**Results of Life-Cycle Test with Alcoa Sorbent
for Reduction of SO₃
CRADA 98-F022, Final Report**

J.S. Hoffman
H.W. Pennline

September 3, 1998

RECEIVED
JUL 01 1999
OSTI

U.S. Department of Energy
Federal Energy Technology Center
626 Cochran's Mill Road
Pittsburgh, PA 15236-0940

and
Sargent & Lundy
55 East Monroe Street
Chicago, IL 60603-5780

**THIS DOCUMENT CONTAINS PROTECTED CRADA INFORMATION, WHICH
WAS PRODUCED ON 09/03/1998, UNDER CRADA 98-F022, AND IS NOT TO BE
FURTHER DISCLOSED FOR A PERIOD OF 5 YEARS FROM THE DATE IT
WAS PRODUCED EXCEPT AS EXPRESSLY PROVIDED FOR IN THE CRADA.**

Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Charles W. Wilson
Frank W. Wilson

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

**Results of Life-Cycle Test with Alcoa Sorbent
for Reduction of SO₃
CRADA 98-F022, Final Report**

J.S. Hoffman
H.W. Pennline

September 3, 1998

U.S. Department of Energy
Federal Energy Technology Center
626 Cochran's Mill Road
Pittsburgh, PA 15236-0940

and
Sargent & Lundy
55 East Monroe Street
Chicago, IL 60603-5780

**THIS DOCUMENT CONTAINS PROTECTED CRADA INFORMATION, WHICH
WAS PRODUCED ON 09/03/1998, UNDER CRADA 98-F022, AND IS NOT TO BE
FURTHER DISCLOSED FOR A PERIOD OF 5 YEARS FROM THE DATE IT
WAS PRODUCED EXCEPT AS EXPRESSLY PROVIDED FOR IN THE CRADA.**

PROTECTED CRADA INFORMATION

TABLE OF CONTENTS

- I. EXECUTIVE SUMMARY
- II. BACKGROUND
- III. LCTS EXPERIMENTAL CHRONOLOGY
- IV. STACK GAS SAMPLING RESULTS
 - A. SO₂
 - B. SO₃
 - C. Pitot Measurements
- V. MATERIAL BALANCE RESULTS
 - A. Sulfur (Gas & Solid Phase)
 - B. Solids
- VI. COMPARISON WITH PAST SAMPLING RESULTS
- VII. REFERENCES
- APPENDIX A STACK GAS SAMPLING REPORT

PROTECTED CRADA INFORMATION

I. EXECUTIVE SUMMARY

Parametric tests (MBCuO-18) were conducted in a Life Cycle Test System (LCTS) to evaluate the potential of removing SO_3 from flue gas using the Moving-Bed Copper Oxide Process (MBCuO). Two test conditions were investigated during operation. MBCuO-18-1 employed natural gas firing with a spiked (nominal 50 ppm) SO_3 level maintained at the absorber inlet; MBCuO-18-2 employed coal firing using an Illinois Coal (Old Ben #24) with no artificial spike of SO_3 .

Stack gas sampling for SO_2 and SO_3 was conducted by Consolidation Coal Company (CONSOL) using a controlled condensation method. Flue gas velocity and moisture measurements were also conducted using a pitot probe. Results for SO_2 by CONSOL agreed exceedingly well with LCTS continuous emission monitor (CEM) measurement as well as with measurement by an external lab. MBCuO-18-1 had an absorber inlet SO_2 value of 2220 ppm SO_2 with 89% SO_2 removal across the absorber as determined by CEM. MBCuO-18-2 had an absorber inlet SO_2 value of 2110 ppm SO_2 with 84% SO_2 removal across the absorber as determined by CEM.

No experimental evidence was found to substantiate the possibility of SO_3 generation by the catalytic conversion of SO_2 in flue gas within a bed of copper-impregnated alumina sorbent. Instead, high removals of SO_3 are observed across the absorber. MBCuO-18-1 had an absorber inlet SO_3 spiked value of 46 ppm SO_3 with 96% SO_3 removal across the absorber as determined by CONSOL. Approximately 6 ppm SO_3 was produced by coal combustion in MBCuO-18-2, with about 73% SO_3 removal across the absorber. The majority of SO_3 is recovered from the condenser in the stack gas sampling equipment, with little or no SO_3 captured on the filter at the front tip of the sample probe.

Pitot measurements by CONSOL agreed very well with LCTS measured parameters. For MBCuO-18-1 and MBCuO-18-2 respectively, LCTS values were noted as: total volumetric flow (113 and 110 SCFM); oxygen (3 and 5%); predicted carbon dioxide (10% and 14%); and predicted moisture (16 and 9%).

Material balances for sulfur around the LCTS were average for closure. Balances based on both gas phase and solid phase sulfur composition were mixed in nature, with 10-30% overall error noted. The gas-phase sulfur balance was greatly improved for MBCuO-18-2 with recalibration of a CEM for SO_2 on the regenerator offgas stream. Material balances for total dust, ash, and sorbent were all in excellent closure, with less than 3% error noted.

Stack gas sampling results of this study were compared to gas sampling results performed in previous parametric tests (MBCuO-15 and MBCuO-16) using EPA Method 8 for SO_2 and SO_3 determination.

PROTECTED CRADA INFORMATION

When compared to CEM values, SO_2 levels were in better agreement using the controlled condensation method versus EPA Method 8. Similar trends in overall SO_2 and SO_3 removal across the absorber were obtained using both sampling methods.

II. BACKGROUND

As part of a continuing investigation of the Moving-Bed Copper Oxide Process (MBCuO), this report summarizes the results obtained from parametric tests for test MBCuO-18. The Life Cycle Test System (LCTS) was operated for one week in mid-April as part of a recent CRADA agreement. A major goal of the testing was to conduct sulfur trioxide (SO_3) measurements across the absorber during LCTS operation using the Moving-Bed Copper Oxide Process. Consolidation Coal Company (CONSOL), based in Library, PA, was subcontracted to conduct the SO_3 sampling via a controlled condensation method.

Motivation for conducting SO_3 measurements across the absorber centers on the possibility that the sorbent could catalytically cause the formation of SO_3 rather than its removal. Copper oxide impregnated alumina facilitates the removal of sulfur dioxide (SO_2) from flue gas via a reaction of the copper with SO_2 to form copper sulfate (CuSO_4). Hence intuition suggests that SO_3 , given its higher oxidation state versus SO_2 , would be more readily removed by the sorbent to form CuSO_4 . However, a question remains that copper oxide impregnated alumina could instead act as a catalyst for SO_2 oxidation to SO_3 in flue gas. Higher levels of SO_3 downstream from the absorber can negatively impact power plant design and operation. Acid dewpoint in the flue gas partially dictates to how low a temperature the flue gas can be cooled prior to venting to the stack. In addition, if slipped ammonia from a selective catalytic reduction step is present in the flue gas, SO_3 can react to form ammonium sulfate, $(\text{NH}_4)_2\text{SO}_4$, which can foul downstream equipment.

Two test conditions were undertaken in MBCuO-18 to help address these issues. Similar testing [1] occurred in two previous series of parametric tests (MBCuO-15 and MBCuO-16), but difficulties were encountered, particularly with sampling for SO_3 , such that results were not quantitatively conclusive. Conditions remaining unchanged from earlier testing include the continued use of 1/8" diameter Alcoa sorbent, Hendrick absorber retention bar screens, and Illinois (Old Ben No. 24) coal.

The Alcoa sorbent used in the current study has been described in previous interim reports [2,3] which utilized the same material. The sorbent, both new and used, was extensively characterized with respect to size, structure, and chemical composition. The substrate is a commercially available alumina manufactured by Alcoa. Copper oxide sorbent was prepared by Alcoa by exposing the

PROTECTED CRADA INFORMATION

substrate to a copper sulfate solution via an incipient wetness procedure. The copper sulfate/alumina spheres (1/8-inch nominal diameter) were then dried in air. The bulk density of the virgin sorbent is approximately 54 lb/ft³. The fresh sorbent contains approximately 6.6 wt% copper and 3.3 wt% sulfur. The material must be initially activated batchwise in the LCTS regenerator to remove the sulfur. Regenerated material is then charged to the vessels, either as initial inventory or as sorbent makeup during LCTS operation to replenish attrited sorbent lost from the system.

Repeat measurements for SO₃ (five) were taken at the absorber inlet and outlet sampling ports during two test conditions. The furnace was fired on natural gas for the first condition (MBCuO-18-1). The second test condition (MBCuO-18-2) utilized an Illinois Coal (Old Ben No. 24).

For MBCuO-18-1, SO₃ levels were elevated using a catalytic system (V₂O₅) fed with SO₂ and air. SO₂ was introduced to the converter at a level equivalent to 100 ppm in the total flue gas. Based on gas chromatographic analysis of gas samples obtained at the reactor exit, approximately 50 percent conversion of SO₂ to SO₃ was estimated. Thus, approximately 50 ppm SO₃ was present in the flue gas at the absorber inlet. This level was independently confirmed by CONSOL's measurements for SO₃ at the inlet. CONSOL also obtained SO₂ measurements as part of the controlled condensation methodology.

For MBCuO-18-2, SO₃ was not artificially elevated using the catalytic system. Instead, only the SO₃ produced from the coal combustion was present in the flue gas.

III. LCTS EXPERIMENTAL CHRONOLOGY

Two parametric test conditions were completed during one week of testing during MBCuO-18. Hand-recorded data and computer-averaged information for MBCuO-18 are given in Tables 1 and 2, respectively. Five repeat measurements were taken for SO₃ and are designated as letters "a" through "e" for both MBCuO-18-1 and MBCuO-18-2. The same chronological order of conditions is maintained between Table 1 and Table 2 so that a one-to-one correspondence exists among the columns of data between the tables.

SO₂ removal and absorber pressure drop (across various reactor components) as a function of time are plotted in Figure 1. Differential pressure instrumentation ports strategically located in the side wall of the absorber allow pressure drop to be measured across several interfaces in the reactor: (1) the front sorbent retention screen; (2) the front half of the sorbent bed; (3) the rear half of the sorbent bed; (4) the rear sorbent retention screen; and (5) total pressure drop which includes both retention screens and entire sorbent bed. The graphs along the left vertical

PROTECTED CRADA INFORMATION

side of Figure 1 display SO_2 removal (designated as "SO2REF") and total absorber pressure drop (designated as "BED DP" or "PDT-19"). The graphs along the right vertical side of Figure 1 display component and total absorber pressure drop. Designations are as follow: Front retention screen as "F SCREEN DP", front half of sorbent bed as "F BED DP", rear half of sorbent bed as "R BED DP", rear retention screen as "R SCREEN DP", and total pressure drop as "Total DP".

The first test condition (MBCuO-18-1) used natural gas firing and represented a repeat of the typical "baseline" condition used in prior testing. Table 3 is a summary of this baseline condition typically repeated at the beginning of each parametric test series. The absorber conditions targeted were approximately: 750°F, 2250 ppm inlet SO_2 , 110 SCFM flue gas, and 0.75 lb/min sorbent. The regenerator baseline conditions were: 850°F, 3 hours sorbent residence time, and 0.6 lb/hr natural gas (twice the stoichiometric requirement). From inspection of Table 3, MBCuO-18-1a yielded results very similar in value to previous baseline conditions. For example, the observed SO_2 removal (88%) historically lies between 86-88%. The measured pressure drop (3.1 inch H_2O) typically ranges between 3-4 inch H_2O . Regenerator off-gas composition is typically 35-40% for both SO_2 and CO_2 , and 15-20% CH_4 , ranges for which the MBCuO-18-1a measured values approached.

The second test condition (MBCuO-18-2) represented a repeat of the baseline condition (MBCuO-18-1) but under coal firing. The absorber conditions targeted were approximately: 750°F, 2070 ppm inlet SO_2 , 110 SCFM flue gas, and 0.75 lb/min sorbent. The regenerator baseline conditions were: 850°F, 3 hours sorbent residence time, and 0.6 lb/hr natural gas (twice the stoichiometric requirement). A lower inlet SO_2 level is targeted to account for difference in flue gas moisture for coal- versus natural gas-firing. Spiking with SO_2 was required to maintain the 2070 ppm level.

Near the conclusion of MBCuO-18-2, the SO_2 removal eventually ended slightly lowered (83-86%) from the baseline condition (MBCuO-18-1). A presumed steady-state condition was initially maintained over the first day (4/15) of MBCuO-18-2. At approximately 20:00 on 4/15, the pressure drop appeared to have leveled off at approximately 7 inch H_2O (see Figure 1, second graph down in both columns of graphs). Historically 8-10 inch H_2O has been observed for the baseline condition with coal firing.

However, MBCuO-18-2 then became problematic with respect to increasing pressure drop across the absorber. At approximately 20:30 on 4/15, the pressure drop (see Figure 1) across the absorber increased excessively as the test condition progressed under 0.75 lb/min sorbent flow and back-pulsing. At approximately 01:00 on 4/16, the pressure drop had grown to 18 inch H_2O . The front half

PROTECTED CRADA INFORMATION

of the sorbent bed was highest in pressure drop (near 10 inch H_2O). This observation is consistent with prior coal-fired testing in which the majority of the pressure drop occurs in the front bed region. However, screen pressure drops, particularly the front screen, were noticeably large and growing. Such "excessive" pressure drop is indicative of fouling by ash in the absorber. Continued back-pulsing cannot solely reverse the accumulation of fines on the retention screens. Instead, the absorber must be "scrubbed" to remove the fines from the system. "Scrubbing" the absorber encompasses circulating sorbent with continuous back-pulsing and bypassing the flow of flue gas around the vessel. Typically, the absorber is purged of ash when a minimum of sorbent corresponding to one vessel inventory has been flowed through the absorber.

The absorber was scrubbed between approximately 3:30 and 7:30 on 4/16. Resumption of MBCuO-18-2 initially yielded lower pressure drop. However, as the second day (4/16) of MBCuO-18-2 progressed, similar behavior in pressure drop was observed. At approximately 17:00 on 4/16, the pressure drop appeared to have leveled off at approximately 8 inch H_2O (see Figure 1, second graph down in left column and third graph down in right column). Unfortunately, rapid growth in pressure drop was again observed, reaching values near 14 inch H_2O at 18:30 on 4/16. The condition was terminated and the absorber was scrubbed for a second time between 19:00 and 22:15 on 4/16.

It was decided to approach MBCuO-18-2 a third time utilizing partial coal firing and adjusting the SO_2 spiking flow accordingly in an effort to alleviate the high absorber pressure drop. Coal firing was gradually increased to full coal firing conditions at 04:00 on 4/17.

With the overall goal of maintaining reasonable and intermediate pressure drop through the absorber, testing for MBCuO-18-2 was finally completed during 4/17. However, it is questionable whether the system actually reached a steady-state condition with respect to ash removal in the absorber. The total pressure drop (see Figure 1, bottom graphs in both columns of graphs) did not truly level off and remain constant. Historical values (MBCuO-14) have ranged as high as 10-11 inch H_2O under full coal firing. For MBCuO-18-2, total pressure drop was near 12 inch H_2O and growing. However, the relative distribution of component pressure drop is similar to MBCuO-14. The front bed half is the dominant component. The rear bed half is roughly one-half of the front bed half. The front screen is usually slightly lower than the rear bed half. The rear screen is normally the lowest in pressure drop.

SO_2 removal for MBCuO-18-2 eventually ended slightly lower (83-86%) than the baseline condition (MBCuO-18-1). This may be indicative of partial fouling of the screens by ash, which in turn can cause

PROTECTED CRADA INFORMATION

flow maldistribution of flue gas through the sorbent bed. Previous LCTS operation, for steady-state conditions, has typically demonstrated that fuel substitution (coal for natural gas) has little or no effect on SO_2 removal while at the same time, the pressure drop is significantly higher due to the ash inventory in the absorber.

IV. STACK GAS SAMPLING RESULTS

Consolidation Coal Company (CONSOL), based in Library, PA, was subcontracted by DOE/FETC to conduct stack gas sampling for two days of LCTS operation. The reader is referred to Appendix A for a final report issued by CONSOL to FETC. Appendix A contains a complete description of the equipment and methodologies employed by CONSOL, as well as major findings for SO_2 , SO_3 , flue gas moisture and volumetric flowrates.

Stack gas sampling was conducted with simultaneous sampling trains at both the inlet and outlet of the absorber. Previous ports installed for prior stack gas sampling [1] were utilized for the current study. Given in Figures 2 and 3 are sketches of the inlet and outlet port, respectively. Each port contains a tap-in tee, followed by a gate valve, followed by a blind flange. The valving hardware allowed insertion and removal of the probe while the flue gas line remained isolated. This minimized the possibility of furnace flameout due to perturbation from probe insertion and removal. A generalized layout of the sampling ports is also included in Appendix A, Fig 1.

Sampling was conducted on 4/14 (MBCuO-18-1) and 4/17 (MBCuO-18-2) during the daylight shifts. Four replicate pairs, and a fifth for the outlet, were taken for MBCuO-18-1. These are denoted in chronological order as MBCuO-18-1a through MBCuO-18-1e. Five replicate pairs were taken for MBCuO-18-2. These are denoted in chronological order as MBCuO-18-2a through MBCuO-18-2e. Flue gas would typically be sampled for 45-60 min at both ports, followed by probe disassembly and sample recovery. In the course of a ten hour period, five sets of samples could be routinely taken.

Flue gas SO_2 and SO_3 concentrations were determined using a controlled condensation method (CCM) originally developed by EPA and modified by CONSOL R&D (see Appendix A). SO_x sampling was conducted at a single point (at the midpoint) within the duct. Gas is passed through a heated sampling probe with well-controlled temperatures such that SO_3 is condensed and trapped in a condenser, while SO_2 and water vapor are passed on through the probe. The remaining gas mixture is passed through a series of miniature glass impingers (four) filled with various solvents. SO_2 is captured in the first two impingers which contain hydrogen peroxide solution. The third impinger is empty, and the last impinger contains silica-

PROTECTED CRADA INFORMATION

gel used to capture moisture. The gas is then passed through a rotameter, a vacuum pump, and a dry test meter. Flue gas moisture was determined by measuring the gain in weight in the liquid and silica gel impingers.

SO₂ and SO₃ are recovered from various components of the sampling train. They include: (1) sample plug used to filter solids at the tip of the probe; (2) sample probe liner; (3) condenser; and (4) impingers. SO₂ is recovered from the first three impingers; the first two impingers contain hydrogen peroxide solution and the third impinger is an empty blank. The three impingers are rinsed with deionized water, followed by dilution to a known volume prior to analysis. SO₃ is trapped among the other three components. SO₃ is distributed among the plug (absorbed on solid particles captured in the filter), among the inner liner of the sample probe, and among the condenser. SO₃ is recovered by rinsing the plug, probe, and condenser with isopropyl alcohol (IPA). The rinsings are kept separate and diluted to a known volume prior to analysis. Individual fractions are analyzed using titration with BaCl₂ to a thorin endpoint.

Flue gas volumetric flow measurements (see Appendix A) were made using a type "S" pitot tube equipped with a Type K thermocouple. Absorber inlet and outlet flow measurements were made for both MBCuO-18-1 and MBCuO-18-2. Pitot measurements were made in one plane using a five-point traverse. A Shortridge electronic micro-manometer was used to determine individual pressure differentials at the traverse points.

A. SO₂

Measurements for SO₂ are summarized in Table 4. Absorber inlet and outlet levels are listed, along with the overall SO₂ removal across the absorber. The data columns are grouped by blocks of four, listing four different analytical/sampling methods by which SO₂ was determined. "CEM" denotes measurement by continuous emission monitor (i.e., SO₂ infrared gas analyzers installed on the LCTS). The specific analyzers and gas treatment method (i.e., Perma Pures) are discussed elsewhere [4]. "Control Cond" refers to CONSOL's measurements using the controlled condensation method. Analysis of CONSOL-obtained samples ("Control Cond" in Table 4) occurred in the field on the same day the sample was taken.

Measurements by CONSOL were independently corroborated by sending several of the liquid samples recovered from the controlled condensation method to a laboratory at FETC for analysis. Although these analyses did not immediately occur after the samples were taken, the samples were kept refrigerated for most of the time prior to analysis. The third and fourth columns in each data block of four in Table 4 contain the results by independent analysis. "Titration" refers to sample analysis using the same titration protocol (BaCl₂) employed in the controlled condensation method.

PROTECTED CRADA INFORMATION

"Ion Chrom" refers to analysis using ion chromatography. Samples were sent to an analytical lab, formerly identified with the Bureau of Mines, to perform both of these analysis. The methodology of analysis by ion chromatography is described elsewhere [1]. Results, reported as liquid sulfate concentrations, were converted back to equivalent gas-phase composition in the flue gas.

Excellent agreement in SO_2 measurements is noted in Table 4. Not only are CONSOL's measurements in good agreement with the CEM values (typically less than 5% relative error), but generally good agreement was obtained between CONSOL's measurements and the results from independent analysis using titration and ion chromatography.

MBCuO-18-1 was a very stable condition, as evidenced by the low statistical variance in absolute SO_2 values and the SO_2 removal for CEM measurements. As previously noted with respect to absorber pressure drop, MBCuO-18-2 was not as stable a condition under coal fire versus natural gas fire in MBCuO-18-1. There is more statistical variance in the absorber outlet SO_2 levels as compared to the absorber inlet. However, this increased error was not greatly reflected in the sample variance for the methods of SO_2 determination.

B. SO_3

For MBCuO-18-1, SO_3 levels were elevated using a catalytic system fed with SO_2 and air. The catalytic system is detailed in a previous study [1] undertaken to measure SO_3 levels around the absorber using EPA Method 8. The SO_3 spike system is sketched in Figure 4. A commercially available catalyst used for the production of sulfuric acid was obtained from Monsanto Company. The catalyst consisted of vanadium salt complexes (V_2O_5) deposited on silica. A stainless steel tubular reactor of approximately 10 in³ was constructed and filled with the catalyst. The reactor operating temperature was held constant at 825°F. Reactor inputs consisted of 0.11-lb/hr SO_2 and 0.16-lb/hr air. The product stream from this reactor was injected into the flue gas flow at a location far upstream from the absorber. Figure 5 shows the piping & instrumentation design (P&ID) layout of the catalytic system and its integration into the overall combustor P&ID. SO_2 was introduced to the catalytic system at a level equivalent to 100 ppm in the total flue gas. Based on gas chromatographic analysis of gas samples obtained at the reactor exit, approximately 50 percent conversion of SO_2 to SO_3 was estimated. Thus approximately 50 ppm SO_3 was predicted to be present in the flue gas at the absorber inlet. As will be discussed below, this level was independently confirmed by CONSOL's measurements for SO_3 at the absorber inlet.

Measurements for SO_3 are summarized in Table 5. Absorber inlet and outlet levels are listed, along with the overall SO_3 removal across the absorber. The data columns are grouped by blocks of three,

PROTECTED CRADA INFORMATION

listing the three different methods by which SO_3 was determined. SO_3 method abbreviations are the same as those adopted in Table 4, except that "CEM" is absent in Table 5. "Control Cond" refers to CONSOL's measurements using the controlled condensation method. "Titration" refers to sample analysis using the same titration protocol (BaCl_2) employed in the controlled condensation method. "Ion Chrom" refers to analysis using ion chromatography.

Based on CONSOL's measurements for both sampling locations for MBCuO-18-1, approximately 96 percent SO_3 removal occurs across the moving bed of sorbent in the absorber, representing a very favorable result. SO_3 levels averaged near 46 ppm at the inlet, again confirming a predicted spike level of nominally 50 ppm. Lesser agreement in absolute SO_3 levels is noted between CONSOL's measurements and the two other SO_3 methods of independent analysis. The two methods ranged 30-50% lower in SO_3 at the absorber inlet versus the controlled condensation values. However, when comparing the difference in absolute values across the absorber, strikingly similar SO_3 removals are noted among the three methods. In fact, the statistical variance in SO_3 removal for CONSOL's measurements for MBCuO-18-1 was remarkably low (less than 1% standard deviation of the mean). This result, along with the SO_2 levels reported in Table 4, reaffirms the steady state condition that was attained for MBCuO-18-1.

For MBCuO-18-2, SO_3 was not artificially elevated using the catalytic system. Instead, only the SO_3 produced from the coal combustion was present in the flue gas. Overall results were again in fairly good agreement. Note that the first outlet measurement for SO_3 (MBCuO-18-2a) was considered to be biased high, and therefore a fifth outlet sample (MBCuO-18-2e) was obtained. Approximately 3-6 ppm SO_3 was produced by coal combustion, with roughly 70-80 percent SO_3 removal across the absorber. In the absence of SO_3 spiking, SO_3 determination by "titration" was not measurable due to the relatively low inlet SO_3 levels. The independent method of SO_3 analysis by ion chromatography revealed consistently lower results versus measurements by controlled condensation.

Based on previous SO_3 sampling experiences of CONSOL, similar discrepancies have been observed by CONSOL in conducting SO_3 sampling and the subsequent chemical analysis of the liquid samples. Per private conversation with Mr. Matthew DeVito of CONSOL, a degradation in the liquid sample may occur with aging, leading to a deficit in analyzed SO_3 . Hence CONSOL attempts to perform the chemical analysis of the liquid samples within a short time period (preferably the same day) of collection. As previously discussed, the titrations for the controlled condensation method were performed by CONSOL on the same day. However, a time lag of more than a week, with samples refrigerated, had passed before samples were analyzed by ion chromatography or repeat titration.

When comparing the difference in absolute values across the absorber, the SO_3 removal was significantly lower (55%) using ion chromatography versus controlled condensation (73%). In either case, the SO_3 removal under coal firing for MBCuO-18-2 is appreciably lower than the SO_3 removal under gas-firing for MBCuO-18-1 (96%). Statistical variability in SO_3 removal is also more pronounced for MBCuO-18-2 versus MBCuO-18-1, again indicating the difficulty in attaining steady state for MBCuO-18-2. The SO_2 removal was also slightly lower (84%) under coal fire versus MBCuO-18-1 (88%). With respect to the direction of flue gas flow through the absorber, these observations are consistent with the possibility of partial blinding by ash of the sorbent retention screen or sorbent bed.

Levels of SO_3 recovered from the various components of the gas sampling train for the controlled condensation method are listed in Table 6. The three sample train locations for SO_3 recovery are (1) sample plug used to filter solids at the tip of the probe, denoted as "Filt"; (2) sample probe liner, denoted as "Probe"; and (3) condenser, denoted as "Cond". The total of the three is denoted by "Tot". SO_3 method abbreviations are the same as those adopted in Table 5.

From inspection of Table 6, the majority of the SO_3 is recovered in the rinsing of the condenser. For MBCuO-18-2, there is little evidence of SO_3 being captured by the filter as indicated by the controlled condensation values. Ion chromatography results show only trace levels (less than 0.2 ppm) of SO_3 .

A concern was that, during sampling, attrited sorbent (in the form of copper sulfate or aluminum sulfate) could compromise the results by sample contamination, especially in the "filter" part of the method. The analysis of sulfate in the recovered liquid sample cannot distinguish the identity of the sulfate precursor (i.e., SO_3 or sulfate). Therefore, several samples were analyzed for dissolved copper and aluminum. Results indicated that dissolved aluminum or copper were two to three orders of magnitude less in value (reported as mg/l) than sulfate levels. Therefore, sample contamination by attrited sorbent is negligible.

C. Pitot Measurements

Flue gas moisture and volumetric flow measurements are listed in Table 7 for MBCuO-18-1 and MBCuO-18-2. Sampling was performed by CONSOL at the absorber inlet and outlet locations. The sampling ports have been previously described [1] and have been illustrated in Figures 2 and 3. Also included in Table 7 are LCTS operational parameters to compare against the pitot measurements. Excellent agreement is noted between the results. Flue gas flowrate, based on an average of inlet and outlet pitot measurements, was approximately 109 SCFM for MBCuO-18-1 and 108 SCFM for MBCuO-18-2. These values are reported on a wet basis. Flue gas flow based on

PROTECTED CRADA INFORMATION

a venturi meter located upstream of the absorber inlet indicated 113 SCFM for MBCuO-18-1 and 110 SCFM for MBCuO-18-2. The venturi meter also measures total flow on a wet basis. Comparison of values in Table 7 represent less than 4% and 2% error respectively for MBCuO-18-1 and MBCuO-18-2.

Gas composition was also monitored as part of CONSOL's stack gas sampling equipment. Results can be compared against CEMS located on the LCTS. Oxygen is measured by CEMS at both the inlet and outlet of the absorber. Oxygen values in Table 7 compare favorably, with about 3% error for MBCuO-18-1 and 6% error for MBCuO-18-2. Carbon dioxide is theoretically predicted by CONSOL based on fuel composition and stoichiometric calculation. Carbon dioxide is measured by CEM at the furnace on the LCTS. CO₂ is not measured at the absorber, but other than possible air in-leakage, differences in sampling location should not affect the CO₂ results. CO₂ values in Table 7 also compare favorably, with about 3% error for MBCuO-18-1 and 6% error for MBCuO-18-2.

Moisture in the flue gas is theoretically predicted based on fuel composition and stoichiometric calculation. Moisture was directly determined by CONSOL as part of the stack gas sampling equipment. Moisture was measured to be approximately 18% for the natural gas-fired condition (MBCuO-18-1) and 9% for the coal-fired condition (MBCuO-18-2). Measured results for moisture are generally in fair agreement with predicted values, with approximately 10% error for MBCuO-18-1 (16.4% H₂O predicted) and 1% error for MBCuO-18-2 (9.1% H₂O predicted).

Flue gas temperature within the duct was measured by CONSOL. The sampling probe contained a thermocouple extended into the gas stream at the tip of the probe. Inlet gas temperature ranged between 805-810°F while outlet gas temperature ranged between 650-660°F. The absorber is maintained such that temperatures within the sorbent bed are near 750°F.

Several LCTS thermocouples are available for comparison of temperature (see Table 2 for LCTS variables which were computer recorded). Several of the LCTS thermocouples relevant for temperature comparison are collected in Table 7. "TE-15" represents temperature located upstream from the absorber, approximately five feet prior to the junction where flue gas can be bypassed around the absorber. "TE-15" was approximately 840-850°F for MBCuO-18-1 and 860-910°F for MBCuO-18-2. "TE-18" represents temperature located immediately at the inlet of the absorber. The thermocouple is mounted within the flanged (3-inch pipe) coupling before the gas is expanded through the inlet gas cone of the absorber. "TE-18" was approximately 745-750°F for MBCuO-18-1 and 755-800°F for MBCuO-18-2.

The sampling probe location for the absorber inlet lies

PROTECTED CRADA INFORMATION

approximately midway along the flue gas duct between "TE-15" and "TE-18". Hence a probe temperature of 805°F for MBCuO-18-1 is logical since the upstream temperature was 840-850°F and the downstream temperature was 745-750°F. A similar rationale exists for MBCuO-18-2. The probe temperature of 810°F for MBCuO-18-2 is intermediate between the upstream temperature of 860-910°F and the downstream temperature of 755-800°F.

Only one thermocouple ("TE-21") is available to compare with the sampling probe temperature for the absorber outlet. "TE-21" lies approximately six feet upstream of the outlet probe location and approximately four feet downstream from the exit pipe flange on the absorber flue gas outlet cone. "TE-21" averaged near 675-680°F for both MBCuO-18-1 and MBCuO-18-2. Thus, CONSOL's probe temperatures at the absorber outlet (650-660°F) compares favorably with "TE-21" and was approximately 25-30°F cooler since the sampling probe was located slightly downstream from "TE-21".

V. MATERIAL BALANCE RESULTS

Material balances for sulfur, and solids collected are summarized for MBCuO-18 parametric test series. A discussion of the results follows.

A. Sulfur

A material balance for sulfur around the life-cycle test system was conducted using two methodologies. At steady state, the amount of sulfur captured in the absorber should equal the amount of SO₂ liberated from the regenerator. In the absorber, SO₂ is removed from the flue gas and captured onto the sorbent in the form of CuSO₄. In the regenerator, sorbent is regenerated by chemically reducing CuSO₄; SO₂ is liberated from the sorbent and exits the vessel with other gas phase products of regeneration. Absorber sulfur removal is based on the difference in gas phase composition of flue gas entering and exiting the absorber. Sulfur evolution in the regenerator can be calculated in one of two manners. First, gas phase composition of the regenerator offgas with flow rate can indicate the amount of SO₂ exiting the regenerator. Alternatively, the difference in solid phase composition (wt% sulfur) of the sorbent entering and exiting the regenerator with solid flow rate can also indicate the amount of sulfur regenerated. Thus the reduction in residual sulfur on the sorbent entering and exiting the regenerator should correspond to the amount of SO₂ observed in the regenerator offgas. Both of these regenerator methodologies can be compared to the absorber method as a check on sulfur recovery.

Table 8 lists calculated sulfur recovery for the various test conditions. Process interruption of the LCTS must occur in order to extract sorbent samples from the various vessels. Since a primary goal of the testing was to maintain continuous steady-state

PROTECTED CRADA INFORMATION

operation for the purpose of repeated stack gas sampling intervals, samples of sorbent were obtained only after the conclusion of stack gas sampling for MBCuO-18-1e and MBCuO-18-2e. Therefore, solid phase sulfur balances could be made for only MBCuO-18-1e and MBCuO-18-2e, although it can be argued that these balances are representative of the two operating conditions for this test.

From past results, the gas phase sulfur balances for MBCuO-18-1 were poor. Generally, the gas phase balances are good and agree to within 10 to 15 percent error. However, the sulfur in the offgas from the regenerator was 20-30% less than the sulfur removed in the absorber. The CEM for measuring SO₂ in the regenerator offgas was suspected to be in error during testing. The SO₂ analyzer was thought to be reading low based on prior baseline operation. This proved to be the case (to be discussed in detail later in this section). At the conclusion of MBCuO-18-1, steps were taken to mitigate the erroneous SO₂ readings from the analyzer. This proved mostly successful for closing the material balance for sulfur. For MBCuO-18-2, the sulfur deficit in the regenerator offgas stream was cut approximately in half. Generally, the gas phase balances were then good and agreed within 5 to 15 percent error.

A good solid phase sulfur balance was obtained for MBCuO-18-1e (within 6%). However, the solid phase sulfur balance for MBCuO-18-2e was in much greater error (30% low in the regenerator). Determination of the solid phase composition of the sorbent for residual sulfur may be inherently more uncertain than the determination of gas phase composition for SO₂. Other sources of error in the solid methodology may include the extraction of solids from the system and whether the solid sample obtained is representative.

Gas composition of inlet and outlet process streams on the regenerator is verified using chromatographic analysis of gas samples. The off-gas stream from the regenerator is periodically sampled (as a "grab sample") and stored in a glass sampling bulb. The natural gas supply header is also sampled to ascertain the composition of reducing gas fed to the regenerator. Composition is determined by gas chromatography (GC) and provides a check on the values measured on-line by CEM. Table 9 shows species identified by GC and CEM. The date and time corresponding to when the data was obtained is also tabulated. CEM data is included over windows of time that coincide nearest to the time period when grab samples were extracted. The presence of oxygen in the GC analysis is most likely due to air in-leakage during the sampling procedure, and the sample analysis should be corrected for this.

The composition of the regenerator off-gases was generally fairly consistent throughout the testing (see Table 9). Comparison of values obtained by GC analysis versus CEM indicates that CH₄ was in fair agreement. A discrepancy is consistently noted for the CO₂,

PROTECTED CRADA INFORMATION

measurements. The CEM values were sometimes about five percentage points higher than the GC values. All gas analyzers are calibrated at a minimum of once per shift (8 hours), but reasons for the discrepancy are unknown.

As mentioned previously, the CEM for SO₂ measurement was thought to be reading low during MBCuO-18-1. This was confirmed by comparison of values obtained by GC analysis versus CEM. Table 9 indicates that CEM values for SO₂ (33-35%) were typically about five percentage points lower than the GC values (38-42%). This was partially responsible for the large sulfur deficit noted for MBCuO-18-1.

The span gas normally used to calibrate the analyzer was unexpectedly depleted at the start of LCTS operation. Lacking a span gas of equivalent composition, a substitute span gas of much higher concentration was used for calibration. However, nonlinearity in the response of the analyzer was causing lower SO₂ readings when sampling the regenerator offgas during MBCuO-18-1. At the conclusion of MBCuO-18-1, a gas blender was used in combination with a pure SO₂ cylinder and nitrogen to perform a multipoint calibration over the entire (0-100%) range. The resulting calibration curve was programmed into the CEM to linearize the response of the analyzer. This recalibration successfully narrowed the difference between CEM and GC values for SO₂ during MBCuO-18-2.

Trace levels (several tenths of a percent) of oxygen are noted in Table 9 for the regenerator off-gas as measured by GC analysis. These values are generally consistent with the oxygen content as determined by CEM. However, it is reasonable to assume that any oxygen fed to the regenerator should be consumed by reaction, and therefore no oxygen should be exiting the regenerator. With respect to the manner in which GC samples are obtained and analyzed (by filling a glass sampling bulb and transferring to the GC), it is plausible that air in-leakage into the sample can occur. If dilution by air is assumed, then the data listed in Table 9 can be corrected for air leakage to yield an oxygen-free composition. However, the data in Table 9 have not been corrected in any manner.

If the GC analyses are corrected for air in-leakage, little variability in the composition of the natural gas header feeding the regenerator is noted. Historically, the methane content is typically around 90 percent, with the next largest component being 5-9 percent of ethane. Trace levels of higher hydrocarbons (propane) are present in the natural gas, but these components are generally not observed in the regenerator product stream (consumed in the regenerator). Ethane is sometimes observable (around 1 percent) in the regenerator off-gases.

Elemental balances for carbon and hydrogen are performed for a

control volume surrounding the regenerator. These balances are included in the hand-recorded data for MBCuO-18 (see Table 1). Timed collections of condensate and bagmeter flow readings were obtained for the regenerator exit stream and are also included in Table 1. These parameters were necessary in order to perform the regenerator material balances. The reducing gas fed to the regenerator (natural gas with an assumed composition of pure methane) contains both carbon and hydrogen. Product gases to be included in the balances and liberated from the regenerator include CO_2 (carbon balance), H_2O (hydrogen balance), and unused reducing gas measured as CH_4 (carbon and hydrogen balance). CEM gas analyses were used to perform the elemental balances. The carbon balance around the regenerator is generally within plus or minus 10 percent. All carbon balances for MBCuO-18 indicated a surplus in the regenerator offgases. Given that CEM values were somewhat high for CO_2 versus GC values, the surplus in carbon can be reduced if GC analyses were used, resulting in better closure for the carbon material balance.

The hydrogen material balance has historically been problematic for the regenerator and was difficult to close in this test (25 percent). The product stream is always in deficit of the input stream. Collection of condensate enters into the material balance for hydrogen and may be a contributing factor, but nearly all of the water in the product stream is thought to be captured by the condenser whose temperature is near 32°F . The calculation of flowrate, using timed bagmeter readings, is apparently not the source of error since the carbon balances around the regenerator are close to balancing.

B. Solids

A material balance for solids around the life-cycle test system was conducted for parametric test series MBCuO-18. Depending on the sampling location, the collected dust is typically a mixture of both attrited sorbent as well as ash from pulverized coal-firing. Only by analysis of the dust for copper content can an approximation be made for partitioning a sample into sorbent and ash fractions.

Materials balances for total dust, as well as sorbent and ash considered individually, are summarized in Table 10. Dust is collected from six locations around the LCTS. The sampling locations are (with abbreviations in Table 10): furnace ashpot; absorber inlet ashpot (AB-IN-POT); absorber outlet ashpot (AB-OUT-POT); furnace baghouse (BH); fluid-bed heater baghouse (FBH); and fluid-bed cooler cyclone (FBC).

The furnace ashpot is located beneath the furnace (downward-fired) such that slag/unburned coal accumulates within this pit. Hence no sorbent fines can appear in these dust samples. The remainder of the ash (as flyash) is carried over from the furnace to the

absorber. Dust can be collected at several locations within the absorber. The absorber inlet ashpot refers to the collection point upstream of the sorbent bed. The flue gas is transitioned from a 3 inch schedule 10 pipe and expanded through a diffuser cone to the maximum cross-sectional bed area (8 ft x 2 ft). Thus the absorber inlet ashpot collects any fines which may settle out of the flue gas as a result of the inlet gas expansion. Similarly, the absorber outlet ashpot refers to the collection point downstream of the sorbent bed. The flue gas is transitioned from the cross-sectional bed area down to a 3 inch schedule 10 pipe. Thus, the absorber outlet ashpot collects any fines blown through the bed which may settle out of the flue gas as a result of the flue gas outlet cone. Dust samples from both the absorber inlet and outlet ashpots can contain sorbent as a result of attrited sorbent small enough to pass through the sorbent retention screens at the front and rear of the sorbent bed. The furnace baghouse traps any fines downstream of the absorber transported by flue gas. Since the LCTS contains the parametric flexibility of flue gas bypass around the absorber for absorber inlet flow control purposes, the furnace baghouse captures fines which have passed either through or around the absorber.

The remaining dust collection points are located along the path of sorbent transport around the LCTS. Any dust trapped by the bed of sorbent in the absorber is carried with the sorbent exiting the vessel. The mixture is pneumatically transported using a transport hopper into the fluid-bed heater. The mixture is segregated by the fluidizing gas based on difference in size and density (weight) of the material. Sufficiently large-sized sorbent remains within the vessel and then is transported by gravity into the regenerator. Dust elutriated from the fluid-bed heater is captured downstream of this vessel in a baghouse. The same principle of operation exists for the fluid-bed cooler located after the regenerator but before the absorber. However, dust elutriated from the fluid-bed cooler is captured downstream by a cyclone instead of a baghouse.

With the exception of the fluid-bed cooler cyclone, all dust collection locations contain isolation valves between the particular equipment/vessel and its corresponding collection drum. This allows on-line accessibility to replace dust-filled drums with empty drums while the LCTS continues to operate. Hence dust amounts can be collected over a particular time window of interest without the need to terminate the test condition. However, the cyclone for the fluid-bed cooler can only be accessed at the end of a test series. The cyclone is emptied only after the vessel has been cooled and flow has been terminated during shutdown of the LCTS. It is for this reason that total dust balances are performed over the entire period of a parametric test series (typically one or two weeks). Any time period shorter than this would require an assumption on the contribution of the fluid-bed cooler cyclone.

Dust inputs to the LCTS occur in two manners. The first

PROTECTED CRADA INFORMATION

contribution is from ash as a result of burning coal. The second input of dust occurs from the addition of fresh sorbent to the system necessary to replenish attrited sorbent which has been lost from the LCTS. Based on ultimate/proximate analysis of the coal, the expected ash is assumed to equal 10 percent of the coal burned. The calculated amount of sorbent makeup takes into account not only the sorbent which has been physically added to the system, but also sorbent which has been withdrawn from the vessels during sampling as well as any changes in vessel inventory. The sorbent residence time within the regenerator can be altered by raising or lowering the bed height, which in turn changes the sorbent inventory.

Given in Table 10 are the material balances for total dust, ash, and sorbent obtained during MBCuO-18. The inputs to the system (expected ash and sorbent makeup) should equal the outputs collected from the system (total dust from the six vessel locations). Any discrepancy is reported as a percent of a particular input or output variable. The error in the total dust balance, listed in footnotes at the bottom of Table 10 in percent, is defined as $(\text{collected dust} - \text{sorbent makeup} - \text{expected ash}) / (\text{sorbent makeup} + \text{expected ash})$. In general, the total dust balance was excellent, agreeing within less than 3% of the input dust (sorbent makeup and expected ash).

Dust samples obtained from the various collection points in the LCTS were analyzed for copper content. Depending on the location, the dust can be a mixture of both ash and attrited sorbent and, based on copper analysis, calculations can be made to partition the mixture into ash and sorbent fractions. This information can then be used to perform material balances for ash and sorbent individually, which is supplemental to the material balances previously performed for total dust mixtures. Given in footnotes at the bottom of Table 10 are dust balances for ash and sorbent fractions obtained for MBCuO-18. The copper content in pure, unspent sorbent is 6.6 wt%, and if analysis of the dust resulted in a copper content greater than 6.6 wt%, the dust was considered to be 100% sorbent with no ash present.

The sorbent balance is defined as $(\text{collected sorbent dust} - \text{sorbent makeup}) / (\text{sorbent makeup})$. In general, the sorbent balance was excellent, agreeing within less than 3% of the input sorbent (sorbent makeup). The material balance for ash is defined as $(\text{collected ash dust} - \text{expected ash}) / (\text{expected ash})$. The ash balance was also excellent, agreeing within less than 3% of the input ash (coal ash expected). Closure of material balances for solids for MBCuO-18 are outstanding when compared to some prior parametric test series where errors often exceeded 20% or more.

VI. COMPARISON WITH PAST SAMPLING RESULTS

The results of the current study (MBCuO-18) can be compared with

PROTECTED CRADA INFORMATION

previous parametric investigations [1] undertaken to quantify SO₃ removal across the absorber. Two series of parametric tests (MBCuO-15 and MBCuO-16) were conducted over several weeks of LCTS operation. Most major LCTS operational parameters (coal, sorbent, temperature, flowrate, etc.) were identical to those used in MBCuO-18.

Stack gas sampling for MBCuO-15 and MBCuO-16 occurred using the same sampling ports at the absorber inlet and outlet. However, samples for SO₂ and SO₃ determination were obtained using a different sampling methodology (EPA Method 8) than used for the current study (controlled condensation method for MBCuO-18). The stack gas sampling was conducted solely by in-house FETC personnel. Composition of impinger solutions as determined by EPA Method 8 (titration) was performed by site-contracted analytical chemistry personnel supporting in-house FETC. In addition, liquid samples obtained for MBCuO-15 and MBCuO-16 were sent to the same independent lab, as was used for MBCuO-18, to perform sulfate analysis using ion chromatography.

Overall test conditions for MBCuO-15 and MBCuO-16 essentially mirrored conditions studied during MBCuO-18. The furnace was fired on coal for all conditions of MBCuO-15. Natural gas and coal firing was utilized during MBCuO-16. The traditional "baseline" condition was maintained during both series of tests. The absorber conditions targeted were approximately: 750°F, 2250 ppm inlet SO₂, 110 SCFM flue gas, and 0.75 lb/min sorbent. The regenerator baseline conditions were: 850°F, 3 hours sorbent residence time, and 0.6 lb/hr natural gas (twice the stoichiometric requirement). For coal fired conditions, a lower inlet SO₂ level is targeted (2070 ppm) to account for difference in flue gas moisture for coal-versus natural gas-firing.

Spiking of SO₃ using a catalytic system was as yet unavailable during MBCuO-15. The catalytic system was first installed for use during MBCuO-16 tests. The flowrate of SO₂ and air fed to the catalytic system was similar to that used in MBCuO-18. SO₂ was introduced to the converter at a level equivalent to 100 ppm in the total flue gas. Approximately 50 percent conversion of SO₂ to SO₃ was estimated, yielding a nominal 50 ppm SO₃ in the flue gas at the absorber inlet.

Measurements for SO₂ and SO₃ are respectively summarized in Tables 11 and 12 for MBCuO-15 and MBCuO-16. Absorber inlet and outlet levels are listed, along with the overall SO₂ and SO₃ removal across the absorber. The data columns are grouped by blocks, listing different analytical/sampling methods by which SO₂ and SO₃ were determined. "CEM" denotes measurement by continuous emission monitor (i.e., SO₂ infrared gas analyzers installed on the LCTS). The specific analyzers and gas treatment method (i.e., Perma Pures) are discussed elsewhere [4]. "Method 8" refers to measurements

PROTECTED CRADA INFORMATION

using EPA Method 8.

Measurements were independently corroborated by sending several of the liquid samples recovered from EPA Method 8 to a laboratory at FETC for analysis. Although these analyses did not immediately occur after the samples were taken, the samples were kept refrigerated for most of the time prior to analysis. The last column in each data block in Tables 11 and 12 contain the results by independent analysis, where "Ion Chrom" refers to analysis using ion chromatography. Samples were sent to an analytical lab, formerly identified with the Bureau of Mines, to perform this analysis. The methodology of analysis by ion chromatography is described elsewhere [1]. Results, reported as liquid sulfate concentrations, were converted back to equivalent gas-phase composition in the flue gas.

Some of the data presented in Tables 11 and 12 was considered invalid in the previous report [1] for various reasons, and has been highlighted with an asterisk. Therefore, such data has been excluded from the statistical averaging presented in the tables. For the current discussion, if either the absorber inlet or absorber outlet value was excluded, then the overall absorber removal value was also considered invalid since it was mathematically derived from the difference in the inlet and outlet values.

Both test conditions for MBCuO-15 (1 and 1a) were performed under coal firing, with no SO₂ spike. Four periods of stack gas sampling (1a-1d) was performed for the first test condition of MBCuO-16, under natural gas fire with SO₂ spiking. The last test condition (MBCuO-16-2) utilized coal firing, but without SO₂ spiking.

Absorber inlet SO₂ and SO₃ levels for MBCuO-16-1a, as determined by EPA Method 8, were considered in error due to a likely leak in the gas sampling train. The moisture content measured in the flue gas was only half of the expected moisture based on natural gas firing. Hence for a given data point, any error encountered during stack-gas sampling using EPA Method 8 would also invalidate the corresponding results obtained using ion chromatography, although analytical comparisons could be made between the two methods which were subjected to the same sampling error. Thus it is logical to exclude ion chromatography results at the absorber inlet for MBCuO-16-1a also.

Absorber inlet SO₂ and SO₃ levels for MBCuO-16-1b were also considered in error as a result of backflushing among the impinger solutions, thus excluding EPA Method 8 and ion chromatography results for MBCuO-16-1b. The absorber outlet SO₂ level for MBCuO-16-1b appears to be biased low relative to the other three readings (MBCuO-16-1a,c,d) and was excluded from the averaging of results. The absorber outlet SO₃ levels for MBCuO-16-1d, both by EPA Method

PROTECTED CRADA INFORMATION

8 and ion chromatography determination, are exceedingly high in comparison to MBCuO-16-1a,b, and c. Contamination of the isopropanol solution was offered as a probable cause for the anomalous absorber outlet SO₂ results for MBCuO-16-1d.

Large discrepancies exist in the SO₂ data when comparing EPA Method 8 and ion chromatography results with CEM values. However, interpretation of data is more difficult since much of the data was excluded from averaging. Absorber inlet SO₂ levels are underpredicted by about 10-40% using EPA Method 8. Inlet SO₂ levels by ion chromatography are much worse, with about 50-70% underprediction versus CEM values. These results can be contrasted against MBCuO-18 (see Table 4), where results are in much better agreement (maximum 15% error) among the different analytical methods. SO₂ removals across the absorber, as measured by EPA Method 8, are in greater error (5-15%) than the results of MBCuO-18 (less than 4% error). The SO₂ removal, typically 86-88% as determined by CEM, is very repeatable for the baseline conditions performed during all three parametric test series (MBCuO-15, 16, and 18).

One probable reason for the low SO₂ concentrations at the absorber inlet by Method 8 in MBCuO-15 and MBCuO-16 was ascertained to be the result of poor sampling location. The duct location for injecting (spiking) SO₂ into the flue gas was only approximately 18 inches upstream from the stack gas sampling port for the absorber inlet. Thus, it was reasoned that residence time was insufficient to fully mix the SO₂ within the flue gas, and a nonhomogeneous flue gas was probably sampled at the stack gas sampling port for the absorber inlet. The CEM sampling port location for the absorber inlet lies further downstream (about 6 feet from the inlet stack gas sampling port and a total of about 7.5 feet from the SO₂ spike port). In addition, a venturi for measuring flue gas flow is located between the stack gas sampling port and the CEM sampling port. Due to the effects of longer residence time, and a higher velocity profile in the venturi, the spiked SO₂ was felt to be fully mixed at the CEM sampling location. Therefore, the CEM measurements are held in higher confidence and are believed to have not been influenced by insufficient mixing.

To eliminate the effect of poor mixing of the SO₂ spike gas, the SO₂ spike was relocated to a position (about 40 feet) upstream of the absorber inlet stack gas sampling port. The relocation occurred prior to conducting MBCuO-18 (controlled condensation measurements). For MBCuO-16 and MBCuO-18, only one location was ever utilized for spiking SO₂ derived from the catalytic system. The SO₂ spike location coincided with the newly relocated SO₂ spike location (approximately 40 feet upstream of the absorber inlet stack gas sampling port). Hence the SO₂ spike was always located far upstream of the stack gas sampling port for the absorber inlet, and therefore complete mixing of SO₂ was achieved for all testing.

PROTECTED CRADA INFORMATION

SO₃ levels for MBCuO-15 and MBCuO-16 (see Table 12) exhibited trends similar to the SO₃ results for MBCuO-18 (see Table 5). Under coal firing, SO₃ for MBCuO-18-2 averaged 5.8 ppm at the absorber inlet and 1.6 ppm at the absorber outlet, yielding about 73% SO₃ removal across the absorber using the controlled condensation method. MBCuO-15-1 is strikingly similar, having 6.4 ppm and 2.0 ppm at the absorber inlet and outlet respectively, with about 69% SO₃ removal across the absorber using EPA Method 8. The absorber inlet SO₃ level for MBCuO-15-1a (27 ppm) is likely an anomaly since SO₃ was not artificially raised with the SO₃ catalytic system under coal fire. A similar argument can be made for excluding the absorber inlet SO₃ value for MBCuO-16-2 (63 ppm).

SO₃ levels under natural gas fire were also similar among MBCuO-16 and MBCuO-18. SO₃ for MBCuO-18-1 averaged 46 ppm at the absorber inlet and 2.6 ppm at the absorber outlet, yielding about 96% SO₃ removal across the absorber as measured by the controlled condensation method. MBCuO-16-1 averaged 57 ppm and 5.3 ppm at the absorber inlet and outlet respectively, with about 96% SO₃ removal across the absorber as measured by EPA Method 8. Both conditions yielded very similar results, with the absorber inlet values approaching the expected nominal 50 ppm of SO₃ using the catalytic spiking system.

However, some differences are apparent in the SO₃ data when ion chromatography results are compared against results using EPA Method 8 and the controlled condensation method. For MBCuO-16-1, a small discrepancy (less than 5%) exists in absorber inlet SO₃ levels between EPA Method 8 (57 ppm) and ion chromatography (54 ppm). Much larger error (30-40%) was observed in absorber inlet SO₃ levels for all of MBCuO-18 (see Table 5), with ion chromatography results much lower than SO₃ levels as measured by the controlled condensation method. MBCuO-15-1 also exhibited large error, with the ion chromatography SO₃ level (3.7 ppm) approximately 40% less than the Method 8 SO₃ level (6.4 ppm). Thus in some instances for absorber inlet SO₃ levels, ion chromatography results agree well with EPA Method 8 results. In other instances, ion chromatography results are 30-40% lower than both EPA Method 8 or controlled condensation values. Absorber outlet SO₃ levels appear to show similar large discrepancy, with ion chromatography results sometimes roughly half of the levels as determined by either EPA Method 8 or controlled condensation method.

It is somewhat difficult to draw definite conclusions when comparing SO₂ and SO₃ results as determined by the two methods of stack gas sampling (controlled condensation versus EPA Method 8). In general, one can conclude that the controlled condensation results of MBCuO-18 have better sample-to-sample repeatability (lower standard deviation) than the EPA Method 8 results of MBCuO-15 and MBCuO-16. However, one must bear in mind that different sampling crews were utilized when performing the stack gas

PROTECTED CRADA INFORMATION

sampling. Certainly the high level of prior sampling experience of CONSOL was reflected in the quality of data obtained. Additionally, it must be remembered that the two methods were not compared simultaneously, but from different tests when the operational parameters were nominally kept constant. However, similar trends in overall SO_2 and SO_3 removal across the absorber were obtained using both sampling methods.

VII. REFERENCES

- [1] Yeh, J.T., Hargis, R.A., Hoffman, J.S., Resnik, K.P., and H.W. Pennline. "Reduction of SO_3 Across the Moving Bed of CuO Sorbent." U.S. DOE/FETC Internal Report, December 16, 1997.
- [2] Pennline, H.W., Hoffman, J.S., Yeh, J.T., Resnick, K.P., and Vore, P.A. PETC Interim Report III: Consortium CRADA PC-95006, August, 1996.
- [3] Hoffman, J.S., Pennline, H.W., Yeh, J.T., and Resnick, K.P. PETC Interim Report IV: Consortium CRADA PC-95006, June, 1997.
- [4] Pennline, H.W., Yeh, J.T., Hoffman, J.S., Longton, E.J., Vore, P.A., Resnik, K.P., and F.N. Gromicko. "Design, Construction, and Operation of a Life-Cycle Test System for the Evaluation of Flue Gas Cleanup Processes." U.S. DOE Topical Report DOE/PETC/TR-96-01, December, 1995.

Table 1: MoCuO-18 Test Conditions

10:40 12:00 13:30 15:00 16:00 08:15 10:10 11:30 13:00 16:55

Test Condition	1a	1b	1c	1d	1e	2a	2b	2c	2d	2e
Coal flow, lb/h	—	—	—	—	—	Y	Y	Y	Y	Y
Natural Gas flow, lb/h	—	—	—	—	—	—	—	—	—	—
ABSORBER (1 ft x 8 ft)	4/14	4/14	4/14	4/14	4/14	4/17	4/17	4/17	4/17	4/17
Absorber temp control	750	750	750	750	750	750	750	750	750	750
TE18, F (gas inlet)	747	747	747	747	747	750	755	775	775	795
TE390, F (sorbent inlet)	740	735	725	725	720	756	750	750	750	750
Flue gas, acfm	113	113	113	113	113	110	110	109	110	109
lb/hr	527	530	527	530	525	515	515	510	515	510
Sorbent flow, #/min	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Inlet SO ₂ , ppm	2230	2220	2220	2210	2220	2080	2080	2090	2100	2120
Outlet SO ₂ , ppm	265	250	240	235	240	285	320	330	335	350
SO ₂ removal eff (exp), %	88	88.5	89	89	89	86	84.5	84	84	83
SO ₂ removal eff (model), %	—	—	—	—	—	—	—	—	—	—
Inlet NO _x , ppm	500	495	495	515	510	355	370	380	375	365
Outlet NO _x , ppm	470	455	440	460	465	375	350	360	350	350
NO _x removal, %	—	—	—	—	—	—	—	—	—	—
SO ₂ flow, lb/hr	2.467	2.466	2.467	2.466	2.466	0.405	0.405	0.405	0.404	0.404
NO flow, lb/hr	0.101	0.101	0.101	0.101	0.101	—	—	—	—	—
NH ₃ flow, lb/h	—	—	—	—	—	—	—	—	—	—
REGENERATOR	—	—	—	—	—	—	—	—	—	—
Regenerator temp control	850	850	850	850	850	850	850	850	850	850
TE381, F	845	845	845	845	850	835	810	815	825	825
TE382, F	840	840	840	845	840	820	815	820	830	830
TE383, F	880	885	880	880	880	860	865	870	865	875
TE384, F	875	875	875	875	880	855	855	855	855	860
TE385, F	895	895	895	895	895	870	875	875	875	875
Resi. time, min	180	180	180	180	180	180	180	180	180	180
NG flow, lb/h	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
H ₂ flow, lb/h	—	—	—	—	—	—	—	—	—	—
N ₂ flow, lb/h	—	—	—	—	—	—	—	—	—	—
NG&H ₂ /(total S), Mol ratio	1	1	1	1	1	1	1	1	1	1
Equivalence Ratio (Phi=1 for NG/S=0.5, H ₂ /S=2)	2	2	2	2	2	2	2	2	2	2
SO ₂ , %	36	35	35	33	33	38	39	39	38	37
CO ₂ , %	41	40	40	39	39	33	34	35	35	33
CH ₄ , %	21	21	22	23	25	32	30	29	30	30
Total, %	98	96	97	95	97	103	103	103	103	100
FLUID-BED HEATER	—	—	—	—	—	—	—	—	—	—
TE373, F (12")	920	920	915	920	920	890	890	890	890	890
TE374, F (24")	915	915	910	915	915	885	885	885	885	885
SO ₂ , ppm	—	—	—	—	—	—	—	—	—	—
WATER	—	—	—	—	—	—	—	—	—	—
Start time	9:30	11:37	13:11	14:30	15:34	08:05	04:42	11:11	12:32	16:30
Start Bagmeter (Pt3)	857.8	909.4	943.4	976.4	001.7	332.0	370.8	402.4	442.3	540.8
Stop time	10:56	12:44	14:10	15:34	16:48	09:23	10:53	12:15	13:43	17:38
Stop Bagmeter (Pt3)	892.8	937.0	967.1	001.7	030.9	363.0	401.0	434.1	471.0	570.2
Interval time (min)	86	67	59	64	74	78	71	64	71	68
Interval bagmeter (Pt3)	35	27.6	23.7	25.3	29.2	31	30.2	26.7	28.7	29.4
Collected H ₂ O (g)	399	289.8	272.2	266	275.7	160.8	341.4	125.5	301.2	283.2
Water, lb/min	0.0102	0.00954	0.0102	0.00916	0.00821	0.00454	0.0106	0.00432	0.00935	0.00918
Drymeter flow, acfm	0.407	0.412	0.402	0.395	0.395	0.397	0.387	0.417	0.404	0.432
SULFUR ABSORBED, Mol/hr	0.0293	0.0293	0.0295	0.0294	0.0295	0.0283	0.0278	0.0275	0.0279	0.0275
SULFUR REGENERATED, Mol/hr	0.0231	0.0228	0.0222	0.0206	0.0206	0.0238	0.0238	0.0257	0.0243	0.0253
SULFUR BALANCE, %	-21.2	-22.2	-24.7	-29.9	-30.2	-15.9	-14.4	-6.5	-12.9	-8.0
(lb Mol H)/hr	—	—	—	—	—	—	—	—	—	—
Regenerator	—	—	—	—	—	—	—	—	—	—
In	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Out	0.122	0.118	0.124	0.118	0.117	0.111	0.144	0.105	0.139	0.143
% Balance	-18.7	-4.3	-17.3	-21.3	-22.0	-26.0	-4.0	-30.0	-7.3	-4.7
(lb Mol C)/hr	—	—	—	—	—	—	—	—	—	—
Regenerator	—	—	—	—	—	—	—	—	—	—
In	0.0375	0.0375	0.0375	0.0375	0.0375	0.0375	0.0375	0.0375	0.0375	0.0375
Out	0.0399	0.0397	0.0394	0.0387	0.0399	0.0408	0.0391	0.0422	0.0415	0.0430
% Balance	+6.4	+5.9	+5.1	+3.2	+6.4	+8.8	+4.3	+12.5	+10.7	+14.7
Copper Flow (lb Mol/hr)	0.0468	0.0468	0.0468	0.0468	0.0468	0.0468	0.0468	0.0468	0.0468	0.0468
Cu/S Molar Ratio	1.41	1.41	1.41	1.42	1.41	1.42	1.42	1.43	1.41	1.41
Utilization (%)	62.4	62.8	63.1	62.7	63.1	60.6	59.5	58.7	59.6	58.9
Absorber	—	—	—	—	—	—	—	—	—	—
Pressure	—	—	—	—	—	—	—	—	—	—
Drop	—	—	—	—	—	—	—	—	—	—
(in H ₂ O)	—	—	—	—	—	—	—	—	—	—
Front Screen	0.1	0.1	0.1	0.1	0.1	1.5	1.6	1.8	1.9	1.7
Front Bed	0.6	0.6	0.6	0.6	0.6	5.5	5.5	7.0	6.0	7.0
Rear Bed	1.7	1.7	1.5	1.3	1.3	1.7	2.2	2.0	2.3	2.5
Rear Screen	0.6	0.6	0.6	0.7	0.7	0.4	0.4	0.3	0.4	0.6
Total	3.1	3.1	2.9	2.8	2.8	9.5	9.8	10.5	10.8	11.5

PROTECTED CRADA INFORMATION

Table 2

MBUO-18	PARAMETER	TAG	EU	1	2	3	4	5	6	7	8	9	10
COMBUSTOR FILE				COMB173	COMB173	COMB173	COMB173	COMB173	COMB176	COMB176	COMB178	COMB178	COMB178
	COMB AIR	FY-1	#/HR	486.2	486.1	486.3	486.2	486.3	410.6	410.0	410.8	410.1	409.8
	MOTIVE AIR	FY-3	#/HR	0.00	0.00	0.00	0.00	0.00	37.97	37.90	37.82	37.03	36.47
	NATURAL GAS	FY-20	#/HR	24.18	24.17	24.18	24.18	24.18	3.13	3.12	3.13	3.13	3.13
	COAL	WKT-26	#/HR	0.00	0.00	0.00	0.00	0.00	32.93	32.77	32.75	32.67	33.24
	FEEDER WY	WY-26	LBS	39.90	39.90	40.07	40.16	40.20	41.00	42.56	40.56	40.44	43.96
	EXCESS AIR	BY-X	%/SA	19.98	19.98	20.03	19.99	20.01	21.97	22.28	22.44	22.41	20.36
	HEAT INPUT	BTU	BTU/HR	644660	644623	644618	644717	644666	658316	656619	656129	656040	652678
	FLUE GAS (M)	FY-15	#/HR	526.2	526.2	526.8	526.6	526.3	523.8	523.8	523.7	519.0	513.8
	FURNACE O2	AT-O2-0	%	3.10	3.07	3.23	2.96	2.92	4.22	4.12	4.06	4.00	4.03
	FURNACE P	PT-6	H2O	-0.10	-0.09	-0.10	-0.10	-0.11	-0.11	-0.07	-0.11	-0.09	-0.09
	COMB AIR P	PT-1	PSIG	4.53	4.46	4.45	4.41	4.43	4.15	4.08	4.12	4.14	4.18
	MOTIVE AIR P	PT-3	PSIG	88.30	88.33	88.37	88.04	88.24	87.50	87.58	87.11	87.58	87.37
	NATURAL GAS P	PT-20	PSIG	5.26	5.26	5.26	5.26	5.26	5.26	5.26	5.26	5.22	5.21
	FLUE GAS P	PT-16	H2O	4.51	4.50	4.52	4.53	4.58	5.41	5.30	5.41	5.28	5.28
	COOL H2O P	PT-26	PSIG	200.00	200.00	200.00	200.00	200.00	200.00	200.00	200.00	200.00	200.00
	THEOR AIR	BY-X	#THEOR	406.26	406.17	406.20	406.26	406.24	367.80	366.26	366.13	366.23	370.83
	FURNACE CO2	AT-CO2-0	PERCENT	9.73	9.73	9.53	9.76	9.77	13.99	14.06	14.16	14.23	14.22
	FURNACE CO	AT-CO-0	PPM	2.03	1.66	1.58	1.90	2.17	90.11	111.66	119.44	97.47	115.82
	MOTIVE AIR V	SY-3	FT/SEC	0.00	0.00	0.00	0.00	0.00	60.13	60.02	59.94	59.96	59.57
	FLUE GAS (M)	FY-16	SCFM	112.8	112.8	112.7	112.9	112.8	112.3	112.2	112.1	111.3	110.1
ABSORBER FILE				ABS182	ABS182	ABS182	ABS182	ABS182	ABS184	ABS184	ABS184	ABS184	ABS184
	INLET SO2	AT-SO2-1	PPM	2229	2218	2225	2215	2223	2081	2081	2089	2101	2111
	INLET NOX	AT-NOX-1	PPM	500	494	493	513	514	348	363	379	377	365
	INLET O2	AT-O2-1	PERCENT	3.11	3.18	3.21	3.03	2.93	4.77	4.72	4.68	4.70	4.55
	OUTLET SO2	AT-SO2-2	PPM	265	250	239	236	239	518	325	335	345	349
	OUTLET NOX	AT-NOX-2	PPM	471	453	440	461	465	375	361	362	353	349
	OUTLET O2	AT-O2-2	PERCENT	3.40	3.54	3.57	3.36	3.21	5.01	4.97	4.93	4.90	4.89
	NO SPIKE	FT-101	#/HR	0.10	0.10	0.10	0.10	0.10	0.00	0.00	0.00	0.00	0.00
	SO2 SPIKE	FT-102	#/HR	2.47	2.47	2.47	2.47	2.47	0.40	0.40	0.40	0.40	0.40
	NH3 SPIKE	FT-103	#/HR	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
	BED DP	POT-19	H2O	3.14	3.10	2.91	2.94	2.80	9.22	9.78	10.29	10.81	11.60
	FLUE GAS (M)	FY-17	#/HR	526.1	529.4	527.3	529.4	529.2	514.8	514.3	507.3	511.7	508.8
	INLET P	FY-17	H2O	6.26	6.57	6.41	6.82	6.29	7.32	7.41	7.06	7.47	7.24
	SCREEN DP	POT-21	H2O	0.59	0.60	0.62	0.67	0.74	0.56	0.37	0.46	0.42	0.93
	GAS INLET	TE-18	DEG F	742	747	743	748	745	753	756	765	777	797
	GAS OUTLET	TE-21	DEG F	678	677	678	678	679	674	675	674	677	688
	SORB IN	TE-390	DEG F	739	736	728	727	704	756	748	751	750	748
	SORB OUT	TE-391	DEG F	701	699	699	699	699	736	702	706	671	661
	SO2 REMOVAL	SO2REF	PERCENT	88.4	88.5	89.0	89.2	89.1	85.8	84.5	84.1	83.8	83.1
	NOX REMOVAL	NOXREF	PERCENT	4.2	6.4	6.7	6.8	6.1	0.0	2.2	2.8	5.2	5.6
	FLUE GAS (M)	FY-17	SCFM	112.8	113.5	113.0	113.5	113.2	110.4	110.3	108.7	108.7	108.1
ABSORBER DP FILE				ABX182	ABX182	ABX182	ABX182	ABX182	ABX184	ABX184	ABX184	ABX184	ABX184
	F SCREEN DP	POT-24	H2O	0.10	0.10	0.10	0.10	0.09	1.50	1.55	1.78	1.90	1.57
	F BED DP	POT-23	H2O	0.56	0.54	0.50	0.58	0.60	5.58	5.42	5.96	6.08	6.82
	R BED DP	POT-22	H2O	1.66	1.64	1.48	1.56	1.55	1.38	2.20	2.50	2.57	2.43
	R SCREEN DP	POT-21	H2O	0.59	0.61	0.62	0.67	0.74	0.56	0.37	0.46	0.42	0.93
	TOTAL DP	POT-19	H2O	3.14	3.10	2.91	2.94	2.80	9.23	9.78	10.29	10.84	11.44
	SO2 REMOVAL	SO2REF	PERCENT	88.3	88.5	89.1	89.1	89.1	85.7	84.4	84.2	83.8	83.1
	NOX REMOVAL	NOXREF	PERCENT	4.3	6.7	6.6	6.6	6.2	0.0	2.4	3.0	5.2	2.4
REGENERATOR FILE				REG182	REG182	REG182	REG182	REG182	REG184	REG184	REG184	REG184	REG184
	QUICK REP O2	AT-O2-4A	PERCENT	0.01	0.01	0.01	0.01	0.01	0.01	2.98	0.94	1.04	1.11
	REGEN SO2	AT-SO2-1	PERCENT	38.87	38.31	34.13	34.23	33.26	38.53	38.17	38.78	37.97	36.47
	REGEN CH4	AT-CH4-4	PERCENT	21.38	21.49	22.27	22.87	24.81	31.78	29.28	29.43	29.82	29.08
	REGEN CO2	AT-CO2-4	PERCENT	40.82	40.23	40.18	39.56	38.85	33.11	33.60	34.82	34.99	34.27
	REGEN H2S	AT-H2S-4	PERCENT	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	REGEN O2	AT-O2-4B	PERCENT	0.04	0.09	0.12	0.14	0.19	0.32	0.51	0.68	0.81	0.49
	NATURAL GAS	FY-300	#/HR	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60	0.60
	NITROGEN	FY-310	#/HR	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	REGEN P	FY-360	H2O	10.20	9.40	9.20	9.27	9.37	9.99	9.72	9.99	9.72	12.06
	SORB LEVEL	LT-380	INCHES	26.02	24.99	24.97	24.98	24.76	25.26	26.14	24.93	24.41	23.51
	TSORB (21)	TE-361	DEG F	846	845	847	848	851	833	812	815	825	826
	TSORB (17)	TE-362	DEG F	841	841	842	844	842	817	816	823	828	831
	TSORB (22)	TE-363	DEG F	881	883	882	880	882	869	864	870	868	873
	TSORB (17)	TE-364	DEG F	874	875	876	876	876	878	852	854	857	856
	TGAS (EXT)	TE-365	DEG F	894	894	895	895	897	873	873	875	874	877
	T OFF GAS	TE-366	DEG F	829	828	828	828	829	824	824	824	824	824
	T COND EX	TE-367	DEG F	33	33	33	33	33	33	33	33	33	33
	T INC EX	TE-368	DEG F	571	570	570	578	578	519	521	531	564	601
	INCIN O2	AT-O2-6	PERCENT	18.63	18.61	18.60	18.57	18.56	19.17	19.19	19.18	19.09	18.98
	INCIN SO2	AT-SO2-6	PPM	366	335	322	333	317	466	518	537	526	540
FLUID BED HEATER FILE				FBH182	FBH182	FBH182	FBH182	FBH182	FBH184	FBH184	FBH184	FBH184	FBH184
	TSORB(17)	TE-373	DEG F	921	920	918	921	920	890	890	890	890	890
	NATURAL GAS	FY-55	#/HR	6.39	6.37	6.44	6.28	6.38	6.09	6.06	6.07	6.03	6.00
	AIRTR AIR (M)	FY-30	#/HR	440.3	438.5	440.3	439.0	439.0	451.2	451.4	452.2	452.4	453.6
	FBH VEL	SY-30	FT/SEC	8.21	8.19	8.20	8.21	8.21	8.20	8.20	8.20	8.20	8.20
	FBH O2	AT-O2-3	PERCENT	16.26	16.26	16.27	16.27	16.21	16.79	16.83	16.86	16.90	17.04
	TAHTR OUT	TE-370	DEG F	933	926	918	919	927	873	873	873	874	886
	T PLENUM	TE-372	DEG F	997	999	996	996	1001	964	963	963	962	947
	TSORB(21)	TE-371	DEG F	918	918	914	919	918	898	897	898	898	887
	T YEN	TE-375	DEG F	852	852	850	853	853	827	827	826	826	826
	THUM OUT	TE-376	DEG F	401	400	400	400	400	400	400	400	400	400
	FBH PRES	PT-376	H2O	8.21	8.33	8.19	8.45	8.41	9.33	9.23	9.15	9.12	9.36
	BED DP	POT-376	H2O	9.90	9.74	10.65	9.99	9.97	10.21	9.99	9.96	10.33	

Natural Gas MBCuO-18-1
2250 ppm SO₂ ABS182.WK3 Reg 3 Hr
110 SCFM 4/12/98 (SUN) - 4/14/98 (TUES) $\phi = 2$

MBCuO-18-1
ABX182.WK3
4/12/98 (SUN) - 4/14/98 (TUES)

Coal MBCuO-18-2
2070 ppm SO₂ ABS183.WK3 Reg 3 Hr
110 SCFM 4/14/98 (TUES) - 4/17/98 (FRI) $\phi = 2$

MBCuO-18-2
ABX183.WK3
4/14/98 (TUES) - 4/17/98 (FRI)

MBCuO-18-2
ABX183.WK3
4/14/98 (TUES) - 4/17/98 (FRI)

Coal MBCuO-18-2
2070 ppm SO₂ ABS184.WK3 Reg 3 Hr
110 SCFM 4/16/98 (THUR) - 4/17/98 (FRI) $\phi = 2$

MBCuO-18-2
ABX184.WK3
4/16/98 (THUR) - 4/17/98 (FRI)

Figure 1: LCTS process variables versus time for MBCUO-18 test conditions.

PROTECTED CRADA INFORMATION

Table 3: Effect of Screen Design and Sorbent on Performance*

Parameter	MBCuO 12-1	MBCuO 13-1	MBCuO 14-1	MBCuO 16-1d	MBCuO 17-1	MBCuO 18-1a
Sorbent	1/8" Alcoa	1/8" Alcoa	1/8" Alcoa	1/8" Alcoa	1/8" Alcoa	1/8" Alcoa
Screen	Bar	Bar	Bar	Bar	Bar	Bar
Bed Dimensions H(ft) x W (ft) x D (in)	4 x 1 x 12	4 x 1 x 12	4 x 1 x 12	4 x 1 x 12	4 x 1 x 12	4 x 1 x 12
SO ₂ Removal (%)	89	88	84	90.5	80	88
Total Absorber Pressure Drop (in H ₂ O)	3.6	4.1	4.1	3.2	3.8	3.1
Regenerator Residence Time (Hr)	3	3	3	3	3	3
Regenerator Off-Gas (Volume %, Dry)						
SO ₂	48	41	45	41	40	36
CO ₂	41	42	34	40	41	41
CH ₄	8	9	27	15	19	21

* Natural Gas Fire; 110 SCFM Flue Gas Flow; 750°F Absorber; 2250 ppm SO₂ Spike; 0.75 lb/min Sorbent Flow; 850°F Regenerator; 2 or 3 Hr Regenerator Residence Time; Twice Stoichiometric Requirement of Methane fed to Regenerator.

Figure 2: Absorber Inlet Sampling Port

Figure 3: Absorber Outlet Sampling Port

Table 4: SO₂ Summary Data

Condition	Absorber Inlet SO ₂ (ppm, dry)				Absorber Outlet SO ₂ (ppm, dry)				SO ₂ Removal (%)			
	CEM	Control Cond	Titration	Ion Chrom	CEM	Control Cond	Titration	Ion Chrom	CEM	Control Cond	Titration	Ion Chrom
MBCuO-18-1a	2229	2077			255	277			88.4	86.7		
MBCuO-18-1b	2218	2157	2131	1884	250	251	256	269	88.5	88.4	88.0	85.7
MBCuO-18-1c	2225	2149			239	267			89.0	87.6		
MBCuO-18-1d	2215	2143			236	266			89.2	87.6		
MBCuO-18-1e					239	270	268	273				
Mean	2222	2132	2131	1884	244	266	262	271	88.8	87.6	88.0	85.7
Std Dev (%)	0.3	1.7	-	-	3.4	3.6	3.2	1.0	0.4	0.8	-	-
Error (%)	-	-4.1	-4.1	-15.2	-	+9.0	+7.4	+11.1	-	-1.4	-0.9	-3.5
MBCuO-18-2a	2081	2042	1985	2095	291	308	273	288	85.8	84.9	86.2	86.3
MBCuO-18-2b	2081	2032			318	393			84.5	80.7		
MBCuO-18-2c	2089	2042			326	327			84.1	84.0		
MBCuO-18-2d	2101	2078	2076	2048	335	340	308	313	83.8	83.6	85.1	84.7
MBCuO-18-2e	2111	2034			349	327			83.1	83.9		
Mean	2113	2046	2031	2072	324	339	291	301	84.3	83.4	85.7	85.5
Std Dev (%)	2.6	0.9	3.2	1.6	6.7	9.5	8.5	5.9	1.2	1.9	0.9	1.3
Error (%)	-	-3.2	-3.9	-1.9	-	+4.6	-10.2	-7.1	-	-1.1	+1.7	+2.5

IDENTIFIER:

PAGE 6 OF 6

REV

Q

1

2

ORIGINATOR:

K. RESNIK

JOB NO.

DATE:

113197

WBS NO.

THIS IS A DESIGN RECORD / PARSONS POWER GROUP INC.

Figure 4: SO₃ Spike Injection System

PROTECTED DATA INFORMATION

82-2003 16-14
82-2003 16-11

NOTES:
1. ALL PIPING SHALL BE 1/2\"/>

**GILBERT/COMMONWEALTH
COPPER DRILL LOTS
COMBUSTION PIPING**

**PITTSBURGH
ENERGY TECHNOLOGY
CENTER, PA**

REV. 1 D-1145

Figure 5: P&ID Layout of SO₃ Spike Injection System

PROTECTED CRADA INFORMATION

Table 5: SO₃ Summary Data

Condition	Absorber Inlet SO ₃ (ppm)			Absorber Outlet SO ₃ (ppm)			SO ₃ Removal (%)		
	Control Cond	Titration	Ion Chrom	Control Cond	Titration	Ion Chrom	Control Cond	Titration	Ion Chrom
MBCuO-18-1a	43.3			1.7			96.1		
MBCuO-18-1b	52.1	25.5	33.8	1.6	0	1.9	96.9	100	94.3
MBCuO-18-1c	39.4			1.9			95.2		
MBCuO-18-1d	50.8			2.4			95.3		
MBCuO-18-1e				5.5		2.2			
Mean	46.4	25.5	33.8	2.6	0	2.1	95.9	100	94.3
Std Dev (%)	13.1	-	-	63.1	-	10.0	0.8	-	-
MBCuO-18-2a	6.5		3.2	5.1*		1.4	21.5*		55.9
MBCuO-18-2b	4.8			0.9			81.3		
MBCuO-18-2c	3.3			0.9			72.7		
MBCuO-18-2d	7.4		4.0	2.1		1.8	71.6		53.8
MBCuO-18-2e	6.8			2.4			64.7		
Mean	5.8		3.6	1.6		1.6	72.6		54.9
Std Dev (%)	29.0		15.8	49.4		17.5	9.4		2.7

* Outlet result for MBCuO-18-2a not used in statistics

Table 6: SO₃ Distribution Summary Data

Condition	Absorber Inlet SO ₃ (ppm)											
	Control Cond				Titration				Ion Chrom			
	Filt	Probe	Cond	Tot	Filt	Probe	Cond	Tot	Filt	Probe	Cond	Tot
MBCuO-18-1a	0	3.5	39.8	43.3								
MBCuO-18-1b	0	8.2	43.9	52.1	NS	0	25.5	25.5	NS	7.6	26.1	33.8
MBCuO-18-1c	0	5.3	34.1	39.4								
MBCuO-18-1d	0	6.6	44.2	50.8								
MBCuO-18-1e												
MBCuO-18-2a	1.6	1.6	3.3	6.5					0.2	0.1	2.9	3.2
MBCuO-18-2b	0	1.1	3.7	4.8								
MBCuO-18-2c	0	1.3	2.0	3.3								
MBCuO-18-2d	0	1.1	6.3	7.4					0.1	0.8	3.1	4.0
MBCuO-18-2e	0	1.1	5.7	6.8								
Condition	Absorber Outlet SO ₃ (ppm)											
	Control Cond				Titration				Ion Chrom			
	Filt	Probe	Cond	Tot	Filt	Probe	Cond	Tot	Filt	Probe	Cond	Tot
MBCuO-18-1a	0	0.5	1.2	1.7								
MBCuO-18-1b	0	1.0	0.6	1.6	NS	0	0	0	NS	0.5	1.4	1.9
MBCuO-18-1c	0	0	1.9	1.9								
MBCuO-18-1d	0	0.4	2.0	2.4								
MBCuO-18-1e	0	0.6	4.9	5.5					0.04	0.4	1.7	2.2
MBCuO-18-2a*	0	0.3	4.8	5.1					0.1	0.1	1.2	1.4
MBCuO-18-2b	0	0.2	0.7	0.9								
MBCuO-18-2c	0	0.2	0.7	0.9								
MBCuO-18-2d	0	0	2.1	2.1					0.1	0	1.7	1.8
MBCuO-18-2e	0	0.3	2.1	2.4								
Condition	SO ₃ Removal (%)											
	Control Cond				Titration				Ion Chrom			
MBCuO-18-1a				96.1								
MBCuO-18-1b				96.9				100				94.3
MBCuO-18-1c				95.2								
MBCuO-18-1d				95.3								
MBCuO-18-1e												
MBCuO-18-2a				21.5								55.9
MBCuO-18-2b				81.3								
MBCuO-18-2c				72.7								
MBCuO-18-2d				71.6								53.8
MBCuO-18-2e				64.7								

* Outlet result for MBCuO-18-2a not used in statistics

PROTECTED CRADA INFORMATION

Table 7: Flue Gas Moisture & Velocity Determination

	MBCuO-18-1		MBCuO-18-2	
	Inlet	Outlet	Inlet	Outlet
Date	4/14/98	4/14/98	4/17/98	4/17/98
Gas Temp, °F	805	650	810	660
% O ₂	3.0	3.3	5.0	5.2
% CO ₂	10.0	9.7	15.0	14.8
% Moisture	18.0	18.0	9.0	9.0
Barometric Pressure, in Hg	28.72	28.72	28.80	28.80
Duct Pressure, in H ₂ O	-6.19	-14.75	-7.37	-24.05
Avg Gas Meter Pres Drop, in H ₂ O	0.844	0.768	0.893	0.795
Avg Velocity, Ft/s	79.5	71.8	79.1	71.9
Flue Gas Flowrate (Pitot)				
acfm (wet)	276	250	275	250
scfm (dry)	89	90	99	97
scfm (wet)	108.5	109.8	108.8	106.6
Flue Gas Flowrate (Venturi) scfm (wet)	113		110	
Flue Gas Temperature, °F				
TE-15 (upstream of inlet probe)	840-850		860-910	
TE-18 (downstream of inlet probe)	745-750		755-800	
TE-21 (upstream of outlet probe)		675-680		675-680
O ₂ , %	3.1	3.4	4.7	4.9
Furnace CO ₂ , %	9.7		14.1	
Predicted Moisture, %	16.4		9.1	

PROTECTED CRADA INFORMATION

Table 8: Gas Phase and Solid Phase Sulfur Recoveries

Test Number and Condition	Sulfur (Wt%) in Sorbent		Sorbent Circulation Rate (lb/min)	SO ₂ (lb-mol/hr)			Error (%)	
	Absorber Outlet	Regenerator Outlet		Removed in Absorber (Gas Phase)	Regenerator Offgas (Gas Phase)	Removed in Regenerator (Solid Phase)	Gas Phase	Solid Phase
MBCUO-18-1a			0.75	0.0293	0.0231		-21.2	
MBCUO-18-1b			0.75	0.0293	0.0228		-22.2	
MBCUO-18-1c			0.75	0.0295	0.0222		-24.7	
MBCUO-18-1d			0.75	0.0294	0.0206		-29.9	
MBCUO-18-1e	3.27	1.3	0.75	0.0295	0.0206	0.0276	-30.2	-6.4
MBCUO-18-2a			0.75	0.0283	0.0238		-15.9	
MBCUO-18-2b			0.75	0.0278	0.0238		-14.4	
MBCUO-18-2c			0.75	0.0275	0.0257		-6.5	
MBCUO-18-2d			0.75	0.0279	0.0243		-12.9	
MBCUO-18-2e	2.61	1.25	0.75	0.0275	0.0253	0.0191	-8.0	-30.5

* Nominal regenerator temperature was 850°F and residence time was 180 min.

PROTECTED CRADA INFORMATION

Table 9: Analysis (dry) by GC and CEM of gas samples from regenerator and natural gas supply.

Date		4/13	4/14	4/14	4/14	4/14	4/14	4/14	4/14	4/14	4/14	4/14	4/14				
Time		17:45	10:29	10:30	12:17	12:17	12:18	13:55	13:55	15:15	15:15	16:07	16:12				
GC (Vol %)																	
	He	0.07	-	0.05	-	-	0.06	-	-	-	-	-	-				
	H2	0.10	-	-	-	-	0.07	-	-	-	-	-	-				
	O2	-	-	-	-	-	2.16	0.29	0.27	-	-	0.34	-				
	N2	1.27	1.90	2.42	1.92	1.87	9.03	2.91	3.10	1.77	1.62	2.47	1.66				
	CH4	87.92	19.36	19.40	20.61	19.63	78.80	21.08	19.67	21.57	21.76	21.84	21.38				
	CO	-	0.43	0.56	0.39	0.43	-	0.45	-	0.52	0.49	0.42	0.43				
	CO2	0.13	35.38	35.77	36.90	35.37	0.15	36.44	34.68	34.80	34.78	33.30	33.34				
	C2H6	9.76	0.98	0.98	1.02	0.98	9.06	0.85	0.80	1.04	1.04	1.04	1.04				
	SO2	-	41.95	40.82	39.16	41.73	-	37.97	41.49	40.31	40.31	40.59	42.15				
	C3H8	0.75	-	-	-	-	0.67	-	-	-	-	-	-				
Date			4/14		4/14			4/14		4/14		4/14					
Time			10:40		12:00			13:30		15:00		16:00					
CEM (Vol %)																	
	CH4		21		21			22		23		25					
	CO2		41		40			40		39		39					
	SO2		36		35			35		33		33					
Date		4/15	4/15	4/16	4/16	4/17	4/17	4/17	4/17	4/17	4/17	4/17	4/17	4/17	4/17	4/17	4/17
Time		15:29	15:30	17:05	17:06	08:42	08:43	08:44	10:20	10:21	11:34	11:35	13:12	13:13	13:14	16:50	16:51
GC (Vol %)																	
	He	0.07	-	0.05	0.08	0.06	0.05	0.04	-	0.04	0.05	0.04	0.05	0.07	0.05	0.03	0.05
	H2	0.12	-	-	0.10	0.11	-	-	-	-	-	-	-	0.09	-	-	-
	O2	-	0.60	0.48	0.31	0.12	1.80	0.65	0.38	0.47	0.43	0.63	0.69	0.15	0.54	0.56	0.51
	N2	0.88	3.80	3.57	1.69	1.24	7.82	3.70	2.92	3.45	3.29	3.87	4.56	1.17	4.33	3.25	3.16
	CH4	88.42	23.80	30.37	87.33	88.24	27.86	29.35	23.88	26.16	26.37	25.04	26.33	87.97	27.34	23.75	25.95
	CO	-	0.46	0.38	-	-	0.58	0.68	0.45	0.50	0.41	0.49	0.43	0.15	0.63	0.47	0.47
	CO2	-	30.91	36.71	-	0.07	28.82	29.76	28.69	29.73	32.16	29.74	30.54	0.07	31.27	28.77	31.18
	C2H6	9.38	1.16	1.40	9.36	9.00	1.54	1.59	1.43	1.50	1.54	1.44	1.44	9.09	1.50	1.25	1.36
	SO2	-	39.25	27.00	-	-	31.48	34.17	42.20	38.10	35.71	38.69	35.90	-	34.29	41.89	37.29
	C3H8	1.14	0.03	0.04	1.12	1.16	0.05	0.05	0.05	0.05	0.05	0.05	0.05	1.24	0.04	0.04	0.04
Date						4/17		4/17		4/17		4/17				4/17	
Time						08:15		10:10		11:30		13:00				16:55	
CEM (Vol %)																	
	CH4					32		30		29		30				30	
	CO2					33		34		35		35				33	
	SO2					38		39		39		38				37	

PROTECTED CRADA INFORMATION

Table 10: Copper Analysis and Dust Balance for MBCuO-18

DUST BALANCE FOR MBCUO-18				
Test Condition	Cu%	lb dust	lb sorbent	lb ash
WARM-UP 4/13/98				
AB-IN-POT	NA	0.08	0.08	0
AB-OUT-POT	NA	4.4	4.4	0
BH	NA	3.8	3.8	0
FBH	NA	37.0	37.0	0
		45.3 (subtotal)	45.3 (subtotal)	0 (subtotal)
#1 4/14/98				
AB-IN-POT	NA	0	0	0
AB-OUT-POT	5.55	4.4	3.7	0.7
BH	0.46	0.6	0.04	0.56
FBH	5.45	28.6	23.6	5.0
		33.6 (subtotal)	27.3 (subtotal)	6.3 (subtotal)
Pre #2 4/15/98	Cu is default	from #1		
AB-IN-POT	0.07	1.0	0.01	0.99
AB-OUT-POT	5.55	3.0	2.5	0.5
BH	0.46	2.4	0.2	2.2
FBH	5.45	21.2	17.5	3.7
		27.6 (subtotal)	20.2 (subtotal)	7.4 (subtotal)
#1-Scrub 4/16/98				
AB-IN-POT	< 0.07	11.0	0	11.0
AB-OUT-POT	5.07	1.4	1.1	0.3
BH	0.15	8.4	0.2	8.2
FBH	3.27	54.2	26.9	27.3
		75.0 (subtotal)	28.2 (subtotal)	46.8 (subtotal)
#1-Scrub 4/16/98				
AB-IN-POT	0.07	4.8	0.05	4.75
AB-OUT-POT	5.20	2.4	1.9	0.5
BH	0.10	7.4	0.1	7.3
FBH	3.02	40.2	18.4	21.8
		54.8 (subtotal)	20.4 (subtotal)	34.4 (subtotal)
#2 4/17/98				
AB-IN-POT	< 0.07	2.6	0	2.6
AB-OUT-POT	5.63	3.4	2.9	0.5
BH	0.15	4.6	0.1	4.5
FBH	2.80	40.4	17.1	23.3
		51.0 (subtotal)	20.1 (subtotal)	30.9 (subtotal)
POST 4/18/98				
AB-IN-POT	0.26	2.4	0.1	2.3
AB-OUT-POT	5.15	1.4	1.1	0.3
BH	0.50	0.2	0.02	0.18
FBH	2.98	24.4	11.0	13.4
FBC	5.99	19.8	18.0	1.8
		48.2 (subtotal)	30.2 (subtotal)	18.0 (subtotal)
Subtotals, lbs		335.5	191.7	143.8
furnace pot ash, lbs				29.2
Total wt lbs		335.5 + 29.2 = 364.7		143.8 fly ash 29.2 furnace pot ? furnace wall 173.0 + ???
COAL FIRED	1695 lbs			coal ash expected = 169.5 lbs
SORBENT ATTRITED	186.99 lbs			

Dust enclosure = output-input = (364.7) - (186.99 + 169.5) = 8.21 lbs (surplus) = 2.3% of input

Sorbent unaccounted for = output-input = 191.7 - 186.99 = 4.71 lbs (surplus) = 2.5% of sorbent makeup

Coal ash unaccounted for = output-input = 173.0 - 169.5 = 3.5 lbs (surplus) = 2.1% surplus of input coal ash

Note: If dust copper analysis is 6.6% or greater the dust is considered as 100% sorbent.

* Indicates default copper analysis value.

PROTECTED CRADA INFORMATION

Table 11: SO₂ Summary Data

Condition	Absorber Inlet SO ₂ (ppm, dry)			Absorber Outlet SO ₂ (ppm, dry)			SO ₂ Removal (%)		
	CEM	Method 8	Ion Chrom	CEM	Method 8	Ion Chrom	CEM	Method 8	Ion Chrom
MBCuO-15-1	2030	1860	843	210	120	231	89.7	93.5	72.6
MBCuO-15-1a	2080	1760	864	295	140	270	85.8	92.0	68.8
Mean	2055	1810	854	253	130	251	87.8	92.8	70.7
Std Dev (%)	1.7	3.9	1.7	23.8	10.8	11.0	3.1	1.1	3.8
Error (%)	-	-11.9	-58.4	-	-48.6	-0.8	-	+5.7	-19.5
MBCuO-16-1a	2190	663*	334*	330	282	147	84.9	57.5*	56.0*
MBCuO-16-1b	2280	335*	158*	300	184*	81.7	86.8	45.1*	48.3*
MBCuO-16-1c	2210	1420	711	200	364	122	91.0	74.4	82.8
MBCuO-16-1d	2220	1364	675	205	364	12.4	90.8	73.3	98.2
Mean	2225	1392	693	259	337	90.8	88.4	73.9	90.5
Std Dev (%)	1.7	2.8	3.7	25.5	14.0	64.8	3.4	1.1	12.0
Error (%)	-	-37.3	-68.9	-	+30.1	-64.9	-	-16.4	+2.4
MBCuO-16-2	2000	1586	945	185	208	91.7	90.8	86.9	90.3
Error (%)	-	-20.7	-52.8	-	+12.4	-50.4	-	-4.3	-0.6

* Data not used in statistics.

PROTECTED CRADA INFORMATION

Table 12: SO₃ Summary Data

Condition	Absorber Inlet SO ₃ (ppm, dry)		Absorber Outlet SO ₃ (ppm, dry)		SO ₃ Removal (%)	
	Method 8	Ion Chrom	Method 8	Ion Chrom	Method 8	Ion Chrom
MBCuO-15-1	6.4	3.73	2.0	0.74	68.8	80.2
MBCuO-15-1a	27	6.11	2.7	1.67	90.0	72.7
Mean	16.7	4.9	2.4	1.2	79.4	76.5
Std Dev (%)	87.4	34.1	20.6	54.8	18.9	6.9
MBCuO-16-1a	27*	24.6*	4	3.01	85.2*	87.8*
MBCuO-16-1b	1140*	890*	10	5.84	99.1*	99.3*
MBCuO-16-1c	53	51.9	2	3.16	96.2	93.9
MBCuO-16-1d	60	55.5	65*	133*	-8.3*	-140*
Mean	57	54	5.3	4.0	96.2	93.9
Std Dev (%)	8.7	4.7	78.5	40.0	-	-
MBCuO-16-2	63	1.36	2	1.52	96.8	-11.8

* Data not used in statistics.

PROTECTED CRADA INFORMATION

APPENDIX A

STACK GAS SAMPLING REPORT

PROTECTED CRADA INFORMATION

Sulfur Trioxide Measurements at the FETC Novel Scrubber

Test Results for April 14 and 17, 1998

By:

CONSOL Inc., R&D
4000 Brownsville Road
Library, PA 15129

Report Date:
August 20, 1998

Team Test Leader:
Matthew S. DeVito
Research Group Leader
412-854-6679 (phone)
412-854-6613 (fax)
mattdevito@consolcoal.com

SUMMARY

CONSOL R&D conducted two days of flue gas measurements at the inlet and outlet of the FETC novel SO₂ scrubber on April 14 and April 17, 1998. Flue gas sulfur dioxide (SO₂) and sulfur trioxide (SO₃) concentrations and the flue gas volumetric flowrates were measured at both the inlet and outlet of the scrubber. Four replicate pairs of samples were completed on April 14 while the test unit was operated on natural gas that was spiked with SO₃. Five additional pairs of samples were completed on April 17 while the unit was operated on coal without SO₃ spiking.

The average SO₃ duct concentration at the reactor inlet for the natural gas, SO₃-spiked tests was 46 ppmv while the average SO₂ duct concentration was 2135 ppmv. The average scrubber SO₃ outlet was 3 ppmv while the SO₂ concentration was 266 ppmv. The average SO₃ removal was 96% and the average SO₂ removal 88%. The volumetric gas flow was 89 dry standard cubic feet per minute (dscfm) at the inlet and 90 dscfm at the outlet.

The average SO₃ duct concentration at the reactor inlet for the coal-fired tests was 5.5 ppmv while the average SO₂ duct concentration was 2046 ppmv. The average scrubber SO₃ outlet was 1.6 ppmv while the SO₂ concentration was 339 ppmv. The average SO₃ removal was 72% and the average SO₂ removal was 83%. The volumetric gas flow was 99 dscfm at the inlet and 97 dscfm at the outlet.

BACKGROUND

In response to a variety of environmental and operational issues, CONSOL R&D developed a unique sampling method for SO₃ measurements for combustion systems. This methodology has been successfully used in a variety of pilot-scale and full-scale test. At the request of personnel from the Federal Energy Technology Center (FETC) of the United States Department of Energy (DOE), CONSOL R&D conducted a series of SO_x measurements across a novel pilot scale SO₂ scrubber which is being evaluated at the FETC Pittsburgh facility. The objective of this work was to characterize SO₃ removal for the pilot scrubber. The CONSOL developed "controlled condensation" method was used to determine the SO₃ concentration. SO₂ removals and volumetric gas flow rates were also determined during this test program. Measurements with the unit operating on natural gas that was spiked with both SO₂ and SO₃ were completed on April 14. A second set of measurements with the system operating on coal was completed on April 17. The results of the testing and a description of the test methods are documented in this report.

EXPERIMENTAL

Sampling Locations

A schematic showing the general locations of the inlet and outlet sampling ports is presented in Figure 1. The measurements were conducted through a "pipe tee" on both ducts. The "pipe tee" was equipped with an isolation valve that was connected to the 3.26" ID flue gas transport duct. The SO_x samples were collected from the mid-point of

the sample duct. A five-point velocity traverse was used to determine flue gas flow rate. The traverse points are indicated in Figure 1.

The sampling locations were under a high negative pressure (7"-24" H₂O). Because of this, special care was taken to assure that the sampling probes could be inserted without causing air in-leakage which could upset to the system. With the isolation valve closed, the sampling probe was inserted into the "tee" section through an air-tight compression fitting. The compression fitting was loosely tightened and the isolation valve was opened. The sampling probe was then inserted into the mid-point of the duct. Once properly located, the compression fitting was completely tighten to eliminate air in-leakage.

Volumetric Flow Rate

Flue gas volumetric flow rate was measured as outlined in EPA Method 2. CONSOL used a 3' type "S" pitot tube equipped with a Type K thermocouple. The individual pressure differentials at the traverse points were determined using a Shortridge electronic micro-manometer. Pitot measurements were made in one plane using a five-point traverse.

SO₂/SO₃ Measurements

Flue gas SO₂ and SO₃ concentrations were determined using a controlled condensation method originally developed by US EPA and modified by CONSOL R&D. A drawing of the CONSOL sampling train is shown in Figure 2. Flue gas is pulled through a temperature-controlled quartz-lined probe fitted with a quartz wool plug to remove particulate matter. The probe temperature is maintained at ~550 °F to minimize SO₃ condensation and SO₂ oxidation. After the filter, the gas sample passes through a water-cooled condenser which is loosely packed with glass wool. A circulating water bath is used to control the condenser temperature to 140 °F. This temperature is below the acid dewpoint. Essentially, all of the SO₃ condenses. However the condenser temperature is above the water dewpoint to eliminate water condensation. The sample gas exits the condenser and enters a bank of miniature impingers. The first two impingers contain a 3% H₂O₂ solution which captures the SO₂. The gas then passes through an empty impinger and finally a silica gel-filled impinger for moisture removal. The gas is then is conveyed through a rotameter, a vacuum pump, and a dry test meter.

Prior to the sampling, the system is leak checked under a vacuum of 10" of Hg. The sample probe is then positioned at the proper location and gas is sampled for 30-60 minutes. The following data is recorded: (1) starting gas volume, (2) interval gas volume, (3) final gas volume, (4) probe temperature, (5) condenser temperature, (6) flue gas duct temperature, (7) dry test meter temperature, (8) flowmeter setting, (9) system vacuum, (10) exit gas O₂ concentration, (11) barometric pressure, and (12) sampling time.

After sampling, the probe is removed from the stack, leak checked, and the train components are disassembled for sample recovery. The sample train components are recovered in the following manner:

Quartz Plug - The quartz plug is removed from the probe tip, placed in a glass bottle, and extracted with 20 mL of isopropyl alcohol (IPA). The solids are filtered and the filtrate is diluted to a known volume prior to analyses.

PROTECTED CRADA INFORMATION

Sample Probe - The quartz probe liner is rinsed with IPA into a glass bottle and diluted to a known volume prior to analysis.

Condenser - The condenser interior is rinsed with IPA into a glass bottle. Three complete rinsings are utilized. The rinsings are diluted to a known volume prior to analysis.

Impingers - The contents of the first three impingers and connecting tubes are rinsed into a collection bottle with deionized (DI) water and diluted to a known volume prior to analysis.

The analyses of the individual fractions is by a BaCl_2 titration to a thorin endpoint as described in EPA Method 6. The quartz plug contains the SO_3 that was absorbed onto the solid particles prior to collection in the sampling train. The gas phase SO_3 value is the sum of the probe and condenser washes. In most cases, the majority of the gas phase SO_3 is found in the condenser rinse. The impingers collect the SO_2 fraction. The SO_x values are reported in ppmv at duct conditions and at 0% oxygen.

RESULTS

SO_2 Measurements for Natural Gas Tests

A summary of the flue gas SO_2 concentrations at duct conditions for each test while firing natural gas are presented in the following table:

Test ID	SO ₂ Conc., ppmv at Duct Conditions		% Removal
	Inlet	Outlet	
Test #1	2077	277	86.7
Test #2	2157	251	88.4
Test #3	2149	267	87.6
Test #4	2143	266	87.6
Test #5	2143 ¹	270	87.4
Average	2134	266	87.5
St. Dev.	32	10	0.6
PRSD	1.5	3.8	0.7

¹ - Estimated from Test #4 inlet value.

In some cases it is beneficial to evaluate gas concentrations at a constant oxygen dilution. For this reason, the values were also calculated at 0% oxygen. A summary of corrected flue gas SO_2 concentrations measured for each test while firing natural gas are presented in the following table:

PROTECTED CRADA INFORMATION

Test ID	SO ₂ Conc., ppmv at 0% Oxygen		% Removal
	Inlet	Outlet	
Test #1	2425	328	86.5
Test #2	2519	297	88.2
Test #3	2509	316	87.4
Test #4	2503	315	87.4
Test #5	2503 ¹	320	87.4
Average	2489	315	87.4
St. Dev.	43	12	0.7
PRSD	1.7	3.9	0.8

1- Estimated from Test #4 inlet value.

These data show very consistent flue gas SO₂ concentrations over the test day. Based on these measurements, the scrubber removed 87.5%±0.7% of the SO₂ at duct conditions.

SO₃ Measurements for Natural Gas Tests

A summary of the flue gas SO₃ concentrations at duct conditions for each test while firing natural gas are presented in the following table:

Test ID	SO ₃ Conc., ppmv at Duct Conditions		% Removal
	Inlet	Outlet	
Test #1	43.2	1.7	96.1
Test #2	52.0	1.6	96.9
Test #3	39.3	1.9	95.2
Test #4	50.8	2.4	95.3
Test #5	50.8 ¹	5.5	89.2
Average	46.3	2.6	94.4
St. Dev.	6.1	1.6	3.1
PRSD	13.1	61	3.3

1- Estimated from Test #4 inlet value.

PROTECTED CRADA INFORMATION

A summary of corrected flue gas SO₃ concentrations (0% oxygen) determined for each test while firing natural gas are presented in the following table:

Test ID	SO ₃ Conc., ppmv at 0% Oxygen		% Removal
	Inlet	Outlet	
Test #1	50.5	2.0	96.0
Test #2	60.7	1.8	97.0
Test #3	45.9	2.2	95.2
Test #4	59.3	2.8	95.3
Test #5	59.3 ¹	6.5	89.0
Average	54.1	3.1	94.5
St. Dev.	7.1	2.0	3.1
PRSD	13.1	65	3.3

1- Estimated from Test #4 inlet value.

The inlet flue gas SO₃ concentrations was between 46 and 60 ppmv while the outlet values were between 2 and 6 ppmv over the test day. Based on these measurements, the scrubber showed an SO₃ removal efficiency of 94.5% ± 3.1% for the gas-fired condition.

SO₂ Measurements for Coal-Fired Test

A summary of the flue gas SO₂ concentrations at duct conditions for each test while firing coal are presented in the following table:

Test ID	SO ₂ Conc., ppmv at Duct Conditions		% Removal
	Inlet	Outlet	
Test #1	2042	308	84.9
Test #2	2032	393	80.7
Test #3	2042	327	84.0
Test #4	2078	340	83.6
Test #5	2034	327	83.9
Average	2046	339	83.4
St. Dev.	20	35	1.8
PRSD	1.0	10.4	2.1

PROTECTED CRADA INFORMATION

As in the natural gas case, the coal-fired results were also calculated on a 0% oxygen basis. A summary of corrected flue gas SO₂ concentrations measured for each test while firing coal are presented in the following table:

Test ID	SO ₂ Conc., ppmv at 0% Oxygen		% Removal
	Inlet	Outlet	
Test #1	2651	404	84.8
Test #2	2638	517	80.4
Test #3	2651	430	83.8
Test #4	2697	447	83.4
Test #5	2641	430	83.7
Average	2656	446	83.2
St. Dev.	25	47	1.8
PRSD	0.9	15	2.2

These data show very consistent flue gas SO₂ concentrations over the test day. Based on these measurements, the scrubber SO₂ removal efficiency was 83.2% ± 1.8% for the coal-fired test.

SO₃ Measurements for Coal-Fired Tests

A summary of the flue gas SO₃ concentrations at duct conditions for each test while firing coal are presented in the following table:

Test ID	SO ₃ Conc., ppmv at Duct Conditions		% Removal
	Inlet	Outlet	
Test #1	4.9	5.1 ¹	---- ¹
Test #2	4.8	0.9	81.3
Test #3	3.3	1.0	69.7
Test #4	7.4	2.1	71.6
Test #5	6.9	2.4	65.2
Average	5.5	1.6	71.9
St. Dev.	1.6	0.6	5.8
PRSD	30	39	8.1

1- Outlet results for Test #1 not used in statistics.

PROTECTED CRADA INFORMATION

A summary of corrected flue SO₃ concentrations (0% oxygen) measured for each test while firing coal are presented in the following table:

Test ID	SO ₃ Conc., ppmv at 0% Oxygen		% Removal
	Inlet	Outlet	
Test #1	6.4	6.7 ¹	---- ¹
Test #2	6.3	1.2	81.0
Test #3	4.3	1.3	69.8
Test #4	9.6	2.8	70.8
Test #5	8.9	3.1	65.2
Average	7.1	2.1	71.7
St. Dev.	2.1	0.8	5.8
PRSD	30	40	8.1

1- Outlet results for Test #1 not used in statistics.

The inlet flue gas SO₃ concentrations ranged from 6 to 9 ppmv while the outlet values ranged from 1 to 3 ppmv over the test day. Based on a field review of the data it appeared that the outlet measurement for the first test was biased high. A decision was made to conduct an additional pair of measurements to verify the outlet concentration. From these results, it was decided to treat the first outlet test as an outlier. After omitting the outlet result from the first test, the scrubber SO₃ removal efficiency was 71.7% ± 5.8% for the coal-fired condition.

All of the SO_x data is contained in Appendix 1.

Flue Gas Moisture Measurements

Flue gas moisture was determined by measuring the weight gain in the liquid and silica gel impingers. From these measurements, the flue gas moisture content is estimated at 18% for the gas-fired and 9% for the coal-fired tests.

Volumetric Flow Measurements

Inlet and outlet duct gas flow rate measurements were made for each firing condition. The results of the measurements are summarized in the following table:

PROTECTED CRADA INFORMATION

	Gas-Fired Conditions		Coal-Fired Conditions	
	Inlet	Outlet	Inlet	Outlet
Date	4/14/98	4/14/98	4/17/98	4/17/98
Gas Temp, °F	805	650	810	660
% O ₂	3.0	3.3	5.0	5.2
% CO ₂	10.0	9.7	15.0	14.8
% Moisture	18.0	18.0	9.0	9.0
Barometric Pressure, "Hg	28.72	28.72	28.80	28.80
Duct Pressure, " H ₂ O	-6.19	-14.75	-7.37	-24.05
Avg ΔP , " H ₂ O	0.844	0.768	0.893	0.795
Avg Vel, fps	79.5	71.8	79.1	71.9
acfm	276	250	275	250
dscfm	89	90	99	97

A complete pitot summary for each of the velocity measurements is provided in Appendix 2.

DISCUSSION

In the controlled condensation method, the condenser is typically operated at a temperature of 140 °F. At this temperature the flue gas is significantly below the acid dewpoint (>200 °F) and above the water dewpoint (~125 °F). By operating below the acid dewpoint, the majority of the SO₃ is condensed and collected on the glass wool in the condenser. However, it is important to prevent water condensation in the condenser. If water condenses in the condenser, gas phase SO₂ would absorb in the water and yield high results.

While firing natural gas, the condenser temperature was maintained at 150°F. The higher temperature was selected because the acid and water dewpoint for this case are higher than for the coal-fired case.

PROTECTED CRADA INFORMATION

During the gas-fired testing, a significant discoloration was observed in the train rinsings. The discoloration did not appear to have any effect on the titrations. However, an additional outlet sample was collected to assure the data quality.

The inlet and outlet SO_3 concentrations from the first coal-fired test had similar SO_3 values. A field review of the next three test showed an approximate 70% reduction in the flue SO_3 concentration across the scrubber. From these data it was decided to run an additional test and treat the first test as an outlier.

The flue gas moisture concentrations should be considered as estimates only. The EPA procedure for determining moisture in a combustion flue gas stream specifies a minimum sampling volume of 20 cubic feet. For these tests, less than 5 cubic feet of gas was collected.

Accurate velocity measurements in small ducts ($<8"$) are difficult with standard EPA-type equipment. For this test program a standard Type "S" pitot tube encased in a 1" OD steel sleeve was used. The placement of the pitot tube in such a small cross-sectional area can significantly block the flue gas path. This can lead to flow distortions. However, a review of the pitot data showed that it compared well with existing plant instrumentation and theoretical calculations.

PROTECTED CRADA INFORMATION

Figure 1. Schematic of Sampling Ports and Points

Figure 2 - CONSOL R&D SO_3 Sampling Train

PROTECTED CRADA INFORMATION

APPENDIX I

SO₃/SO₂ Summary Data for Each Sample Pair

PROTECTED CRADA INFORMATION

**SO₂ Sampling Results from FETC Test Unit
TEST #1**

DATE	4/14/98	4/14/98	
START TIME	0935	0935	
END TIME	1025	1025	
LOCATION	INLET	OUTLET	
MEASURED METER VARIABLES			
SAMPLE TIME [Minutes]	50	50	
BAROMETRIC PRESSURE [in Hg]	28.72	28.72	
SAMPLE VOLUME [ft ³]	4.80	4.60	
METER TEMPERATURE [° F]	72.3	71.9	
ORIFICE PRESSURE [in H ₂ O]	0.01	0.01	
Y FACTOR	1.015	1.050	
DSCF SAMPLED	4.638	4.601	
CONDENSER TEMP [° F]	155	150	
CC/MIN @ COND	3059	3010	
DUCT OXYGEN [APPROX %]	3.00	3.25	
DUCT TEMP DURING TEST [° F]	822	652	
DSCFM [based on pitot traverse]	90	90	
Moisture Weight Gain, g	22	13.4	
Water Volume, dscf	1.0362	0.63114	
% Moisture in Gas Sample	18.3	12.1	
% Moisture at Duct Conditions	19.8	19.0	
SO₂			
SO ₂ in IMPINGERS			SO₂ Removal
lb/DSCF	3.17E-04	2.91E-05	
lb/hr	1.71	0.16	
PPMV, As Sampled	1915	176	
PPMV, @ 0% Oxygen	2425	328	86.5%
PPMV, @ Duct Conditions	2077	277	86.7%
SO₃			
SO ₃ in FILTER PLUG			
lb/DSCF	0.00E+00	0.00E+00	
lb/hr	0.00E+00	0.00E+00	
PPMV, As Sampled	0.0	0.0	
PPMV, @ 0% Oxygen	0.0	0.0	
PPMV, @ Duct Conditions	0.0	0.0	
SO ₃ in PROBE			
lb/DSCF	6.59E-07	6.64E-08	
lb/hr	3.56E-03	3.59E-04	
PPMV, As Sampled	3.2	0.3	
PPMV, @ 0% Oxygen	4.0	0.6	
PPMV, @ Duct Conditions	3.5	0.5	
SO ₃ in CONDENSER			
lb/DSCF	7.59E-06	1.52E-07	
lb/hr	4.10E-02	8.20E-04	
PPMV, As Sampled	36.7	0.7	
PPMV, @ 0% Oxygen	46.5	1.4	
PPMV, @ Duct Conditions	39.8	1.2	
SO₃ Removal			
GAS PHASE SO ₃ [lb/DSCF]	8.25E-06	2.18E-07	
GAS PHASE SO ₃ [lb/hr]	4.45E-02	1.18E-03	
GAS PHASE SO ₃ [Duct PPM]	43.2	1.7	
GAS PHASE SO ₃ , 0% OXYGEN	50.5	2.0	96.1%
TOTAL PHASE SO ₃ [lb/DSCF]	8.25E-06	2.18E-07	
TOTAL PHASE SO ₃ [lb/hr]	4.45E-02	1.18E-03	
TOTAL PHASE SO ₃ [Duct PPM]	43.2	1.7	96.2%
TOTAL SO ₃ , 0% OXYGEN	50.5	2.0	
% SO ₃ in SOLIDS [filter plug/total]	0.0	0.0	

PROTECTED CRADA INFORMATION

SO₂ Sampling Results from FETC Test Unit TEST #2

DATE	4/14/98	4/14/98	
START TIME	1150	1150	
END TIME	1240	1240	
LOCATION	INLET	OUTLET	
MEASURED METER VARIABLES			
SAMPLE TIME [Minutes]	48	48	
BAROMETRIC PRESSURE [" Hg]	28.72	28.72	
SAMPLE VOLUME [ft ³]	5.10	5.30	
METER TEMPERATURE [° F]	78.7	77.1	
ORIFICE PRESSURE [" H ₂ O]	0.01	0.01	
Y FACTOR	1.015	1.050	
DSCF SAMPLED	4.869	5.250	
CONDENSER TEMP [° F]	137	145	
CC/MIN @ COND	3247	3548	
DUCT OXYGEN [APPROX %]	3.00	3.25	
DUCT TEMP DURING TEST [° F]	812	650	
DSCFM [based on pitot traverse]	90	90	
Moisture Weight Gain, g	23.5	20.2	
Water Volume, dscf	1.10685	0.95142	
% Moisture in Gas Sample	18.5	15.3	
% Moisture at Duct Conditions	19.2	18.5	
SO₂			
SO ₂ in IMPINGERS			SO₂ Removal
lb/DSCF	3.45E-04	3.44E-05	
lb/hr	1.86	0.19	
PPMV, As Sampled	2085	208	
PPMV, @ 0% Oxygen	2519	297	
PPMV, @ Duct Conditions	2157	251	88.2%
			88.4%
SO₃			
SO ₃ in FILTER PLUG			
lb/DSCF	0.00E+00	0.00E+00	
lb/hr	0.00E+00	0.00E+00	
PPMV, As Sampled	0.0	0.0	
PPMV, @ 0% Oxygen	0.0	0.0	
PPMV, @ Duct Conditions	0.0	0.0	
SO ₃ in PROBE			
lb/DSCF	1.63E-06	1.66E-07	
lb/hr	8.81E-03	8.98E-04	
PPMV, As Sampled	7.9	0.8	
PPMV, @ 0% Oxygen	9.5	1.2	
PPMV, @ Duct Conditions	8.2	1.0	
SO ₃ in CONDENSER			
lb/DSCF	8.77E-06	9.98E-08	
lb/hr	4.74E-02	5.39E-04	
PPMV, As Sampled	42.4	0.5	
PPMV, @ 0% Oxygen	51.2	0.7	
PPMV, @ Duct Conditions	43.9	0.6	
			SO₃ Removal
GAS PHASE SO ₃ [lb/DSCF]	1.04E-05	2.66E-07	
GAS PHASE SO ₃ [lb/hr]	5.62E-02	1.44E-03	
GAS PHASE SO ₃ [Duct PPM]	52.0	1.6	
GAS PHASE SO ₃ , 0% OXYGEN	60.7	1.8	97.0%
TOTAL PHASE SO ₃ [lb/DSCF]	1.04E-05	2.66E-07	
TOTAL PHASE SO ₃ [lb/hr]	5.62E-02	1.44E-03	
TOTAL PHASE SO ₃ [Duct PPM]	52.0	1.6	97.0%
TOTAL SO ₃ , 0% OXYGEN	60.7	1.8	
% SO ₃ in SOLIDS [filter plug/total]	0.0	0.0	

SO₂ Sampling Results from FETC Test Unit
TEST #3

DATE	4/14/98	4/14/98	
START TIME	1320	1320	
END TIME	1405	1405	
LOCATION	INLET	OUTLET	
MEASURED METER VARIABLES			
SAMPLE TIME [Minutes]	45	45	
BAROMETRIC PRESSURE [in Hg]	28.64	28.64	
SAMPLE VOLUME [ft ³]	4.20	4.20	
METER TEMPERATURE [° F]	85.1	83.2	
ORIFICE PRESSURE [in H ₂ O]	0.01	0.01	
Y FACTOR	1.015	1.050	
DSCF SAMPLED	3.952	4.102	
CONDENSER TEMP [° F]	143	145	
CC/MIN @ COND	2840	2958	
DUCT OXYGEN [APPROX %]	3.00	3.25	
DUCT TEMP DURING TEST [° F]	814	660	
DSCFM [based on pitot traverse]	90	90	
Moisture Weight Gain, g	17.2	15.3	
Water Volume, dscf	0.81012	0.72063	
% Moisture in Gas Sample	17.0	14.9	
% Moisture at Duct Conditions	19.0	18.1	
SO₂			
SO ₂ in IMPINGERS			SO₂ Removal
lb/DSCF	3.18E-04	3.66E-05	
lb/hr	1.72	0.20	
PPMV, As Sampled	1921	221	
PPMV, @ 0% Oxygen	2509	316	87.4%
PPMV, @ Duct Conditions	2149	267	87.6%
SO₃			
SO ₃ in FILTER PLUG			
lb/DSCF	0.00E+00	0.00E+00	
lb/hr	0.00E+00	0.00E+00	
PPMV, As Sampled	0.0	0.0	
PPMV, @ 0% Oxygen	0.0	0.0	
PPMV, @ Duct Conditions	0.0	0.0	
SO ₃ in PROBE			
lb/DSCF	9.72E-07	0.00E+00	
lb/hr	5.25E-03	0.00E+00	
PPMV, As Sampled	4.7	0.0	
PPMV, @ 0% Oxygen	6.1	0.0	
PPMV, @ Duct Conditions	5.3	0.0	
SO ₃ in CONDENSER			
lb/DSCF	6.30E-06	3.19E-07	
lb/hr	3.40E-02	1.72E-03	
PPMV, As Sampled	30.4	1.5	
PPMV, @ 0% Oxygen	39.8	2.2	
PPMV, @ Duct Conditions	34.1	1.9	
			SO₃ Removal
GAS PHASE SO ₃ [lb/DSCF]	7.27E-06	3.19E-07	
GAS PHASE SO ₃ [lb/hr]	3.93E-02	1.72E-03	
GAS PHASE SO ₃ [Duct PPM]	39.3	1.9	
GAS PHASE SO ₃ , 0% OXYGEN	45.9	2.2	95.2%
TOTAL PHASE SO ₃ [lb/DSCF]	7.27E-06	3.19E-07	
TOTAL PHASE SO ₃ [lb/hr]	3.93E-02	1.72E-03	
TOTAL PHASE SO ₃ [Duct PPM]	39.3	1.9	95.3%
TOTAL SO ₃ , 0% OXYGEN	45.9	2.2	
% SO ₃ in SOLIDS [filter plug/total]	0.0	0.0	

SO₂ Sampling Results from FETC Test Unit
TEST #4

DATE	4/14/98	4/14/98	4/14/98	
START TIME	1445	1445	1600	
END TIME	1533	1533	1642	
LOCATION	INLET	OUTLET	OUTLET	
MEASURED METER VARIABLES				
SAMPLE TIME [Minutes]	45	45	45	
BAROMETRIC PRESSURE [in Hg]	28.64	28.64	28.62	
SAMPLE VOLUME [ft ³]	5.00	5.20	4.40	
METER TEMPERATURE [° F]	87.9	86.6	88.4	
ORIFICE PRESSURE [in H ₂ O]	0.01	0.01	0.01	
Y FACTOR	1.015	1.050	1.050	
DSCF SAMPLED	4.680	5.047	4.254	
CONDENSER TEMP [° F]	139	144	147	
CC/MIN @ COND	3341	3633	3077	
DUCT OXYGEN [APPROX %]	3.00	3.25	3.25	
DUCT TEMP DURING TEST [° F]	815	670	660	
DSCFM [based on pitot traverse]	90	90	90	
Moisture Weight Gain, g	21.2	14.1	18.3	
Water Volume, dscf	0.99852	0.66411	0.86193	
% Moisture in Gas Sample	17.6	11.6	16.8	
% Moisture at Duct Conditions	19.9	16.8	20.1	
SO₂				
SO ₂ in IMPINGERS				SO ₂ Removal (test 4)
lb/DSCF	3.13E-04	3.04E-05	3.75E-05	
lb/hr	1.69	0.16	0.20	
PPMV, As Sampled	1892	184	227	
PPMV, @ 0% Oxygen	2503	315	320	87.4%
PPMV, @ Duct Conditions	2143	266	270	87.6%
SO₃				
SO ₃ in FILTER PLUG				
lb/DSCF	0.00E+00	0.00E+00	0.00E+00	
lb/hr	0.00E+00	0.00E+00	0.00E+00	
PPMV, As Sampled	0.0	0.0	0.0	
PPMV, @ 0% Oxygen	0.0	0.0	0.0	
PPMV, @ Duct Conditions	0.0	0.0	0.0	
SO ₃ in PROBE				
lb/DSCF	1.21E-06	6.05E-08	1.03E-07	
lb/hr	6.55E-03	3.27E-04	5.54E-04	
PPMV, As Sampled	5.9	0.3	0.5	
PPMV, @ 0% Oxygen	7.8	0.5	0.7	
PPMV, @ Duct Conditions	6.6	0.4	0.6	
SO ₃ in CONDENSER				
lb/DSCF	8.07E-06	2.81E-07	8.47E-07	
lb/hr	4.36E-02	1.52E-03	4.57E-03	
PPMV, As Sampled	39.0	1.4	4.1	
PPMV, @ 0% Oxygen	51.6	2.3	5.8	
PPMV, @ Duct Conditions	44.2	2.0	4.9	
GAS PHASE SO ₃ [lb/DSCF]	9.28E-06	3.42E-07	9.49E-07	SO ₃ Removal (test 4)
GAS PHASE SO ₃ [lb/hr]	5.01E-02	1.85E-03	5.13E-03	
GAS PHASE SO ₃ [Duct PPM]	50.8	2.4	5.5	
GAS PHASE SO ₃ , 0% OXYGEN	59.3	2.8	6.5	95.2%
TOTAL PHASE SO ₃ [lb/DSCF]	9.28E-06	3.42E-07	9.49E-07	
TOTAL PHASE SO ₃ [lb/hr]	5.01E-02	1.85E-03	5.13E-03	
TOTAL PHASE SO ₃ [Duct PPM]	50.8	2.4	5.5	95.3%
TOTAL SO ₃ , 0% OXYGEN	59.3	2.8	6.5	
% SO ₃ in SOLIDS [filter plug/total]	0.0	0.0	0.0	

PROTECTED CRADA INFORMATION

SO₂ Sampling Results from FETC Test Unit TEST #5

DATE	4/17/98	4/17/98	
START TIME	0810	0810	
END TIME	0852	0910	
LOCATION	INLET	OUTLET	
MEASURED METER VARIABLES			
SAMPLE TIME [Minutes]	42	55	
BAROMETRIC PRESSURE [in Hg]	28.69	28.69	
SAMPLE VOLUME [ft ³]	1.40	4.40	
METER TEMPERATURE [°F]	69.8	73.0	
ORIFICE PRESSURE [in H ₂ O]	0.01	0.01	
Y FACTOR	1.015	1.050	
DSCF SAMPLED	1.358	4.387	
CONDENSER TEMP [°F]	135	140	
CC/MIN @ COND	1032	2567	
DUCT OXYGEN [APPROX %]	4.80	5.00	
DUCT TEMP DURING TEST [°F]	820	655	
DSCFM [based on pitot traverse]	90	90	
Moisture Weight Gain, g	3	11.3	
Water Volume, dscf	0.1413	0.53223	
% Moisture in Gas Sample	9.4	10.8	
% Moisture at Duct Conditions	9.9	10.8	
SO₂			
SO ₂ in IMPINGERS			SO ₂ Removal
lb/DSCF	3.21E-04	5.09E-05	
lb/hr	1.73	0.27	
PPMV, As Sampled	1941	308	
PPMV, @ 0% Oxygen	2651	404	84.7%
PPMV, @ Duct Conditions	2042	308	84.9%
SO₃			
SO ₃ in FILTER PLUG			
lb/DSCF	3.21E-07	0.00E+00	
lb/hr	1.74E-03	0.00E+00	
PPMV, As Sampled	1.6	0.0	
PPMV, @ 0% Oxygen	2.1	0.0	
PPMV, @ Duct Conditions	1.6	0.0	
SO ₃ in PROBE			
lb/DSCF	3.21E-07	5.97E-08	
lb/hr	1.74E-03	3.22E-04	
PPMV, As Sampled	1.6	0.3	
PPMV, @ 0% Oxygen	2.1	0.4	
PPMV, @ Duct Conditions	1.6	0.3	
SO ₃ in CONDENSER			
lb/DSCF	6.43E-07	9.95E-07	
lb/hr	3.47E-03	5.37E-03	
PPMV, As Sampled	3.1	4.8	
PPMV, @ 0% Oxygen	4.2	6.3	
PPMV, @ Duct Conditions	3.3	4.8	
SO₃ Removal			
GAS PHASE SO ₃ [lb/DSCF]	9.64E-07	1.05E-06	
GAS PHASE SO ₃ [lb/hr]	5.21E-03	5.70E-03	
GAS PHASE SO ₃ [Duct PPM]	4.9	5.1	
GAS PHASE SO ₃ , 0% OXYGEN	6.4	6.7	-5.2%
TOTAL PHASE SO ₃ [lb/DSCF]	1.29E-06	1.05E-06	
TOTAL PHASE SO ₃ [lb/hr]	6.94E-03	5.70E-03	
TOTAL PHASE SO ₃ [Duct PPM]	6.5	5.1	22.0%
TOTAL SO ₃ , 0% OXYGEN	8.5	6.7	
% SO ₃ in SOLIDS [filter plug/total]	25.0	0.0	

PROTECTED CRADA INFORMATION

SO₂ Sampling Results from FETC Test Unit TEST #6

DATE	4/17/98	4/17/98	
START TIME	0950	0950	
END TIME	1038	1045	
LOCATION	INLET	OUTLET	
MEASURED METER VARIABLES			
SAMPLE TIME [Minutes]	48	50	
BAROMETRIC PRESSURE [in Hg]	28.69	28.69	
SAMPLE VOLUME [ft ³]	3.90	5.00	
METER TEMPERATURE [° F]	76.7	76.7	
ORIFICE PRESSURE [in H ₂ O]	0.01	0.01	
Y FACTOR	1.015	1.050	
DSCF SAMPLED	3.733	4.951	
CONDENSER TEMP [° F]	140	140	
CC/MIN @ COND	2503	3186	
DUCT OXYGEN [APPROX %]	4.80	5.00	
DUCT TEMP DURING TEST [° F]	820	660	
DSCFM [based on pitot traverse]	90	90	
Moisture Weight Gain, g	8.1	10.3	
Water Volume, dscf	0.38151	0.48513	
% Moisture in Gas Sample	9.3	8.9	
% Moisture at Duct Conditions	11.0	10.0	
SO₂			
SO ₂ in IMPINGERS			SO ₂ Removal
lb/DSCF	2.84E-04	5.81E-05	
lb/hr	1.53	0.31	
PPMV, As Sampled	1717	351	
PPMV, @ 0% Oxygen	2638	517	80.4%
PPMV, @ Duct Conditions	2032	393	80.6%
SO₃			
SO ₃ in FILTER PLUG			
lb/DSCF	0.00E+00	0.00E+00	
lb/hr	0.00E+00	0.00E+00	
PPMV, As Sampled	0.0	0.0	
PPMV, @ 0% Oxygen	0.0	0.0	
PPMV, @ Duct Conditions	0.0	0.0	
SO ₃ in PROBE			
lb/DSCF	1.87E-07	3.53E-08	
lb/hr	1.01E-03	1.90E-04	
PPMV, As Sampled	0.9	0.2	
PPMV, @ 0% Oxygen	1.4	0.3	
PPMV, @ Duct Conditions	1.1	0.2	
SO ₃ in CONDENSER			
lb/DSCF	6.55E-07	1.32E-07	
lb/hr	3.54E-03	7.14E-04	
PPMV, As Sampled	3.2	0.6	
PPMV, @ 0% Oxygen	4.9	0.9	
PPMV, @ Duct Conditions	3.7	0.7	
SO₃ Removal			
GAS PHASE SO ₃ [lb/DSCF]	8.42E-07	1.68E-07	
GAS PHASE SO ₃ [lb/hr]	4.55E-03	9.05E-04	
GAS PHASE SO ₃ [Duct PPM]	4.8	0.9	
GAS PHASE SO ₃ , 0% OXYGEN	6.3	1.2	80.9%
TOTAL PHASE SO ₃ [lb/DSCF]	8.42E-07	1.68E-07	
TOTAL PHASE SO ₃ [lb/hr]	4.55E-03	9.05E-04	
TOTAL PHASE SO ₃ [Duct PPM]	4.8	0.9	81.2%
TOTAL SO ₃ , 0% OXYGEN	6.3	1.2	
% SO ₃ in SOLIDS [filter plug/total]	0.0	0.0	

PROTECTED CRADA INFORMATION

SO₃ Sampling Results from FETC Test Unit TEST #7

DATE	4/17/98	4/17/98	
START TIME	1110	1110	
END TIME	1205	1205	
LOCATION	INLET	OUTLET	
MEASURED METER VARIABLES			
SAMPLE TIME [Minutes]	42	54	
BAROMETRIC PRESSURE [in Hg]	28.80	28.80	
SAMPLE VOLUME [ft ³]	2.00	4.40	
METER TEMPERATURE [° F]	72.6	80.0	
ORIFICE PRESSURE [in H ₂ O]	0.01	0.01	
Y FACTOR	1.015	1.050	
DSCF SAMPLED	1.937	4.347	
CONDENSER TEMP [° F]	135	140	
CC/MIN @ COND	1472	2590	
DUCT OXYGEN [APPROX %]	4.80	5.00	
DUCT TEMP DURING TEST [° F]	840	660	
DSCFM [based on pitot traverse]	90	90	
Moisture Weight Gain, g	4.7	8.2	
Water Volume, dscf	0.22137	0.38622	
% Moisture in Gas Sample	10.3	8.2	
% Moisture at Duct Conditions	12.4	8.2	
SO₂			
SO ₂ in IMPINGERS			SO₂ Removal
lb/DSCF	2.79E-04	5.42E-05	
lb/hr	1.51	0.29	
PPMV, As Sampled	1687	327	
PPMV, @ 0% Oxygen	2651	430	83.8%
PPMV, @ Duct Conditions	2042	327	84.0%
SO₃			
SO ₃ in FILTER PLUG			
lb/DSCF	0.00E+00	0.00E+00	
lb/hr	0.00E+00	0.00E+00	
PPMV, As Sampled	0.0	0.0	
PPMV, @ 0% Oxygen	0.0	0.0	
PPMV, @ Duct Conditions	0.0	0.0	
SO ₃ in PROBE			
lb/DSCF	2.25E-07	5.02E-08	
lb/hr	1.22E-03	2.71E-04	
PPMV, As Sampled	1.1	0.2	
PPMV, @ 0% Oxygen	1.7	0.3	
PPMV, @ Duct Conditions	1.3	0.2	
SO ₃ in CONDENSER			
lb/DSCF	3.38E-07	1.51E-07	
lb/hr	1.83E-03	8.13E-04	
PPMV, As Sampled	1.6	0.7	
PPMV, @ 0% Oxygen	2.6	1.0	
PPMV, @ Duct Conditions	2.0	0.7	
SO₃ Removal			
GAS PHASE SO ₃ [lb/DSCF]	5.63E-07	2.01E-07	
GAS PHASE SO ₃ [lb/hr]	3.04E-03	1.08E-03	
GAS PHASE SO ₃ [Duct PPM]	3.3	1.0	
GAS PHASE SO ₃ , 0% OXYGEN	4.3	1.3	70.2%
TOTAL PHASE SO ₃ [lb/DSCF]	5.63E-07	2.01E-07	
TOTAL PHASE SO ₃ [lb/hr]	3.04E-03	1.08E-03	
TOTAL PHASE SO ₃ [Duct PPM]	3.3	1.0	70.6%
TOTAL SO ₃ , 0% OXYGEN	4.3	1.3	
% SO ₃ in SOLIDS [filter plug/total]	0.0	0.0	

SO₂ Sampling Results from FETC Test Unit
TEST #8

DATE	4/17/98	4/17/98	
START TIME	1230	1230	
END TIME	1330	1325	
LOCATION	INLET	OUTLET	
MEASURED METER VARIABLES			
SAMPLE TIME [Minutes]	60	54	
BAROMETRIC PRESSURE [° Hg]	28.80	28.80	
SAMPLE VOLUME [ft ³]	5.00	5.00	
METER TEMPERATURE [° F]	88.0	89.0	
ORIFICE PRESSURE [° H ₂ O]	0.01	0.01	
Y FACTOR	1.015	1.050	
DSCF SAMPLED	4.706	4.859	
CONDENSER TEMP [° F]	144	140	
CC/MIN @ COND	2540	2895	
DUCT OXYGEN [APPROX %]	4.80	5.00	
DUCT TEMP DURING TEST [° F]	850	658	
DSCFM [based on pitot traverse]	90	90	
Moisture Weight Gain, g	7.1	10.4	
Water Volume, dscf	0.33441	0.48984	
% Moisture in Gas Sample	6.6	9.2	
% Moisture at Duct Conditions	9.3	11.0	
SO₂			
SO ₂ in IMPINGERS			SO ₂ Removal
lb/DSCF	2.46E-04	4.67E-05	
lb/hr	1.33	0.25	
PPMV, As Sampled	1484	282	
PPMV, @ 0% Oxygen	2697	447	83.4%
PPMV, @ Duct Conditions	2078	340	83.6%
SO₃			
SO ₃ in FILTER PLUG			
lb/DSCF	0.00E+00	0.00E+00	
lb/hr	0.00E+00	0.00E+00	
PPMV, As Sampled	0.0	0.0	
PPMV, @ 0% Oxygen	0.0	0.0	
PPMV, @ Duct Conditions	0.0	0.0	
SO ₃ in PROBE			
lb/DSCF	1.62E-07	0.00E+00	
lb/hr	8.77E-04	0.00E+00	
PPMV, As Sampled	0.8	0.0	
PPMV, @ 0% Oxygen	1.4	0.0	
PPMV, @ Duct Conditions	1.1	0.0	
SO ₃ in CONDENSER			
lb/DSCF	9.28E-07	3.59E-07	
lb/hr	5.01E-03	1.94E-03	
PPMV, As Sampled	4.5	1.7	
PPMV, @ 0% Oxygen	8.1	2.8	
PPMV, @ Duct Conditions	6.3	2.1	
SO₃ Removal			
GAS PHASE SO ₃ [lb/DSCF]	1.09E-06	3.59E-07	
GAS PHASE SO ₃ [lb/hr]	5.89E-03	1.94E-03	
GAS PHASE SO ₃ [Duct PPM]	7.4	2.1	
GAS PHASE SO ₃ , 0% OXYGEN	9.6	2.8	71.3%
TOTAL PHASE SO ₃ [lb/DSCF]	1.09E-06	3.59E-07	
TOTAL PHASE SO ₃ [lb/hr]	5.89E-03	1.94E-03	
TOTAL PHASE SO ₃ [Duct PPM]	7.4	2.1	71.6%
TOTAL SO ₃ , 0% OXYGEN	9.6	2.8	
% SO ₃ in SOLIDS [filter plug/total]	0.0	0.0	

PROTECTED CRADA INFORMATION

SO₂ Sampling Results from FETC Test Unit TEST #9

DATE	4/17/98	4/17/98	
START TIME	1630	1630	
END TIME	1715	1715	
LOCATION	INLET	OUTLET	
MEASURED METER VARIABLES			
SAMPLE TIME [Minutes]	54	48	
BAROMETRIC PRESSURE [° Hg]	28.93	28.93	
SAMPLE VOLUME [ft ³]	4.00	5.00	
METER TEMPERATURE [° F]	88.5	90.0	
ORIFICE PRESSURE [° H ₂ O]	0.01	0.01	
Y FACTOR	1.015	1.050	
DSCF SAMPLED	3.778	4.872	
CONDENSER TEMP [° F]	140	138	
CC/MIN @ COND	2251	3255	
DUCT OXYGEN [APPROX %]	4.80	5.00	
DUCT TEMP DURING TEST [° F]	870	660	
DSCFM [based on pitot traverse]	90	90	
Moisture Weight Gain, g	6	8	
Water Volume, dscf	0.2826	0.3768	
% Moisture in Gas Sample	7.0	7.2	
% Moisture at Duct Conditions	9.2	9.2	
SO₂			
SO ₂ in IMPINGERS			SO ₂ Removal
lb/DSCF	2.55E-04	4.23E-05	
lb/hr	1.38	0.23	
PPMV, As Sampled	1542	255	
PPMV, @ 0% Oxygen	2641	430	83.7%
PPMV, @ Duct Conditions	2034	327	83.9%
SO₃			
SO ₃ in FILTER PLUG			
lb/DSCF	0.00E+00	0.00E+00	
lb/hr	0.00E+00	0.00E+00	
PPMV, As Sampled	0.0	0.0	
PPMV, @ 0% Oxygen	0.0	0.0	
PPMV, @ Duct Conditions	0.0	0.0	
SO ₃ in PROBE			
lb/DSCF	1.73E-07	4.48E-08	
lb/hr	9.36E-04	2.42E-04	
PPMV, As Sampled	0.8	0.2	
PPMV, @ 0% Oxygen	1.4	0.4	
PPMV, @ Duct Conditions	1.1	0.3	
SO ₃ in CONDENSER			
lb/DSCF	9.01E-07	3.36E-07	
lb/hr	4.87E-03	1.81E-03	
PPMV, As Sampled	4.4	1.6	
PPMV, @ 0% Oxygen	7.5	2.7	
PPMV, @ Duct Conditions	5.7	2.1	
SO₃ Removal			
GAS PHASE SO ₃ [lb/DSCF]	1.07E-06	3.81E-07	
GAS PHASE SO ₃ [lb/hr]	5.80E-03	2.06E-03	
GAS PHASE SO ₃ [Duct PPM]	6.9	2.4	
GAS PHASE SO ₃ , 0% OXYGEN	8.9	3.1	65.1%
TOTAL PHASE SO ₃ [lb/DSCF]	1.07E-06	3.81E-07	
TOTAL PHASE SO ₃ [lb/hr]	5.80E-03	2.06E-03	
TOTAL PHASE SO ₃ [Duct PPM]	6.9	2.4	65.6%
TOTAL SO ₃ , 0% OXYGEN	8.9	3.1	
% SO ₃ in SOLIDS [filter plug/total]	0.0	0.0	

PROTECTED CRADA INFORMATION

APPENDIX 2

Velocity Traverse Data

FETC TEST REACTOR

Method 2 Velocity Measurements

Location	INLET	Duct ID,"	3.26	Barometric	28.72
Date	4/14/98	Duct Dim.		Static	-6.19
Time	1100	Duct Area,ft ²	0.0580	Dry Bulb	805
Tube I.D.	S-50A	% O ₂	3.0	Wet Bulb	ND
C-Factor	0.797	% CO ₂	10.0	% H ₂ O	18.0
Operator(s)	MSD	% N ₂	87.0	W.M.Wt	27.61

PORT/ POINT	DISTANCE [° From Wall]	TEMP [Deg-F]	DELTA P [° H ₂ O]	VELOCITY [Ft/Sec]
SIDE-1	0.5	805	0.981	85.9
SIDE-2	1.0	805	0.977	85.8
SIDE-3	1.5	805	0.835	79.3
SIDE-4	2.0	805	0.762	75.7
SIDE-5	2.5	805	0.663	70.6
Average		805.0	0.844	79.5
Maximum		805	0.981	85.9
Minimum		805	0.663	70.6
SDEV		0.0	0.123	5.9

[Points numbered from back of port]

DATA SUMMARY	
Velocity, [fps]	79.5
Velocity, [fpm]	4768
acfm	276
scfm	109
dscfm	89
Ex Air Free cfm	76
Est. MM Btu/hr Heat Input	0.62

FETC TEST REACTOR

Method 2 Velocity Measurements

Location	OUTLET	Duct ID,"	3.26	Barometric	28.72
Date	4/14/98	Duct Dim.		Static	-14.75
Time	1100	Duct Area, ft ²	0.0580	Dry Bulb	650
Tube I.D.	S-50A	% O ₂	3.3	Wet Bulb	ND
C-Factor	0.797	% CO ₂	9.7	% H ₂ O	18.0
Operator(s)	MSD	% N ₂	87.0	W.M.Wt	27.58

PORT/ POINT	DISTANCE [° From Wall]	TEMP [Deg-F]	DELTA P [° H ₂ O]	VELOCITY [Ft/Sec]
SIDE-1	0.5	650	1.007	82.5
SIDE-2	1.0	650	0.832	75.0
SIDE-3	1.5	650	0.699	68.7
SIDE-4	2.0	650	0.663	67.0
SIDE-5	2.5	650	0.638	65.7
Average		650.0	0.768	71.8
Maximum		650	1.007	82.5
Minimum		650	0.638	65.7
SDEV		0.0	0.137	6.3

[Points numbered from back of port]

DATA SUMMARY	
Velocity, [fps]	71.8
Velocity, [fpm]	4307
acfm	250
scfm	110
dscfm	90
Ex Air Free cfm	76
Est. MM Btu/hr Heat Input	0.62

FETC TEST REACTOR

Method 2 Velocity Measurements

Location	INLET	Duct ID,"	3.26	Barometric	28.80
Date	4/17/98	Duct Dim.		Static	-7.37
Time	0745	Duct Area,ft ²	0.0580	Dry Bulb	810
Tube I.D.	S-50A	% O ₂	5.0	Wet Bulb	ND
C-Factor	0.797	% CO ₂	15.0	% H ₂ O	9.0
Operator(s)	MSD	% N ₂	80.0	W.M.Wt	29.47

PORT/ POINT	DISTANCE [° From Wall]	TEMP [Deg-F]	DELTA P [° H ₂ O]	VELOCITY [Ft/Sec]
SIDE-1	0.5	805	1.126	89.1
SIDE-2	1.0	805	1.017	84.7
SIDE-3	1.5	805	0.805	75.3
SIDE-4	2.0	805	0.795	74.9
SIDE-5	2.5	805	0.723	71.4
Average		805.0	0.893	79.1
Maximum		805	1.126	89.1
Minimum		805	0.723	71.4
SDEV		0.0	0.152	6.7

[Points numbered from back of port]

DATA SUMMARY	
Velocity, [fps]	79.1
Velocity, [fpm]	4745
acfm	275
scfm	108
dscfm	99
Ex Air Free cfm	75
Est. MM Btu/hr Heat Input	0.60

PROTECTED CRADA INFORMATION
FETC TEST REACTOR

Method 2 Velocity Measurements

Location	OUTLET	Duct ID,"	3.26	Barometric	28.80
Date	4/17/98	Duct Dim.		Static	-24.05
Time	1220	Duct Area,ft ²	0.0580	Dry Bulb	660
Tube I.D.	S-50A	% O ₂	5.2	Wet Bulb	ND
C-Factor	0.797	% CO ₂	14.8	% H ₂ O	9.0
Operator(s)	MSD	% N ₂	80.0	W.M.Wt	29.44

PORT/ POINT	DISTANCE [° From Wall]	TEMP [Deg-F]	DELTA P [° H ₂ O]	VELOCITY [Ft/Sec]
SIDE-1	0.5	660	0.910	77.1
SIDE-2	1.0	657	0.824	73.3
SIDE-3	1.5	658	0.814	72.9
SIDE-4	2.0	655	0.705	67.7
SIDE-5	2.5	656	0.723	68.6
Average		657.2	0.795	71.9
Maximum		660	0.910	77.1
Minimum		655	0.705	67.7
SDEV		1.7	0.074	3.4

[Points numbered from back of port]

DATA SUMMARY	
Velocity, [fps]	71.9
Velocity, [fpm]	4315
acfm	250
scfm	107
dscfm	97
Ex Air Free cfm	73
Est. MM Btu/hr Heat Input	0.59