_2O) would be substantial. This makes gold-based MerCAP™ technology economically unattractive compared to other mercury control options for scrubbed plants, such as activated carbon injection or mercury oxidation technologies.
- Alternative substrate materials have been tested in the laboratory and in flue gas slipstream tests to identify more economical alternatives to electroplated gold substrates. A number of carbon-based substrates have shown promise in a number of tests conducted in simulated and actual flue gas. A carbon cloth substrate

showed promise in laboratory testing, but proved to be mechanically unsuitable to this application. Granulated activated carbon beds appear to be one of the most promising alternatives. The use of granulated fixed carbon beds at the back end of particulate controls (EPRI MercScreen™) is currently being actively evaluated as a lower cost alternative to gold-based MerCAP™.

2.3 Carbon-Based MerCAP™ Testing

This program initially focused on the use of gold plated substrates downstream of wet and dry scrubbers. However, the viability of this type of substrate was limited by lower than expected mercury removal and a dramatic increase in material costs. Since this program was initially proposed the price of gold has more than doubled, subsequently making the technology less attractive from a cost standpoint. Further development of MerCAP™ has focused on the use of fixed structures downstream of ESPs using activated carbon-based substrates due to the relatively low costs of activated carbon and its proven ability to remove mercury from flue gas.

The use of activated carbon in a MerCAP™ configuration has several potential advantages over powdered activated carbon injected into a duct upstream of a particulate collection device. These include:

- No carbon contamination of the fly ash captured in an ESP, thus ensuring preservation of fly ash sales;
- Enhanced particulate collection;
- Potential for greater carbon utilization compared to ACI;
- Potential for recycling and reactivating carbon material; and
- Potential to oxidize mercury not captured in the MerCAP™ system subsequently enhancing mercury collection in a downstream wet scrubber.

A pilot-scale test system was constructed at Southern Company's Alabama Power Plant Miller to evaluate the carbon-based MerCAP™ technology. This unit was attached to the back end of an existing pilot ESP that treats an approximate 1-2 MWe equivalent slipstream of flue gas obtained from upstream of the full-scale ESP. Five different commercial activated carbons were tested in a louvered fixed-bed reactor that had been modeled and designed under a related EPRI test program. The evaluated carbons consisted of 9-mm pellets, 4-mm pellets, and 4x8 granules. Each test was conducted for 1-2 weeks with initial mercury removals ranging from 68% to 92%. The 4-mm pellets and 4x8 granules showed the greatest initial mercury removal and were able to maintain greater than 80% removal for over 24 hours. The mercury adsorption capacities ranged from 67 to 186 μg Hg/g at a normalized inlet mercury concentration of 50 $\mu g/Nm^3$. The larger pellets showed faster breakthrough and lower adsorption capacities, indicating that the bed was likely mass transfer limited in the current configuration.

Although the tests were run in a batch mode, it is envisioned that a full-scale carbon-based MerCAP™ installation would operate as a continuous moving bed that would constantly remove and refresh the carbon material. This method would maintain a high level of mercury removal while allowing the carbon to be regenerated externally. Future efforts will focus on developing a moving bed apparatus, as well as improving and optimizing the carbon material performance.

3.0 Experimental

This section describes the experimental methods and equipments used at the two host sites for the MerCAP™ evaluation testing.

Site 1 MerCAP™ Testing

3.1 Host Site Description – Site 1

Great River Energy's Stanton Station is located in Stanton, North Dakota. Unit 10 is a 60 MW unit equipped with a Spray Dryer Absorber (SDA) and Fabric Filter for pollution control. Figure 3-1 provides a schematic representation of the unit and Table 3-1 summarizes the key operational parameters of the unit.

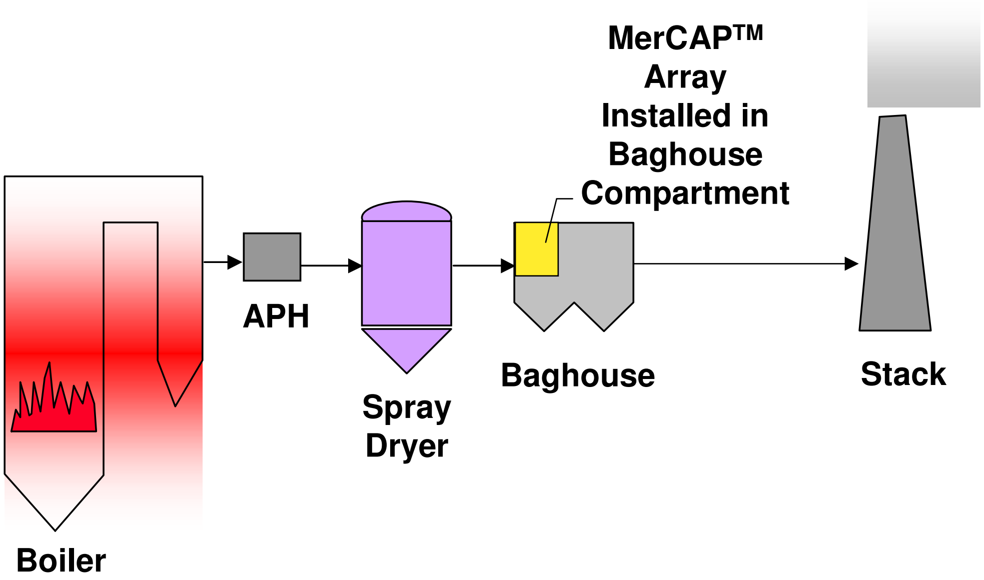


Figure 3-1. Stanton Unit 10 Schematic Representation

Table 3-1. Stanton Station Unit 10 Operational Parameters

	Stanton Unit 10
Boiler	
Type	Combustion Engineering, PC Tangential
Nameplate (MW)	60 Gross
Fuel	
Type	North Dakota Lignite / Powder River Basin Subbituminous
Source	
Particulate Control	
Type	Reverse Gas Baghouse
Manufacturer	Research-Cottrell
Baghouse Air/Cloth Ratio (acf/ft^2)	2:1
Baghouse Cleaning Cycle	4 to 6-hour
Device Inlet/Outlet Temp (°F)	190 – 210
NO_x Controls	Low-NO_x Burners
SO_2 Controls	
Type	Lime Spray Dryer
Manufacturer	Research-Cottrell
Ca/S Molar Ratio	Varies
Recycle Rate (lb lime/lb recycle)	None
Inlet/Outlet Temp (°F)	350 / 190 (NDL) 410 / 210 (PRB)
Flue Gas Flow Rate (scfm)	160,000

3.1.1 Description of MerCAP™ Array

A single compartment of the Unit 10 baghouse was utilized for the Stanton MerCAP™ installation. The baghouse compartment location allowed for the array to be designed for particulate-free gas flow and face velocities at approximately 8 ft/sec. The large footprint of the baghouse compartment easily accommodated the MerCAP™ array as well as the instrumentation and mercury monitoring systems to monitor the technology as part of the demonstration. Figure 3-2 shows a schematic of the baghouse compartment and MerCAP™ array as installed at Stanton Unit 10.

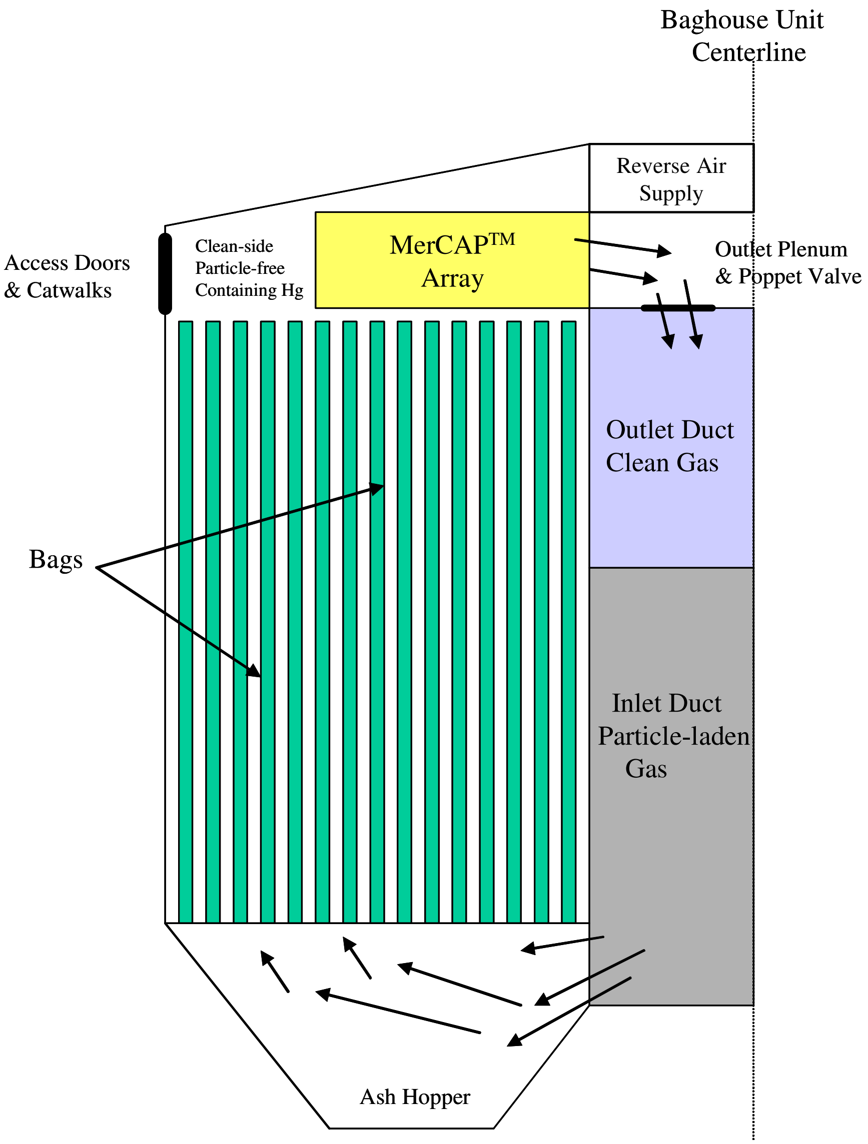


Figure 3-2. MerCAP™ Array Schematic – Site 2 Installation

MerCAP™ substrates were arranged in four separate square tube duct sections that rested atop the bag hangers inside of the baghouse compartment. The four duct sections were gas sealed to the outlet plenum of the compartment thereby forcing gas flow down the duct sections. Each individual duct section was sized at a12-ft length to accommodate the 10-foot active length of sorbent substrates with two feet of extra length used to straighten the gas flow prior to passing over the substrates.

Each installed duct section was supplemented by individual inlet and outlet mercury sampling systems, and instrumentation to monitor gas flow. Pressure drop across the MerCAP™ array and gas temperature on the clear-air side of the compartment were also monitored. Plant instrumentation provided differential pressure across the entire baghouse compartment (inlet duct to outlet duct). Figure 3-3 shows a photograph of the inlet of one of the four duct sections installed in the baghouse compartment.

Figure 3-3. MerCAP™ Array Duct Section 1 Stanton Unit 10 Baghouse Compartment

Figure 3-3 shows the gold MerCAP™ substrates installed in the duct section at 1-inch plate spacing. For ease of handling the plates were built into 2-foot cubic containers that slid into the duct sections. Later in the course of the program, this allowed for testing of varied active length in a quick, convenient manner. Also shown in the foreground of Figure 3-3 is the inlet mercury sampling systems for each duct section. The colored lines running back along the outer edge of the duct section were differential pressure lines to measure the flow down each duct section and the pressure drop across the array. The outlet mercury sampling array is not shown in the figure, but mimics that of the inlet array shown.

3.1.2 Substrate Pretreatment and Orientation

Due to concerns of damage to such a large number of substrates with extended flue gas exposure, the project team agreed to a staged installation into the full-scale array. Substrates were installed into duct section 1 first. The first set of substrates that was installed was subjected to a nitric acid (30 vol. %) wash prior to installation. Previous testing had shown the acid wash to improve substrate performance. The sorbent plates installed in duct section 1 were oriented in the base case design arrangement of 1-inch plate spacing and 10-feet of active length. These substrates were removed from the compartment on a single occasion following the rupture of several bags in the fabric filter compartment. The substrate plates were coated with a fine layer of fly-ash and were blown off with compressed air to clear fly-ash fowling.

Following a period of 3 months, during which the substrates in duct 1 were closely monitored, additional substrates were installed into duct sections 2 and 3. Duct section 2 contained plates arranged exactly as those in section 1, but the substrates were not acid-pretreated prior to installation. Section 3 received plates that were spaced at ½-inch intervals with 10-feet of overall active length. The plates installed into duct 3 were also not acid-pretreated prior to initial installation. Installing substrates into duct 3 at ½-inch plate spacing required twice the number of substrate plates as either section 1 or section 2. This meant that all of the substrates manufactured for the full-scale demonstration were housed in duct sections 1, 2, and 3. Duct section 4 remained empty and was used to evaluate any mercury removal or speciation attributable to the stainless steel duct arrays used to house the MerCAP™ substrates.

3.2 Description of Equipment – Site 1

3.2.1 Mercury Sampling Equipment

One Apogee CMM system was utilized to monitor and quantify gas-phase mercury emission rates. The Apogee CMM is a research-oriented instrument that employs wet-chemistry impinger-based sample conditioning equipment. The equipment is designed and constructed to be portable and capable of handling the rigors of field sampling. Apogee CMMs are routinely deployed in conditions that would render similar equipment useless; including temperatures ranging from 0°F to 120+°F (-18° to 49°C), as well as exposure to high vibration, abrasive dust, wind, sunlight, and other harsh environmental conditions. Apogee CMMs can be configured to automatically sample two channels at discreet intervals continuously. This allows a single CMM unit to measure total vapor-phase mercury (TVM) and elemental vapor-phase mercury (EVM) at a single location or any combination of the two from two separate locations. In many instances the ability of the Apogee CMM to sample from two locations allows one CMM to perform the duties of two comparable CMM systems. For this program the single CMM was used to measure TVM at the inlet and outlet of the MerCAP™ array to quantify mercury removal performance.

The CMM consists of a commercially-available cold vapor atomic absorbance (CVAA) spectrometer coupled with a gold amalgamation system (Au-CVAAS). The CMM measures and controls the sample gas flow using a precision mass flow controller to record the sample gas volume for each sample cycle. Sensors built into the CMM measure vacuum and sample gas oxygen content to detect any failures in the sample transport systems as well as to standardize emission rates at varied gas compositions. (Typically mercury concentrations are corrected to 3% oxygen content to account for in leakage and dilution effects) A generic sketch of the Apogee CMM is shown in Figure 3-4 and a photograph of an Apogee CMM and sample extraction system is shown in Figure 3-5.

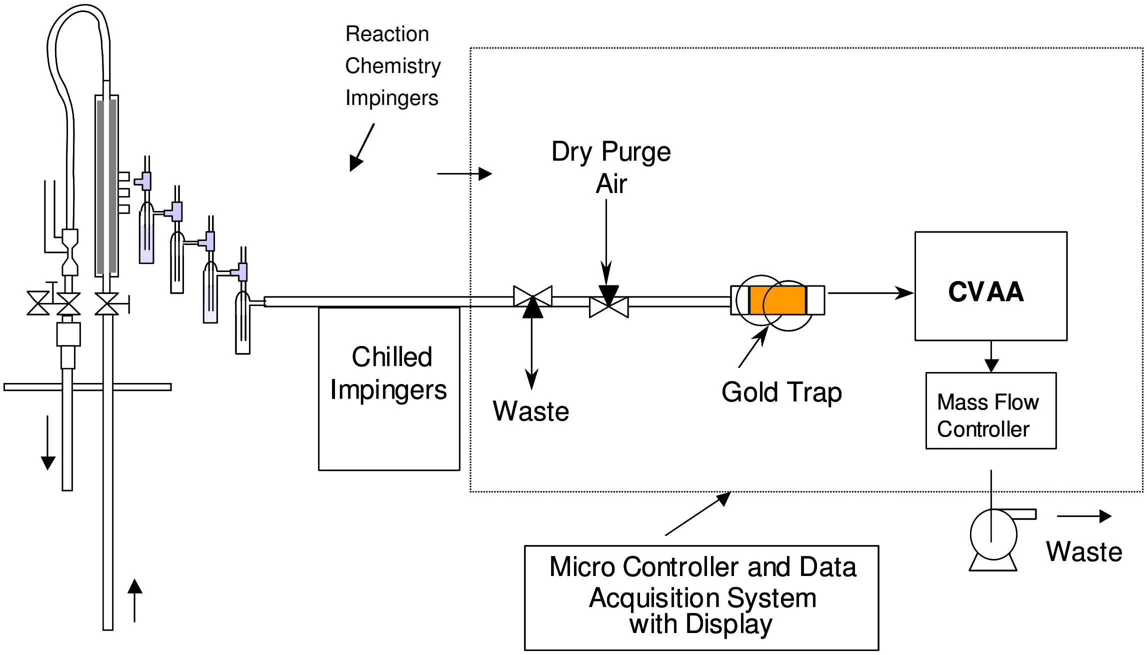


Figure 3-4. Apogee CMM Schematic.

Figure 3-5. Apogee Mercury CMM and Sample Extraction System.

Although it is very difficult to transport non-EVM in sampling lines, EVM can be transported without significant problems. Since the Au-CVAAS measures mercury by using the distinct lines of the UV absorption characteristic of EVM, the non-elemental fraction is either converted to EVM (for total mercury measurement) or removed (for measurement of the elemental fraction) near the sample extraction point. This minimizes any losses due to the sampling system.

For TVM measurements, all non-elemental vapor-phase mercury in the flue gas must be converted to EVM. A reduction solution of stannous chloride in hydrochloric acid is used to convert oxidized vapor-phase mercury (OVM) to EVM. The solution is mixed as prescribed in the draft Ontario Hydro Method for Manual Mercury Measurements. To measure elemental mercury, an impinger of potassium chloride (KCl) solution mixed as prescribed by the draft Ontario Hydro Method replaces the stannous chloride solution to capture oxidized mercury. The oxidized fraction of the vapor-phase mercury concentration, OVM, is computed by difference. The impinger solutions that comprise the sample conditioning system are continuously refreshed to assure continuous exposure of the sample gas to active chemicals.

Apogee QSIS™ sample extraction systems are utilized in concert with the CMM and sample conditioning systems to ensure an unbiased mercury measurement. The QSIS™ extraction system includes the Apogee QSIS™ Probe and controls. This system enables the sampling of vapor-phase mercury from combustion flue gas without introducing sampling artifacts. The Apogee QSIS™ sample extraction system is protected by a U.S. patent and has been used extensively by a number of testing groups demonstrating a proven performance track record. Figure 3-6 shows a schematic of the Apogee QSIS™ Probe. For this program the QSIS™ system was modified to be utilized with the MerCAP™ array.

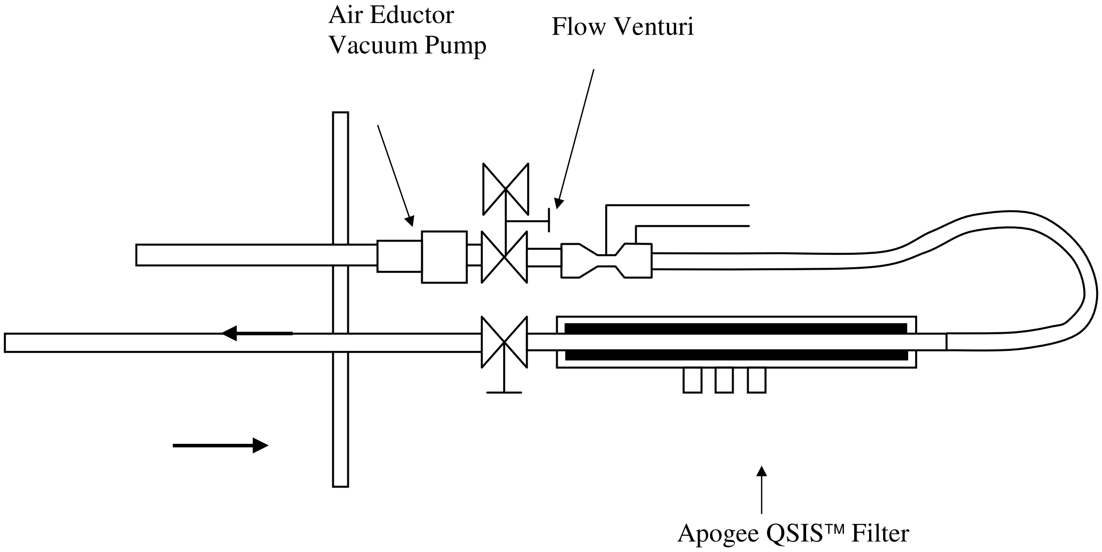


Figure 3-6. Apogee QSIS™ Probe.

3.2.2 Additional Testing Equipment

Additional equipment to perform Method 324 carbon trap mercury measurements was also utilized during this program. A standard low-flow gas-sampling box and stainless steel probe were utilized in accordance with the method specifications. The gas sampling box was calibrated and certified prior the start of this test program.

Ontario Hydro manual measurements were also conducted as part of this test program by URS Group, as described in Section 3.5.3. URS Group maintains and utilizes sampling equipment in accordance with all EPA specifications to perform these measurements.

3.3 Experimental Procedures – Site 1

3.3.1 Full-Scale Evaluations

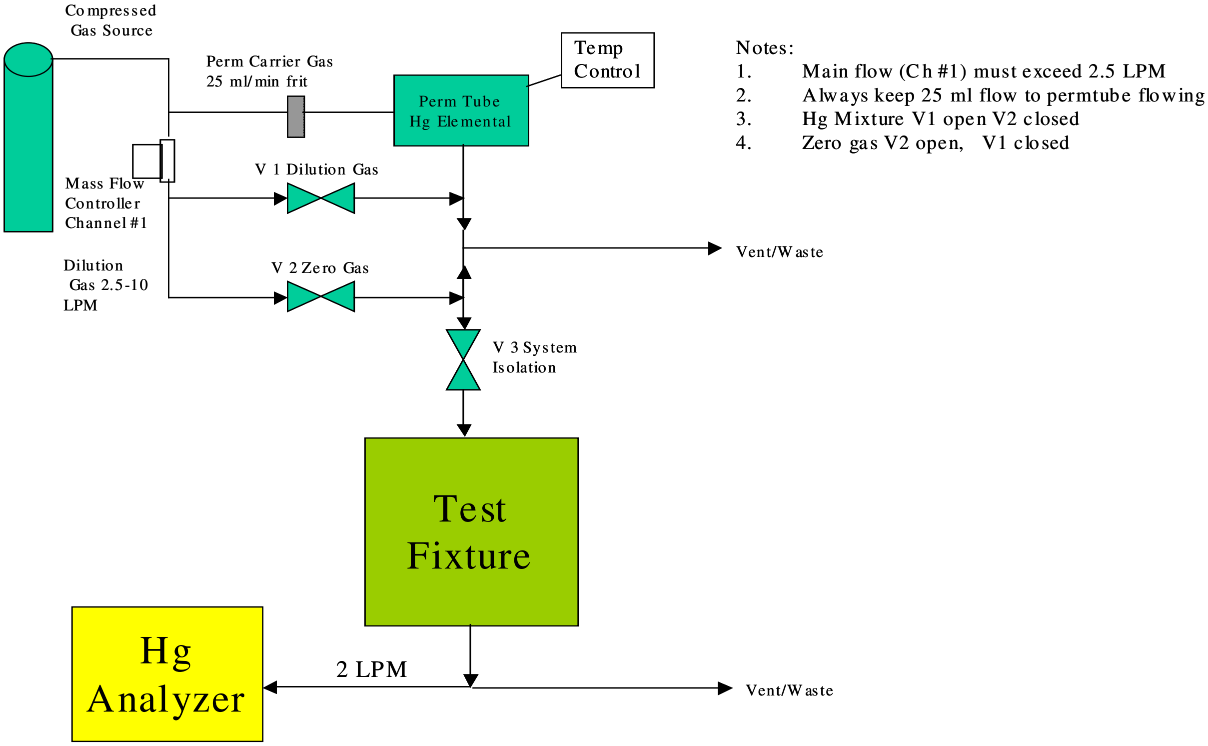
Full-scale evaluations were performed on the MerCAP™ array installed in the Stanton Unit 10 baghouse compartment. Inlet and outlet mercury measurements tracked the mercury removal performance of the array. Variations in plate geometry, plate spacing, and active length could be evaluated easily by utilizing the four independent duct sections of the array. Duct 1 of the array was always maintained as the baseline section housing 10 feet of substrates with a plate spacing of 1 inch. Parametric evaluations of plate spacing, active length, and plate geometry were conducted by making modifications to the other duct sections. By maintaining duct section 1 as a standard throughout the tests, each parametric iteration could be directly compared to the base design case.

Following the installation of the CMM, performance evaluations of the full-scale MerCAP™ array were conducted remotely utilizing automation built into the sampling array and the CMM. The mercury monitoring system utilized a prototype version of the Apogee Dry Sample Conditioning System (DSCS). The system enabled the CMM to run unattended, monitored remotely over the last 8 months of this program. With a fully functional CMM continuously monitoring the inlet and outlet mercury concentrations of the full-scale array, parametric evaluations of plant operational parameters were easily accomplished remotely with the help of plant personnel. Apogee personnel remotely monitored the mercury CEM before, during, and after an evaluation and recorded all data for analysis. Working with plant personnel over the phone, a series of tests were conducted including a test run of low-temperature in-situ regeneration of the array, and effects of varying the operation parameters of the SDA.

3.3.2 Small-Scale Evaluations

Small-scale evaluations of alternative sorbent materials and samples taken from the full-scale sorbent structures were conducted in the Apogee laboratory facility. A CMM and field sampling equipment were used to document and quantify mercury removal performance and capture capacity of substrate samples and promising alternative sorbent materials. Specially designed quartz glass and Teflon™ equipment was used to ensure no biasing of results obtained in the small-scale evaluations. Figure 3-7 shows a photograph of the laboratory test equipment, including an apparatus for testing plate and screen material (left) and an apparatus for fixed bed and fluidized bed testing (right). Figure 3-8 is a schematic representation of the small-scale test equipment used to evaluate different sorbent substrates.

Figure 3-7. Small-Scale Test Equipment



Notes:
1. Main flow (Ch #1) must exceed 2.5 LPM
2. Always keep 25 ml flow to permtube flowing
3. Hg Mixture V1 open V2 closed
4. Zero gas V2 open, V1 closed

Figure 3-8. Schematic Representation of Small-Scale Test Facility

3.4 Host Site Description – Site 2

Plant Yates Unit 1 is a 100 MW (gross) Eastern bituminous coal-fired plant equipped with a cold-side ESP (SCA = 173 ft^2/1000afcm) for particulate control and a Chiyoda CT-121 scrubber for SO_2 control. The Chiyoda scrubber is a jet bubbling reactor (JBR) and will heretofore be referred to as the JBR or the scrubber.

Additional characteristics of Unit 1 are summarized in Table 3-2. Figure 3-9 illustrates the basic plant configuration and pilot-scale MerCAP™ reactor location for Yates Unit 1. Two different pilot configurations were used during this program, as described below.

Table 3-2. Yates Unit 1 Configuration

	Yates Unit 1
Boiler	
Type	CE Tangential Fired
Nameplate (MW)	100
Coal	
Type	Eastern Bituminous
Sulfur (wt %, dry)	~1.0
Mercury (mg/kg, dry)	~0.16
Chloride (mg/kg, dry)	300-1400
ESP	
Type	Cold-Side
ESP Manufacturer	Buell (1968 and 1971 vintage, refurbished in 1997)
Specific Collection Area (ft^2/1000 acfm)	173
Plate Spacing (in.)	11
Plate Height (ft)	30
Electrical Fields	4
Mechanical Fields	4
ESP Inlet Temp. (°F)	310
ESP Design Flow Rate (ACFM)	490,000
NO_x Control	Low NO_x Burners
SO_2 Control	Chiyoda CT-121 wet scrubber (JBR)
Flue Gas Conditioning	None

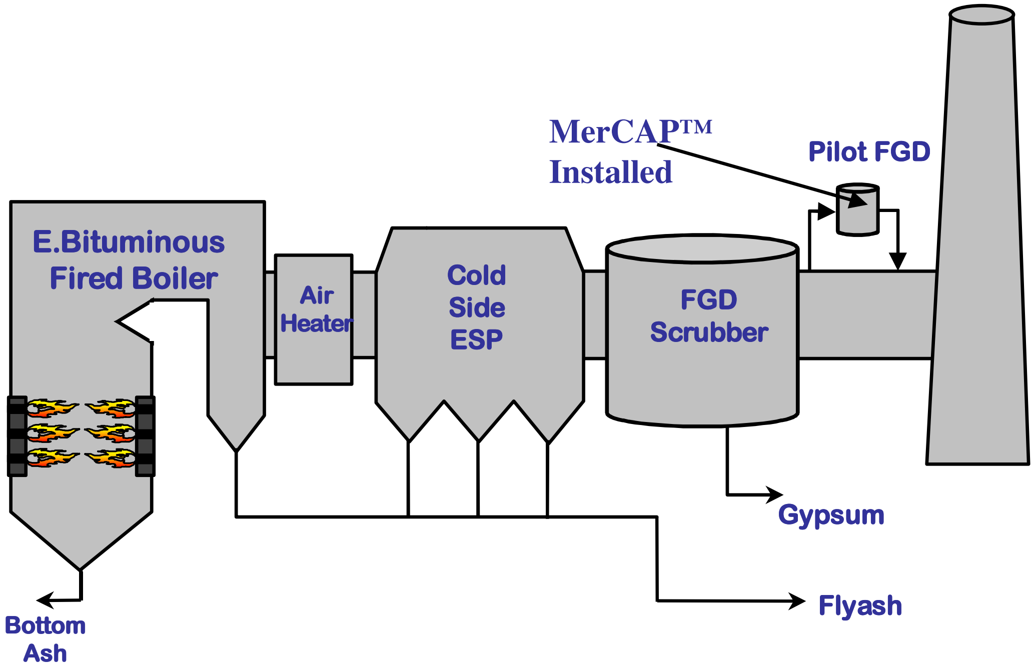


Figure 3-9. Plant Yates Unit 1 Configuration.

3.4.1 Description of Pilot MerCAP™ Reactor

Tests at Plant Yates were conducted to evaluate gold MerCAP™ performance downstream of a wet FGD absorber in flue gas derived from Eastern bituminous coal. The fixed sorbent structure was configured in a horizontal reactor, depicted in Figure 3-10, designed to obtain a slipstream of flue gas (approximately 2800 acfm) from downstream of the Unit 1 JBR reactor. The ductwork and fan used to transport the slipstream were part of an existing pilot reactor installed previously by Southern Company. The reactor was designed to operate with saturated flue gas in a temperature range of 110°-150°F (43°-66°C). A drain at the bottom of the reactor housing was designed to remove excess water.

Figure 3-11 is a photograph of the constructed reactor housing that contained the gold substrates for the MerCAP™ installation at Plant Yates. The reactor vessel consisted of a 21-in wide by 12-in high rectangular vessel capable of housing multiple fixed sorbent structure arrays. Figure 3-12 shows a photograph of one of the three initial MerCAP™ gold substrate modules that was installed in the pilot housing. Each module consisted of an array of parallel gold-coated screens 12-in by 12-in in size. Each module was sized with a 12-in by 21-in face to allow for a proper fit within the reactor housing. A ¼ -inch parallel plate spacing was used for the sorbent array. Each module was 12 inches in length, resulting in an effective MerCAP™ plate length of 36 inches when three modules were installed. The theoretical linear flue gas velocity across the sorbent surface was 26 ft/sec at the design gas flow rate of 2800 acfm. Prior to being secured in the individual substrate modules, the gold-coated screens were subjected to a nitric acid (30 vol. %) wash. Previous testing had shown the acid wash to improve the performance of the substrates, as described above.

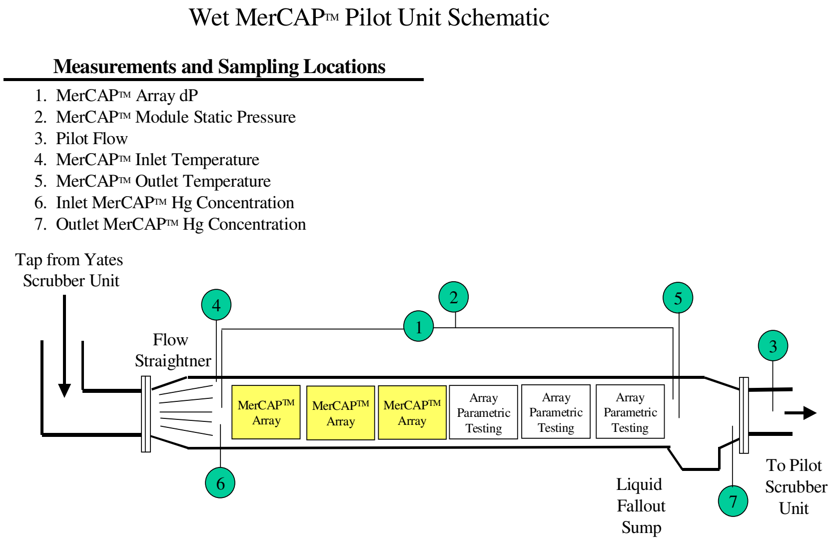


Figure 3-10. Pilot MerCAP™ Reactor – Site 2

The test unit fabrication was completed in February 2005; the reactor was then shipped to Plant Yates for installation. The MerCAP™ test unit was not immediately installed on Unit 1 due to scheduling conflicts associated with a planned unit outage and two other DOE test programs (i.e., DE-FC26-03NT41987 and DE-FC26-04NT42309) being conducted at Plant Yates; the latter involved reconfiguration of the Southern Company pilot scrubber system in order to conduct a series of scrubber additive tests. Final ducting and installation of the MerCAP™ reactor was completed during a unit outage in November 2005. Final installation of the pilot unit fan was completed in January 2006.

Figure 3-13 illustrates the configuration for the initial MerCAP™ pilot unit installed at Plant Yates. The reactor was installed in a long horizontal run of pipe that originally ran to the inlet of Southern Company's pilot FGD scrubber. This was previously identified as the best location for the installation because the MerCAP™ unit could be easily retrofitted into the existing system at this location and because the run of pipe was relatively close to the ground, thus aiding in the gold plate installation and flue gas sampling activities. The flue gas fan, located downstream of the reactor, provided the motive force for the flue gas across the MerCAP™ unit. Flue gas exiting the MerCAP™ reactor flowed back to the Unit 1 duct, re-entering just upstream of the full-scale JBR unit.

Figure 3-11. Wet MerCAP™ Housing for Installation at Plant Yates

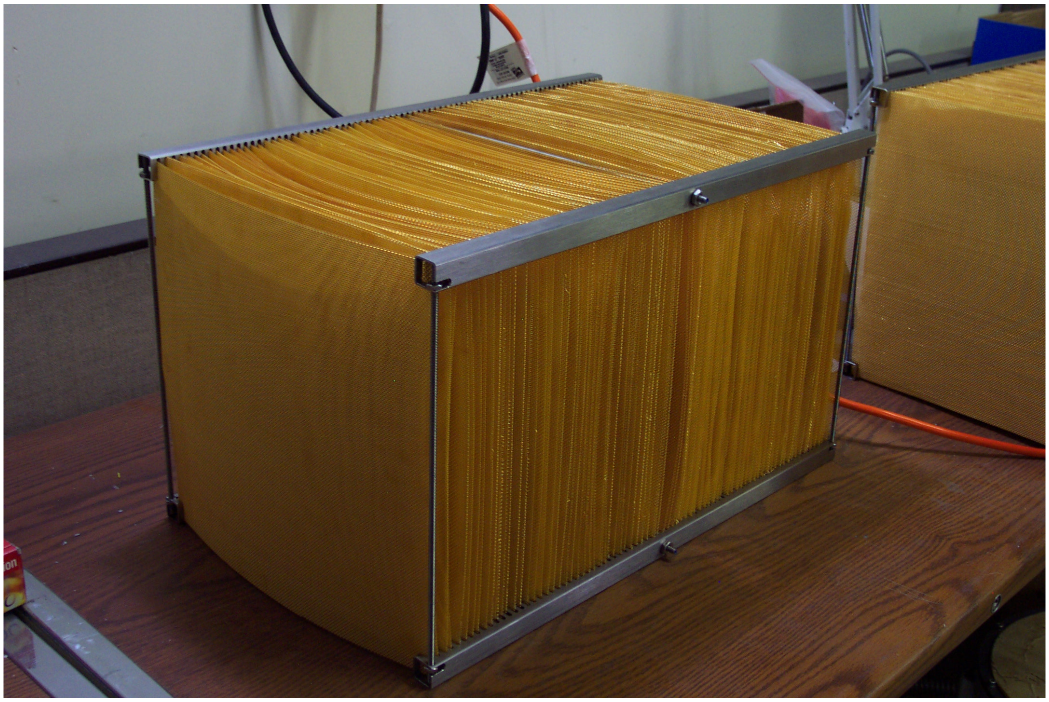


Figure 3-12. Gold Substrate Module for the Wet MerCAP™ System (1 of 3)

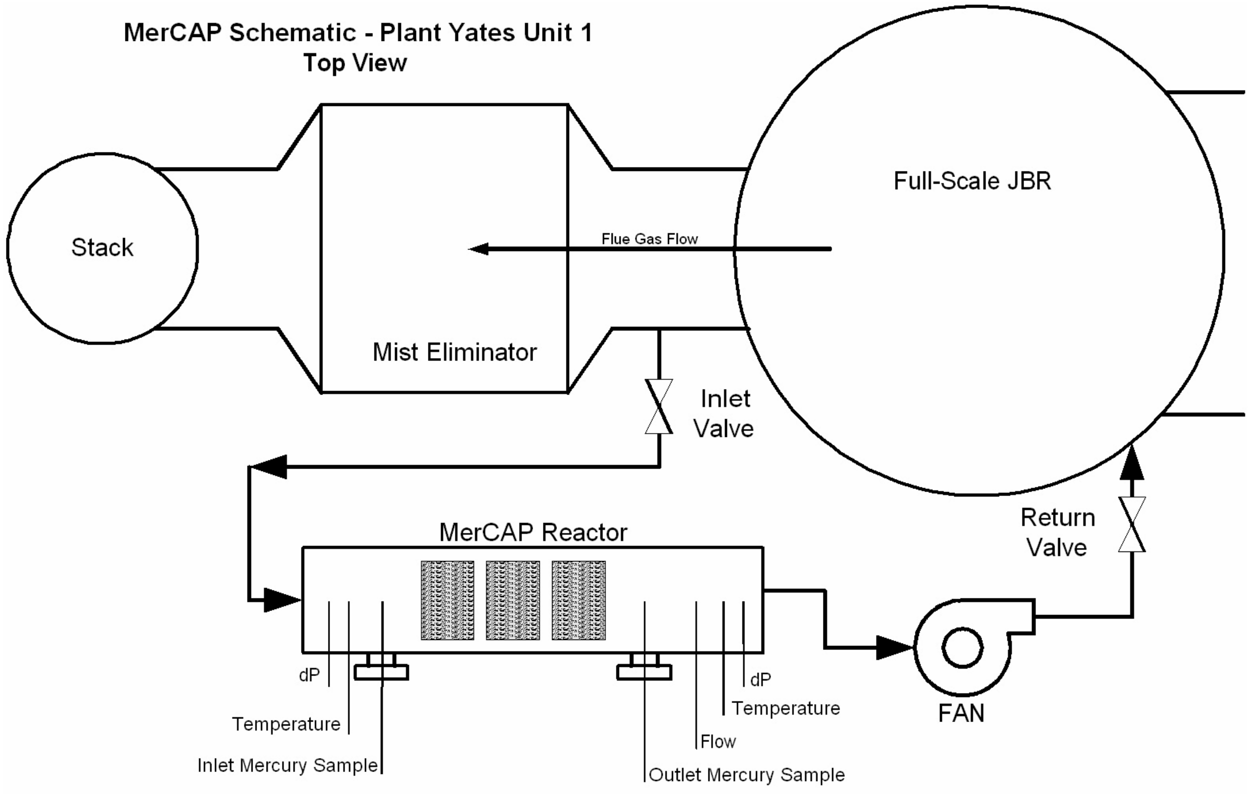


Figure 3-13. Initial MerCAP™ Installation at Plant Yates Unit 1

The MerCAP™ reactor was designed to be constantly monitored for inlet and outlet temperature, static pressure, pressure drop, and flue gas flow. A data logger located on site continuously collected the process data. Ports fitted upstream and downstream of the gold plates (Figure 3-11) allowed access points for conducting flue gas mercury measurements. A wash water system was fitted to the system to allow for periodic cleaning of the gold screens. The wash system consisted of a series of spray nozzles designed to provide a co-current rinse of the parallel MerCAP™ screens. The system used plant service water and was controlled to provide periodic system rinses using a solenoid valve coupled to an automatic timer. Water added during the rinse cycle was removed from the reactor using drains located at the bottom of the reactor housing.

The initial pilot unit configuration was found to be insufficient for achieving the desired flue gas flow across the MerCAP™ system. This was due to a combination of limited fan power and pressure differential between the slipstream take-off and re-entry locations. This problem was alleviated by refurbishing the fan and reconfiguring the slipstream duct configuration.

Figure 3-14 illustrates the re-configured pilot MerCAP™ system. Here, flue gas exiting the reactor and fan was re-ducted to flow to a port downstream of the JBR absorber, as opposed to the original installation that had the flue gas return upstream of the JBR. With this new configuration the pressure drop across the entire MerCAP™ (slipstream) system was reduced from nearly 20 in. H_2O to approximately 3 in. H_2O.

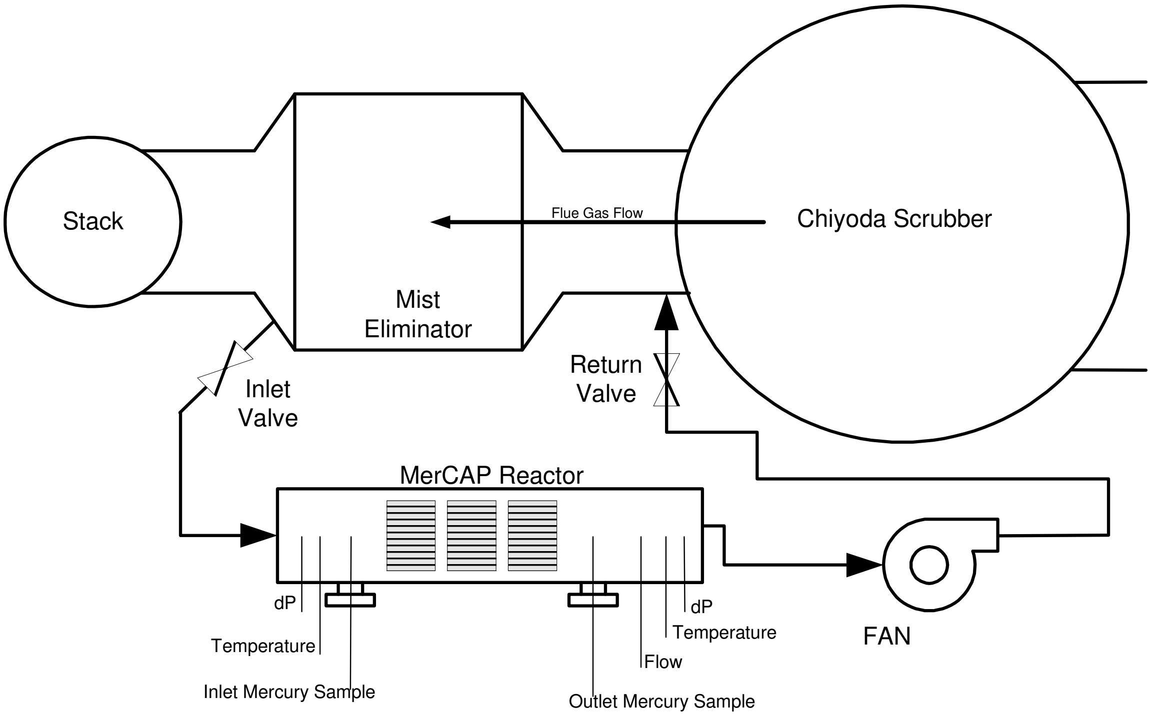


Figure 3-14. Reconfigured MerCAP™ Installation at Plant Yates Unit 1

3.5 Description of Test Equipment – Site 2

3.5.1 Mercury Sampling Equipment

Additional details pertaining to the EPRI SCEM mercury analyzer are provided in this section since it is not a standard EPA method. Flue gas vapor-phase mercury analyses were made using an EPRI semi-continuous analyzer, depicted in Figure 3-15. Figure 3-16 shows a photo of the analyzer control system and detector unit. At each sample location, flue gas was extracted at a single point from the duct and then drawn through an Apogee QSIS™ sample extraction system, described below, to remove particulate matter. The mercury analyzer consists of a cold vapor atomic absorption spectrometer (CVAAS) coupled with a gold amalgamation system (Au-CVAAS). Since the Au-CVAAS measures mercury by using the distinct lines of the UV absorption characteristics of elemental mercury, the non-elemental fraction is converted to elemental mercury prior to analysis using a chilled reduction solution of acidified stannous chloride. Several impingers containing alkaline solutions are placed downstream of the reducing impingers to remove acidic components from the flue gas; elemental mercury is quantitatively transferred through these impingers.

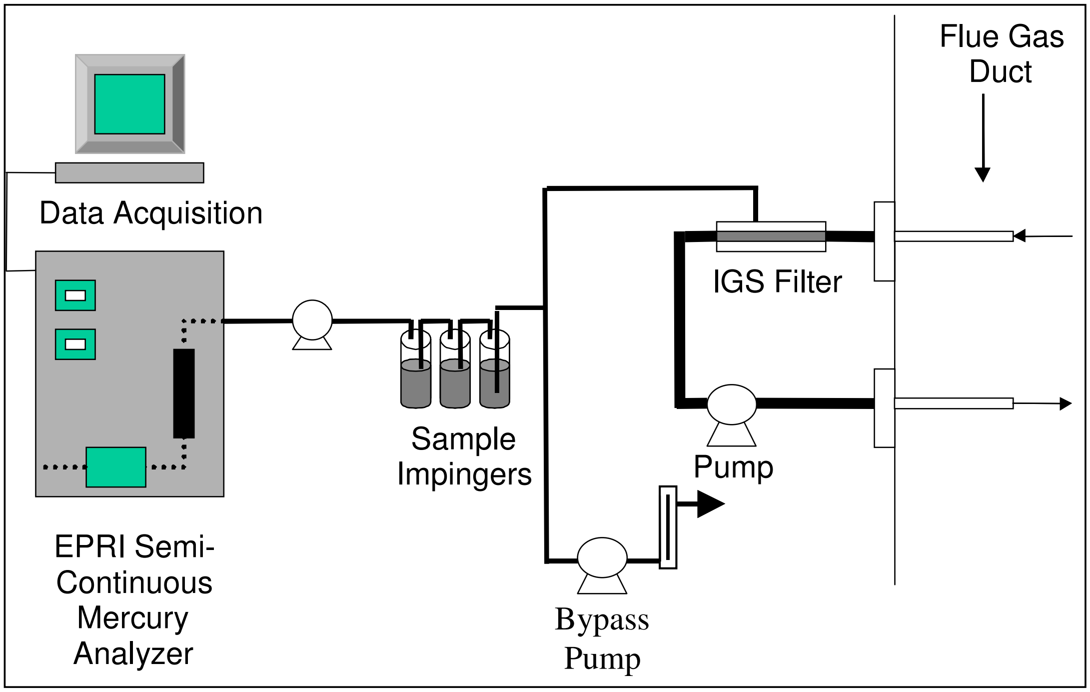


Figure 3-15. Schematic of EPRI Semi-Continuous Mercury Analyzer

Gas exiting the impingers flows through a gold amalgamation column where the mercury in the gas is adsorbed (<60° C). After adsorbing mercury onto the gold for a fixed period of time (typically 1 minute), the mercury concentrated on the gold is thermally desorbed (>400° C) in nitrogen or air, and sent as a concentrated mercury stream to a CVAAS for analysis. Therefore, the total flue gas mercury concentration is measured semi-continuously with a 1-minute sample time followed by a 2-minute analytical period.

To measure elemental mercury only, an impinger containing either 1M potassium chloride (KCl) or 1M Tris Hydroxymethyl (aminomethane) and EDTA is placed upstream of the alkaline solution impingers to capture oxidized mercury. Oxidized forms of mercury are subsequently captured and maintained in the KCl or Tris impingers while elemental mercury passes through to the gold amalgamation system. Comparison of "total" and "elemental" mercury measurements yields the extent of mercury oxidation in the flue gas.

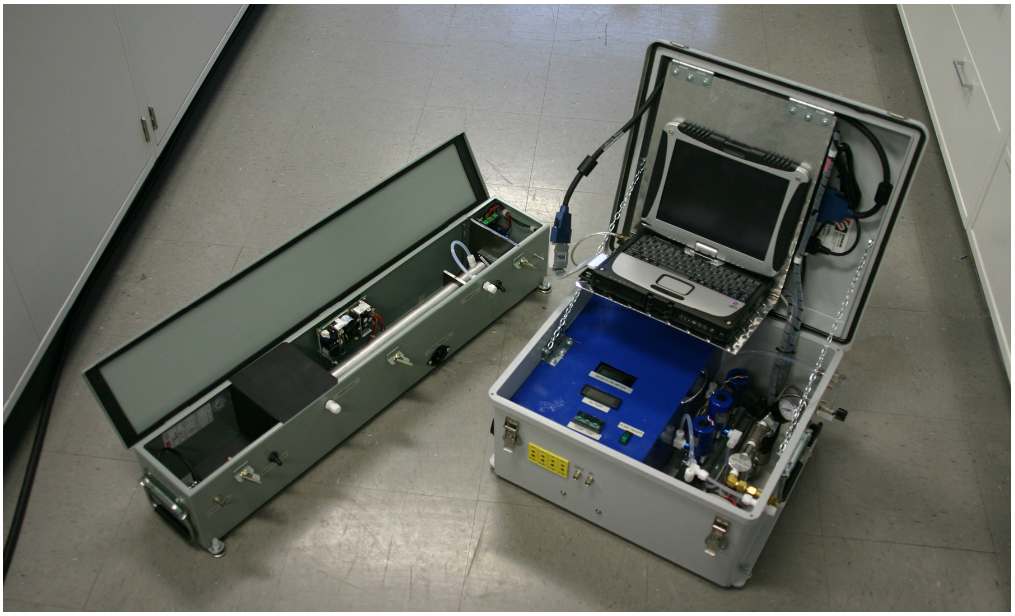


Figure 3-16. Sampling Control Module and Detector of EPRI SCEM

Apogee QSIS™ sample extraction systems are utilized in concert with the SCEM system and sample conditioning systems to ensure an unbiased mercury measurement. The QSIS™ extraction system includes the Apogee QSIS™ Probe and controls. This system enables the sampling of vapor-phase mercury from combustion flue gas without introducing sampling artifacts. Figure 3-17 shows a schematic of the Apogee QSIS™ Probe that was utilized with the MerCAP™ pilot system. This inertial gas separation filter consists of a heated stainless steel tube lined with sintered material. A secondary sample stream is pulled across the sintered metal filter and then is directed through the mercury analyzer at a rate of approximately 1-2 L/min thus providing near real-time feedback during the various measurement periods.

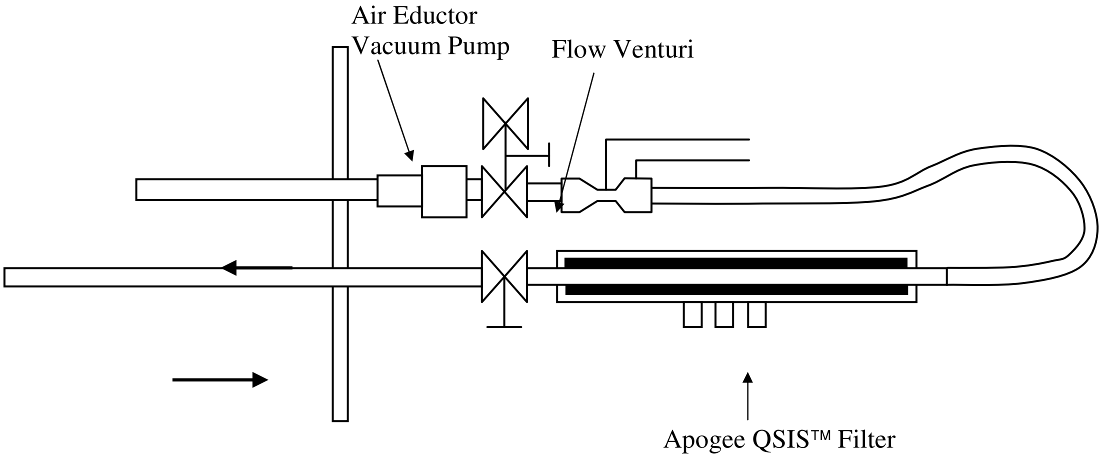


Figure 3-17. Apogee QSIS™ Probe

3.5.2 Additional Sampling Equipment

Additional manual gas sampling equipment was utilized during this program to perform Ontario Hydro measurements. Procedures were carried out as defined in ASTM procedure number D6784 - 02, "Standard Test Method for Elemental, Oxidized, Particle-Bound and Total Mercury in Flue Gas Generated from Coal-Fired Stationary Sources (Ontario Hydro Method)". Sampling equipment was maintained and calibrated by trained URS personnel in accordance with all EPA specifications to perform these measurements. Figure 3-18 depicts the sampling equipment and configuration used for the Ontario Hydro measurements.

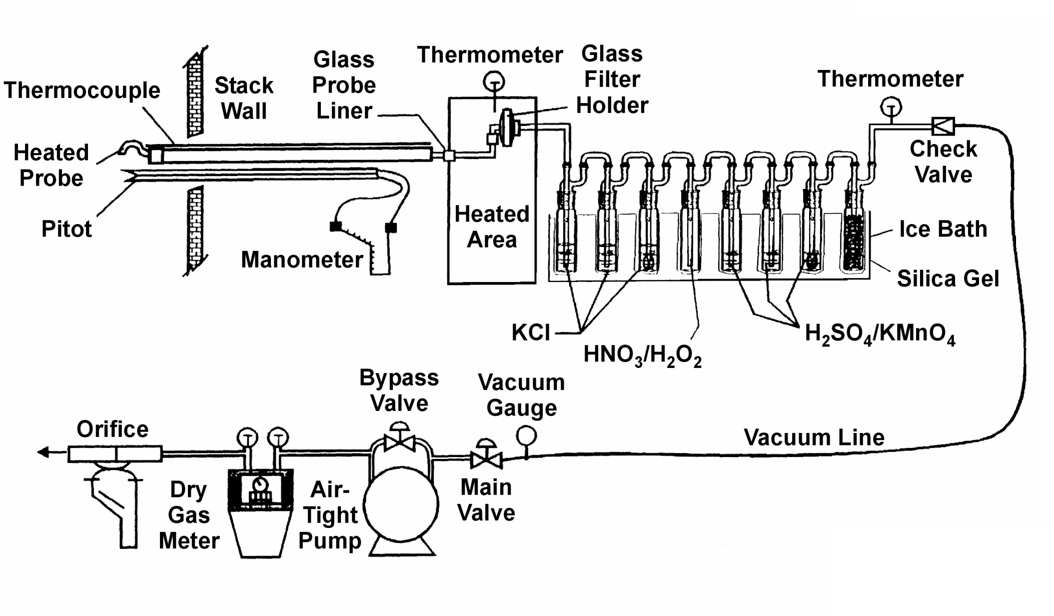


Figure 3-18. Ontario Hydro Sampling System

3.6 Experimental Procedures – Site 2

Tests were conducted at Plant Yates Unit 1 to evaluate gold MerCAP™ performance in flue gas obtained downstream of a wet FGD absorber. Prior to conducting pilot-scale tests, a series of small-scale slipstream tests were conducted in order to both re-verify the MerCAP™ ability to remove mercury from the Unit 1 flue gas and evaluate the impacts of wash water rinsing frequency on performance. Results were used to design the operating parameters used for the pilot scale reactor. Pilot testing was conducted using the reactor described in Section 3.4.2 to evaluate MerCAP™ performance over extended flue gas exposure periods. Procedures used during the various tests are described in this section.

3.6.1 Small-Scale Evaluations

Prior to the pilot scale test program at Plant Yates, a series of slipstream tests were conducted to verify mercury removal performance of the gold-coated sorbent screens in the Unit 1 flue gas. Test objectives included evaluation of the mercury screen formulation proposed for the pilot test as well as determination of the need for MerCAP™ screen washing during extended operation.

EPRI's wet MerCAP™ slipstream test system was configured to obtain flue gas from the Unit 1 stack, just downstream of the JBR scrubber. Figure 3-19 illustrates the slipstream MerCAP™ system that consists of three 12-inch long sections of gold plated stainless steel screens. The MerCAP™ test column consisted of an array of seven gold-coated screens spaced evenly across a 1.87" x 1.87" square channel. Flue gas flowed parallel to the screens. The total length of the parallel screen reactor was 36-inches.

A dual gas fan assembly was used to obtain an 8-17 scfm slipstream from downstream of the Unit 1 FGD module. The flue gas was passed through the sorbent reactor containing the gold-coated plates (1-3 ft length). A ¼-inch plate spacing was used for the MerCAP™ screens which were wetted with wash water during the test. The flue gas flow across the MerCAP™ array was monitored and controlled using a venture tube and valve configured downstream of the reactor. Flue gas was pulled across the screens with a linear velocity of approximately 14 ft/sec. The reactor column was wrapped with heating tape and insulated and the temperature was controlled at 130°F (54°C) using a thermocouple inserted in the flue gas, just downstream of the sorbent array.

The slipstream system was equipped with a washing system that sprayed the screens with water at regular intervals using an electronic timer. The wash water was sprayed at the top of the wet MerCAP™ column thus rinsing the sorbent plate surfaces in a co-current manner relative to the flue gas flow. For most of the testing the screens were washed for 5 seconds out of every minute for half an hour every 2 hours. Thus, the total rinse time over each 30-minute washing period was 2.5 minutes. Deionized water, obtained from the Unit 1 FGD laboratory, was used as the washing liquid. Wash water was recycled in batch mode during each test and replaced periodically. The solution pH was routinely monitored to ensure an operating range between 4-8.

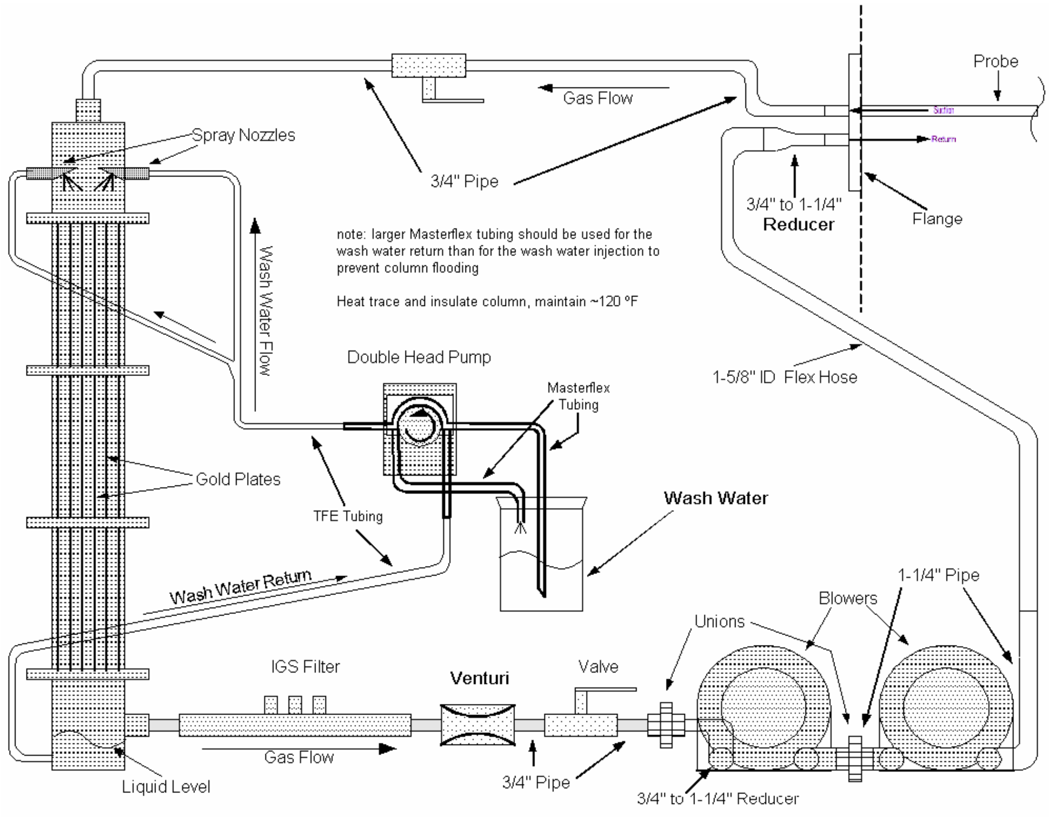


Figure 3-19. EPRI Slipstream MerCAP™ Reactor Schematic

The wet MerCAP™ unit was placed into service in November 2004, and was allowed to run continuously until late January 2005. A single set of gold-coated sorbent screens were used for the entire test program. Mercury concentrations were measured with a single EPRI SCEM system. Inlet mercury measurements were made by obtaining duct flue gas using a QSIS probe that was configured in an adjacent port to the slipstream MerCAP™ unit. Reactor outlet mercury concentrations were obtained by sampling flue gas from a heated IGS filter located immediately downstream of the MerCAP™ unit. Measurements were cycled between the two locations during each test to determine the extent of mercury removal across the MerCAP™ system.

Initial tests were conducted to evaluate mercury removal across the slipstream MerCAP™ reactor in the absence of a water wash rinse of the substrate screens. Subsequent tests were performed in which varying degrees of water rinsing (of the screens) were implemented. Figure 3-20 shows the rinsing nozzles as configured in the slipstream reactor. In most cases, this involved an automated water rinse conducted for a set time period and set to cycle at a given frequency. For example, some tests involved a 30-minute rinsing cycle that occurred every two hours. Rinsing was continuous during the water wash period. In some tests a continuous (i.e., non-timed) water rinse was implemented.

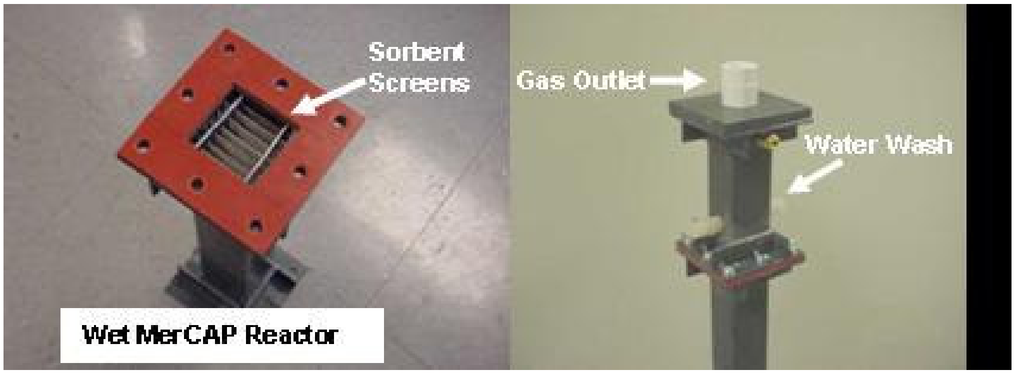


Figure 3-20. Photos of Slipstream MerCAP™ Reactor

Over the first several weeks of testing, measurements were made on a routine basis and a number of different rinsing options were investigated. Based on the results of these tests a rinsing procedure, involving a cycling method as described above, was determined and implemented as part of a longer-term continuous gas exposure test. This test was conducted for a period of four weeks. Measurements were made periodically to verify MerCAP™ performance during the longer-term test.

3.6.2 Pilot-Scale Evaluations

Pilot-scale tests were conducted at Plant Yates Unit 1 to evaluate the gold MerCAP™ technology when installed downstream of a wet FGD absorber in flue gas derived from Eastern bituminous coal. The pilot reactor described in Section 3.4.2 (Figure 3-10) was configured in a slipstream that received flue gas from downstream of the Plant Yates Unit 1 JBR scrubber. The slipstream was part of an existing pilot scrubber setup installed previously by Southern Company. The MerCAP™ reactor vessel (Figure 3-11) was installed in a horizontal orientation upstream of a fan used to derive the motive force for flue gas flow across the system. Two flow configurations were used during the pilot program, as depicted in Figures 3-13 and 3-14; the primary difference between the two configurations was the location of the flue gas return from the pilot system to the full-scale duct.

The objective of the test program was to evaluate the mercury removal performance of gold-coated screens arranged in a MerCAP™ system configuration for a period of six months. The screens were prepared using an established procedure involving the washing and nickel pre-coating of a stainless steel screen (18 x 18 mesh) substrate followed by placement of a 13-15 micro-inch gold coating on the surface using a standard electroplating technique. Optimization of the gold-coated screen fabrication and pre-treatment (prior to installation for mercury control) was evaluated in previous EPRI test programs and is discussed for Site 1, above. The prepared gold-coated screens were arranged in a parallel configuration in three separate fixed modules, depicted in Figure 3-12 and described in Section 3.4.2. The modules were placed in the horizontal MerCAP™ reactor, reacted with flue gas and evaluated for mercury removal performance. The reactor operated at a nominal temperature of 120°F (49°C) during the test program. The reactor was configured with a wash water system that allowed for routine in situ cleaning of the gold screens.

During the pilot test program, the MerCAP™ reactor was constantly monitored for inlet and outlet temperature, static pressure, pressure drop, and flue gas flow. A data logger located on site was used to continuously collect this data. Ports fitted immediately upstream and downstream of the gold screen modules provided access points for flue gas measurements to be made. During long-term testing, the pilot unit was checked periodically to ensure that all operating parameters were maintained at the desired settings.

Mercury measurements were made using a single EPRI SCEM system, described in Section 3.5.2. To evaluate mercury removal performance, the analyzer was cycled between the inlet and outlet sampling locations throughout a given measurement period. Average mercury concentrations for a set of measurements conducted at a given location would be calculated and subsequently compared to average values determined for the other sampling location (for measurements taken immediately before or afterwards). For long-term testing phases of the program, mercury measurements were made periodically (typically every 2-5 weeks) when test personnel visited the host site.

Visual inspections of the gold sorbent arrays were made on several occasions during the test program. This was done by temporarily stopping flow and isolating the pilot unit from the full-scale ducts, then opening the top of the reactor housing to view the sorbent modules. In some cases, a manual washing of the screens was conducted by spraying the modules with a high-pressure water stream.

Tests were conducted during this program to evaluate the ability of the gold MerCAP™ technology to remove mercury from the saturated flue gas from downstream of the FGD absorber. Several operating parameters were evaluated during the program, including the impacts on performance of the flue gas flow rate across the reactor, the number of gold substrate arrays installed, the use and frequency of a water wash rinse, and exposure time to flue gas.

Table 3-3 lists the various flue gas flow rates evaluated during this program. The flow was varied from 1300 to 5000 acfm (120°F; 49°C) during parametric testing. This resulted in linear velocities (across the sorbent screens) ranging from 12 – 48 ft/sec. The range of theoretical mercury removals for these flow rates, based on mass transfer properties, was 61-74% for a fully charged reactor. Long-term operation was generally conducted with a gas flow rate of 2700 acfm across the pilot reactor.

Table 3-3. Flue Gas Flow Rates Evaluated During Site 2 Pilot Tests.

Flue Gas Flow Rate (acfm*)	Flue Gas Linear Velocity (ft/s)	Theoretical MerCAP™ Mercury Removal (% of Inlet)		
		36-in Length	24-in Length	12-in Length
1300	12	74	59	36
2700	25	68	53	31
3200	30	66	51	30
3600	34	64	50	29
5000	48	61	47	27

* - Reactor Operating of 120°F (49°C)

Ontario Hydro measurements were made on several occasions to validate measurements made using the EPRI SCEM system. Trained testing crews from URS Group conducted the manual measurements following ASTM Method D6784-02. Simultaneous Ontario Hydro samples were obtained from the Unit 1 stack (i.e., for direct comparison to the pilot inlet measurements) and the outlet of the MerCAP™ pilot unit. During each Ontario Hydro sampling period, the SCEM was cycled between the inlet and outlet locations to obtain sufficient comparison data. Samples obtained from Ontario Hydro sampling were shipped to URS's Austin, Texas analytical laboratory for analysis.

A number of the flue gas-treated sorbent screens were characterized at the end of the test to evaluate impacts of flue gas exposure on their surface properties. Samples were analyzed by scanning electron microscopy (SEM) couple with energy dispersive X-ray spectroscopy (EDS) for chemical composition mapping. Results were compared to those of 'fresh' untreated gold-coated screen to determine the impacts of flue gas exposure. The surface analyses were conducted at M&M Engineering (Austin, TX).

3.6.3 Gold Sorbent Cleaning

It was determined at several times during the pilot program that manual cleaning of the horizontal MerCAP™ array was required due to build-up of solid material on some plates. The primary manual cleaning method involved washing the plates with a pressurized water rinse, as mentioned above. This involved stopping flue gas flow to the reactor, removing the top of the reactor vessel, and spraying the sorbent array from above. A drain, located at the bottom of the vessel, was opened to allow the spent rinse water to vacate the reactor.

On some occasions, it was determined that a manual water rinse was not adequate to clean the MerCAP™ plates resulting in the need to remove them from the vessel for more stringent cleaning. Several cleaning techniques were attempted including acid rinsing and brushing. The best technique was determined to be using a stiff bristled brush to remove the surface deposits, and then acid rinsing with continued brushing. The plates were cleaned in this manner using a 0.5% solution of nitric acid and DI water. After the substrates were cleaned with acid, they were thoroughly rinsed with water and allowed to dry in an oven at approximately 450°F (232°C) before being reassembled and placed back in the reactor.

4.0 Results and Discussions

This section describes results from the results conducted at Host Sites 1 and 2.

4.1. Results and Discussion – Site 1

4.1.1 Full-Scale Evaluation Results

Prior to December 18, 2005, mercury concentration measurements were periodically conducted on the Site 1 MerCAP™ array. An automated CMM monitored the MerCAP™ array continuously starting on December 18, 2005. The addition of the remote monitoring capability allowed several parametric evaluations of plant operation changes to be conducted. The data and results of these evaluations are presented below. Measurements of the mercury concentrations at the inlet to and outlet of each duct section were utilized to quantify performance. Additionally, gas flow, velocity, and pressure drop data was also collected across the MerCAP™ array and included in the overall analysis.

<u>Overview of Full-Scale Array Mercury Removal Performance</u>

Mercury removal performance data was gathered periodically from the initial start-up of the MerCAP™ array in August 2004 through December 2005. The data was collected on a continuous basis starting on December 18, 2005 and continuing through to the ultimate shut-down and removal of the full-scale array from service in July 2006. Analysis of this data showed that variability in the mercury removal performance of the full-scale array can be correlated to variations in plant process variables. The key variables identified by analysis of mercury removal performance data are flue gas temperature and the operation of the SDA.

Analysis of data collected during periods of stable unit operation, particularly with regard to flue gas temperature, demonstrated that the MerCAP™ array could consistently achieve 30-40% mercury capture following one year of continuous service. However, temperature variations observed on a regular basis, especially following the fuel switch to PRB coal, had a significant effect on the MerCAP™ performance. In some cases temperature variations actually correlated with mercury being emitted from the sorbent structures.

Table 4-1 summarizes the mercury removal performance data collected over the entire Site 1 program, from the initial start-up of the full-scale array in August 2004 through its removal from service in July 2006. The table includes data from parametric evaluations to investigate impacts of MerCAP™ geometry, plate spacing, substrate pretreatment, and plant process variables.

Table 4-1. Summary of Full-Scale Array Mercury Removal Performance

Date	Description	Service Time (Hours)	Hg Concentration (µg/Nm^3)		Removal (%)	Temp (°F)
			Inlet Total	Outlet Total		
8/22/04	Initial start-up and installation of gold in Duct 1 (1-inch spacing, 10 feet)	4	7.8	0.9	89.0	177
8/28/04	24-hour average of Duct 1 gold at start-up plus 6 days (1-inch spacing, 10 feet)	147	8.6	4.7	45.2	1845
9/28/04	24-hour average of Duct 1 gold at start-up plus 5 weeks (1-inch spacing, 10 feet)	916	7.5	4.8	35.2	184
Host Site Fuel Switched to PRB Coal from North Dakota Lignite						
11/19/04	Initial start-up of unwashed gold in Duct 2 (1-inch spacing, 10 feet)	15	3.0	2.0	32.2	213
	Initial start-up of unwashed gold in Duct 3 (1/2-inch spacing, 10 feet)	15	3.0	1.7	41.3	
1/25/05	Duct 1 24-hour average (1-inch spacing, 10 feet)	3758	4.0	2.6	34.7	189
	Duct 2 24-hour average after acid wash and reinstallation (1-inch spacing, 10 feet)	1600	4.0	1.9	52.6	
	Duct 3 24-hour average after acid wash and reinstallation (1/2-inch spacing, 10 feet)	1600	4.0	1.7	58.8	
12/20/05	Duct 1 24-hour average after sampling system rebuild (1-inch spacing, 10 feet)	11637	7.2	6.8	6.0	214
12/22/05	Duct 2 48-hour average after sampling system rebuild (1-inch spacing, 10 feet)	9573	7.4	5.7	23.1	199
12/23/05	Duct 3 24-hour average after sampling system rebuild (1/2-inch spacing, 10 feet)	9598	6.8	6.0	10.9	196
2/19/06	Duct 1 10-hour average preceeding regeneration run (1-inch spacing, 10 feet)	12350	4.6	4.2	10.3	194
	Duct 1 90-minute average during regeneration heat cycle (1-inch spacing, 10 feet)	12352	5.6	16.7	-197.2	248
	Duct 1 5-hour average during regeneration cycle, after mercury desorb spike (1-inch spacing, 10 feet)	12356	4.4	2.7	37.4	260
2/20/06	Duct 2 26-hour average after new lime feed to SDA, SO$_2$ control at 95%+ (1-inch spacing, 10 feet)	11014	2.0	0.5	76.5	195
2/21/06	Duct 1 16-hour average after new lime feed to SDA, SO$_2$ control at 95%+ (1-inch spacing, 10 feet)	13142	4.5	1.7	62.0	195
2/23/06	Duct 1 48-hour average after new lime feed to SDA, SO$_2$ control at 95%+ (1-inch spacing, 10 feet)	13190	4.7	2.3	52.1	195
4/25/06	Duct 1 – 10-feet, 1-inch spacing (48-hour Average)	14650	2.5	1.2	39.2	203
	Duct 2 – Empty (48-hour Average)	N/A		2.5	0.0	
	Duct 3 – 40 Plates Perpendicular to Flow (48-hour Average)	N/A		2.4	4.7	
	Duct 4 – 8-feet Active Length Carbon Cloth (48-hour Average)	N/A		2.2	9.7	

Table 4-1. (Continued)

Date	Description	Service Time (Hours)	Hg Concentration ($\mu g/Nm^3$)		Removal (%)	Temp (°F)
			Inlet Total	Outlet Total		
5/5/06	Duct 1 – 10-feet, 1-inch Spacing (10-day Average)	14900	3.6	2.3	36.2	209
	Duct 2 – 8-feet Active Length Carbon Cloth (10-day Average)	N/A		3.8	0	
	Duct 3 – 5 Plates Perpendicular to Flow (10-day Average)	N/A		3.2	7.4	
	Duct 4 – 4-feet Active Length, 1-inch Plate Spacing, Acid Washed Gold (10-day Average)	N/A		2.6	26.5	
7/7/06	Duct 1 – 10-feet, 1-inch Spacing (24-hour Average) ***In service for 23 months continuously***	16400	3.8	1.7	54.6	219
	Duct 2 – 2-feet Active Length, 1/2-inch Plate Spacing, Acid Washed Gold (24-hour Average)	N/A		1.7	56.5	
	Duct 3 – 2-feet Active Length, 1-inch Plate Spacing, Acid Washed Gold (24-hour Average)	N/A		2.8	25.8	
	Duct 4 – 4-feet Active Length, 1-inch Plate Spacing, Acid Washed Gold (24-hour Average)	N/A		2.7	30.6	

After nearly two years of service the base case substrates installed in duct section 1 were able to achieve 30 to 40% mercury removal under normal operation of Unit 10. The removal increased to over 50% with increased sulfur scrubbing from the SDA, as seen on July 7, 2006. The combination of flue gas temperature and the level of acid gas (i.e., SO_2) present in the flue gas at the inlet to the MerCAP™ array directly affected the mercury removal performance. During periods of low gas temperatures and high levels of sulfur scrubbing by the SDA, the mercury removal performance of the MerCAP™ array was demonstrably higher than when the extent of sulfur scrubbing was lower and gas temperatures were higher. Additional discussion of the gas temperature and SDA operation effects is included below.

In addition to the gold-based sorbent evaluation, tests were conducted to evaluate an alternate MerCAP™ sorbent substrate material. A sample of a carbon cloth material was tested in the full-scale array from May 5 through June 14, 2006. Although this material had displayed promise in laboratory testing, it failed to achieve appreciable mercury capture during full-scale testing. In addition, the material lacked sufficient mechanical strength to withstand the gas velocities encountered in the full-scale array over extended periods of time. Each time the carbon cloth substrates were removed from flue gas service the material was found to be heavily damaged and was observed to be "thread-bare" and tattered prior to removal.

Orienting the substrate plates perpendicular to the gas flow did not achieve appreciable mercury removal performance. In April 2006, 40 plates were tested in a perpendicular (to flow) arrangement, meaning that the gas was forced to pass through 40 plates configured in series. Additional tests evaluating arrangements of 5 plates were tested in May and June 2006. Mercury removal was less than 10% for all tests with the perpendicular plate arrangement. This compared poorly with the performance of the base case gold MerCAP™ design in duct section 1 which achieved 35 to 40% removal.

Pre-treatment of the sorbent substrates in a nitric acid wash was demonstrated to improve mercury removal performance and increase the service time between sorbent regeneration cycles. The gold-based substrates installed in duct section 1 were washed prior to installation and maintained a consistent 30 to 40% mercury removal over the 23-month service time. Substrates that were installed into duct sections 2 and 3, and were not acid washed prior to installation, demonstrated remarkably lower initial mercury removal (32% versus 89% for 1-inch plate spacing) and showed a rapid degradation in removal performance to levels at or near 10% removal. The substrates that were installed in duct sections 2 and 3 were removed from service in December of 2004, treated with a nitric acid wash, and returned to service in January of 2005. The performance of the washed substrates was markedly improved after the acid wash process and remained comparable to that of the duct 1 substrates over the remainder of the program.

Tests conducted with substrates arranged with a ½-inch plate spacing did not show appreciable increases in mercury removal over the arrays with 1-inch plate spacings. Although some improvement was observed, the increased mercury removals observed were less than predicted by mass-transfer properties. Additionally, varying the active length of substrate plates did not demonstrate a direct correlation between the amount of substrates and mercury removal. The implication of these sets of data is difficult to interpret, but suggests a mechanism other than mass transfer dominating the mercury removal performance of the technology.

Balance of Plant Impacts

The primary impact of the MerCAP™ technology on the balance of plant operations is the additional duct pressure drop caused by the sorbent substrates and associated support hardware. The pressure drop across two of the ten host baghouse compartments were monitored with a data acquisition system during this program. Baghouse compartment 1, housing the MerCAP™ array, and compartment 6 (no arrays) are mirror images of each other at the inlet end of the Stanton Station Unit 10 baghouse. The tube sheet differential pressure drop (pressure drop across the filter bags) was monitored in both compartments to determine the overall impact of the MerCAP™ array on the baghouse compartment. Additionally, the pressure drop specifically across the MerCAP™ array was monitored within compartment 1.

As a result of the MerCAP™ array installed in compartment 1, the differential pressure increased by an average of 1.5 inches of water (in. H_20) while the adjacent compartment 6 (no array installed) showed no increase. Prior to installation of the MerCAP™ substrates, the physical duct structures installed in the top of compartment 1 (to house the MerCAP™ array) resulted in 0.15 inches of water of the total reported pressure increase. These duct sections forced the flue gas exiting the bags filters to pass through the MerCAP™ substrates prior to exiting the compartment. The MerCAP™ ducts have fairly severe entrance and exit planes. Severe changes in entrance and exit areas are often associated with increased flow resistance. A permanently installed MerCAP™ system could be more thoroughly engineered to optimize entrance and exit flue gas flow patterns.

Full-Scale Results for North Dakota Lignite Coal

From the initial start-up of the MerCAP™ array in August 2004 through November 2004, Stanton Unit 10 burned a local North Dakota lignite coal. Only the substrates installed in duct section 1 treated flue gas derived from the lignite fuel. Figure 4-1 shows the mercury removal performance of the MerCAP™ substrates as a function of service time with the Lignite fuel being fired.

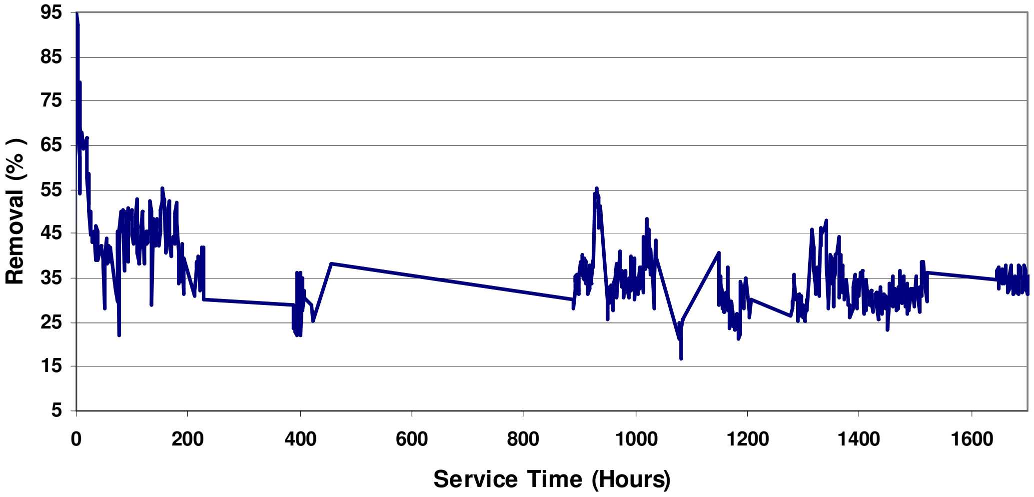


Figure 4-1. Mercury Removal Performance North Dakota Lignite

The MerCAP™ substrates initially achieved mercury removal in excess of 90%, but performance degraded rapidly until stabilizing between 30 and 40% capture. Previous testing of this substrate arrangement had demonstrated removals of 50 to 60% at the same site. Later analysis showed that lower sulfur levels in the coal feed to the unit had lessened the required lime slurry feed to the SDA. The impact of lime slurry feed rate to the SDA on mercury removal performance was investigated later in the program and those results are discussed below.

Full-Scale Results Powder River Basin Coal

On November 3, 2004, Stanton Unit 10 switched fuels from a local North Dakota Lignite to a Powder River Basin subbituminous coal. The fuel switch was observed to cause remarkable changes in key operations parameters. Duct temperatures were, in general, significantly higher with the PRB fuel and varied significantly. Also, the lime slurry feed to the SDA was decreased due to the lower sulfur content of the PRB fuel. Figure 4-2 shows a plot of the measured duct temperature at the inlet and outlet of the MerCAP™ array over a several day period following the fuel switch.

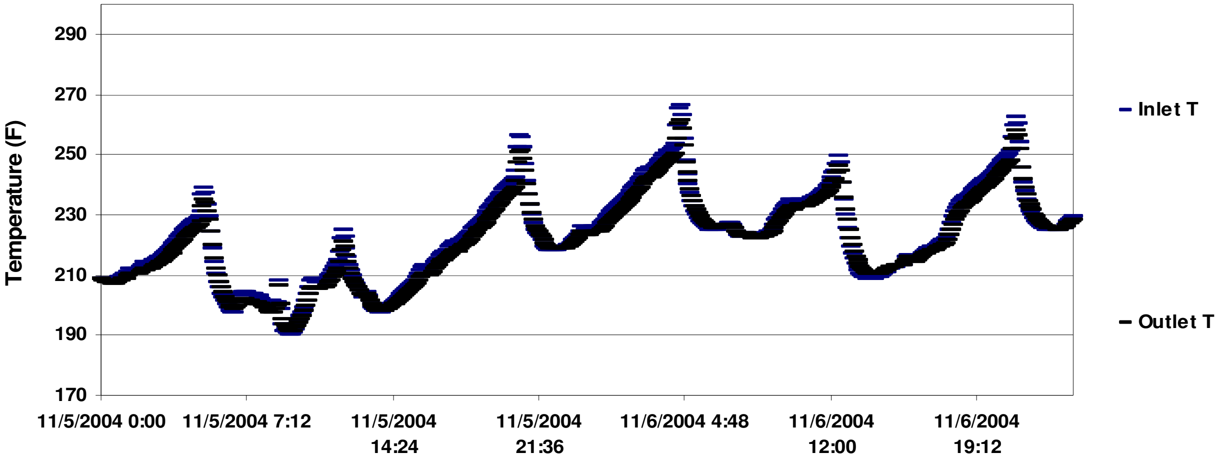


Figure 4-2. Post PRB Fuel Switch Duct Temperature

As can be seen in Figure 4-2, duct temperature varied widely following the fuel switch. In addition, the average duct temperature was approximately 30 to 40 °F higher than prior to the fuel switch. Figure 4-3 shows the mercury removal performance of the MerCAP™ substrates following the fuel switch. Mercury removal was significantly impacted by a combination of factors, including increased flue gas temperature, higher gas velocities, and lower SDA scrubbing efficiencies.

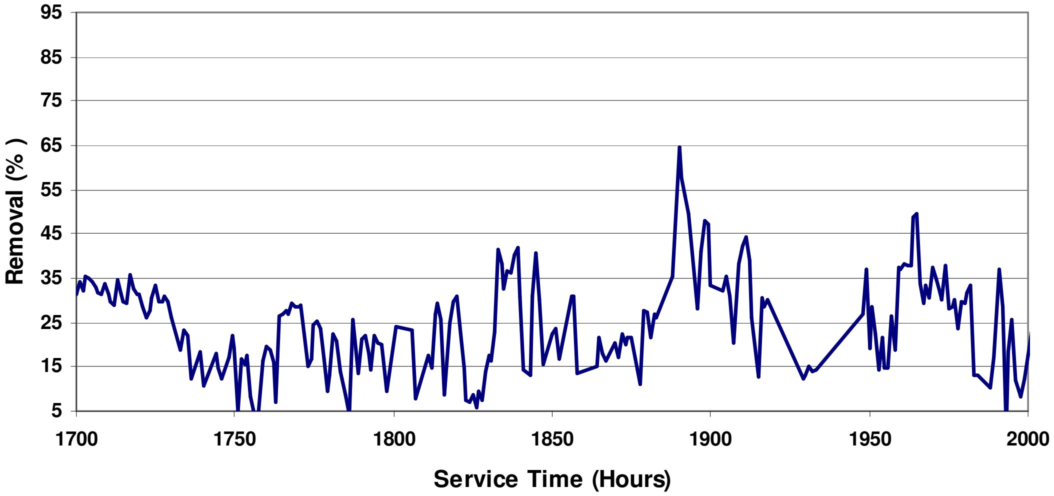


Figure 4-3. Duct 1 Substrate Mercury Removal Performance Following Fuel Switch

Following the fuel switch, mercury removal performance of the duct 1 substrates became very sporadic, swinging widely and inversely with gas temperature; in general, the overall average mercury removal was lower, ranging from 15 to 25%.

Shortly after the switch to PRB coal, MerCAP™ substrates were installed into duct sections 2 and 3. These substrates were not pretreated with an acid wash unlike the substrates already in service in duct section 1. The substrates installed in duct section 2 matched the configuration of those in duct section 1, with 1-inch plate spacing and 10 feet of active length. The duct 3 substrates were configured in ½-inch plate spacing and 10 feet of active length in order to investigate possible performance improvements that might be achieved by modifying the geometry of the MerCAP™ substrates. Figure 4-4 shows the initial MerCAP™ performance following installation of sorbent substrates into duct sections 2 and 3.

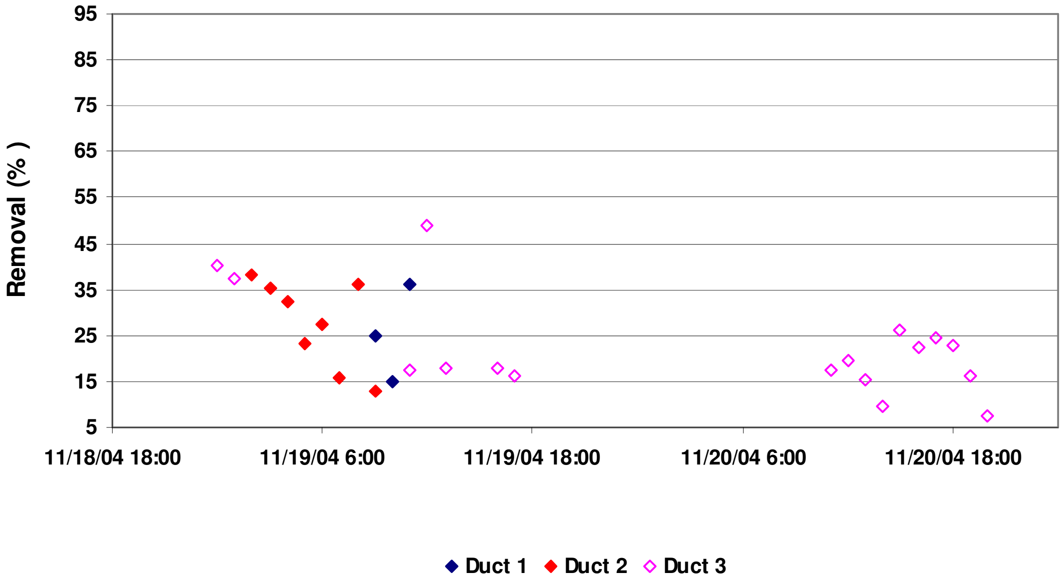


Figure 4-4. Initial Operation Substrates in Ducts 2 and 3

The initial performance of the duct 2 and 3 substrates did not match the initial high removal seen in August 2004 with the duct 1 substrates. Rather, the initial removal performance of both ducts 2 and 3 matched the existing mercury removal performance of duct section 1, which had been in service for over 3 months. In addition, little difference between the performance of ducts 2 and 3 was observed. This was surprising considering the different plate spacings of the respective configurations. These results suggest that some other mechanism(s) besides mass transfer was limiting the MerCAP™ mercury removal performance.

After just one month of operation the substrates in ducts 2 and 3 had degraded in terms of mercury removal performance to roughly 5 to 15% capture for duct 2 and 15 to 25% for duct 3; this compared to a consistent level of 20 to 35% capture achieved by duct 1. The substrates in ducts 2 and 3 were removed from service and subjected to an acid cleaning treatment. The substrates were returned to service in January 2005. Figure 4-5 shows the mercury removal performance just before ducts 2 and 3 were pulled from service. Figure 4-6 shows the mercury removal performance following re-installation of the substrates.

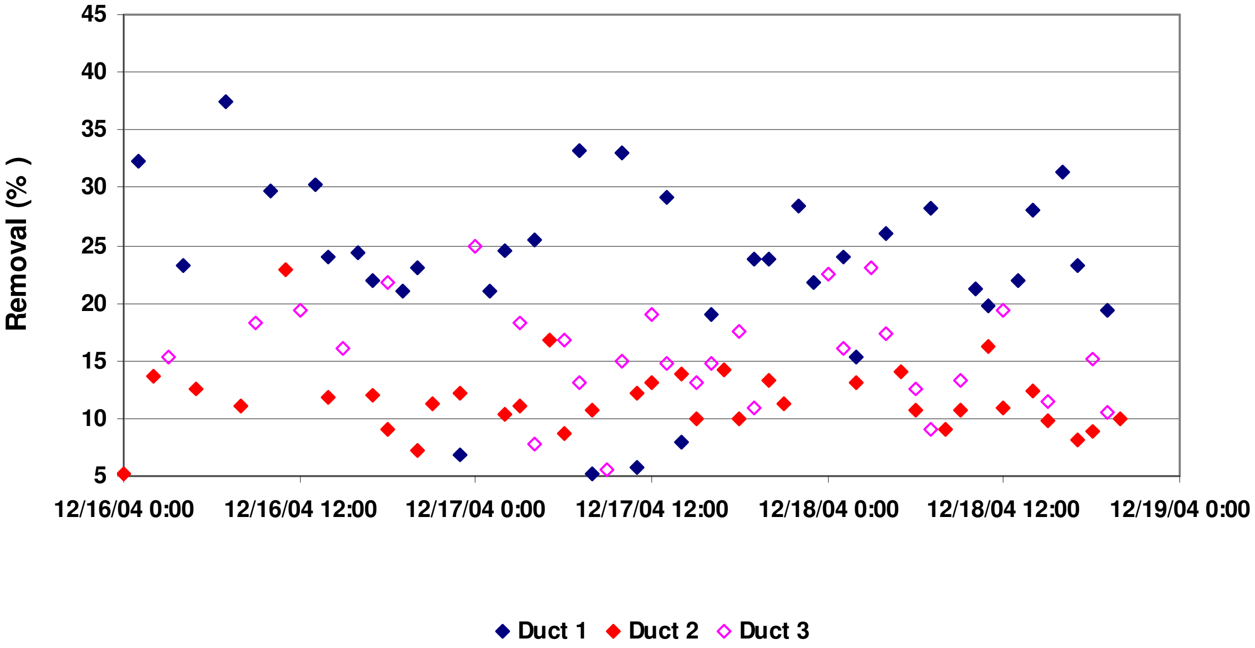


Figure 4-5. Mercury Removal Performance Prior to Ducts 2 and 3 Removal from Service for Acid Treatment

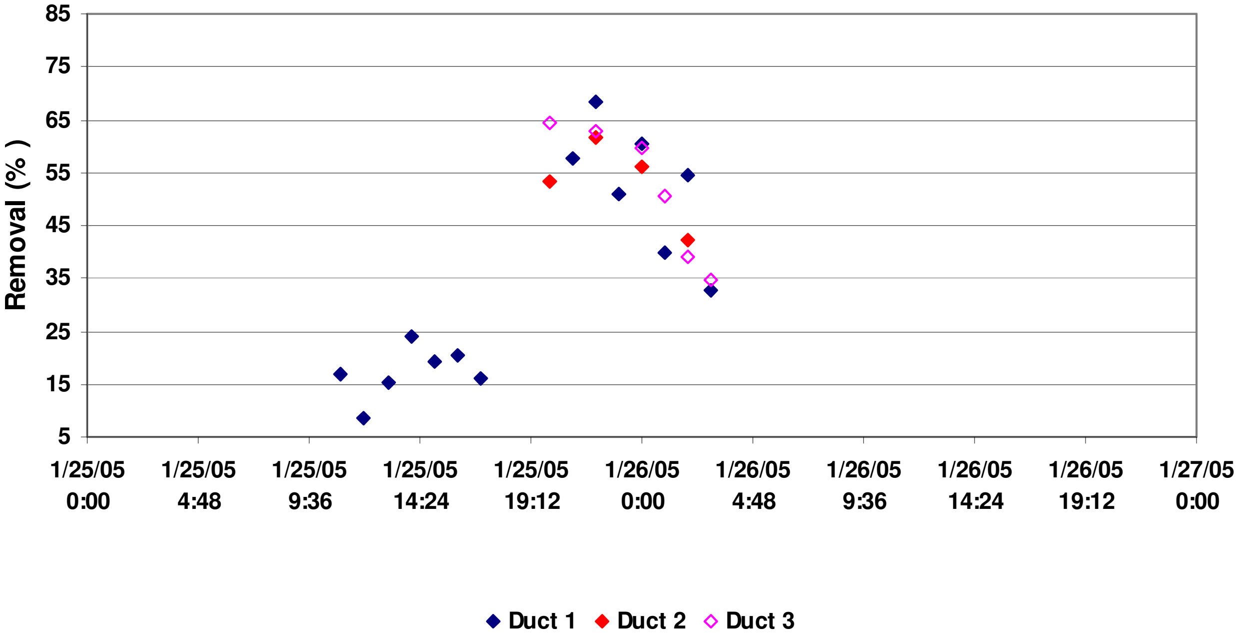


Figure 4-6. Mercury Removal Performance Following Substrate Acid Treatment

Following the acid treatment of the duct 2 and 3 substrates, mercury removal matched that of the substrates in duct 1. Table 4-2 provides a comparison of the substrate performance before and after acid treatment. Overall, treating the substrates with a nitric acid wash increased mercury removal performance over that of non-treated MerCAP™ substrates. The acid treatment also appeared to result in mercury capture remaining stable over longer periods of time, as observed by duct 1 substrates operating continuously for nearly 23 months.

Table 4-2. Comparison of Mercury Removal Results and Acid Treatment

Duct Section	Substrate	Plate Spacing	Install Date	Hours in Service	Average Hg Removal	Measured Outlet Oxidized Hg
Duct 1	Acid Treated	1-Inch	8/22/04	5,308	30 – 35%	35 – 40%
Duct 2	Non-Acid Treated	1-Inch	11/18/04	1,035 1,470	15 –18% 10%	20%
Duct 2	Post Acid Treatment	1-Inch	1/25/05	Reinstalled after treatment	52%	N/A
Duct 3	Non-Acid Treated	½-Inch	11/18/04	1,035 1,470	25 – 30% 12%	20 – 25%
Duct 3	Post Acid Treatment	½-Inch	1/25/05	Reinstalled after treatment	58%	N/A

From January 2005 through December 2005, the MerCAP™ sorbent arrays ran continuously without any changes to the substrate geometries or arrangements. Mercury removal performance was observed to vary inversely to gas temperature during this time and removal rates ranged from highs of 40 to 50% to low points where some mercury appeared to emit from the substrates when gas temperatures peaked above 250°F (121°C).

Gas Temperature Effects

As has been mentioned above, the temperature of the flue gas was observed to have dramatic impacts on the mercury removal performance of the MerCAP™ substrates. The host site was able to provide some measure of control over gas temperatures for short periods of time, which enabled the collection of data to directly verify the effect. Figure 4-7 shows a plot of CMM data and gas temperatures demonstrating the impact of gas temperature on the mercury removal performance of the substrates. These results show that as the gas temperature increased so too did the outlet mercury concentration. In some cases, the outlet mercury levels actually spiked above those at the inlet, indicating that mercury was being emitted from the substrate plates. Using the observations gained from data such as that shown in Figure 4-7, a test was conducted to determine if in-situ regeneration of the substrates at relatively low temperatures was possible.

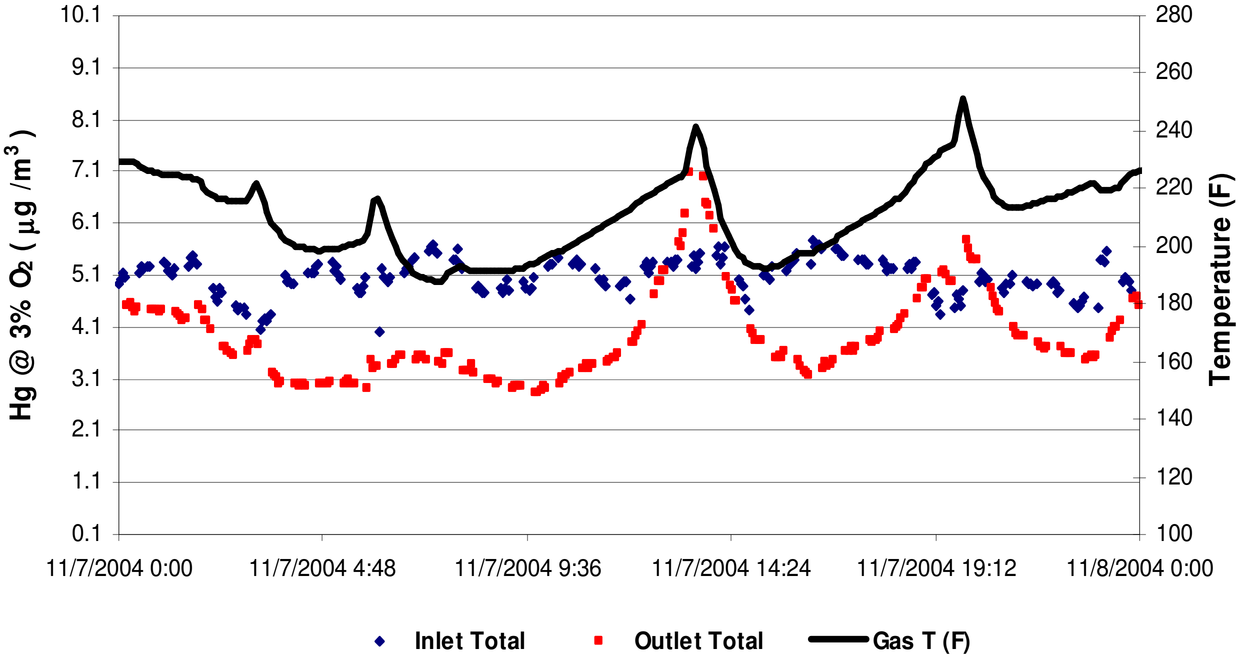


Figure 4-7. Gas Temperature Effect on MerCAP™ Mercury Removal

For normal MerCAP™ regeneration, substrates would be heated to temperatures in excess of 800°F (427°C) to volatilize all of the captured mercury. Such a process would have to be conducted ex situ meaning the substrates would have to be removed from the duct. It would be desirable to regenerate the sorbent substrates in situ in order to simplify the overall processing steps and reduce costs. To achieve this, regeneration would need to be carried out at a lower temperature (i.e., a temperature lower than 800°F but higher than duct temperature (during normal flue gas exposure). A test was conducted on January 19, 2006 in which the duct gas temperature was increased to approximately 280°F (138°C) to heat the substrates and determine if in-situ regeneration occurred. Figure 2-15 shows results from the mercury concentration measurements and flue gas temperatures during the test.

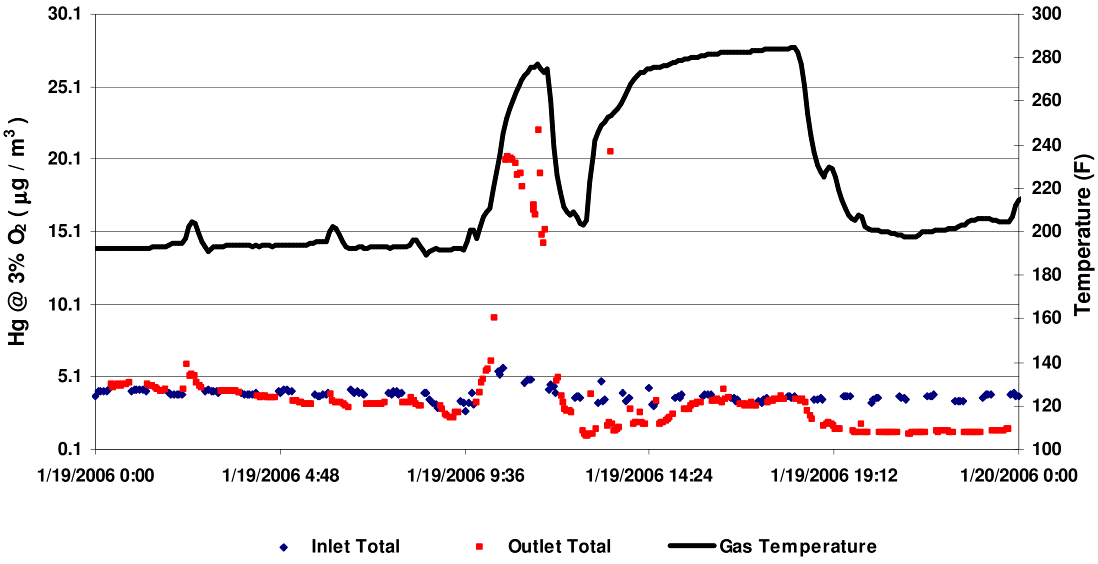


Figure 4-8. In-Situ Regeneration Test

Figure 4-8 shows that the flue gas temperature spike was accompanied by a corresponding spike in the outlet mercury concentration. After approximately 60 to 90 minutes at the increased temperature, the MerCAP™ array ceased to emit any mercury in excess of the inlet concentration value. Once the temperature was reduced back to the normal operating range (<200°F), the mercury removal performance returned to the normal range of 25 to 35% capture. Immediately following this test, a second elevated-temperature test was conducted to determine if additional regeneration could be achieved. Here, a longer spike in gas temperature did not cause additional mercury emissions from the MerCAP™ sorbent surfaces. This indicates that the substrates were regenerated, to the extent that they could be at 280°F (138°C) during the first shorter-term elevated temperature test.

Spray Dryer Absorber Parametric Results

Tests conducted at Stanton Unit 10 showed that in addition to gas temperatures, changes in the water and lime slurry feed rates to the SDA affected mercury removal performance of the downstream MerCAP™ substrates. Tests were conducted to investigate and quantify this effect by changing the feed rates of lime slurry and water to the SDA. Also, a different lime feedstock, designed to increase SDA sulfur capture, was also tested. On February 30, 2005 a test was conducted where the lime slurry and water feed rates to the SDA were varied. Figure 4-9 shows the results of the test.

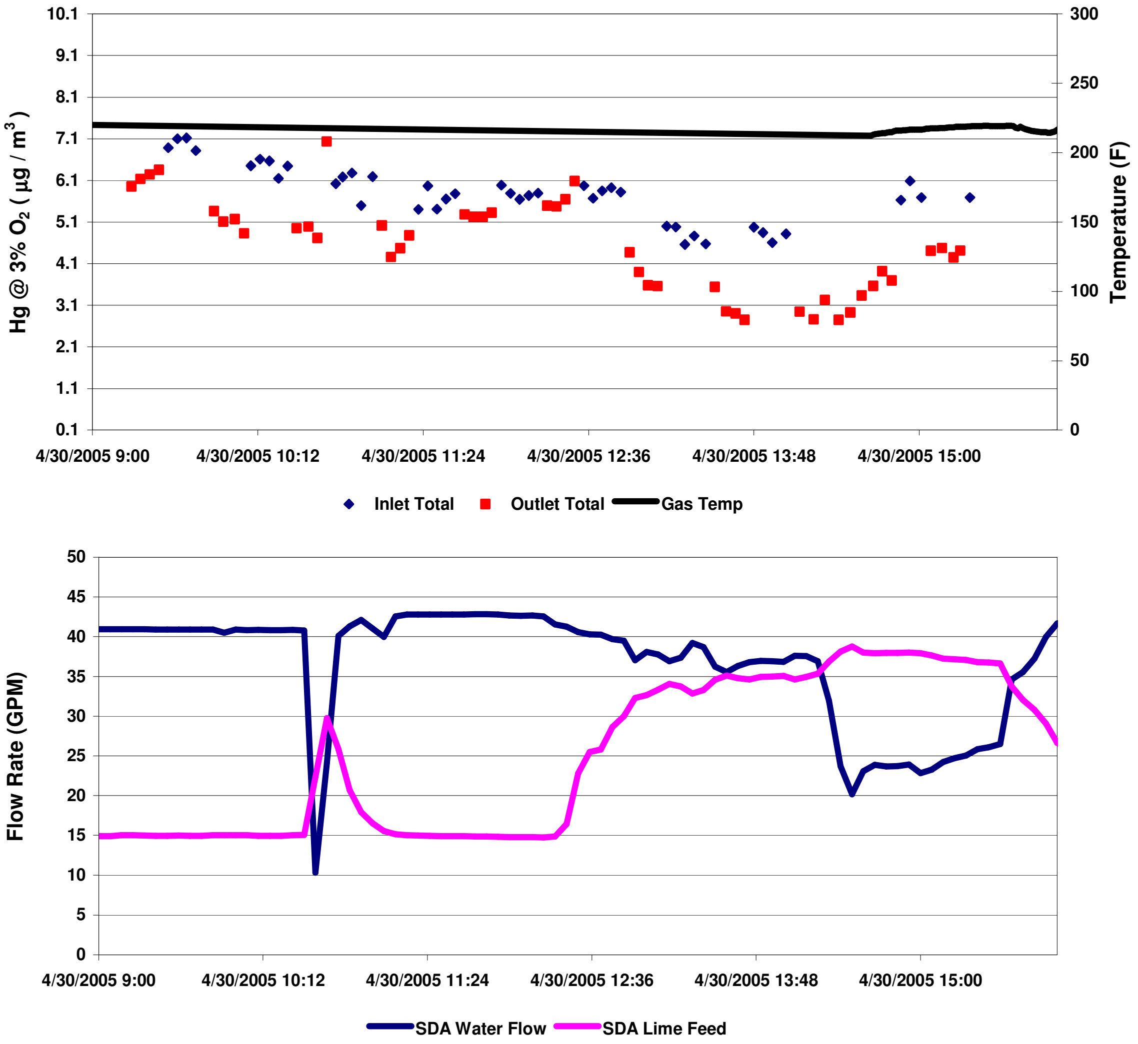


Figure 4-9. SDA Parametric Test Results

Figure 4-9 shows the impact of SDA lime slurry feed rate on mercury removal by the MerCAP™ array. When the lime feed rate was increased (after 12:00 noon on April 30, 2005), the spread between the inlet and outlet mercury concentrations increased relative to the prior period; mercury removal across the MerCAP™ array subsequently increased from 20 to 25% up to 40%. All other process conditions were held constant during the test in order to isolate the impact of lime slurry feed. After a period of approximately 90 minutes the water feed to the SDA was then decreased. The subsequent mercury removal rate remained constant and unaffected by the change in water feed rate to the SDA.

In addition, a high efficiency lime reagent was fed to the SDA on February 20, 2006 resulting in increased sulfur (i.e., SO_2) removal. Figure 4-10 shows the CMM data just preceding and following the change in SDA lime reagent. Table 4-3 shows a summary of the results for the MerCAP™ substrates during the high efficiency lime tests.

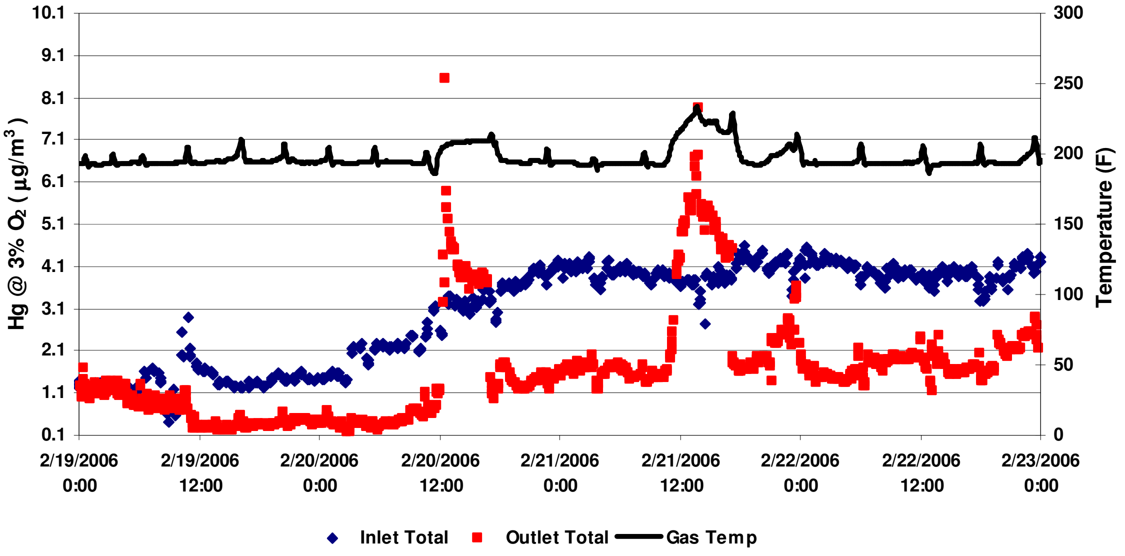


Figure 4-10. Lime Change Test Results

Figure 4-10 shows that prior to changing the lime reagent, mercury removal rates were low, averaging approximately 10 to 15%. Following the change to the high efficiency lime, mercury removals increased to 40 to 50% capture. This indicates a dramatic impact in performance when SO_2 removal was increased from <70% to greater than 95%.

Table 4-3. High Efficiency Lime Reagent Impact on MerCAP™ Mercury Removal

MerCAP™ Array Duct Section / Description	Hg Conc. (µg/m^3 @ 3% O_2)		Removal (%)	Gas Temp (%)	Comments
	Inlet	Outlet			
Duct 2: 1-Inch Plate Spacing, 10-Foot Active Length	2.0	0.5	76.5	195	26-hour average after new lime feed to SDA, SO_2 control at 95%+
Duct 1: 1-Inch Plate Spacing, 10-Foot Active Length	4.5	1.7	62.0	195	16-hour average after new lime feed to SDA, SO_2 control at 95%+
Duct 1: 1-Inch Plate Spacing, 10-Foot Active Length	4.7	2.3	52.1	195	48-hour average after new lime feed to SDA, SO_2 control at 95%+

Substrate Geometry Parametric Results

Alterations to the plate orientation within the MerCAP™ array were conducted in an effort to ascertain impacts on mercury removal performance. Over the months of April 2006 through July 2006 several geometry modifications were made to the substrate plates in the full-scale array. Table 4-4 summarizes the results of the geometry modifications.

Table 4-4. Geometry Parametric Results

Date	Description	Removal (%)	Gas Temp (°F)	Lime Feed (GPM)	Comments
4/25/2006	Duct 1 – 10 Feet 1-inch Plate Spacing	39.2	202.8	21.0	2-Day Average
	Duct 2 – Empty	0.0			
	Duct 3 – 40 Plates Perpendicular to Flow	4.7			
5/5/2006	Duct 1 – 10 Feet 1-inch Plate Spacing	36.2	209.2	21.5	10-Day Average
	Duct 3 – 5 Plates Perpendicular to Flow	7.4			
	Duct 4 – 4 Feet 1-inch Plate Spacing	26.5			
7/7/2006	Duct 1 – 10 Feet 1-inch Plate Spacing	54.6	218.6	N/A	1-Day Average
	Duct 2 – 2 Feet ½-inch Plate Spacing	56.5			
	Duct 3 – 2 Feet 1-inch Plate Spacing	25.8			
	Duct 4 – 4 Feet 1-inch Plate Spacing	30.6			

Results showed that orienting the substrate screens perpendicular to flow, such that gas was forced to flow through several screens in series, resulted in mercury removals ranging only from 5 to 10%. Varying the active length of the MerCAP™ substrate plates in the parallel plate reactor had no appreciable impact on mercury removal. Specifically, the data collected on July 7, 2006 demonstrated that increasing the active length of the substrates from two to four feet only increased mercury removal by 5%. Data collected on July 7, 2006 represented the first instance where decreasing the MerCAP™ substrate plate spacing demonstrated any mark able effect on mercury capture. It is unclear whether this single data point is indicative of the impact of decreased plate spacing on mercury removal or if it stands as a single anomalous reading.

4.1.2 Alternate Substrate Material Test Results

Tests were conducted to determine if lower cost sorbent materials might be appropriate for use in the MerCAP™ process. Based on the performance of materials evaluated in laboratory tests, it was determined that fixed-structure activated carbon sorbents were the best low-cost alternative to gold for this application. Based on previous data collected in laboratory evaluations a sample of activated carbon cloth was obtained and placed in service in the MerCAP™ array. While the material showed promise as a mercury sorbent during the laboratory tests, it lacked sufficient mechanical strength to withstand the environment inside the baghouse compartment. On each instance where the material was installed and tested, it was found to be torn and frayed from the gas flow at the end of the test. Testing of this material was subsequently suspended.

4.1.3 Verification of CMM Readings

The CMM was used throughout this program to measure the mercury removal performance of the MerCAP™ arrays. Periodically, quality control tests were conducted using the manual Ontario Hydro method and a sorbent tube measurement method to verify the accuracy of the CMM instrument. Table 4-5 provides a comparison between the CMM measurements and those collected using the manual Ontario Hydro method.

Table 4-5. Ontario Hydro Measurement Results Comparison

Date	Description	CMM Hg^T	OH Hg^T	Difference
		(μg/m^3 @ 3% O_2)		(%)
2/1/05	Inlet	4.25	5.37	20.9
	Outlet	3.78	5.81	34.9
2/2/05	Inlet	4.29	6.27	31.6
	Outlet	3.04	1.75	-73.4
5/12/05	Inlet	8.24	8.38	1.67
	Outlet	6.68	7.73	13.6

The early Ontario Hydro measurements were hindered by a design problem with the outlet sampling port. The outlet sampling port used for manual measurements was offset from the back edge of the MerCAP™ duct sections by several feet, which allowed for gas flowing through individual array channels to remix prior to being sampled by the OH probe. Using a modified version of the OH method where the sample was pulled from the CMM extraction system produced much better agreement between the CMM and OH measurements, as seen in the May 2005 measurements.

In addition to using OH measurements to verify the accuracy of the CMM measurements, periodic manual sorbent trap (Method 324) measurements were also conducted. Table 4-6 provides a summary of the manual sorbent trap measurements conducted under this program.

Table 4-6. Sorbent Trap Measurements Results Comparison

Date	Time	Sample Location	CMM Hg^T	Sorbent Trap Hg^T	Difference
			(μg/m^3 @ 3% O_2)		(%)
1/25/05	13:22 – 14:20	Inlet	4.29	4.56	5.92
		Outlet	3.35	3.48	3.74
1/27/05	9:22 – 9:49	Outlet	3.82	3.96	3.54
		Outlet	3.82	3.83	0.26
4/30/05	11:28 – 12:27	Inlet	5.73	4.71	-21.7
		Outlet	5.38	4.92	-9.35
4/30/05	13:13 – 14:09	Inlet	4.77	3.96	-20.5
		Outlet	3.02	2.40	-25.8
7/7/06	10:29 – 10:59	Inlet	4.98	4.72	-5.55
		Outlet	3.82	3.59	-6.47
7/7/06	12:20 – 12:50	Inlet	4.83	5.36	9.97
		Outlet	2.85	2.87	0.85
7/7/06	13:05 – 13:30	Inlet	4.94	5.00	1.10
		Outlet	3.00	Trap Broke	N/A
7/7/06	13:45 – 14:22	Inlet	4.94	5.36	7.68
		Outlet	3.45	3.61	4.49
7/7/06	14:33 – 15:05	Inlet	5.09	5.94	14.28
		Outlet	3.59	4.41	18.70

In general, the sorbent trap measurements agreed well with the CMM measurements with most of the measurements agreeing to within 15%. As an additional check of the CMM accuracy, coal mercury measurements were used to calculate a theoretical mercury concentration at the inlet to the MerCAP™ array. Figure 4-11 shows a comparison between the CMM and (coal-derived) calculated mercury data. Results showed that the CMM data agreed quite well with the predicted concentration value obtained from coal mercury content.

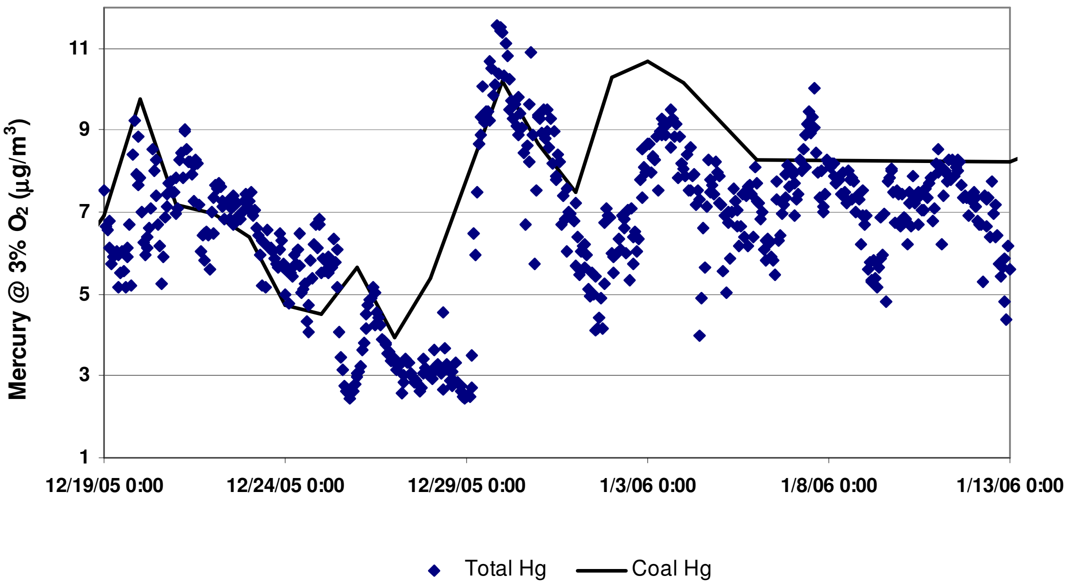


Figure 4-11. Theoretical Inlet Mercury (based on coal Hg) and CMM Comparison

4.1.4 Substrate Regeneration Testing

A key consideration to the economics of the MerCAP™ technology is the ability of the substrates to be regenerated over multiple cycles in order to prolong their effective lifetime. As part of this program, a single set of substrates designed for a slipstream test probe was subjected to six regeneration cycles. The mercury removal performance was evaluated before and after each regeneration cycle. Table 4-7 summarizes the results of the regeneration cycle testing.

Table 4-7. Substrate Regeneration Results

Regeneration Cycle #	Date of Regen.	Hg Removal Before Regen. (%)	Mass of Hg Desorbed (mg)	Hg Removal After Regen. (%)	Regeneration Method
1	07/26/04	0 - 5	Not Measured	Initially >90, Then 35 - 45	Chemical
2	2/1/05	10 – 15	4.9	15 – 20	Thermal
3	2/2/05	15 - 20	11.4	30 – 35	Thermal
4	2/3/05	30 – 35	0.4	35 – 40	Thermal
5	4/29/05	Not Measured	4.5	Not Measured	Thermal
6	5/12/05	20 - 30	Trap Broke	30-40	Thermal

In general, mercury capture performance was increased following each of the regeneration cycles, and was within the observed range of substrate performance from the full-scale array. Based on these results, as well as physical examination of the substrates following each regeneration cycle, there appeared to be no adverse impacts from the regeneration cycles.

Mercury removed from the substrates during each regeneration cycle was captured downstream of the MerCAP™ array using large sorbent trap tubes. Because it was not possible to conduct mercury measurements across the substrates during regeneration (measurements were made prior to and after each regeneration cycle), it was not possible to conduct mercury mass balance calculations for the arrays during the tests.

Laboratory tests were conducted on gold coupon samples to more thoroughly investigate the two regeneration methods (thermal and chemical). Results from these tests showed that both chemical and thermal methods were effective at regenerating the gold-coated sorbent screens. A description of the laboratory regeneration investigations is provided in Appendix C.

4.1.5 Small-Scale Laboratory Results and Discussion

Electroplated Gold Samples

Tests were conducted to evaluate the ability of different gold-based sorbent formulations to remove mercury from flue gas. A series of sample coupons were installed in the Stanton Station Unit 10 baghouse compartment that contained the full-scale MerCAP™ system. These samples were specially handled and washed before and after exposure to flue gas. The coupon testing had two objectives: (1) to determine if water washing of exposed gold was comparable to acid washing, and, (2) to see if surface contaminants could be detected by analysis of the acid washes. If surface contaminates were sulfur-based, it was hypothesized that a water wash would be suitable to remove sulfur-based compounds. A water-only wash of the MerCAP™ substrates would be simpler and more economical than the acid wash process. After being in service for 22-days, the coupons were removed from service and performance tested in a laboratory reactor before and after being subjected to washes. Results showed that the water-only wash did not restore the gold-coated coupons to pre-exposure mercury removal performance levels. The same coupon was then subjected to acid washing and, when retested, performed comparably to new gold coupons.

Comparisons of pre- and post-acid wash baths did not reveal any consistent or apparent contaminating species. No specific element consistently showed up in the washes of the exposed MerCAP™ coupons samples that would cause fouling of the gold.

Alternate Substrate Materials

Laboratory tests were conducted to determine the feasibility of using alternate sorbent materials in the MerCAP™ process. Several alternate substrate materials were investigated during this program. Potential materials were chosen based on their potential beneficial properties associated with economics, mercury capture performance, or increased durability. Tested materials included a gold leaf product, a silver sand material, and a charcoal (activated carbon) cloth product.

A gold leaf product was procured and tested in a laboratory experimental system. Gold leaf is commercially available as a high surface area, high purity material. Small samples were tested in both a parallel plate configuration and in a fluidized bed configuration using particle flakes of the gold-based reagent. The samples tested were a high purity gold leaf that had not yet been processed in such a way to possess a nanoporous structure.

Dr. Jonah Erlbacher of John Hopkins University has conducted experiments in formation of high surface area gold. The simplest method of producing these high surface areas is to start with 50% purity gold leaf product and then to subject it to a nitric acid bath. In this process, called dealloying, the nitric acid dissolves the balance of impure metals leaving a nanoporous sponge of gold. Dr. Erlbacher reports surface areas of 2 m^2/gram which is comparable to commercial supported catalyst.

The gold leaf used is commercially available in 3-inch by 3-inch sheets with a typical thickness of 90 nanometers (3.5 micro-inches). This product is approximately 3-4 times thinner than the layer of electroplated pure gold used in large-scale MerCAP™ testing. The raw material is mechanically worked (rolling and hammering) and is highly fragile due to its minimal thickness. Specimens tested in the laboratory were sandwiched between two layers of stainless steel screen. The gold leaf has a significant economic advantage over the electroplating method in that the approximate cost per square foot is reduced by more than 50%. The primary economic advantage is the thinner more uniform layer of pure gold. Electroplated MerCAP™ substrates require a higher grade of gold solution and significant process cost above the raw gold cost (+30%). A suitable method has yet to be developed to support or bond the gold leaf to a substrate comparable to the current design. However, if the gold leaf can be used in a fluidized bed configuration or can be adequately supported in the flue-gas stream it has potential economic benefits over electroplating.

The commercial gold leaf tested in the laboratory demonstrated comparable removal efficiencies and performance as the electroplated gold used to date. Nanoporous sponge gold samples were not procured and tested. It is expected that their additional surface area would either improve the mercury capture efficiency or increase the overall capacity. The technical challenge is to develop a method of bonding gold leaf material to a substrate that would be durable enough to withstand flue-gas exposure, or alternatively utilize the dealloying concept to leave a nanoporous structure of gold after plating an impure amalgam of gold and other metals. A third iteration would be the utilization of the gold leaf with direct injection into the flue gas upstream of the baghouse or in a self contained fluidized bed apparatus.

A silver sand coated sample was provided by Mr. Tom Obst and a colleague who developed an electrodeless process to plate or coat precious metals on to various substrates. The sample of silver-coated sand was tested in a laboratory-scale packed bed configuration and reacted with elemental mercury mixed in a nitrogen gas stream. Previous EPRI field tests demonstrated that silver coatings are not suitable for MerCAP™ applications due to the rapid reaction of sulfur compounds in coal flue-gas stream with the silver. However, the sample was run in a fluidized bed configuration in the laboratory to determine if the electrodeless process was detrimental to the silver gold amalgamation. The sample achieved 89% capture of elemental mercury. The static bed thickness was 0.2 inches (0.5 centimeters) and the face velocity across the bed was calculated at 2 ft/s (0.6 m/s).

An additional alternative substrate material examined was a carbon cloth, or “Charcoal Cloth”, which is produced in the UK by Charcoal Cloth International and marketed in the U.S. by Calgon Carbon Corporation under the name “Zorflex”. The material is manufactured in 39.3-inch (1 meter) wide rolls and is produced in two different weights, FM10 and FM100. Apogee was quoted a current cost for the FM10 product at $3.90-$4.50 per square foot ($42-$48 per square meter) for untreated product. In large quantities the cost is reported at $2.4-$2.80 per square foot. The material can be produced as untreated or treated with potassium iodine or bromine compounds; costs for treated product is approximately $0.20 more per square foot ($2 more per square meter).

Calgon provided a sample of the FM10 series material with a potassium iodine treatment. This sample was laboratory tested in both a parallel flow configuration and a cross flow configuration. In the parallel configuration the sample was cut to a 0.625-inch wide by 6-inch long specimen comparable to the MerCAP™ gold screen samples and supported in the test fixture. Mercury removals between 55% and 62% were measured and laboratory capacity results suggested that a single layer of the charcoal fabric supported in the MerCAP™ array could maintain removal rates for 3-5 days. Laboratory tests were conducted as both parallel and cross flow geometries with equal results. Further full-scale testing of the sample in one of the four MerCAP™ ducts revealed that the material lacked sufficient mechanical strength and disintegrated at 20 ft/s gas velocities. However, this testing has led to the concept of using pelletized or granular activated carbon as a low cost short term substrate that can be kept segregated from fly-ash to minimize balance of plant impacts.

Full-Scale Array Samples

Full-scale MerCAP™ substrate screens (one-foot full sheet portions) were periodically removed from service and subjected to laboratory testing to demonstrate the effectiveness of both chemical and thermal regeneration methods and to quantify the total mercury captured on the substrates as a function of flue gas service time.

On November 18, 2004 ducts 3 and 4 in compartment 6 at Stanton were filled with MerCAP™ screens and, in the process, a sample swatch was removed from a screen from duct 1 that had been in service since the start of the full-scale demonstration. The swatch was shipped to the Apogee laboratory and desorption tests were conducted to determine the quantity of mercury present on the screen. From the continuous data collected during the Stanton MerCAP™ program and the amount of mercury that was present on the screens, a mercury mass balance calculation was performed.

Chemical desorption of a 5/8-inch x 6-inch screen sample was conducted by placing it in a desiccant drying bed to remove all water from the sample and then placing it in a heated 50% nitric acid bath. Next, the nitric acid sample was sent out for a mercury concentration test and a final dry weight of the sample was obtained. As seen in Table 4-8, both samples lost physical weight in the nitric acid bath. The results from the chemical analysis are listed in Table 4-9.

Table 4-8. Dry Weight of Samples Before and After Chemical Bath

Sample	Wt before (g)	Wt after (g)	Wt lost (g)	Time in Bath (hr)
1	5.882	5.8414	0.0406	6
2	6.3523	6.3029	0.0494	6

Table 4-9. Mercury Concentration and Weight of Mercury

Sample #	Mercury Concentration (ug/L)	Mercury from coupon (g)	Other weight loss (g)
1	17000	0.001292	0.0236
2	27000	0.002133	0.0224

The weight of mercury removed from the coupons in the nitric acid bath was less than the total physical weight lost by the coupons. This occurred because the nitric acid bath reacts with the stainless steel that is exposed and it also removes other elements present in the flue-gas that had adsorbed to the screen. The reason for the discrepancy in mercury concentration between the two samples is that both samples were removed from different parts of the screen. Sample 1 was taken from parts of the screens that were closer to the wall; sample 2 was removed from part of the screen that is in the middle of the duct section. From these concentrations, calculations were made to determine the total amount of mercury removed from duct section 1 from the start of the program until November 18, 2004, when sample swatches were removed. From the calculations using the average amount of mercury removed from the samples, the gold screens in duct section 1 removed 26.3 grams of mercury.

From the data collected by the Apogee CMM at the Stanton Unit 10, a mass balance was performed and the calculated amount of mercury that was removed from the flue-gas stream was 34.7 grams. The mass balance closure is approximately 76% (difference between actual and calculated mass values) for the first 2100 hours of service on Duct 1.

4.2. Results and Discussion – Site 2

A series of tests were performed at Georgia Power's Plant Yates Unit 1 to evaluate MerCAP™ performance in flue gas obtained downstream of a wet FGD absorber. The objective of the test program was to evaluate the ability of gold-based MerCAP™ to remove mercury from the water-saturated flue gas for an extended time period and to subsequently determine the feasibility of the technology for full-scale implementation. A series of small-scale slipstream tests were conducted to both re-verify the MerCAP™ ability to remove mercury from the Unit 1 flue gas and evaluate the impacts of wash water rinsing frequency on performance. Results were used to design the operating parameters used for a pilot scale reactor that was installed at Plant Yates. Pilot testing was conducted using a horizontal 2800 acfm slipstream reactor to evaluate gold-based MerCAP™ performance over extended flue gas exposure periods. Results obtained during the test program are described in this section.

4.2.1 Small-Scale Slipstream Testing Results

A series of tests were conducted at Plant Yates using a small-scale slipstream reactor to evaluate mercury removal by the gold-coated screen substrates planned for use in the pilot test. Previous slipstream tests at Plant Yates Unit 1 had indicated that gold-coated screens were capable of achieving >80% of the theoretical mercury removal, based on mass transfer limitations, for relatively short periods of time. Figure 4-12 shows an example of these results. The tests conducted in this program were similar to the previous tests, but used the same MerCAP™ screen formulation as planned for the pilot scale test. The previous slipstream tests were relatively short-term in nature (i.e., <48 hours). The tests conducted under this program evaluated performance during longer-term continuous exposure to flue gas.

The mobile slipstream reactor system, described in Section 3.6.2 (Figures 3-19 and 3-20), was configured at the Unit 1 stack and operated over a two-month period, from November 2004 to January 12, 2005. The MerCAP™ reactor was loaded with fresh gold-coated screen substrates prior to starting the test. All testing was conducted with the same sorbent screens. The reactor temperature was maintained at 130°F (54°C) for all tests. A single EPRI SCEM analyzer was used to measure mercury across the MerCAP™ reactor. Comparison of reactor inlet and outlet measurements was made to determine the extent of removal achieved. Mercury concentrations in the inlet gas ranged between 0.7 and 3.3 $\mu g/Nm^3$ (at 3% O_2) for these tests. The measured mercury speciation in the inlet gas ranged from approximately 16 to 86% oxidized mercury present.

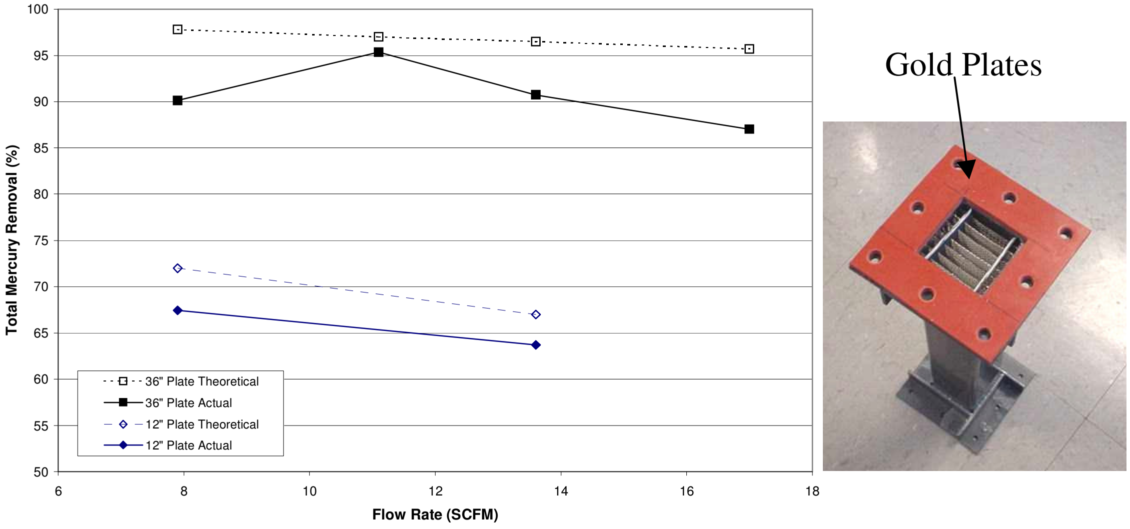


Figure 4-12. Previous Slipstream Results for MerCAP™ Mercury Removal at Plant Yates

Table 4-10 provides a summary of the pertinent results obtained during the small-scale slipstream tests at Plant Yates. The values represent averages calculated from inlet and outlet mercury measurement for a given test or a specific time period.

Table 4-10. Summary of Small-scale Slipstream MerCAP™ Test Results.

Date	Test Condition	Inlet Total Hg (μg/Nm^3)	Inlet Elemental Hg (μg/Nm^3)	Flue Gas Speciation (% Oxidized Hg)	Outlet Total Hg (μg/Nm^3)	Total Hg Removal (%)
11/14/04	No wash	1.93	0.86	56%	1.61	17%
11/15/04	15 min wash per 2 hours	1.36	0.86	37%	0.58	58%
11/15/04	30 minute wash per 2 hours	1.39	0.41	71%	0.34	76%
11/20/04	20 minute wash per 2 hours	1.03	0.80	23%	0.44	57%
11/26/04	4.5 hours of continuous wash*	0.78	0.70	10%	0.49	37%
11/27/04	10 hours of continuous wash*	1.06	0.81	24%	0.26	75%
12/3/04	30 minute wash per 2 hours	1.51	1.05	30%	0.43	71%
12/12/04	15 minute initial wash*	1.33	1.12	16%	0.76	43%
12/12/04	7.5 hours of continuous wash	1.25	1.05	16%	0.13	90%
12/13/04	13.5 hours of continuous wash	1.25	1.05	16%	0.07	94%
Extended Duration Test						
1/12/05	Lost wash water overnight*	2.32	0.57	75%	2.50	0%
1/12/05	30 minute wash per 2 hours**	2.32	0.57	75%	0.98	58%
1/12/15	30 minute wash per 2 hours***	4.18	0.60	86%	0.72	83%
1/21/05	30 minute wash per 2 hours	1.72	-	-	0.78	55%

* - No water wash for prior >24 hour period
** - Automated wash re-established for 6 hours
*** - Automated wash re-established for 14 hours

Upon loading the gold screen substrates in the MerCAP™ reactor, flue gas flow was started. No water rinse was implemented during the initial test. Mercury measurements indicated initial removals of greater than 80% with the fresh substrates. However, this value dropped considerably to less than 20% removal after three days of continuous flue gas exposure. Subsequent tests were then performed to evaluate the impact of a water rinse of the MerCAP™ system on mercury removal performance. The rinsing system was operated, as described in Section 3.6.2, using deionized water.

An initial test was conducted in which a 15-minute water rinse was implemented once every 2 hours. Figure 4-13 shows the impact of this rinsing frequency. Mercury levels at the outlet of the reactor increased immediately after implementing the rinsing procedure with values slowly decreasing over the next 2-3 hours. This phenomenon was observed on several occasions and suggests that the water rinse dislodged some mercury, possibly associated with ‘other’ material that had built up in the absence of the rinse, from the MerCAP™ surfaces. After completing 4-6 rinsing cycles, the mercury removal across the reactor increased to an average of 58%; thus, the water rinse resulted in an overall improvement in removal of approximately 40%. The water rinse frequency was then increased to a 30-minute wash performed once every 2 hours. This resulted in additional improvement in performance, with an average mercury removal of 76% achieved after 4 rinsing cycles.

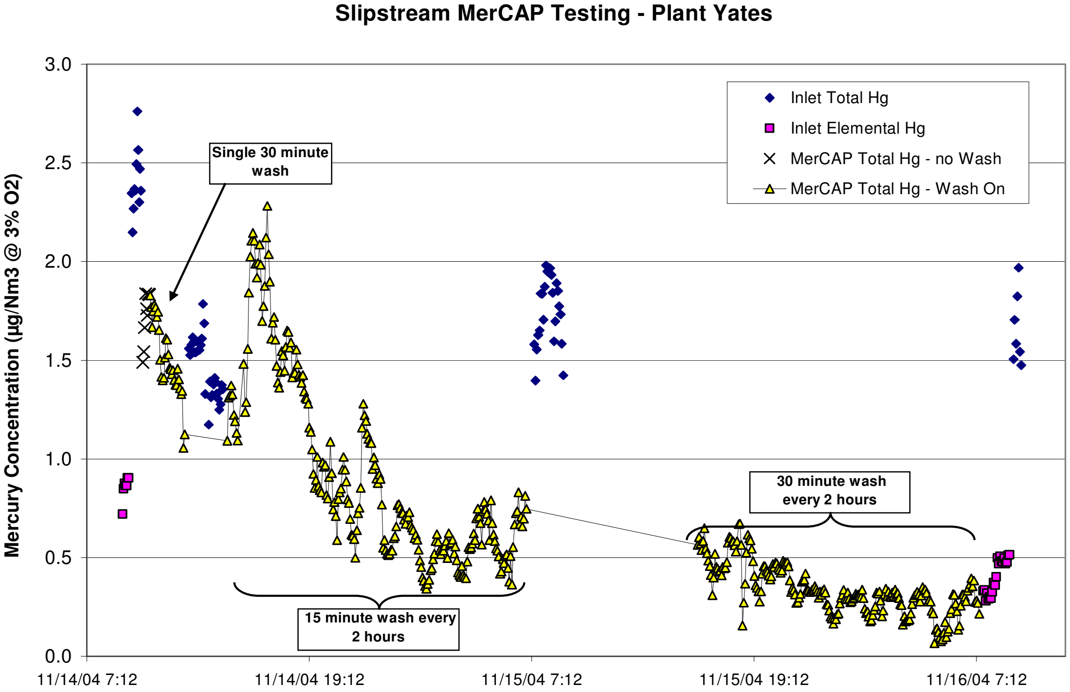


Figure 4-13. Impact of Water Wash on Slipstream MerCAP™ Reactor Performance.

The reactor was then set up to run with a 20 minute rinse conducted once every 2 hours. After several days of continuous operation, the average mercury removal was measured to be 57%. These results were similar to those with the 15-minute per 2 hour rinsing cycle. This was surprising due to the improvement observed with the 30-minute rinsing procedure. It was not known if (the longer) run time played a factor in the in the 20-minute rinse test results. To further evaluate this, the (20-minute) test was allowed to run for an additional five days in an attempt to evaluate how run-time impacts performance at a consistent rinsing frequency. Unfortunately, the rinsing system failed (on 11/25/04) resulting in the system operating for over 24 hours with no rinse. Initial mercury measurements after this time indicated <10% removal.

A continuous water rinse of the reactor was then implemented in an attempt to recover substrate performance. Figure 4-14 shows results from this attempt. Following an initial spike in outlet mercury levels, as described above, the removal rapidly improved to approximately 40% after one hour. The rinse was then turned off, resulting in a rapid decrease in mercury removal. The rinse was then turned back on and allowed to run continuously over night to determine how effective it was in improving and sustaining performance. Results showed a slow decrease in outlet mercury levels with average removals of 37% and 75% measured after 4.5 and 10 hours of continuous rinsing, respectively. Although these results continued to demonstrate a positive impact of rinsing on MerCAP™ performance, the longer time required for performance recovery suggested that factors associated with prolonged flue gas exposure may lessen or inhibit the impact of the water rinse.

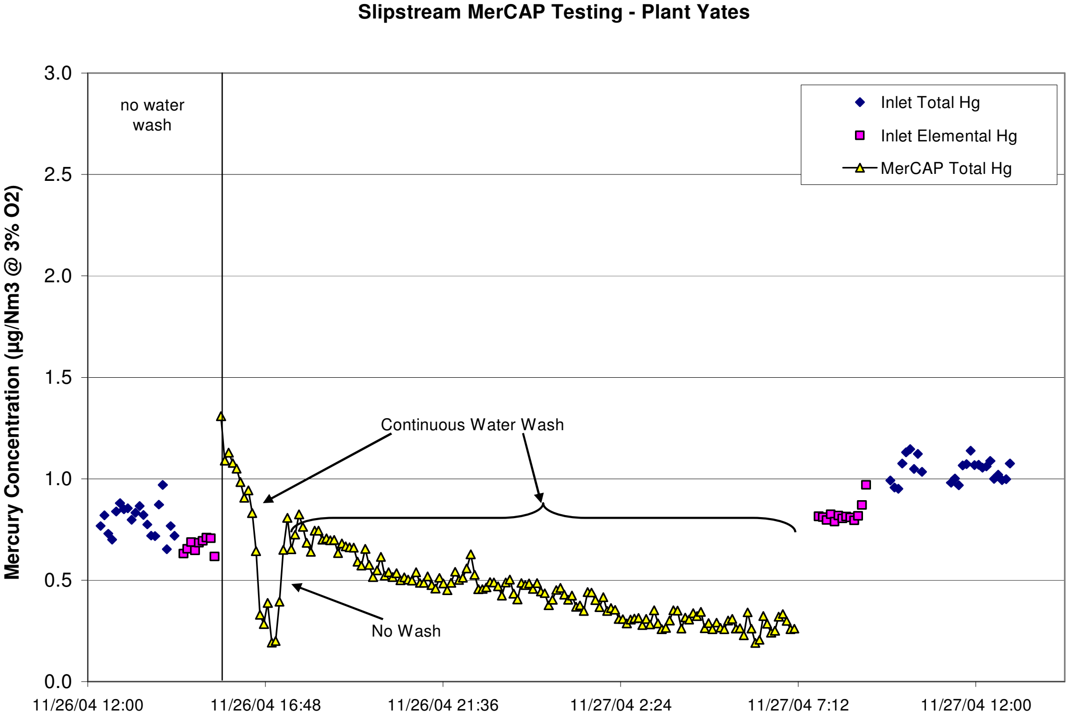


Figure 4-14. Impact of Continuous Water Wash on MerCAP™ Performance.

Based on the obtained results, it was desirable to determine possible impacts of a catastrophic failure of the water rinse system. To evaluate this, the water rinse was turned off for a period of five days while the MerCAP™ reactor continued to treat flue gas. Mercury removal decreased to just below 40% during this period. This represented less of a drop in performance than observed previously. Although the reason for this is not understood, it is possible that the extended continuous rinse conducted prior to the test may have played some role. Figure 4-15 shows results following re-implementation of the water rinse at a 30-minute interval once every 2 hours. Relatively quick recovery was observed, with over 70% removal achieved after five rinsing cycles (i.e., 10 hours). Results showed a clear correlation of increasing, then decreasing removal with each water rinsing cycle. Once stabilized, outlet mercury values consistently ranged from 0.1 – 0.6 µg/Nm^3. This level of removal was effectively maintained for over twelve hours; the system was allowed to run at these condition for several more days. These results suggest that an effective water rinsing scheme may be critical for the control of mercury emissions across a wet MerCAP™ system.

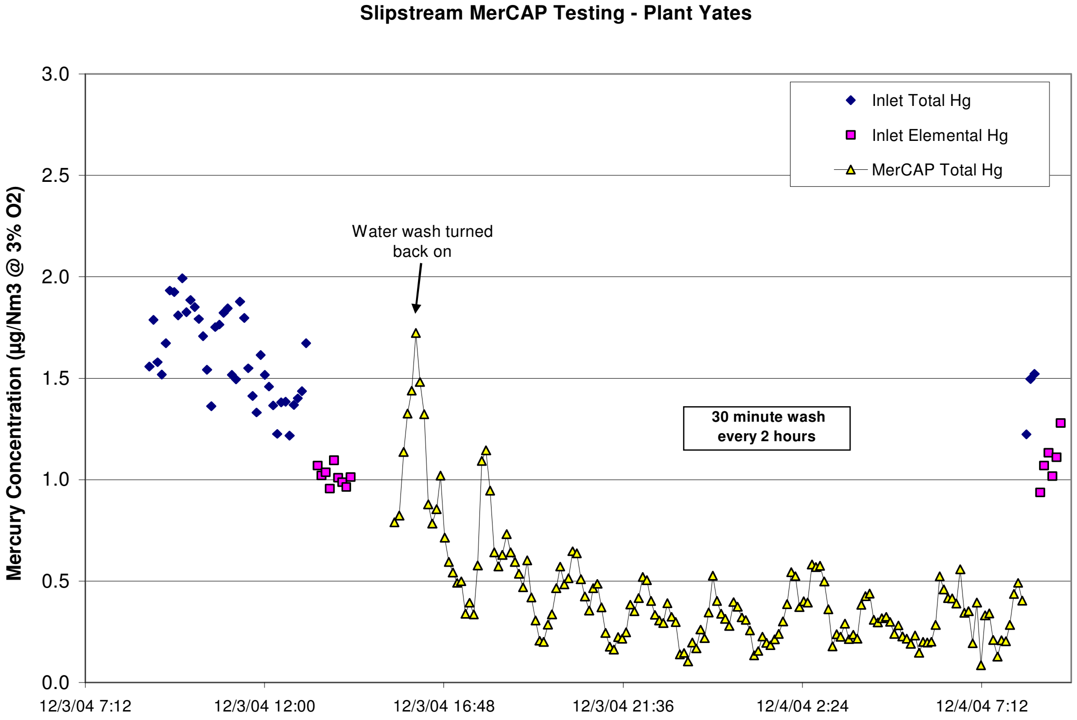


Figure 4-15. MerCAP™ Mercury Removal With Water Wash Cycling.

Despite the consistent results observed during the first 24 hours of operation following implementation of the 30 minute/2 hour rinse, performance dropped off to approximately 40% removal over the next week of operation. It was decided to implement a longer-term continuous rinse of the sorbent arrays in an attempt to recover the ‘initial’ performance. It was also desired to determine the level of removal that could be achieved with an intensive rinsing process. Figure 4-16 shows the results from this test. After an appreciable initial improvement in performance, outlet mercury levels continued to slowly decrease with continued rinsing. Measurements showed average mercury removals of 90% and 94% after 7.5 and 13.5 hours of continual rinsing, respectively. Upon terminating the rinse, outlet mercury levels immediately started to increase; only 60% removal was observed one hour after the rinse was turned off.

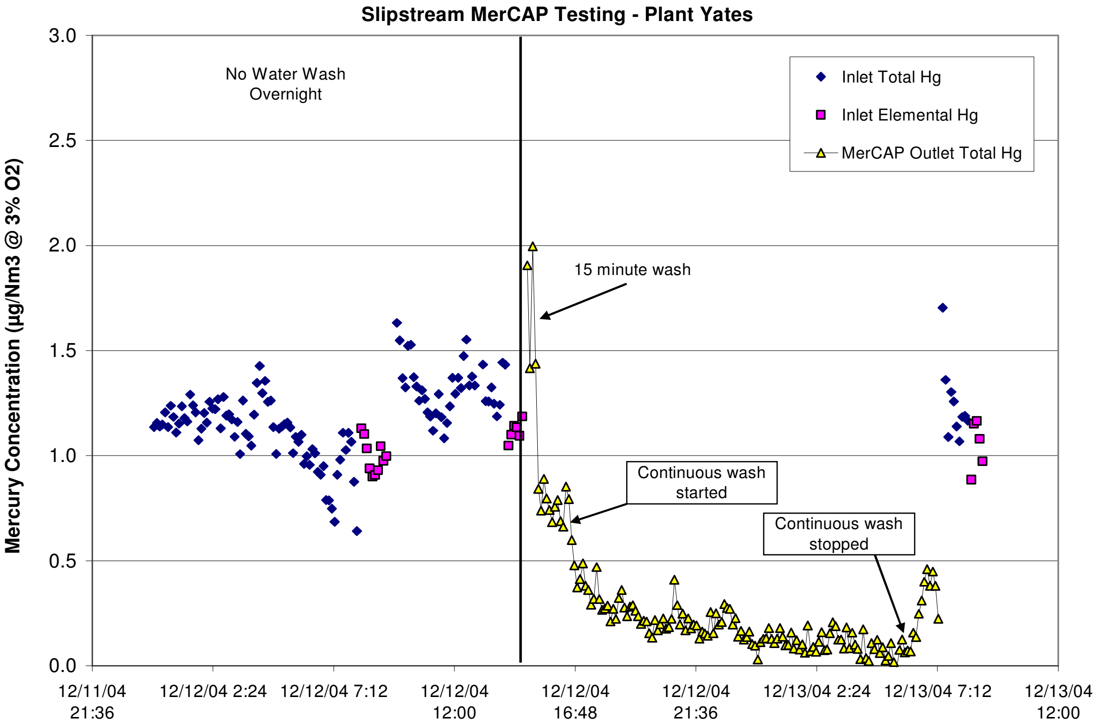


Figure 4-16. Recovery of MerCAP™ Performance after Losing Water Wash System.

After approximately one month of flue gas exposure operating under a variety of rinsing process scenarios, the wet MerCAP™ slipstream unit was allowed to run continuously with limited supervision for approximately four weeks. During this time, the water rinse was set for a 30-minute duration conducted once every two hours.

Upon arriving on site after approximately three weeks of continuous operation, it was determined that the wash water reservoir tank had been depleted for an undetermined amount of time; the reason for the water loss from the closed system was not determined. The tank was refilled with DI water, and allowed to wash for one hour before mercury measurements were made. Figure 4-17 contains a plot of these measurements.

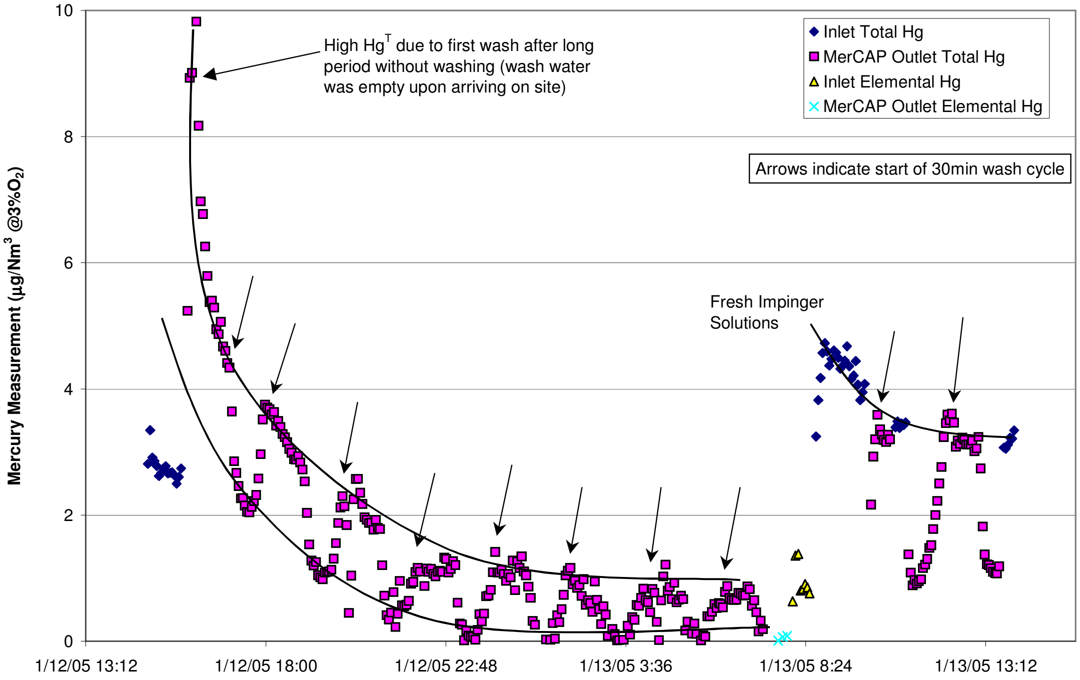


Figure 4-17. MerCAP™ Performance Cycling with Water Wash.

Following re-implementation of the water wash, the characteristic large spike of mercury (at the outlet) initially occurred and then dissipated over the course of 2-3 hours. During each subsequent wash cycle the mercury removal appeared to improve with the typical cycling effect, correlating to the rinse cycles, observed. The range of the outlet mercury levels measured during each subsequent cycle appeared to decrease showing signs of effective system recovery and stabilization. Results indicated that an average mercury removal of 58% was achieved after 6 hours of re-establishing the rinse system; this increased to over 80% after 14 hours. These results were promising as they showed that the substrate screen performance could be recovered after losing the water rinse after seven weeks of effective flue gas exposure (i.e., four weeks of parametric tests plus three weeks of long-term testing).

Similar performance was observed over the final week of the test (i.e., greater than 80% mercury removal observed with operating rinse system). Following completion of the test, the MerCAP™ slipstream reactor was dismantled and the gold-coated screen substrates were removed for inspection. The flue gas exposure (for 8 total weeks) had no visible impact on the integrity of the sorbent screens. No signs of material deposition or corrosion were observed, indicating that the water wash system was effective at protecting the screens.

Summary of Small-scale Slipstream Tests

Results from the small-scale slipstream tests verified the mercury removal performance of the gold-coated screen substrates in flue gas obtained downstream of the Plant Yates Unit 1 FGD absorber. Mercury removals as high as 90% were observed during the tests, suggesting similar or better performance than measured in previous tests at Plant Yates. The substrates evaluated in this test were prepared the same way as those planned for the pilot scale test suggesting that the pilot reactor should achieve desired levels of mercury removal. Results from the slipstream tests also indicated the importance of an effective water wash system for rinsing the MerCAP™ sorbent screens. Although the best results were obtained when a continuous water wash was used, high levels of removal were obtained and sustained using a cycling approach where routine periodic rinses were performed. Results showed good correlations between performance and rinsing cycles, suggesting that it might be possible to adjust the latter to control mercury emissions within a desired window. Loss of the water rinse resulted in a rapid degradation in MerCAP™ performance to levels ranging from 0 – 20%, thus suggesting its vital role in the process. Results for this two-month program showed that the performance of the MerCAP™ screens could be effectively recovered after periods of no rinsing, simply by re-implementing the water wash.

4.2.2 Pilot-Scale MerCAP™ Evaluation Results

A pilot-scale test program was conducted at Plant Yates to evaluate the gold-based MerCAP™ technology. A horizontal reactor was configured to receive flue gas from downstream of the Unit 1 FGD absorber. Two different MerCAP™ arrays were tested, using two different pilot system configurations depicted in Figures 3-13 and 3-14, respectively. Pilot testing was conducted to evaluate gold MerCAP™ mercury removal performance over an extended period of flue gas exposure. Gas phase mercury measurements were made to evaluate mercury removal and oxidation across the fixed sorbent reactor. Post-test analyses were made to characterize the integrity of the gold-plated MerCAP™ screens and provide explanation for the relatively poor performance observed.

This section provides a summary of the results of the pilot testing at Plant Yates including those for mercury removal performance and post-test sorbent characterization testing. A discussion of the project schedule and various delays encountered is also provided.

Pilot testing of the wet gold-based MerCAP™ technology was conducted over several periods of continuous operation between January 2006 and September 2007. A number of process modifications and program delays were encountered during this period. Table 4-11 lists the schedule for the completed test program. Tests were conducted with two separate MerCAP™ arrays. Mercury removal performance data was gathered periodically from the initial start-up of each MerCAP™ array throughout the test period. Post-test characterization of the sorbent screens was conducted to evaluate the impact of flue gas exposure on substrate integrity. Analysis of this data has shown variability in the removal performance of the pilot-scale array can be correlated to particulate build-up on and corrosion of the MerCAP™ sorbent surfaces. Details of the various tests and associated activities listed in the table are discussed below.

Table 4-11. Project Schedule for Plant Yates Pilot MerCAP™ Testing.

Date	Event
November 2004 – January 2005	Small-Scale slipstream MerCAP™ tests at Yates
February 2005	MerCAP™ reactor fabrication complete
November 2005	Ductwork installation completed
December 2005	MerCAP™ pilot reactor vessel installed
January 2006	Fan installation completed
January 2006	Gold sorbent arrays installed / testing started
February 2006	Fan failure – loss of substrates
March 2006	Pilot unit ductwork reconfigured
June 2006	Fabrication of new MerCAP™ substrates completed
July 2006	New gold substrates installed / testing started
August 2006	Ontario Hydro Measurements
September 2006 – April 2007	MerCAP™ taken offline to avoid contamination by Southern Company test on Yates Unit 1
April 2007	MerCAP™ testing re-started
May 2007	Ontario Hydro Measurements
August 2007	Ontario Hydro Measurements
September 2007	MerCAP™ system shut down and dismantled

Initial MerCAP™ Test Configuration

The pilot unit was installed at Plant Yates and configured as discussed in Section 3.4.2. Fabrication of the pilot reactor, illustrated in Figure 3-10, was completed in February, 2005. Installation of the pilot system ducting was completed in October, 2005. The reactor was then shipped to the host site and installed, as shown in Figure 3-5; installation was completed in December 2005. The pilot fan was installed in early January 2006 and flow testing was then performed. The gold MerCAP™ arrays (see Figure 3-12) were installed in January 2006 after which performance testing was immediately started.

Prior to charging the MerCAP™ reactor with the gold sorbent substrates, baseline mercury measurements were conducted across the empty reactor. A single EPRI SCEM analyzer was used to sequentially measure flue gas from the inlet and outlet of the reactor. Table 4-12 lists the average values obtained from each location. The measurements showed an average inlet mercury value of 1.21 $\mu g/Nm^3$. The measured outlet value was slightly higher indicating no removal across the empty chamber.

The MerCAP™ reactor was then charged with three gold substrate array modules providing an overall length of 36 inches. The test was then started by opening the isolation values at the inlet and outlet to the pilot system and starting the flue gas fan. Mercury measurements were made to evaluate removal performance of the fixed sorbent. Figure 4-18 shows the results for the first 24 hours of operation.

Upon starting flue gas flow across the reactor at 1300 acfm, the outlet mercury levels dropped nearly to zero. Initial results indicated approximately 97% mercury removal by the MerCAP™ unit. The outlet values showed a gradual increase over the next 12-18 hours. After 12 hours of continuous operation the removal dropped to approximately 81%. After 19 hours of operation, approximately 75% removal was measured. This value was similar to that expected when considering mass-transfer properties (Table 3-2). Based on the shape of the outlet mercury curve (Figure 4-18), removal performance appeared to stabilize after 14-16 hours of operation. The system was subsequently allowed to operate under continuous flue gas exposure.

Table 4-12. Mercury Measurements Made Across the Pilot MerCAP™ Reactor.

Date/Time	Total Ave. Mercury Concentration (µg/Nm^3 @ 3% O2)	
	Inlet	Outlet
Baseline Period		
1/13/06: 13:30 - 14:37	-	1.30
1/13/06: 14:55 - 17:19	1.21	-
MerCAP Testing		
1/13/06: 19:16 - 19:33	1.24	-
1/13/06 19:44 - 1/14/06 07:18	-	0.20
1/14/06: 08:14 - 11:03	2.49	-
1/14/06: 11:10 - 14:15	-	0.47*
1/14/06: 16:41 - 22:28	1.95**	-

* - Mercury oxidation measured to be 0%

** - Mercury oxidation measured to be 46%

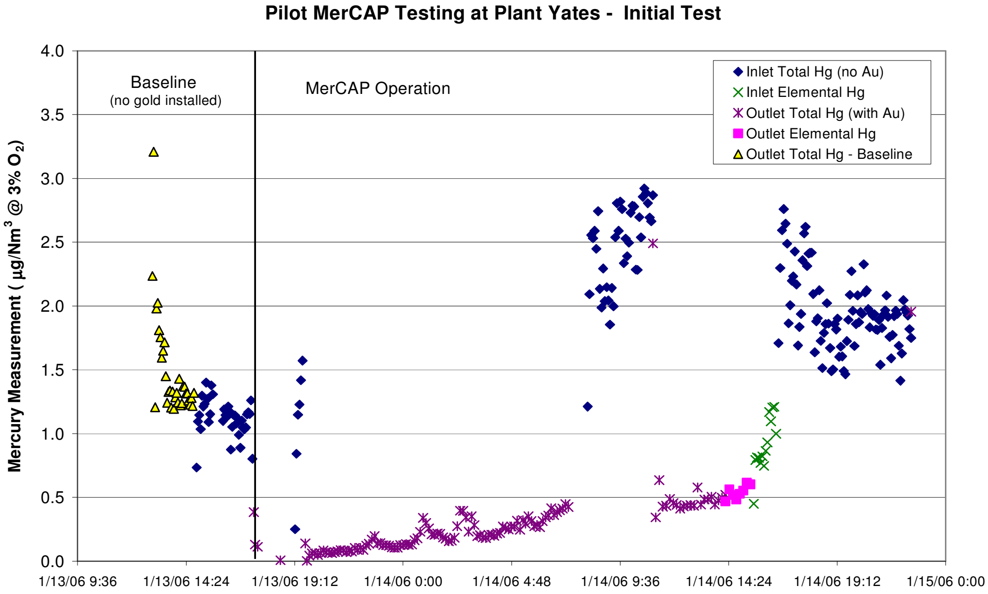


Figure 4-18. Initial MerCAP™ Mercury Removal Results

The speciation of the mercury entering the MerCAP™ reactor was approximately 50% oxidized during this test whereas the mercury speciation exiting the unit was greater than 95% elemental (i.e., at a time when approximately 25% mercury breakthrough was observed). The inlet oxidation values were much higher than expected, considering the source of the flue gas was the outlet of a wet FGD system. Previous full-scale flue gas measurements downstream of the Unit 1 FGD absorber showed mercury oxidation values less than 25% for all measurements (Cooperative Agreement DE-FC26-03NT41987). No full-scale flue gas measurements were made during this program. Thus, it is not known if the high oxidation values were indicative of that in the stack flue gas or if they were the result of mercury oxidation occurring within the inlet duct of the pilot system. The outlet oxidation results suggest a preferential adsorption of oxidized form(s) of mercury by the MerCAP™ unit. The high fraction of elemental mercury at the MerCAP™ reactor outlet did not correlate with previous lab or slipstream tests that indicated appreciable mercury oxidation by the gold-coated screens. They do, however, correlate with observations made during full-scale testing at Site 1.

Following the initial measurement period, the MerCAP™ unit was allowed to run with continuous flue gas flow for a period of two weeks. Additional measurements were then made to characterize performance. These showed no mercury removal across the reactor (i.e., inlet and outlet values were similar). Upon further inspection, it was discovered that the pilot system fan had failed and that flow had reversed itself across the MerCAP™ reactor. This resulted in flue gas from the inlet of the full-scale FGD absorber pushing back through the pilot system. It was later determined that the fan was not powerful enough to overcome the pressure at the inlet of the JBR and that the flue gas was traveling backwards through the system even though the fan was operating.

The MerCAP™ system was then shut-down for sorbent inspection and determination of a suitable plan forward. Inspection of the MerCAP™ array showed appreciable corrosion and degradation of the gold-coated plates. This was likely due to the exposure of the plates to untreated flue gas. Figures 4-19 and 4-20 show the damaged plates during the inspection. The combination of high SO_2 concentration in the gas and appreciable condensation across the unheated reactor likely resulted in a very corrosive environment that was too harsh for the gold screen substrates. This resulted in severe corrosion and buckling of the screen substrates (Figure 4-19). A detailed inspection and evaluation of the MerCAP™ plates was made. Many screens showed visible loss or absence of gold coating (Figure 4-20). It was subsequently determined that they could not be cleaned and that the corrosion damage was sufficient to where the screens were not suitable for re-use in the reactor.

The MerCAP™ substrates were then disassembled and the reactor was cleaned. Plans were then made for preparing new sorbent arrays for the Yates pilot program. Additional plans were made to reconfigure the pilot system to decrease the overall system pressure-drop and prevent chances for exposure to untreated flue gas, as described in the next section.

Figure 4-19. Corroded Gold Screens in the MerCAP™ Reactor Following Flue Gas Flow Reversal.

Figure 4-20. Corroded Gold Screens in the MerCAP™ Reactor

Modified MerCAP™ Test Configuration

The original pilot system configuration was not successful due to pressure drop constraints associated with the full-scale tie-in locations and pilot fan limitations. This, coupled with direct duct assess to untreated flue gas (i.e., from upstream of the full-scale FGD absorber) led to the destruction of the MerCAP™ sorbent array. To overcome the system limitations and eliminate the chance of MerCAP™ exposure to untreated flue gas, the pilot system was reconfigured as shown in Figure 3-14. Here, flue gas exiting the reactor was routed to a port downstream of the FGD absorber, as opposed to the original installation that had the flue gas return upstream of the FGD unit. Inlet flue gas to the pilot unit was obtained from the same location as previously. With this new configuration the pressure drop across the entire MerCAP™ (slipstream) system was reduced from nearly 20 in. H_2O to approximately 3 in. H_2O.

Ductwork modifications for the new configurations were completed in March 2006. A new set of gold-coated screens were prepared using the same procedure as with the first batch and the MerCAP™ modules were assembled; this effort was completed in June 2006. The new MerCAP™ array, consisting of three 1-ft (long) MerCAP™ arrays, was installed in the pilot reactor in July 2006 immediately following a series of baseline measurements that verified consistent flue gas mercury levels across the empty reactor.

Mercury measurements across the MerCAP™ reactor were made immediately following installation of the new gold substrates (July 13th, 2006). Flue gas was initially flowed across the reactor at a rate of 3600 acfm resulting in average outlet mercury levels of about 3.1 $\mu g/Nm^3$. With inlet value of about 3.6 $\mu g/Nm^3$, this indicated an approximate removal of only 15%. This value was much lower than expected and compared to initial results of the first pilot test and theoretical calculations (Table 3-3).

A series of parametric tests was conducted to determine any impact of flue gas flow rate across the MerCAP™ reactor on performance. Table 4-13 lists results from these tests as well as additional tests and measurements conducted over the first 2½ months of operation. The flue gas flow rate was varied between 1300 and 3600 acfm for periods ranging from 4 – 12 hours each. Results from these tests indicated no apparent impact of gas flow rate on mercury removal, with the latter ranging only from 3–15%; theoretical removals for this range were 60-74%. A graphical representation of the data is provided in Figure 4-21; here, flow rate values (on the X-axis) are normalized for the length of the MerCAP™ sorbent bed installed. Tests conducted over the first three days of operation showed no impact of flow rate on performance. The fact that removal values tended to decrease over the first three days, regardless of the flue gas flow rate, suggested a greater impact of gas exposure time than flow rate. This impact, shown graphically in Figure 4-22, indicates a consistent decrease in removal, from approximately 15% to 2%, over the first 55 hours of operation. This was similar to the initial drop-off in performance observed during the first test with the primary difference being the much lower overall extent of removal observed in the second test.

Table 4-13. MerCAP™ Mercury Measurement Results – Modified Pilot Unit Configuration.

Date	Flow Rate	Gold Length	Inlet Hg	Outlet Hg	% Hg Removal
	(acfm)	(inches)	(μgNm^3 @ 3%O$_2$	(μgNm^3 @ 3%O$_2$	
7/13/2006	3600	36	3.61	3.08	15%
7/13/2006	2700	36	3.51	3.07	13%
7/14/2006	2700	36	4.23	3.88	8%
7/14/2006	1900	36	3.98	3.58	10%
7/14/2006	1300	36	3.98	3.61	9%
7/15/2006	1300	36	2.03	1.96	3%
7/15/2006	2700	36	4.23	4.11	3%
8/4/2006	2700	36	6.19	6.06	2%
8/6/2006	2700	12	4.52	3.84	15%
8/18/2006	2700	12	3.41	3.24	5%
8/18/2006	1300	12	3.53	3.30	6%
9/23/2006	2550	12	4.76	4.33	9%
9/24/2006	2700	12	2.53	2.26	11%
9/25/2006	2700	12	4.73	4.03	15%
9/25/2006	2700	12	2.12	2.04	4%

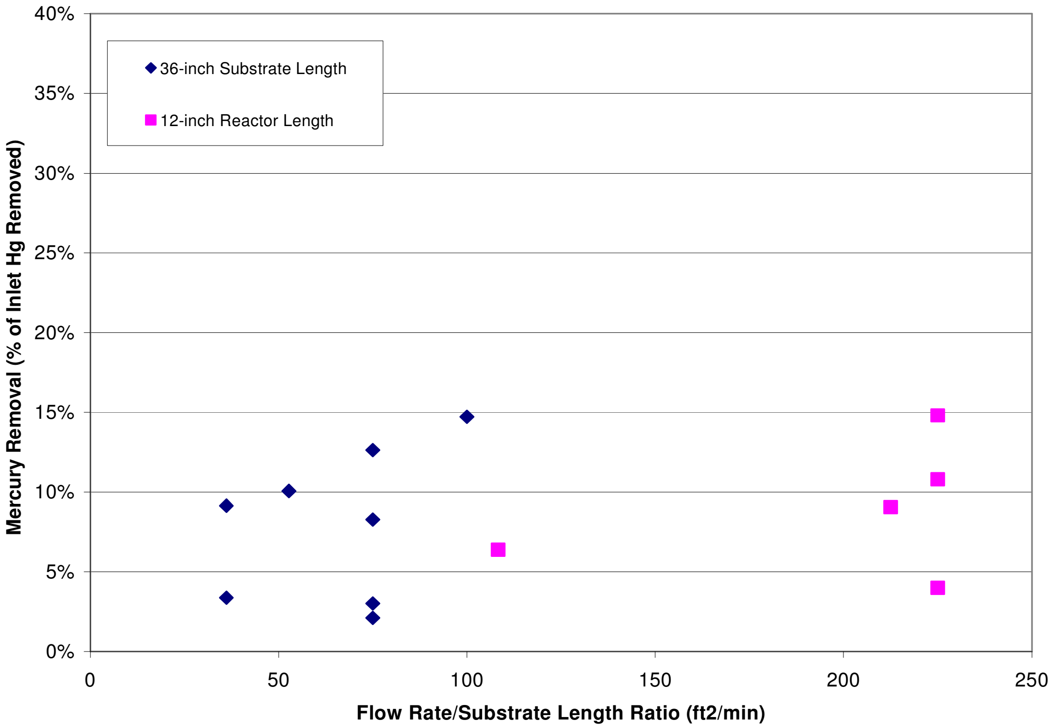


Figure 4-21. Impact of Gas Flow Rate and MerCAP™ Sorbent Array Length on Mercury Removal.

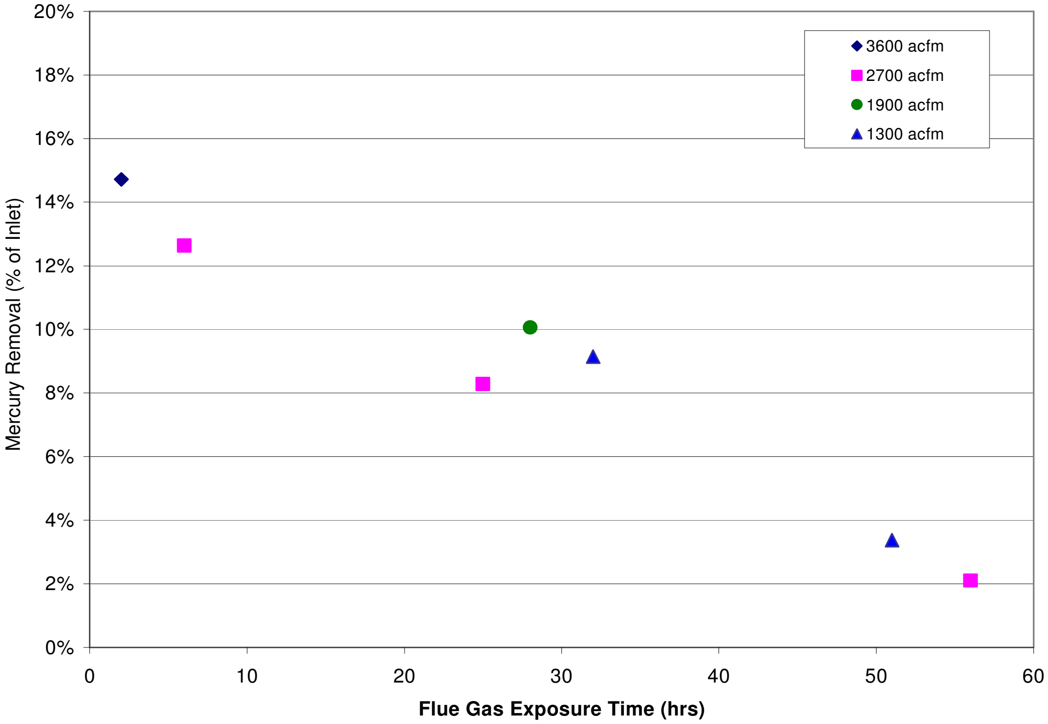


Figure 4-22. Impact of Run Time on MerCAP™ Mercury Removal.

The pilot system was allowed to run continuously for several weeks. Additional performance measurements were then made (on 8/04/06) to characterize the mercury removal performance. These indicated virtually no removal across the pilot reactor (Table 4-13). At this point, the pilot unit was temporarily taken off line for inspection of the MerCAP™ sorbent array. The reactor vessel was isolated and opened up for inspection of the sorbent modules. Although no visible signs of screen corrosion were observed, particulate deposition on the sorbent screens was visible. The deposition was most prevalent in the latter stages of the reactor. This suggests that the co-current rinsing system was not adequately cleaning all the substrate surfaces in the reactor.

Attempts to manually wash the solids from the installed MerCAP™ array were not successful, so it was decided to remove the second and third gold modules from the reactor in order to subject them to a cleaning and/or regeneration process. The MerCAP™ vessel was re-sealed and re-started with just one gold screen module configured (i.e., total sorbent array length of 12 inches). The water wash system was modified to add more water during a given rinse and set up to rinse the plates once every three hours.

After the second two sections of gold were removed and the wash system improved, the MerCAP™ system was able to achieve approximately 15% mercury removal upon start-up (Table 4-13). This value was comparable to the performance observed upon initial startup of the 3-module array. These results indicate the importance of an effective water rinse for achieving appreciable mercury removal with a wet gold MerCAP™ system.

They also suggest that the initial mercury removal observed with the 3-module array may have been achieved primarily by the first module (which likely received the most efficient water rinse of the three modules).

The single module system was allowed to run continuously for twelve days at a flue gas flow rate of 2700 acfm before being characterized again for mercury removal. Measurement results indicated a decrease in removal performance to approximately 5% (Table 4-13). This was considerably lower than the theoretical removal of 31% for a single sorbent module configuration (Table 3-3). No appreciable change was observed after decreasing the flue gas flow to 1300 acfm. To further evaluate the impact of rinsing the wet MerCAP™ screens, the rinse system was turned off for an eight hour period on August 17th, 2006. Results over that period, shown in Figure 4-23, showed virtually no mercury removal across the single sorbent array. Upon re-establishing the water rinse, the relatively low levels of mercury removal were again observed.

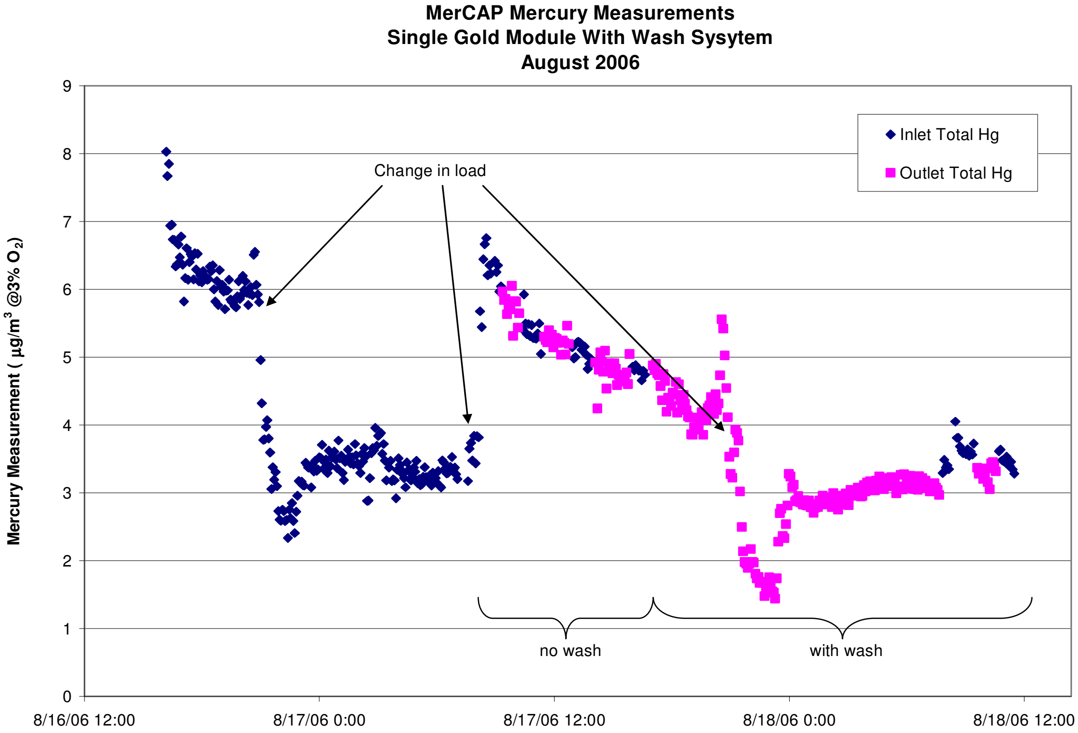


Figure 4-23. Impact of Water Rinse on Mercury Removal by Single Module MerCAP™ System.

The pilot system was run for an additional month in single-module mode with enhanced water rinsing to determine if any changes in performance occurred. Mercury measurements were again made (September 2006) to evaluate performance. Results showed continued low levels of mercury removal (approximately 10%) across the MerCAP™ system. Measurements were collected continuously over a three day period to characterize removal across the system while the plant varied load (i.e., during normal operation). Figure 4-24 shows how mercury levels at the inlet to the pilot unit fluctuated as unit load changed over the period. These changes resulted in no appreciable changes to the MerCAP™ performance, with outlet emissions tracking those of the inlet with only low levels of removal observed.

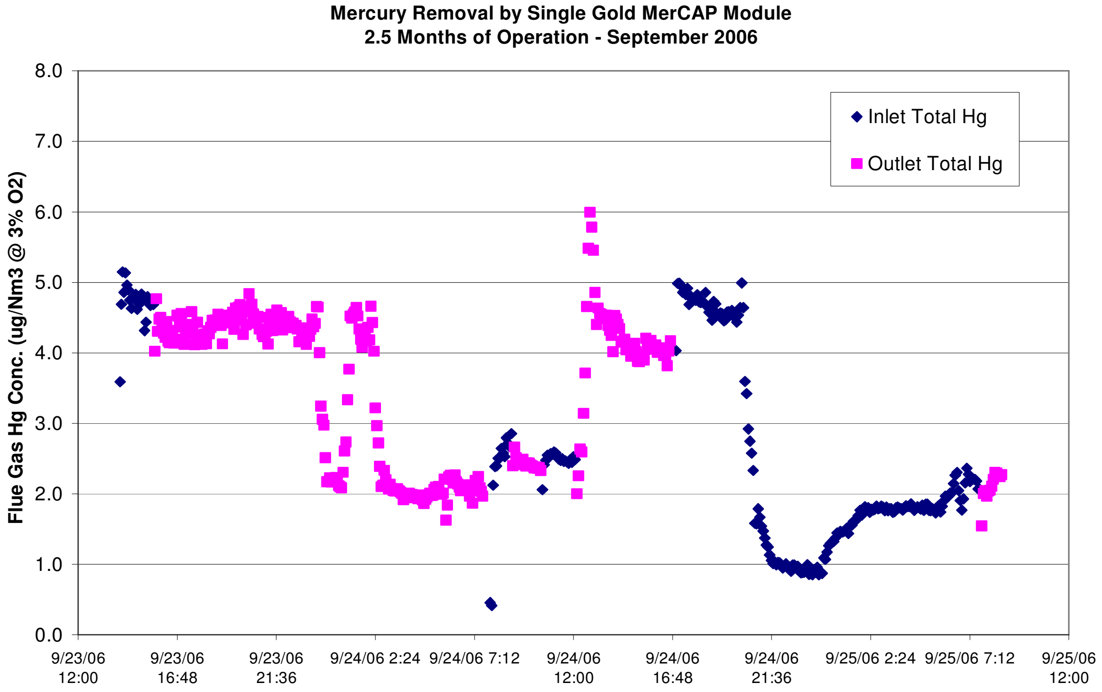


Figure 4-24. Mercury Removal by Single-Module MerCAP™ Array after 2.5 Months of Operation

Although the mercury removal levels were quite low, the results obtained during the single module test showed some promise in that the removal extent was sustained during the 2.5 months of operation. This was likely due, at least in part, to the enhance water rinse process that was implemented during this period.

The pilot system was shut down and isolated from the full-scale unit immediately after the measurements made in late September 2006 to allow for the plant to conduct some previously planned (unrelated) full-scale tests on Unit 1. The MerCAP™ system was taken off line as it was believed that the full-scale testing would likely have impacted the MerCAP™ test.

The pilot MerCAP™ system remained off-line for approximately six months as the plant conducted both the unrelated extended test program and a planned unit outage. During this period the gold MerCAP™ modules, previously removed from the pilot reactor, were cleaned and inspected for signs of corrosion or gold loss. It was found that the solid material that had coated the gold surfaces was difficult to remove, requiring physical scrubbing of the screens. Upon cleaning, some loss of gold from various screens was observed, particularly from screens configured in the second (i.e., middle) module within the reactor. Areas of gold loss were characterized by their lack of metallic gold color and were estimated to represent approximately 10% of the total surface area of the second module.

The MerCAP™ pilot unit was re-started at Plant Yates in April 2007. Following re-establishment of flue gas flow and measurements to verify no removal across the empty reactor, the vessel was charged with the same first gold-screen module evaluated in the previous 2½-month test. Flue gas flow was started across the cleaned module at 2700 acfm (120°F; 49°C) and allowed to run in this configuration for 24 hours. Mercury measurements were made across the reactor and indicated removals of 11% and 3% after only 16 and 21 hours of flue gas exposure, as shown in Table 4-14. These results were similar to those obtained at the end of the previous test indicating no improvement after the manual screen cleaning process.

The reactor was then shut down and an additional gold screen module was installed (i.e., total screen length of 24 inches). The newly installed module was the (cleaned) third module from the previous testing. Here, the first module was configured as it was previously while the other (previous third) module was configured immediately downstream of the first. It was decided to initially forego installation of the previous second module due to the gold loss sustained during the earlier test.

The pilot test was re-started with a flue gas rate of 5000 acfm (120°F; 48 ft/sec linear velocity). Initial measurements showed that 23% of the mercury was removed across the 2-module system (Table 4-14). These results showed improved performance over operation with only one module in service (i.e., approximately twice the removal obtained) although the observed removal was only about half of the (theoretical) removal expected at these conditions. The pilot unit was operated overnight and then re-measured for mercury removal. Results indicated no change in performance over the first 17 hours of operation. Upon reducing the flue gas flow to 2700 acfm (25 ft/sec linear velocity), mercury removal initially increased to 44%. However, the removal subsequently decreased to 29% over the next several hours. Theoretical mercury removal at these conditions was 53%.

The pilot unit was allowed to run continuously for the next 23 weeks. A flue gas flow rate of 2700 acfm (avg. temp=120°F; 49°C) was maintained across the vessel resulting in a linear gas velocity of 25 ft/sec across the sorbent screens. Mercury measurements were made periodically to determine removal performance and extent of oxidation across the reactor. Manual Ontario Hydro samples were obtained on multiple occasions, as described in Section 4.2.2.3, to validate the mercury analyzer results. Table 4-14 lists the average results from the mercury SCEM measurements made during the test period.

Additional mercury measurements were made after approximately one month of operation (May 2007). Results for several of the measurement cycles indicated just over 20% mercury removal across the MerCAP™ reactor (Table 4-14). Measurements during several cycles indicated even lower removals (11-13%). These results suggest a decrease in performance over the first month of operation of the cleaned gold screen modules. In an attempt to compensate for this the water wash frequency was tripled to provide a wash once every hour, as opposed to once every three hours.

Table 4-14. MerCAP™ Flue Gas Mercury Measurements at Plant Yates

Run Time	Plate Length	Flow Rate	Inlet Hg	Outlet Hg	Hg Removal
(hr)	(in)	(ACFM)	(µg/Nm^3)	(µg/Nm^3)	(%)
16	12	2700	3.270	2.92	11%
21	12	3200	4.30	4.18	3%
2	24	5000	3.95	3.05	23%
17	24	5000	5.03	3.71	26%
22	24	2700	6.55	3.67	44%
24	24	2700	5.04	3.43	32%
25	24	2700	4.47	3.17	29%
808	24	2700	3.20	2.47	23%
813	24	2700	2.93	2.28	22%
834	24	2700	3.68	3.22	13%
836	24	3800	3.67	3.39	8%
840	24	2700	4.55	3.52	23%
862	24	2700	3.97	3.53	11%
883	24	2700	3.04	2.71	11%
1152	24	2700	6.37	5.49	14%
1169	24	2700	7.53	6.28	17%
1172	24	2700	9.80	7.68	22%
2348	24	2700	6.91	6.05	12%
3356	24	2700	3.21	3.31	-3%
3361	24	2700	3.20	3.23	-1%

Figure 4-25 shows how the inlet and outlet data tracked over the measurement period. Outlet emissions ranged from 1 – 4 µg/Nm^3, tracking closely to the inlet values. Outlet speciation data showed that approximately 30 – 55% of the mercury at the outlet was present in the oxidized form. This compared to nearly 100% elemental mercury at the inlet, indicating that a portion of the mercury not removed by the MerCAP™ system was being oxidized by the gold screens.

Measurements made after 1150 hours of continuous run time showed that the MerCAP™ unit was removing approximately 14-22% of the total mercury present in the inlet flue gas. This suggested a continued decline in performance over time. Subsequent measurements made after 2350 hours of operation showed only 12% removal. After an additional seven weeks of operation no removal across the reactor was measured. Figure 4-26 illustrates the decline in mercury removal over the first 4½ months of operation.

Measurement results indicated an appreciable decrease in mercury removal performance over the first 3300 hours of operation. Analysis of mercury speciation results suggested a similar trend. Table 4-15 lists speciation data obtained by the SCEM measurements during the test. Measurements made after 800 hours of operation showed 30-50% oxidation of the mercury exiting the MerCAP™ reactor. This value decreased to 6-13%

after 1150 hours of flue gas exposure. No oxidation was measured after 3300 hours of operation. These results track those for mercury removal and indicate that the overall reactivity of the sorbent screens decreased to a point of non-reactivity during the testing period.

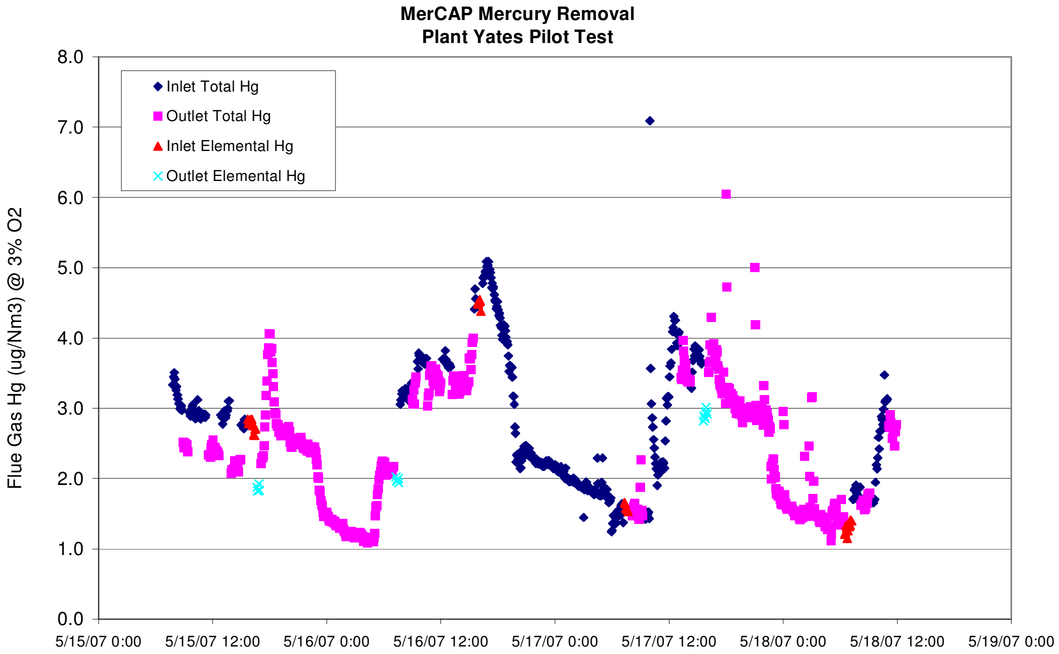


Figure 4-25. MerCAP™ Hg Removal Measurements; 800–880 hrs of Operation.

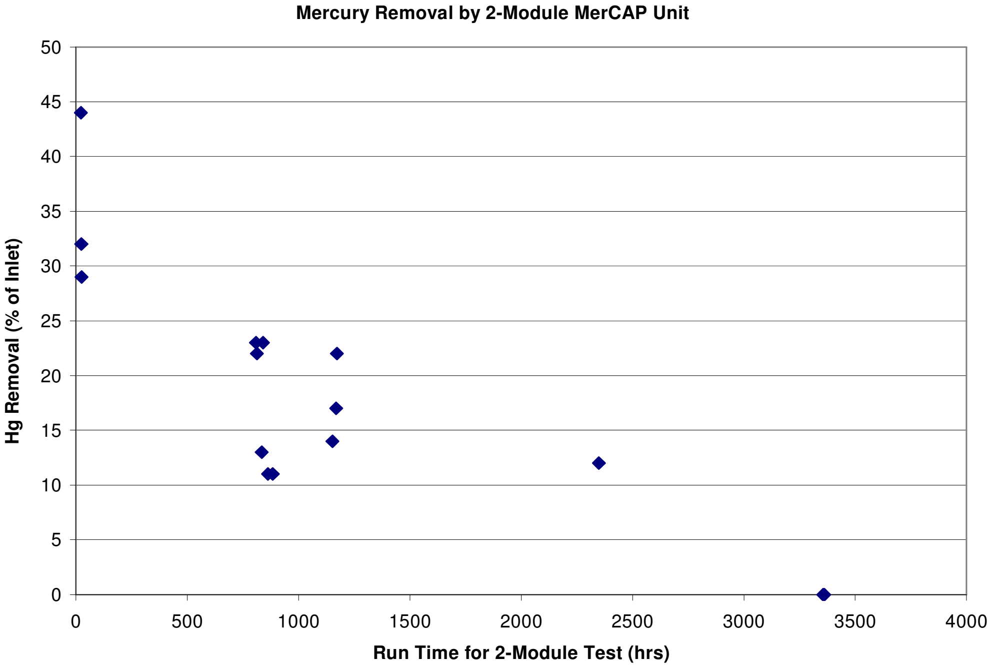


Figure 4-26. Impact of Gas Exposure Time on MerCAP™ Mercury Removal; 2700 acfm, two gold modules installed.

Table 4-15. Mercury Oxidation Data for the Plant Yates Pilot MerCAP™

Run Time	Plate Length	Flow Rate	Inlet			Outlet			Hg^o Oxidation across MerCAP
			Hg^T	Hg^o	Hg^o Oxidation	Hg^T	Hg^o	Hg^o Oxidation	
(hr)	(in)	(ACFM)	(µg/Nm^3)	(µg/Nm^3)	(%)	(µg/Nm^3)	(µg/Nm^3)	(%)	(%)
816	24	2700	2.78	2.76	0%	2.61	1.86	29%	33%
840	24	2700	4.75	4.49	6%	2.67	1.98	26%	56%
857	24	2700	1.61	1.59	1%	-	-	-	-
863	24	2700	-	-	-	3.80	2.91	23%	-
879	24	2700	1.49	1.30	13%	-	-	-	-
1152	24	2700	5.99	4.05	32%	5.49	3.80	31%	6%
1169	24	2700	-	-	-	6.28	5.04	20%	-
1172	24	2700	9.80	2.67	73%	-	-	-	-
1176	24	2700	8.94	7.42	17%	7.68	6.48	16%	13%
3353	24	2700	3.21	2.90	10%	3.65	3.22	12%	-11%
3356	24	2700	3.20	2.80	12%	3.06	2.82	8%	-1%
3362	24	2700	3.20	3.21	0%	3.39	3.15	7%	2%

Following flue gas measurements made after 3350 hours, the water rinse was again increased in an attempt to promote mercury removal by the gold screens. After three additional weeks of run time (total run time for this test was 23 weeks), measurements still indicated that no mercury removal was occurring. The pilot unit was subsequently taken off line for inspection of the sorbent screens. This inspection revealed severe degradation of the MerCAP™ screens, including appreciable visible signs of corrosion and loss of gold coating over many of the installed screens. Further inspection showed appreciable flaking of the gold coating which was worsened by attempts to manually wash the substrates. Based on results of the measured performance and visual inspection, the decision was made to stop the test at this time. The pilot unit was subsequently disassembled and removed from the site.

Ontario Hydro Measurements

Ontario Hydro (OH) measurements were made in conjunction with three separate rounds of SCEM measurements during August 2006, May 2007, and August 2007. The ports used for the Ontario Hydro measurements were located upstream of the inlet SCEM port and downstream, of the outlet SCEM port. SCEM data was collected simultaneously during the Ontario Hydro measurements, and was averaged during those periods in order to make a comparison. Ontario Hydro data corresponded reasonably well to the data collected by the SCEMs and confirmed the low levels of mercury removal across the MerCAP™ reactor. Table 4-16 lists the comparison of these data for the three sets of Ontario Hydro measurements conducted.

Table 4-16. Comparison of Ontario Hydro and SCEM Measurements

	Date	Time	Inlet Mercury (µg/Nm3)			Outlet Mercury (µg/Nm3)			MerCAP Hg Removal
			Hg_{Tot}	Hg_{Elem}	Hg Oxidation	Hg_{Tot}	Hg_{Elem}	Hg Oxidation	
OH-1 Data	8/4/2006	9:03-11:03	6.7	6.1	8.8	12.7	18.8	51.4	-88.9
		11:29-13:29	7.7	7.2	6.5	6.9	6.1	18.0	12.2
		14:02-16:02	19.7	18.7	4.6	7.9	5.5	20.3	60.0
		Average	11.4	10.7	6.6	9.2	10.1	29.9	-5.6
SCEM-1 Data	8/4/2006	9:03-11:03	5.8	4.6	21.4	6.4	5.9	7.8	-10.1
		11:29-13:29	6.2	6.0	3.7	5.9	4.4	24.9	4.8
		14:02-16:02	6.2	4.5	27.9	5.6	6.1	-8.9	9.7
		Average	6.1	5.0	17.7	6.0	5.5	7.9	1.5
OH-2 Data	5/29/2007	14:40-17:40	4.8	4.8	1.0	5.1	4.6	9.8	-6.3
	5/30/2007	8:00-11:00	2.1	2.1	0.0	3.9	3.9	0.0	-18.0
		11:40-14:40	7.5	7.5	0.5	6.3	6.5	-3.2	16.0
		Average	4.8	4.8	0.5	5.1	5.0	2.2	-2.8
SCEM-2 Data	5/29/2007	14:40-17:40	6.2	4.1	33.9	5.5	3.8	30.9	11.3
	5/30/2007	8:00-11:00	7.5	2.7	64.0	6.3	5.04	20.0	16.0
		11:40-14:40	9.8	7.4	24.5	7.7	6.5	15.6	21.4
		Average	7.8	4.7	40.8	6.5	5.1	22.2	16.2
OH-3 Data	8/29/2007	08:53-11:53	2.3	2.3	0.0	2.1	2.1	0	8.7
		12:30-15:30	2.8	2.8	0.0	2.6	2.6	0	7.1
		16:00-18:54	2.7	2.7	0.0	2.5	2.5	0	7.4
		Average	2.6	2.6	0.0	2.4	2.4	0.0	7.7
SCEM-3 Data	8/29/2007	08:53-11:53	3.2	2.9	9.4	3.6	3.2	11.1	-12.5
		12:30-15:30	3.2	2.8	12.5	3.1	2.8	9.7	3.1
		16:00-18:54	3.2	3.2	-0.3	3.3	3.2	3.0	-3.1
		Average	3.2	3.0	7.2	3.3	3.1	7.9	-4.2

Figures 4-27 and 4-28 show results for SCEM and OH measurements made in August 2006 and May 2007, respectively. The Ontario Hydro results in both of these plots confirm the low level of mercury removal observed with the SCEMs. They also confirm mercury oxidation across the MerCAP™, ranging from 3 - 9% during August 2006. The SCEM data showed some oxidation during this period in the range of 0-2%; however the oxidation measured with the SCEMs in May 2007 (22-40%) was not supported by Ontario Hydro results that only showed mercury oxidation at the inlet and outlet in the range of 0.5-2.2%. The reasons for this discrepancy are not known. One possible reason may be that mercury oxidation was occurring across the IGS filters supplying the mercury analyzers. This possibility was addressed during the test program; the IGS filters were replaced after 3300 hours of operation. No oxidation was measured by the SCEM analyzer at that time.

Increased water washing frequency had no effect on the removal efficiency of the system in May and August of 2007. Each round of Ontario Hydro measurement with the increased wash confirmed that there was minimal mercury removal across the MerCAP™ reactor.

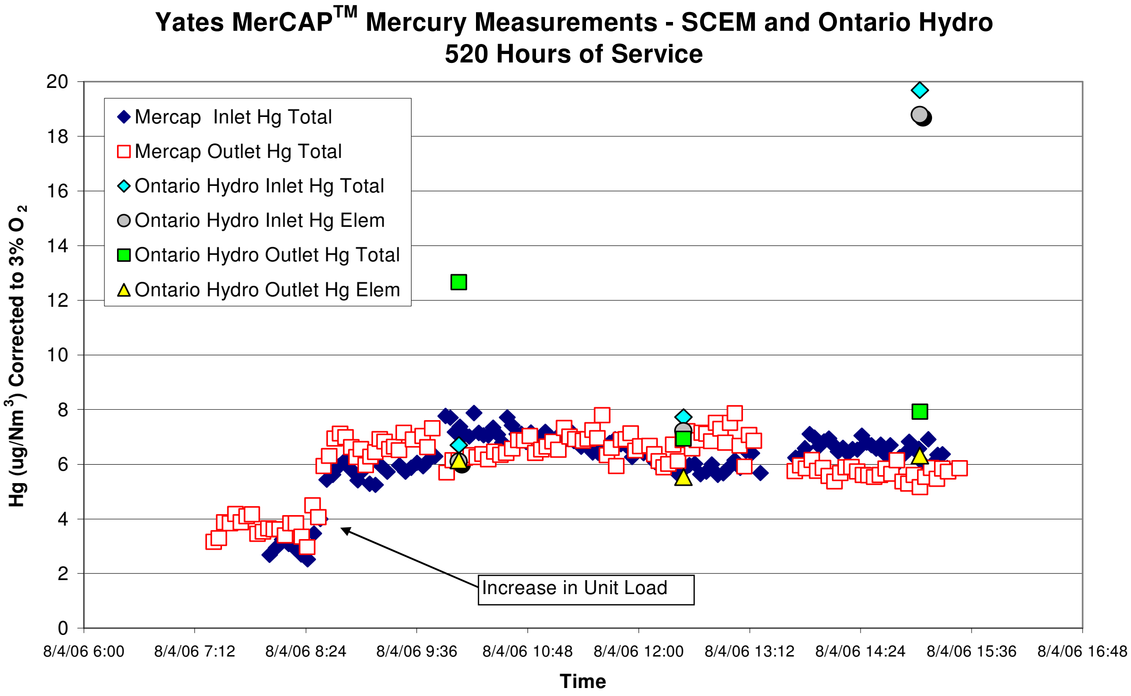

Yates MerCAP™ Mercury Measurements - SCEM and Ontario Hydro
520 Hours of Service

Figure 4-27. SCEM and Ontario Hydro Mercury Measurements across the MerCAP™ at Plant Yates

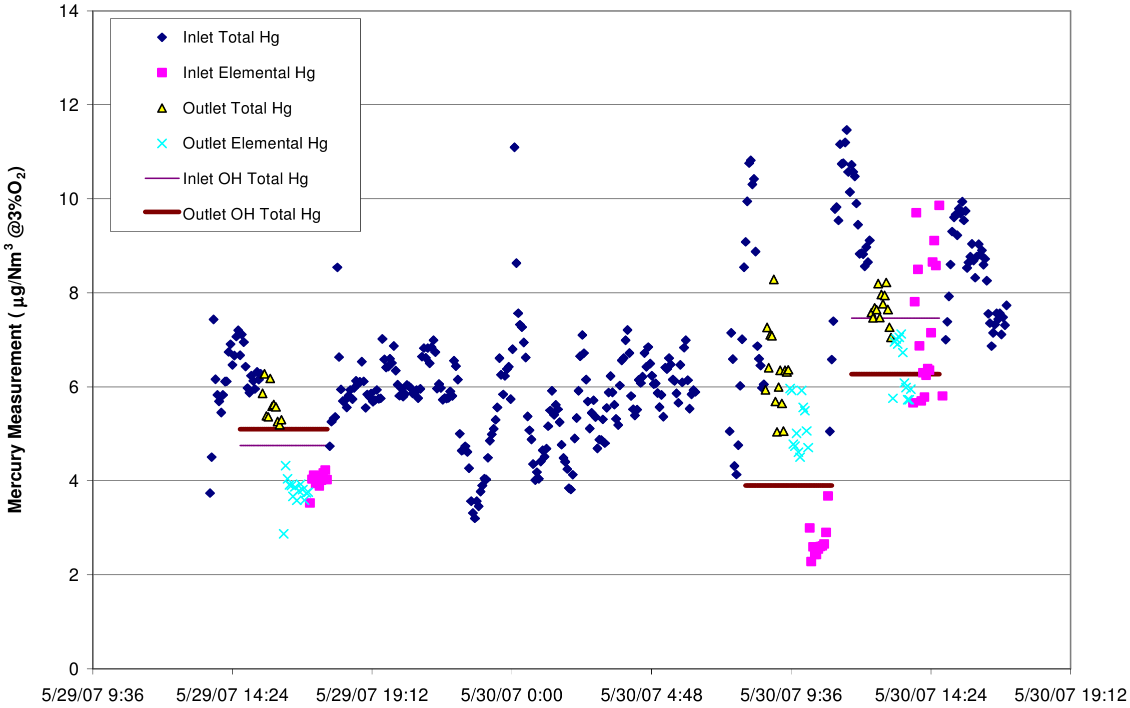


Figure 4-28. SCEM and Ontario Hydro Measurements across the MerCAP™ System at Plant Yates

Gold Substrate Characterization

The exposure of the gold-coated screens to saturated flue gas was found to result in apparent corrosion of and solid deposition onto the sorbent substrate surfaces. Upon inspecting the substrate arrays after the initial (attempted) test, the 2½-month continuous test (2006), and the 5-month continuous test (2007), it was discovered that many of the plates were fouled with a dark coating. An example of this coating is shown in Figure 4-29. In addition, corrosion and loss of the gold surfaces at the screen surface, as depicted in Figure 4-20, was also observed. These observations along with the correlating degradation in MerCAP™ mercury removal performance indicated that the gold-coated screen formulation was not robust enough to withstand the challenges of the corrosive saturated flue gas to which it was contacted.

Figure 4-29. Gold Substrates after One Month of Flue Gas Service (2006 test).

A number of the damaged sorbent screens were characterized to evaluate their surface properties. Samples were analyzed by scanning electron microscopy (SEM) coupled with energy dispersive X-ray spectroscopy (EDS) for chemical composition mapping. Results were compared to those of ‘fresh’ untreated gold-coated screens to determine the impacts of the flue gas exposure. Surface analyses were conducted at M&M Engineering (Austin, TX).

Figure 4-30 shows an SEM photograph of an untreated gold-coated screen sample. The fresh samples were relatively clean but (all) did contain some areas where carbon-containing deposits (black deposits in photo) were present. EPRI is continuing to investigate the nature of the various deposits that form on the gold sorbent surfaces. The light-colored gold appears to be coated in a relatively smooth fashion over parts of the screen. However, much of the coating appears rough, containing many defects present over much of the surface. Figure 4-31 shows a typical EDS scan for clean gold-coated screen. These analyses showed that the primary elements present in the surface region of the substrate were from the gold coating, the nickel pre-coating, and the stainless steel substrate.

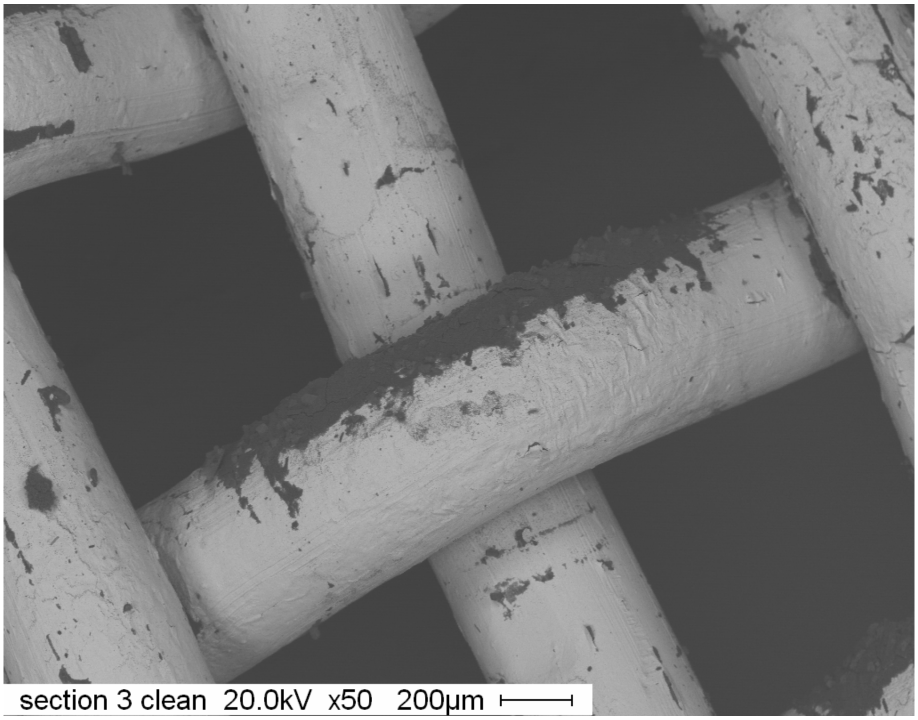


Figure 4-30. Scanning Electron Micrograph of Clean Gold Screen Surface.

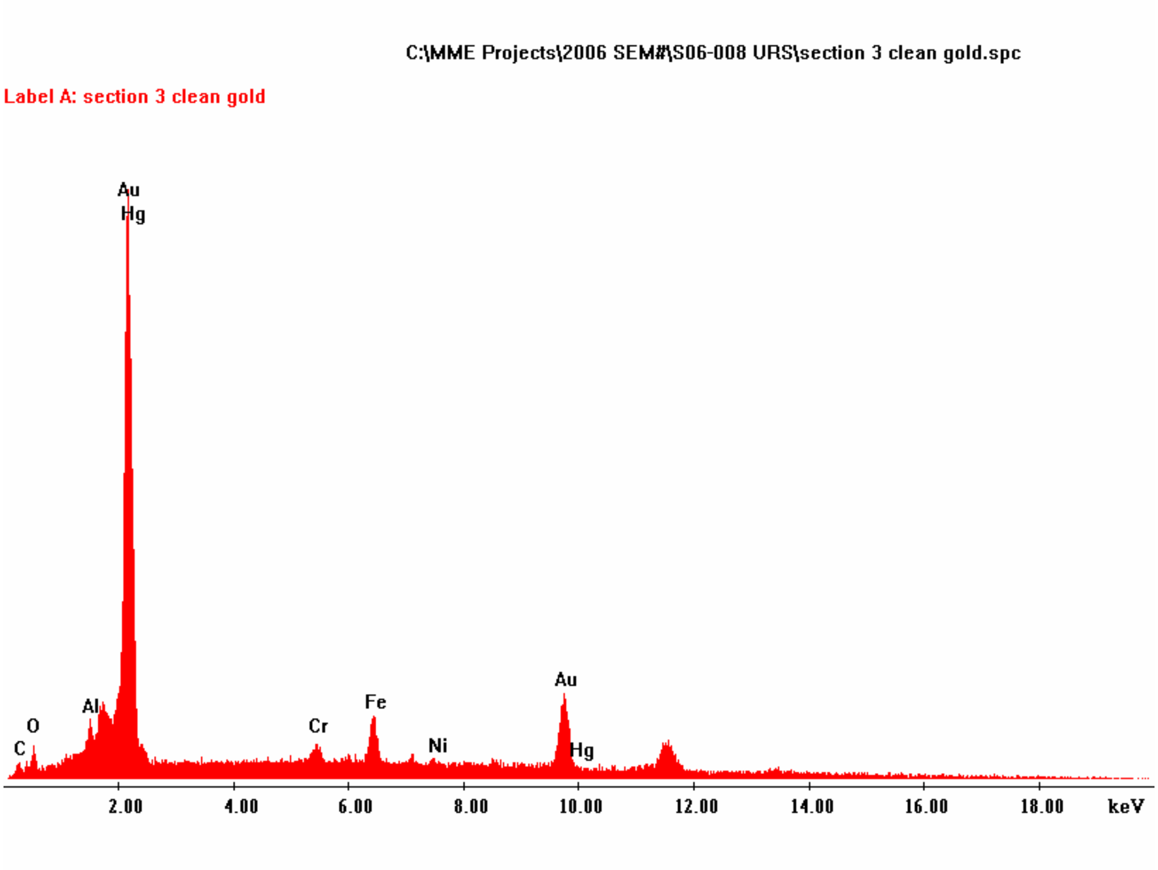


Figure 4-31. EDS Scan of Clean Gold Surface.

Figures 4-32 and 4-33 show SEM photographs of two sorbent samples obtained from screens possessing visible dark solid deposits. In both cases, the dark deposition appears to coat most of the gold-coated surface. Most of the lighter-colored gold is covered and much of what is present appears to be either elevated from the screen surface. It cannot be determined from these analyses if the dark deposition is covering gold material or replacing gold that was originally there. Some of the apparent gold material present in Figure 4-33 shows signs of flaking off from the bulk surface. The results observed with these two screens were typical of those observed with most treated screens evaluated.

Figure 4-34 shows results for an EDS scan of the screen sample shown in Figure 4-33. This sample showed a much lower concentration of gold, relative to other species, than with the fresh screen sample. This, along with the higher relative concentrations of iron (Fe), chromium (Cr), and nickel (Ni) in this sample, suggests a diminished gold coating present in the treated sample. This sample showed a high concentration of sulfur at the surface. This suggests that the gold reacted with either SO_2 in the flue gas or possibly with FGD byproduct emitted from the FGD absorber. In addition, trace levels of corrosive chlorine were also present in the treated sample. Relatively high oxygen levels were observed compared to untreated samples. This may be associated with the products of various metal corrosion reactions occurring at the surface or the presence of sulfur oxides at the gold surface. Fairly high levels of copper and manganese were also detected in the treated sample.

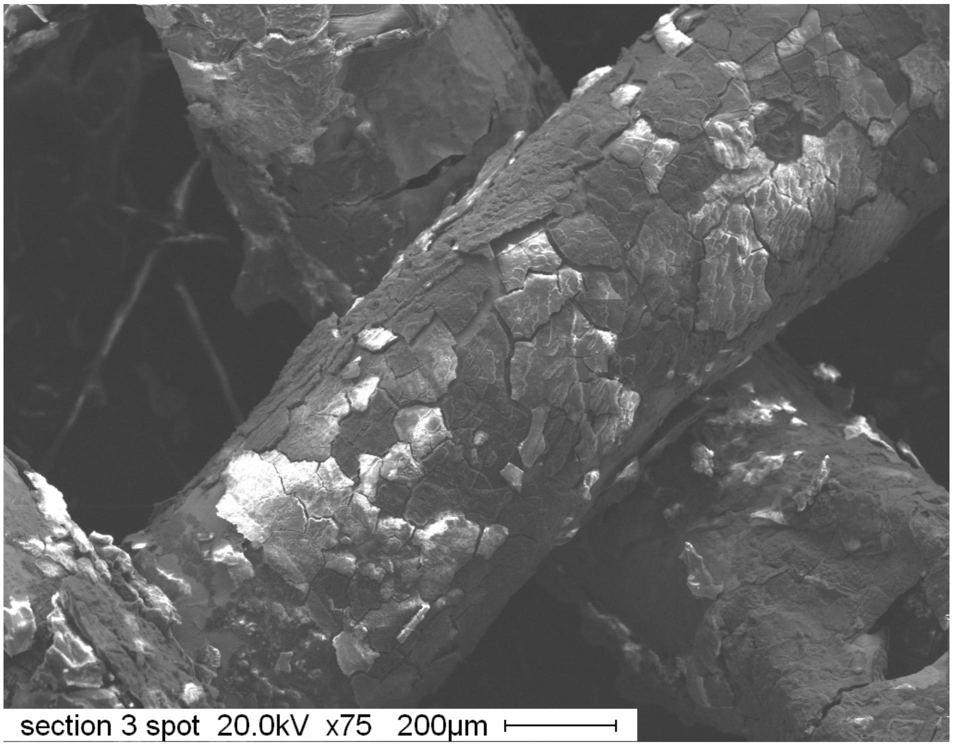


Figure 4-32. Scanning Electron Micrograph of Fouled Gold Screen Section.

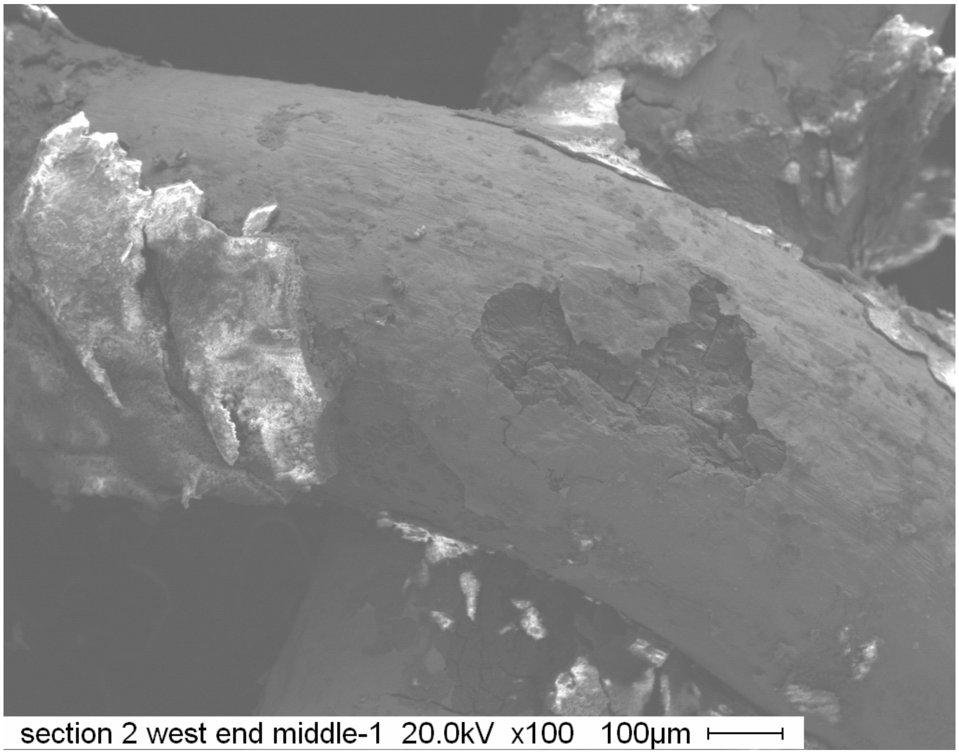


Figure 4-33. Gold Screen from Module 2

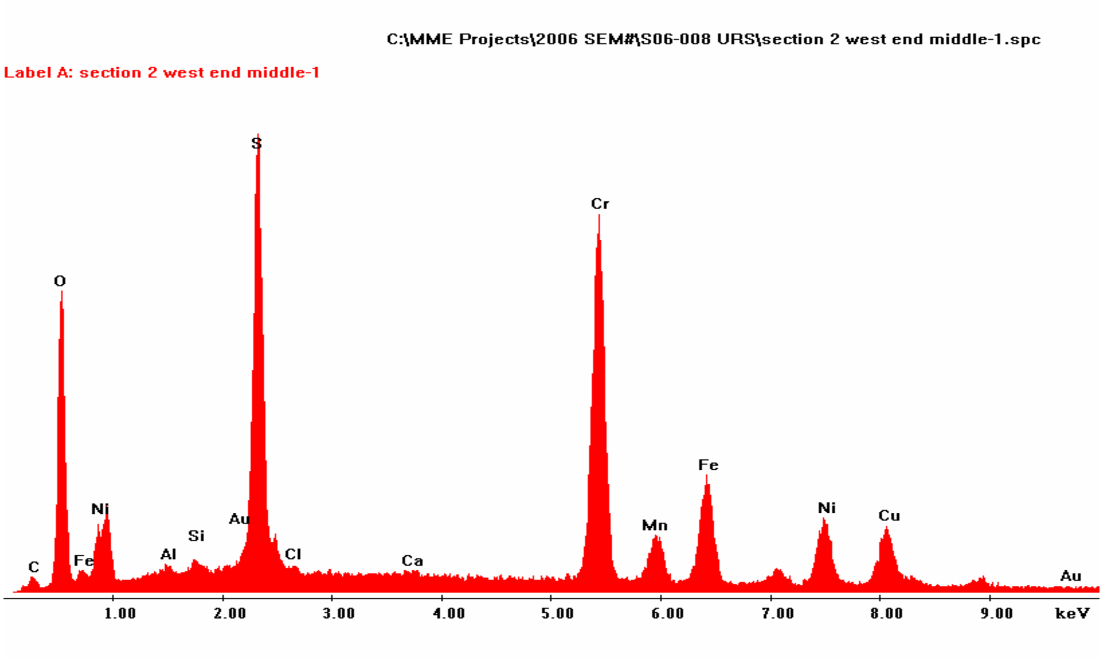


Figure 4-34. EDS Scan for Screen Pictured in Figure 4-33

Figure 4-35 shows an SEM photograph of a flue gas-treated screen that appeared relatively clean upon removing it from the reactor with the exception of one fairly small visibly discolored spot present. It is believed that this screen may be showing the first signs of the deposition and corrosion reactions that resulted in much of degradation observed in other screens. The photo in Figure 4-35 focuses on the dark area of the screen and indicates a dark layer of material depositing directly on the gold surface (i.e., the lighter material under the dark material. Figure 6 contains a photo of one discolored spot on a gold screen from module 3 that was otherwise mostly gold-colored.

Figure 4-36 shows the EDS scan for the surface shown in Figure 4-35. Although the gold surface appears to be in tact below the dark-colored deposition, the relative size of the gold peak is small compared to the peaks for the substrate material (Ni, Fe, Cr) when comparing this sample to an untreated screen. The sample also contains relatively high levels of sulfur and oxygen with smaller amounts of silica and chlorine. This suggests the presence of fly ash and possibly FGD scrubber carry-over materials present at the screen surface. The fact that the relative levels of stainless steel component species and nickel pre-cursor are much higher compared to gold in this sample (compared to clean gold) suggests that either the gold layer is reduced with the presence of the deposition material or that the substrate material is corroded and/or diffuses into the gold. The presence of copper in the treated samples (Figure 4-34 and 4-36) is surprising, as the source is not known; copper is not part of the precursor material or the gold coating procedure. This suggests that the gold surface may react with copper present in flue gas.

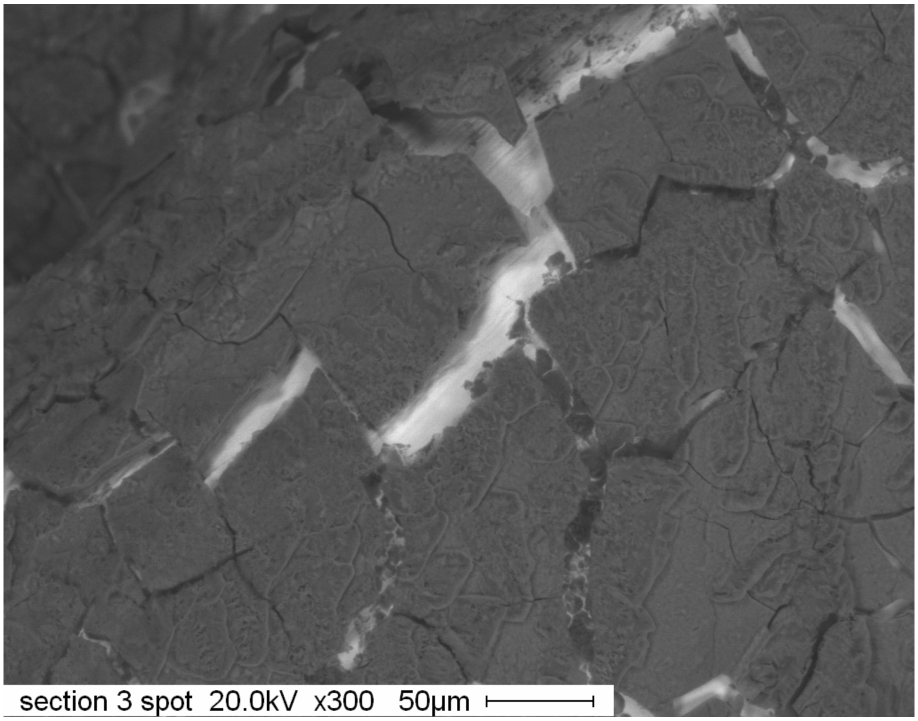


Figure 4-35. SEM Photo of a Discolored Spot on a Relatively Clean Screen

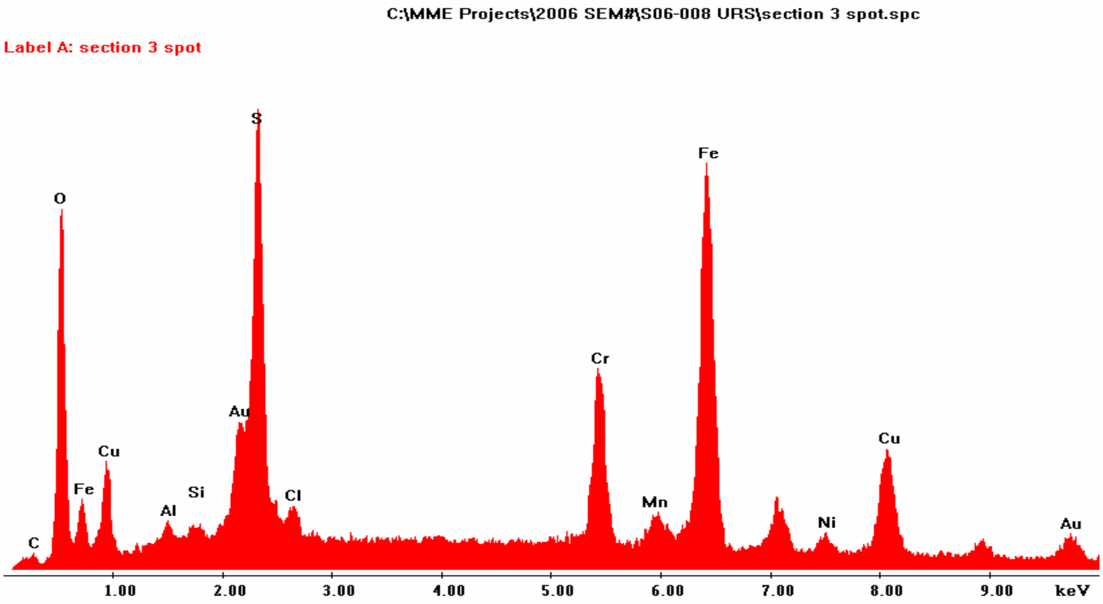


Figure 4-36. EDS Scan for Screen Pictured in Figure 4-35

Additional surface analysis results for flue gas treated gold-coated screens are provided in the appendix to this report. Although the results did not provide sufficient information to determine the exact cause of the sorbent screen degradation mechanisms, they did confirm both the presence of foreign materials on the screens, a relative decrease in the amount of gold at the surface, and corrosion of the stainless steel substrate material. This information provides additional validation to the premise that the gold-coated screens are not robust enough to stand up to the corrosive environment provided by saturated flue gas.

EPRI continues to evaluate the various mechanisms involved with the interactions between gold surfaces and flue gas.

Process Costs

Short-term exposure tests at various field sites showed performance similar to those theoretically predicted and observed in laboratory testing; however field testing at Sites 1 and 2 indicated that actual mercury removal is 60-80% less than expected, based on mass transfer considerations. The following is a cost estimate for the mercury amalgamating metal (such as gold used in this projection) needed for mercury removal by parallel metal-coated plates sized for 80% mercury removal. This estimate has been scaled up from original cost estimates to account for the larger amount of gold necessary to achieve this removal.

For a 500 MW plant and a flue gas rate of 25 ft/sec (7.6 m/s) in the duct, plates 60 feet long and spaced 0.5 inches (1.3 cm) apart are needed. The housing for this unit would be approximately 20 feet tall by 75 feet wide. Pressure drop across the 0.5 inch (1.3 cm) spaced plates at duct velocity is expected to be ~15 inches of water (3.7 kPa). If the same gold coating used in the pilot demonstration is used in the full scale application, approximately 18,000 troy ounces of gold will be required for a 0.3-μm thick coating on these plates. With the assumption that the plates can be regenerated and reused, the cost of the gold alone will be ~$15,660,000 (at $870 per ounce). This does not include costs for the metal screen or design and construction of the reactor housing. The total cost for a full scale MerCAP system could be in the range of $30-$50 million dollars. By comparison, cost estimates for installation of other mercury control technologies such as ACI or a fixed carbon bed are in the range of $4-$20 million dollars. Site 1 results indicated relatively short lifetime (e.g., <6 months) for the gold based sorbent when configured downstream of a wet FGD absorber. Considering the high costs required to charge a MerCAP™ reactor with gold-based substrates, this lifetime does not appear to be feasible for a full-scale implementation of this technology.

Project Schedule and Delays

The MerCAP™ project schedule was subjected to a number of delays over the life of the Site 2 project. Figure 4-37 contains a timeline of key events from the originally anticipated start date at the end of 2004 until the final completion of field work in September 2007.

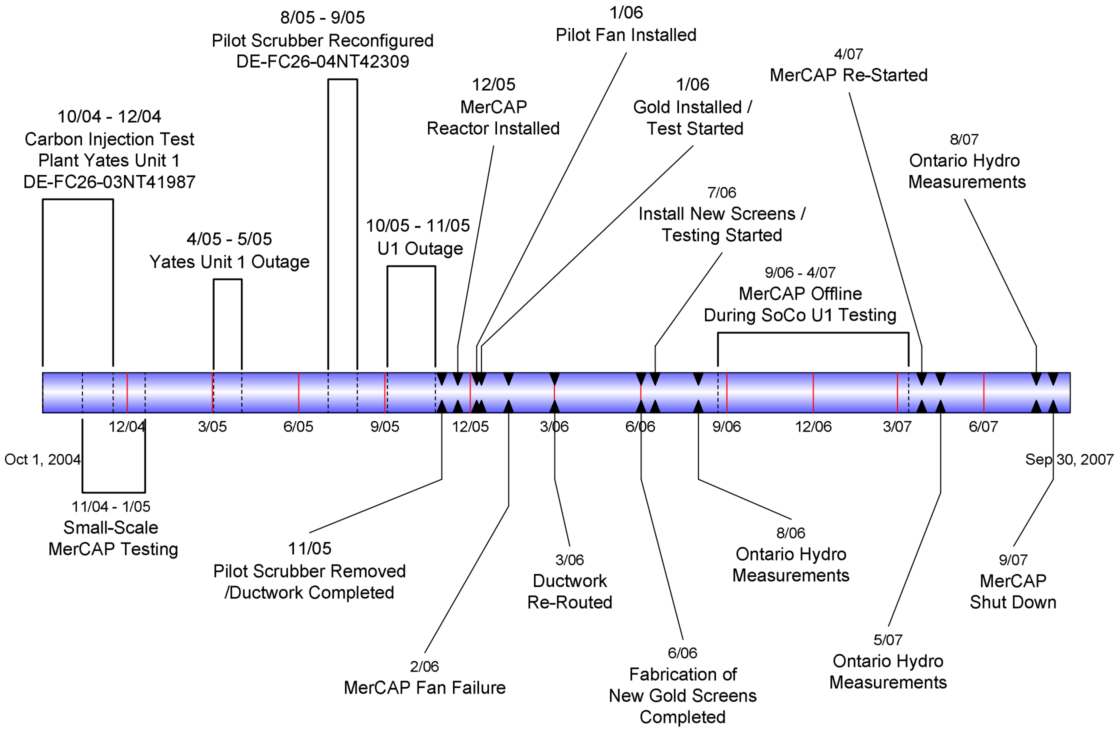


Figure 4-37. MerCAP™ Project Timeline

When this project was originally proposed, it was anticipated that the testing at Site 2 would begin at the end of 2004; however this was initially delayed by a competing DOE activated carbon injection program conducted at Plant Yates Unit 1 from October to December 2004 (i.e., DE-FC26-03NT41989). At that time, it was decided that an EPRI sponsored small-scale slipstream MerCAP™ reactor would be installed in the Yates Unit 1 stack. This testing was described in detail earlier in this report. A series of outages and another competing pilot scrubber test at Plant Yates further delayed the program until late in 2005.

The original intent of this program was to install the MerCAP™ system in a pre-existing pilot scrubber owned by Southern Company and installed on Plant Yates Unit 1. In 2005 Southern Company decided to move this scrubber away from Yates and instead build a slipstream with a fan that would be suitable for the MerCAP™ pilot unit. The ductwork for this system was installed in November 2005, with the installation of the MerCAP™ reactor housing and fan occurring in December 2005 and January 2006, respectively. Shortly after this work was completed the gold substrates were loaded into the reactor and the system was started in January 2006.

The MerCAP™ reactor experienced a catastrophic failure after approximately 4 weeks after the start of testing that lead to backward flow of highly acidic flue gas and eventual disintegrated the gold substrates. As described earlier in this report, the pilot fan was pushing against a large pressure rise at the inlet of the Chiyoda JBR. When the fan failed, the cooled flue gas from downstream of the full-scale water quench backed up through the MerCAP™ system. Because the post-quench flue gas was below the acid dew point, the water that condensed on the gold substrates was highly acidic and caused them to corrode immediately. The ductwork was re-routed in March of 2006 to eliminate the pressure rise by both drawing and returning flue gas from downstream of the JBR scrubber.

A new set of substrates were manufactured in June 2006 and were installed and tested starting in July of 2007. The test was temporarily suspended in September 2007 while an unrelated full-scale test program was conducted at Plant Yates by the host utility. The decision to suspend the MerCAP™ test was due to the possibility that the full-scale test at the plant might influence the results. The project team decided to isolate the MerCAP™ until this program was completed in April 2007 at which time the program was restarted. The field testing was finally concluded in September 2007 at which point the MerCAP™ system was taken off line and disassembled. The reactor housing and associated hardware was returned to the URS labs in Austin, TX for storage.

5.0 Carbon-Based MerCAP™ Testing

5.1 Introduction

After the Site 1 and Site 2 gold MerCAP™ tests were completed, an initial engineering analysis showed that the gold-based MerCAP™ technology would not be economically competitive compared to other mercury control processes, such as ACI or mercury oxidation technologies. This was primarily due to the relatively low mercury removals achieved during long-term testing of the technology, along with the increasing cost of the gold that doubled since this program was originally proposed. The project team determined that lower-cost alternate materials should be evaluated in the fixed-structure MerCAP™ configuration. Activated carbon was chosen because of its proven ability to remove mercury and relatively low cost. There were several stages in the development of this technology including slipstream tests in actual flue gas, laboratory evaluations, modeling and design of the large-scale pilot system, and finally pilot testing at a utility host site. Much of the development work was funded by EPRI and Southern Company in related projects (sometimes identified by the EPRI trademark name MercScreen™) that culminated in the pilot-scale carbon-based MerCAP™ program at Southern Company's Plant Miller conducted under this program.

5.2 Slipstream Testing

A diagram of the slipstream test reactor is illustrated in Figure 5-1. The same slipstream apparatus was installed and tested at Southern Company's Georgia Power Plant Yates and Alabama Power Plant Miller. The reactor was configured as a set of three beds placed in series with sample ports between each bed for mercury and pressure drop measurements. The bed depth was altered by pouring in different volumes of carbon material. The system was also equipped with a quartz wool pre-filter to eliminate some of the incoming fly ash. This filter was removed for some of the tests in order to evaluate the impact of the entire ash loading on adsorption and pressure drop. A blower was used to provide the motive force with a venturi to measure flue gas flow through the system. The gas flow rate was intended to simulate those typically found in an ESP, therefore a linear velocity of 3-6 ft/s was targeted.

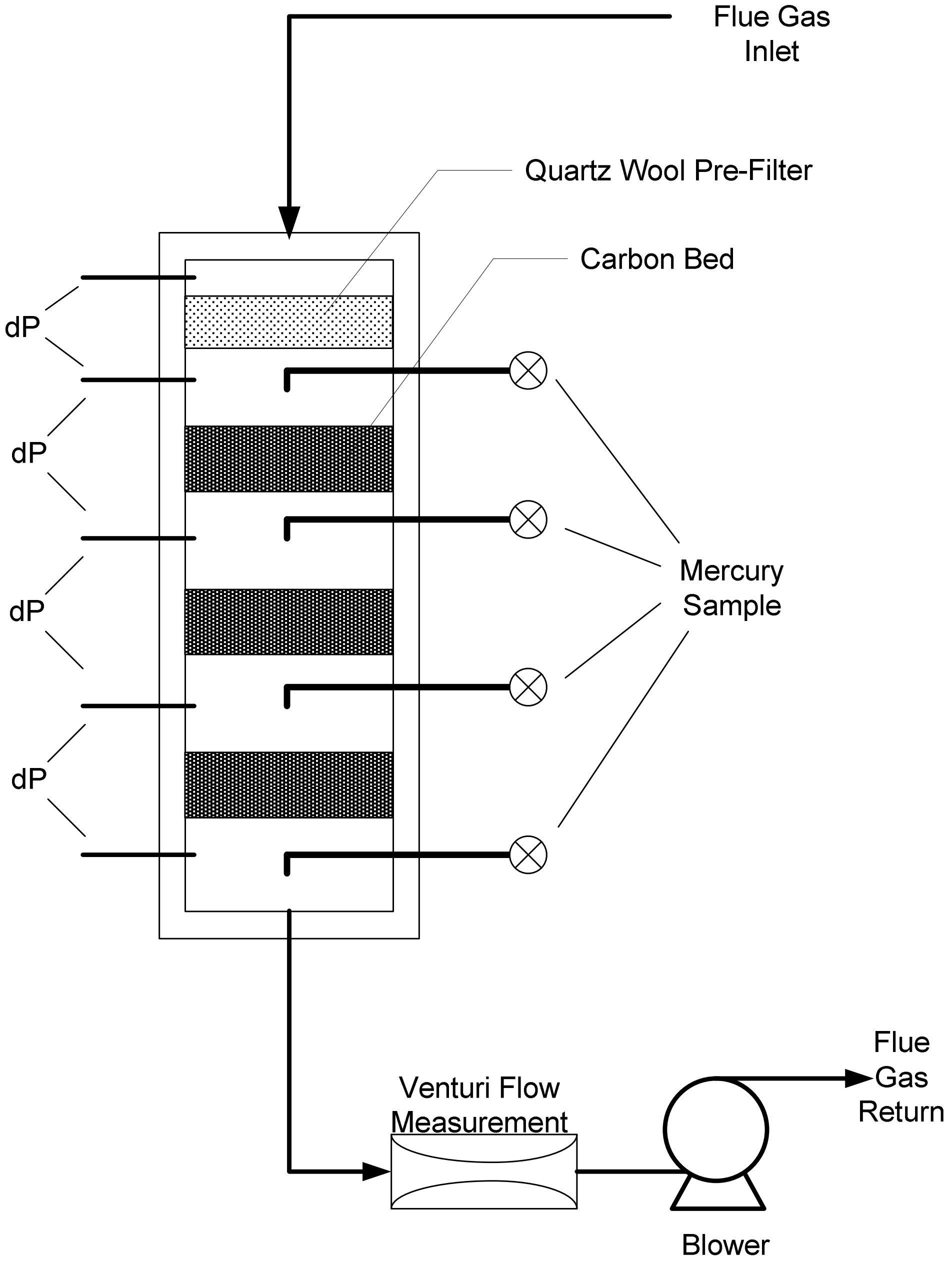


Figure 5-1. Slipstream Test Reactor.

5.2.1 Test Methods

An EPRI mercury semi-continuous mercury emission monitor (SCEM) was used during this program to monitor vapor-phase mercury concentrations in the flue gas. The SCEM used is a research-oriented instrument that employs wet-chemistry impinger-based sample conditioning equipment. The mercury instrument consists of a cold vapor atomic absorbance (CVAA) spectrometer coupled with a gold amalgamation system (Au-CVAA). The SCEM was calibrated daily using elemental vapor-phase mercury (EVM).

Although it is very difficult to transport non-EVM in sampling lines, EVM (Hg^0) can be transported without significant problems. Since the Au-CVAAS measures mercury by using the distinct lines of the UV absorption characteristic of Hg^0, the non-elemental fraction is either converted to EVM (for total mercury measurement) or removed (for measurement of the elemental fraction) near the sample extraction point. This minimizes any losses due to the sampling system.

For total vapor-phase mercury measurements, all non-elemental vapor-phase mercury in the flue gas must be converted to EVM. A solution of stannous chloride in hydrochloric acid is used to convert Hg^{2+} to Hg^0. The solution is mixed as prescribed in the draft Ontario Hydro Method for manual mercury measurements. To measure elemental mercury, an impinger of potassium chloride (KCl) solution mixed as prescribed by the draft Ontario Hydro Method replaces the stannous chloride solution to capture oxidized mercury. The oxidized fraction of the vapor-phase mercury concentration (OVM or Hg^{2+}) is computed by difference.

5.2.2 Slipstream Testing – Plant Yates

The slipstream MerCAP™/MercScreen™ system was set up at Southern Company's Plant Yates Unit 1. A description of Unit 1 is provided in Section 3.4. The MercScreen™ unit was located downstream of the ESP, but upstream of the FGD system. The flue gas temperature in the reactor was maintained at 280°F (130°C) which is approximately the same as the gas temperature in the duct at this location. A series of parametric tests were performed to evaluate several different sorbents for mercury removal, mercury oxidation, and pressure drop. Table 5-1 contains a list of the carbon sorbents tested at Plant Yates. The sorbents were supplied as pellets (formed from activated carbon powder with binders) or granules (granular activated carbon) by various carbon manufacturers.

Table 5-1. Sorbents Tested at Plant Yates.

Test #	Sorbent Name	Sorbent Type	Gas Velocity (ft/s)	Bed 1 Depth (in.)	Bed 2 Depth (in.)	Bed 3 Depth (in.)
1	Calgon WS-465	4 mm pellets	5	1	1.5	2
2	Calgon WS-465	4 mm pellets	5	2	1	1
3	Norit RB4C	4 mm pellets	5	2	1	-
4	Norit Darco Hg	4x10 granules	5	1	1	-
5	Norit Darco Hg-LH	4x10 granules	5	1	1	-
6	Norit Darco Hg	4x10 granules	3	2	2	-
7	Norit Darco Hg	4x10 granules	5	2	2	-

Mercury Adsorption

Flue gas measurements of total mercury were performed at the inlet and outlet of each bed to evaluate mercury removal performance. The test was considered complete when the sorbent was removing less than approximately 20% of the inlet mercury. Figure 5-2 shows the mercury removal curve for two tests conducted with Norit Darco Hg granules. This plot is representative of all of the tests in that the mercury removal across each bed started at or near 100% and then began showing breakthrough within the first 10-20 hours. The bed depth of each cup in Figure 5-2 was 2 inches. The initial adsorption rate was the same for each test regardless of gas velocity; however, the overall duration of the test at 5 ft/s was shorter compared to the test at the lower velocity. This is most likely due to the shorter residence time in the bed at the higher velocity.

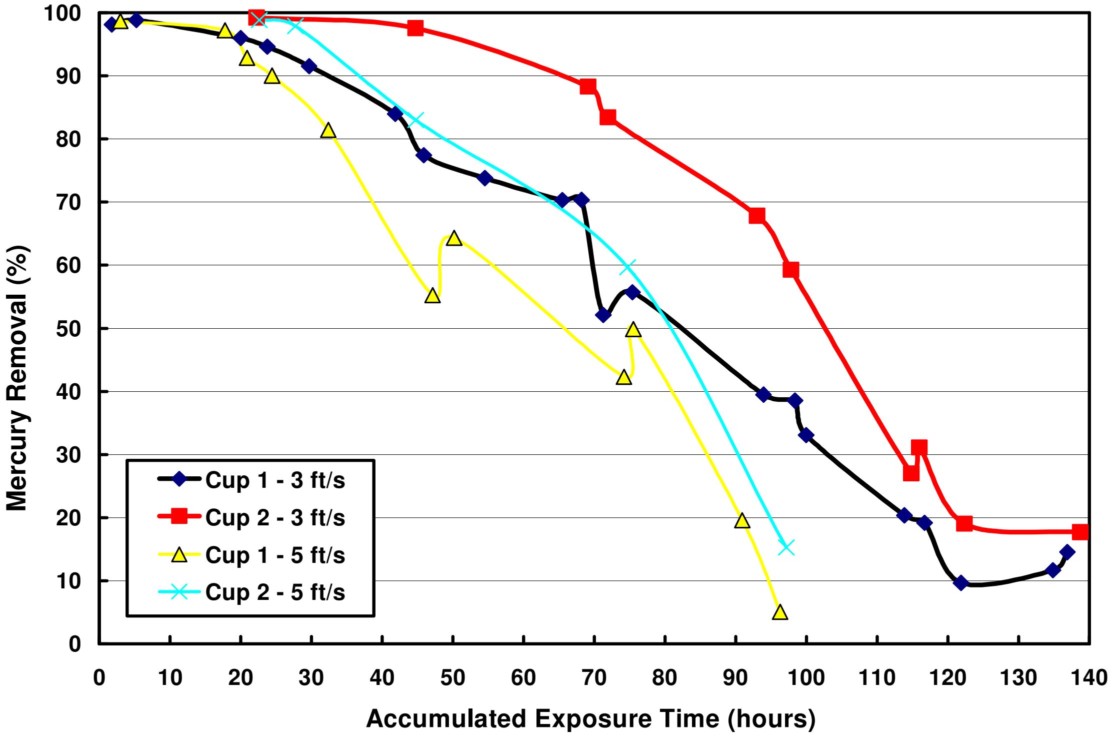


Figure 5-2. Mercury Removal by Norit Darco Hg Granules; Plant Yates Slipstream Tests (2-inch bed depth)

Pressure Drop

A fixed carbon bed would be expected to remove at least some of the particulate matter present in the flue gas. The build-up of ash on the bed would be expected to increase the pressure drop across the reactor. An appreciable increase in pressure drop could limit the effective lifetime of the bed. Thus, pressure drop was monitored across the slipstream beds during each test. Figure 5-3 shows a comparison of measured pressure drop across the beds for granular and pelletized sorbents. Plant Yates Unit 1 is equipped with a relatively small ESP (SCA=173 ft^2/1000 acfm), therefore a larger amount of fly ash was collected on the fixed beds at Yates than might be expected at a plant that has a larger

ESP (i.e., with greater particulate collection efficiency). The starting pressure drop across the granulated bed was approximately 1.4 in. H_2O/inch of bed depth at a flue gas velocity of 5 ft/s. With the excess fly ash captured in the bed, the pressure drop across the granulated bed increased rapidly to approximately 10 in. H_2O, whereas the pelletized bed gained only a couple of inches of water for the same duration.

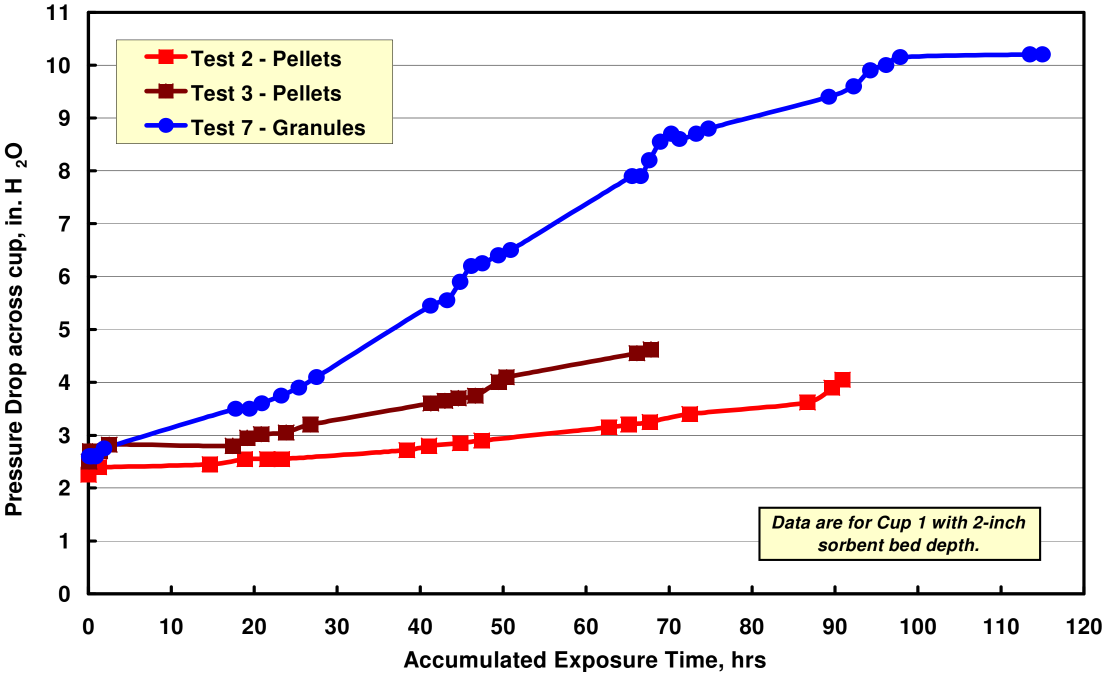


Figure 5-3. Pressure Drop Across Granular Sorbents During Mercury Removal Tests

Mercury Oxidation

The oxidation of the elemental mercury across the carbon beds was high throughout each test. Even though the inlet mercury was already approximately 50-60% oxidized, the mercury exiting the fixed beds was 90-99% oxidized. This represents an oxidation of approximately 70-90% of the elemental mercury present at the inlet. Due to time constraints, the oxidation was only measured while the carbon material was still adsorbing mercury. Future tests will evaluate the ability of the carbon to oxidize elemental mercury beyond the effective mercury adsorption period.

5.2.3 Slipstream Testing – Plant Miller

The slipstream MerCAP™/MercScreen™ system that was used at Plant Yates was transported to Southern Company's Plant Miller where it was set up on a pre-existing pilot COHPAC™ II system installed on Miller Unit 3. Plant Miller fires PRB coal and is equipped with cold-side ESPs. The pilot COHPAC™ II unit draws flue gas from the ESP inlet and the air heater inlet, and is equipped with its own ESP for particulate removal. The fabric filters from the baghouse section of the COHPAC™ II had been removed, thus making the pilot ESP the only form of particulate control upstream of the MercScreen™ system. In order to maintain consistency with the testing at Plant Yates, the flue gas temperature in the COHPAC II and MercScreen™ reactor was maintained at 280°F (138°C). A series of parametric tests were performed to evaluate several different sorbents for mercury removal, mercury oxidation, and pressure drop. Table 5-2 lists the carbon sorbents tested at Plant Miller.

Table 5-2. Sorbents Tested at Plant Miller

Test #	Sorbent Name	Sorbent Type	Gas Velocity (ft/s)	Bed 1 Depth (in.)	Bed 2 Depth (in.)	Bed 3 Depth (in.)
1	Norit Darco Hg	4x10 granules	3	2	2	-
2	Norit Darco Hg-LH	4x10 granules	3	2	2	2
3	Norit Sorbonorit	4 mm pellets	5	2	2	2
4	Norit Darco Hg-LH	4x10 granules	5	2	2	2
5	Norit Darco Hg	4x10 granules	5	2	2	2
6	Norit Sorbonorit	4 mm pellets	3	2	2	2

Sorbent Mercury Adsorption

Mercury adsorption tests were conducted at Plant Miller in an identical fashion as the tests at Plant Yates. The granular Norit Darco Hg and Darco Hg-LH materials and the 4-mm pelletized Sorbonorit material were tested at flue gas velocities of 3 and 5 ft/s. Figure 5-4 contains a comparison plot of data collected at Yates and Miller at these flow rates using Darco Hg. This sorbent performed slightly better, with respect to mercury capture, at Plant Miller than at Plant Yates. At each gas velocity tested, the Darco Hg removed a greater fraction of the flue gas mercury in the PRB coal-derived flue gas. This could be explained by higher levels of inhibiting flue gas constituents, such as SO_2 and SO_3, which are present in bituminous-derived flue gas.

Figure 5-5 shows a comparison of the chemically treated Darco Hg-LH sorbent and the untreated Darco Hg sorbent tested at Plant Miller. At a flue gas velocity of 3 ft/s, little improvement in mercury adsorption was observed with the treated sorbent. However, the Darco Hg-LH showed much improved performance at a gas velocity of 5 ft/s compared to the untreated carbon. This improved performance is consistent with previous data collected using treated sorbents in PRB derived flue gas. The lack of improvement using Darco Hg-LH at 3 ft/s may suggest that a treated sorbent may be most useful when the contact or residence time is not sufficient. Overall, the data appeared to show that a 2-inch carbon bed may be able to maintain mercury removals of >90% at typical ESP gas velocities for more than 2 days of operation.

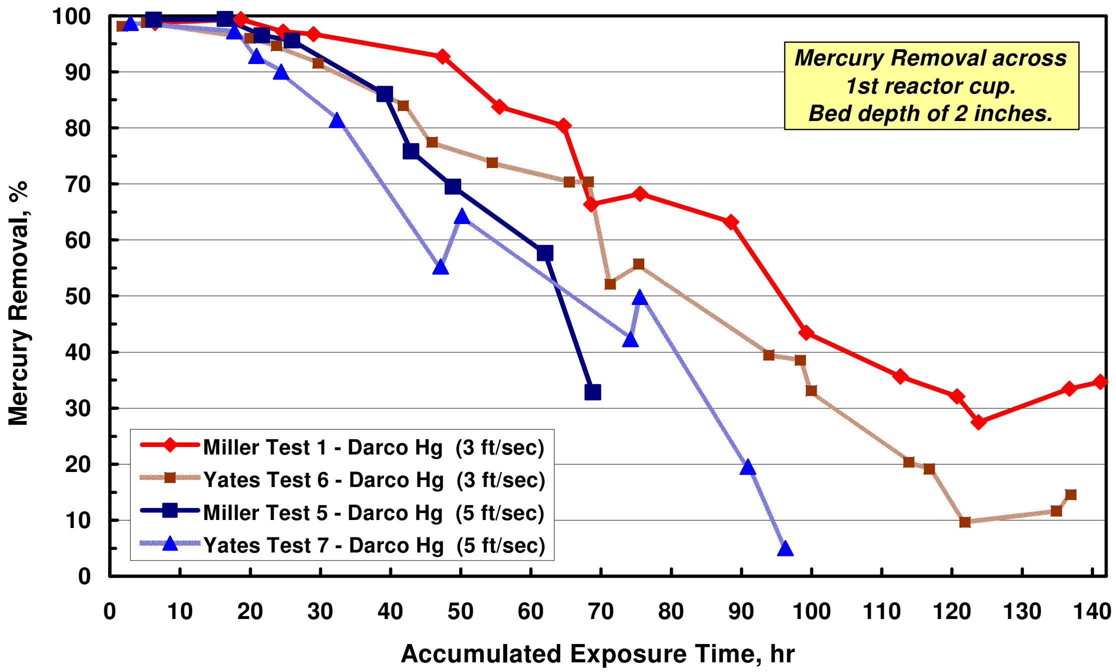


Figure 5-4. Mercury Removal by Norit Darco Hg at Plants Miller and Yates

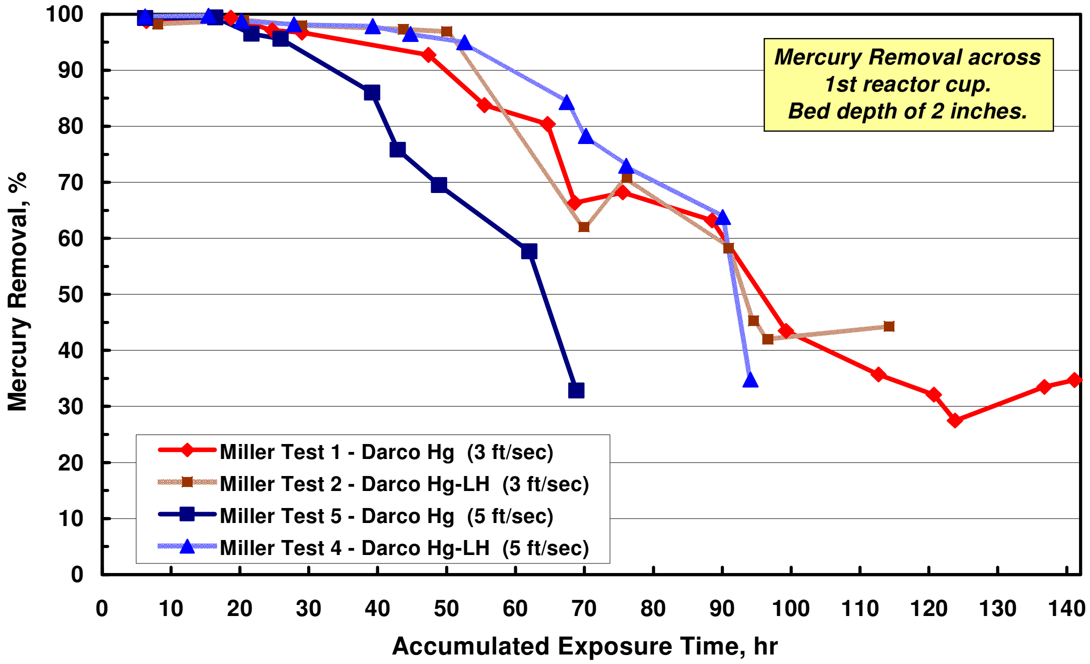


Figure 5-5. Comparison of Norit Darco Hg and Darco Hg-LH Performance at Plant Miller

Pressure Drop

The pressure drop measured across the sorbent beds at Plant Miller was similar to that measured at Plant Yates. Figure 5-6 contains a comparison plot of granules and 4-mm pellets at gas velocities of 3 and 5 ft/s. As with the tests at Plant Yates, the pressure drop of the granulated material increased appreciably over time as fly ash entered the system, whereas the pressure drop across the pellets remained relatively stable. Based on the pressure drop results it was apparent that the particulate loading at the outlet of the pilot COHPAC™ II at Miller was lower than at Yates, thus causing the pressure drops at Miller to increase more slowly than the tests conducted at Yates.

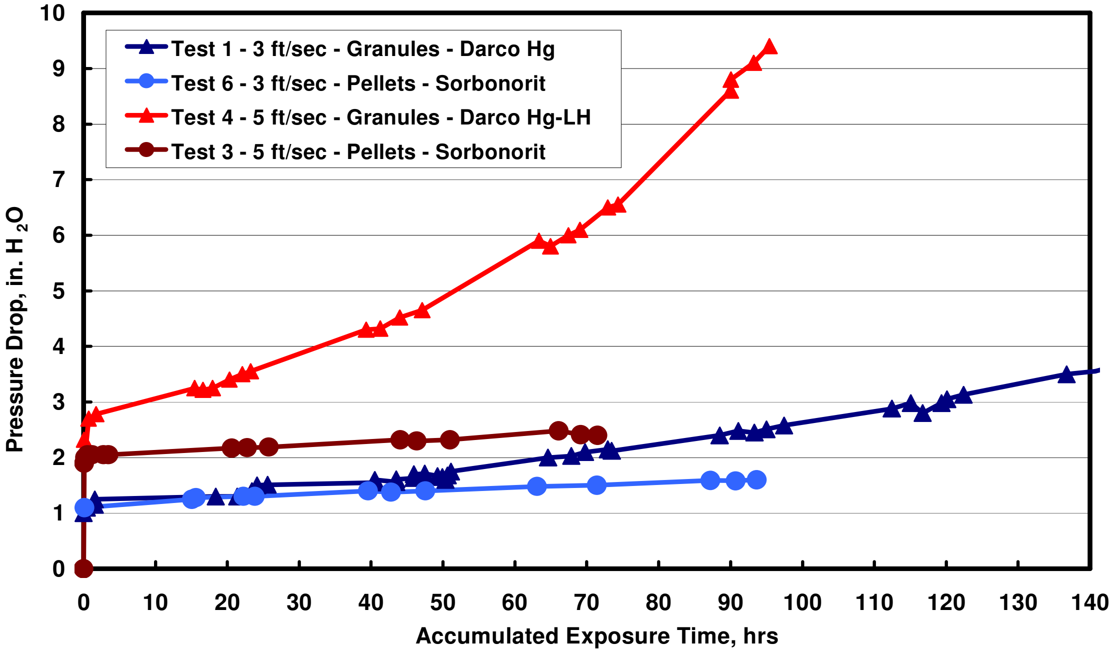


Figure 5-6. Pressure Drop across Pellets and Granules at Plant Miller (2-inch beds)

Mercury Oxidation

Measurements were made to characterize flue gas mercury speciation at the inlet and outlet of the fixed carbon reactor. Inlet mercury oxidation values at Plant Miller were generally less than 20%, typical of a PRB-derived flue gas. Figure 5-7 shows a comparison of mercury oxidation for the tests at Plant Miller, as well as the oxidation measured during two tests at Plant Yates. Over 80% of the elemental mercury was oxidized across the carbon beds for all sorbents tested; values were typically greater than 90%. These high levels were maintained for periods greater than 60 hours. Recall that mercury breakthrough across the carbons was generally observed after 20 – 40 hours of run time. This indicates that the mercury exiting the carbon bed was present primarily in an oxidized form. The extent of mercury oxidation decreased for some sorbents as flue gas exposure times increased beyond 60 hours. The Norit Sorbonorit and the Darco Hg-LH were able to maintain oxidation levels greater than 97% throughout the duration of their respective tests, however.

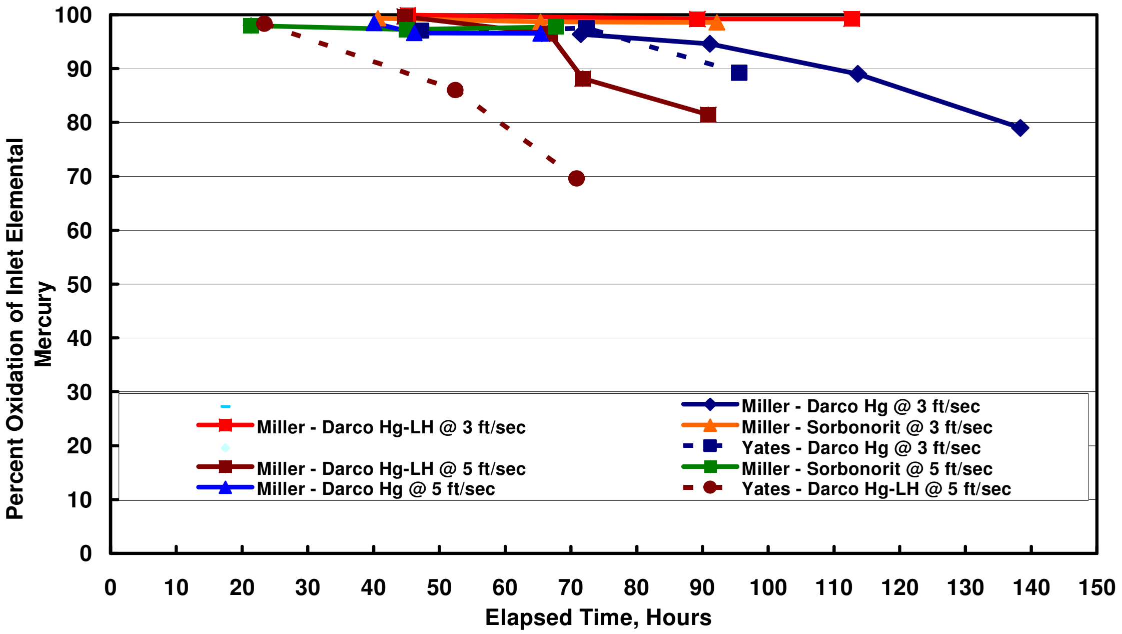


Figure 5-7. Elemental Mercury Oxidation by Mercury Sorbents at Plant Miller

5.3 Laboratory Testing

Laboratory tests were conducted at URS’s Austin Mercury Sorbent Laboratories to evaluate potential carbon materials for testing in the pilot reactor. These tests were sponsored by EPRI and used an EPRI bench scale apparatus to evaluate mercury adsorption across the carbon sorbents. A diagram of the test apparatus appears in Figure 5-8. A simulated flue gas is prepared by mixing known volumes of various reagent gas streams. Moisture is added to the reaction gas by flowing a known volume of nitrogen gas through a temperature-controlled saturator. Mercury is added to the gas by flowing a nitrogen carrier stream through a temperature-controlled permeation chamber containing the desired mercury species; elemental mercury was added during these tests. Tests were conducted in a simulated PRB flue gas intended to mimic the expected conditions at Plant Miller. The test conditions are listed in Table 5-3.

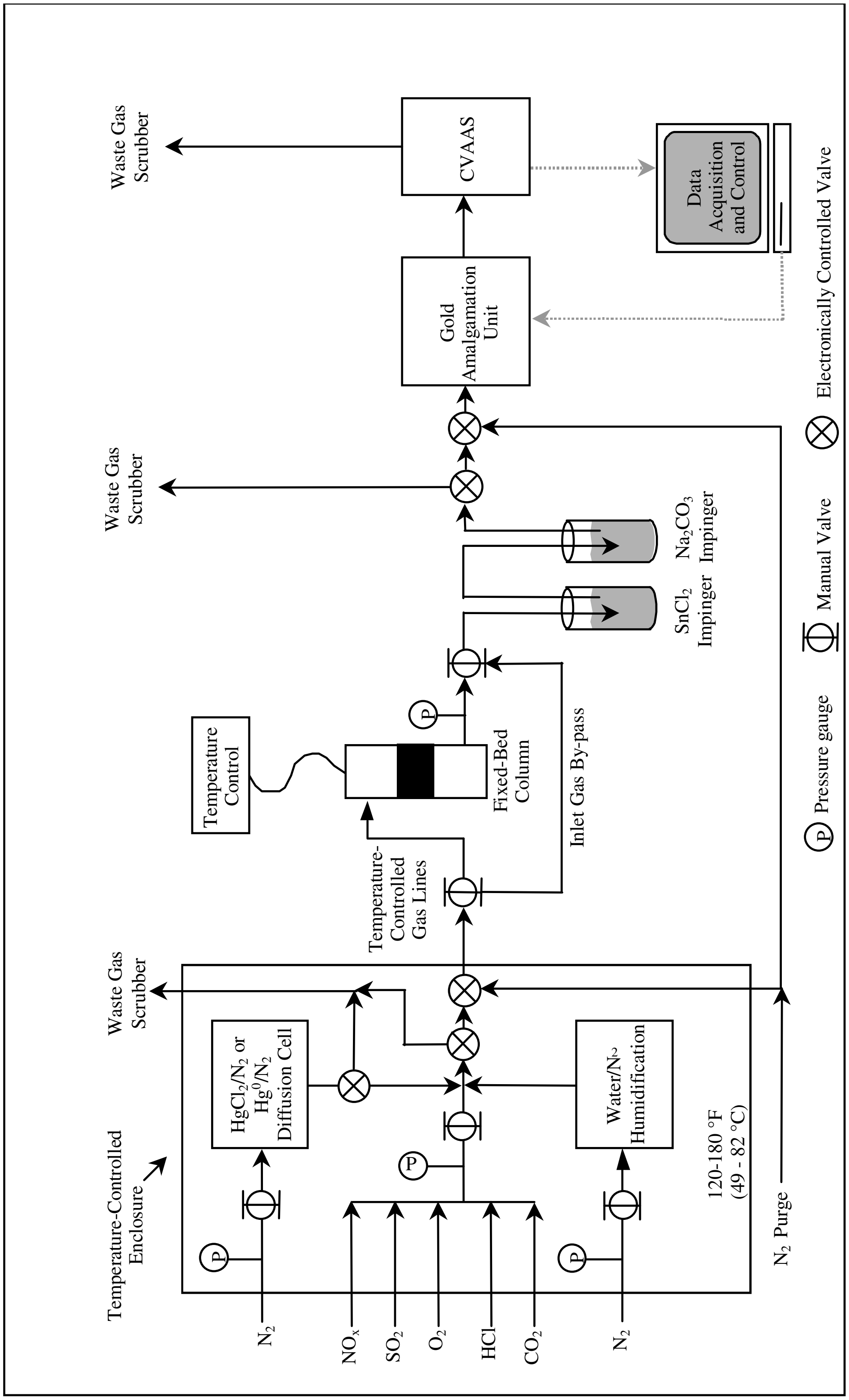


Figure 5-8. EPRI Bench Scale Apparatus

To perform the mercury adsorption tests, a known mass of the pelletized or granular material was loaded into a glass column and heated to the desired temperature (300°F [149°C]; no flow) for at least 30 minutes. During this period, the simulated flue gas was measured for "inlet" mercury concentration. Tests were started by flowing simulated flue gas horizontally through the sorbent bed at a flow rate of 46 L/min (actual flow rate at 75°F). This flue gas flow rate was chosen to create a gas velocity in the column equal to 5 ft/s. The effluent gas stream flowed through heated lines to a semi-continuous mercury analyzer for analysis. The mercury analyzer has been described in previously in this report. The inlet and outlet flue gas streams are plumbed into the analyzer such that the analyzer can switch streams at regular intervals in order to measure both concentrations semi-continuously throughout the test.

Adsorption tests were allowed to proceed until adsorption equilibrium was reached. Figure 5-9 contains a representative breakthrough curve for the laboratory tests. The percent breakthrough is determined as a function of time by normalizing the measured mercury concentration at the outlet of the sorbent bed to the inlet mercury concentration. The area between the breakthrough curve and 100% breakthrough represents the total mass of mercury adsorbed as a function of time. The adsorption capacity of the sorbent (µg Hg adsorbed/g sorbent) at time *t* is determined by summing the total mass of mercury adsorbed through time *t* (area above the breakthrough curve) and dividing by the sorbent mass. The initial breakthrough capacity is defined at the time when mercury is first detected at the outlet; this value is generally only determined when initial breakthroughs of less than 5% are achieved. The 100% breakthrough (equilibrium) capacity is defined at the time when the outlet mercury concentration is first equal to the inlet concentration.

In the case that the equilibrium capacity is not reached within several days, but a trend toward breakthrough is established, the breakthrough curve can be extrapolated to the point where the outlet mercury concentration equals the inlet concentration. The equilibrium adsorption capacity can then be calculated by integrating the curves to determine the theoretical mass of mercury that would have been adsorbed on the sorbent had it been left to run to completion. This was the case with the Carbon Activated 4-mm pellets and the Norit Darco Hg-LH 4x8 granules.

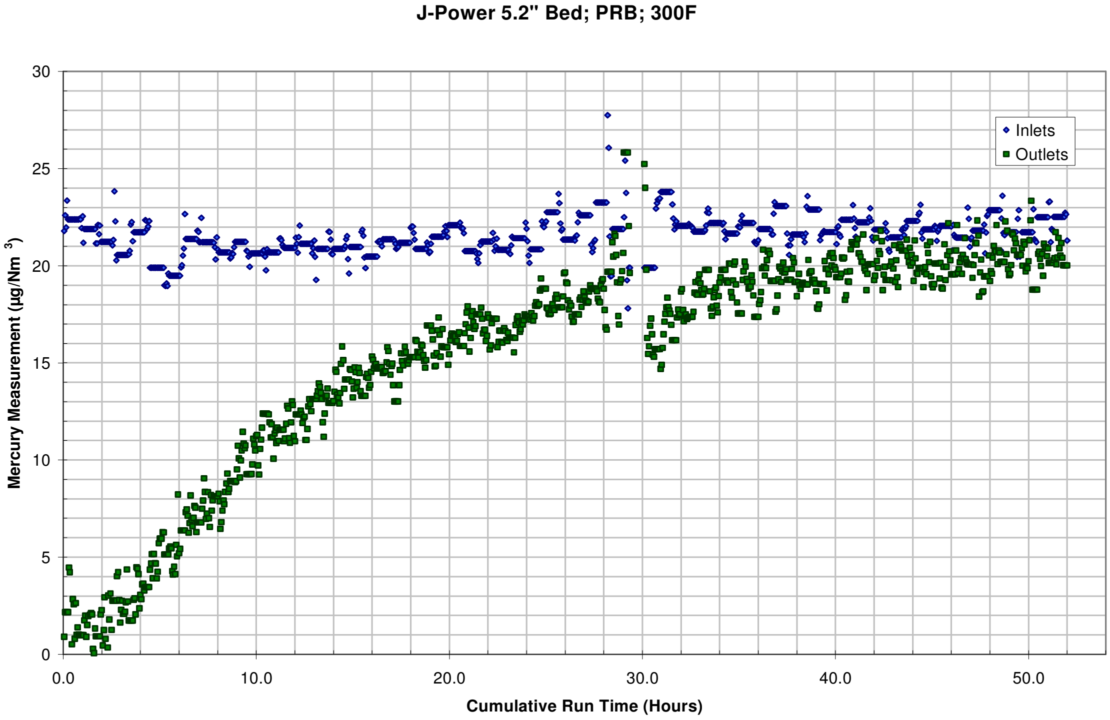


Figure 5-9. Representative Breakthrough Curve for Lab Tests – J-Power Sorbent.

Table 5-3. Simulated Flue Gas Test Parameters (PRB Flue Gas Simulation)

Flue Gas Parameter	Test Value
SO_2 (ppm)	400
NO_x (ppm) [95% as NO]	200
HCl (ppm)	2
H_2O (%)	7
CO_2 (%)	12
O_2 (%)	5
Hg^0 (µg Hg/Nm^3)	~25
Temperature (°F)	300
Flow Rate (L/min @ 75°F)	46

Because it is not possible to precisely control the inlet mercury at specific levels and because mercury adsorption is affected by mercury concentration, results for different sorbents cannot be directly compared without correcting for differences in concentration. To do this, URS corrects all lab and field measurements to an inlet mercury concentration of 50 µg/Nm^3 by assuming a linear dependence of capacity on concentration. This is a reasonable estimate for the benchmark Norit Darco Hg carbon based on the laboratory results but may not be valid for all sorbents at all conditions; this value was chosen since a large number of previous laboratory tests were conducted at a concentration close to this.

Four of the carbons tested in the pilot field program were screened in the laboratory tests. Table 5-4 contains a summary of the results obtained in the lab. Based on the high mercury capacities and/or high levels of initial mercury removal observed, all of these carbons were later tested at pilot scale. Even though the calculated equilibrium capacity of the J-Power sorbent was low compared to the other sorbents, the initial removal was greater than the other samples. The decision to proceed with this sample was based on this high adsorption rate and the concept that a moving bed of carbon could maintain a high level of mercury removal over time if the material was refreshed rapidly. This concept is discussed in greater depth later in this report.

Table 5-4. Laboratory Screening Test Results for the Pilot Carbon MerCAP Tests

Vendor	Type	Bed Length (in)	Gas Velocity (ft/s)	Initial Hg Removal (% inlet Hg)	Capacity (µg/g @ 50µg/Nm^3)
Winfield	9-mm pellets (brominated)	5	5	50	430
Carbon Activated	4-mm pellets	3.75	5	80	1054
Norit	Darco Hg-LH 4x8 granules	3.75	5	88	982
J-Power	<9-mm pellets	5.2	5	95	3

5.4 Pilot Testing – Plant Miller

5.4.1 Site Description

The host site for the carbon-based MerCAP™ tests was Southern Company's Alabama Power Plant Miller Unit 3 located in Birmingham, Alabama. Unit 3 is a 700 MW pulverized coal unit that fires exclusively PRB coal in a wall-fired furnace. The pilot test unit was located on an existing pilot COHPAC™ unit that draws two slipstreams of flue gas from upstream of the air heater (~600°F; 315°C) and ESP (~250°F; 121°C). The two flue gas streams are combined in various ratios just upstream of the COHPAC™ in order to achieve the desired flue gas temperature in the pilot system. The pilot COHPAC™ unit was modified prior to this testing program to remove the baghouse section of the unit, essentially making it a pilot ESP. The system is equipped with a fan and is capable of flue gas flows ranging from 3000 acfm to approximately 10,000 acfm. This represents flue gas velocities ranging from 3 ft/s to 9 ft/s at 300°F (149°C).

5.4.2 Flow Modeling

In order to create a horizontal fixed bed with minimal pressure drop, a louvered holder was designed for this application. The inspiration for this design came from the J-Power ReACT™ system that uses a similar system for SO_2 and multi-pollutant control. The advantages of a louvered design include lower pressure drop than a perforated plate, the ability to operate in a batch mode or as a moving bed, and the ability to handle a number of different types of sorbent.

A CFD model was created to examine the flow through the proposed system and test the feasibility of a full-scale system. The models examined a number of parameters including the vane angle, and the offset of the front and rear sets of vanes. Figure 5-10 shows two models with vane angles of 60^{o} and 80^{o}. It is apparent from these analyses that the flow at the outlet of the fixed bed is highly stratified and collected at the top of the outlet duct.

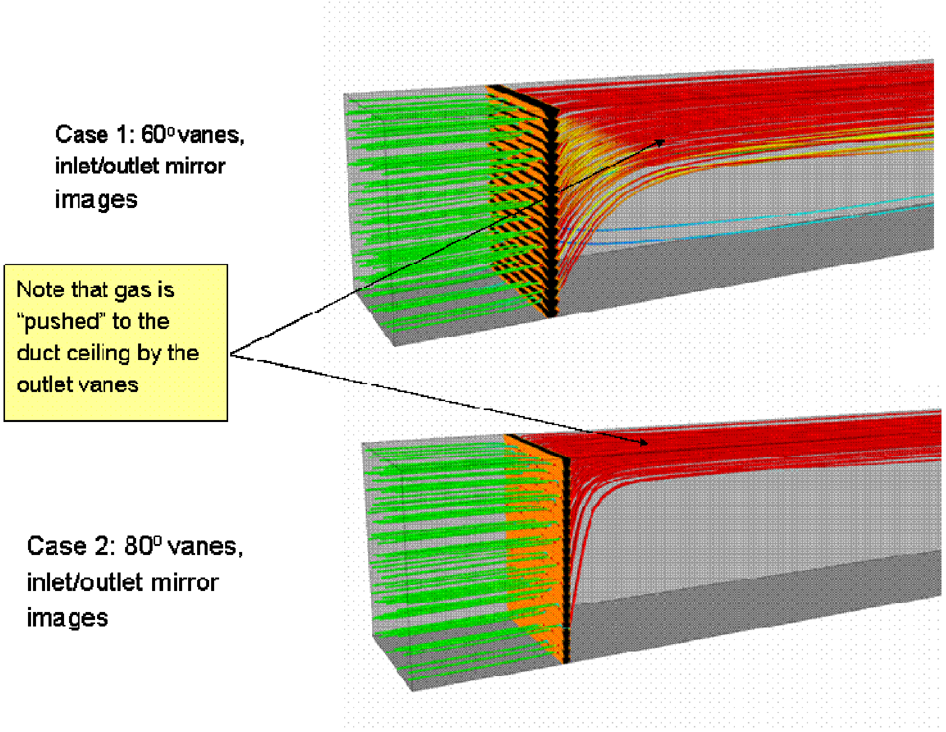


Figure 5-10. Flue Gas Streamlines, Colored by Velocity

In order to prevent this stratification, a flow straightener was added to the back row of vanes. Also, the back row was offset from the front row by 50%. The result of these modifications appears in Figure 5-11. Because the outlet flow is well distributed, the decision was made to design the pilot louvers using a 60^{o} angle, 50% offset, and add the flow straighteners.

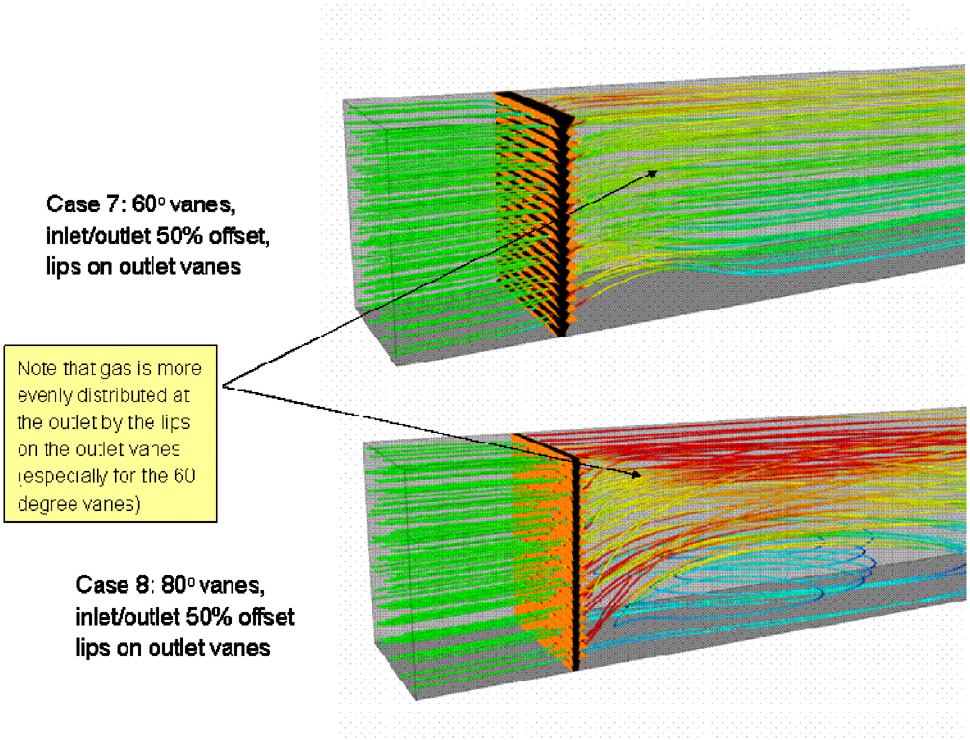


Figure 5-11. CFD Model of Louver Design with Flow Straighteners and Offset (Isometric View)

Figure 5-12 shows a detail of the flow through a cross section of the louver design. From this view it is evident that the offset of the louvers prevents a "short circuit" of the bed and will achieve uniform flow through the carbon material. This is important as the mercury removal and efficiency of the sorbent will depend on gas contact throughout the bed.

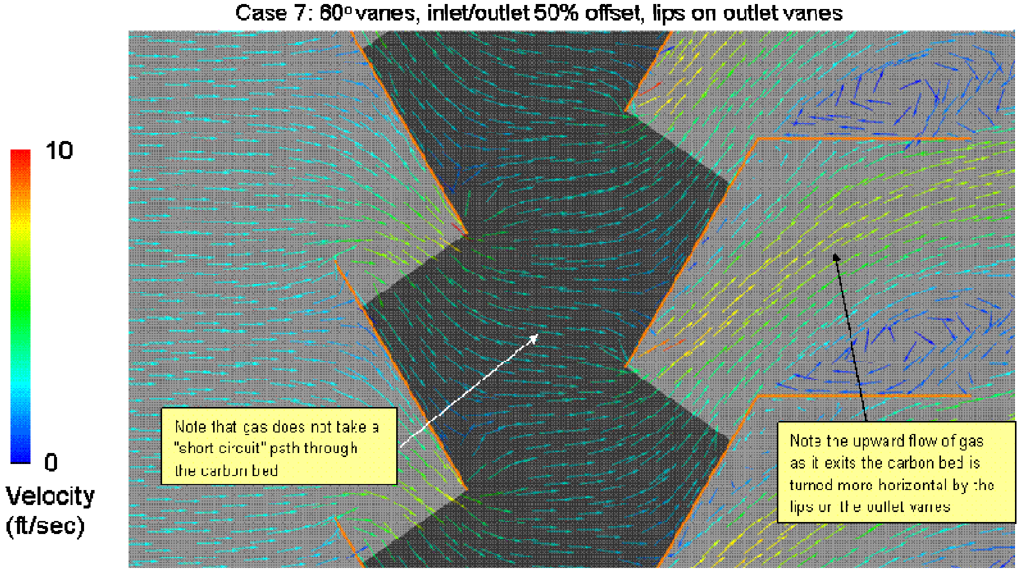


Figure 5-12. Louver Cross Section – Gas Vectors Colored by Velocity

5.4.3 Test Apparatus

A pilot-scale reactor was fabricated based on results from the modeling effort. The reactor consisted of a louvered sorbent holding vessel sized to fit within the existing pilot unit located at Plant Miller. The louvered device developed by the model was welded to a frame that acts as a cartridge that can be raised and lowered into a slot on the pilot housing. The cartridge is removed from the pilot in order to change sorbent material or to inspect the fixed bed. A picture of the louvered apparatus appears in Figure 5-13. In this photo, the louvered cartridge is resting in its external holder that was used to support the cartridge while loading and unloading carbon. The cartridge is maneuvered using an overhead jib crane that was installed specifically for this purpose. The cartridge is filled with carbon at the ground level, and is then lifted over the MerCAP™ housing and then lowered into one of the two slots designed to accommodate the cartridge. Once the cartridge is in place a pair of inflatable seals are inflated that run down the entire length of both sides of the cartridge. The purpose of these seals is to prevent gas from sneaking around the cartridge without passing through the carbon bed.

Figure 5-13. Carbon-Based MerCAP™ at Plant Miller

Once the bed was in place and the gas tight lid secured, the pilot system was put into service by starting the COHPAC™ fan, closing the air purge valve, and opening the flue gas valve at the inlet to the COHPAC™ ESP. An Apogee QSIS extraction probe was installed in a test port on the side of the housing and was used for outlet mercury measurements. An additional QSIS probe was installed in an upstream port on the pilot

COHPAC™ for inlet gas-phase measurements. Additional ports on the COHPAC™ and outlet duct work were used for particulate measurements along with particulate monitors from BHA that were located at these locations.

5.4.4 Pilot-Scale Testing – Plant Miller

Five different mercury sorbent materials were tested in the pilot unit at Plant Miller. These included chemically treated 4x8 granules from Norit Americas, 4-mm and 9-mm pellets from Carbon Activated, a 9-mm palletized material from J-Power that is similar to that used in their ReACT demonstration tests, and a chemically treated 9-mm pellet from Winfield Industries. Table 5-5 contains a summary of some of the key parameters of these tests, and Figure 5-14 contains a plot of the mercury removal results for all of the tests.

Table 5-5. Carbon-Based MerCAP Test Parameters and Results Summary

Test #	Carbon Vendor	Carbon Type	Gas Velocity (ft/s)	Test Length (Hr)	Final Cartridge ΔP (in H_2O)	Initial Hg Removal (%)	Hg Removal - 30 hours (%)	Capacity (µgHg/g @50 µg/Nm^3)
1	Carbon Activated	4-mm Pellet	3	44	0.40[1]	92	50[1]	72[1]
2	Winfield	9-mm Pellet brominated	3	114	0.42	77	25	48
3	Carbon Activated	9-mm pellet	3	41	0.26	68	27	70
4	J-Power	<9-mm pellet	3	71	0.79	85	33	67
5	Norit	Darco Hg-LH 4x8 granules	3	242	0.93 (226 hrs) 1.85 (241 hrs)[2]	90	70	186

([1] Carbon Bed Ruptured after ~25 hours, [2] Following low temperature operation)

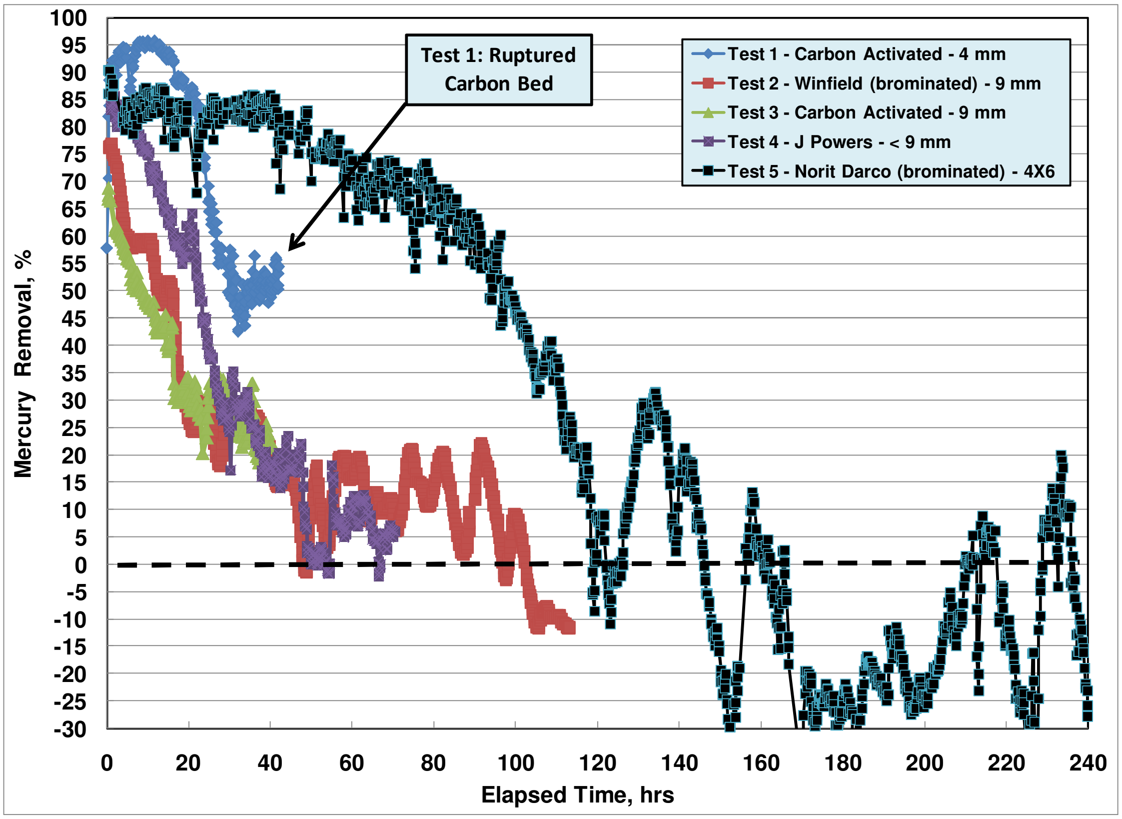


Figure 5-14. Mercury Removal over Time for Carbon-Based MerCAP™ Sorbents

Of the five carbon materials tested, the 4-mm pellets and the 4x8 granules showed the highest initial mercury removal as well as longer durations of removal. The 9-mm pellets demonstrated initial adsorptions ranging from 68% to 85%, however these beds showed relatively rapid breakthrough with only 25% to 33% mercury removal observed after 30 hours of operation. Both of the smaller 4-mm and 4x8 granules showed initial mercury removals of approximately 90% and sustained mercury removals above 50% after 30 hours of flue gas exposure.

It was expected that the bed of 4-mm carbon would sustain a higher level of mercury removal for a longer period of time than the larger sorbent materials; this was due to the greater gas contacting properties for the smaller particles and set bed width. However, the 4-mm carbon bed was ruptured after about 24 hours of operation when a sampling port was opened on the pilot system allowing a large in-rush of air to sweep into the vessel. This was recognized immediately as the pressure drop across the bed decreased rapidly during this event. This test may be repeated during a future program to properly evaluate the performance of this material.

The pressure drop across all of the beds was less than 2 in. H_2O, which represents the target maximum for these tests. The greatest pressure drop observed was 1.85 in. H_2O that occurred at the end of the test with the 4x8 granules. There is some speculation that the rise in pressure drop during this period was the result of soot blowing and boiler deslagging that would have increased the moisture content of the flue gas. Additional tests are necessary to quantify this effect and examine how routine boiler operation might affect this technology.

The mercury adsorption capacities for the larger 9-mm pellets were comparable and in the range of 67-70 µg Hg/g at an inlet mercury concentration of 50 µg/Nm^3. The adsorption capacities have been normalized to a standard inlet concentration because of the effect this factor has on the final capacity calculation. The smaller 4x8 granules had a capacity of 186 µg Hg/g, which is an order of magnitude greater than the larger pellets. Previous slipstream tests with even smaller Norit Darco Hg-LH 4x10 granules showed capacities in the range of 300-800 µg Hg/g. This could be a function of the sorbent material surface properties or an indication that the bed is mass transfer limited. The project team decided that the next step should be to lengthen the bed thickness by constructing a second cartridge that could be placed in series with the first, thus effectively doubling the bed thickness. The Norit Darco Hg-LH 4x8 granules were then loaded into both cartridges, and system was started in a manner similar to the previous tests. Figure 5-15 contains a plot that compares the double bed (test 6) with the previous single bed (test 5).

The initial mercury removal across both beds was comparable to the single bed for the 70 hours at which point the double bed maintained a higher level of removal. Total breakthrough for the double bed occurred at approximately 200 hours compared to approximately 120 hours for the single bed. The mercury adsorption capacity of both beds was approximately 183 µg Hg/g at an inlet mercury concentration of 50 µg/Nm^3. This is comparable with the single bed that had a capacity of approximately 186 µg Hg/g.

The initial pressure drop across both beds started at approximately 1.4 in. H_2O and remained steady for approximately 80 hours at which point it began to rise. After 200 hours the cumulative pressure drop across the two beds reached approximately 4 in. H_2O. 3 in. H_2O of this pressure drop was contributed by the first bed. During this test, the pressure drop appeared to rise more rapidly than in the previous tests. This could have been caused by a number of different factors including the function of the pilot ESP in the COHPAC™ unit that seemed to have increased sparking rate during this test, or de-slagging operations in the plant that increase the humidity in the flue gas.

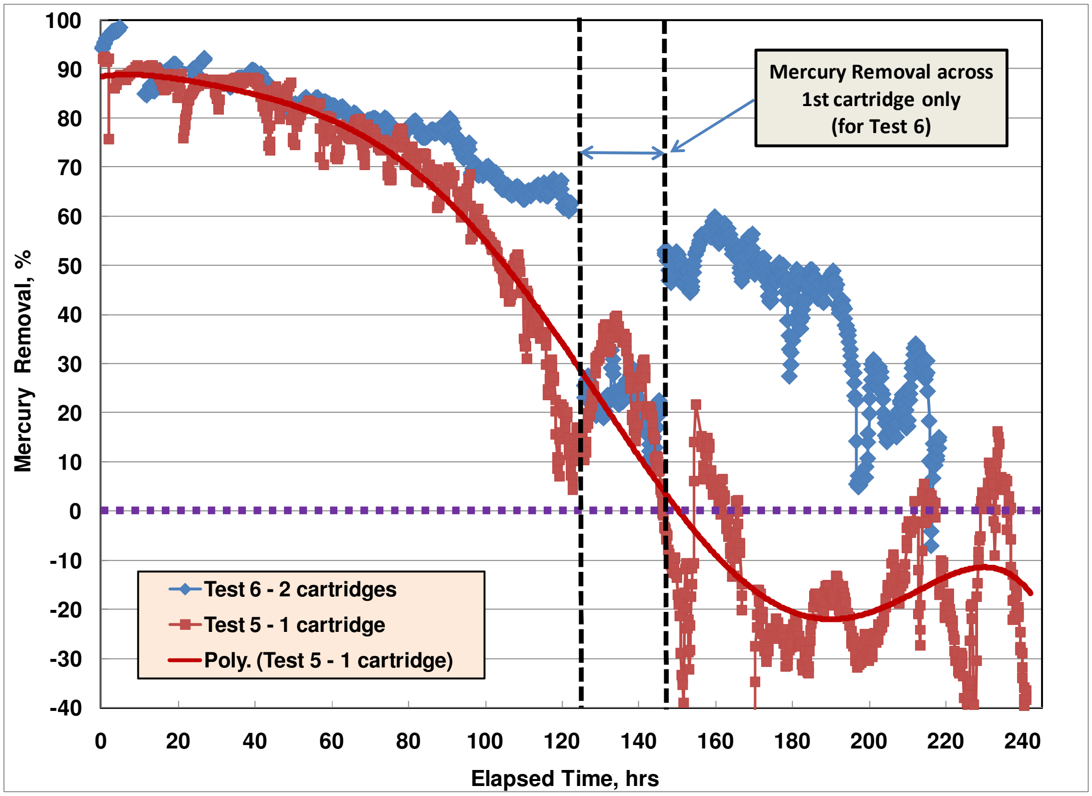


Figure 5-15. Mercury Removal across the carbon-MerCAP™ Beds for Tests 5 and 6

6.0 Conclusions

6.1 Site 1 Conclusions

The data and observations collected during the Site 1 testing program support the following conclusions:

- Long term demonstration of the MerCAP™ technology showed its ability to achieve modest mercury removals of 30 to 50% over extended time periods when operated downstream of a spray-dryer fabric filter (SD-FF) unit. A single set of substrates operated for 23 months continuously over the course of this program. Mercury capture performance was found to be directly affected by flue gas temperature with removal tracking inversely with gas temperature. At temperatures >200 °F (93°C), mercury removal effectiveness decreased dramatically as temperature increased. In some cases, outlet mercury levels spiked to levels well above those at the inlet with increased operating temperature, indicating possible re-volatilization of captured mercury from the MerCAP™ substrate.
- Operating parameters of the full-scale spray dryer absorber (SDA) were found to directly affect the mercury removal performance of the MerCAP™ substrates. Increased acid gas scrubbing was shown to dramatically increase mercury capture independent of gas temperature. Mercury removal was increased from 20% to 25% with the SDA system off to 40% capture with the absorber operating.
- Tests conducted with a high efficiency lime reagent (i.e., lime with higher surface area, lower density) in the SDA demonstrated the most effective manner of increasing mercury removal performance of the MerCAP™ system. Prior to feeding the high efficiency lime reagent to the SDA, mercury removal was measured at 25 to 30% capture. Following the change in lime product mercury removal increased to 60 to 70% for ducts 1 and 2 for the first 24 hours of operation and stabilized near 50% capture for the duration of the ‘high efficiency’ period. High levels of sulfur dioxide (SO_2) removal (>95%) were achieved with the enhanced lime reagent suggesting a possible inhibitory impact of the acid gas component on MerCAP™ performance.
- Variation of MerCAP™ plate spacing and active length did not demonstrate a direct correlation to mercury removal, indicating that a mechanism other than mass transfer dominates the mercury capture performance of the gold substrates. Comparison of SDA operation and mercury capture results indicated that temperature and acid gas constituents are the most likely limiting factors.
- Both thermal and chemical regeneration of slipstream-scale MerCAP™ substrates demonstrated no adverse impact to mercury capture performance after six regeneration cycles were performed. In general, mercury capture performance was increased following each regeneration cycle. No degradation in performance was observed as a function of the number of regeneration cycles performed on the substrates. The mercury liberated from the substrates was captured and analyzed from four of the six cycles to verify mercury removal by the small-scale substrates during unmonitored service time.

- Throughout the test program, minimal oxidation of vapor-phase mercury was observed across the MerCAP™ array; most of the vapor-phase mercury exiting the MerCAP™ reactor was present in the elemental form. It is likely that oxidative catalysis of vapor-phase mercury by the MerCAP™ substrates was inhibited due to the lack of acid gases and low halogen levels in the flue gas.
- During the course of this program the cost of commodity gold increased from approximately \$280/ounce to > \$900/ounce. Original cost estimates to install the MerCAP™ technology to the entire baghouse of Stanton Unit 10 (60 MWe) were roughly 2.0 to 2.5 million dollars. The increased cost of gold used as the substrate for the technology increases the costs of installation dramatically. Furthermore, the extent of mercury removal achieved by the installed MerCAP™ reactor during this program (i.e., ~40% average) was appreciably lower than the reactor design removal and the 55% removal goal of the program. This indicates that a full-scale MerCAP™ installation would require a much larger reactor size than predicted by mass-transfer model predictions. This results in gold-based MerCAP™ being economically unattractive compared to other options such as activated carbon injection for applications similar to that of Site 2.
- Alternative substrate materials were tested in the laboratory to determine the possibility of identifying more economical alternatives to electroplated gold substrates. A carbon cloth substrate showed promise in laboratory testing, but proved to be mechanically unsuitable to this application. Granulated carbon beds are one of the most promising alternatives. The use of granulated fixed carbon beds at the back end of particulate controls (MercScreen™) is currently being actively evaluated as a lower cost alternative to gold-based MerCAP™.

6.2 Site 2 Conclusions

The objective of the Site 2 program was to evaluate the performance of gold-based MerCAP™ for mercury removal in flue gas downstream of a wet FGD absorber. Testing at Plant Yates included a series of small-scale slipstream tests followed by a pilot-scale test program. The data and observations collected under this program support the following conclusions:

6.2.1 Slipstream Tests

- Results from small-scale slipstream tests showed that mercury removals as high as 90% could be achieved by the gold-coated screen substrates in flue gas obtained downstream of the Plant Yates Unit 1 FGD absorber. Results also indicated the importance of an effective rinse-water process for cleaning the MerCAP™ sorbent screens. Although the best results were obtained when a continuous water wash was used, high levels of removal were still obtained and sustained for over a month of continuous operation using a cycling approach where routine periodic rinses were performed.
- The correlation between rinsing frequency and MerCAP™ performance indicated that some species in the saturated flue gas reacted with the gold surfaces inhibiting their ability to remove mercury. Results showed that even after decreased mercury removal was observed following extended flue gas exposure,

the gold screens could be rejuvenated with an intensive water wash. This suggested that the reactions between the gold surfaces and inhibiting species in the flue gas did not permanently alter the gold coating. Inspection of the gold screens after 2 months of continuous flue gas exposure showed no signs of surface degradation or damage.

6.2.2 Pilot-Scale Tests

- MerCAP™ mercury capture performance across the pilot scale system was considerably lower than that observed in slipstream tests and predicted by mass transfer properties. Initial removals observed with fresh or cleaned gold screen substrates were only about one third of what was predicted by mass transfer model predictions. Specific causes for the lower-than-expected removals are not understood, but may include interactions between the gold surfaces and inhibiting species in the flue gas, inadequate rinsing of the screens, or unexplained poor flow patterns across the MerCAP™ arrays. Results from the pilot tests suggest that a much larger MerCAP™ reactor (than initially thought) would be required to obtain desired mercury removals.
- Parametric tests indicated no strong correlation between flue gas flow rate and mercury removal performance of the MerCAP™ system. In all cases the removal was considerably lower than predicted by mass transfer properties. Pilot tests confirmed the need for a routine water rinse of the MerCAP™ plates for mercury removal to be achieved. However, after prolonged exposure to flue gas, an intensive water rinse was not sufficient to regenerate the gold screens. Pilot parametric flow and rinsing tests therefore did not correlate well to earlier results obtained using the small-scale slipstream device.
- Pilot test results indicated that the gold MerCAP™ performance decreased with increased exposure to flue gas. Longer-term tests showed rapid declines in performance over the first 1-2 days of operation followed by a slow continual decline thereafter. Results from the second longer-term test showed that removal dropped from just over 30% to 0% in under 5 months of operation. The decline was observed with both the adsorption and oxidation of mercury by the gold sorbent, indicating a general loss of mercury reactivity (over time) with the sorbent. Test results indicated that a full-scale MerCAP™ system would require multiple shut-downs per year for regeneration or sorbent replacement.
- Pilot test results showed that the gold-based sorbents did not adequately withstand the wet flue gas environment to which they were exposed. The failure of the initial test resulted from the very rapid destruction of the substrates when exposed to unscrubbed flue gas (i.e., a condition that would not be expected for an actual installation). Long-term exposure of scrubbed flue gas caused severe corrosion and damage to the MerCAP™ sorbent substrates, ultimately resulting in appreciable loss of gold from the screens. The use of a continuous water rinse of the screens might be expected to increase the sorbent lifetime. However, the low tolerance of the screens to flue gas exposure would create a high-risk situation for sorbent loss regardless of the rinsing process used.

- The relatively poor results observed during this pilot test program, along with an appreciable increase in the price of gold over the past six years, greatly impact the estimated costs for the gold MerCAP™ technology. Pilot results, showing appreciably lower mercury removals than predicted by mass transfer properties, suggest that a much larger reactor would be required to achieve over 80% mercury removal than originally thought. Assuming a gold price of $870 per troy ounce, the gold cost (alone) to charge a MerCAP™ reactor required for a 500 MWe power plant would be over $15M. This does not take into account costs associated with sorbent re-charging or regeneration. Pilot-scale results predict that in order to achieve 90% mercury removal, a wet gold MerCAP™ reactor would need to be 60-feet long (for a 20-ft x 75-ft duct). The associated costs for the enlarged reactor structure and resulting pressure drop (i.e., as high as 15 in. H_2O) would be substantial. This makes gold-based MerCAP™ technology economically unattractive compared to other mercury control options for scrubbed plants, such as activated carbon injection or mercury oxidation technologies.
- Alternative substrate materials have been tested in the laboratory and in flue gas slipstream tests to identify more economical alternatives to electroplated gold substrates. A number of carbon-based substrates have shown promise in a number of tests conducted in simulated and actual flue gas. Granulated activated carbon beds appear to be one of the most promising alternatives. The use of granulated fixed carbon beds at the back end of particulate controls (EPRI MercScreen™) is currently being actively evaluated as a lower cost alternative to gold-based MerCAP™.

6.3 Carbon-Based MerCAP™ Testing Conclusions

A pilot-scale test system was constructed at Southern Company's Alabama Power Plant Miller to evaluate the carbon-based MerCAP™ technology. This unit was attached to the back end of an existing pilot ESP that treats an approximate 1-2 MWe equivalent slipstream of flue gas obtained from upstream of the full-scale ESP. Five different commercial activated carbons were tested in a louvered fixed-bed reactor that had been modeled and designed under a related EPRI test program. The evaluated carbons consisted of 9-mm pellets, 4-mm pellets, and 4x8 granules. Each test was conducted for 1-2 weeks with initial mercury removals ranging from 68% to 92%. The 4-mm pellets and 4x8 granules showed the greatest initial mercury removal and were able to maintain greater than 80% removal for over 24 hours. The mercury adsorption capacities ranged from 67 to 186 μg Hg/g at a normalized inlet mercury concentration of 50 $\mu g/Nm^3$. The larger pellets showed faster breakthrough and lower adsorption capacities, indicating that the bed was likely mass transfer limited in the current configuration.

The carbon-based MerCAP™ system demonstrated the ability to remove high levels of mercury (>80%) with a fixed bed of carbon material for periods up to approximately 60 hours with acceptable pressure drop less than 1.4 in. H_2O. This technology also appears to be more economically feasible than the gold MerCAP™ system due to the more robust performance and relative cost of the carbon compared to gold. The pilot proof-of-concept test of the carbon-based MerCAP™ was successful, however further development is necessary to optimize the carbon mercury adsorption capacity and particle size, as well as operation of the carbon MerCAP™ in a continuous mode. By continuously refreshing and removing carbon from the bed it will be possible to maintain high levels of mercury removal and reasonable pressure drop by removing fly ash buildup that causes bed plugging. Future development of this technology will also examine the feasibility of regenerating the carbon material to enhance the economic advantages of this technology.

7.0 REFERENCES

This report contains no references.

Appendix A: Sampling and QA/QC Procedures

During testing, the CMM sampling time is set to collect nominally 20 ng of mercury per sampling cycle. The noise level of the analyzer operating at a field site is conservatively calculated as 1 ng, thus collecting 20 ng provides a signal-to-noise ratio of 20.

The CMM is calibrated following installation at the field site for elemental mercury, sample flow rate, and oxygen concentration. The calibration of both the Au-CVAA component of the CMM, which measures the mass of elemental mercury desorbed, and the mass flow controller, which measures the total sample volume through the CMM, is checked daily during testing. The CMM is calibrated by introducing a spike of vapor-phase elemental mercury into the CMM upstream of the gold-amalgamation system. The mercury vapor for the spike is drawn from the air space in a vial containing liquid elemental mercury. The mercury spike concentration is calculated from the vapor pressure of mercury and the temperature of the vial. The vial temperature is measured with a precision thermistor. Connecting the operating controller in series with a calibrated mass flow meter checks the calibration of the mass flow controller within the CMM.

Documentation of CMM calibration is recorded on calibration data sheets and any system maintenance is recorded in the project notebook. CMM calibration data sheets are kept on file at Apogee and are available upon request. A calibration file for additional equipment, which contains manufacturers' certification of calibration, is also maintained by Apogee.

Data verification of computer calculations is conducted manually on a periodic basis. Any data collected during periods of suspected operational inconsistencies is rejected as questionable data.

Appendix B: Data Variability Protocols and Procedures

In the normal course of mercury monitoring activities with a semi-continuous emissions monitor, variability in collected data is encountered. Variability can be attributed to several factors including normal plant operation, changes in fuel source characteristics, individual operator style/procedures, environmental changes, and instrument variability/repeatability error. Apogee Scientific, Inc. has the following procedures and protocols to communicate and report the variability encountered in data collected.

- Standard variance is assumed and reported as one standard deviation.
- Unless otherwise reported all data/results have been quality checked for instrument malfunction and operator error.
- Average values are calculated using all data values unless QA/QC has marked a value or series of values as anomalous or suspect.
- All statistical quantities are calculated using accepted standard equations and procedures.
- Mercury removal results for sorbent addition are reported in terms of a removal “band” corresponding to the largest and smallest differences between average inlet and outlet concentrations with standard variance.

Error of the instrument is NOT included in variance reporting.

Appendix C: Results of Laboratory Investigations of Substrate Regeneration Methods

Results of Mercury Separation Tests on Gold Coupons

Objective:

To investigate the possibility of regenerating exposed gold coupons through either chemically or thermally separating mercury.

Test matrix:

All the tests were conducted with coupons that are made of gold felt with the dimensions of 5/8-inch wide x 6-inch long. All coupons were desiccated and weighed before and after each test.

1. The chemical separation was explored by means of preparing a chemical bath that was a 50/50 mix of water and nitric acid.
    a. Two gold coupons (samples 8 and 9) were soaked in the baths for different periods of time (4 and 26.95 hours respectively).
    b. A coupon that was not exposed to mercury was soaked in a bath for 8 hours.
    c. Chemical baths then tested for various wastes (Test has not occurred yet)
2. The thermal separation was conducted by means of exposing coupons to heat via a quartz furnace tube that was inline with mercury analyzers.
    a. Air flowed through the system at 5 LPM (MFC controlled)
    b. Air was preheated to 350^{o}F (177°C) before furnace tube
    c. Heater set points were 150^{o}F (66°C) and 1000^{o}F (537°C); lower and upper respectively

Results:

The tests revealed that both the chemical and thermal methods were affective in removing mercury from the gold coupons. Table C1 shows the results of soaking the coupons in a chemical bath for varying lengths of time.

Table C1. Results of Chemical Treatment of Coupons

Sample Number	Time Spent in Chemical Bath (hr)	Physical Weight Change of Coupon (g)	(g) of Hg removed per in2
6*	0	0.000	0.000
8	4	0.238	0.063
9	26.95	0.323	0.086
10	8	0.000	0.000

*Sample 6 was not soaked in chemical bath

Sample 10 was never exposed to mercury and when soaked in the acid bath for 8 hours no weight loss occurred. Samples 8 and 9 both experienced mercury removal from soaking in the chemical bath. Sample 9 had more mercury separation than sample 8 because it was left in the chemical bath for ~23 hours longer.

Table C2 below contains the results of exposing the coupons to heat via the furnace tube over extended periods of time.

Table C2. Results of Thermal Treatment of Coupons

Sample Number	Time in Furnace Tube (hr)	Rate of Weight Lost as Seen Through Analyzer (ug/min)	Weight Lost Calculated Through Lab Analyzer (g)
6	30.53	76.86	0.1408
8	56.60	47.13	0.0688
9	23.20	19.04	0.0265
10*	0.00	0.00	0.00

*Sample 10 was not placed in Furnace tube

The samples were placed in the furnace tube until the lab analyzer's mercury detection was less than 1 ug/m^3. Samples 8 and 9 have progressively less mercury evolving from the surface because those samples were both soaked for longer periods of time respectively. Table C3 below compares the physical weight loss through soaking in a chemical bath and the amount of mercury removed in the furnace tube as measured by the analyzer.

Table C3. Comparison Table between Furnace Tube and Chemical Bath

Sample Number	Soaked in Chemical Bath	Exposed to Furnace Tube	Physical Weight Change of Coupon from Chemical Bath (g)	Weight Lost Calculated Through Lab Analyzer During Furnace Tube (g)
6	no	yes	0.00	0.141
8	yes	yes	0.238	0.069
9	yes	yes	0.323	0.027
10	yes	no	0.00	0.00

As seen in Table C3, samples 8 and 9 lost majority of their weight through the soak in the chemical bath. Sample 10 experienced no change because it was never exposed to mercury. Figure C1 below shows the curves of the thermal removal of mercury from the coupons. The x-axis is time related, thus data point 7 is when the furnace tube was raised to its maximum temperature of 1000°F (537°C).

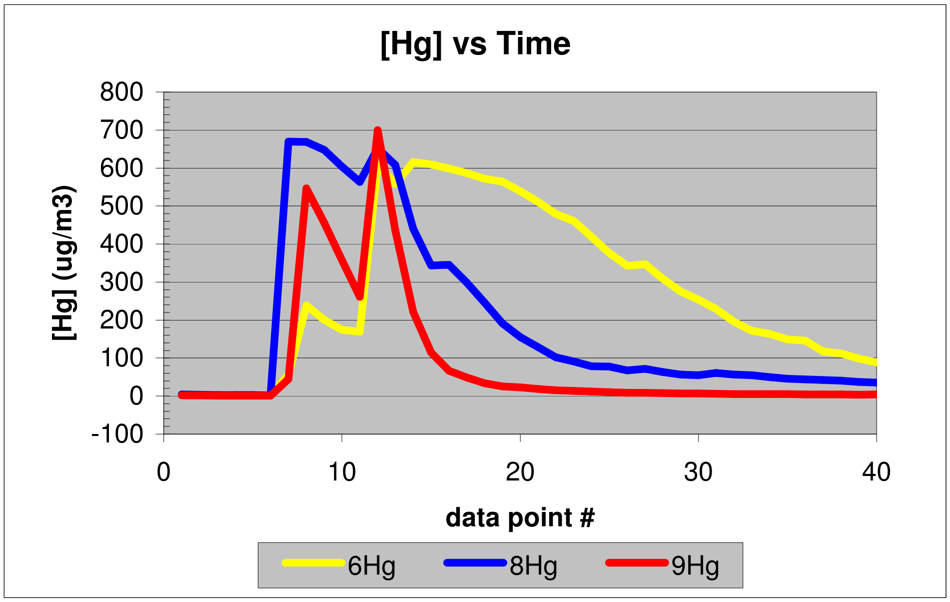


Figure C1. Curves of Thermal Removal of Mercury for Various Coupons

As seen in this plot the chemically treated coupons flashed of mercury in less time than sample 6. This occurs because a large amount of mercury that was available on the coupons was removed during the soak in the acid bath.

Conclusions:

- Mercury removal occurs through both the chemical and thermal methods that were used.
- Longer exposure to a chemical bath removes more mercury.
- The coupons that were chemically treated experience more mercury removal (g) per square inch.

Appendix D: Ontario Hydro Sampling Sheet Data

Stanton Inlet Baseline

Run Designation	Run 1	Run 2	Run 3
Date	9/9/2004	9/9/2004	9/9/2004
Time Start	12:20	16:15	19:36
Time Stop	14:20	18:15	21:36
	12:20-14:20	16:15-18:15	19:36-21:36
Duct Diameter (ft) *(equivalent if square duc*	0.00	0.00	0.00
Pitot Tube Correction Factor	0.84	0.84	0.84
Nozzle Diameter (inches)	0.300	0.300	0.300
DGMCF	1.003	1.003	1.003
Standard Temperature (F)	68	68	68
Barometric Pressure Measured (" Hg)	28.07	28.07	28.07
Stack Elevation (ft) (relative to Barometer)	0	0	0
Barometric Pressure (" Hg)	28.07	28.07	28.07
Average Stack Temperature (¦F)	182.5	200.5	185.8
Average DGM Temp (¦F)	80.4	95.7	81.2
Average Delta H (in wc)	0.30	0.30	0.30
Condensed Water (g)	187.8	185.1	183.7
Test Duration (minutes)	120	120	120
Static Pressure (in wc)	-11.00	-11.00	-11.00
% CO	0	0	0
% CO2	13	13	12
% O2	7	7	7
% N2	80	80	81
% H2	0	0	0
% CH4	0	0	0
Meter Volume (acf)	38.965	39.146	38.299
Average square root of delta p	0.144	0.151	0.200
Absolute Stack Pressure (in Hg)	27.26	27.26	27.26
Absolute Stack Temperature (¦R)	643	661	646
Flue Gas Moisture (%)	19.8	19.9	19.8
Moisture at saturation	59.3	87.0	63.7
Moisture used in Calculation	19.81	19.95	19.75
Gas Molecular Weight (Wet) (g/g-mole)	27.91	27.89	27.79
Corrected Volume of Gas sampled (acf)	39.08	39.26	38.41
Volume at Meter (dscf)	35.851	35.027	35.187
Average Gas Velocity (f/sec)	9.51	10.09	13.26
Avg Flow Rate (acfh)	0	0	0
Avg Flow Rate (acfm)	0	0	0
Avg Flow Rate (scfh)	0	0	0
Avg Flow Rate (scfm)	0	0	0
Avg Flow Rate (dscfh)	0	0	0
Avg Flow Rate (dscfm)	0	0	0
Isokinetic Sampling Rate (%)	177.70	168.53	125.59

Stanton Inlet Gold Mercap

Run Designation	Run 1	Run 2	Run 3
Date	9/8/2004	9/8/2004	9/9/2004
Time Start	14:30	17:57	8:25
Time Stop	16:30	19:57	10:25
	14:30-16:30	17:57-19:57	08:25-10:25
Duct Diameter (ft) *(equivalent if square duc*	0.00	0.00	0.00
Pitot Tube Correction Factor	0.84	0.84	0.84
Nozzle Diameter (inches)	0.301	0.301	0.301
DGMCF	1.003	1.003	1.003
Standard Temperature (F)	68	68	68
Barometric Pressure Measured (" Hg)	28.24	28.24	28.07
Stack Elevation (ft) (relative to Barometer)	0	0	0
Barometric Pressure (" Hg)	28.24	28.24	28.07
Average Stack Temperature (¦F)	164.7	162.5	161.0
Average DGM Temp (¦F)	85.8	83.3	62.7
Average Delta H (in wc)	0.30	0.30	0.30
Condensed Water (g)	171.0	166.2	175.9
Test Duration (minutes)	120	120	120
Static Pressure (in wc)	-11.00	-11.00	-11.00
% CO	0	0	0
% CO2	12	12	12
% O2	8	8	8
% N2	80	80	80
% H2	0	0	0
% CH4	0	0	0
Meter Volume (acf)	39.099	38.148	38.151
Average square root of delta p	0.141	0.141	0.141
Absolute Stack Pressure (in Hg)	27.43	27.43	27.26
Absolute Stack Temperature (¦R)	625	622	621
Flue Gas Moisture (%)	18.4	18.2	18.6
Moisture at saturation	39.3	37.3	36.3
Moisture used in Calculation	18.37	18.24	18.60
Gas Molecular Weight (Wet) (g/g-mole)	27.99	28.01	27.96
Corrected Volume of Gas sampled (acf)	39.22	38.26	38.27
Volume at Meter (dscf)	35.838	35.125	36.294
Average Gas Velocity (f/sec)	9.16	9.14	9.17
Avg Flow Rate (acfh)	0	0	0
Avg Flow Rate (acfm)	0	0	0
Avg Flow Rate (scfh)	0	0	0
Avg Flow Rate (scfm)	0	0	0
Avg Flow Rate (dscfh)	0	0	0
Avg Flow Rate (dscfm)	0	0	0
Isokinetic Sampling Rate (%)	173.83	169.85	176.49

Stanton Outlet Baseline

Run Designation	Run 1	Run 2	Run 3
Date	9/9/2004	9/9/2004	9/9/2004
Time Start	12:20	16:15	19:36
Time Stop	14:20	18:15	21:38
	12:20-14:20	16:15-18:15	19:36-21:38
Duct Diameter (ft) *(equivalent if square duc*	0.00	0.00	0.00
Pitot Tube Correction Factor	0.84	0.84	0.84
Nozzle Diameter (inches)	0.326	0.326	0.300
DGMCF	0.999	0.990	1.003
Standard Temperature (F)	68	68	68
Barometric Pressure Measured (" Hg)	28.07	28.07	28.07
Stack Elevation (ft) (relative to Barometer)	0	0	0
Barometric Pressure (" Hg)	28.07	28.07	28.07
Average Stack Temperature (¦F)	184.7	201.1	186.0
Average DGM Temp (¦F)	84.5	91.0	83.1
Average Delta H (in wc)	1.50	0.95	0.95
Condensed Water (g)	383.2	315.7	306.4
Test Duration (minutes)	120	120	122
Static Pressure (in wc)	-11.00	-11.00	-11.00
% CO	0	0	0
% CO2	12	12	12
% O2	9	9	7
% N2	79	79	81
% H2	0	0	0
% CH4	0	0	0
Meter Volume (acf)	76.12	76.12	65.011
Average square root of delta p	0.447	0.387	0.387
Absolute Stack Pressure (in Hg)	27.26	27.26	27.26
Absolute Stack Temperature (¦R)	645	661	646
Flue Gas Moisture (%)	20.6	18.0	19.5
Moisture at saturation	62.2	88.0	64.0
Moisture used in Calculation	20.64	17.98	19.50
Gas Molecular Weight (Wet) (g/g-mole)	27.75	28.07	27.82
Corrected Volume of Gas sampled (acf)	76.04	75.36	65.21
Volume at Meter (dscf)	69.457	67.922	59.624
Average Gas Velocity (f/sec)	29.65	25.85	25.67
Avg Flow Rate (acfh)	0	0	0
Avg Flow Rate (acfm)	0	0	0
Avg Flow Rate (scfh)	0	0	0
Avg Flow Rate (scfm)	0	0	0
Avg Flow Rate (dscfh)	0	0	0
Avg Flow Rate (dscfm)	0	0	0
Isokinetic Sampling Rate (%)	94.79	105.48	107.84

Stanton Outlet Gold Mercap

Run Designation	Run 1	Run 2	Run 3
Date	9/8/2004	9/8/2004	9/9/2004
Time Start	14:30	17:57	8:25
Time Stop	16:30	19:57	10:25
	14:30-16:30	17:57-19:57	08:25-10:25
Duct Diameter (ft) *(equivalent if square duc*	0.00	0.00	0.00
Pitot Tube Correction Factor	0.84	0.84	0.84
Nozzle Diameter (inches)	0.301	0.301	0.301
DGMCF	0.999	0.999	1.003
Standard Temperature (F)	68	68	68
Barometric Pressure Measured (" Hg)	28.24	28.24	28.07
Stack Elevation (ft) (relative to Barometer)	0	0	0
Barometric Pressure (" Hg)	28.24	28.24	28.07
Average Stack Temperature (¦F)	179.4	179.2	178.0
Average DGM Temp (¦F)	74.0	74.1	66.0
Average Delta H (in wc)	0.30	0.30	0.30
Condensed Water (g)	183.5	184.6	181.6
Test Duration (minutes)	120	120	120
Static Pressure (in wc)	-11.00	-11.00	-11.00
% CO	0	0	0
% CO2	12	12	12
% O2	8	8	8
% N2	80	80	80
% H2	0	0	0
% CH4	0	0	0
Meter Volume (acf)	38.852	37.706	36.347
Average square root of delta p	0.224	0.141	0.141
Absolute Stack Pressure (in Hg)	27.43	27.43	27.26
Absolute Stack Temperature (¦R)	639	639	638
Flue Gas Moisture (%)	19.3	19.8	19.9
Moisture at saturation	55.0	54.8	53.6
Moisture used in Calculation	19.27	19.84	19.95
Gas Molecular Weight (Wet) (g/g-mole)	27.88	27.81	27.80
Corrected Volume of Gas sampled (acf)	38.81	37.67	36.46
Volume at Meter (dscf)	36.252	35.172	34.359
Average Gas Velocity (f/sec)	14.68	9.30	9.32
Avg Flow Rate (acfh)	0	0	0
Avg Flow Rate (acfm)	0	0	0
Avg Flow Rate (scfh)	0	0	0
Avg Flow Rate (scfm)	0	0	0
Avg Flow Rate (dscfh)	0	0	0
Avg Flow Rate (dscfm)	0	0	0
Isokinetic Sampling Rate (%)	113.54	175.17	171.68

Stanton Inlet SD

Run Designation	Run 1	Run 2	Run 3
Date	2/1/2005	2/1/2005	2/1/2005
Time Start	10:26	13:55	17:09
Time Stop	12:28	15:55	19:09
	10:26-12:28	13:55-15:55	17:09-19:09
Duct Diameter (ft) *(equivalent if square duc*	0.00	0.00	0.00
Pitot Tube Correction Factor	0.84	0.84	0.84
Nozzle Diameter (inches)	0.320	0.320	0.320
DGMCF	1.005	1.005	1.005
Standard Temperature (F)	48	48	48
Barometric Pressure Measured (" Hg)	28.44	28.44	28.44
Stack Elevation (ft) (relative to Barometer)	0	0	0
Barometric Pressure (" Hg)	28.44	28.44	28.44
Average Stack Temperature (¦F)	189.9	206.3	197.1
Average DGM Temp (¦F)	75.2	86.3	87.5
Average Delta H (in wc)	0.30	0.30	0.30
Condensed Water (g)	132.5	145.0	147.7
Test Duration (minutes)	122	120	120
Static Pressure (in wc)	-14.00	-14.00	-14.00
% CO	0	0	0
% CO2	12	14	12.5
% O2	8	5.5	5.5
% N2	80.5	80.5	82
% H2	0	0	0
% CH4	0	0	0
Meter Volume (acf)	39.846	38.664	38.818
Average square root of delta p	0.100	0.115	0.100
Absolute Stack Pressure (in Hg)	27.41	27.41	27.41
Absolute Stack Temperature (¦R)	650	666	657
Flue Gas Moisture (%)	14.3	16.1	16.3
Moisture at saturation	69.3	97.5	80.6
Moisture used in Calculation	14.25	16.06	16.29
Gas Molecular Weight (Wet) (g/g-mole)	28.48	28.46	28.23
Corrected Volume of Gas sampled (acf)	40.05	38.86	39.01
Volume at Meter (dscf)	36.157	34.373	34.431
Average Gas Velocity (f/sec)	6.55	7.65	6.62
Avg Flow Rate (acfh)	0	0	0
Avg Flow Rate (acfm)	0	0	0
Avg Flow Rate (scfh)	0	0	0
Avg Flow Rate (scfm)	0	0	0
Avg Flow Rate (dscfh)	0	0	0
Avg Flow Rate (dscfm)	0	0	0
Isokinetic Sampling Rate (%)	219.82	190.71	218.23

Stanton Outlet SD

Run Designation	Run 1	Run 2	Run 3
Date	2/1/2005	2/1/2005	2/1/2005
Time Start	10:30	13:58	17:12
Time Stop	12:30	15:59	19:12
	10:30-12:30	13:58-15:59	17:12-19:12
Duct Diameter (ft) *(equivalent if square duc*	0.00	0.00	0.00
Pitot Tube Correction Factor	0.84	0.84	0.84
Nozzle Diameter (inches)	0.320	0.320	0.320
DGMCF	0.994	0.994	0.994
Standard Temperature (F)	48	48	48
Barometric Pressure Measured (" Hg)	28.44	28.44	28.44
Stack Elevation (ft) (relative to Barometer)	0	0	0
Barometric Pressure (" Hg)	28.44	28.44	28.44
Average Stack Temperature (¦F)	190.3	205.2	194.2
Average DGM Temp (¦F)	76.6	87.2	90.2
Average Delta H (in wc)	0.30	0.75	0.82
Condensed Water (g)	146.4	213.3	221.2
Test Duration (minutes)	120	121	120
Static Pressure (in wc)	-14.00	-14.00	-14.00
% CO	0	0	0
% CO2	13	13	12.5
% O2	8	5	5
% N2	79.5	82	82.5
% H2	0	0	0
% CH4	0	0	0
Meter Volume (acf)	38.365	58.352	60.711
Average square root of delta p	0.351	0.350	0.338
Absolute Stack Pressure (in Hg)	27.41	27.41	27.41
Absolute Stack Temperature (¦R)	650	665	654
Flue Gas Moisture (%)	16.2	15.9	15.9
Moisture at saturation	69.7	95.2	75.8
Moisture used in Calculation	16.20	15.87	15.90
Gas Molecular Weight (Wet) (g/g-mole)	28.37	28.33	28.26
Corrected Volume of Gas sampled (acf)	38.13	58.00	60.35
Volume at Meter (dscf)	34.341	51.286	53.073
Average Gas Velocity (f/sec)	23.04	23.26	22.29
Avg Flow Rate (acfh)	0	0	0
Avg Flow Rate (acfm)	0	0	0
Avg Flow Rate (scfh)	0	0	0
Avg Flow Rate (scfm)	0	0	0
Avg Flow Rate (dscfh)	0	0	0
Avg Flow Rate (dscfm)	0	0	0
Isokinetic Sampling Rate (%)	61.80	92.39	98.95

Stanton Outlet SD

Run Designation	Run 1	Run 2	Run 3
Date	2/2/2005	2/2/2005	2/2/2005
Time Start	10:20	13:10	17:25
Time Stop	12:20	15:10	19:25
	10:20-12:20	13:10-15:10	17:25-19:25
Duct Diameter (ft) *(equivalent if square duc*	0.00	0.00	0.00
Pitot Tube Correction Factor	0.84	0.84	0.84
Nozzle Diameter (inches)	0.320	0.320	0.320
DGMCF	0.994	0.994	0.994
Standard Temperature (F)	48	48	48
Barometric Pressure Measured (" Hg)	28.44	28.44	28.44
Stack Elevation (ft) (relative to Barometer)	0	0	0
Barometric Pressure (" Hg)	28.44	28.44	28.44
Average Stack Temperature (¦F)	195.2	197.8	200.1
Average DGM Temp (¦F)	77.9	86.5	89.3
Average Delta H (in wc)	0.84	0.84	0.84
Condensed Water (g)	181.6	249.7	241.6
Test Duration (minutes)	120	120	120
Static Pressure (in wc)	-14.00	-14.00	-14.00
% CO	0	0	0
% CO2	11	13	14.5
% O2	9	8	6
% N2	80	79	79.5
% H2	0	0	0
% CH4	0	0	0
Meter Volume (acf)	61.346	61.606	62.17
Average square root of delta p	0.361	0.391	0.405
Absolute Stack Pressure (in Hg)	27.41	27.41	27.41
Absolute Stack Temperature (¦R)	655	658	660
Flue Gas Moisture (%)	13.1	17.3	16.8
Moisture at saturation	77.4	81.7	85.8
Moisture used in Calculation	13.06	17.28	16.76
Gas Molecular Weight (Wet) (g/g-mole)	28.54	28.26	28.46
Corrected Volume of Gas sampled (acf)	60.98	61.24	61.80
Volume at Meter (dscf)	54.861	54.224	54.447
Average Gas Velocity (f/sec)	23.73	25.90	26.74
Avg Flow Rate (acfh)	0	0	0
Avg Flow Rate (acfm)	0	0	0
Avg Flow Rate (scfh)	0	0	0
Avg Flow Rate (scfm)	0	0	0
Avg Flow Rate (dscfh)	0	0	0
Avg Flow Rate (dscfm)	0	0	0
Isokinetic Sampling Rate (%)	93.07	88.95	86.27

Stanton IGS

Run Designation	Run 1	Run 2	Run 3
Date	2/2/2005	2/2/2005	2/2/2005
Time Start	10:26	13:15	16:03
Time Stop	12:26	15:15	19:09
	10:26-12:26	13:15-15:15	16:03-19:09
Duct Diameter (ft) *(equivalent if square duc*	0.00	0.00	0.00
Pitot Tube Correction Factor	0.00	0	0
Nozzle Diameter (inches)	0.000	0.000	0.000
DGMCF	0.961	0.961	0.961
Standard Temperature (F)	48	48	48
Barometric Pressure Measured (" Hg)	28.44	28.44	28.44
Stack Elevation (ft) (relative to Barometer)	0	0	0
Barometric Pressure (" Hg)	28.44	28.44	28.44
Average Stack Temperature (¦F)	#DIV/0!	#DIV/0!	#DIV/0!
Average DGM Temp (¦F)	54.0	57.7	52.2
Average Delta H (in wc)	1.00	1.00	1.00
Condensed Water (g)	14.6	24.5	23.0
Test Duration (minutes)	120	120	120
Static Pressure (in wc)	-14.00	-14.00	-14.00
% CO	0	0	0
% CO2	11	11	11
% O2	5	5	5
% N2	84	84	84
% H2	0	0	0
% CH4	0	0	0
Meter Volume (acf)	15.796	16.67	17.241
Average square root of delta p	1.276	1.313	1.328
Absolute Stack Pressure (in Hg)	27.41	27.41	27.41
Absolute Stack Temperature (¦R)	#DIV/0!	#DIV/0!	#DIV/0!
Flue Gas Moisture (%)	4.4	6.9	6.2
Moisture at saturation	#DIV/0!	#DIV/0!	#DIV/0!
Moisture used in Calculation	#DIV/0!	#DIV/0!	#DIV/0!
Gas Molecular Weight (Wet) (g/g-mole)	#DIV/0!	#DIV/0!	#DIV/0!
Corrected Volume of Gas sampled (acf)	15.18	16.02	16.57
Volume at Meter (dscf)	14.299	14.981	15.661
Average Gas Velocity (f/sec)	#DIV/0!	#DIV/0!	#DIV/0!
Avg Flow Rate (acfh)	#DIV/0!	#DIV/0!	#DIV/0!
Avg Flow Rate (acfm)	#DIV/0!	#DIV/0!	#DIV/0!
Avg Flow Rate (scfh)	#DIV/0!	#DIV/0!	#DIV/0!
Avg Flow Rate (scfm)	#DIV/0!	#DIV/0!	#DIV/0!
Avg Flow Rate (dscfh)	#DIV/0!	#DIV/0!	#DIV/0!
Avg Flow Rate (dscfm)	#DIV/0!	#DIV/0!	#DIV/0!
Isokinetic Sampling Rate (%)	#DIV/0!	#DIV/0!	#DIV/0!

Plant Yates - Ontario Hydro Sampling

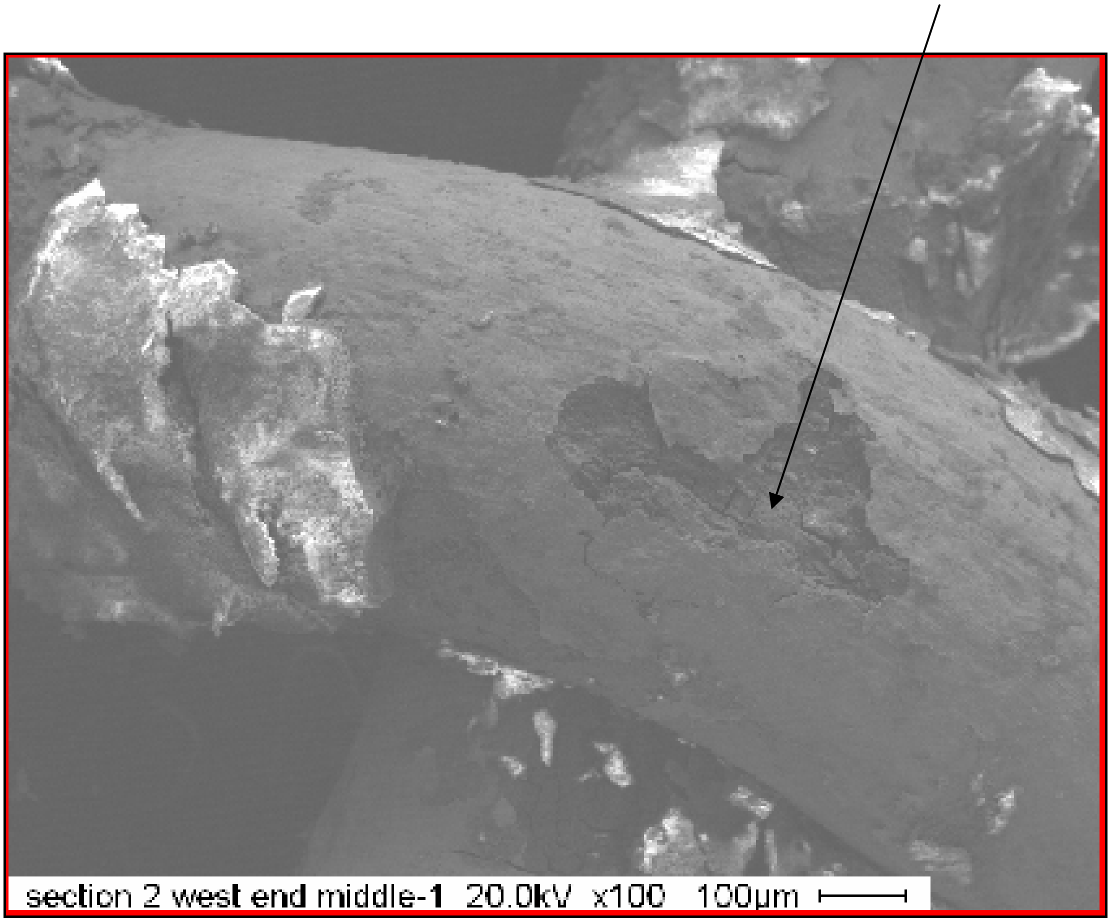
Date	8/4/2006	8/4/2006	8/4/2006	8/4/2006	8/4/2006	8/4/2006
Location/Condition	Inlet	Inlet	Inlet	Outlet	Outlet	Outlet
Run	1	2	3	1	2	3
Worksheet Tab Name	**Inlet R1**	**Inlet R2**	**Inlet R3**	**Outlet R1**	**Outlet R2**	**Outlet R3**
Start Time	9:00	11:35	14:05	9:00	11:35	14:05
End Time	11:00	13:35	16:05	11:00	13:35	16:05
Source Area (ft^2)	1.54	1.54	1.54	1.54	1.54	1.54
Nozzle Diameter (")	0.279	0.279	0.279	0.279	0.279	0.279
DGM #	N-43	N-43	N-43	N-55	N-55	N-55
DGM Calibration Factor (Y_D)	1.018	1.018	1.018	1.008	1.008	1.008
□H@	1.779	1.779	1.779	1.8194	1.8194	1.8194
Pitot (Cp)	0.84	0.84	0.84	0.84	0.84	0.84
Stack Barometric Pressure ("Hg)	29.38	29.38	29.38	29.38	29.38	29.38
Static Pressure ("H_2O)	-0.50	-0.50	-0.50	-10.00	-10.00	-10.00
Test Duration (min)	120	120	120	120	120	120
Minutes per point	15	15	15	15	15	15
Meter Volume x DGMCF (ft^3)	60.689	61.033	56.998	80.232	68.079	71.555
Impinger Mass Gain (g)	189.5	196.9	186.5	245.5	228.6	230.4
Meter Temperature (R)	544.6	565.7	574.8	550.0	568.7	573.5
Average □H (in H_2O)	0.79	0.76	0.63	1.39	0.97	1.10
Meter Pressure ("Hg)	29.44	29.44	29.43	29.48	29.45	29.46
% H_2O at saturation	11.7	13.1	12.8	10.8	11.1	15.0
% H_2O	11.7	13.1	12.8	10.8	11.1	14.3
% CO_2	13.5	14.0	14.0	13.5	14.0	14.0
% O_2	7.8	6.9	6.9	7.8	6.9	6.9
% N_2	78.8	79.2	79.1	78.8	79.1	79.1
Dry Molecular Weight (mw_{dry})	30.5	30.5	30.5	30.5	30.5	30.5
Source Molecular Weight (mw_g)	29.0	28.9	28.9	29.1	29.1	28.7
Avg. SQRT Delta P	0.40	0.39	0.35	0.53	0.44	0.47
Avg. Source Temperature (R)	580.6	584.1	582.7	576.2	577.1	588.4
Avg. Source Pressure ("Hg)	29.34	29.34	29.34	28.64	28.64	28.64
Gas Velocity (ft/s)	23.5	23.2	21.1	31.5	26.3	28.5
Stack Gas Flow Rate (acfm)	2,174	2,142	1,949	2,908	2,427	2,631
Stack Gas Flow Rate (dscfm)	1,710	1,649	1,511	2,275	1,890	1,935
Standard Sample Volume (dscf)	57.854	56.012	51.462	75.851	62.181	64.829
Average Isokinetic %	102.2	102.6	102.9	100.7	99.4	101.2
Average sqrt(□H)	0.89	0.87	0.79	1.18	0.98	1.05
Y(qa)	1.003	0.996	0.981	0.992	0.992	1.010
□Y (± 5%)	-1.4%	-2.2%	-3.7%	-1.6%	-1.6%	0.2%

Ontario Hydro Gas Concentration Results
Yates Mercap
Aug-07

50%

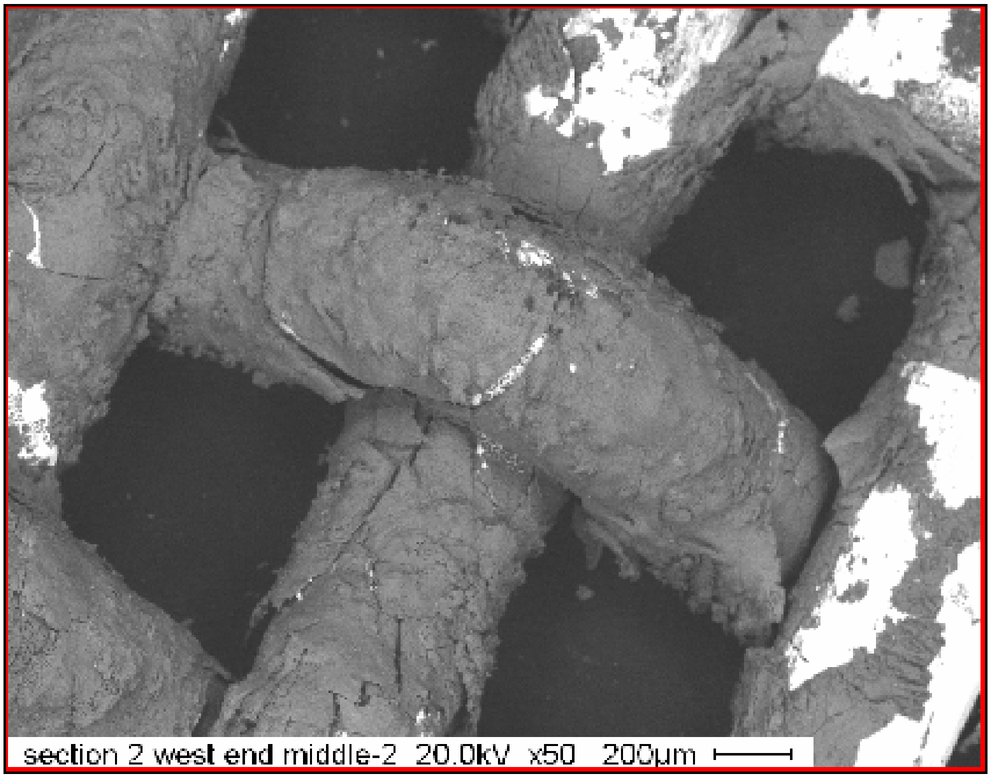
Mercury Analytical Results		**Inlet R1**	**Inlet R2**	**Inlet R3**	**Outlet R1**	**Outlet R2**	**Outlet R3**
Date		29-Aug-07	29-Aug-07	29-Aug-07	29-Aug-07	29-Aug-07	29-Aug-07
Time(exact minutes)		180	180	174	180	180	174
Gas Volume (dscf)		100.27	95.80	91.87	85.98	78.74	91.88
Moisture (%)		11.8	13.2	13.5	10.60	11.9	11.9
Oxygen (%)		11.5	10.0	9.0	11.5	11.0	9.0
Mercury Found (ug/sample) - Entered Analytical Results							
Probe and Nozzle Rinse		<0.030	<0.020	<0.032	0.07	0.032	<0.026
Filter		<0.012	<0.012	<0.012	<0.012	<0.012	<0.012
Ash (analyzed separately)							
Potassium Chloride		<0.44	<0.501	<0.462	<0.412	<0.418	<0.468
Nitric Acid Impinger		<0.183	<0.168	<0.173	<0.174	0.16	0.2
Permanganate Impinger		6.60	7.53	7.13	5.03	5.59	6.43
Mercury Found (ug/sample) - Separated Less Than Signs							
Probe and Nozzle Rinse		< 0.03	< 0.02	< 0.032	0.067	0.032	< 0.026
Filter		< 0.012	< 0.012	< 0.012	< 0.012	< 0.012	< 0.012
Ash (analyzed separately)		0	0	0	0	0	0
Potassium Chloride		< 0.44	< 0.501	< 0.462	< 0.412	< 0.418	< 0.468
Nitric Acid Impinger		< 0.183	< 0.168	< 0.173	< 0.174	0.163	0.171
Permanganate Impinger		6.6	7.53	7.13	5.03	5.59	6.43
Mercury Found (ug/sample) - Formatted Results							
Probe and Nozzle Rinse		<0.03	<0.02	<0.03	0.07	0.03	<0.03
Filter		<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Ash (analyzed separately)		0.00	0.00	0.00	0.00	0.00	0.00
Potassium Chloride		<0.44	<0.50	<0.46	<0.41	<0.42	<0.47
Nitric Acid Impinger		<0.18	<0.17	<0.17	<0.17	0.16	0.17
Permanganate Impinger		6.60	7.53	7.13	5.03	5.59	6.43
Totals (ug/sample) (calculations, etc)							
Particulate Mercury	**sum of <**	< 0.042	< 0.032	< 0.044	< 0.012	< 0.012	< 0.038
	sum of hits	0	0	0	0.067	0.032	0
	calculated sum	< 0.042	< 0.032	< 0.044	0.067	0.032	< 0.038
Oxidized Mercury		< 0.44	< 0.501	< 0.462	< 0.412	< 0.418	< 0.468
Elemental Mercury	**sum of <**	< 0.183	< 0.168	< 0.173	< 0.174	< 0	< 0
	sum of hits	6.6	7.53	7.13	5.03	5.753	6.601
	calculated sum	6.6	7.53	7.13	5.03	5.753	6.601
	particulate	< 0.042	< 0.032	< 0.044	0.067	0.032	< 0.038
	oxidized	< 0.44	< 0.501	< 0.462	< 0.412	< 0.418	< 0.468
	elemental	6.6	7.53	7.13	5.03	5.753	6.601
	sum of <	< 0.482	< 0.533	< 0.506	< 0.412	< 0.418	< 0.506
	sum of hits	6.6	7.53	7.13	5.097	5.785	6.601
Total Mercury	**calculated sum**	6.6	7.53	7.13	5.097	5.785	6.601
Totals (ug/sample) Formatted Results							
Particulate Mercury		<0.04	<0.03	<0.04	0.07	0.03	<0.04
Oxidized Mercury		<0.44	<0.50	<0.46	<0.41	<0.42	<0.47
Elemental Mercury		6.60	7.53	7.13	5.03	5.75	6.60
Total Mercury		6.60	7.53	7.13	5.10	5.79	6.60
Concentration (ug/m3)							
Particulate Mercury		< 0.014791698	< 0.011796436	< 0.016912695	0.0275182	0.014351832	< 0.014604851
Oxidized Mercury		< 0.154960649	< 0.184687957	< 0.177583295	< 0.169216393	< 0.187470799	< 0.179870276
Elemental Mercury		2.324409738	2.775848928	2.740625309	2.065918579	2.580190208	2.53701644
Total Mercury		2.324409738	2.775848928	2.740625309	2.093436779	2.59454204	2.53701644
Concentration (ug/m3) - Formatted results							
Particulate Mercury		<0.01	<0.01	<0.02	0.03	0.01	<0.01
Oxidized Mercury		<0.15	<0.18	<0.18	<0.17	<0.19	<0.18
Elemental Mercury		2.32	2.78	2.74	2.07	2.58	2.54
Total Mercury		2.32	2.78	2.74	2.09	2.59	2.54

Appendix E – Additional SEM Photographs of MerCAP™ Screens Treated at Site 2

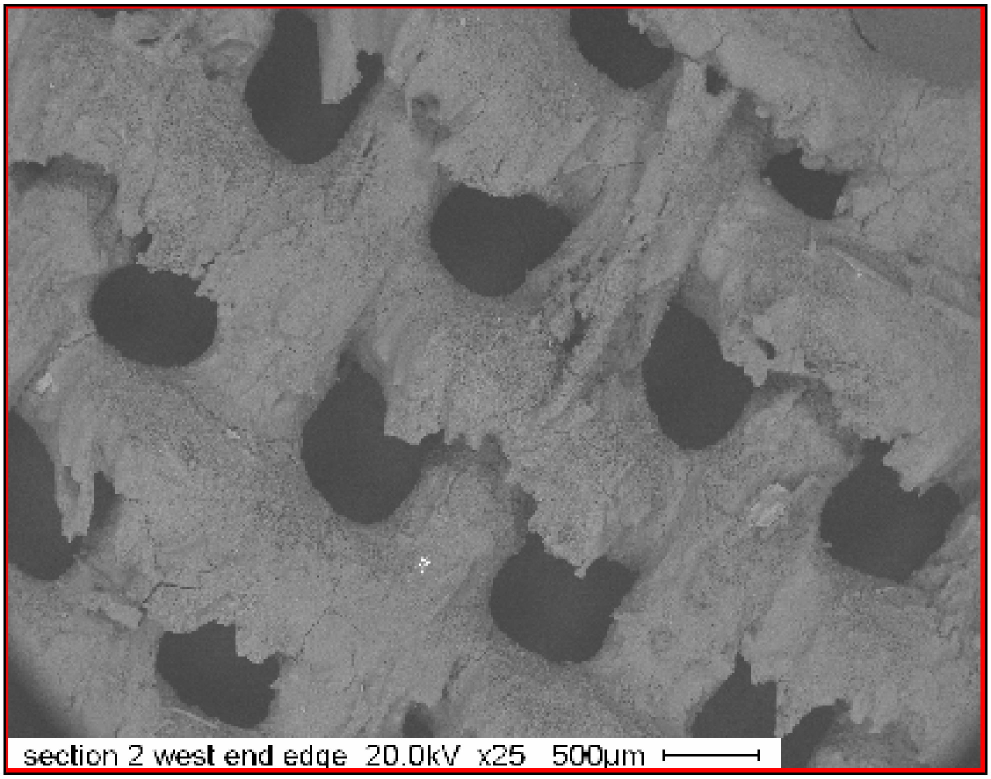


Section 2 west end middle-1

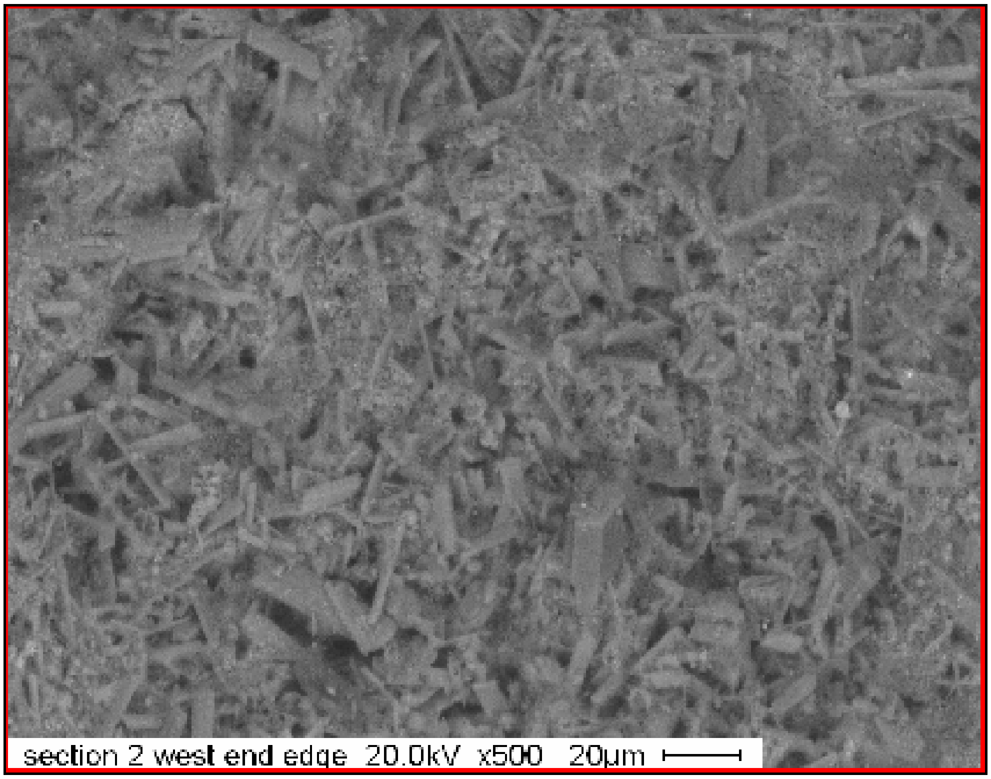
Section 2 west end middle-2 SEI



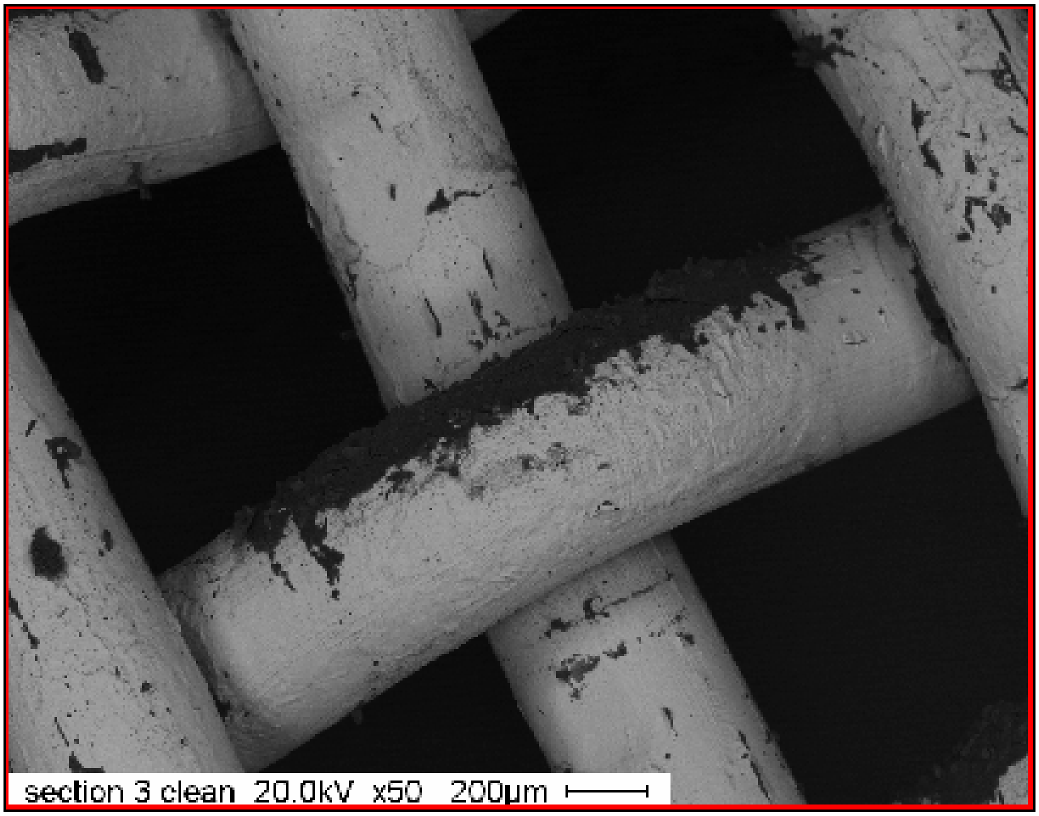
Section 2 west end middle-2 BEI

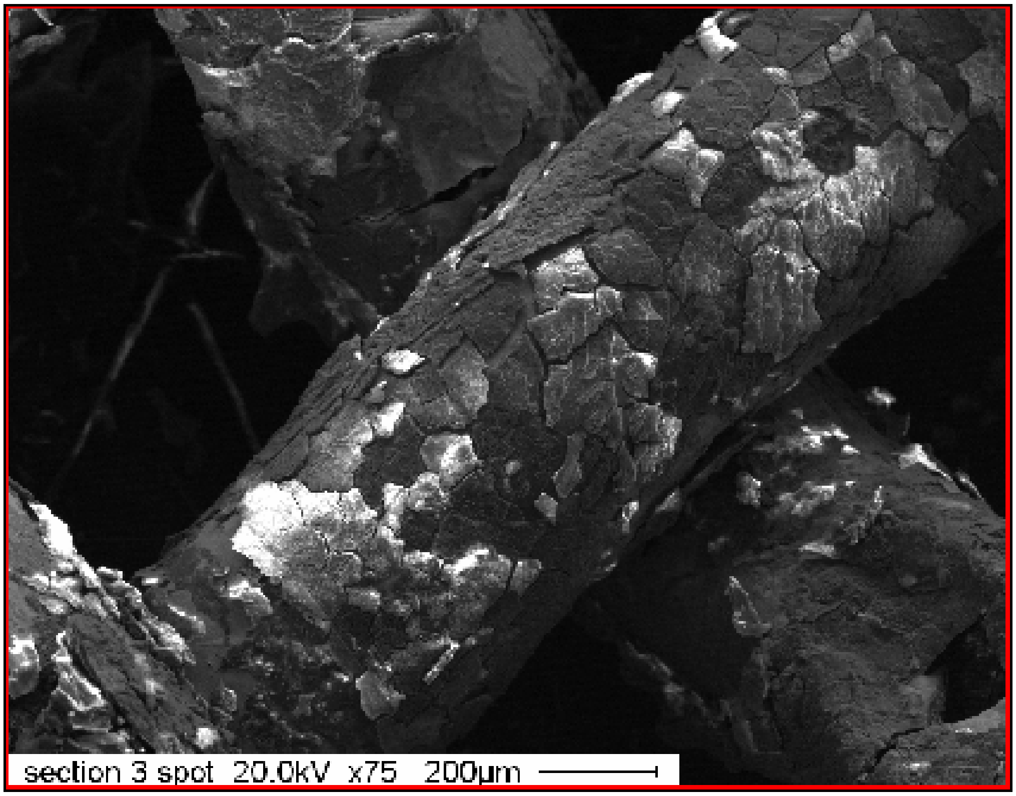


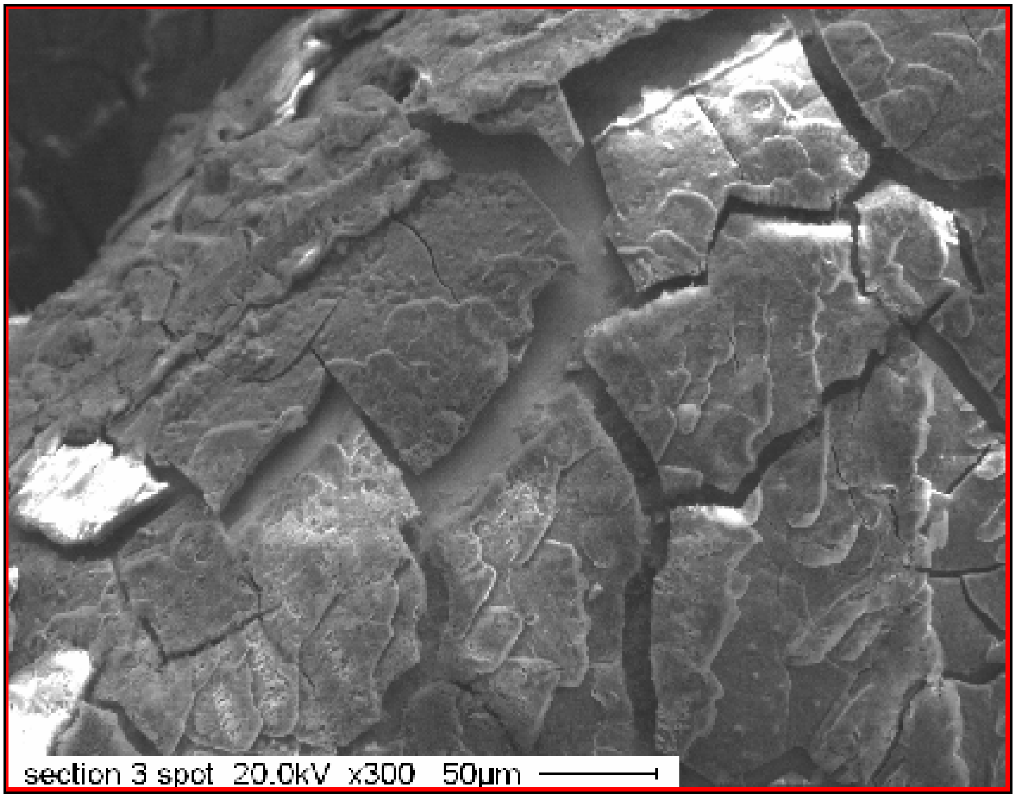
Section 2 west end edge BEI

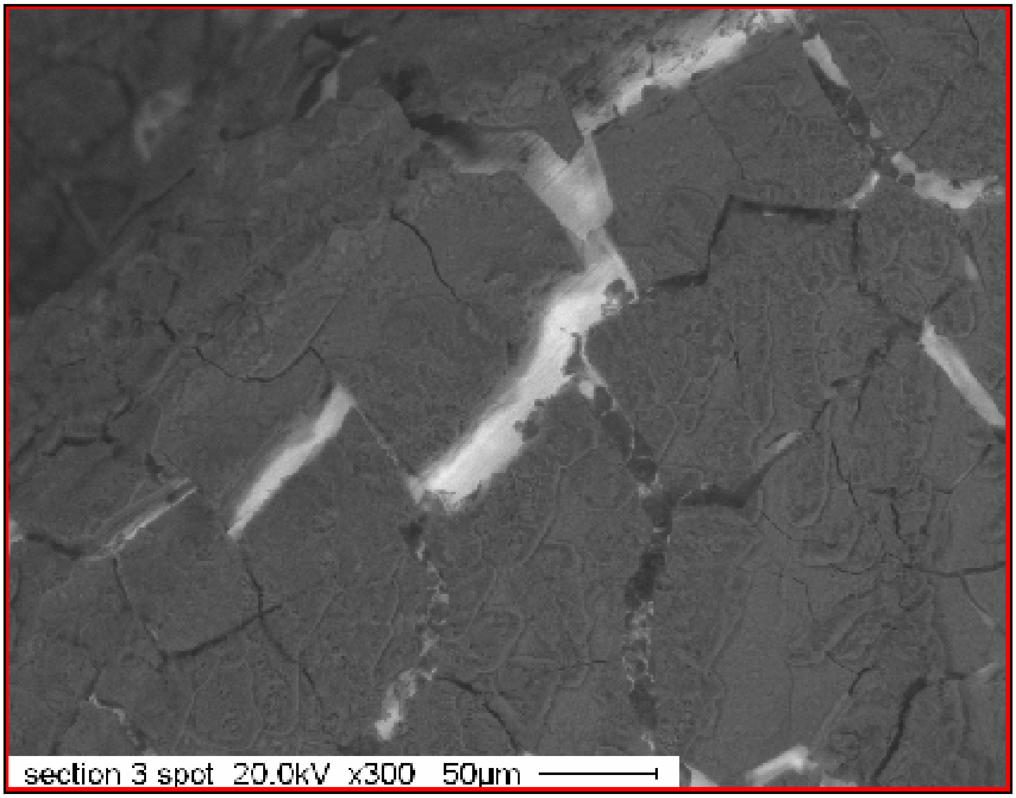


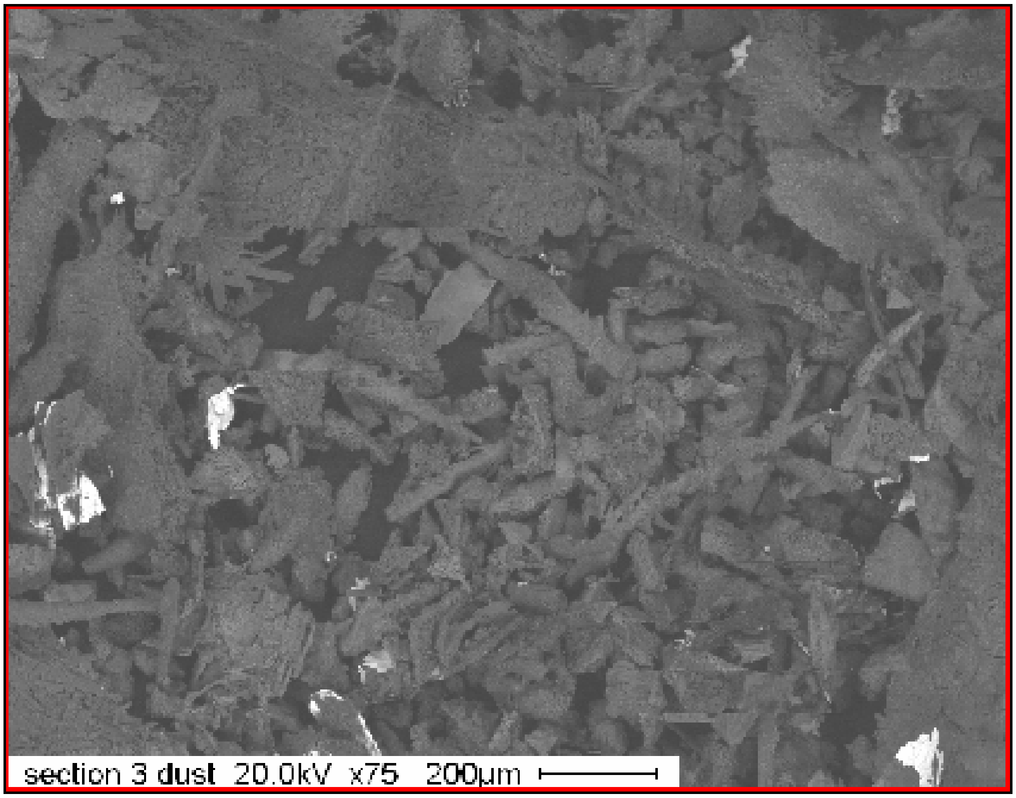
Section 2 west end edge BEI




section 3 spot 20.0kV x75 200µm


section 3 spot 20.0kV x300 50µm


section 3 spot 20.0kV x300 50µm


section 3 dust 20.0kV x75 200µm