

Fate of Mercury in Synthetic Gypsum Used for Wallboard Production

Topical Report, Task 2 Wallboard Plant Test Results

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ABSTRACT

This report presents and discusses results from Task 2 of the study “Fate of Mercury in Synthetic Gypsum used for Wallboard Production,” performed at a full-scale commercial wallboard plant. Synthetic gypsum produced by wet flue gas desulfurization (FGD) systems on coal-fired power plants is commonly used in the manufacture of wallboard. This practice has long benefited the environment by recycling the FGD gypsum byproduct, which is becoming available in increasing quantities, decreasing the need to landfill this material, and increasing the sustainable design of the wallboard product. However, new concerns have arisen as recent mercury control strategies involve the capture of mercury in FGD systems. The objective of this study is to determine whether any mercury is released into the atmosphere when the synthetic gypsum material is used as a feedstock for wallboard production. The project is being co-funded by the U.S. DOE National Energy Technology Laboratory (Cooperative Agreement DE-FC26-04NT42080), USG Corporation, and EPRI. USG Corporation is the prime contractor, and URS Group is a subcontractor.

The project scope includes five discrete tasks, each conducted at various USG wallboard plants using synthetic gypsum from different FGD systems. The five tasks will include 1) a baseline test, then variations representing differing power plant 2) emissions control configurations, 3) treatment of fine gypsum particles, 4) coal types, and 5) FGD reagent types. Process stacks in the wallboard plant are being sampled using the Ontario Hydro method. Two stack locations are being sampled on each task, from a dryer for the wet gypsum as it enters the plant and from a gypsum calciner. A third stack, from the dryer for the wet wallboard product, was not tested in this task but has been or will be tested as part of Tasks 1, 4 and 5. Also at each site, in-stream process samples are being collected and analyzed for mercury concentration before and after each significant step in wallboard production. The Ontario Hydro results, process sample mercury concentration data, and process data are being used to construct mercury mass balances across the wallboard plants.

Task 2 was conducted at a wallboard plant processing synthetic gypsum from a power plant that fires a medium- to high-sulfur bituminous coal. The power plant has a limestone forced oxidation FGD system, with the forced oxidation conducted in the reaction tank integral with the FGD absorber, and with no gypsum fines blow down. During the production of the synthetic gypsum used during this test, a selective catalytic reduction (SCR) system installed on this plant for NO_x emissions control was not in service (the catalyst was bypassed). Task 1 was conducted with material from the same power plant but with the SCR in service.

The results of the Task 2 stack testing, as measured by the Ontario Hydro method, detected only 0.3% of the gypsum mercury content being evolved from the raw gypsum dryer mill stack, and 2.6% loss from the gypsum calciner stack. About 90% of the mercury detected by the stack testing was in the form of elemental mercury. According to the project plan, stack testing was not conducted on the wallboard product dryer kiln stack. Analyses of process samples collected across the wallboard product dryer kiln indicated an additional 5% mercury loss there. The total mercury loss across the entire wallboard plant represented about 8% of the incoming synthetic gypsum mercury content.

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INTRODUCTION

This report presents and discusses results from Task 2 of the study “Fate of Mercury in Synthetic Gypsum used for Wallboard Production,” performed at a full-scale commercial wallboard plant. The objective of this project is to measure whether any mercury evolves from synthetic gypsum produced by wet flue gas desulfurization (FGD) systems on coal-fired power plants, when that material is used as a feedstock for wallboard production. The project is being co-funded by the U.S. DOE National Energy Technology Laboratory (Cooperative Agreement DE-FC26-04NT42080), USG Corporation, and EPRI. USG Corporation is the prime contractor, and URS Group is a subcontractor.

Background

To address concerns about air quality, the U.S. Congress passed the Clean Air Act Amendments of 1990, which placed significant restrictions on sulfur dioxide emissions from coal-fired power plants. To reduce sulfur dioxide emissions and meet the Clean Air Act standards, many electric utilities installed wet FGD systems on their coal-fired plants. These FGD systems combine the sulfur dioxide gases released during coal combustion with a sorbent such as limestone or lime. In many of these wet FGD systems, the resulting byproduct is oxidized to produce synthetic gypsum. The synthetic gypsum produced is commonly used as a feedstock for wallboard production. The reuse of the synthetic gypsum is environmentally beneficial and is also economically attractive for both the power and wallboard industries. The Clean Air Interstate Rule, signed by the U.S. EPA in March 2005, will further regulate sulfur dioxide emissions. Greater amounts of synthetic gypsum will be created, potentially causing a large increase in the volume of this material to going to landfills. Establishing wallboard manufacturing plants near both power plants and population centers can reduce the quantity landfilled, while increasing the sustainable design of the wallboard product by reducing transportation and use of fossil fuels.

A number of mercury control strategy plans for U.S. coal-fired power generating plants involve the capture of oxidized mercury from flue gases treated by wet FGD systems. For example, in finalizing the Clean Air Mercury Rule on March 15, 2005, the U.S. EPA recognized mercury emissions reduction “co-benefits” possible for coal-fired plants that are equipped with selective catalytic reduction (SCR) for NO_x control and wet FGD systems for SO₂ control. SCR systems on bituminous coal fired plants have been observed to oxidize most of the elemental mercury in the SCR inlet gas. Also, a number of proposed mercury control processes involve using low-temperature catalysts or injected chemicals to oxidize elemental mercury and promote increased mercury removal across FGD systems.

For these processes to be effective at overall mercury control, the mercury must stay in the FGD byproducts and not be re-emitted to the atmosphere or into ground water. Measurements by URS Group and others have indicated that nearly all of the mercury scrubbed from flue gases in most U.S. wet FGD systems ends up in the solid byproducts. Very little mercury is typically found in the FGD liquors. Thus, mercury stability in FGD solid byproducts is an important aspect of mercury capture in FGD systems.

Most FGD systems use lime or limestone reagent and employ forced oxidation to produce gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) as the solid byproduct. Much of the gypsum byproduct is reused, primarily as a feedstock for wallboard manufacturing. Those that do not produce gypsum instead produce a calcium sulfite hemihydrate ($\text{CaSO}_3 \cdot \frac{1}{2}\text{H}_2\text{O}$) byproduct. Most calcium sulfite byproducts are landfilled, although some is reused as mine fill.

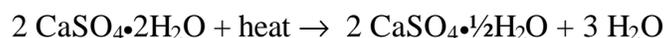
Approximately 70% of all of the FGD byproduct reuse in the U.S. is gypsum used as wallboard feedstock. During the year 2005, synthetic gypsum from FGD systems is expected to represent 30% of the U.S. wallboard plant feedstock.

This raises new technical questions: What is the fate of mercury in synthetic gypsum in the wallboard plant process? How much mercury is released into the atmosphere during the production of wallboard using synthetic gypsum? Is the amount of mercury released counterproductive to controlling mercury emissions from coal-fired power plants?

Even if mercury is not released in significant quantities during wallboard production, there remains a question as to the stability of mercury in the wallboard product. As an example, at the end of its product life cycle, most wallboard ends up in municipal landfills. What is the stability of mercury in wallboard produced from synthetic gypsum? Will the mercury leach into the acidic aqueous environment in a municipal landfill? This project is intended to collect data from commercial wallboard plants processing FGD synthetic gypsum to help answer these questions.

The Wallboard Production Process

Figure 1 shows an overview of the wallboard production process. In the process, synthetic gypsum is dried to produce “land plaster,” which is gypsum that contains no free moisture, only chemically bound waters of hydration. The land plaster is then calcined to produce the “beta” form of calcium sulfate hemihydrate according to the following chemical reaction:



The beta hemihydrate is also commonly called “stucco” or “plaster of Paris.” The stucco is subsequently mixed with water and a number of additives to form a slurry that is extruded between two sheets of paper to form the wallboard. The hemihydrate re-hydrates to form gypsum by the reverse of the reaction shown above. This re-hydration consumes much of the water in the slurry, and causes the gypsum formed to set up as a cohesive solid. The wet board travels down a conveyor belt while it is setting up. After adequate residence time to set up, the board is cut to approximate length then dried to remove free moisture (excess water not consumed by the re-hydration reaction). The dried product is cut to final length then stacked for shipping.

The initial gypsum drying and calcining steps described above occur in a section of the plant called the mill. The dryers are typically direct gas fired. Their purpose is to remove the free moisture in the synthetic gypsum (typically 8 to 12% by weight of the raw material) prior to calcining. The dryers consequently operate at temperatures well below the gypsum calcining temperature of 262°F. The solids are dried by direct contact between the wet particles and the hot

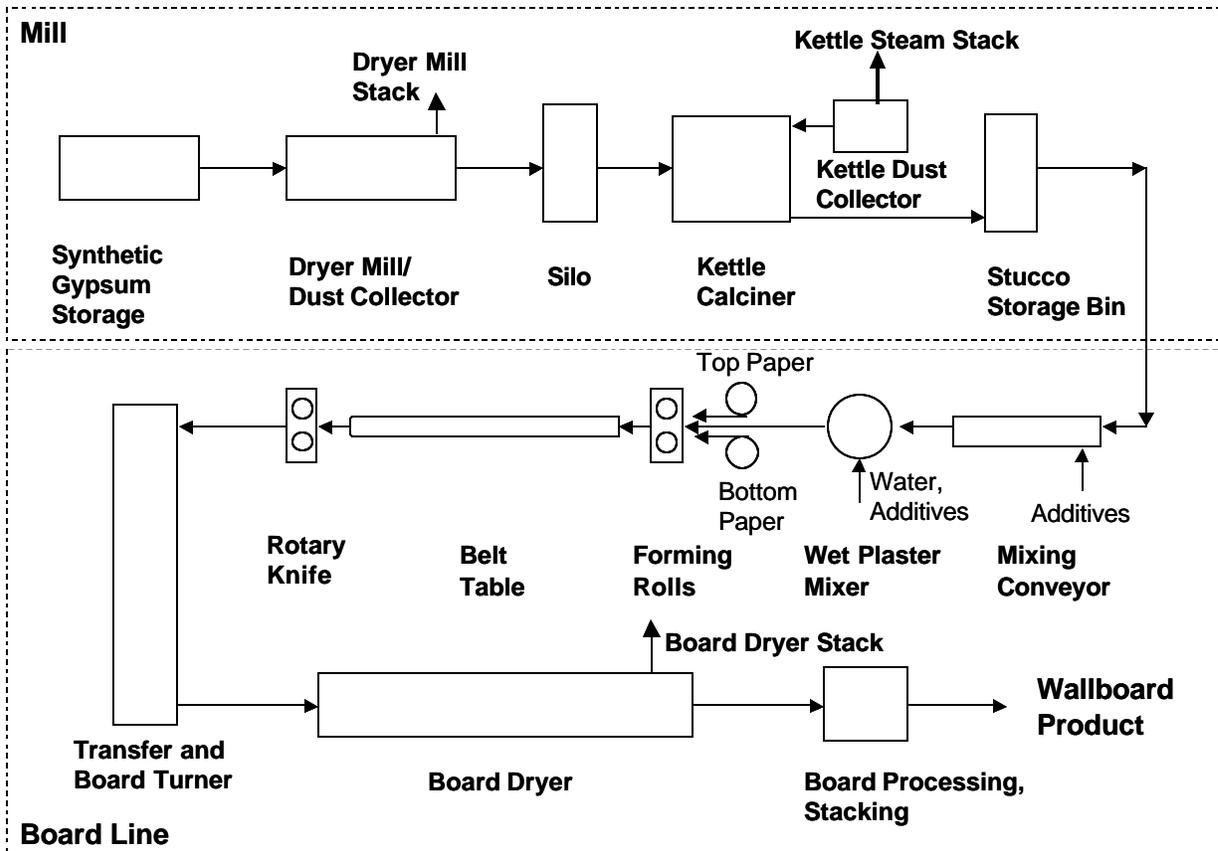


Figure 1. Simplified Schematic of the Wallboard Production Process Using Synthetic Gypsum Feedstock.

flue gas. The moisture-free synthetic gypsum (land plaster) is collected in mechanical collectors or a fabric filter and placed in intermediate storage silos prior to feeding to the calciners.

In the calcining step, the solids temperature must be raised above 262°F to promote release of 1-½ waters of hydration, but must be kept below 325°F to avoid forming anhydrous calcium sulfate (no remaining waters of hydration). The calciners used at the wallboard plant tested are indirect-fired kettle calciners, so the vent gas from the solids side of the kettle is primarily a mixture of steam and air. A kettle calciner dust collector removes fine stucco particles from this vent gas. The recovered fine particles are then incorporated into the product stucco. The stucco leaving the kettle is cooled and placed in a bin for intermediate storage, to provide a buffer between the mill and board line.

In the board line, the cooled stucco from the silo is fed to a mixer, where “gauging” water is added to form a viscous slurry. The gauging water is typically of high quality (e.g., potable water). A number of proprietary additives are mixed with the wet slurry produced from the stucco.

This wet slurry is continuously extruded between two sheets of paper that are fed from rolls above and below the extruder. One type of paper is used for the face of the wallboard product

and another for the back. The dimensions of the formed board are set by rollers and edge shoes. The formed board travels down a long conveyor belt that provides residence time for the stucco to re-hydrate and take a set. At the end of this belt, the formed board is cut and inverted so the face paper is facing up.

The board then enters a dryer. The dryer is zoned to operate over a range of temperatures, typically over 400°F at the dryer entrance and about 200°F at the exit. However, the board residence time in the dryer is controlled to limit the temperature of the dried board. This temperature must be limited to avoid any of the set-up solids re-calcining to the hemihydrate form. Thus, the bulk of the re-hydrated gypsum solids in the wallboard product stay well below 262°F in temperature. From the dryer, the dried board is cut to final size, has end tape applied, and is stacked for shipment.

Any potential mercury losses during the wallboard process are assumed to occur during the thermal processes, with losses most likely during the calcining step. The synthetic gypsum particles are raised to the highest temperature in the process during this step (above 262°F). Losses are also possible from the synthetic gypsum dryer and the finished wallboard dryer, although the maximum temperatures to which the gypsum is raised are lower in the dryers (approximately 170°F to 230°F).

Project Overview

This project is intended to provide information about the fate of mercury in synthetic gypsum produced by FGD systems on coal-fired power plants, when used as feedstock for wallboard production. Solid samples from various locations in the wallboard process, including the wallboard product, are being collected and analyzed for mercury content. Simultaneous flue gas measurements are being made using the Ontario Hydro method to quantify any mercury releases to the atmosphere during wallboard production. Most of the testing is concentrated in the mill processes where the synthetic gypsum is dried and calcined. Any potential mercury releases from the synthetic gypsum solids are thought to result from thermal desorption. It is in the mill portion of the process where the feedstock sees the highest process temperatures and where the evolution of waters of hydration may promote mercury desorption.

Initially, a limited amount of testing was to be conducted in the downstream board line, where the calcined gypsum is slurried, mixed with proprietary additives and formed into wallboard. The project plan was for the board dryer kiln stack flue gas to only be measured for mercury content at the first test site. Lesser mercury release was expected in the board kiln because it is downstream of the mill, and the re-hydrated gypsum solids typically see lower temperatures than in the mill. However, once results were available from Task 1, showing appreciable mercury loss from the board dryer kiln stack, stack testing for the board dryer kiln was added to the project scope for Tasks 4 and 5.

The solid and flue gas mercury concentration and plant process data are being used to calculate mercury balances across the operating wallboard plant.

Samples of each synthetic gypsum tested are being evaluated in laboratory simulated calcining tests to provide comparison data and evaluate a lab technique for screening synthetic gypsum

samples. Also, wallboard produced from synthetic gypsum will be leached according to the Toxicity Characteristic Leaching Procedure (TCLP) to provide an indication whether wallboard disposed of in municipal landfills will have a tendency to release mercury into groundwater.

The project will investigate wallboard produced from a variety of synthetic gypsum sources, all from FGD systems on coal-fired power plants, but from different coal types, power plant emissions control configurations and FGD conditions. The project is structured in five tasks. As shown in Table 1, each task involves one commercial wallboard plant test. This report summarizes the results from Task 2, which investigated a commonly used synthetic gypsum feedstock, produced by a power plant that fires high-sulfur bituminous coal and that has a limestone, forced oxidation (LSFO) FGD system that produces wallboard grade gypsum byproduct. The power plant also has an SCR for NO_x control, but the SCR was not in service (the catalyst was bypassed) when the gypsum tested was produced. The FGD system does not incorporate gypsum fines blow down.

Table 1. Project Test Matrix

Task	1	2	3	4	5
Synthetic Gypsum Source:					
Power Plant	A	A	B	C	D
Coal Type	High sulfur bituminous	High sulfur bituminous	High sulfur bituminous	Texas lignite	High sulfur bituminous
FGD Reagent	Limestone	Limestone	Limestone	Limestone	Lime
Forced Oxidation Mode	In Situ	In Situ	In Situ	In Situ	External
Gypsum Fines Blow Down?	No	No	Yes	No	Yes
SCR Status	In service	Bypassed	In service	No SCR	To be determined
USG Wallboard Plant Tested	1	1	2	3	1

Additional tasks include tests on synthetic gypsum feedstocks produced from:

- The same plant included in Task 2, but with the SCR operating. Since SCR catalysts have been observed to promote mercury oxidation, having the SCR in service may impact the amount of mercury captured in the FGD byproduct and could impact mercury losses during wallboard production,
- A high-sulfur, bituminous LSFO plant that employs gypsum fines blow down,
- A plant that fires a low rank coal (Texas lignite) rather than bituminous coal, and
- A plant that uses lime rather than limestone FGD reagent, and employs external rather than in situ forced oxidation.

Each of these variables is thought to impact the amount of mercury in the synthetic gypsum feedstock and/or possibly impact the stability of that mercury in the wallboard production process.

To investigate all five of these synthetic gypsum feedstocks, tests will be conducted at three different USG wallboard plants, since no one plant uses all five as a feedstock. The relationship between synthetic gypsum types and USG plants proposed for investigation is summarized in Table 1. Note that the power plants and USG wallboard plants are not identified by name, only by letter or number codes, in accordance with an agreement for anonymity at the beginning of the project.

This report presents and discusses the results of the wallboard plant testing conducted as part of Task 2, including Ontario Hydro measurements in the dryer mill and kettle calciner stacks, process sample mercury content, process data, and mercury balance results. A previous report has presented and discussed the results of the tests conducted as part of Task 1.¹ Planned laboratory evaluations, including simulated gypsum calcining tests and mercury leaching from wallboard product samples by TCLP, have not been completed yet and will be reported later in the project.

Report Organization

The remainder of this report is organized into four sections: Experimental, Results and Discussion, Conclusion, and References. The section entitled Experimental describes the experimental methods used to conduct the mercury testing at a commercial wallboard plant as part of Task 2, including stack testing, process sampling, and off-site chemical analyses. The Results and Discussion section presents results from the stack testing, process sample analyses, process data collected, and mercury balance calculations. The Conclusion section provides preliminary conclusions that can be made from the results of this commercial wallboard plant mercury test.

EXPERIMENTAL

A description of the project test matrix was provided in the Introduction section. This section begins with an explanation of the rationale used for choosing this particular FGD synthetic gypsum for the base case test conditions. The remainder of the section presents details of how the Task 2 wallboard plant mercury test was conducted, including stack testing by the Ontario Hydro method, process sample collection and analyses, and process data collection.

Rationale for Selecting the Synthetic Gypsum Tested

The Task 1 wallboard plant test involved testing the fate of mercury in synthetic gypsum from a high-sulfur, bituminous-coal-fired power plant equipped an operating SCR and with an LSFO FGD system that does not employ fines blow down (Power Plant A). This combination was selected for the first test because the synthetic gypsum produced at Power Plant A has a relatively high mercury content. Higher mercury content should enhance the accuracy of these tests. Furthermore, previous laboratory testing funded by EPRI² and initial full-scale tests by USG³ suggest that small measurable mercury losses could be expected from this feedstock during wallboard production. For these reasons, it was thought that testing this material as the first case might be a USG worst-case scenario for potential mercury losses during wallboard production.

Previous testing has shown that, at least for some plants that fire high-sulfur bituminous coal, having an SCR in service tends to increase the percentage oxidation of mercury in the flue gas upstream of an FGD system, and to increase the percentage capture of mercury in the FGD.^{4,5} Many plants that are equipped with SCR only operate them during the “ozone season,” from May 1 through September 30 each year, and bypass the SCR catalyst the remainder of the year. For such plants, one might expect that synthetic gypsum produced from their FGD systems would contain more mercury with the SCR operating during the ozone season than that produced during the remainder of the year.

Gypsum fines blow down is believed to be an important variable. Most synthetic gypsum used as a wallboard plant feedstock is subject to a number of quality control specifications by the wallboard manufacturer, including maximum moisture content, minimum gypsum content, maximum chloride content, and particle size distribution. A number of FGD variables affect the ability to meet the solids particle size distribution specification. These variables include the gypsum crystal residence time in the FGD absorber loop, FGD reagent chemical composition, and the amount of physical abrasion to which the crystals are exposed as they are recirculated and dewatered. Some FGD systems cannot meet the wallboard manufacturer’s particle size specification unless they separate a portion of the byproduct containing the smallest particle sizes. This separation is typically accomplished with hydrocyclones. The separated fines are either discarded or sold for other uses. Other plants need to purge a portion of the hydrocyclone overflow as a means of limiting chloride buildup in the FGD liquor. These plants blow down gypsum fines as part of the chloride purge. In still other plants, there is no need to separate the fines and/or purge chlorides, and the fines are included in the byproduct sent to the wallboard plant.

Laboratory testing conducted by URS for EPRI has indicated that the mercury concentration in gypsum fines can be as much as an order of magnitude higher than in the larger particles.² This suggests that mercury precipitates and/or adsorbs at gypsum surfaces, since the fines have a much higher surface area to mass ratio than larger particles. It is also possible that mercury adsorbs on or precipitates with fine particles of impurities that enter the FGD system with fly ash in the flue gas or with the FGD reagent. Upwards of half of the mercury removed by the FGD system can be in the fines. Fines blow down therefore significantly lowers the mercury concentration in the synthetic gypsum byproduct going to the wallboard plant.

Task 2 involved testing at Wallboard Plant 1 and with gypsum from Power Plant A, as during Task 1, but with material produced while the SCR was not in service (catalyst bypassed). As for the material tested as part of Task 1, the Power Plant A FGD system was operated without fines blow down. It was expected that with the SCR out of service the synthetic gypsum produced from the Power Plant A FGD system would contain less mercury than during the ozone season, with the SCR in service. It was thought that if less mercury were contained in the gypsum produced with the SCR out of service, it might correspondingly reduce the amount of mercury thermally evolved in the wallboard plant.

Commercial Wallboard Plant Test Procedures

Commercial wallboard plants often operate with a blend of feedstocks from a number of FGD systems. Rarely does one power plant generate enough synthetic gypsum to feed the entire production of a modern wallboard plant, so most wallboard plants process synthetic gypsum from two or more power plants. Each synthetic gypsum has unique processing conditions within the wallboard plant process. Therefore, to minimize excessive swings in wallboard plant operating conditions, most plants blend the available feedstocks to produce an “average” material for processing.

However, for this test, Wallboard Plant 1 was operated on 100% feedstock from Power Plant A. It would be difficult to elucidate the effects of power plant and FGD variables on mercury losses during wallboard production if synthetic gypsum blends were being processed during measurements. Also, the feedstock to the mill typically contains recycled material, which can include recycled wallboard, wallboard samples, material recycled from the calciner during shut downs, etc. Because recycle consists of material from a variety of sources, it was felt that recycle would add variability to the incoming feed mercury concentration and possibly its stability. Therefore, the wallboard plant test was conducted with no recycle feed to the plant and during the use of Power Plant A synthetic gypsum only.

Two periods of wallboard plant testing were conducted in USG Wallboard Plant 1, with the first in the mill and the second in the board line as described below. Figure 2 illustrates the wallboard production process. Process streams that were sampled as part of the test, as described below, are marked with “S” followed by a number that represents a sample location. The sample numbers are used in the data tables later in the report.

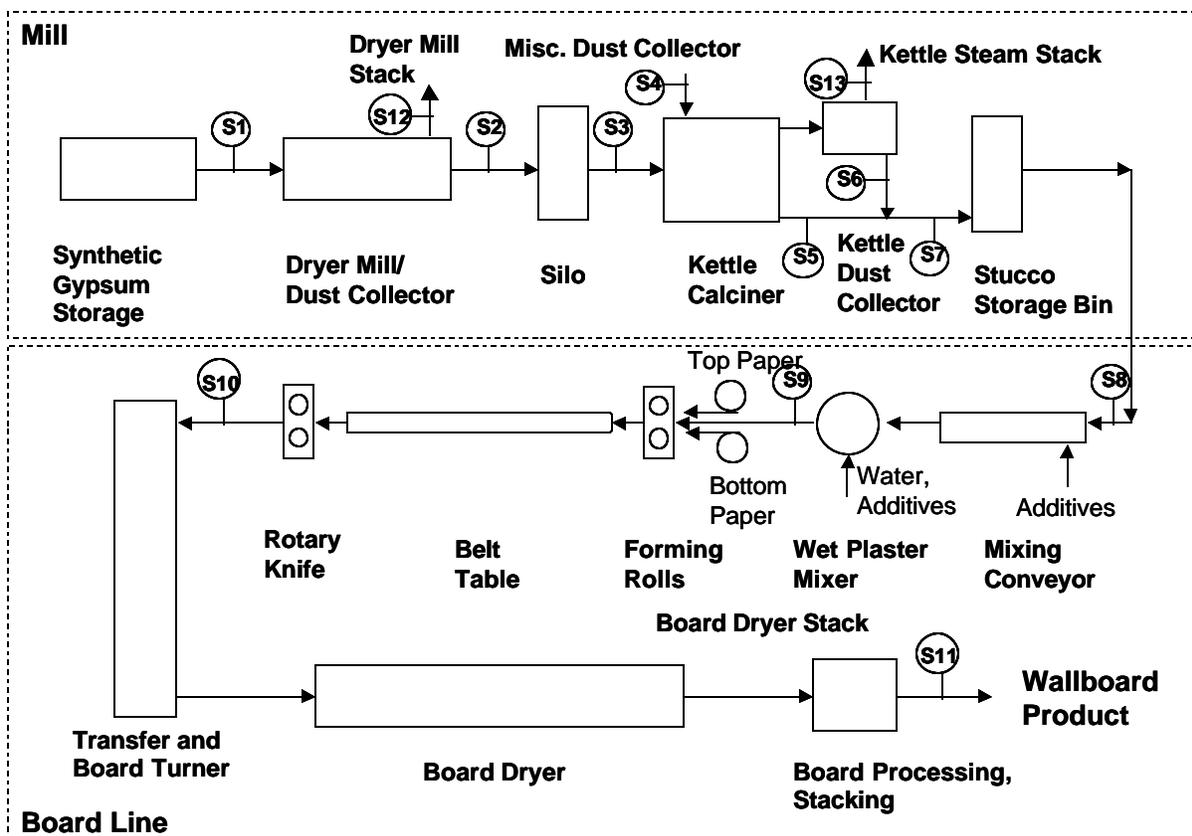


Figure 2. Schematic of a Wallboard Plant Showing Task 2 Sampling Locations

Mill Testing

Stack Sampling

On the first test day, simultaneous gas measurements were conducted using the Ontario Hydro Method (ASTM D6784-02) on a gypsum dryer (dryer mill) stack and the downstream kettle calciner steam stack on a single train of the plant. However, note that the method was modified slightly for sampling at the kettle calciner steam stack, as described below. Triplicate runs were made at each of these two locations.

The kettle calciners are indirect-fired vessels. The gaseous stream from the calciner that could contain mercury from the synthetic gypsum is the “steam stack,” which is a mixture of the water calcined from the gypsum when forming stucco ($\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$) and aeration air introduced at the bottom of the kettle. The other stack from the kettle calciner contains the flue gas from the burners, which are natural gas fired. This stream is not expected to have measurable mercury content.

The steam stack gas is significantly wetter than and typically does not contain species present in coal flue gases (e.g., CO_2 , SO_2 and HCl), for which the Ontario Hydro Method was developed and validated. Consequently, the method was modified slightly to ensure proper sampling and speciation under these conditions.

As mentioned above, the kettle calciner steam stack gas is mostly water. Since the Ontario Hydro Method measures mercury in a dry gas sample, it was speculated that the mercury content of the dry gas, which represents less than half of the total gas stream, could be greater than 100 $\mu\text{g}/\text{Nm}^3$, which is the stated upper measurement limit for which the method was developed.⁶ When sampling above this limit, there was concern that reagents in the collection impingers would be depleted. To avoid this issue and to reduce the quantity of water collected in the impingers during the run, the Ontario Hydro runs on the kettle calciner were reduced in duration from 120 minutes to approximately 60 minutes. Also, additional impinger volume was added to the train to collect the large amount of condensed moisture expected.

The dryer mill is direct fired, so its stack gas is a true flue gas and the standard Ontario Hydro Method should be appropriate for sampling this stream. Therefore, the dryer mill Ontario Hydro sampling runs were for a full 120 minutes, as per the method. The kettle calciner sampling runs were started about 30 minutes after the dryer mill runs began, so the kettle calciner sample would be collected in the middle of the dryer mill sample collection period.

Process Sampling

During each of the three runs, process samples were collected from the dryer feed solids, dryer product solids (land plaster to intermediate silo), calciner feed (land plaster from intermediate silo), and calciner product stucco to the stucco storage bin. These four streams represent the feeds and products for the dryer mill and kettle calciner. Three additional solid stream samples were collected: the solids collected in a “miscellaneous” dust collector from transfer points in the mill, which are added to the calciner feed solids; the solids collected from the kettle calciner dust collector, which are incorporated into the product stucco; and the stucco solids exiting the kettle calciner, prior to having the dust collector solids added. These three sample types were analyzed for mercury concentration, but these data were not used for any of the mercury balance or mercury loss calculations.

All seven of these process solids samples were collected as “grab” samples during the middle part of each Ontario Hydro run. No attempt was made to collect time-integrated samples, e.g., by collecting small sample aliquots at periodic intervals throughout the Ontario Hydro sampling periods and compositing the aliquots into a single sample. It was felt that the incoming raw gypsum would be homogenous enough that one grab sample per run would adequately represent the feedstock and other process solids. These 21 grab samples (seven locations times three Ontario Hydro runs) were subsequently analyzed for mercury content, moisture content, and other parameters.

Process data were also collected for the run period, including dryer and calciner feeder speeds and operating temperatures.

Board-Line Testing

Stack Testing

According to the project plan, no stack sampling was conducted on the board dryer kiln stack gas as part of Task 2; only process samples were collected. Samples were collected of the feed

stucco, the slurry fed to the board forming machine, and the wet and dry product wallboard. The timing of this sample collection was coordinated with the plant to approximately correspond with the processing of stucco material calcined during the previous mill testing. This took into account the residence time in the stucco storage bin between the mill and board line, although such timing could not be exact. Triplicate sample sets were collected, spaced apart in time roughly corresponding with the elapsed time between the three previous Ontario Hydro measurement runs in the mill.

As for the mill testing effort, key process data were collected for the board-line sample collection period. These data included the stucco feed rate, water and additive feed rates (not included in this report), paper thickness and weight, board production rate, and the dryer flue gas temperatures.

As the Task 2 sampling effort was completed, all process and Ontario Hydro method samples were recovered, stabilized, and labeled, then shipped to URS and USG laboratories for analyses. Method blanks and reagent blanks for the Ontario Hydro method samples were included with the sample sets as a quality assurance/quality control measure.

Representative coal samples and power plant and FGD process data were also collected by the utility operating Power Plant A that produced the synthetic gypsum being evaluated. The coal samples will be analyzed for ultimate and proximate analyses, chlorine and mercury content. The coal data along with the power plant and FGD process data will be used to document typical conditions under which the synthetic gypsum evaluated was produced.

All of the mill and board-line process samples collected were analyzed for mercury content by cold vapor atomic absorption after digestion in hydrofluoric acid. A number of samples were analyzed for other parameters, including gypsum moisture content, particle size distribution, specific surface area, and chloride content.

The mercury concentration analytical results, along with plant process data, were used to construct a mercury balance across the mill and the board line. The mercury balances show individual stream flow rates and mercury concentrations (except for the additives used in the board line), the amount of mercury entering and leaving the plant in each process stream, and overall mercury mass balance closures. Data are shown for individual sampling runs and as means and 95% confidence intervals about the means for the triplicate measurements.

The coal data, power plant data, and FGD process data from the power plant producing the synthetic gypsum evaluated have not yet been collected and tabulated. These data will be reported later in the project.

RESULTS AND DISCUSSION

This section provides technical results for the Task 2 wallboard plant test. Results presented include gypsum and process sample analysis results, Ontario Hydro flue gas measurement results, plant process data, and mercury balance results. Each type of result is discussed in a separate subsection below.

Gypsum and Process Sample Mercury Analysis Results

Table 2 summarizes the results of mercury and free moisture content analyses conducted by URS on the raw gypsum, stucco product, and intermediate process samples collected during the mill test on December 1, 2004. Table 3 shows results for additional characterization of these samples conducted by USG, including mercury and moisture content (both free and combined [water of hydration] moisture) as well as other parameters. Table 4 shows the results for mercury and free moisture content analyses conducted by URS on stucco, wallboard product, and intermediate process samples collected from the board line later in the evening of the same day.

Table 2. Task 2 Raw Gypsum and Mill Process Sample Mercury and Moisture Analyses, URS Results

Sample Number	Sample Description	Mercury Content, mg/g (dry basis)					Free Moisture Content, wt% as received			
		Run 1	Run 2	Run 3	Mean	95% C.I.*	Run 1	Run 2	Run 3	Mean
S1	Raw Gypsum Feed to Dryer Mill	1.13	1.11	1.07	1.10	±0.04	11.1	11.1	11.2	11.1
S2	Land Plaster from Dryer Mill	1.08	1.08	1.02	1.06	±0.04	0.04	0.06	0.07	0.06
S3	Land Plaster to Kettle Calciner	1.11	1.13	1.12	1.12	±0.01	0.06	0.06	0.06	0.06
S4	Misc. Dust Collector Solids to Kettle Calciner	1.46	1.51	1.57	1.51	±0.06	0.32	0.28	0.33	0.31
S5	Kettle Calciner Product, as measured	1.18	1.18	1.20	1.20	±0.02	0.01	<0.01	0.24	0.08
	Kettle Calciner Product, dry gypsum basis	1.01	1.04	1.03	1.02	±0.02	-	-	-	-
S6	Kettle Calciner Dust Collector Solids, as measured	2.11	2.08	2.16	2.12	±0.05	0.30	0.24	0.37	0.30
	Kettle Calciner Dust Collector Solids, dry gypsum basis	1.84	1.81	1.88	1.84	±0.04	-	-	-	-
S7	Product Stucco, as measured	1.21	1.20	1.19	1.20	±0.01	0.20	<0.01	0.59	0.26
	Product Stucco, dry gypsum basis	1.03	1.02	1.02	1.02	±0.01	-	-	-	-

*95% Confidence Interval of mean

Table 3. Task 2 Raw Gypsum and Mill Process Sample Characterization, USG Results

Sample	Run	Moisture Content, wt%		Mercury Content, mg/g		Soluble Salts, ppm		Particle Size Distribution (microns)			Blaine Surface Area, cm ² /gm	
		Free	Com-bined	As measured, dry basis	Dry Gypsum basis	Total	Cl ⁻	Mean Dia.	Particle Size at % Less Than			
									10%	50%		95%
S1 – Raw Gypsum Feed to Dryer Mill	1	12.0	20.3	1.00	1.00	71.8	51.0	50.8	24.6	45.3	97.7	1132
	2	11.1	20.2	1.07	1.07	60.9	43.1	51.1	24.8	45.4	98.5	1110
	3	11.6	20.2	1.05	1.05	113	51.9	49.4	23.8	44.4	94.9	1168
Mean		11.6	20.2	1.04	1.04	81.9	48.7	50.4	24.4	45.0	97.0	1137
95% C.I.*		±0.6	±0.0	±0.04	±0.04	±31.1	±5.5	±1.1	±0.6	±0.7	±2.2	±33
S2 – Land Plaster from Dryer Mill	1	0.07	19.4	0.98	0.97	108	61.1	48.3	22.6	43.0	93.9	1257
	2	0.06	19.4	0.94	0.93	83.8	59.5	47.3	22.1	42.7	91.3	1290
	3	0.07	19.5	1.03	1.02	94.6	57.3	51.2	24.6	45.9	97.8	1233
Mean		0.07	19.4	0.98	0.97	95.4	59.3	48.9	23.1	43.9	94.3	1260
95% C.I.		±0.01	±0.1	±0.05	±0.05	±13.6	±2.2	±2.3	±1.5	±2.0	±3.7	±32
S3 – Land Plaster to Kettle Calciner	1	0.06	18.9	1.02	1.00	108	57.3	47.9	22.3	43.2	93.2	1327
	2	0.09	19.0	1.05	1.03	86.7	52.9	47.7	22.2	43.1	92.4	1303
	3	0.08	18.8	1.10	1.08	89.8	57.7	47.6	22.0	43.4	92.1	1354
Mean		0.08	18.9	1.06	1.04	94.7	56.0	47.7	22.2	43.2	92.6	1328
95% C.I.		±0.02	±0.1	±0.05	±0.05	±12.8	±3.0	±0.2	±0.1	±0.1	±0.7	±29
S4 – Misc. Dust Collector Solids to Kettle Calciner	1	0.11	6.93	NA [#]	NA	155	66.6	39.7	14.8	35.5	82.0	2518
	2	0.05	6.87	NA	NA	206	79.8	38.0	13.9	34.5	78.1	2721
	3	0.05	6.87	NA	NA	170	81.4	38.3	14.8	34.9	77.5	2773
Mean		0.07	6.89	-	-	177	75.9	38.6	14.5	35.0	79.2	2671
95% C.I.		±0.04	±0.04	-	-	±30	±9.2	±1.1	±0.6	±0.6	±2.8	±152
S5 – Kettle Calciner Product	1	0.03	6.57	1.20	1.02	204	77.4	47.6	21.8	42.6	93.9	2129
	2	0.03	6.54	1.20	1.03	200	70.5	47.0	22.2	42.7	91.0	2074
	3	0.00	6.47	1.25	1.07	147	64.6	47.3	22.2	42.9	92.1	2118
Mean		0.02	6.53	1.22	1.04	184	70.8	47.3	22.1	42.7	92.3	2107
95% C.I.		±0.02	±0.06	±0.03	±0.03	±36	±7.2	±0.3	±0.3	±0.2	±1.7	±33
S6 – Kettle Calciner Dust Collector Solids	1	0.15	8.15	NA	NA	249	92.2	32.6	10.9	29.7	67.4	3391
	2	0.11	8.26	NA	NA	237	39.3	32.7	10.6	30.0	67.0	3107
	3	0.16	8.28	NA	NA	184	86.4	31.6	10.4	28.9	65.2	3214
Mean		0.14	8.23	-	-	223	72.6	32.3	10.6	29.6	66.5	3237
95% C.I.		±0.03	±0.08	-	-	±39.5	±32.8	±0.7	±0.3	±0.6	±1.3	±162
S7 – Product Stucco	1	0.00	6.50	1.20	1.02	220	77.9	48.0	22.0	43.0	94.5	2030
	2	0.00	6.38	1.25	1.07	181	68.0	46.9	21.9	42.6	91.0	2052
	3	0.00	6.47	1.22	1.04	189	80.8	46.6	21.6	42.3	90.7	2173
Mean		0.00	6.45	1.22	1.04	197	75.6	47.1	21.8	42.6	92.0	2085
95% C.I.		-	±0.07	±0.03	±0.03	±23	±7.6	±0.8	±0.3	±0.4	±2.4	±87

*95% Confidence Interval of mean

#NA – results not available

Table 4. Task 2 Stucco, Wallboard Product and Intermediate Process Sample Mercury Analyses, URS Results

Sample Number	Sample Description	Mercury Content, mg/g (dry basis)					Free Moisture Content, wt% as received			
		Run 1	Run 2	Run 3	Mean	95% C.I.	Run 1	Run 2	Run 3	Mean
S8	Stucco Feed, as measured	1.15	1.19	1.22	1.19	±0.03	<0.01	<0.01	<0.01	<0.01
	Stucco Feed, dry gypsum basis	0.97	1.00	1.03	1.00	±0.04	<0.01	<0.01	<0.01	<0.01
S9	Slurry to Forming Rolls	1.00	1.01	1.10	1.04	±0.04	27.3*	28.2*	29.9*	28.5*
S10	Wet Wallboard	0.96	0.98	1.02	0.98	±0.03	#	#	#	#
S11	Dry Wallboard Product	0.88	0.93	0.98	0.93	±0.03	<0.01	<0.01	<0.01	<0.01

*Moisture content measured after sample set up, consuming some free moisture to rehydrate the stucco

Samples were not stored in a sealed bag, and had air dried by the time the analysis was conducted, no moisture content measured

In each of these three tables and throughout this section of the report, a mean and a 95% confidence interval about that mean are shown for key values in the table. The mean values represent the arithmetic average of the results from three runs, while the 95% confidence interval is a measure of observed variability of that value during the three runs. Specifically, the 95% confidence interval represents a range above and below the mean for the three runs in which we have a 95% confidence level that the true average for these three measurements would lie. The 95% confidence interval values were all calculated using the “CONFIDENCE” worksheet function in Microsoft Excel 2003[®] spreadsheet software.

The results from the URS analyses in Table 2 show that the raw gypsum feedstock, product stucco, and intermediate samples were relatively consistent in mercury content from run to run. The 95% confidence intervals about the mean values, also shown in the table, represent relatively small percentages of the measured values. The raw gypsum feed contained a mean value of 1.10 µg/g (ppm) of mercury and 11.1% moisture, the latter of which is within the typical range for FGD gypsum.

The mercury concentration was higher than was measured in Task 1 for gypsum from Power Plant A with the SCR in service (0.96 µg/g). This result is surprising. It was expected that the gypsum mercury concentration measured during Task 2 would be lower than in Task 1 because the SCR was not in service and the catalyst was being bypassed when this gypsum was produced. As discussed earlier in this report, SCR catalysts have been previously observed to oxidize elemental mercury in flue gases from bituminous coal, and promote greater mercury capture in wet FGD systems. This result suggests that the SCR at Power Plant A has little effect on mercury oxidation and capture by the FGD system, and/or that effects of variability in the coal mercury content are more significant than the SCR effect for this plant.

As at Wallboard Plant 1, the kettle calciner dust collector solids showed significantly higher mercury concentrations than the other process streams. This is likely because it is the finer

gypsum particles with greater surface area, and stucco formed from these particles, that are collected in the dust collector. Also, note that, notwithstanding potential mercury losses in the kettle calciner, mercury should be more concentrated in the kettle calciner product and in the product stucco than in the upstream samples, because of the evolution of 1½ waters of hydration in the calciner. For this reason, additional rows of data are shown in Table 2 expressing the mercury content in the stucco samples (S5, S6 and S7) on a dry gypsum basis. This accounts for the effects of the loss of waters of hydration by the stucco. The adjusted values can be compared directly to see apparent mercury losses across the dryer mill and kettle calciner.

The results of USG analyses in Table 3 are similar to results reported previously for the Task 1 tests at Wallboard Plant 1, also while processing gypsum from Power Plant A, and show expected trends. The raw gypsum had a mean particle diameter of 50 microns and a Blaine surface area of about 1100 cm²/g. Downstream of the dryer mill, all of the samples contained essentially no free moisture (0.1 wt% or less), and calcining increased the Blaine surface area to about 2100 cm²/g. The surface area increase is due to the loss of waters of hydration from the particles. The USG analyses show that the raw gypsum contained 11.6% free moisture on average, which is in relatively good agreement with the value of 11.1% from the URS analyses as shown in Table 2.

The USG mercury analyses range from being 7% lower than to 2% greater, on average, than the corresponding URS analysis results. This is considered good agreement between two labs using different analytical techniques to analyze different aliquots from the same sample.

As was seen in the Task 1 results, the samples from both dust collectors tended to have smaller mean particle sizes and higher Blaine surface areas than the solids in the main process streams. These results are likely because it is the finer gypsum and gypsum impurity particles, and land plaster or stucco formed from these particles, that are collected in the dust collectors.

The results from the board-line testing in Table 4 show that the mean mercury concentration in the stucco feed to the wallboard plant (1.19 µg/g) was identical to the mean for the product stucco going to the stucco storage bin during the mill tests. This suggests that the attempt to time-phase the board-line sampling to reflect the stucco produced in the mill the day before was successful, and/or that the stucco mercury concentration is relatively consistent for this feedstock.

Conversely to what was described for the kettle calciner, in the board line, the slurry and wallboard should have lower mercury concentrations than the feed stucco due to the 1½ waters of hydration gained on re-hydration of the stucco. To account for this effect, a row has been added to Table 4 showing the feed stucco mercury concentration on a dry gypsum basis. This allows any loss of mercury from the feed stucco to be observed directly by comparing mercury concentrations of the feed and product on a common dry gypsum basis. However, the effects of mercury in the additives, water, and paper added in the board line on the mercury content of the wallboard product must also be considered, as addressed later in this section in the mercury mass balance discussion.

Ontario Hydro Stack Sampling Results

The Ontario Hydro Method stack sampling results are summarized in following tables. Table 5 summarizes gas flow rate, temperature, and major component concentrations. The results in the table show that the dryer mill stream composition was consistent with a very dilute flue gas from natural gas firing, with only 2% CO₂ and 18% oxygen. The moisture content was relatively high at 16% due to the free moisture from the gypsum that is evolved in the dryer. The dryer mill flue gas temperature was less than 200°F, as would be expected because of the need to keep the dried gypsum below its initial calcining temperature of 262°F.

Table 5. Task 2 Ontario Hydro Results – Summary of Exhaust Gas Conditions

Sample Number	Run No.	Date (2005)	Time (24-h)	Flow Rate		Temperature (°F)	H ₂ O (%)	CO ₂ (%)	O ₂ (%)
				acfm*	dscfm [#]				
Dryer Mill (1 of 2)									
S12	1	12/1	0938-1144	58,700	39,900	172	14.7	1.0	18.9
	2	12/1	1253-1459	58,900	40,400	173	14.7	1.1	19.0
	3	12/1	1548-1754	58,100	39,800	173	14.8	1.1	18.8
	Mean			58,600	40,000	172	14.8	1.1	18.9
Kettle Calciner (1 of 2)									
S13	1	12/1	1008-1117	13,900	4,280	260	56.0	0.0	20.9
	2	12/1	1321-1433	14,100	4,390	262	55.7	0.0	20.9
	3	12/1	1620-1728	14,200	4,440	260	55.7	0.0	20.9
	Mean			14,100	4,370	261	55.8	0.0	20.9

*acfm = Actual cubic feet per minute at stack conditions

[#]dscfm = Dry standard cubic feet per minute; standard conditions are 68°F, 29.92 in.Hg, and 0 percent moisture

The kettle calciner results for exhaust gas composition showed that, as expected, the stream consisted primarily of air and steam evolved from the gypsum in the calciner. In the Task 1 testing, the kettle calciner exhaust gas showed elevated CO₂ concentrations and lowered oxygen concentrations, an indication of a flue gas leak into the indirect-fired side of the kettle. This had apparently been corrected by the time the Task 2 testing was conducted. The measured moisture content of the kettle calciner steam stack gas was quite high, at 56%, mostly due to the waters of hydration released from the gypsum. The stack moisture content was about the same during the Task 1 sampling at Wallboard Plant 1.

Table 6 summarizes the mercury concentration and mass rate data. These results show that for both stacks, the mercury was almost entirely in the elemental form (Hg⁰). This is quite surprising, given that it is predominantly water-soluble oxidized mercury (Hg⁺²) that is removed in wet FGD systems, while elemental mercury is virtually insoluble and not removed at significant percentages. However, the same effect was seen in the Task 1 results at Wallboard

Plant 1. There is still no clear explanation for this phenomenon. One possibility is that a portion of the oxidized mercury absorbed in the FGD system undergoes reduction reactions after the mercury is deposited in the byproduct solids, to reduce a portion of the oxidized mercury to the elemental form. Note that in the elemental form, mercury is not expected to readily deposit near the point of emission but ascends into the atmosphere and contributes to the overall global cycle.⁷

Table 6. Task 2 Ontario Hydro Results – Speciated Mercury Emissions Data

Sample Number	Run No.	Date (2005)	Time (24-h)	Concentration ($\mu\text{g}/\text{Nm}^3$)*				Total Mercury Emission Rate (lb/h) [#]
				Particle-Bound, Hg^{P}	Oxidized, Hg^{+2}	Elemental, Hg^0	Total Hg	
Dryer Mill (1 of 2)								
S12	1	12/1	0938-1144	0.08	<0.07	2.36	2.44	3.64×10^{-4}
	2	12/1	1253-1459	0.09	<0.07	1.97	2.06	3.12×10^{-4}
	3	12/1	1548-1754	0.08	<0.07	0.62	0.70	1.04×10^{-4}
	Mean			0.08	<0.07	1.65	1.73	2.60×10^{-4}
	95% Confidence Interval			0.01	-	1.03	0.91	1.56×10^{-4}
Kettle Calciner (1 of 2)								
S13	1	12/1	1008-1117	1.34	14.3	155	170	2.73×10^{-3}
	2	12/1	1321-1433	2.55	13.1	151	167	2.74×10^{-3}
	3	12/1	1620-1728	2.63	21.0	145	169	2.80×10^{-3}
	Mean			2.18	16.1	150	169	2.76×10^{-3}
	95% Confidence Interval			0.82	4.8	6	2	0.04×10^{-3}

* $\mu\text{g}/\text{Nm}^3$ = Micrograms per normal cubic meter (dry gas at 32°F, at as measured O_2 concentration)

[#] lb/h = Pounds per hour

The total mercury concentration data show that on a dry gas basis, the concentrations in the kettle calciner steam stack are greater than $100 \mu\text{g}/\text{Nm}^3$, while the dryer mill stack averaged less than $2 \mu\text{g}/\text{Nm}^3$. However, the dry flue gas rate at the kettle calciner stack is much lower than from the dryer mill stack. When the mercury emissions are compared on a mass basis, the losses at the kettle calciner steam stack are still a factor of 10 higher than from the dryer mill stack. In the Task 1 results, there was less difference between the mass emissions rate between these two stacks (approximately at factor of 2). During the Task 2 testing, the dryer mill flue gas concentrations were lower than were measured during Task 1, but the kettle calciner steam stack concentrations were higher.

Plant Process Data

Plant process data are summarized in Table 7 for the mill tests and Table 8 for the board-line sampling. Some of the process data collected during the tests have not been reported here due to

their proprietary nature. Note that in the mill, solids feed rates are not measured directly, but are controlled on a relative basis by the speed of the solids feeders, and expressed as a percentage of full feeder speed. However, the mill supervisor can estimate feed rates based on the rate of level change in the stucco storage bins compared to wallboard production rates.

Table 7. Task 2 Mill Average Test Process Conditions

Date	12/1/2005
Time	0938-1754
Dryer Mill A Burner Output, % of full scale	36
Dryer Mill A Feed Rate Output, % of full scale	51
Estimated Dryer Mill Wet Feed Rate, tons/hr	53
Dryer Mill A Dust Collector Inlet Temperature, °F	176
Dryer Mill A Dust Collector Outlet Temperature, °F	167
Kettle A Feed Set Point, % of full scale	71
Estimated Kettle Calciner Land Plaster Feed Rate, tons/hr	47
Kettle A #3 (Mid-kettle) Thermocouple, °F	300

Table 8. Task 2 Board-line Sampling Process Conditions

Date	12/1/2004	12/1/2004	12/2/2004	
Time	2000	2200	0000	Mean
Kiln Wet Zone 1 Temperature, °F	450	442	451	437
Kiln Wet Zone 2 Temperature, °F	336	328	337	333
Kiln End Temperature, °F	224	221	222	224

The rates shown in Table 7 for the dryer mill and kettle calciner are based on an estimated 53 ton/hr average dryer mill feed rate for the day-long test, adjusted for percent moisture to produce an estimated land plaster feed rate to the kettle calciner of 47 tons/hr. The process conditions shown in Tables 7 and 8 were used as the basis for mercury balance calculations discussed in the following subsection. The dryer mill and calciner feed rates, and the board speed in the board dryer kiln (not shown) represent typical plant operation.

Mercury Balance Results

Table 9 summarizes the mercury balance data for the mill testing. Details are shown on the mercury balance intermediate calculation results, based on input data taken from previous tables in this report.

The mercury balance data are shown in several ways. First, the percentage mercury loss from the gypsum solids being processed is calculated, with that percentage being calculated two ways: one based on the apparent loss by comparing inlet and outlet solids mercury concentrations, and the other based on the inlet concentration versus the Ontario Hydro measurement results for mercury losses from the stacks. The other form of presenting the data is an actual mercury balance, with individual balance closure percentages shown across the dryer mill, kettle calciner, and overall mill. These mercury balances were calculated from the inlet solids mercury

Table 9. Mercury Balance Results for the Task 2 Mill Test

Run Number	Run 1	Run 2	Run 3	Mean	95% C.I.
Feed to Dryer Mill (Raw Gypsum):					
Feed rate, tons/hr	53	53	53	53	-
Wt% moisture	11.1	11.1	11.2	11.1	±0.1
Hg content, µg/g, dry basis (from Table 2)	1.13	1.11	1.07	1.10	±0.04
Total Hg to dryer mill, g/hr	48	47	45	47	±2
Dryer Mill Product (Land Plaster):					
Dry rate, tons/hr	47	47	47	47	±0
Hg content, µg/g (from Table 2)	1.08	1.08	1.02	1.06	±0.04
Total Hg from dryer mill, g/hr	46	46	44	45	±2
Measured solids Hg loss rate, g/hr	2.2	1.1	1.8	1.7	±0.6
Measured Hg loss rate at stack, lb/hr (from Table 6)	3.64×10^{-4}	3.12×10^{-4}	1.04×10^{-4}	2.60×10^{-4}	$\pm 1.56 \times 10^{-4}$
Measured Hg loss rate at stack, g/hr	0.17	0.14	0.05	0.12	±0.07
% Hg loss across dryer mill, by solids analysis	4.6%	2.4%	4.0%	3.7%	±1.3%
% Hg loss across dryer mill, by Ontario Hydro	0.3%	0.3%	0.1%	0.3%	±0.1%
Land Plaster Feed to Kettle Calciner:					
Feed rate, tons/hr	47	47	47	47	±0
Hg content, µg/g (from Table 2)	1.11	1.13	1.12	1.12	±0.01
Total Hg to kettle calciner, g/hr	47	48	47	48	±0
Product Stucco:					
Product rate, tons/hr, calculated	40	40	40	40	±0
Hg content, µg/g (from Table 2)	1.21	1.20	1.19	1.20	±0.01
Total Hg from kettle calciner, g/hr	44	44	43	44	±0
Measured solids Hg loss rate, g/hr	3.3	4.3	4.3	4.0	±0.7
Measured Hg loss rate at stack, lb/hr (from Table 6)	2.73×10^{-3}	2.74×10^{-3}	2.80×10^{-3}	2.76×10^{-3}	$\pm 0.04 \times 10^{-3}$
Measured Hg loss rate at stack, g/hr	1.2	1.2	1.3	1.3	±0.0
% Hg loss across kettle calciner, by solids analysis	6.9%	9.0%	9.1%	8.4%	±1.4%
% Hg loss across kettle calciner, by Ontario Hydro	2.6%	2.6%	2.7%	2.6%	±0.0%
Mass Balance Closures:					
Dryer mill Hg closure, output vs. input, %	96%	98%	96%	97%	±1%
Kettle Calciner Hg balance closure, output vs. input, %	95%	94%	94%	94%	±1%
Overall Mill Hg balance closure, %	94%	95%	98%	96%	±2%

concentrations and flow rates, outlet solids mercury concentrations and flow rates, and mercury losses in the flue gases based on the Ontario Hydro results.

The results show that mercury losses across the dryer mill and kettle calciner were low on a percentage basis. The mean for the dryer mill was a 0.3% loss of mercury in the raw gypsum calculated from the Ontario Hydro stack results, with a higher percentage of 3.7% being indicated by the solids analyses results. For the kettle calciner, the percentage loss was 2.6%

based on the Ontario Hydro stack results, and again, a higher percentage of 8.4% indicated by the solids analysis results.

The total mercury loss measured across the mill averaged 2.9% based on the Ontario Hydro results for the two stacks, and 11.8% based on solids analyses when considering the percentage losses across the dryer mill and kettle calciner together. When expressed on a mass basis, the mercury losses across the entire mill measured by Ontario Hydro totaled 1.4 g/hr, which is about 4% higher than those reported in Task 1.

The mercury balances show reasonably good closures, particularly considering the measurements were made across a full-scale, commercial plant and that the solids samples were small “grab” samples taken from large process streams and are not composites taken over the duration of each test. The average mercury balance closure was 97% across the dryer mill and 94% across the kettle calciner. Individual measurement run closures were all within 6% of 100%. The mercury balance closure across the entire mill was 96%.

The mercury balance results show an apparent, but small bias, in that the mass balance closures across the dryer mill, kettle calciner, and overall mill show less than 100% mercury recovery for every run. If the errors associated with quantifying mercury losses were random, one would expect some mercury balance closures to be greater than 100% and some to be less than 100%.

One apparent bias is seen when comparing the S2 dryer mill product land plaster mercury concentrations to the corresponding S3 kettle calciner feed land plaster concentrations. These two samples represent the input to and output from an intermediate storage silo between the dryer mill and kettle calciner. This silo causes a time delay between when solids are processed in the dryer mill and when those same solids are processed in the kettle calciner. These samples would not be expected to be identical for individual test runs, since the dryer mill and kettle calciner were sampled simultaneously rather than staggered to account for this silo residence time. However, on the average for the day, this storage silo residence time should have less of an effect on results, and the two streams should average nearly the same mercury concentration. This is not the case, though, as in both the URS and USG analyses the mean mercury concentrations for the S3 kettle calciner feed were higher than in the S2 dryer mill product land plaster by 6 to 8%. Since only three grab samples of each were collected, and each sample represents a small aliquot of a much larger process stream, this apparent bias may be random and coincidental.

Since the overall mill mass balance closures are reasonably good, this apparent bias is not of significant concern. However, the presence of this bias underlines the difficulty of quantifying small percentage mercury losses by analyzing grab samples of process streams. For this reason, the mercury loss percentages calculated from the Ontario Hydro measurements on the process stacks are believed to be more accurate than the percentages based on solid sample analyses.

The results of mercury balance calculations across the board line are shown in Table 10. It was not possible to calculate a rigorous mercury mass balance across the board line because, in accordance with the test plan, no flue gas mercury concentration measurements were made on the board dryer kiln stack. It was possible to compare the mercury concentration of the stucco

feed to the board line to the mercury concentration of the wet slurry going to board forming, and to the mercury concentration of the wet wallboard, although the mercury concentrations of the additives, water, and paper added to the stucco were not measured (also according to the test plan). However, by using the additive and paper mercury concentrations measured previously at Wallboard Plant 1 as part of Task 1, their effects on the mercury concentration in the wet slurry and wet wallboard was estimated. As shown in Table 10, using these estimates, the amount of mercury in the wet wallboard showed acceptable closure with the amount of mercury in the incoming stucco, with mass closures averaging 106%. This suggests that the estimates used for the mercury content in the additives and paper were reasonably accurate.

Table 10. Mercury Loss Calculation Results for the Task 2 Board-Line Test

Run Number	Run 1	Run 2	Run 3	Mean	95% C.I.
Hg in Feed to Board Line:					
Relative Stucco Feed Rate, % of test average	100	100	100	100	-
Hg Concentration in Stucco, µg/g (dry) (from Table 4)	1.15	1.19	1.22	1.19	±0.04
Hg in Stucco Feed, % of total Hg into Board Line	99.8	99.8	99.8	99.8	±0.0
Hg in Water Added, % of total Hg into Board Line (estimated)	0.0	0.0	0.0	0.0	±0.0
Hg in Additives, % of total Hg into Board Line (estimated)	0.0	0.0	0.0	0.0	±0.0
Hg in Paper, % of total Hg into Board Line (estimated)	0.1	0.1	0.1	0.1	±0.0
Hg in Slurry to Board Forming:					
Hg Concentration in slurry, µg/g (dry) (from Table 4)	1.00	1.01	1.10	1.04	±0.06
Moisture in Set Up Slurry, wt%	27.3	28.2	29.9	28.5	±1.5
Hg in Slurry, % closure with stucco + est. water + est. additives	111%	107%	115%	111%	±4%
Hg in Wet Wallboard to Kiln:					
Hg Concentration in Wet Wallboard, µg/g (dry) (from Table 4)	0.96	0.98	1.02	0.98	±0.04
Hg in Wet Wallboard, % closure with stucco + est. water + est. additives + paper	106%	105%	106%	106%	±4%
Hg in Wallboard Product:					
Hg Concentration in Wallboard Product, µg/g (dry) (from Table 4)	0.88	0.93	0.98	0.93	±0.05
% Hg Loss Across Board Dryer Kiln , by solids analysis (compared to wet wallboard)	8.0%	4.5%	4.1%	5.5%	±2.4%

Mercury losses across the board dryer kiln were estimated from the measured decrease in mercury concentration in the wallboard product relative to the feed streams. When comparing the product to the wet wallboard, the mercury loss across the board dryer kiln averaged 5.5%, with a 95% confidence interval of ±2.4% about the mean. This percentage loss estimate for the board line is higher than was measured by flue gas Ontario Hydro measurements at Wallboard Plant 1, Task 1 (1.9%). However, the uncertainty is greater for the percentage measured in Task 2, since it is based on measured differences in mercury concentrations for grab samples of these two process samples.

Summary of Mercury Loss Calculations

The data collected as part of this test were used to calculate an observed, overall percentage mercury loss from the raw gypsum feed during the wallboard production process, by two methods. One was to sum the measured losses from the process stacks, as measured by the Ontario Hydro method, and compare that total to the amount of mercury coming into the wallboard plant in the raw gypsum feed. The data on which this calculation was based are found in Tables 6 and 9 for the mill process stacks. However, because in accordance with the test plan, the board dryer kiln stack was not sampled by the Ontario Hydro method, the losses across the board line had to be estimated from the change in solids concentration across the board line. The second method was to compare the mercury concentrations in the raw gypsum feed to the concentrations in the dry wallboard product. Data on which this calculation was based are found in Tables 2 and 4. Results from these two types of calculations are shown in Table 11.

Table 11. Summary of Task 2 Overall Mercury Loss During Wallboard Production

	Run 1	Run 2	Run 3	Mean	95% C.I.
Total Hg Loss from Mill Process Stacks by Ontario Hydro Method, g/hr*	2.8	2.8	2.6	2.7	±0.1
Total Hg Loss Across Board Dryer Kiln, based on solids analyses, g/hr	7.1	4.2	3.9	5.1	±2.0
Total Hg to Wallboard Plant, g/hr [#]	96	95	91	94	±3
Observed Overall Percentage Hg Loss based on Ontario Hydro Method	10.3%	7.4%	7.2%	8.3%	±2.0%
Hg Concentration in Raw Gypsum Feed to Wallboard Plant, µg/g	1.13	1.11	1.07	1.10	±0.04
Hg Concentration in Wallboard Product, µg/g	0.88	0.93	0.98	0.93	±0.05
Observed Percentage Hg Loss Across Wallboard Plant based on solids analyses	22%	16%	8.3%	16%	±8%
Observed Percentage Hg Loss Across Wallboard Plant based on solids analyses, corrected for estimated Hg added with additives and paper in board line	22%	16%	8.5%	16%	±8%

* Assumes two dryer mill and kettle calciner stacks, one board dryer kiln stack

[#] Includes mercury in raw gypsum feed plus mercury added by additives and paper in the board line

The results in Table 11 show a mean loss of 8.3% of the plant input mercury across Wallboard Plant 1 by the first calculation method. This represents the sum of 2.9% loss out the two process stacks measured by the Ontario Hydro Method and 5.4% loss of the plant input mercury estimated from the change in wallboard mercury concentration across the board dryer kiln (calculated after correcting for mercury added with additives and paper in the board line).

By the second method, comparing the mercury concentrations in the raw gypsum feed to those in the dry wallboard product, a higher, 16% loss percentage was calculated (after correcting for the estimated amount of mercury added with additives and paper in the board line).

The two methods do not agree well with respect to the mean percentage mercury loss from the wallboard plant feed. However, the overall percentage mercury loss by the second method, based entirely on analysis of process solids for mercury concentration, has a much greater uncertainty than by the first method, which relies on Ontario Hydro method results for the mill losses. It is believed that the mean loss percentage calculated by the first method, using Ontario Hydro method results, provides the better measure of the overall percentage mercury loss from Wallboard Plant A during the Task 2 testing.

CONCLUSION

The use of synthetic gypsum in making wallboard has long benefited the environment by recycling the FGD gypsum byproduct, decreasing the need to landfill and increasing the sustainable design of the wallboard product. In the future, increasing numbers of FGD systems will be operating in the U.S. in response to EPA's Clean Air Interstate Rule, signed on March 10, 2005, which calls for further reductions in sulfur dioxide emissions from coal-fired power plants. Correspondingly, greater amounts of synthetic gypsum will be produced to either be recycled or landfilled. The Clean Air Mercury Rule, signed by EPA on March 15, 2005, takes into account the expectation that significant mercury emissions reductions will be obtained as a "co-benefit" of increased control of SO₂ (and NO_x) emissions. This study investigates the potential for mercury to be released in the atmosphere when synthetic gypsum material is used as a feedstock for wallboard production.

Task 2 evaluated the use of synthetic gypsum from a limestone forced-oxidation FGD system on a plant that fires high-sulfur bituminous coal, does not have an SCR in service (catalyst bypassed), and does not employ gypsum fines blow down. These results indicated an average of 8% of the incoming mercury was emitted during wallboard production. These losses were distributed across the dryer mill (<1%), kettle calciner (3%) and board dryer kiln (5%). The dryer mill and kettle calciner loss percentages were measured by the Ontario Hydro method at the stack from each process, while the board dryer kiln losses were quantified by solids analysis.

Mercury losses across the dryer mill and kettle calciner as measured by solids analyses indicate greater mercury loss percentages than the Ontario Hydro results, but the solids analysis result is believed to be less accurate. For the board dryer kiln, solids analyses were the only method available to estimate mercury losses because, according to the project plan, Ontario Hydro measurements were not made at the board dryer kiln stack as part of Task 2. It is not known whether the percentage mercury loss for the board dryer kiln based on solids analyses is biased high, as were the results for the mill when compared to Ontario Hydro results. However, it should be noted that the percentage mercury loss across the board dryer kiln reported above is nearly three times the percentage measured by the Ontario Hydro method in Task 1, while the percentage mercury loss across the mill was similar for the two tasks.¹ This suggests the possibility of a high bias in the board dryer kiln mercury loss results for Task 2.

The measured mercury losses from Wallboard Plant 1 totaled nearly 8 grams per hour, considering that there are two dryer mills, two kettle calciners, and one board dryer kiln. These mercury losses amount to approximately 0.1 lb of mercury emitted per million square feet of wallboard produced or 0.083 grams of mercury per ton of dry gypsum processed. Based on Task 2 results and approximate industry production rates, the wallboard industry would emit less than one ton of mercury compared to the current power industry emissions of 48 tons reported by the Environmental Protection Agency. According to this calculation, the estimated wallboard industry emissions would be less than 1.5% of current power industry emissions. Previous results from Task 1 of this project would predict even lower mercury emissions from the wallboard industry, of less than 1% of current power industry emissions. However, the results from Tasks 1 and 2 represent a relatively small subset of the power plants, coal types, FGD conditions and wallboard plant conditions corresponding with synthetic gypsum use for wallboard production.

Actual U.S. wallboard industry mercury emissions may vary from estimates made from Task 1 and 2 results.

Of the two flue gas streams measured for mercury content by the Ontario Hydro Method, the kettle calciner steam stack showed the higher mercury concentrations, with a mean concentration of $169 \mu\text{g}/\text{Nm}^3$ when reported on a dry gas basis at actual flue gas oxygen concentrations. Due to differences in mass flow rate and moisture content, this mercury concentration cannot be compared to typical concentrations in coal-fired power plant stack flue gases. The kettle calciner steam stack gas was measured to have a relatively high moisture content of 56%. The mercury concentrations are considerably lower when expressed on a wet flue gas basis, which is the condition under which it is actually released into the atmosphere. Furthermore, the flow rate from this kettle calciner steam stack was relatively low, two orders of magnitude lower than the flue gas flow rate from a typical power plant firing bituminous coal.

As was seen in the Task 1 results, the Task 2 Ontario Hydro results for the two mill stacks sampled show the mercury was almost entirely in the elemental form (Hg^0). This is contrary to what was expected given that it is predominantly water-soluble oxidized mercury (Hg^{+2}) that is removed in wet FGD systems, while elemental mercury is virtually insoluble and not removed at significant percentages.

In comparing the Task 1 and Task 2 results, the expected effect of having an SCR in service at Power Plant A was not seen. That is, the mercury concentration in the raw gypsum input to Wallboard Plant 1 was actually higher during Task 2, with the SCR out of service (bypassed) than in Task 1, where the SCR was in service. This suggests that the SCR at Power Plant A had little effect on mercury capture in the FGD system, and/or that the coal fired at Power Plant A had a higher mercury content when the raw gypsum processed during Task 2 was produced. The SCR apparently had little effect on mercury losses across the mill portion of Wallboard Plant 1, as the mercury loss across the mill was approximately 3% in the results from both tasks. The SCR being out of service appeared to have increased mercury losses across the board dryer kiln, as the percentage loss measured in Task 2 was nearly three times that measured in Task 1. However, as described above, there is greater uncertainty in the percent loss measured across the board dryer kiln in Task 2.

Future testing as part of Tasks 3 through 5 of this project will determine if the mercury loss percentages and mass rates from FGD gypsum used for wallboard production vary significantly for gypsum representing other power plant and FGD conditions. Other conditions include fines blow down from the FGD system, low rank coal versus bituminous coal, and lime versus limestone FGD reagent.

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