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**Sonic Enhanced Ash Agglomeration
and Sulfur Capture**

By:

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PREFACE

This seventh Quarterly Technical Progress Report presents the results of work accomplished during the period December 24, 1990 through March 31, 1991 under Contract No. DE-AC21-88MC26288 entitled "Sonic Enhanced Ash Agglomeration and Sulfur Capture." The statement of work has been provided in previous quarterly reports and will, therefore, no longer be provided in this and subsequent quarterly documents.

The major objective of the Phase I test program is to confirm the feasibility of the MTCI bimodal particle size approach to enhance particulate control by acoustic ash agglomeration. An ancillary objective of the Phase I effort is to demonstrate and confirm the feasibility of an acoustic field to enhance sulfur capture by increasing sorbent reactivity. Phase I tests are designed to cover the frequency range between 50 and 1400 Hz, establish monomodal baseline performance as a benchmark from which to measure the degree of enhancement expected from the bimodal approach, and, finally, to confirm the effectiveness of low-frequency fields over high-frequency fields for realistic particulate streams. The major objective of the Phase II test program is to demonstrate proof-of-concept through laboratory experimental activities at both atmospheric and pressurized (9 atm.) conditions.

The modeling and experimental verification of the acoustic agglomeration of bimodal distributions have provided strong indications of both the effectiveness of the modeling and the bimodal agglomeration of small particles. The numerical results matched those observed experimentally.

The pulse combustor test was completed and shakedown tests on natural gas and at different excess air levels were completed. The frequency of operation was almost a pure monotone.

A series of tests on the calcination rate of limestone in the pulse combustor was performed and samples analyzed by Penn State indicated a 69 percent calcination rate. A comparison of particle size techniques:

- Photo - sedimentation
- Laser - diffraction
- Bahco - air classification
- Malvern

resulted in the selection of the Bahco because the Bahco method generally yielded higher fines content than the other methods.

Two runs with gas firing and solids loading provided evidence of agglomeration.

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SECTION 1.0

INTRODUCTION

1.1 PROJECT DESCRIPTION AND WORK STATUS

A major concern with the utilization of coal in directly fired gas turbines is the control of particulate emissions and reduction of sulfur dioxide, and alkali vapor from combustion of coal, upstream of the gas turbine. Much research and development has been sponsored on methods for particulate emissions control and the direct injection of calcium-based sorbents to reduce SO₂ emission levels. The results of this research and development indicate that both acoustic agglomeration of particulates and direct injection of sorbents have the potential to become a significant emissions control strategy.

The Sonic Enhanced Ash Agglomeration and Sulfur Capture program focuses upon the application of an MTCI proprietary invention (Invention Disclosure filed) for simultaneously enhancing sulfur capture and particulate agglomeration of the combustor effluent. This application can be adapted as either a "hot flue gas cleanup" subsystem for the current concepts for combustor islands or as an alternative primary pulse combustor island in which slagging, sulfur capture, particulate agglomeration and control, and alkali gettering as well as NO_x control processes become an integral part of the pulse combustion process.

The goal of the program is to support the DOE mission in developing coal-fired combustion gas turbines. In particular, the MTCI proprietary process for bimodal ash agglomeration and simultaneous sulfur capture will be evaluated and developed. The technology embodiment of the invention provides for the use of standard grind, moderately beneficiated coal and WEM for firing the gas turbine with efficient sulfur capture and particulate emission control upstream of the turbine. The process also accommodates injection of alkali gettering material if necessary. This is aimed at utilization of relatively inexpensive coal fuels, thus realizing the primary benefit being sought by direct firing of coal in such gas turbine systems. The proposed technology

provides for practical, reliable, and capital (and O&M) cost-effective means of protection for the gas turbine from impurities in the coal combustor effluent.

1.2 PROGRAM OBJECTIVES

The major objective of the Phase I test program is to confirm the feasibility of the MTCI bimodal particle size approach to enhance particulate control by acoustic ash agglomeration. An ancillary objective of the Phase I effort is to demonstrate and confirm the feasibility of an acoustic field to enhance sulfur capture by increasing sorbent reactivity. Phase I tests are designed to cover the frequency range between 50 and 1400 Hz, establish monomodal baseline performance as a benchmark from which to measure the degree of enhancement expected from the bimodal approach, and, finally, to confirm the effectiveness of low-frequency fields over high-frequency fields for realistic particulate streams.

The program will demonstrate the effectiveness of a unique approach which uses a bimodal distribution composed of large sorbent particles and fine fly ash particles to enhance ash agglomeration and sulfur capture at conditions found in direct coal-fired turbines. Under the impact of high-intensity sound waves, sorbent reactivity and utilization, it is theorized, will increase while agglomerates of fly ash and sorbents are formed which are readily collected in commercial cyclones. The work will extend the concept from the demonstration of feasibility (Phase I), through proof-of-concept (Phase II) to the construction (Phase III) of a coal-fired pulsed combustor with in-furnace sorbent injection. For Phase I, Pennsylvania State University will conduct studies for enhanced sulfur capture in The Combustion Laboratory and agglomeration tests in the High Intensity Acoustic Laboratory.

1.3 SUMMARY STATUS FOR THE PERIOD

The modeling and experimental verification of the acoustic agglomeration of bimodal distributions have provided strong indications of both the effectiveness of the modeling and the bimodal agglomeration of small particles. The numerical results matched those observed experimentally.

The pulse combustor test was completed and shakedown tests on natural gas and at different excess air levels were completed. The frequency of operation was almost a pure monotone.

A series of tests on the calcination rate of limestone in the pulse combustor was performed and samples analyzed by Penn State indicated a 69 percent calcination rate. A comparison of particle size techniques:

- Photo - sedimentation
- Laser - diffraction
- Bahco - air classification
- Malvern

resulted in the selection of the Bahco because the Bahco method generally yielded higher fines content than the other methods.

Two runs with gas firing and solids loading provided evidence of agglomeration.

SECTION 2.0
TECHNICAL DISCUSSION OF THE WORK
ACCOMPLISHED DURING THE REPORTING PERIOD

**2.1 MODELING OF ACOUSTIC AGGLOMERATION
OF BIMODAL DISTRIBUTIONS**

The results of numerical computations on the Penn State University bimodal acoustics agglomeration program (BAAP) were compared with those generated from the bimodal agglomeration tests completed last month. The following sets of standard data were chosen for the numerical computations:

Standard parameter Set (III):

maximum diameter	1,400 μm
upper size of the first bin	0.1 μm
minimum diameter	0.1 μm
Acoustic Agglomeration System	vertical

Particle Distribution

density of the bin with the smallest particles	2,500 kg/m^3
density of the bin with the largest particles	1,500 kg/m^3

<u>INPUT DATA</u>	<u>FIRST MODE</u>	<u>SECOND MODE</u>
mass fraction	0.12	0.88
geometric mean [μm]	5	50-150
geometric mean [μm], σ	2	2

Numerical computations with these data sets were performed by adjusting the operating conditions to match those used in the pilot-scale tests.

Figure 1 compares particle size distributions in the 1 to 10 μm region before and after bimodal acoustical agglomeration measured in the group #1 tests (1/29/91) with those calculated numerically. The key to the figures is: before AA refers to baseline conditions, no sound source; after AA experimental refers to acoustic agglomeration tests; and after AA numerical is the results from the BAAP model. After application of a sound field at a

Bimodal Agglomeration 1-29-91

	Mass loading	Geometric mean size
Sorbent	22.66 g/m ³	88 microns
Fly ash	7.55 g/m ³	5 microns
Total	30.21 g/m ³	

Sound Frequency: 44 Hz
 Acoustic Particle Velocity: >15.84 m/s
 Air flow : 14 CFM

FIGURE 1: COMPARISON OF THE PARTICLE SIZE DISTRIBUTION WITH AND WITHOUT SOUND FOR THE NUMERICAL AND EXPERIMENTAL TEST DATA

frequency of 44 Hz and a sound pressure level (SPL) of 160 dB for 0.6 seconds, the particle size distributions predicted by the BAAP approach those obtained from the experiment on the down-fired combustor.

Additional numerical experiments were conducted to determine whether the parameters that produced a "fit" between theory and the group #1 experiments were the same for the subsequent group #2 tests (performed on 1-30-91) having similar operating conditions. Results are shown in Figure 2. After application of a sound field at a frequency of 44 Hz and SPL of 160 dB for 0.8 seconds, the computationally determined particle size distributions are similar to those observed experimentally in the group #2 tests. The shift from a 0.6 second residence time for the group #1 tests to a 0.8 residence time for the group #2 tests is within the accuracy of the experimental measurements.

The mass loadings of fly ash and sorbent were adjusted in the numerical program to match the operating conditions in test groups #3 and #4 (completed last month). Figures 3 and 4 are plots of the particle size distribution with and without sound in the bimodal acoustic agglomeration experiments and numerical computations for two different mass loadings. The numerical results match those observed experimentally, i.e., that bimodal agglomeration of the small particles occurred for the higher mass loading conditions.

Based on the above results, it is concluded that modeling of the acoustic agglomeration of bimodal distributions with the PSU BAAP has been accomplished.

Earlier numerical and experimental studies have shown that the agglomeration process is highly dependent on the residence time of the particles in the sound field. Long residence times require low air flow rates which, in turn, require a large agglomeration chamber and consequently, high power output sound sources. To provide guidelines for designing agglomerators, an analysis was performed to evaluate the dependance of the bimodal agglomeration process on residence time to assess the effectiveness of the process over different time increments and size ranges.

Bimodal Agglomeration 1-30-91

	Mass loading	Geometric mean size
Sorbent	22.66 g/m ³	88 microns
Fly ash	7.55 g/m ³	5 microns
Total	30.21 g/m ³	
Sound Frequency: 44 Hz		
Acoustic Particle Velocity: >15.84 m/s		
Air flow : 14 CFM		

FIGURE 2: COMPARISON OF THE PARTICLE SIZE DISTRIBUTION WITH AND WITHOUT SOUND FOR THE NUMERICAL AND EXPERIMENTAL TEST DATA

Bimodal Agglomeration 2-4-91

	Mass loading	Geometric mean size
Sorbent	15.0 g/m ³	88 microns
Fly ash	2.5 g/m ³	5 microns
Total	17.5 g/m ³	
Sound Frequency: 44 Hz		
Acoustic Particle Velocity: >15.84 m/s		
Air flow : 14 CFM		

FIGURE 3: COMPARISON OF THE PARTICLE SIZE DISTRIBUTION WITH AND WITHOUT SOUND FOR THE NUMERICAL AND EXPERIMENTAL TEST DATA

Bimodal Agglomeration 2-7-91

	Mass loading	Geometric mean size
Sorbent	9.5 g/m ³	88 microns
Fly ash	2.1 g/m ³	5 microns
Total	11.1 g/m ³	

Sound Frequency: 44 Hz
Acoustic Particle Velocity: >15.84 m/s
Air flow : 54 CFM

FIGURE 4: COMPARISON OF THE PARTICLE SIZE DISTRIBUTION WITH AND WITHOUT SOUND FOR THE NUMERICAL AND EXPERIMENTAL TEST DATA

In the numerical studies reported in previous monthly reports, a series of runs was conducted using the standard parameter set (given previously) and varying the residence time of the particles in the agglomerator. The resulting particle size distributions were calculated and the gain in the percentage of mass in the bin size above $11\ \mu\text{m}$ was determined. **Figure 5** shows a linear dependence of the mass accumulation in the bin containing particles greater than $11\ \mu\text{m}$ with increasing time up to 3.5 seconds. It can be concluded that for the given sound pressure level (SPL)(160dB), a residence time of at least 3.5 seconds should be used to ensure an efficient removal of small particles. Above 3.5 seconds the incremental effectiveness of the process decreases. If, however, agglomeration of all the small particles is the desired goal, this can only be achieved by exposure times in the sound field for a relatively long period of time.

To evaluate the influence of the mass loading of the sorbent particles on the agglomeration process, a numerical study was conducted by treating the sorbent mass loading as a variable parameter. The mass loading of the sorbent in the system was varied to establish the optimum value for maximizing the removal of particles in the small size range (below $11\ \mu\text{m}$). The ratio of the mass accumulated in the bin size above $11\ \mu\text{m}$ after agglomeration to the total mass in all bin sizes below $11\ \mu\text{m}$ before agglomeration was used as a measure of the effectiveness of the process. Expressed as a percentage, this ratio is plotted as a function of the sorbent mass loading in the range from 5 to $25\ \text{g/m}^3$ in **Figure 6**. An almost linear increase in the effectiveness of the process was obtained as the mass loading was increased. This was expected because the presence of a high concentration of the larger particles in the agglomerator enhances the likelihood of collisions with the smaller particles due to orthokinetic interactions.

The influence of fly ash loading on the bimodal agglomeration process was also investigated. A similar numerical analysis to that for the sorbent was carried out and the percentage of mass removed from all bin sizes below $11\ \mu\text{m}$ as a function of fly ash loading is plotted in **Figure 7**. In contrast to the previous results, a non-linear function was obtained. Only at very high mass loadings (3.5 to $5\ \text{g/m}^3$) is the relationship approximately linear.

FIGURE 5: COMPUTED PERCENTAGE OF MASS IN THE SIZE-BIN CONTAINING PARTICLES GREATER THAN 11 μ M AS A FUNCTION OF RESIDENCE TIME IN THE AGGLOMERATOR

FIGURE 6: PERCENTAGE OF MASS REMOVED FROM THE BIN SIZES BELOW 11 μM AS A FUNCTION OF THE MASS LOADING OF THE SORBENT

FIGURE 7: PERCENTAGE OF MASS REMOVED FROM THE BIN SIZES BELOW 11 μm AS A FUNCTION OF THE MASS LOADING OF THE FLY ASH

Interestingly, in the lower mass loading range, the effectiveness of the process decreases with increased mass loading of fly ash.

PHASE 2, TASK B: LOW-FREQUENCY NOISE SOURCE TESTS

To eliminate the possibility of contaminating the impactor measurements with residual dust trapped in the combustor, a steel plate liner was installed inside the combustor's refractory lining. Figure 8 is a schematic diagram of the down-fired combustor with the liner. A series of tests to validate the bimodal agglomeration results previously observed was conducted with the modified configuration. For these measurements, the total mass collected in the impactors was similar for the sound and no sound cases. This had not been the case previously. The ratio of the fly ash to sorbent mass was 1:3, and their densities are 2,000 and 1,500 kg/m³, respectively. The fly ash and sorbent were injected into the combustor individually and alone to measure their particle size distributions with the impactor. More than 75 percent of the fly ash was found in the small particle size range (<13 μm) and more than 73 percent of the sorbent particles were greater than 13 μm . The calculated mass ratio of particles less than 13 μm is 41.5 percent in the absence of sound with 58.5 percent of the particles greater than 13 μm . The experimentally determined mass ratios were 39.2 and 60.8 percent, respectively. The similarity between the calculated and experimental values illustrates the good collecting ability of the impactors.

The results of the test are plotted in Figure 9 which shows that 32.86 percent of the small particles were agglomerated into the larger particle size range. This is consistent with the theoretical predictions and provides additional evidence that bimodal agglomeration occurs under the test conditions described.

Work was conducted this reporting period to measure the sorbent and fly ash particle sizes and observe the material collected in the preseparator (material > 11 μm) using a scanning electron microscope (SEM). This was done because the mass balance closure without the liner was poor and independent confirmation of bimodal agglomeration was sought. The sorbent was prepared for the testing by double screening the material using 150 and 200 mesh

**FIGURE 8: HIGH-INTENSITY, LOW-FREQUENCY VIBRATION
DISK NOISE SOURCE AND DOWN-FIRED
COMBUSTOR WITH LINER**

Bimodal Agglomeration runs on 3-28-91 with steel plate liner

Operating Conditions

Static pressure: 1.0 atm

Temperrature: 70 °F

Sound Frequency: 44 Hz

Acoustical particle velocity: >15.84m/s

	Mass loading	Geometric mean size
Sorbent	15.0 g/m ³	88 μm
Fly ash	5.0 g/m ³	5 μm

Total mass collected:	With sound run #1	80.19 mg
	With sound run #2	78.59 mg
	No sound	81.16 mg

FIGURE 9: PARTICLE SIZE DISTRIBUTIONS WITH SOUND AS DETERMINED EXPERIMENTALLY WITH IMPACTORS

screens producing sorbent with a geometric mean size of 88 μm . The fly ash, which was produced for a previous bimodal agglomeration project by grinding electrostatic precipitator (ESP) fly ash that was collected from a utility power station, was reported to have a geometric mean size of 5 μm . The individual particle sizes of the sorbent and fly ash were measured using two laser particle sizing instruments and an SEM to determine the actual particle sizes used in the testing.

There was good agreement among the measured particle sizes using the different instruments. Size analyses of the fly ash and sorbent were conducted with a Malvern 2600 Particle Size Analyzer. The Malvern Particle Size analyzer is an optical, non-imaging technique used to make in situ particle size measurements. The results, reported as $D(v,0.9)$, $D(v,0.5)$, and $D(v,0.1)$ values, are the particle sizes where, respectively, 90%, 50%, and 10% of the particles, by volume, are less than the indicated size. The $D(v,0.9)$, $D(v,0.5)$, and $D(v,0.1)$ values for the fly ash are 36.3, 12.6, and 4.2 μm , respectively. The $D(v,0.9)$, $D(v,0.5)$, and $D(v,0.1)$ values for the sorbent are 156.1, 114.1, and 654.3 μm , respectively.

Photomicrographs were taken of the sorbent fly ash using the SEM and the particle sizes were determined visually from the micrographs. The sorbent was uniform in size with the average particle size of approximately 115 μm . The fly ash varied in size and shape and was predominantly angular. This is probably the result of grinding the fly ash collected from the ESP. The average particle size was 10-11 μm .

The fly ash was also tested in a second laser diffraction device, a Microtrac, to compare the results with those from the Malvern. The average $D(v,0.84)$, $D(v,0.5)$, and $D(v,0.16)$ values were 32.7, 13.0, and 4.6 μm , respectively.

Photomicrographs were taken of the preseparator material collected during hot and cold tests with and without sound. Small particles were observed on the surface of the large limestone particles for each of the tests. As a result, it cannot be stated with certainty that bimodal agglomeration was observed using the SEM micrographs.

In summary, the volume median diameters of the sorbent and fly ash are approximately 114 and 13 μm , respectively. The particle size distributions of the sorbent and fly ash are coarser than those used in the bimodal agglomeration numerical experiments. Verification of bimodal agglomeration using SEM micrographs of the preseparator material was not possible. However, the impactor results presented in Figure 9 offer evidence that bimodal agglomeration occurred under the test conditions described.

2.2 LOW-FREQUENCY NOISE SOURCE TESTS

A series of bimodal agglomeration tests were completed using the vibrating disk noise source and transition piece on the down-fired combustor under cold flow conditions. Limestone and fly ash were fed from separate feeders into air-entrainment chambers and pneumatically injected into two opposing ports at the top of the combustor. Particulate sampling was conducted using the last port of the combustor to investigate particle agglomeration. A nine-stage Anderson Mark III cascade impactor was used to determine the particle size distribution of particles 11 μm and smaller. A preseparator collected particles larger than 11 μm and the small particle size distribution was determined for particles as small as 0.24 μm . The cyclone stages and preseparator were weighed before and after collecting a particle sample and the impactor was operated for ten minutes to collect the sample.

The results from the testing this month are preliminary. Further work is being performed in order to conduct a mass balance between the starting material (sorbent and fly ash) and collected particles.

A strong agglomeration effect was observed in the small particle size range for the low frequency (44 Hz) sound field.

The following operating conditions were used for the first group of tests:

Total mass loading:	30.21 g/m ³
Fly ash mass loading:	7.55 g/m ³
Sorbent mass loading:	22.66 g/m ³

Air flow rate:	14 CFM
Temperature:	70°F
Static pressure:	1.0 atm
Viscosity:	1.85×10^{-5} kg/m-s
Frequency:	44 Hz
Acoustic particle velocity:	15.84 m/s
The mean particle size of the sorbent:	88 μm
The mean particle size of the fly ash:	5 μm

The results in Figure 10 show the particle size distribution in the 1 to 10 μm region before and after application of the sound field at 44 Hz with an approximate acoustic particle velocity of 15m/s. There is a significant difference between the sound and no sound cases. Figure 11 shows the mass distributions of the particles from these tests. For the first test group, 50 percent of the mass of the particles is shifted from the smaller sizes (2.5 μm) into larger sizes (13.5 μm). When viewing the cumulative percent mass plots it must be noted that the upper stokes midpoint diameter value was arbitrarily chosen for these graphs. The particle size distribution of the material collected in the preseparator was not determined; therefore, the final midpoint diameter is probably much larger than the graphs indicate.

The tests were repeated to determine reproducibility. Similar results were observed as shown in Figures 12 and 13. Figures 14 and 15 summarize the two groups of tests.

The theoretical acoustic agglomeration model predicts that the particle mass loading will affect the particle size distribution achieved during bimodal acoustic agglomeration. The fly ash and sorbent mass loadings were unusually high in the first group of tests, therefore, mass loadings of the fly ash and sorbent more typical of those commonly found in coal combustion processes were used in two additional groups of tests. In these tests, the particle size and mass loading were 5-10 microns and 1-5 g/m³, respectively, for the fly ash, and 50-100 microns and 5-20 g/m³, respectively, for the sorbent particles. Two groups of tests were conducted with the following operating conditions:

Operating Conditions of Agglomerator
 Static pressure: 1.0 atm
 Temperature: 71 Deg. F
 Sound frequency: 44 Hz
 Acoustical particle velocity: 15.84 m/s

	<u>Mass loads</u>	<u>Geometric mean size</u>
Sorbent	22.66 g/m ³	88 μm
Fly ash	7.55 g/m ³	5 μm

Air flow: 14 CFM

FIGURE 10: THE PARTICLE SIZE DISTRIBUTION WITH AND WITHOUT SOUND IN THE FIRST GROUP OF TESTS

Operating Conditions of Agglomerator

Static pressure: 1.0 atm

Temperature: 70 Deg. F

Sound frequency: 44 Hz

Acoustical particle velocity: 15.84 m/s

	Mass loads	Geometric mean size
Sorbent	22.66 g/m ³	88 μm
Fly ash	7.55 g/m ³	5 μm

Air flow: 14 CFM

FIGURE 11: CUMULATIVE PARTICLE SIZE DISTRIBUTION WITH AND WITHOUT SOUND FOR THE FIRST GROUP OF TESTS

Operating Conditions of Agglomerator

Static pressure: 1.0 atm

Temperature: 71 Deg. F

Sound frequency: 44 Hz

Acoustical particle velocity: 15.84 m/s

	Mass loads	Geometric mean size
Sorbent	22.66 g/m ³	88 μm
Fly ash	7.55 g/m ³	5 μm

Air flow: 14 CFM

FIGURE 12: THE PARTICLE SIZE DISTRIBUTION WITH AND WITHOUT SOUND IN THE SECOND GROUP OF TESTS

Operating Conditions of Agglomerator

Static pressure: 1.0 atm

Temperature: 70 Deg. F

Sound frequency: 44 Hz

Acoustical particle velocity: 15.84 m/s

	Mass loads	Geometric mean size
Sorbent	22.66 g/m ³	88 μm
Fly ash	7.55 g/m ³	5 μm

Air flow: 14 CFM

FIGURE 13: CUMULATIVE PARTICLE SIZE DISTRIBUTION WITH AND WITHOUT SOUND FOR THE SECOND GROUP OF TESTS

Operating Conditions of Agglomerator

Static pressure: 1.0 atm

Temperature: 71 Deg. F

Sound frequency: 44 Hz

Acoustical particle velocity: 15.84 m/s

	<u>Mass loads</u>	<u>Geometric mean size</u>
Sorbent	22.66 g/m ³	88 μm
Fly ash	7.55 g/m ³	5 μm

Air flow: 14 CFM

FIGURE 14: THE PARTICLE SIZE DISTRIBUTION WITH AND WITHOUT SOUND IN THE FIRST AND SECOND GROUPS OF TESTS

Operating Conditions of Agglomerator

Static pressure: 1.0 atm

Temperature: 70 Deg. F

Sound frequency: 44 Hz

Acoustical particle velocity: 15.84 m/s

	<u>Mass loads</u>	<u>Geometric mean size</u>
Sorbent	22.66 g/m ³	88 μm
Fly ash	7.55 g/m ³	5 μm

Air flow: 14 CFM

FIGURE 15: CUMULATIVE PARTICLE SIZE DISTRIBUTION WITH AND WITHOUT SOUND FOR THE FIRST GROUP OF TESTS

Temperature:	70°F
Static pressure:	1 atm
Viscosity:	1.85×10^{-5} kg/m-s
Frequency:	44 Hz
Acoustical particle velocity:	15.84 m/s
The mean particle size of the fly ash:	5 μ m
The mean particle size of the sorbent:	88 μ m

The bimodal agglomeration experimental test matrix was:

	AIR FLOW (CFM)	FLY ASH MASS LOADING (g/m ³)	SORBENT MASS LOADING (g/m ³)
TEST GROUP #3	42	2.5	15
TEST GROUP #4	54	2.5	10

Figures 16 and 17 are plots of the particle size distribution with and without sound for test group #3. Figures 18 and 19 show the distributions of the mass loading for test group #4. Bimodal agglomeration of the small particles occurred in both test groups.

Tests are currently being conducted firing natural gas in the down-fired combustor to investigate the effect of temperature (>1000°F) on the bimodal agglomeration process.

PHASE 2, TASK B: LOW-FREQUENCY NOISE SOURCE TESTS

A set of tests was conducted in the down-fired combustor (fired with natural gas) to investigate the effect of temperature on the bimodal agglomeration process.

The following operating conditions were used for the tests:

Total mass loading:	17.5 g/m ³
Fly ash mass loading:	2.5 g/m ³
Sorbent mass loading:	15 g/m ³
Air flow rate:	2,050 CFM

Operating Condition of Agglomerator
 Static pressure: 1.0 atm
 Temperature: 66 deg F
 Sound frequency: 44Hz
 Acoustical particle velocity: 15.84 m/s

	<u>Mass load</u>	<u>Geometric mean size</u>
Sorbent	15.0 g/m ³	88μm
Fly ash	2.5 g/m ³	5μm
Air flow: 42.4 CFM		

FIGURE 16: THE PARTICLE SIZE DISTRIBUTION WITH AND WITHOUT SOUND IN GROUP 3 TESTS

Operating Condition of Agglomerator

Static pressure: 1.0 atm

Temperature: 66 deg F

Sound frequency: 44Hz

Acoustical particle velocity: 15.84 m/s

	<u>Mass load</u>	<u>Geometric mean size</u>
Sorbent	15.0 g/m ³	88μm
Fly ash	2.5 g/m ³	5μm
Air flow: 42.4 CFM		

FIGURE 17: CUMULATIVE PARTICLE SIZE DISTRIBUTION WITH AND WITHOUT SOUND FOR THE GROUP 3 TESTS

Operating Conditions of Agglomerator
 Static pressure: 1.0 atm
 Temperature: 71 Deg. F
 Sound frequency: 44 Hz
 Acoustical particle velocity: 15.84 m/s

	Mass loads	Geometric mean size
Sorbent	9.5 g/m ³	88 μm
Fly ash	2.1 g/m ³	5 μm
Air flow: 54 CFM		

FIGURE 18: THE PARTICLE SIZE DISTRIBUTION WITH AND WITHOUT SOUND IN GROUP 4 TESTS

Bimodal Agglomeration 2-8-91

FIGURE 19: CUMULATIVE PARTICLE SIZE DISTRIBUTION WITH AND WITHOUT SOUND FOR THE GROUP 4 TESTS

Temperature:	650 °F
Static pressure:	1.0 atm
Viscosity:	1.856×10^{-5} kg/m-s
Frequency:	44 Hz
Acoustic particle velocity:	>15.84 m/s
Mean particle size of the sorbent:	88 μm
Mean particle size of the fly ash:	5 μm

A significant agglomeration effect was observed in the small particle size range under the high-temperature conditions examined. It should be noted that the down-fired combustor and the vibrating disk noise source began to exhibit a strong resonance condition when the temperature of the combustion chamber reached 550°C. This condition was maintained until the temperature reached the final operating condition of 650°C.

The results in Figure 20 show the shift in particle size distribution in the 1 to 10 μm region before and after application of the sound field. In order to perform a mass balance on the individual materials (sorbent and fly ash) and the collected particles, the fly ash and sorbent were injected into the combustor individually to measure their particle size distributions, as measured by the impactors. Figure 21 shown the particle size distribution of the fly ash and sorbent without sound. Some small particles (<12 μm) were found in the sorbent sample. Additionally, large particles (>12 μm) were sampled in fly ash. Further work in measuring the individual particle sizes using two laser particle sizing instruments and a scanning electron microscope is underway. To eliminate the possibility of affecting the impactor measurements with residual dust trapped in the combustor, a steel plate liner is being installed within the combustor's refractory lining.

A final set of tests was conducted to determine if the fly ash by itself would agglomerate at the low frequency of #4 Hz. Figure 22 is a plot of the fly ash particle size distribution with and without sound. As expected from theory which predicts that the fly ash would be fully entrained at 44 Hz, there is no significant difference between the sound and no sound cases.

Bimodal Agglomeration 2-14-91

Bimodal Agglomeration 2-14-91

Operating Conditions

Static pressure: 1.0 atm

Temperature: 650°C

Sound frequency: 44 Hz

Acoustical particle velocity: >15.84 m/s

	Mass loading	Geometric mean size
Sorbent	5.0 g/m ³	88 μm
Fly ash	2.5 g/m ³	5 μm
Total	17.5 g/m ³	

FIGURE 20: THE PARTICLE SIZE DISTRIBUTION WITH AND WITHOUT SOUND FOR AN OPERATING TEMPERATURE OF 650 DEGREES C

Sorbent & Fly ash Distribution **No Sound 2-21-1991**

Operating Conditions

Static Pressure: 1.0 atm
 Temperature: 72 °F
 Mass Loading of Sorbent: 15g/m³
 Mass Loading of Fly Ash: 5g/m³
 Flow Rate: 42 CFM

FIGURE 21: THE PARTICLE SIZE DISTRIBUTION OF SORBENT AND FLY ASH AS SAMPLED BY THE IMPACTORS

Agglomeration Fly Ash 2-21-1991

Agglomeration of Fly Ash 2-21-91

Operating Conditions

Static Pressure: 1.0 atm
 Temperature: 72 Deg. F
 Mass Loads Fly Ash: 5g/m³
 Flow Rating of 42 CFM
 Sound Frequency: 44 HZ
 Acoustic Particle Velocity >15.84 m/s

FIGURE 22: THE PARTICLE SIZE DISTRIBUTION OF FLY ASH WITH AND WITHOUT SOUND

The SBIR pulse combustor test facility was completed. The SBIR pulse combustor test facility is composed of an F.D. fan, air plenum, pulse combustor, tailpipe, decoupler, cyclone, and I.D. fan. Figure 23 shows a drawing of the SBIR pulse combustor test facility. After completion of the test facility, one shakedown test was performed to characterize the pulse combustor performance. The pulse combustor was fired on natural gas with the new gas/coal injector (Figure 24). The shakedown test results are as follows:

Firing Rate:	950,000 Btu/hr
Chamber Mean Temperature:	2170°F
Air Plenum Pressure:	+ 36" H ₂ O
Combustion Chamber Pressure:	+ 31" H ₂ O
Decoupler Pressure:	+ 9 H ₂ O
Flue Gas Analysis at End of Tailpipe:	O ₂ (%) = 7.2, CO (ppm) = 0, NO _x (ppm) = 23, CO ₂ (%) = 7.2, UHC (%) = 0.1
Operating Frequency:	80 Hz
Peak-to-peak Dynamic Pressure:	3.7 psia

After the shakedown test, a series of tests were performed to determine the pulse combustor performance characteristics at different excess air levels. Table 1 summarizes the results of these tests. The test results indicate a slight increase in SPL inside the combustion chamber with an increase in excess air level. The pulse combustor operated fine at different excess air levels and the frequency of operation was almost a pure monotone. Figure 25 shows a frequency signal trace of the pulse combustor during Test No. 189104 which is similar to those in other tests.

A series of tests were performed to determine the maximum firing rate of coal in a gas/coal fuel mixture in the pulse combustor and keeping an acceptable SPL inside the combustion chamber (> 170 dB). The coal feed rate was regulated using a K-Tron screw feeder. Figure 26 shows the calibration curve for the K-Tron screw feeder using pulverized coal obtained from Energy International Inc. Table 2 shows the ultimate and proximate analyses for this coal. The coal was transported pneumatically into the combustion chamber using a 1-inch eductor. Table 3 summarizes the test results of the pulse

FIGURE 23: SBIR PULSE COMBUSTOR TEST FACILITY

FIGURE 24: BIMODAL GAS AND COAL INJECTOR

TABLE 1:
TEST RESULTS OF PULSE COMBUSTOR (1/8/91)

FUEL: N. GAS

TEST #	FIRING RATE (BTU/HR)	AIR		TAIL-PIPE		AIR		Flue gas at the end of tailpipe										CHAMBER		EXCESS COMBUSTION	
		PLENUM TEMP. (F)	CHAMBER TEMP. (F)	PIPE TEMP. (F)	DECOPLER TEMP. (F)	PLENUM PRESSURE ("H2O)	CHAMBER PRESSURE ("H2O)	TAILPIPE PRESSURE ("H2O)	DECOPLER PRESSURE ("H2O)	O2 (%)	CO (PPH)	HOx (PPH)	CO2 (%)	UHC (%)	SPL (dB)	FREQ. (HZ)	AIR (%)	EFFICIENCY (%)			
189101	1,258,915	180	---	2240	1791	23	20	7.5	2.5	2.7	3	44	9.6	0.2	173.49	88	13.36	99.65			
189102	1,462,797	187	2500	2292	1809	34	29	10.5	3.5	3.3	0	45	9.4	0.1	175.50	96	16.88	99.82			
189103	1,462,797	165	2340	2250	1788	36	32	11.5	5.0	4.1	0	39	8.9	0.1	173.97	90	21.97	99.81			
189104	1,462,797	167	2490	2220	1791	39	33	12.5	5.5	5.3	0	35	8.3	0.1	175.20	92	30.57	99.79			
189105	1,462,797	151	2460	2174	1752	44	37	15.5	8.5	6.1	5	30	7.8	0	176.53	92	37.07	100.00			

FREE RUN

Heas

FIGURE 25: FREQUENCY SIGNAL TRACE (TEST No. 189104)

FIGURE 26: CALIBRATION CURVE - "K" TRON FEEDER

TABLE 2: ULTIMATE AND PROXIMATE ANALYSIS OF
THE PULVERIZED PITTSBURGH NO. 8
COAL USED IN SBIR PULSE COMBUSTOR

Proximate Analysis

	As Received	Dry Basis
	-----	-----
% Moisture	1.70	xx
% Ash	5.33	5.42
% Volatile	36.67	37.30
% Fixed Carbon	56.30	57.28
	-----	-----
	100.00	100.00

Ultimate Analysis

% Moisture	1.70	xx
% Carbon	80.59	81.98
% Hydrogen	4.94	5.03
% Nitrogen	1.44	1.46
% Sulfur	1.28	1.30
% Ash	5.33	5.42
% Oxygen (diff)	4.72	4.81
	-----	-----
	100.00	100.00

Fusion Temperature of Ash (° F)

	Reducing	Oxidizing
	-----	-----
Initial Deformation (IT)	2382	2525
Softening (ST)	2497	2660
Hemispherical (HT)	2575	2700+
Fluid (FT)	2680	2700+

**TABLE 3:
TEST RESULTS OF PULSE COMBUSTOR (1/9/91)**

FUEL: N. GAS, AND GAS/COAL MIXTURE																						
TEST #	FIRING RATE (BTU/HR)	AIR		TAIL-PIPE TEMP. (F)	DECOPLER TEMP. (F)	AIR PLENUM PRESSURE ("H2O)	Flue gas at the end of tailpipe										EXCESS AIR (%)	COMBUSTION EFFICIENCY (%)				
		TEMP. (F)	PLENUM TEMP. (F)				CHAMBER PRESSURE ("H2O)	CHAMBER PRESSURE ("H2O)	CHAMBER TAILPIPE DECOPLER PRESSURE ("H2O)	O2 (%)	CO (PPM)	NOX (PPM)	CO2 (%)	UHC (%)	CHAMBER SPL (dB)	FREQUENCY (HZ)						
199101	1,365,277	86.8	2029	1950	1610	>50	>50	>36	33	9.3	176	18	6.1	0.0	171.35	82	71.97	100.00				
ABOVE TEST 100% N. GAS																						
199102	1,419,934	85.4	2150	1970	1760	>50	>50	>36	33	9.3	2800	437	6.1	0.3	160.22	68	71.97	---				
ABOVE TEST 60% GAS, 40% COAL																						
199103	1,448,149	89.1	2112	1970	1662	>50	>50	>36	33	9.2	760	278	6.2	0.1	169.78	78	70.60	---				
ABOVE TEST 83% GAS, 17% COAL																						
199104	1,448,149	89.6	2119	1980	1641	>50	>50	>36	33	9.1	632	295	6.2	0.1	172.68	84	69.24	---				
ABOVE TEST 83% GAS, 17% COAL, MOVING THE GAS/COAL INJECTOR 2" DOWN FROM PREVIOUS RUN																						
199105	1,426,281	88.6	2135	1955	1669	>50	>50	>36	33	9.1	840	399	6.2	0.1	171.26	80	69.24	---				
ABOVE TEST 70% GAS, 30% COAL, GAS/COAL INJECTOR LOCATION SAME AS TEST # 199104																						
199106	1,365,277	88.5	2082	1916	1599	>50	>50	>36	33	9.2	193	32	6.2	0.0	174.55	90	70.60	100.00				
ABOVE TEST 100% GAS, GAS/COAL INJECTOR LOCATION SAME AS TEST # 199104																						

combustor firing with gas/coal mixture. The location of the gas/coal injector inside the combustion chamber is important for the operation of the pulse combustor. As is shown in Table 3, the difference between Test No. 199101 and Test No. 199106 is the location of the gas/coal injector, in which the chamber SPL has increased from 171.35 dB to 174.55 dB from Test No. 199101 to 199106. The pulse combustor was fired at 71 percent excess air in order to avoid slagging of the coal ash.

During the above tests, the gas/coal injector traverse mechanism did not allow moving the injector further down into the combustion chamber to the desired location. After modifying the injector traversing mechanism, a long duration test was performed by firing gas/coal mixture. The best location for the gas/coal injector has been found to be at the start of the inlet divergent section to the combustion chamber. The maximum coal firing rate achieved in a gas/coal mixture was 30 percent coal firing. Table 4 summarizes the test results. Figures 27 through 31 show the O_2 , CO, NO_x , SO_2 , and CO concentrations in flue gas during Test No. 1129102. A total of 150 lb of pulverized coal was fed into the pulse combustor. The ratio of coal to gas firing rate is about 45 percent coal and 55 percent gas. Pulse combustor operation was very stable with an operating frequency of 86 Hz and a pure monotone dynamic pressure signal. The SPL inside the combustion chamber was 174 dB. Figure 32 shows the frequency signal trace for Test No. 1129102. Pulverized No. 8 coal was used for the above test. The fluidic temperature of the ash for this coal in oxidizing environment is + 2700°F. During the test, the combustion chamber temperature was kept around 2500°F in order to avoid slagging of the coal ash; however, after the test, the inside of the combustion chamber was inspected and a layer of slag was observed in the combustion chamber. It is believed that the thermocouple inside the combustion chamber reads an average temperature due to the oscillating flow which is considerably lower than the actual gas temperature. In order to avoid slagging of the coal ash, the combustion chamber temperature should be kept at a thermocouple reading of about 2100°F.

TABLE 4:
TEST RESULTS OF PULSE COMBUSTOR (1/12/91)

FUEL: N. GAS/COAL MIXTURE

TEST #	FIRING RATE (BTU/HR)	AIR		TAIL PIPE TEMP. (F)	CHAMBER TEMP. (F)	AIR		CHAMBER		Flue gas at the end of tailpipe										EXCESS AIR (%)	COMBUSTION EFFICIENCY (%)
		PLENUM TEMP. (F)	TEMP. (F)			DECOPLER TEMP. (F)	PLENUM PRESSURE ("H2O)	CHAMBER PRESSURE ("H2O)	TAILPIPE PRESSURE ("H2O)	DECOPLER PRESSURE ("H2O)	O2 (%)	CO (PPM)	NOx (PPM)	CO2 (%)	SO2 (PPM)	SPL (dB)	FREQUENCY (HZ)				
1129101	1,176,163	87	2317	2036	---	>60	>50	36.00	30	6.1	22	48	7.2	---	---	176.23	86	37.80	100.0		
ABOVE TEST WAS 100% GAS																					
1129102	1,177,525	100	2490	2090	---	>60	>50	27.25	22.50	6.7	554	630	7.5	87	87	174.79	86	38.20	96.81		
ABOVE TEST WAS 45% COAL AND 55% GAS

**FIGURE 27: O₂ CONCENTRATION TIME HISTORY
(FOR TEST #1129102)**

**FIGURE 28: CO CONCENTRATION TIME HISTORY
(FOR TEST #1129102)**

**FIGURE 29: NO_x CONCENTRATION TIME HISTORY
(FOR TEST #1129102)**

**FIGURE 30: SO₂ CONCENTRATION TIME HISTORY
(FOR TEST #1129102)**

**FIGURE 31: CO₂ CONCENTRATION TIME HISTORY
(FOR TEST #1129102)**

FIGURE 32: FREQUENCY SIGNAL TRACE (TEST No. 1129102)

In order to investigate the effect of oscillating flow on the calcination rate of limestone, one test was performed in which limestone powder was injected into the gas-fired pulse combustion chamber. Table 5 shows the summary of this test. Table 6 shows the size distribution and the chemical analysis of the limestone used in this test. Limestone was injected through the aerovalve into the combustion chamber at a rate of 9 lb/hr (solids loading in combustion chamber of 1.5 gm/m^3). A total of 36 lbs of limestone was injected into the pulse combustion chamber which was at 2400°F and 16.85 lbs of solids was collected in the cyclone catch pot. It represents about 0.24 sec of residence time for the limestone. After the test, a sample of cyclone catch material was sent to Penn State University for chemical analysis, in which it showed 69 percent calcination for the limestone.

After the limestone injection tests, one test was planned in which limestone, ash, and coal are mixed together as follows and injected into the pulse combustor:

9 lb/hr of ash:	(corresponds to burning 100% coal with 10% ash, 1.4 MMBtu/hr firing rate)
9 lb/hr of limestone:	(corresponds to 100% burning on coal, with 3% sulfur coal and $\text{Ca/S} = 2$).

The mixture was planned to be injected into the pulse combustion chamber. However, during the warm-up of the pulse combustor on gas, a performance deterioration of the pulse combustor was noticed, dynamic pressure was much lower on gas than that in previous tests at the same firing rates, and also, the flue gas analysis showed lower combustion efficiencies. At this point the test was terminated and the unit was inspected for any damage or breakage of refractory. Fortunately, the refractory combustion chamber was not damaged; however, a hole was found in the water-jacketed tailpipe where the metal surface had been ground to weld a fitting. It was decided to replace the water-cooled tailpipe section with a new tailpipe assembly.

TABLE 5:
TEST RESULTS OF PULSE COMBUSTOR (1/16/91)

FUEL: N. GAS, AND LIMESTONE INJECTION
TEST #: 1169101

TIME	FIRING RATE (BTU/HR)	AIRPLENUM TEMP. (F)	CHAMBER TEMP. (F)	TAILPIPE TEMP. (F)	DECOPLER TEMP. (F)	AIRPLENUM PRESSURE ("H2O)	CHAMBER PRESSURE ("H2O)	TAILPIPE PRESSURE ("H2O)	DECOPLER PRESSURE ("H2O)	O2(%)	CO(PPM)	NOx(PPM)	CO2(%)	UHC(%)	CHAMBER SPL (dB)	FREQUENCY (HZ)	COMBUST EFFICIENCY (%)
15.05	1,194,618	98.4	2226	2140	---	75	70	30	29	5.4	24	43	8.2	0.0	173.42	96	100.00
15.45	1,194,618	99	2234	2144	--	75	70	32	29.5	5.6	34	45	8.0	0.0	172.45	100	100.00
16.05	1,194,618	99	2242	2158	---	75	70	32.5	30	5.7	33	45	8.0	0.1	172.65	100	99.80
LIMESTONE INJECTION STARTED AT 9.0 LB/HR FEED RATE @ TIME 16.15																	
16.30	1,194,618	99	2324	2079	---	75	68	30	29	5.6	43	39	8.0	0.1	173.35	100	99.80
17.00	1,194,618	99	2390	2058	---	75	68	29.5	28	5.6	55	39	8.0	0.1	172.62	100	99.80
17.30	1,194,618	100	2412	2033	---	76	69	28	27	5.6	46	39	8.0	0.0	172.31	102	99.99
18.00	1,194,618	101	2412	2029	---	77	70	28.5	26.5	5.6	138	39	8.0	0.2	172.76	100	99.60
18.30	1,194,618	101	2413	2027	---	76	69	29	26	6.1	24	38	7.8	0.1	172.11	102	99.80
19.15	1,194,618	100	2406	2011	---	76	69	29	26	6.1	55	38	7.8	0.2	173.30	102	99.60
19.45	1,194,618	100	2403	1996	---	76	69	29	26	6.3	50	38	7.8	0.2	173.37	102	99.60
20.10	1,194,618	100	2410	2008	---	77	70	29	26	6.2	40	37	7.8	0.2	173.37	102	99.60

TABLE 6: CHEMICAL AND PARTICLE SIZE ANALYSIS
ANALYSIS OF THE LIMESTONE POWDER
USED IN TEST NO. 1169101

Particle Size Analysis

Size	% Weight Retained
425 um	9.1
300 um	12.5
212 um	11.0
150 um	15.9
75 um	18.3
45 um	7.4
-45 um	25.8

Chemical Analysis

	Weight %
CaCO ₃	89.18
CaO	49.94

The initial deformation temperature of the coal fly ash obtained from the Baltimore Gas & Electric Company was found to be about 2300°F. This in conjunction with the oscillating flow field in the pulse combustion chamber required that the combustion chamber be operated at a mean temperature of about 2000°F to avoid slagging. Computations indicated that a water-cooled tailpipe would then result in an agglomeration chamber temperature of between 1500 and 1600°F. In order to better simulate conditions relevant for gas turbine applications, it was decided to design and fabricate a new tailpipe assembly comprising a hot tailpipe and a radiatively coupled, annular, external water jacket. This made it possible to operate the agglomeration chamber in the 1900 - 2000°F range. Recall that the original pulse combustor design with water-cooled tailpipe was meant for elevated pressure operation and not for atmospheric pressure application. Based on the results from room temperature frequency mapping of the agglomeration chamber and the desire to achieve a "lock-in" or resonance condition between pulse combustor and agglomeration chamber, the tailpipe was designed for 80 Hz operation at 2000°F mean temperature.

After the tailpipe assembly was fabricated and the water jacket was tested for leaks, the pulse combustor was assembled and installed on the bimodal test facility. The plumbing and instrumentation work were completed and the instruments were calibrated. After completion of the Bimodal test facility, three shakedown tests were performed on February 25, 28, and March 2. Test results are shown in Table 7.

During the first shakedown test on February 25, gas was injected at a fixed location through four slit-type holes spaced 90 degrees apart into the upper part of the combustion chamber inlet section. The pulse combustor did not pulse due to the poor fuel/air mixing inside the combustion chamber.

During the second shakedown test on February 28, a new gas/solid injector was fabricated and tested. Figure 33 shows a drawing of the new gas/solids injector used in this test. This injector was designed to inject the solids through the 3/4-inch tube into the tailpipe and inject gas into the combustion

TABLE 7:

SHAKEDOWN TEST RESULTS OF BIMODAL ATMOSPHERIC UNIT

TEST #	TEST DATE	FIRING RATE TO H.E. T1 (BTU/HR)	WATER										GAS										CO2 (%)
			T1 (F)	T2 (F)	T3 (F)	T4 (F)	T5 (F)	T6 (F)	T7 (F)	T8 (F)	T9 (F)	P1 ("H2O)	P2 ("H2O)	P3 ("H2O)	P4 ("H2O)	P5 ("H2O)	O2 (%)	CO (%)	MOX (PPM)				
62259101	2/25/91	680,000	---	76.5	2000	1905	1781	1600	434	257	---	---	---	+24	+17	+4.25	1.25	-4.50	2.4	0	57	9.9	
COMMENTS: PULSE COMBUSTOR NOT PULSING, FIXED GAS INJECTION LOCATION, GAS ROTAMETERS INADEQUATE																							
2289101	2/28/91	827,000	7.0	85.3	1704	1894	1857	1781	253	154	121	47	+58	+52	+36	3.00	-4.0	9.8	0	30	5.8		
2289102	2/28/91	827,000	1.5	89.0	1923	1923	1902	1841	420	312	224	48	+58	+52	+36	3.50	-3.25	10.0	100	31	5.7		
COMMENTS: PULSE COMBUSTOR NOT PULSING, NEW GAS/SOLIDS INJECTOR																							
3029101	3/02/91	1,080,000	0	103	2324	2165	2120	2050	585	448	1042	54	+55	+50	+40	4.5	+0.2	7.2	0	37	7.7		
	3/02/91	1,080,000	2.5	105	2351	2187	2148	2082	208	202	217	51	+56	+50	+34	4.4	+2.1	7.3	0	37	7.7		
	3/02/91	1,080,000	>1	108	2377	2187	2147	---	---	---	218	215	51	+56	+51	+34	1.75	+1.5	7.6	0	38	7.9	
	3/02/91	1,080,000	0	116	2092	2048	2021	1970	915	665	881	84	+57	+52	+34	4.0	+1.5	9.2	0	28	6.7		

COMMENTS: PULSE COMBUSTOR IS OPERATING NICE, ORIGINAL GAS/SOLID INJECTOR, STEAM LEAK INTO THE FLUE GAS

T1: AIRPLENUM TEMP.

T2: COMBUSTION CHAMBER TEMP.

T3: TOP A.A. CHAMBER TEMP.

T4: MIDDLE OF A.A. CHAMBER TEMP.

T5: BOTTOM OF A.A. CHAMBER TEMP.

T6: INLET TO CYCLONE TEMP.

T7: BEFORE INSITEC TEMP.

T8: WATER-IN TEMP.

T9: WATER-OUT TEMP.

P1: AIRPLENUM STATIC PRESSURE

P2: COMBUSTION CHAMBER STATIC PRESSURE

P3: A.A. CHAMBER STATIC PRESSURE

P4: DELTA P ACROSS CYCLONE

P5: I.D. FAN SUCTION BEFORE INSITEC

FIGURE 33: BIMODAL GAS, LIMESTONE AND ASH INJECTOR

chamber. This configuration would provide an independent traversing advantage for both gas and solids injection. Since the gas/solid injector outside diameter was 1.5 inches, the aerovalve was changed from 1.50 inches diameter to 2.80 inches throat diameter. The pulse combustor was tested with this new gas/solids injector. Again, the pulse combustor did not pulse due to the poor mixing of fuel/air and the flame was torching into the acoustic agglomeration chamber.

For the shakedown test on March 2, the gas/solid injector was changed to the original gas/solid injector which was used during the testing of the same pulse combustor on the SBIR test stand. Figure 34 shows a drawing of the original gas/solid injector. The main difference between the original gas/solid injector and the new gas/solid injector is the size of the impactor plate used for redirecting the gas flow and also to reduce the forward momentum of the gas inside the combustion chamber. The impactor plate is 2 inches in diameter in the original gas/solid injector and 1.5 inches in the new gas/solid injector.

The pulse combustor was test-fired with the original gas/solid injector. The pulse combustor operated very nicely, with a frequency of 84 Hz and SPL of 173.3 dB inside the combustion chamber. Dynamic pressure measurements throughout the bimodal system were as follows:

	<u>SPL (dB)</u>	<u>Frequency (Hz)</u>
Combustion Chamber:	173.3	84
Top of A.A. Chamber:	136.6	84
Middle of A.A. Chamber:	146.5	84
Bottom of A.A. Chamber:	150.1	86
Inlet to Cyclone:	140.3	86

At this condition, the pulse combustion chamber temperature was 2324°F and acoustic agglomeration chamber temperature was 2110°F. From frequency mapping of the acoustic agglomeration chamber in cold conditions, the first resonant frequency of the agglomeration chamber was found to be 38 Hz at 70°F, which corresponds to 84 Hz at 2110°F gas temperature. During the test at this condition suddenly the flow inside the bimodal system started to pulse at low frequency and the static pressure manometers throughout the system started to

FIGURE 34: BIMODAL GAS AND COAL INJECTOR

vibrate appreciably for a few minutes and then everything became quite. The combustion chamber SPL was measured at this time to be 178.1 dB and a frequency of 86 Hz. It is believed that at this time the pulse combustor operating frequency locked-in with the resonant frequency of the acoustic agglomeration chamber and a standing wave pattern (quarter wave) was achieved in the agglomeration chamber. Dynamic pressure measurements throughout the bimodal system at this condition were as follows:

	<u>SPL (dB)</u>	<u>Frequency (Hz)</u>
Combustion Chamber:	178.1	86
Top of A.A. Chamber:	137.6	172
Middle of A.A. Chamber:	146.5	86
Bottom of A.A. Chamber:	150.1	86
Inlet to Cyclone:	140.2	84

At this time, steam flow at a high rate was observed from the I.D. fan outlet and the test was terminated. After the system was cooled down, the first three sections of the heat exchanger were pressure tested with water and in one of the sections a water leak into the flue gas side was observed. At this point the entire heat exchanger section was disassembled and all the sections were pressure tested. After inspection, additional cracks were observed in welds connecting the pipes to the flanges. Also, cracks were observed in the water-shell section of the pulse combustor tailpipe. It is believed that the initial crack was started in the heat exchanger section due to inadequate water distribution in those sections which resulted in overheating of the inner pipe and expansion of the pipes and since the inner pipe is welded at both ends, the normal stress caused by the expansion resulted in cracking of the welds. All the heat exchanger pipes were rewelded. The unit is being prepared for testing.

The particle size analyses obtained by different techniques (photo-sedimentation, laser diffraction, Bahco air classification, and Malvern) were compared to select the method appropriate for evaluating agglomeration effectiveness. The results are presented in Figures 35 through 37. Coal fly ash/limestone mixture was used for analysis so as to closely simulate the cyclone and baghouse catch streams. Recall that cyclone is intended to be the only particulate collection device for this application. An examination of

COAL FLY ASH/LIMESTONE MIXTURE SIZE ANALYSES

FIGURE 35: COMPARISON OF BAHCO AND LASER DIFFRACTION SIZE ANALYSES

COAL FLY ASH/LIMESTONE MIXTURE SIZE ANALYSES

FIGURE 36: COMPARISON OF BAHCO AND MALVERN SIZE ANALYSES

COAL FLY ASH/LIMESTONE MIXTURE SIZE ANALYSES

FIGURE 37: COMPARISON OF BAHCO AND PHOTO-SEDIMENTATION SIZE ANALYSES

the results indicated that the Bahco method generally yielded higher fines (< 30 microns) content than the other methods. The fact that Bahco uses air as the medium, estimates Stokes equivalent diameter which has relevance for cyclone capture, and automatically accounts for differences in particle density, shape, and porosity, it was decided to select this method. Figures 35 and 36 suggest that both laser diffraction and Malvern underestimate fines below 30 microns and in particular those below 10 microns. Note that accuracy in this size range is vital for properly evaluating acoustic agglomeration test data. The discrepancy arises because both laser diffraction and Malvern estimate geometric diameter which is independent of particle density, mass distribution, and porosity. Note that it is not uncommon for coal fly ash to contain cenospheres. Photosedimentation and Bahco results are reasonably close (Figure 37). Photosedimentation also tries to estimate the Stokes equivalent diameter. However, photosedimentation uses a liquid as a medium and this poses problems with pore penetration in case of porous solids. Also, the liquid selection becomes a compromise when solids of two or more densities are present in the particulate sample. Consequently, Bahco is the method of choice for particle size analysis in this program.

The results of the Bahco size analyses performed on the feed material (coal fly ash, limestone, and coal fly ash/limestone mixture) are presented in **Figure 38**. It is seen that a substantial proportion of coal fly ash is below 15 microns in size while a substantial fraction of limestone exceeds 15 microns in size. The mixture (30% by weight of coal fly ash and 70% by weight of limestone) consists of about 40 percent by weight below 15 microns in size and about 80 percent by weight below 200 microns in size.

Two tests were run on the bimodal test facility. In both cases, the fuel supplied to the pulse combustor was natural gas. In the first test, the solids - coal fly ash - were injected into the pulse combustion chamber at the rate of 60 lb/hr to yield a solids mass loading of about 10 g/m³ in the agglomeration chamber. With solids injection into the pulse combustion

FEED PARTICLE SIZE ANALYSIS

FIGURE 38: FEED PARTICLE DISTRIBUTION

FIGURE 39: CYCLONE CATCH MATERIAL

FIGURE 40: CYCLONE CATCH MATERIAL

issues and determine the bimodal test facility modifications necessary to accomplish the program objectives.

The limestone calcination result reported in the January monthly report was compared with literature calcination data.^(1,2) Figures 41 and 42 present the results on the extent of calcination. Recall that the MTCI test was performed in the SBIR pulse combustor test facility. The MTCI test corresponds to different residence times at different temperatures and therefore the datapoint is shown in Figures 41 and 42 as a horizontal time band at the measured 69 percent calcination. The time band extends from the computed minimum steady-state gas residence time of 24 ms in the pulse combustor (combustion chamber and tailpipe) at a mean temperature of about 2200°F to the computed maximum steady-state gas residence time of 192 ms in the system (pulse combustor and decoupler) at a mean temperature of about 1675°F. The residence time in the cyclone was not included because the cyclone temperature of about 1400°F was considered low for any significant calcination to have occurred. An examination of Figures 41 and 42 indicates that calcination under pulsating combustion conditions provides a substantial increase in the calcination rate. Samples were sent to Penn State University for BET surface area measurements. Mercury porosimetry measurements were made instead, and the surface area obtained for the calcined material was 5.1 m²/g in comparison to that for the raw limestone of 0.95 m²/g. Note that the mercury molecule is much bigger than N₂ and CO₂ and therefore the BET surface areas are likely to be larger than the values repeated above. It is proposed to send samples to an outside laboratory for BET surface area, pore size, and pore volume measurements so that calcination characteristics under pulsating combustion conditions can be better defined.

The Bahco size analyses performed on the limestone before and after calcination are shown in Figure 43. About 25 percent by weight of material before calcination is below 20 microns in size while the size fraction below 20 microns after calcination increases significantly to about 80 percent by weight. This indicates substantial fragmentation - breakup of particles to yield subparticles - due to thermal shock and rapid calcination. This provides further testimony to high calcination rate under pulsating combustion

(a) St. Genevieve Limestone

(b) Marianna Limestone

**FIGURE 41: COMPARISON OF LIMESTONE CALCINATION RATES
IN FLOW REACTOR⁽¹⁾ AND PULSE COMBUSTION (MTCI)**

FIGURE 42: COMPARISON OF CALCINATION RATES IN DISPERSED-PARTICLE FLOW REACTORS: 90 MICRONS LIMESTONE PARTICLES, 1090°C⁽²⁾ WITH MTCI TEST DATA

FIGURE 43: EFFECT OF CALCINATION ON LIMESTONE SIZE DISTRIBUTION

conditions. While this fragmentation is likely to enhance sulfur capture, it generates additional small particles (< 10 microns) which need to agglomerate. Studies are necessary under simultaneous calcination and sulfation conditions to evaluate this effect.

SECTION 3.0

PLANS FOR NEXT PERIOD

Additional lime will be calcined for the Penn State testing.

A new 750 KBtu pulse combustor will be designed with a heat transfer controlled tailpipe to provide temperature profile shaping.

Additional tests on micronized coal will be conducted in the facility.

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