

**MONITORING POWER PLANT EFFICIENCY USING THE MICROWAVE-EXCITED  
PHOTOACOUSTIC EFFECT TO MEASURE UNBURNED CARBON**

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## Monitoring Power Plant Efficiency Using the Microwave-Excited Photoacoustic Effect to Measure Unburned Carbon

**DOE Award No. DE-FC22-01NT41220**

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### **ABSTRACT**

Three test instruments are being evaluated to determine the feasibility of using photo-acoustic technology for measuring unburned carbon in fly ash. The first test instrument is a single microwave frequency system previously constructed to measure photo-acoustic signals in an off-line configuration. This system was assembled and used to begin testing parameters thought to be influential in the resulting photo-acoustic signal output. A standard modulation frequency was chosen based upon signal to noise data gained from experimentation. Sample heterogeneity was tested and found not to be influential. Many other tests were performed during the second quarter. Preliminary results show that compression and photo-acoustic volume have an impact on photo-acoustic signal. Conclusions regarding the data for sample bulk density, temperature, humidity, moisture content, and linearity are pending further review. Conclusions for ambient temperature and humidity are pending further review as well.

Simultaneously, a second instrument is to be constructed based in part on lessons learned with the first instrument, and to expand the capabilities of the first instrument. Improvements include a control loop to allow more constant microwave power output and an ability to operate over a range of microwave frequencies. To date, the design of the second instrument has been completed and most of the components received. The third instrument will be designed based on the experiences of the first two instruments and will operate in an on-line carbon-in-ash monitoring system for coal-fired power plants.

**Keywords:** fly ash, carbon monitor, unburned carbon, boiler instrumentation

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## **INTRODUCTION**

The objective of this project is to explore the use of the microwave-excited photoacoustic (MEPA) effect for quantitative analysis of granular and powdered materials. The focal point of the research will center on the measurement of unburned carbon in fly ash, an important parameter in the electric utility industry used to determine plant efficiencies. The culmination of this project will be an on-line carbon-in-ash monitor for coal-fired power plants.

The approach to this project includes work with three MEPA instruments. The first instrument is a single microwave frequency, off-line instrument built at Iowa State University as part of proof-of-concept evaluations. It will be used to evaluate precision and accuracy of the MEPA technique. The second instrument will be constructed as part of this project. It will be a microwave spectrometer based on MEPA and will be used to evaluate a variety of industrially important powders, including fly ash and pulverized coal. The final instrument will be built based on the results of work with the previous two instruments and will be used as an on-line monitor of unburned carbon in fly ash.

## **EXPERIMENTAL**

### **The Single Microwave Frequency, Off-Line Instrument**

After initial difficulties reported in the previous quarterly report were overcome, the system has operated both reliably and repeatably. Testing was continued to determine parameters that affect photoacoustic measurement accuracy and precision. To date, variables that have been examined which may influence the photoacoustic signal include: sample heterogeneity, sample bulk density, sample compression, sample moisture content, modulation frequency, signal-to-noise ratio, and photoacoustic volume.

Testing continued with the fly ash sample taken from Duquesne/Elrama boiler 3B located in Pennsylvania. The selected fly ash was tested ‘as received’ to serve as a baseline measurement for comparison purposes. The fly ash was then subjected to the necessary treatments to represent a change in the variable under consideration, while holding all other variables constant. Test parameters and setup for the compression test and the photoacoustic volume test are outlined in Appendix A and C, respectively. The Standard Operating Procedure (SOP) for compression of the samples is shown in Appendix B.

### **The Microwave Spectrometer**

The microwave spectrometer to be constructed in the second year is shown schematically in Figure 1. The majority of the effort spent on this task to date has been in designing the instrument and procuring parts for broadband operation.

All the equipment, with the exception of the 2 to 10 GHz amplifier (shown in Figure 1 with a dashed line around it), has been received. New designs for the test cell (shown in Figure 1 with a dotted line around it) will be completed during the third quarter of this project. The microwave generator is a synthesized signal generator capable of generating signals from 50 MHz to 26 GHz. This capability covers the 500 MHz to 10 GHz band specified for this project. Three separate couplers are used to cover the 500 MHz to 10 GHz band. The detectors and attenuators are broadband units.

Various coal samples were obtained from the Coal and Organic Petrology Laboratories at Pennsylvania State University. These samples were chosen to represent a spectrum of pulverized coal fuels currently used in the United States. Upon completion, the microwave spectrometer will be used to examine these coal samples to determine if MEPA can be utilized in a feed-forward configuration.

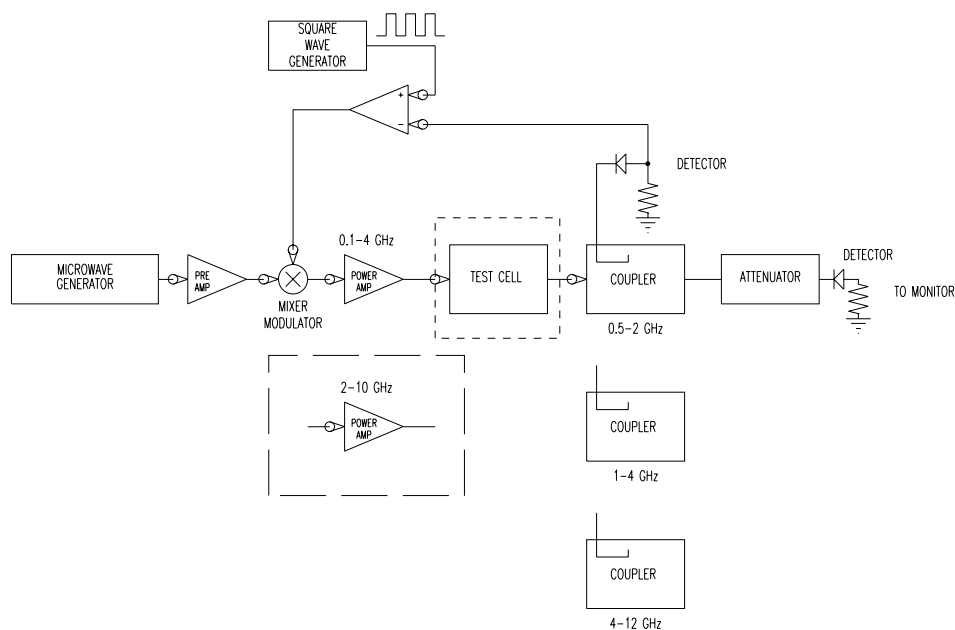


Fig. 1. The microwave spectrometer to be constructed in the second quarter.

## RESULTS AND DISCUSSION

The results of the t-Test to determine if sample compression affects the photoacoustic signal are summarized in Table 1.

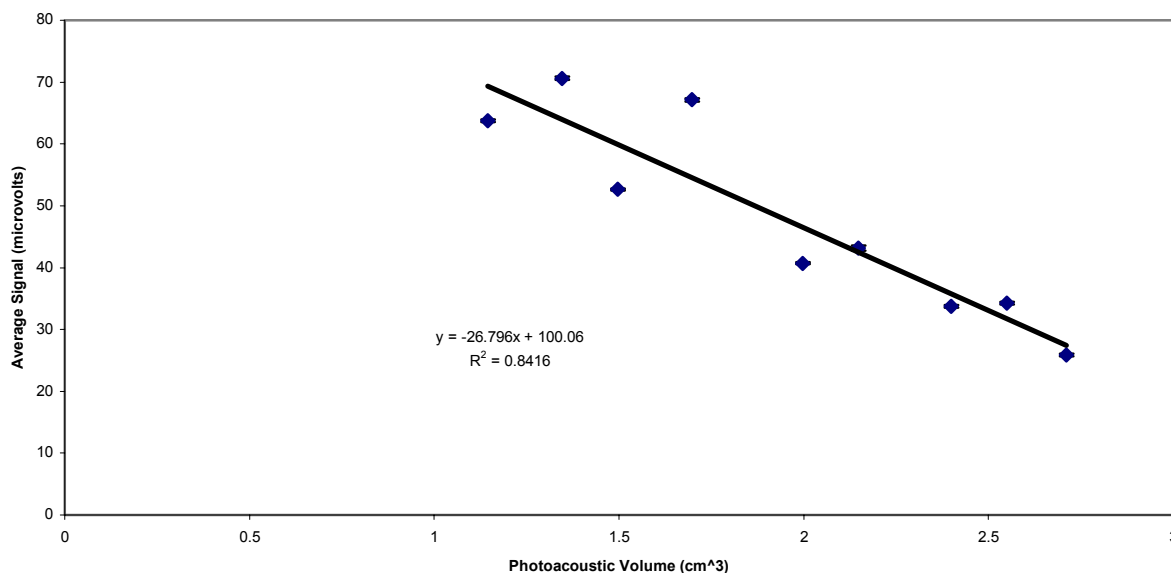
Table 1. t-Test: Two-sample assuming equal variances (Microsoft Excel 2000)

	<i>TestIA (<math>\mu_1</math>)</i>	<i>TestIIIA (Compression <math>\mu_2</math>)</i>
Mean	5.47617E-05	6.33142E-05
Variance	3.21471E-11	1.46737E-11
Observations	10	10
Pooled Variance	2.34104E-11	
Hypothesized Mean Difference	0	
df	18	
t Stat	-3.952522001	
P(T<=t) one-tail	0.000466759	
t Critical one-tail	1.734063062	
P(T<=t) two-tail	0.000933518	
t Critical two-tail	2.100923666	
Null hypothesis ( $H_0$ ): $\mu_1 - \mu_2 = 0$		
Research hypothesis ( $H_a$ ): $\mu_1 - \mu_2 \neq 0$		
	Rejection region: $ t \text{ Stat}  > t \text{ Critical two-tail}$	Summary: Reject null

The null hypothesis is that there is no difference between signals obtained from ‘as received’ samples of fly ash and the signals obtained from compressed fly ash. Application of the t-test allows us to reject the null hypothesis. Therefore, we conclude that compression of the fly ash does influence the resulting MEPA signal.<sup>1</sup>

The results for the photoacoustic volume test are plotted in Figure 2. The negative slope shown in Figure 2 indicates that photoacoustic signal decreases linearly with photoacoustic volume, a relationship consistent with photoacoustic theory.

**Figure 2. Signal Measured for 22360AT vs. Photoacoustic Volume (Test XIII: Photoacoustic Volume, Dried) 4/11/02**



## CONCLUSION

Photoacoustic signal is affected by sample compression and photoacoustic volume. This elevates the importance that sample preparation and loading has on any measurement. Future cell designs will need to reflect the dependence on these important parameters.



## REFERENCES

- <sup>1</sup> Ott, R. Lyman (1993). *An Introduction to Statistical Methods and Data Analysis*. Belmont: Duxbury Press, pp. 215, 266.

## APPENDIX A

# SYSTEM TEST SETUP

### GENERAL INFORMATION

VERSION: 1.0Principle Investigator: Brown (Suby), WeberDate: 1/30/02Test Group: NETL (DOE)Phone: (515) 382-9006Test Name: TestIIIAE-mail: asuby@iastate.eduExpected duration of test: 2 hoursProgram: Lock-in2.bas, PAS.xlsData: ☒ Public ☐ PrivateDescription of test: Compression.

1) Set aside in a reserve bottle 3.12 grams of sample.

2) Weigh and record the weight of the empty sample cup.

3) Fill cup with sample obtained from the reserve bottle (see procedures entitled "Filling the Sample Holder" (SampleSOP.doc)), compress the sample as directed by the procedures entitled "Compressing a Fly Ash Sample" (CompSampSOP.doc), and weigh and record the cup and sample.

4) Measure PA signal, and dump sample back into reserve bottle.

\*\*\*DO NOT MIX BACK INTO ORIGINAL FLY ASH CONTAINER FOR THIS TEST.

5) Repeat test procedure 10 times on the contents of the reserve bottle over the course of just a few minutes.

Objective of test: To determine whether compression of the sample affects the measurement.Variables under consideration: Photoacoustic Volume, Sample bulk densityVariables to be held constant: Mass, Sample Temp and Humidity (assumed), Ambient Temp and Humidity (assumed), Modulation Frequency

### SPECIAL REQUIREMENTS

### SYSTEM SETUP DATA COLLECTED BY: NL

#### SAMPLE INFORMATION:

Sample Designation: 22360AT

#### Sample Preparation:

- ☐ "As Received" (no preparation)  
☒ Compressed  
☐ Ground  
☐ Dried

Notes:Deliverables:1) t-test comparison to TestIA results.

#### SYSTEM INFORMATION:

Modulation Frequency: 20Raw Data File Naming Convention:

1) Refer to the Document Entitled "Raw Data File Naming Convention for the Lock-in Data Acquisition System" (DOSDataCon.doc)

Notes:

1) Refer to the system Standard Operating Procedures (SystemSOP.doc)

## APPENDIX B

### Compressing a Fly Ash Sample (CompSampSOP.doc)

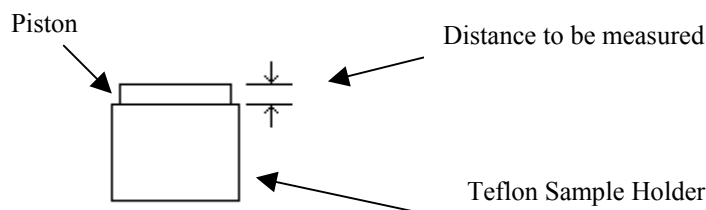
#### Items Needed:

1. 1 kg compression weight.
2. Piston.
3. Teflon sample holder.
4. Small steel ruler or caliper.

#### Procedures:

1. Insert the aluminum piston into the empty Teflon sample holder.
2. Measure and record the distance between the top of the piston and the top of the Teflon sample holder. See Figure A1.
3. Remove the piston and fill the sample holder with fly ash as directed in the procedures entitled “Filling the Sample Holder” (SampleSOP.doc).
4. Insert the aluminum piston into the Teflon sample holder until it rests on the fly ash.
5. Measure and record the distance between the top of the piston and the top of the Teflon sample holder. See Figure A1.

Figure A1.



6. Compress the sample by placing the 1 kg brass weight on top of the piston. Measure and record the new distance between the top of the piston and the top of the Teflon sample holder.
7. Reweigh the sample and Teflon sample holder to see if sample was lost during the compression process. If significant weight change occurred, repeat steps 1-5.

## APPENDIX C

**SYSTEM TEST SETUP**

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**GENERAL INFORMATION**VERSION: 1.0Principle Investigator: Brown (Suby), WeberPhone: (515) 382-9006Test Group: NETL (DOE)E-mail: asuby@iastate.eduTest Name: TestXIIIProgram: Lock-in2.bas, PAS.xlsExpected duration of test: 2 hoursData: ☒Public ☐PrivateDate: 4/4/02Description of test: Photoacoustic Volume.1) Set aside in a reserve bottle enough sample to completely fill the holder plus a little.2) Weigh and record the weight of the empty sample holder.3) Fill the sample holder with sample obtained from the reserve bottle so that the height of the sample in the cup is approximately 0.9" before compression. Record the height.4) Compress the sample (CompSampSOP), measure and record the compressed sample height, weigh and record the holder and sample.5) Measure PA signal, and dump sample back into reserve bottle.\*\*\*DO NOT MIX BACK INTO ORIGINAL FLY ASH CONTAINER FOR THIS TEST.6) Repeat procedures 1-5. Decrease the starting sample height in 3) by 0.05" for each iteration until a height of 0.5" is attained. (i.e. 0.9", 0.85", 0.80, etc.)Objective of test: To determine whether photoacoustic volume of the sample affects the measurement.Variables under consideration: Photoacoustic Volume, MassVariables to be held constant: Sample Temp and Humidity (assumed), Ambient Temp and Humidity (assumed), Modulation Frequency, Sample bulk density

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**SPECIAL REQUIREMENTS**

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**SAMPLE INFORMATION:**Sample Designation: 22360AT**Sample Preparation:**☐ "As Received" (no preparation)☒ Compressed☐ Ground☒ DriedNotes:Deliverables:1) t-test comparison to TestIA results.

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**SYSTEM INFORMATION:**Modulation Frequency: 20Raw Data File Naming Convention:1) Refer to the Document Entitled "Raw Data File Naming Convention for the Lock-in Data Acquisition System" (DOSDataCon.doc)Notes:1) Refer to the system Standard Operating Procedures (SystemSOP.doc)