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Subpilot-Scale Testing of Acoustically Enhanced Cyclone Collectors

Final Report
September 1988 - September 1994

M.A. Galica
A.H. Campbell
D.C. Rawlins

August 1994

Work Performed Under Contract No.: DE-AC21-88MC25010

For
U.S. Department of Energy
Office of Fossil Energy
Morgantown Energy Technology Center
Morgantown, West Virginia

By
Solar Turbines, Inc.
San Diego, California

DISCLAIMER

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P.O. Box 85376
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EXECUTIVE SUMMARY

Gas turbines are used to recover energy from high temperature exhaust gases in coal-fired pressurized-fluidized bed, combined-cycle power generation systems. However, prior to entering the turbine hot-section, the majority of the fly ash must be removed in order to protect the turbine components from erosion, corrosion, and deposition of the ash. The U.S. Department of Energy under the direction of the Morgantown Energy Technology Center (METC) sponsored the development of an acoustically enhanced cyclone collector which offers the potential of achieving environmental control standards under Pressurized Fluid Bed Combustors (PFBC) conditions without the need for post-turbine particulate control. Pulse combustors developed by Manufacturing and Technology Converstion International, Inc. (MTCI) produced the acoustic power necessary to agglomerate ash particles into sizes large enough to be collected in a conventional cyclone system. A hot gas cleanup system that meets both turbine protection and emissions requirements without post-turbine particulate controls would also have improved overall system economics.

The objectives of this program were to experimentally verify, on the sub-pilot scale, the effectiveness of an acoustically enhanced cyclone collector under high temperature, high pressure conditions typical of PFBC combined cycle power generating systems.

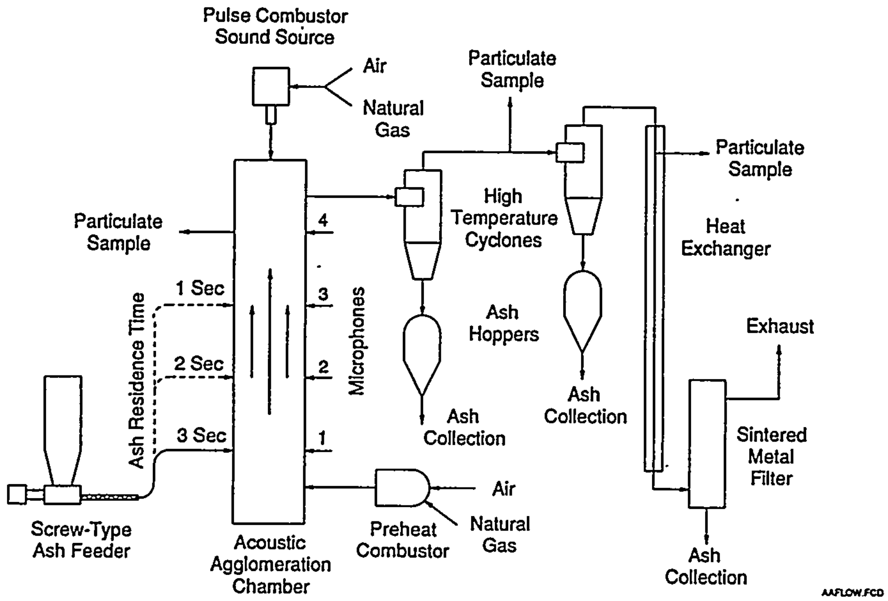
The acoustically enhanced cyclone collector was evaluated with two distinct goals in mind: (1) determine the effects of varying the major operating parameters on agglomeration efficiency, and (2) optimize the agglomeration system to provide maximum particle removal efficiency.

The test facility consisted of natural gas-fired pulse combustors of varying frequencies, an agglomeration chamber, a preheat combustor, a two-stage high temperature, high pressure cyclone system, and several particulate removal devices. The following diagram is the basic hardware configuration.

The agglomeration test program consisted of facility shakedown and pulse combustor optimization tests, followed by demonstration tests where flyash obtained from several power stations was fed into the agglomeration chamber for sound exposure, and collected for size distribution measurements. The agglomeration tests were divided into two main groups: high and low frequency tests. The other independent operating variables include sound frequency, sound intensity, ash residence time within the agglomeration chamber, ash loading in the bulk gas stream, system pressure, and chamber temperature.

Pulse combustor performance was optimized in both high and low frequency modes to maximize sound pressure level and promote high agglomeration efficiencies.

Fly ash particles were removed from the flowing gas stream through three water cooled sample probes. The samples were then collected in either an Andersen Cyclade™ cascade sampler or a Balston Filter. The Cyclade™ was used for determining particle size distribution, while the Balston Filters yielded only total mass loading.



High Frequency Agglomeration Flow Diagram

System characterization tests were performed at three high frequency levels; 1000, 2000 and 3000 Hertz. Agglomeration tests were performed with ash only at the 1000 Hertz level. A successful sound/no sound comparison test was performed with ash being injected into the 3 second residence time port. The mass fraction of ash less than 10 microns was reduced in tests where the pulse combustor was tuned in compared to the no sound tests, signifying that in an active sound field, the percentage of small particles is decreased through agglomeration, resulting in larger particles which are more likely to be cleaned using conventional cleanup devices.

Low frequency agglomeration tests were performed at the 150 Hertz level. Test results showed much higher mass fraction percentages for all micron size ranges compared to the ash prior to agglomeration. A general trend toward better agglomeration was found during tests at high pressures compared to low pressures. However, due to large particle separation in the sample line, only a comparative and not quantative analysis of the results was possible.

Based upon the results of this test program, pulse combustors have been shown to be an acceptable method of providing the acoustic environment for the agglomeration of flyash. Further testing in the high frequency mode is required to determine whether the reduction in the small micron mass fraction with the operating acoustic sound source is truly significant. Additional test hardware improvements and verifications are necessary to reach significant conclusions in the low frequency mode.

1.0

INTRODUCTION

Acoustically enhanced cyclone collectors offer the potential of achieving environmental particulate control standards under pressurized fluidized bed combustion (PFBC) conditions without the need for post turbine particulate control. The objective of this program is to extend acoustic agglomeration technology from the laboratory to the sub-pilot scale. The effects of high intensity sound on the agglomeration of fly ash particles were investigated in a simulated PFBC effluent stream. The test facility consisted of a variable residence time acoustic agglomeration chamber with a vitiated air preheat combustor, an ash injection system utilizing an auger feeder, a natural gas fired pulse combustor sound source, and a two-stage high temperature/high pressure cyclone. Fly ash for these tests was obtained from the TVA (Tennessee Valley Authority) Shawnee Station circulating fluidized bed combustor (CFBC) as well as the Tri State G&T Nucla Power Station CFBC (Colorado) and the Tidd PFBC Demonstration Plant.

The acoustically enhanced cyclone collector was evaluated with two distinct goals in mind: (1) determine the effects of the major operating parameters on acoustic agglomeration efficiency, and (2) optimize the agglomeration system performance for maximum particulate removal efficiency. Data obtained during these tests provided direct information on the effects of sound intensity and frequency, particle residence time, ash loading, and pressure on the enhancement of cyclone collection efficiency with acoustic agglomeration. These data, in conjunction with results from an acoustic agglomeration computer model, are used to evaluate the economic and engineering feasibility of an acoustically enhanced cyclone collector for a full scale pressurized fluidized bed combustor.

The main program objective was to demonstrate, on the subpilot-scale, the effectiveness of an acoustically enhanced cyclone collector under high temperature, high pressure conditions found in coal-fired pressurized fluidized bed combustion combined cycle power generating systems. The data obtained will be used to design an acoustically enhanced cyclone gas cleanup system which would meet the New Source Performance Standards (NSPS) particulate control level with capital and operating costs significantly lower than currently available with conventional cyclones and post turbine particulate control.

2.0

BACKGROUND

In coal-fired pressurized fluidized bed combustor (PFBC) combined-cycle power generation systems, gas turbines are used to recover energy from the high temperature gases exiting the PFBC. Before the gases enter the turbine, most of the fly ash from the coal must be removed by hot gas cleanup devices in order to protect the turbine components from erosion, corrosion, and deposition of the ash. Conventional, high efficiency cyclone systems are capable of removing a sufficient quantity of ash to protect the turbine hardware; however, these systems are not capable of meeting the stringent environmental particulate emissions regulations. A hot gas cleanup system that meets both turbine protection and environmental emissions requirements without post-turbine cleanup devices should also have improved overall system economics compared to a system with conventional cyclones prior to the gas turbine and a baghouse or electrostatic precipitator after the turbine.

Acoustic agglomeration can increase the cyclone collection efficiency by increasing the average particle size of the ash. In this concept, the ash-laden effluent stream from the PFBC is passed through a high intensity sound field prior to entering the cyclone train. The high intensity sound causes the smallest particles to oscillate with the sound waves, while the largest particles travel with the bulk gas flow, unaffected by the sound. Due to the increased motion of the smallest particles, the number of collisions between the small and large ash particles increases. When the ash particles come into close contact, they agglomerate, being held together by molecular forces (Ref. 1). The design and operational simplicity of acoustic agglomeration prior to a conventional cyclone train offers significant economic advantage over other hot gas cleanup methods.

A major goal of this program is to establish whether a full-scale agglomerating cyclone system can meet NSPS particulate emission standards and still provide a 15% reduction in the fixed and operating costs of the cleanup system relative to conventional hardware (conventional cyclones coupled with post-turbine control).

3.0

DISCUSSION

The program was divided into three phases summarized below, covering the test facility design, experimental testing, and commercial assessment.

Phase I - The initial phase of the program consisted of a detailed design of the subpilot-scale acoustic agglomeration test facility and the preparation of an experimental test plan. Due to the high costs and unavailability of operating PFBC's and the need to accurately control the input flow parameters, the test facility was based upon a simulated PFBC effluent stream in which fluidized bed fly ash was injected into a high temperature, high pressure vitiated air stream. High intensity sound was produced within the agglomeration chamber using a natural gas fired pulse combustor.

Phase II - The second phase covered the fabrication and installation of the test hardware and the execution of the acoustic agglomeration tests, including system characterization tests with various pulse combustors supplied by MTCI (Manufacturing and Technology Conversion International, Inc.). The testing phase included detailed parametric tests to identify the dependence of critical operating variables on the agglomeration efficiency, and duration test to assess the durability of the system.

Phase III - The final phase was never performed but was to provide a commercial assessment of the system. An engineering and cost analysis of a full-scale design for an acoustically enhanced cyclone collection system, integrated with a PFBC combined-cycle system, was planned.

3.1 PHASE I - TEST FACILITY DESIGN

The acoustic agglomeration test facility consisted of a vertical, refractory lined agglomeration chamber that had a maximum residence time of approximately 3 seconds. High pressure air (135 psig) was preheated to approximately 1650°F with a natural gas combustor then fly ash was injected into the air stream to simulate PFBC operating conditions. A natural gas fired pulse combustor was used to generate high intensity sound at selected frequencies to enhance acoustic agglomeration of the fine, fly ash particulate. A two-stage high temperature, high pressure cyclone system was used to separate the ash particles from the bulk air flow. A heat exchanger and a sintered metal filter cooled the air and removed particulates for local environmental control. Samples of the fly ash particulate were removed from the gas stream in three locations: near the exit of the agglomeration chamber, between the two cyclones, and after the final cyclone. These samples were analyzed for particle size distribution and mass loading within the gas stream to determine the effects of the high intensity sound and other operating parameters on the agglomeration of the fly ash.

3.1.1 Pulse Combustor

A pulse combustor, supplied by MTCI, typically consists of a flow diode, a combustion chamber, and a resonance tube, or tailpipe. Fuel and air enter the combustion chamber where a glow plug ignites the mixture. As the gas expands, the flow diode permits preferential exiting flow in the direction of the resonance tube with significant momentum (Ref. 2). A vacuum is created in the combustion chamber due to the inertia of the gases in the tailpipe. This inertia permits only a small fraction of exhaust gases to return to the combustion chamber; the balance of the exhaust exits the resonance tube. Since chamber pressure is below inlet pressure, air and fuel are drawn into the chamber where auto ignition takes place. Again, the flow diode constrains reverse flow, and the cycle repeats. Once the first cycle is initiated, operation is self-sustaining.

The rapid pressure oscillations in the combustion chamber generate an intense oscillating flow field which travel the length of the agglomeration chamber. Pulse combustors experience very high mass transfer and heat transfer rates within the combustion zone. While these combustors tend to have very high heat release rates (typically 10 times those of conventional burners), the vigorous mass transfer and high heat transfer within the combustion region result in a more uniform temperature. Therefore, peak temperatures attained are much lower than in the case of conventional systems and results in a significant reduction in the formation of nitrogen oxides. The high heat release rates also require a smaller combustor size for a given firing rate, and a reduction in the residence time required.

The various pulse combustorsconstructed for this program include designs for 1000, 2000, and 3000 Hertz in the high frequency range, 150 and 600 Hertz, in the low frequency range, and a 63 Hertz combustor for ultra-low frequency testing. All pulse combustors were metal lined and water cooled.

3.1.2 Agglomeration Chamber

The acoustic agglomeration chamber was designed for a 200 acfm fixed volumetric air flow rate. The chamber had an internal diameter of 12 inches with a total height of 20 feet, and corresponds to a bulk gas velocity of approximately 4.25 feet/second. The chamber was oriented vertically to offset any potential problems with particles settling within the gas flow passages. The modular steel casing was fabricated from 20 inch pipe with approximately 4 inches of Kaolite 2200 insulating refractory lining the inside walls of the pressure vessel. The insulation limited the gas temperature drop within the agglomeration chamber to less than 30°F while maintaining an outside metal shell temperature of less than 300°F. The Kaolite refractory was painted with a low porosity, high temperature coating (Zyp Coating) in order to reduce the porosity at the surface and minimize acoustic attenuation into the refractory.

The location of the pulse combustor sound source was originally within the agglomeration chamber, but was subsequently moved to the top of the chamber. This allowed easier integration of the various pulse combustors within the system and reduced the flow restrictions through the 12 inch diameter ducting.

A preheat combustor was located at the bottom of the agglomeration chamber during high frequency testing and at the top of the chamber during low frequency testing. This combustor was used to produce the entering PFBC gas stream temperature conditions. The combustor itself consisted of a horizontal refractory lined natural gas duct burner, with attached dilution zone. It was connected to the bottom elbow of the chamber during the high frequency tests and in a straight, horizontal section during the low frequency tests. High pressure air, controlled by a Fisher valve, regulated the air flow into the test chamber at 0.7037 pounds per second. The total flow rate was divided into two approximately equal flow streams; roughly 40% of the air was used for preheat combustion in a 6 inch diameter duct burner and the remainder used for cooling the combustor exit gas to operating temperatures.

Natural gas was supplied to the combustor through a ring manifold cast inside the refractory. The fuel-air mixture was ignited using a Solar Saturn production torch ignitor. Flame stabilization was achieved and recirculation zones established between the central air jet and the walls of the combustor. The gas temperature was reduced to an average of 1650°F by injecting part of the combustion air through a ring dilution manifold at the end of the primary combustion zone. A primary zone/dilution zone arrangement was necessary in the combustor since the overall fuel/air ratio required to achieve a bulk gas temperature of 1650°F is below the lean blowout limit of natural gas.

The agglomeration chamber had three ten inch diameter ports, located axially, through which ash injection took place. These ports were located at distances upstream of the particulate sampling probe, and corresponded to gas residence times in the chamber of 1, 2, and 3 seconds, respectively.

A water cooled particulate sample probe was placed near the flow exit of the agglomeration chamber and was capable of traversing radially from the chamber centerline to the wall to obtain samples for particle size distribution at different radial locations. Samples of the untreated ash fed and of the agglomerated ash collected in the cyclone were to be obtained for particle size distribution.

Flyash was injected through the three ports located along the axial length of the agglomeration chamber. The tubes were uncooled so that the hot main gas flow past the tubes would preheat the flyash prior to its injection into the bulk flow. Each tube had vertical risers on the end to allow the ash to be injected perpendicularly to the bulk gas flow to promote rapid radial mixing.

3.1.3 High Frequency Configuration

The frequency range studied during these tests was 1000 to 3000 Hz. Three pulse combustors were fabricated and tested by MTCI with nominal frequencies of 1000, 2000, and 3000 Hertz. The maximum sound intensity range was dependent upon the turndown achieved by each of the pulse combustors. Other variables controlled during these tests were ash residence time, ash loading, ash particle size, and system pressure. Chamber temperature and ash type wre varied only during the low frequency tests.

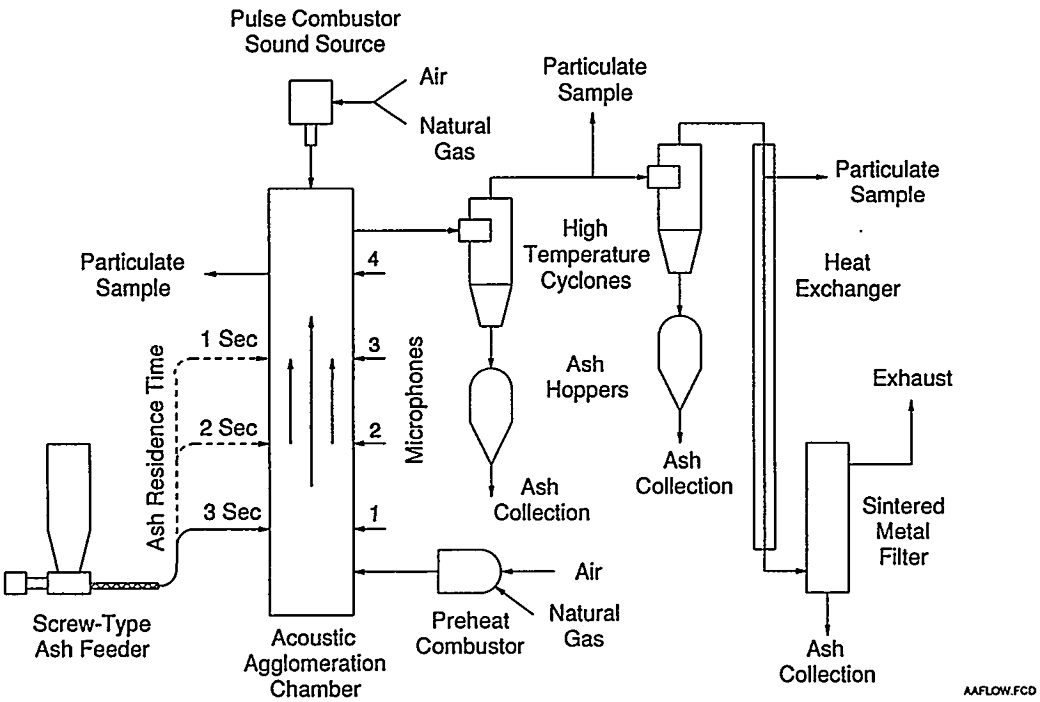


Figure 1. High Frequency Agglomeration Flow Diagram

A flow diagram of the test facility for high frequency agglomeration tests is shown in Figure 1. In this arrangement, air entered the system through the preheat combustor at the bottom of the agglomeration chamber. The bulk flow of the air was in an upward direction. Ash was injected near the bottom of the chamber, and the particle sample was withdrawn from the top of the chamber. The pulse combustor sound source was located at the top of the agglomeration chamber firing downward. This produced a counter-current flow between the ash particulate flow direction and the sound propagation direction. With this configuration, the combined fuel and air flow rate of the high frequency combustors was approximately 15-30% of the total gas flow into the system.

Once the ash laden gas stream reached the top of the agglomeration chamber where the first particulate sample was taken, the exhaust went onto a two-stage high temperature, high pressure, cyclone system. In between the two cyclones, a second particulate sample was withdrawn. A third sample was extracted at the entrance to a heat exchanger, downstream of the final cyclone. These last two samples were collected in Balston filters. After the heat exchanger, the exhaust travelled through a sintered metal filter (SMF), which was the final ash clean-up device prior to the stack. Ash collection was also done in a batch-mode at the exit of the SMF mainly for final ash knockout.

The gas flow rate into the ash sample probe was measured during sampling so that the particulate loading within the gas stream could be calculated. Other measurements obtained during each test included air and fuel flow rate, ash feed rate, chamber gas temperature, pressure, sound intensity and frequency.

Four microphones loctions shown in Figure 1correspond to the 3 potential ash injection ports and the particulate sample port. Signals from the individual microphones were transmitted to a Rockland System Analysis Workstation which performed a Fast Fourier Transform on the data and produced real time frequency and sound pressure level plots for each microphone that was continuously monitored by the operator to insure optimal pulsations.

3.1.4 <u>Low Frequency Configuration</u>

The low frequency combustors studied during this investigation were on the order of 550 Hz (nominal 560 Hz), 150 Hz (nominal 170 Hz), and the ultra-low at 63 Hz (nominal 68 Hz). With the low frequency pulse combustors, the total air and gas flow rate drawn through the pulse combustor increased relative to the bulk flow through the agglomeration chamber. To minimize the variation in air flow between the agglomeration chamber and the cyclones, the test facility was modified. The preheat combustor was moved to the top of the agglomeration chamber and a refractory-lined duct was installed between the bottom of the chamber and the inlet to the first stage cyclone. During testing, it was unnecessary to use the preheat combustor for generating the heat required for PFBC conditions, as the low frequency pulse combustors provided sufficient heat.

Ash was injected near the top of the chamber and the particulate sample withdrawn near the bottom during the low frequency tests. Thus, the bulk flow of the gas was downward, with a co-current flow between the injected ash and the sound waves as illustrated in Figure 2. With this arrangement, additional ducting was required to bring the exhaust back up to the entrance of the two-stage high temperature, high pressure cyclone (see Figure 3). Also, all the chamber and Cyclade™ electrical heaters had to be relocated to the bottom of the chamber along with the associated instrumentation and sample line plumbing. The remainder of the test facility was unchanged.

Dilution air was injected circumferentially around the transition duct from the pulse combustor to the agglomeration chamber to control the temperature of the combustor exhaust entering the chamber. The cooling air injection ports are shown in Figure 4. The flange for the preheat combustor used in the high frequency testing and the ash inlet can also be seen in this figure. The agglomeration chamber remained common to both high and low frequency testing as only the flow direction changed.

3.1.5 <u>Ash Feed System</u>

A oratry disc feeder system was originally planned for this program. However, problems in feeding the fine fly ash were experienced because of an insufficient angle of inclination within the ash hopper and a narrow groove width on the rotary disc. Excellent results were obtained using an existing auger-type feeder, shown in Figure 5 with the ash hopper, in place of the disc feeder. The auger proved successful in feeding the fly ash stably over the range of ash feed rates necessary for the acoustic agglomeration tests. Based upon the volumetric air flow rate through the agglomeration chamber, the flyash feed rate ranged from two to fifty-five pounds per hour and corresponds to particulate loadings from 1-12 grains per standard cubic foot at 200 acfm.

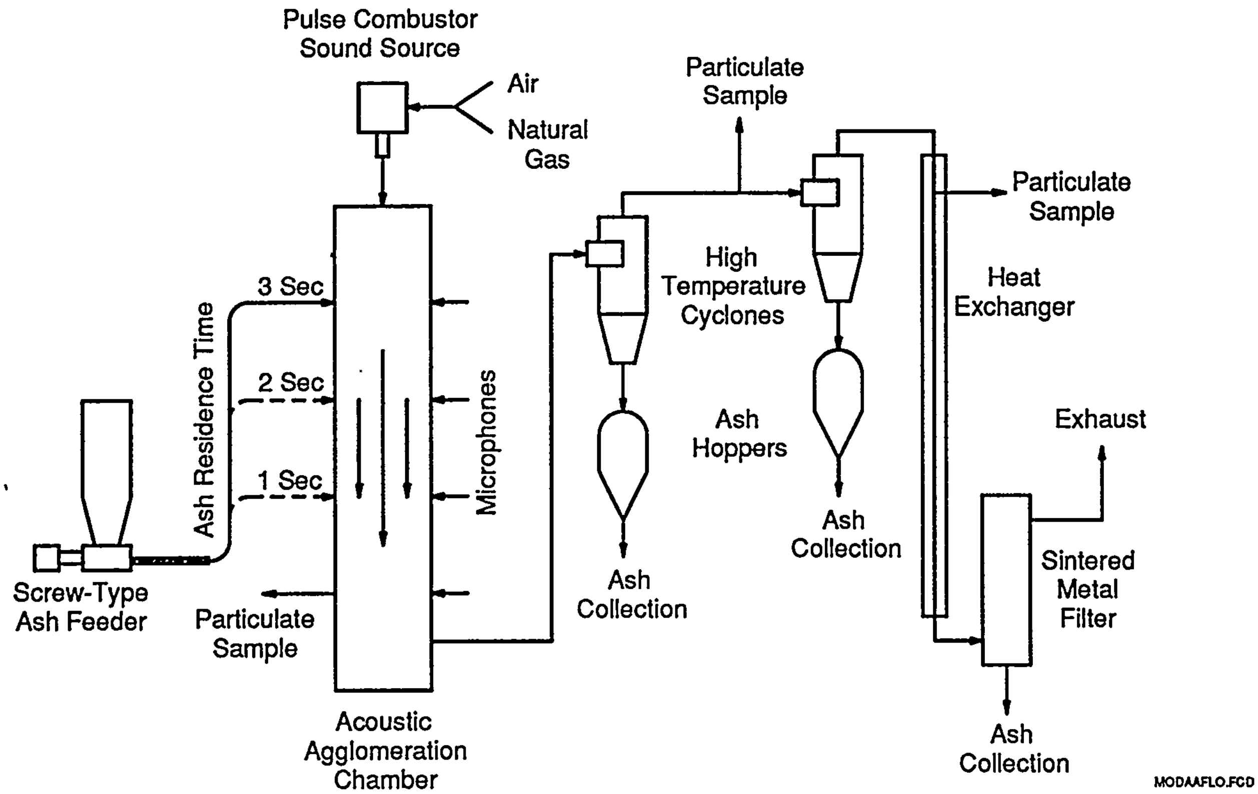
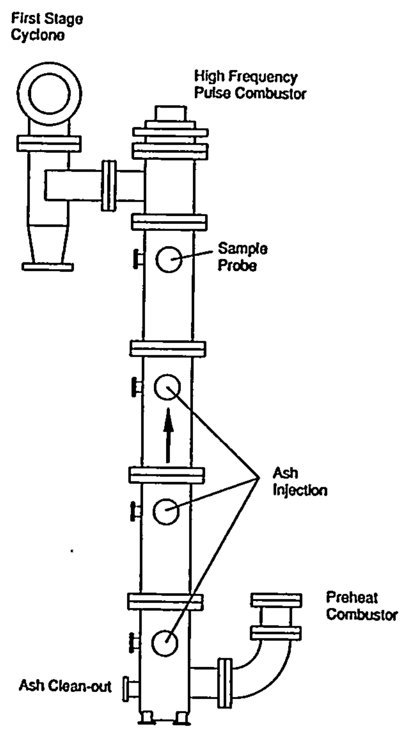
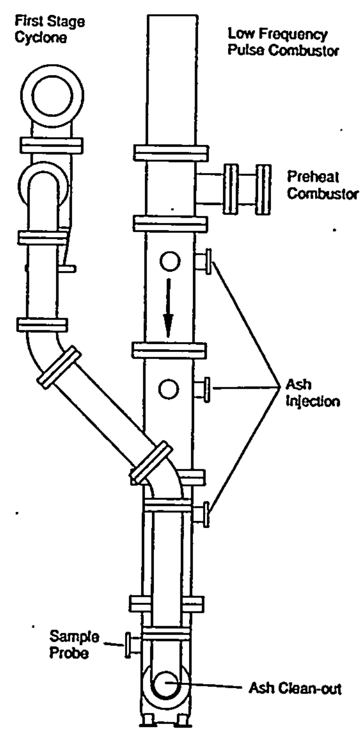


Figure 2. Low Frequency Agglomeration Flow Diagram



High Frequency Configuration.



Low Frequency Configuration.

Figure 3. Hardware Changes From High to Low Frequency Testing

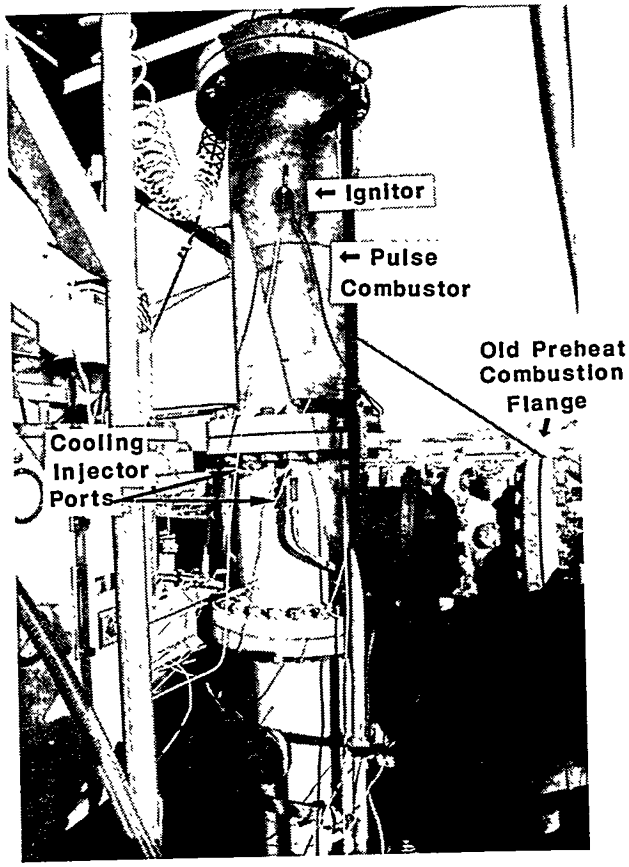


Figure 4. Low Frequency Combustor and Cooling Air Injection Ports

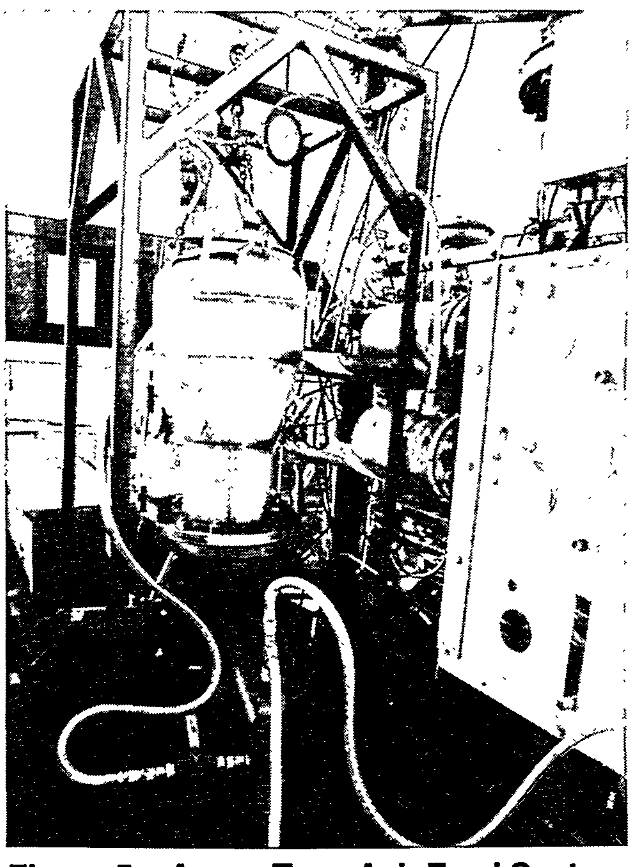


Figure 5. Auger-Type Ash Feed System

The ash storage hopper was an ASME certified unfired pressure vessel capable of with standing the 135 psig pressures seen in the agglomeration chamber. Attached to the hopper was an air operated vibrator to insure a constant flow of ash into the auger as the fine ash particles tended to pack together into a solid mass if left unagitated.

The injection tube inside the agglomeration chamber was fabricated from high temperature resistent Inconel and was uncooled to provide maximum heating of the ash particles prior to injection into the bulk gas stream. The injection tube directed the ash radially into the chamber to provide rapid dispersion of the ash across the chamber diameter.

3.1.6 Ash Characterization

Flyash from the Nucla Power Station Circulating Fluidized Bed in Colorado had originally been identified as the primary source ash for agglomeration tests. However, under direction from Morgantown Energy Technology Center (METC), the order was cancelled and ash from the TVA Shawnee Station Bubbling Bed Pilot Plan was recommended as the replacement. The coal used in that plant was a West Kentucky bituminous with approximately 4% sulfur. The flyash collected in the baghouse contained about 10% carbon, while the ash collected in the transfer bin (waste stream from multicyclone train) contained about 5% carbon. The bulk density of the baghouse ash was approximately 43 pounds per cubic foot and about 75 pounds per cubic foot for the ash collected on the cyclone.

The test plan proposed to use the size distribution of the ash as one of the test variables. One ash size was to have a mean diameter of approximately 5 microns, corresponding to the average ash size collected in a baghouse (classified ash), the other ash size was to be larger, similar to the ash size distribution as it leaves the fluidized bed, but prior of the first set of cyclones (full sized ash).

These two size distributions of ash were obtained from TVA using the following approach. The classified ash was collected directly from the baghouse without modification (some crushing was done if the ash was significantly larger than a 5 micron mass mean). The full sized ash was obtained by uniformly mixing equal quantities (by weight) of the baghouse flyash with the cyclone catch from the transfer bin. The mixing was performed using a rotating drum mixer. Although ash was also obtained from the Tidd and Nucla plants, the ash from TVA was used in all of the high and low frequency agglomeration tests.

The ash used for the low frequency testing was consisted of fifty percent baghouse fly ash and 50% cyclone bottoms char ash by weight, from the TVA Shawnee Station, AFBC. The particle size distribution for each constituent was analyzed by an independent outside laboratory and the results are shown in Figures 6 and 7 for the fly and char ash, respectively. The resulting distribution for the mixture is shown in Figure 8. By making a couple of assumptions, such as (1) the density of the ash samples is uniform versus size, and (2) the densities of both ash types is the same, then the estimated distribution of particles in the unagglomerated ash is shown in Table 1. About twenty percent of the total ash feed into the system has a particle size less than or equal to 8.65 microns. The remainder of the ash (approximately eighty percent) has a particle size greater than 8.65 microns. The normalized compositional analysis of the char and fly ash given in Table 2 is based upon seven different runs of each sample.

Table 1. TVA Ash Mixture Particle Size Distribution (9 microns and below) for 50% Char and 50% Fly Ash

Particle Size Range- Microns	Percent Ash Volume in Size Range	Particle Size Range- Microns	Percent Ash Volume in Size Range
8.65 - 7.75	2.75	3.20 - 2.80	2.00
7.75 - 6.70	2.60	2.80 - 2.40	1.50
6.70 - 5.85	2.40	2.40 - 2.05	0.70
5.85 - 4.95	1.80	2.05 - 1.75	0.55
4.95 - 4.30	1.85	1.75 - 1.50	0.25
4.30 - 3.70	1.95	1.50 - 1.30	0.00
3.70 - 3.20	2.10	1.30 - 0.00	0.05

Table 2. Compositional Analysis of the TVA Char and Fly Ash (50-50% by Weight)

	TVA Char Sample	TVA Fly Ash Sample		TVA Char Sample	TVA Fly Ash Sample
CO_2 %	2.37	5.51	Mg %	0.96	1.33
C %	6.45	10.3	Fe %	4.25	5.52
H %	0.2	0.2	$CaCO_3$ %	5.39	12.5
S %	5.56	5.76	$CaSO_4$ %	23.74	24.5
Ca %	26.61	21.5	CaO %	24.46	12.9

Size Microns	Under	In Band (%)	Size Microns	Under	In Band (%)
118.4	100	0.2	11.1	43.5	4.5
102.1	99.8	0.8	9.6	39	4.7
88.1	99	1.4	8.3	34.3	4.4
76	97.6	2	7.2	29.8	4
65.6	95.6	2.8	6.2	25.8	3.6
56.6	92.8	3.6	5.3	22.2	3.7
48.8	89.2	4.2	4.6	18.5	3.9
42.1	85.1	4.4	4	14.6	4.2
36.3	80.6	4.4	3.4	10.3	4
31.3	76.3	4.3	3	6.3	3
27	72	4.4	2.6	3.4	1.4
23.3	67.6	4.8	2.2	1.9	1.1
20.1	62.7	4.9	1.9	0.8	0.5
17.4	57.8	4.9	1.6	0.3	0
15	52.9	4.8	1.4	0.3	0.1
12.9	48.1	4.6	1.2	0.2	
D(v,0.5) = 13.7 µm D(v,0.1) = 3.4 µm D(3,2) = 7.7 µm			D(v,0.9) = 50.3 µm D(4,3) = 21.1 µm		

Particle Diameters		Volume Percentiles	
D(4,3)	21.11 µm	Dv. 1	3.38 µm
D(4,2)	12.75 µm	Dv. 2	4.87 µm
D(4,1)	7.78 µm	Dv. 3	7.20 µm
D(3,2)	7.71 µm	Dv. 5	13.71 µm
D(3,1)	4.72 µm		
D(3,0)	3.21 µm	Dv. 6	18.54 µm
		Dv. 7	25.21 µm
D(2,1)	2.89 µm	Dv. 8	35.55 µm
D(2,0)	2.07 µm	Dv. 9	50.28 µm
D(1,0)	1.48 µm	Span	3.42
		UNIF.	17.57

Distribution	Mean	Stan. Dev.	Skew.
Volume	21.11	20.28	1.54
Surface	7.71	10.16	3.58
Length	2.89	3.73	6.26
Number	1.43	1.45	6.78

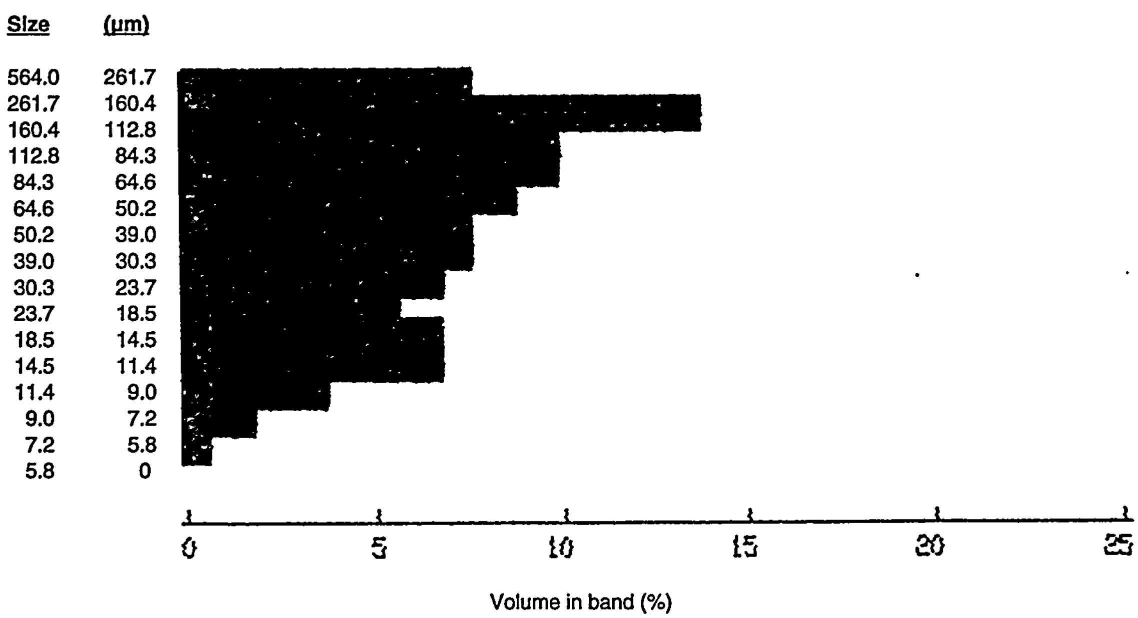


Figure 6. Particle Size Analysis for TVA Fly Ash

Size Microns	Under	In Band (%)	Size Microns	Under	In Band (%)
564.0	100.0	0.1	53.1	44.0	5.7
487.0	99.9	0.1	45.8	38.2	5.5
420.0	99.8	0.1	39.5	32.7	5.0
362.0	99.7	0.1	34.1	27.7	4.5
312.0	99.7	0.0	29.4	23.2	4.1
270.0	99.7	1.6	25.4	19.1	3.7
233.0	98.0	4.7	21.9	15.4	3.2
201.0	93.3	6.1	18.9	12.2	2.7
173.0	87.2	5.5	16.3	9.53	2.1
149.0	81.7	4.4	14.1	7.4	1.7
129.0	77.3	4.7	12.1	5.7	1.0
111.0	72.5	5.5	10.5	4.7	1.0
95.9	67.1	5.9	9.0	3.7	0.8
82.7	61.1	5.8	7.8	2.9	0.8
71.4	55.4	5.7	6.7	2.1	0.8
61.6	49.7	5.7	5.8	1.3	

D(v,0.5) = 62.1 µm D(v,0.9) = 184.9 µm
D(v,0.1) = 16.7 µm D(4,3) = 83.8 µm
D(3,2) = 31.7 µm

Particle Diameters		Volume Percentiles	
D(4,3)	83.82 µm	Dv. 1	16.74 µm
D(4,2)	51.54 µm	Dv. 2	26.18 µm
D(4,1)	27.12 µm	Dv. 3	36.49 µm
D(4,0)	16.00 µm	Dv. 4	47.86 µm
D(3,2)	31.69 µm	Dv. 5	62.07 µm
D(3,1)	15.43 µm		
D(3,0)	9.22 µm	Dv. 6	80.24 µm
		Dv. 7	103.34 µm
D(2,1)	7.51 µm	Dv. 8	141.02 µm
D(2,0)	4.97 µm	Dv. 9	184.89 µm
D(1,0)	3.29 µm	Span	2.71
		UNIF.	45.75

Distribution	Mean	Stan. Dev.	Skew.
Volume	83.82	69.20	1.35
Surface	31.69	40.65	2.76
Length	7.51	13.48	6.31
Number	3.29	3.72	11.81

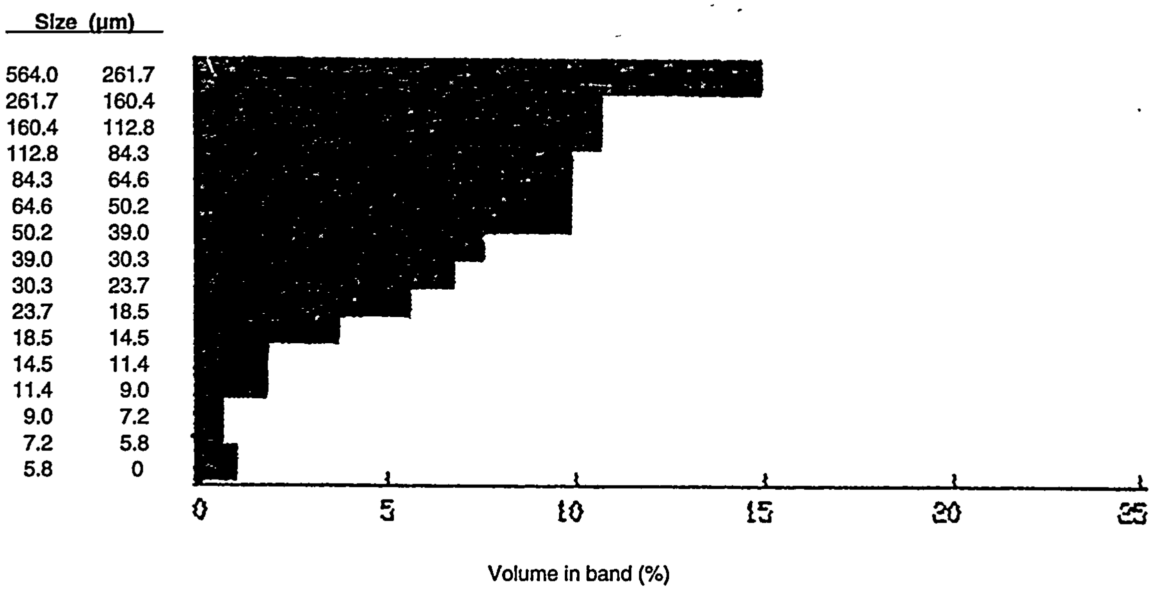


Figure 7. Particle Size Analysis Results for TVA Char Ash

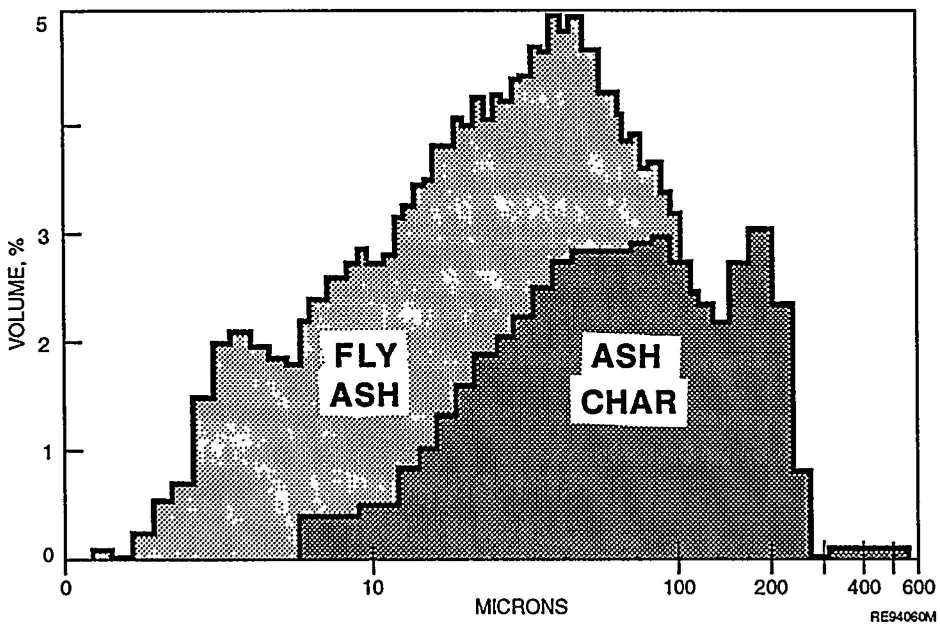


Figure 8. Volume/Size Distribution of 50% TVA Fly and 50% TVA Char Ash

3.1.7 Particulate Sampling

Fly ash particulates were removed from the flowing gas stream, through three water cooled sample probes located within the agglomeration chamber, between the two cyclones and the other after the final cyclone. After the ash sample was removed from the gas stream, it was collected in either an Andersen Cyclade™ cascade sampler or a Balston Filter. The sample collected from within the agglomeration chamber was passed to the Cyclade™, while the other two went to the Balston Filters (see Figures 1 and 2).

An isokinetic sample probe was designed to provide a 300°F gas stream to the Andersen Cyclade™, at a flow rate of 0.5 acfm. The probe was water cooled (except for the probe entrance which was uncooled and fabricated from Inconel) and had an overall length of 4 feet. This length was sufficient to cool the exiting chamber gas from 1650°F to approximately 300°F prior to and entering the Andersen sampler and particulate classification. Thermocouples were mounted within the probe at the entrance and the exit to monitor the gas temperature so that isokinetic sampling would be achieved. The mass flow rate was adjusted by down stream valves to maintain a gas velocity into the probe of 4.25 feet/second.

The seven stage Cyclade™ (Model number 286-2, Figure 9) is constructed of Stainless Steel 316 and consists of 6 small cyclones in series followed by a backup filter that segregates the ash into discrete size classes. The sampler has five equally spaced particle size cuts (D_{50}) on a logarithmic scale within the range of 1-15 microns. The nominal flowrate is one actual cubic foot per minute but acceptable flows range from 0.2 to 1.25 cubic feet per minute. The first cyclone separates all particle sizes larger than 15 microns from the gas stream which amounted to about 80-85 percent of the total ash injected into the system. The unit is compact enough to fit through a 4 inch diameter port. After each test run, each of the individual cyclones in the Cyclade™ is disassembled and

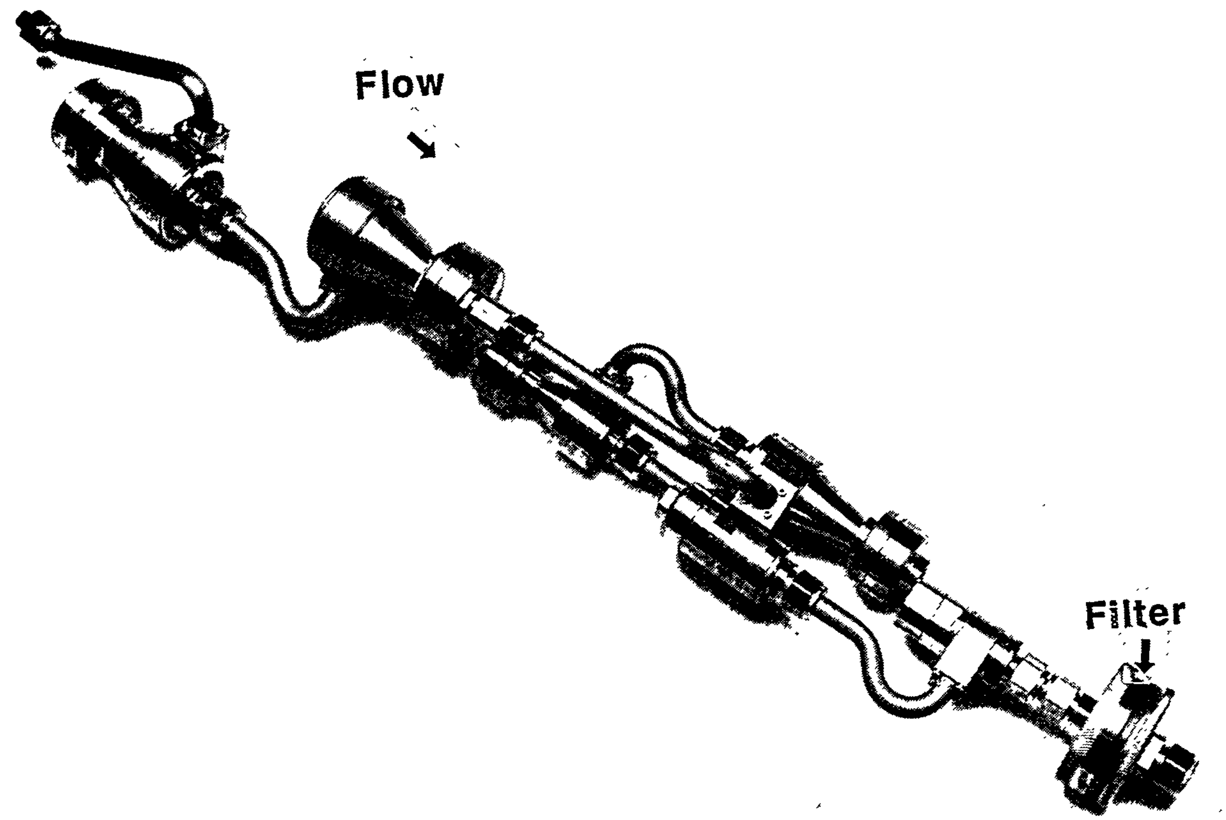


Figure 9. Seven Stage Cyclade (Model Number 286-2)

the mass of the ash collected weighed using a Fisher Scientific Electronic Analytical balance (Model XA-200). This balance has the capability of measuring samples to the nearest tenth of a milligram with a repeatability of ± 0.1 milligram.

The principle of operation of a cyclone particle size-fractionating sampler is shown in Figure 10. Particles suspended in the stack gas are sampled isokinetically through the sampling nozzle. Gas enters the cyclone body tangentially and creates a vortex flow pattern. The maximum temperature of the sampler is limited by the Viton "O" rings in the filter holder which should be maintained below 500°F. Centrifugal forces cause particles larger than the cut-point of the cyclone to migrate radially outward to the wall of the cyclone body and collection cup where they are deposited. Extremely large samples can be collected because as deposits on the inner wall built up, they move downstream into the collection cup where they are retained. Since the centrifugal forces are greater than the gravitational forces, the cyclone operates in any orientation. Particles smaller than the cut-point pass through the first cyclone entering the second cyclone, which has smaller dimensions. This creates a stronger vortex pattern, and smaller particles are collected from the gas stream and so on for each successive cyclone stage. The back-up filter collects all particles smaller than the cut-point of the last cyclone in the series.

Based on experimental data from the manufacturer, the following equations were used for the each of the six cyclone stages in the Cyclade™ to determine the particle size cutoff points:

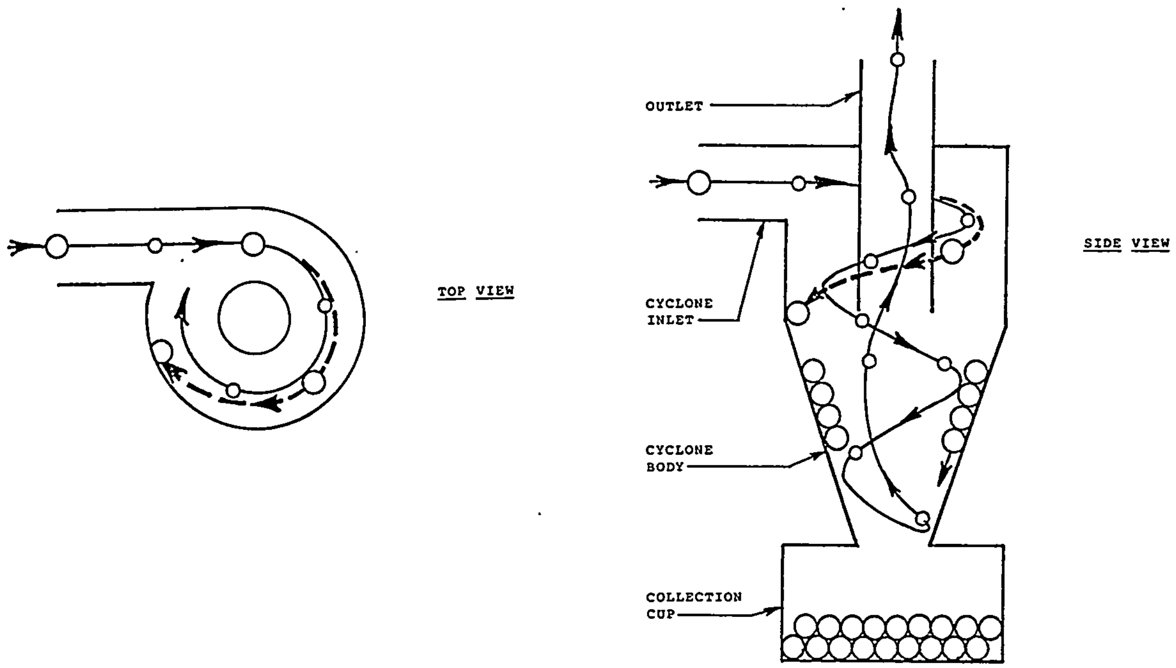


Figure 10. Principles of Cyclade Operation

Cyclone stage 9	$D_{50} = (0.091\mu - 10.136)\ Q^{-0.579}$
Cyclone stage 1	$D_{50} = (0.040\mu - 1.9)\ Q^{-0.55}$
Cyclone stage 2	$D_{50} = (0.025\mu - 2.4)\ Q^{-0.78}$
Cyclone stage 3	$D_{50} = (0.024\mu - 3.09)\ Q^{-0.80}$
Cyclone stage 4	$D_{50} = (0.0084\mu - 0.907)\ Q^{-1.02}$
Cyclone stage 5	$D_{50} = (0.0031\mu - 0.152)\ Q^{-1.09}$

where:

D_{50} = diameter of a particle having a 50 percent probability of collection, microns
μ = stack gas viscosity at stack temperature at the inlet of the Cyclade™ system, 10^{-6} poise (micropoise)
Q = sampling flow rate at actual stack temperature and pressure at the inlet of the Cylclade system, ft^3/min

For the low frequency testing, the flowrate (Q) was maintained constant throughout and the viscosity varied between the high and low pressure testing. The average cutoff points for each Cyclade stage for the high pressure (135 psig) tests were:

Stage 9 - 14 microns	Stage 3 - 3.6 microns
Stage 1 - 10 microns	Stage 4 - 1.8 microns
Stage 2 - 5.2 microns	Stage 5 - 1.2 microns

And for the low pressure (35 psig) testing the corresponding cutoff points averaged:

Stage 9 - 12.2 microns	Stage 3 - 3.1 microns
Stage 1 - 9.0 microns	Stage 4 - 1.6 microns
Stage 2 - 4.5 microns	Stage 5 - 1.0 microns

The Balston Filters were used to determine only the total mass loading with in the gas stream and not particle sizing. The Balston Microfibre Filter Tube had a 99.99% efficiency for all particles greater than 0.1 microns.

Excessive cooling of the particle laden gas sample occurred during operation of the sample probes such that water condensed inside the sample tubing between the water cooled sample probe and the pressurized canister holding the Cyclade™ and Balston Filters. This caused the ash to form a paste along the tubing walls, preventing it from flowing into the filters or Cyclade™. Electrical heaters were added to maintain the temperature of the sample gasses above the water dew point temperature.

The two Balston filters, collecting particulates after each of the cyclone separators, are shown above the Cyclade™ collection canister in Figure 11. This was the configuration during the high frequency tests as the Cyclade™ was moved to the bottom of the chamber during the low frequency tests. Not seen behind the control panel are the electrically heated sample lines from the flow stream taps to the canisters to prevent water condensation. Each of the canisters was also electrically heated and heavily insulated to prevent water condensation.

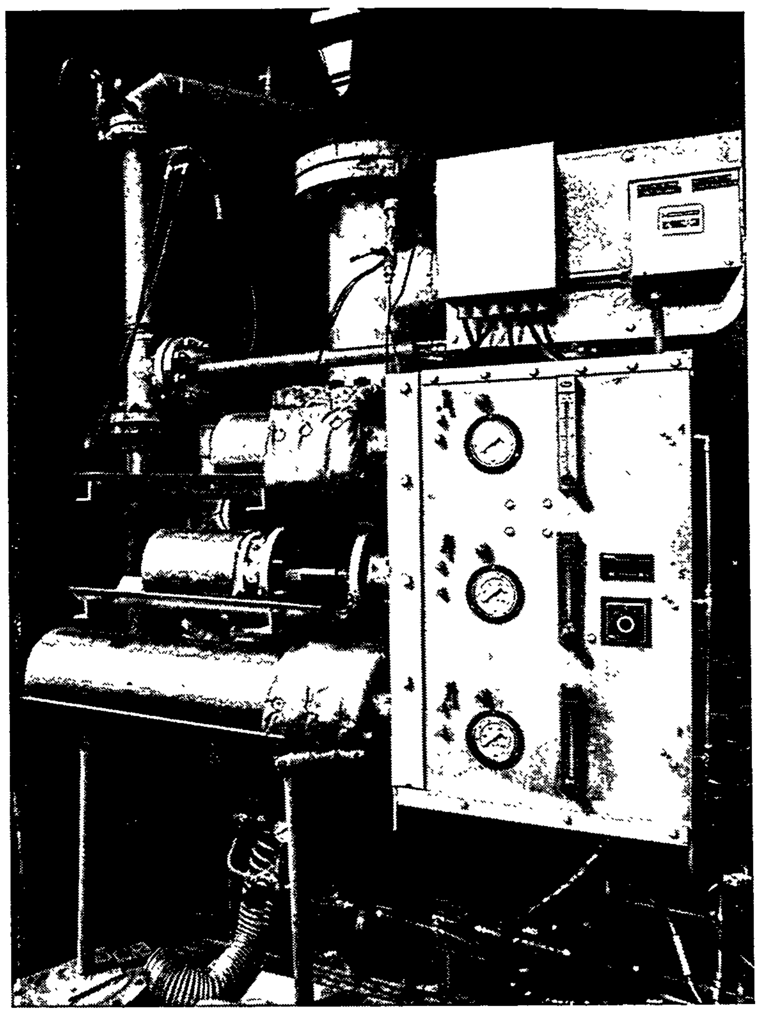


Figure 11. Particulate Sampling Collection Canisters

3.1.8 Ash Collection

The ash hoppers below the high temperature cyclones (Figure 12) were originally designed as water cooled vessels with knife gate valves at the top and bottom of the hopper. Their function is to allow ash removal from the cyclones without shutting down the test. The water cooling caused water to condense within the hopper and an insufficient angle of inclination on the hopper allowed bridging to occur above the knife gate valves, thus preventing the hoppers from emptying the ash completely when the gate valves were opened. These hoppers were redesigned with non-water cooled walls and a steeper angle of inclination at the exit. The top knife gate valves were removed during these tests to simplify the system but would have been reinstalled prior to long term durability testing.

3.2 PHASE II - SYSTEM DEVELOPMENT

The system development phase of the program covers the fabrication and installation of the test hardware and the initial acoustic agglomeration tests, including system characterization tests with various pulse combustors supplied by MTCI. The tests included detailed parametric tests to identify the dependence of critical operating variables on the agglomeration efficiency that were divided into high and low frequency.

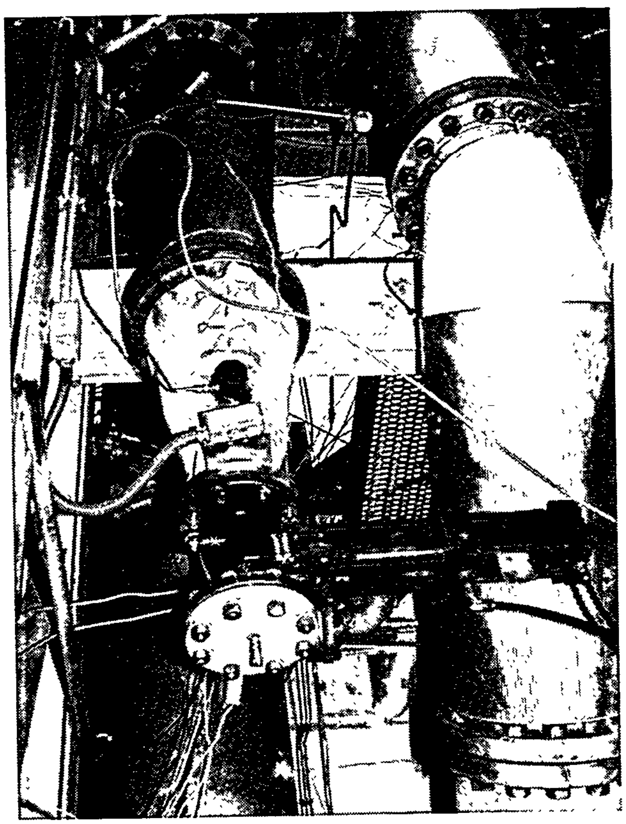


Figure 12. No.1 High Temperature Cyclone with Ash Hopper

3.2.1 Test Plan

The acoustically enhanced cyclone collector was evaluated with two distinct goals in mind: (1) determine the effects of the major operating parameters on acoustic agglomeration efficiency, and (2) optimize the agglomeration system performance for maximum particulate removal efficiency. During the tests, ash samples were collected from the bulk gas stream at the exit of the agglomeration chamber, between the two cyclones, and also from the discharge pipe of the final cyclone. The main dependent variables of interest were the mass mean particle size and size distribution of the ash before and after the agglomeration process, and the cyclone collection efficiency of the unagglomerated and agglomerated particulate streams.

The acoustic agglomeration tests were divided into two main groups, high and low frequency. Six independent variables were originally identified for parametric testing. These variables were: (1) sound frequency, (2) sound intensity, (3) ash residence time within the agglomeration chamber, (4) ash loading in the bulk gas stream, (5) system operating pressure, (6) agglomeration chamber temperature. Only one ash type was used during the initial screening tests.

The test matrix which were later modified, was developed using a statistical experimental design approach. First, a two-level fractional factorial design was used to obtain basic information about each independent test variable. Next, a three-level response surface design was used to determine optimum operation conditions.

The initial testing of the high frequency pulse combustors had shown that the sound intensity of the pulse combustor cannot be independently controlled. When the pulse combustor became tuned-in, the sound intensity within the chamber could only be varied by a few dB by changing the pulse combustor firing rate. Therefore, the maximum achievable sound intensity for the combustor was used in all testing and not considered a variable.

Changes in system pressure were not expected to show a significant effect on the overall agglomeration efficiency of the fly ash. The operation of the test facility at low pressures was more difficult than at higher pressures since all of the control systems were designed to operate optimally at the full system pressure of 135 psig. At 35 psig, longer preheat times were required to heat and maintain the agglomeration chamber walls to the desired temperatures. In order to facilitate the testing, system pressure was not varied during the component screening tests. It was, instead, varied only at the optimal conditions of the other independent variables.

The statistical experimental design planned for the detailed parametric tests was changed to allow for a more complete coverage of the independent variable operating ranges. Instead of using a two-level fractional factorial design to obtain basic information on each of the test variables followed by a three-level Box-Behnken design used to determine the optimum operating conditions, a two level full factorial design was used on the key independent variables. The four variables expected to have the greatest effects on agglomeration efficiency are the sound frequency, ash residence time, ash loading, and ash size distribution. The three remaining independent variables, system pressure, system temperature, and ash type would be studied only at the optimum conditions of the first four variables. These changes were required because of the operational complexity of the test facility and the length of time required to perform each test.

The test plan required that ash collected in the cyclone ash hoppers and the sintered metal filter would be removed and weighed after each test. During the test facility shakedown and the initial acoustic agglomeration tests, poor mass balance closure on the ash flow rates were obtained because of an inability to quantitatively remove the ash from the cyclone hoppers and the sintered metal filter vessel. To alleviate this problem, a large element Balston filter system was installed and placed in the Cyclone™ exhaust line in parallel with the sintered metal filter. During each test, the total flow from the cyclones was diverted from the sintered metal filter through the new Balston filter system for a short time period in order to collect a quantitative sample of the ash exiting the cyclones over a know time period. The ash hoppers and the sintered metal filter were only emptied at the end of each test day instead of with every sample collected.

At each test condition, the system was set at the design conditions for pressure, temperature and ash loading, with the pulse combustor operating at the maximum achievable sound level intensity, and ash samples were withdrawn through the sampling probe. The Cyclade™ and Balston filters were then isolated from the system pressure, removed , and replaced with clean systems. The pulse combustor was then de-tuned so as to produce minimal acoustic energy and a "no-sound" set of ash samples was collected at the same basic operating conditions. By not emptying the ash hoppers after each sample conditions, the sample time required to collect a "sound" and "no-sound" sample at a fixed test condition was decreased from 12 to 6 hours. This was performed under high frequency conditions.

Table 3 shows the planned set points for the six independent variables tested during the two-level fractional factorial tests for high frequency testing. Test conditions were maintained as close as possible to the set points to minimize the errors in the data analysis. The only differences in the operating conditions between the micronized and full-size ash tests (besides the ash size) was the ash loading in the bulk gas stream. A low loading was to be used with the micronized ash to simulate a pre-cleaning cyclone after the PFBC prior to the agglomeration chamber and a high loading with the full-sized ash would simulate the entire particulate effluent from the PFBC.

Table 4 shows the set points for the four independent variables tested during the low frequency two-level full factorial tests and Table 5 lists the tests performed. Test conditions were maintained as close as possible to the set points to minimize the errors in the data analysis. The low frequency acoustic agglomeration test sequence closely parallels the testing performed at high frequency.

Table 3. High Frequency Agglomeration Set Points

Variable		Set Points	
		Low	High
Micronized Ash	Sound Frequency (Hz)	1000	3000
	Sound Intensity (dB)*	140	165
	Ash Residence Time (s)	1	3
	System Pressure (psia)	50	150
	Ash Loading (gr/scf)	1	3
Full-Sized Ash	Sound Frequency (Hz)	1000	3000
	Sound Intensity (dB)*	140	165
	Ash Residence Time (s)	1	3
	System Pressure (psia)	50	150
	Ash Loading (gr/scf)	6	12
* Intensity set point dependent upon achievable range.			

Table 4. Low Frequency Agglomeration Set Points

Description		Test Plan	
		Lo SP	Hi SP
Variable Conditions	Ash Residence Time (s)	1	3
	Ash Loading (gr/scf)	6	12
Conditions at Optimal Settings	System Pressure (psig)	35	135
	System Temperature (F)	1600	2000
	Ash Type	Tidd	Nucla

Table 5. Test Plan for of Low Frequency (170 Hz) Testing

Test	LF-1	LF-2	LF-3	LF-4	LF-5	LF-6	LF-7	LF-8
Ash Residence Time (s)	3	3	3	3	3	3	3	3
Ash Loading (gr/scf)	6	12	6	12	6	12	6	12
System Pressure (psig)	35	35	135	135	35	35	135	135
System Temperature (F)	1600	1600	1600	1600	1600	1600	1600	1600
Ash Type	TVA	TVA	TVA	TVA	Nucla	Nucla	Nucla	Nucla
Note: TVA is a mixture of 50% Char ash and 50% fly ash (by weight).								

Following these tests, a third ultra low frequency combustor was to be tested with a maximum sound pressure level developed at 63 Hz. Initial testing was to be similar to the low pressure tests (Table 4). This combustor was built and delivered but never tested.

3.2.2 High Frequency Testing

The high frequency agglomeration tests (1000-3000 Hz) were performed with ash feeding only at the 1000 Hz level. System characterization and injector optimization tests were completed with the 2000 Hz and 3000 Hz combustors. System evaluations were completed with several ash injections tests performed. Based upon a technical directive from METC, a shift to low frequency work resulted and hardware modifications were incorporated. This shift was based upon test results not obtained under this contract and indicated that a higher agglomeration occurred at low frequency, approximately 100-200 Hz, as opposed to higher frequencies.

3.2.2.1 High Frequency Pulse Combustor Characterization

The high frequency pulse combustor sound sources were fabricated and tested by MTCI. Modifications to the fuel/air injectors were made by MTCI to provide easier ignition and eliminate the potential of the flame to propagate back into the injector.

Pulse combustor testing began with the 1000 Hz Schmidt tube type combustor. The single burner from MTCI is shown in Figure 13. Air and natural gas fuel were ignited at the tip of the injector shown. Once this sound source had been characterized, the 2000 Hz and 3000 Hz (Figure 14) T-burners were tested.

The 1000 Hz pulse combustor was capable of producing sound pressure levels (SPL) (integrated from 0-20,000 Hz) as high as 165 dB at approximately 1170 Hz. The sound pressure level of the fundamental frequency was approximately 6-10 dB lower than the integrated value. One of the planned test variables for the agglomeration tests was to vary the SPL over a range of 145 to 165 dB. The stable operating envelope of the pulse combustor did not allow this wide of a range in SPL output. Reducing the fuel input to the combustor by half only reduced the SPL within the agglomeration chamber by approximately 6 dB. Therefore, sound intensity was not used as an independent variable in any of the agglomeration tests.

The SPL was nearly constant down the length of the agglomeration chamber with only a 2 to 5 dB attenuation measured during the initial characterization tests. The 2000 and 3000 Hz T-burners did not achieve high intensity pulsations in this test facility and new fuel injectors were fabricated to use with these combustors.

Typical sound pressure level data is shown in Figure 15 for microphones 1-4 for the (a) 1000 Hz combustor and (b) 3000 Hz combustor. Microphones were numbered 1-4 beginning at the entrance of the agglomeration chamber. The 1000 Hz Schmidt tube achieved the goal of 160 dB in the agglomeration chamber. Both the 2000 and 3000 Hz combustors were unable to achieve sufficient acoustic intensity. The noise in the frequency spectra below approximately 300 Hz was due to flow and combustion noise produced by the preheat combustor of the agglomeration chamber (note, the preheat combustor was not fired during which sound pressure level data for the T-burners was taken).

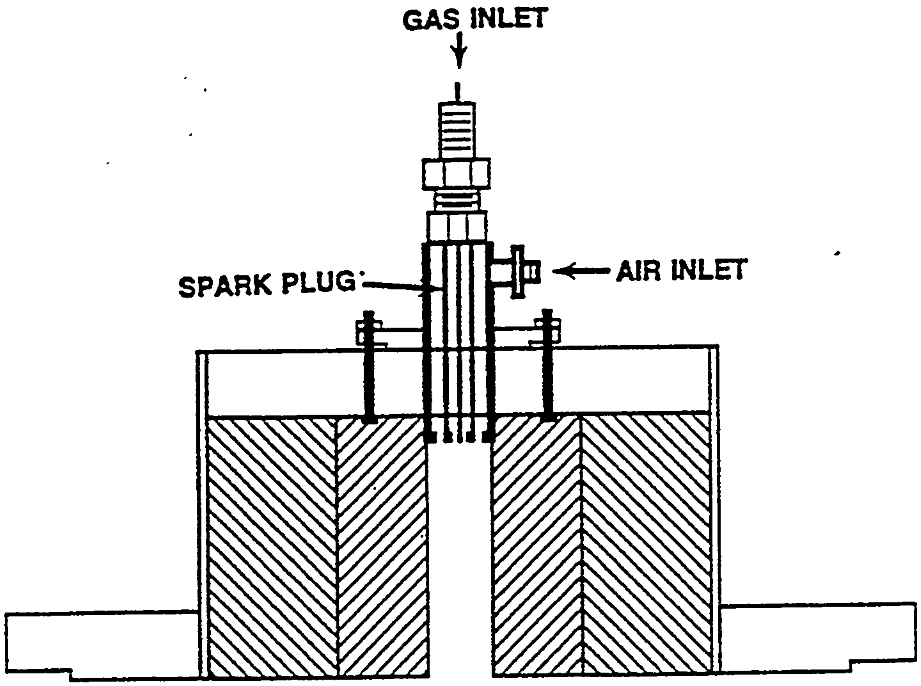


Figure 13. 1000 Hz Pulse Generator - Schmidt Tube Type Combustor

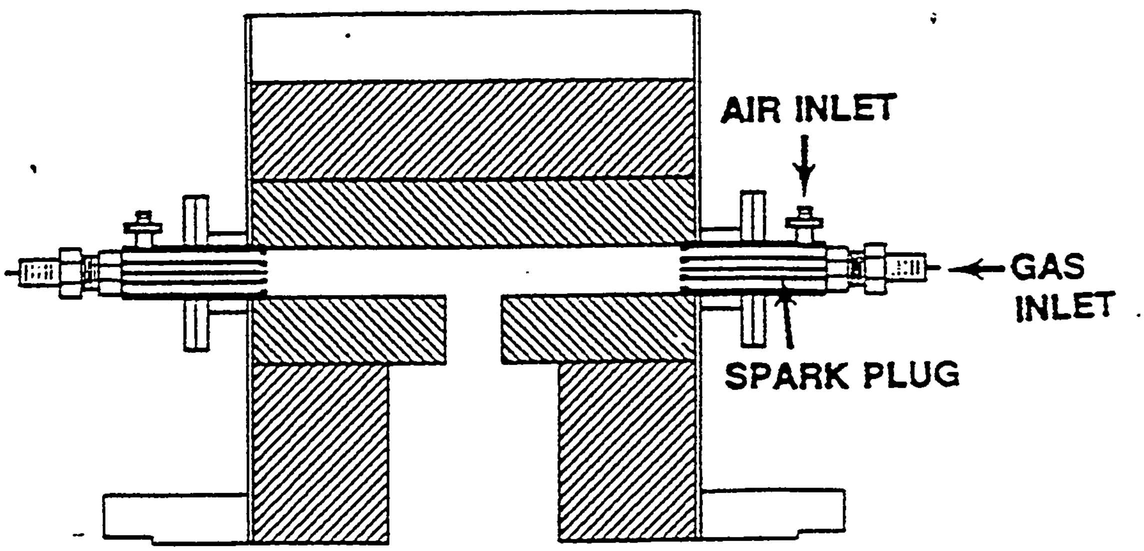


Figure 14. 3000 Hz Pulse Generator T-Burner

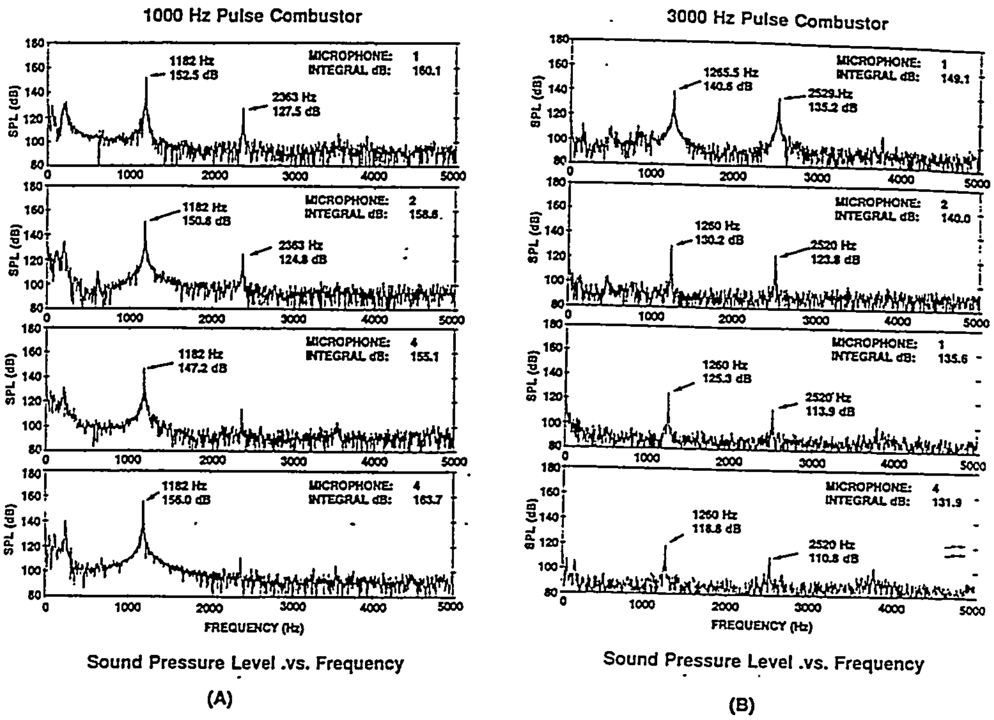


Figure 15. Sound Pressure Level Data For 1000 and 3000 Hz Pulse Combustors From Microphones 1-4.

Pulse combustor performance was not influenced significantly by firing rate or pressure over the operating ranges tested in this facility. Increasing and decreasing both parameters had no significant effect on the pulsations. With the existing facility, there was no control over the sound intensity of the pulse combustors and the frequency could only be altered by changing pulse combustors.

3.2.2.2 Test Results

During the many tests that were performed in the high frequency configuration, few resulted in agglomeration data. The majority of the tests centered around debugging the operation, pulse combustor, and ash feed system. The major problems centered around the cooling water system and the pulse combustor injector.

Water pump problems resulted in an insufficient amount of cooling water entering the rig that caused unexpected shutdowns. These problems disappeared with the installation of a higher pressure and flow water pump.

The pulse combustor fuel injector tube burned up shortly after light-off of the pulse combustor during several tests. Material modifications were made as well as resizing of the main injector holes. Eight injectors were fabricated; one at 0.0625", three at 0.0781" (a-c), and four at 0.0938" (a-d). Figure 16 illustrates the modification made to the injectors. These changes were made to eliminate the weld cracking problem of the previous design and to provide easier ignition of the pulse combustor.

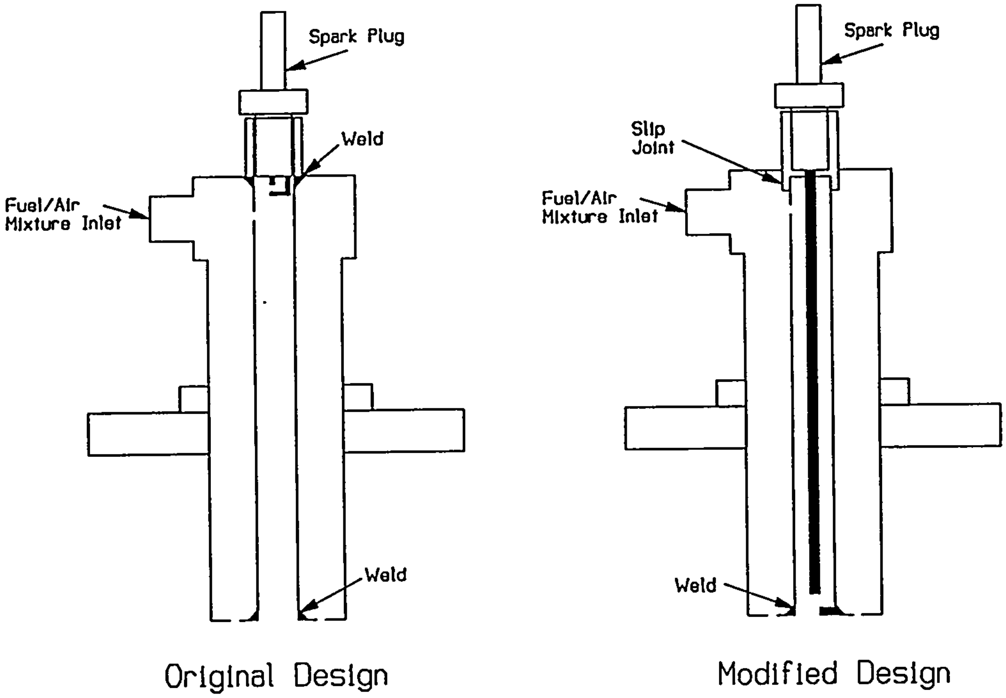


Figure 16. Pulse Combustor Fuel Injector Modifications

Tests 22 and 23 were performed with one of the three fuel injectors with 0.0781" ports. In both tests, the pulse combustor lit easily after the agglomeration chamber was preheated and fine tuning of the pulse combustor was achieved within approximately 30 minutes. No microphone data was collected in Test 22 due to problems with the wiring for the microphone data acquisition system. Test 23 was a repeat of the operating conditions used in Test 22. Acoustic data was collected only from the microphone at the top of the agglomeration chamber during this test. The system operating conditions are presented in Table 6. Test 24 was performed with one of the three fuel injectors with 0.0938" ports. The system operating conditions (agglomeration chamber pressure, temperature and flow rate) were maintained the same as in the previous two tests. This fuel injector also provided easy ignition and stable operation. Data from all four microphones were collected during this test; however, the top microphone data was lost because of a loose connection in the data acquisition system. The data from the bottom microphone (#4) showed significantly lower sound pressure levels than that of microphones 2 and 3. Upon inspection of the mounting system, a large cake of ash was found blocking the port of microphone #4.

Tests 23 and 24 were performed to determine the operating envelope of the 1000 Hz pulse combustor. The fuel and air inputs to the pulse combustor were varied over a wide range while maintaining the pulse combustor in a tuned mode. Figures 17 and 18 show the effect of the pulse combustor firing rate on the integrated sound pressure level from 0 to 10,000 Hz and on the frequency of the maximum peak produced. (The lines on these figures represent smoothed data points only and no statistical significance should be attributed to them. They are shown only to aid in comparing the data.) The combustor firing

Table 6. Typical Acoustic Agglomerator Data Point Output (Test 23, Data Point 18)

Date: May 14, 1991
Time: 13:06:57
Test Number: 23
Data Point: 18

MEASURED DATA

Measured Temperature Data (Deg. F)

4690.0	78.0	78.0	83.0	76.0	574.0	109.0	497.0	73.0	2231.0
88.0	75.0	122.0	83.0	523.0	210.0	221.0	74.0	70.0	70.0
1731.0	1504.0	1529.0	1506.0	1311.0	191.0	1181.0	169.0	1211.0	172.0
1056.0	205.0	1607.0	1612.0	1627.0	1866.0	1979.0	4688.0	309.0	4689.0
335.0	182.0	171.0	76.0	78.0	77.0	1424.0	1401.0	1014.0	93.0
4691.0	4679.0	4691.0	105.0	123.0	103.0				

Measured Pressure Transducer Data (psig/d)

91.7	93.3	-0.1	94.2	99.9	8.350	76.1	8.010	88.8

Measured Flow Meter Data (acfm)

0.223	2.304	0.000	1.950

Measured Load Cell Data (lb)

0.0

CALCULATED VALUES

Preheat Combustor Air 0.4328 pps

Preheat Combustor Fuel 0.0122 pps
2.3040 acfm
(Fuel/Air 0.028) 0.8968 MMBtu/hr

Pulse Combustor Air 0.0176 pps
1.9500 acfm

Pulse Combustor Fuel 0.0012 pps
0.2230 acfm
0.0855 MMBtu/hr

Chamber Gas Flow Rate 193.43 acfm
Ash Residence Time 3.025 sec

Feeder Air 0.0000 pps
0.0000 acfm

Ash Feeder Speed 0.000 vdc

Feed Rate (Vdc Calib) 0.000 pph
Feed Rate (Load Cell) 0.000 pph

Total Ash Fed 0.0 lb

Probe	Set Press	Elapsed time	ACFM
1	65.4	0: 0	0.362
2	68.5	0: 0	0.379
3	59.8	0: 0	0.339

	LC	Tach	
Ash Loading	0	0	ppmw
	0.00	0.00	gr/acf
	0.00	0.00	gr/acf
	0.00	0.00	g/m3

Gas Mass Balance Closure 1.03 %
Exhaust Air Flow 0.4799 pps
Pulse Combustor Gas/Total Gas 16.30 %
Pulse Combustor Fuel/Total Fuel 8.71 %
Total Fuel Used 1386 scf (1 atm, 60 F)

Sample System Heaters	1	2	3	4	5	6
	282	272	285	283	288	287

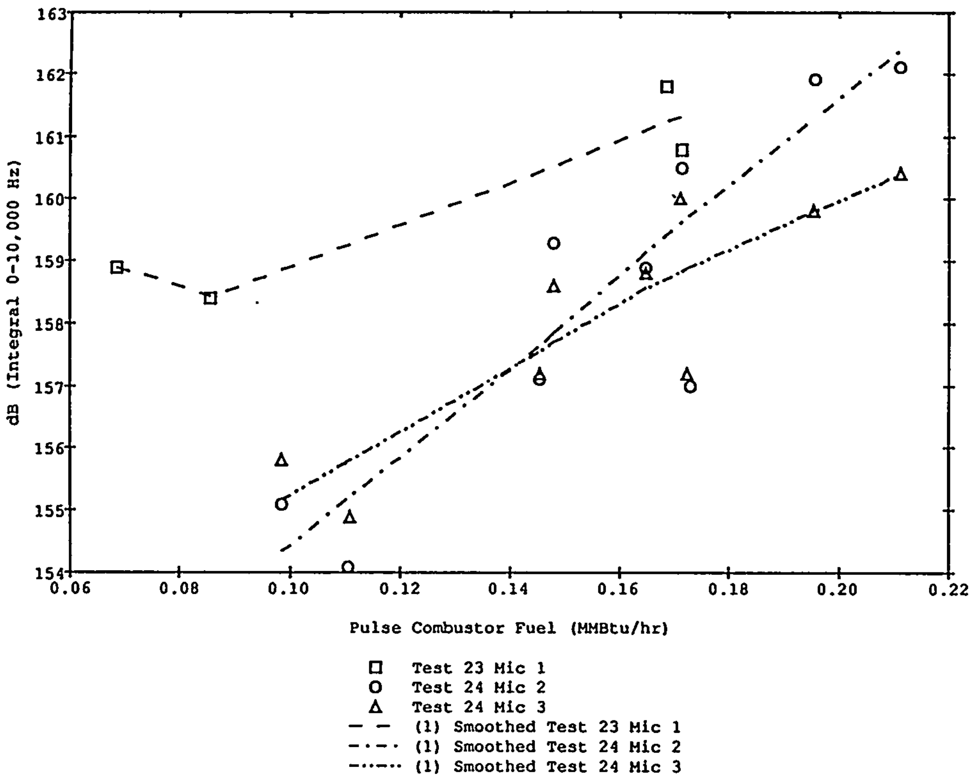


Figure 17. Effect of Pulse Combustor Firing Rate on Sound Intensity

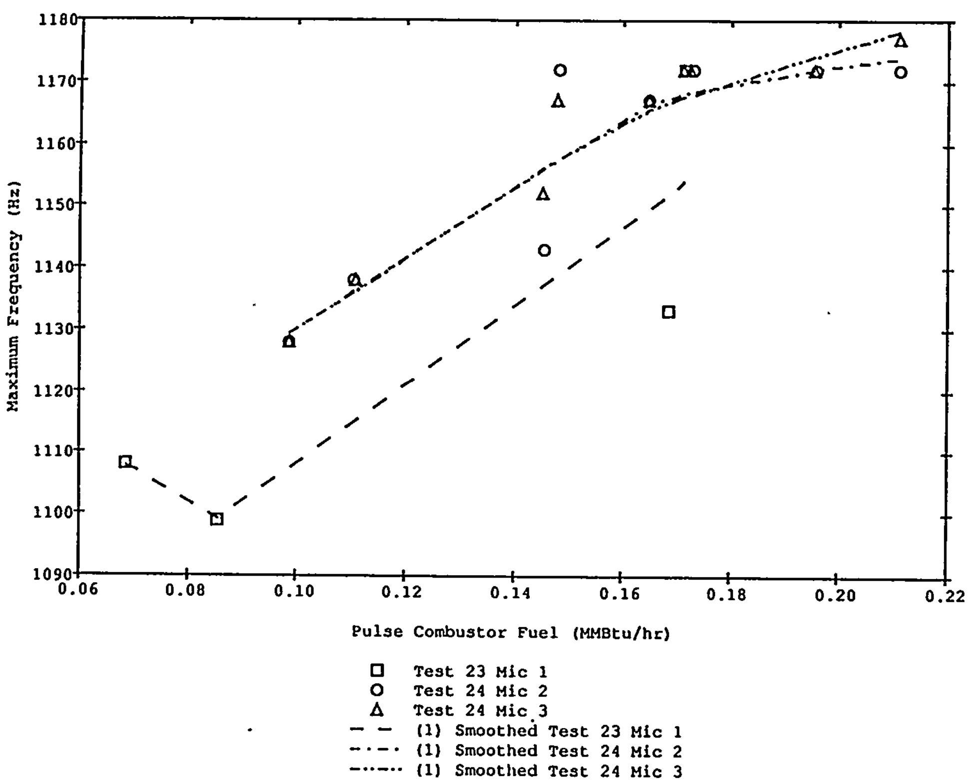


Figure 18. Effect of Pulse Combustor Firing Rate on Sound Frequency

range covered both the lower and upper limits of the combustor stability at 90 psig. As can be seen from these figures, both the frequency and intensity of the sound increase with increased firing rate. This range of fuel input only provided a maximum of 8 dB difference in the sound produced. One of the independent variables for the parametric testing was the sound intensity produced by the pulse combustor with a target level between 145 and 165 dB. It is apparent from these tests that the pulse combustors were not capable of producing and maintaining this broad range in sound intensity. The initial parameter screening tests were performed at a fixed sound level of approximately 160 dB. Further testing of the pulse combustors was made to try and achieve stable operation at lower firing rates, but was unsuccessful.

The effect of the pulse combustor equivalence ratio on the sound frequency and intensity are shown in Figures 19 and 20. There does not appear to be any direct correlation between the equivalence ratio and the sound produced by the pulse combustor. These figures have been included to show the range of equivalence ratios which produce stable operation.

Test Number 37 was performed with fuel injector 0.0781(b). After preheating the agglomeration chamber to steady-state conditions, the pulse combustor was ignited. This injector did not produce stable high amplitude pulsations under any conditions within the tested operating range. The fuel and air to the systems were turned off and the fuel injector was changed to 0.0781(a) while the agglomeration chamber remained hot. This fuel injector produced stable pulsations with the maximum peak amplitude at approximately 155 dB.

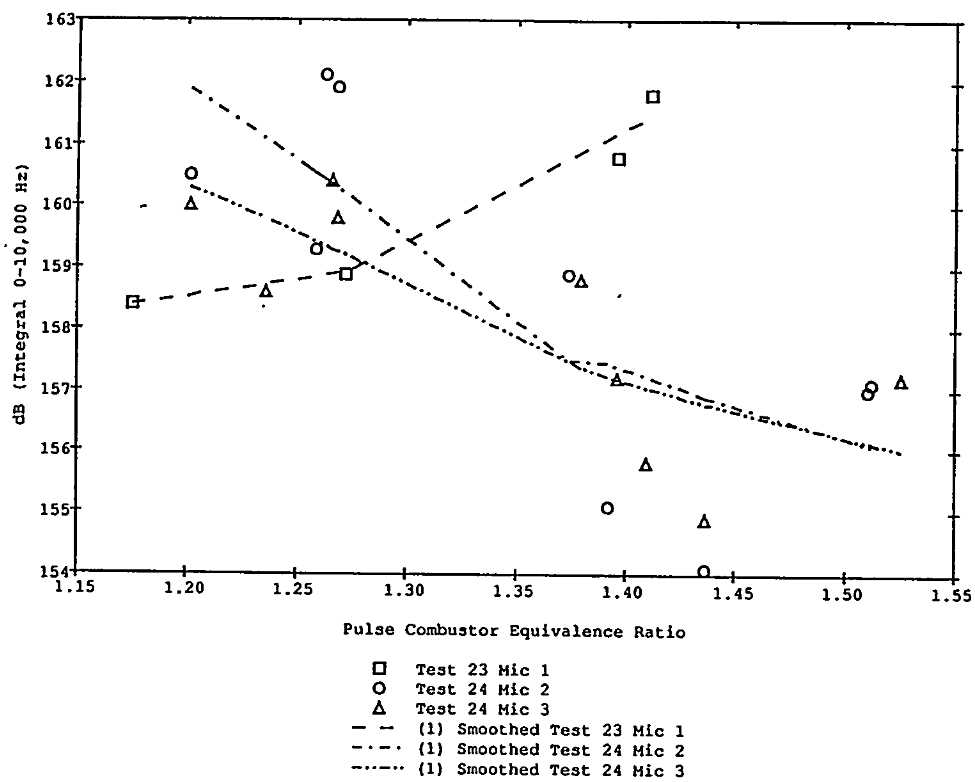


Figure 19. Effect of Pulse Combustor Equivalence Ratio on Sound Intensity

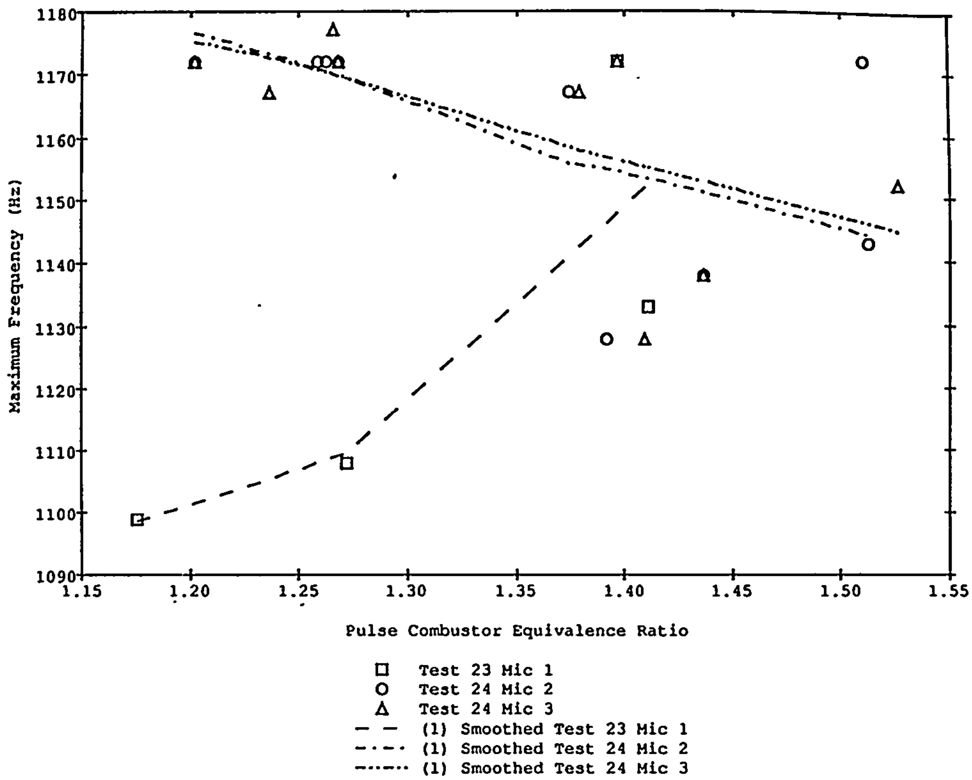


Figure 20. Effect of Pulse Combustor Equivalence Ratio on Sound Frequency

Test Number 38 was performed with injectors 0.0781(c), 0.0938(b), 0.0938(c), and 0.0938(d). Injector 0.0781(c) would not tune in properly. Injector 0.0938(b) tuned in easily with a maximum peak amplitude of 157 dB at a frequency of 1130 Hz. Injector 0.0938(c) was tuned in for brief periods on time (seconds); however, the pulsations were never stable. Approximately 30 minutes after ignition of the pulse combustor, the frequency shifted from approximately 1130 to 675 Hz. The system was quickly shut down and the fuel injector was examined. About half of the face of the fuel injector had burned away, along with the entre pilot injector tube. The exterior surface of the fuel injector also showed significant oxidation. After allowing the system to cool, fuel injector 0.0938(d) was installed on the pulse combustor. The pulse combustor was reignited and tuned in very quickly. This test was aborted shortly after the pulse combustor was tuned in due to a leak in the fuel/air supply line to the pulse combustor. This leak was attributed to damage sustained when injector 0.0938(c) burned up. Examination of the fuel injector after this test showed oxidation on the face of the fuel injector.

After Test Number 38 all six remaining fuel injectors were plasma sprayed with a ceramic thermal barrier coating to reduce the potential of the stainless steel face from overheating and causing the fuel injector to burn up. This plasma spray process was performed at Solar Turbines Incorporated where similar techniques have been used on gas turbine combustor fuel injectors to extend their lifetimes.

Test Number 39 was performed using fuel injectors 0.0938(d) and 0.0625(a). Injector 0.0938(d) tuned in very easily and produced dB levels similar to those obtained at the end of Test 38, thus indicating that the thermal barrier coating had no effect on the operation of the pulse combustor. Injector 0.0625(a) could not be tuned in.

Only three of the seven fuel injectors produced high amplitude pulsations. The reason for the other injectors not producing pulsations was never determined.

Five tests were performed to determine the operating envelopes of the 2000 and 3000 Hz T-burner pulse combustors. The variables used during these tests were the fuel injectors, fuel flow rate, fuel/air ratio, and system pressure. Stable operation of the pulse combustors with high amplitude pressure oscillations was not obtained during any of these tests.

Tests 41 through 43 used the 3000 Hz T-burner with fuel injector combinations of two with 0.0781" holes, two with 0.0938" holes, and one each of 0.0781" and 0.0938" holes. Moderate pulsations were achieved will all three combinations. Figure 21 shows the optimal results obtained with the two 0.0781" fuel injectors (Test 43). Microphone 1 is at the top of the agglomeration chamber, four and one-half feet from the exit of the pulse combustor. Microphones 1, 2, 3, and 4 are each spaced four feet three inches apart with microphone 4 near the bottom of the chamber. The maximum peak sound pressure level of 140.6 dB was measured at 1265 Hz. The acoustic intensity dropped off rapidly down the length of the agglomeration chamber. The second peak at 2529 Hz is the peak which was expected to produce the maximum acoustic power for the nominal 3000 Hz T-burner.

Tests 41 and 42 were performed at approximately 70 psig and Test 43 was performed at 135 psig. No change in the pulse combustor performance was apparent by varying pressure. The pulse combustor was fired between 270,000 and 450,000 Btu/hr and increasing the firing rate was not as significant on the pulse combustor performance as the equivalence ratio. The strongest pulsations were achieved between equivalence ratios of 0.83 to 1.17.

Tests 44 and 45 were performed with the 2000 Hz T-burner using two 0.0781" fuel injectors. Optimal sound pressure levels from this pulse combustor are shown in Figure 22 (Test 45). These results were similar to those obtained with the 3000 Hz combustor. Tests using two 0.0938" fuel injectors could not be performed since one of the two remaining fuel injectors was burned beyond repair during Test 42.

Typical sound pressure level data obtained with the 1000 Hz Schmidt tube pulse combustor (Test 38) are shown in Figure 23. The magnitude of the primary peak was much higher than seen with the T-burners. Also, the sound intensity did not drop off significantly down the length of the agglomeration chamber. The noise in the frequency spectra below approximately 300 Hz was due to flow and combustion noise produced by the preheat combustor. The preheat combustor was not fired during the tests from which Figures 21 and 22 were prepared.

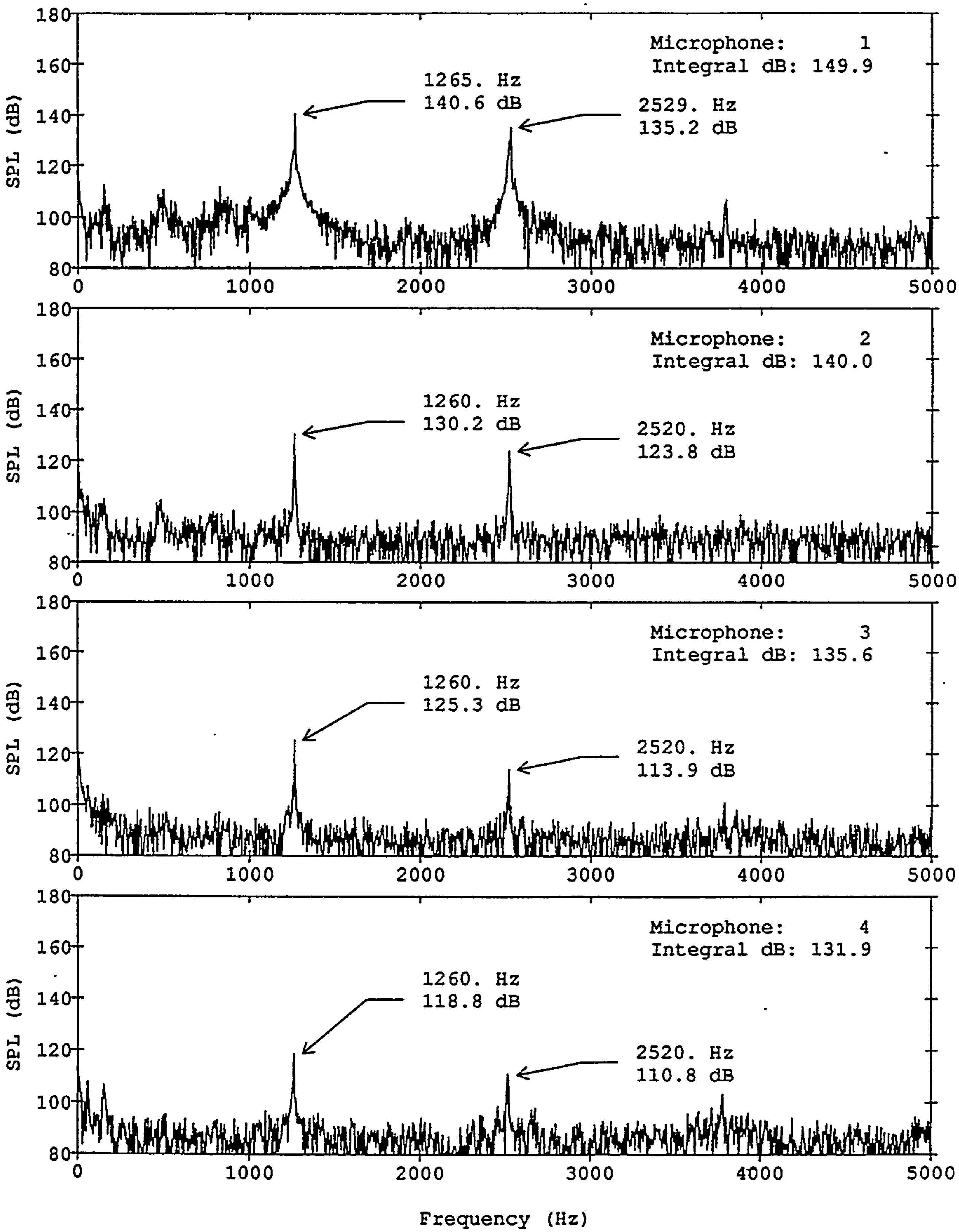


Figure 21. Sound Pressure Level vs. Frequency for the 3000 Hz Pulse Combustor (Test 43).

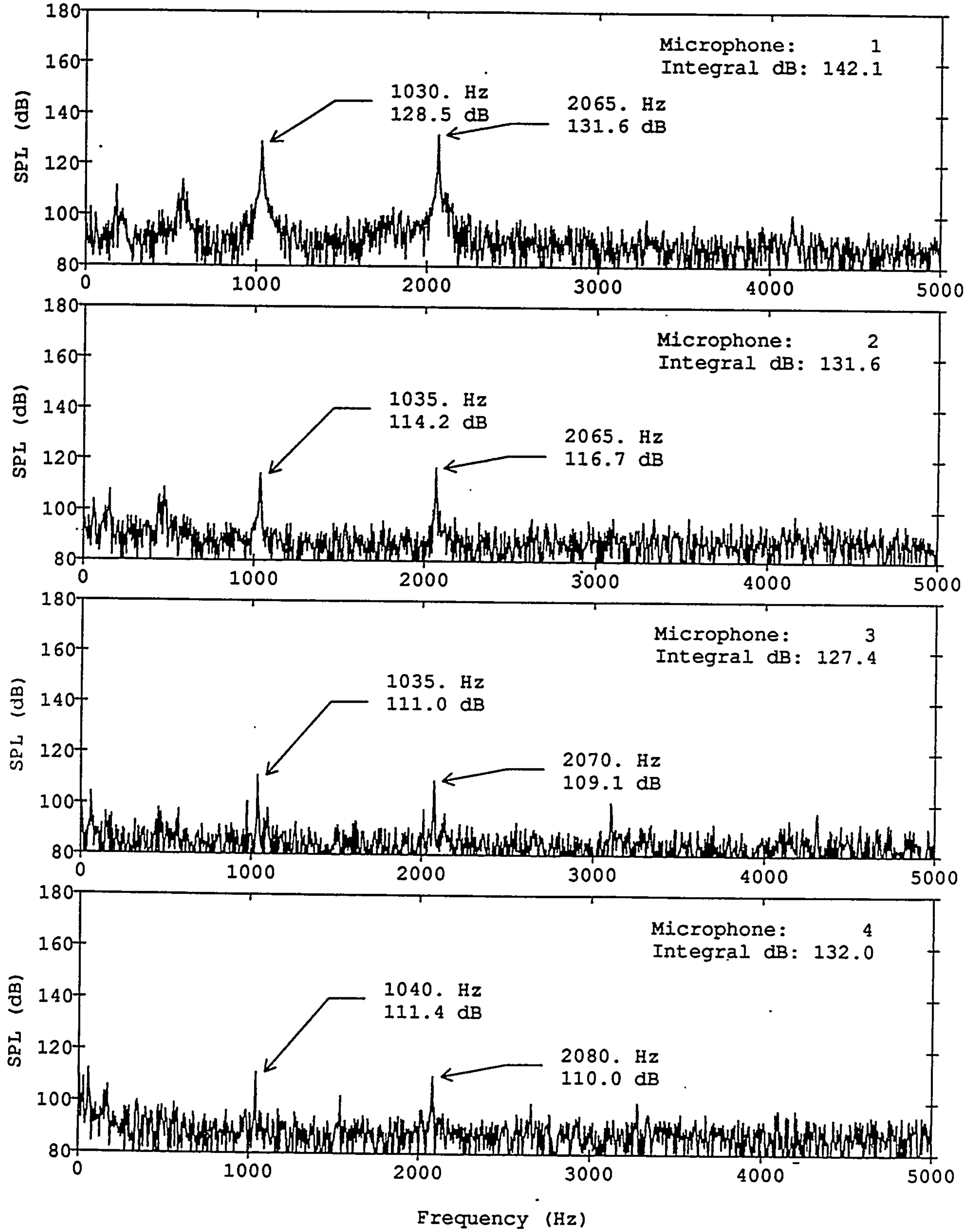


Figure 22. Sound Pressure Level vs. Frequency for the 2000 Hz Pulse Combustor (Test 45).

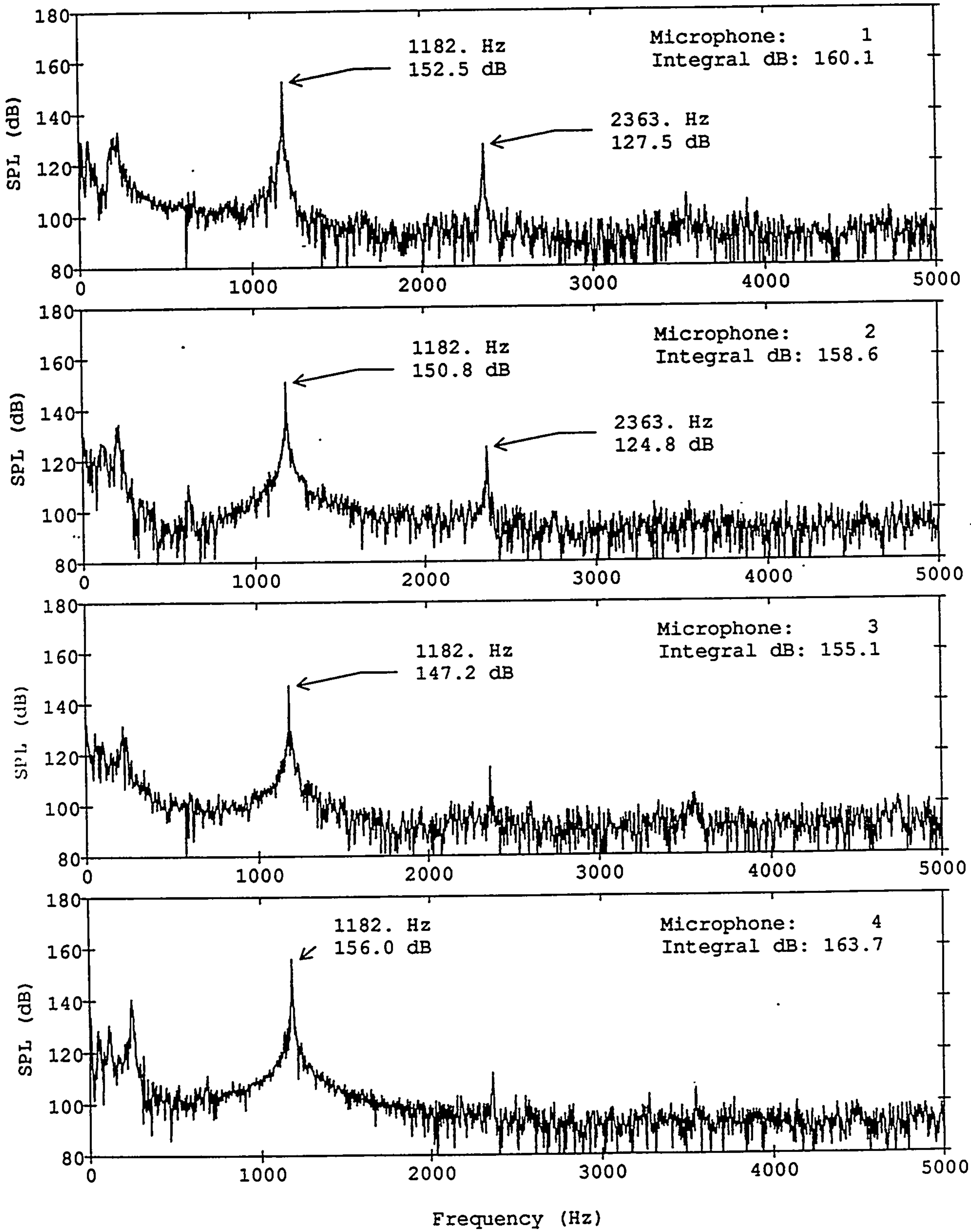


Figure 23. Sound Pressure Level vs. Frequency for the 1000 Hz Pulse Combustor (Test 38).

Test 46 was used to verify the successful operation of the 1000 Hz pulse combustor prior to injecting ash into the system. Due to the previous problems experienced with the 2000 and 3000 Hz burners, there was concern that the fuel injector may have been damaged. This test was successful. The average sound pressure level produced by the pulse combustor in the agglomeration chamber was 159.6 dB at 1083 Hz (Figure 24). At the end of the test the air flow to the pulse combustor was increased to de-tune the pulse combustor. This allowed the pulse combustor to supply heat to the top of the agglomeration chamber without providing significant acoustic energy. The average sound pressure level measured with the pulse combustor de-tuned was 145 dB. As can be seen in Figure 25, all of the sound energy was low frequency noise generated by the air flowing through the preheat combustor and agglomeration chamber. This noise was present with or without the pulse combustor operating.

Test 47 was a full ash agglomeration test using a mixture of the cyclone bottoms char and baghouse fly ash from the TVA Shawnee Station AFBC. The initial particle size distribution of the ash, measured in liquid suspension with a Malvern Particle Sizer, had a geometric mass mean diameter of 29.5 microns with a geometric standard deviation of 3.8. Approximately 20 percent of the ash particles were less than 10 microns in diameter. Figure 26 shows the ash size distribution of the sample collected in the Cyclade after a 3 second residence time in the agglomeration chamber with the pulse combustor producing 156.6 dB at 1157 Hz. Only about 7 percent of this ash sample was less than 10 microns. An attempt to obtain a second Cyclade sample with the pulse combustor de-tuned was aborted due to failure of ash feeder air flow turbine meter.

Test 48 was an attempt to collect the 'no-sound' comparison sample for Test 47. This test was also aborted during the ash sampling process due to excessive temperature on the final sampling probe.

One successful comparison sample was taken in which ash samples were collected both with and without sound, with ash being injected into the 3 second residence time port. The particle size distributions for the samples collected from Tests 47, 48, and 49, and measured with the Andersen Cyclade at the exit of the agglomeration chamber, are presented in Figure 26. The mass fraction of ash less than approximately 10 microns was 7.2% in Test 47, when the pulse combustor was tuned in. This mass fraction increased to 12.2% and 10.9% respectively in the two "no sound" tests. This signifies that in an active sound field, the percentage of small particles is decreased through agglomeration, resulting in larger particles which are more likely to be cleaned by conventional means. Further testing is required to determine whether the reduction in the small micron mass fraction with the operating acoustic sound source is truly significant.

Although more injector characterization tests were to be performed with the 2000 and 3000 Hz pulse combustors, METC supplied technical direction to cease all high frequency tests and make necessary modifications to begin low frequency testing.

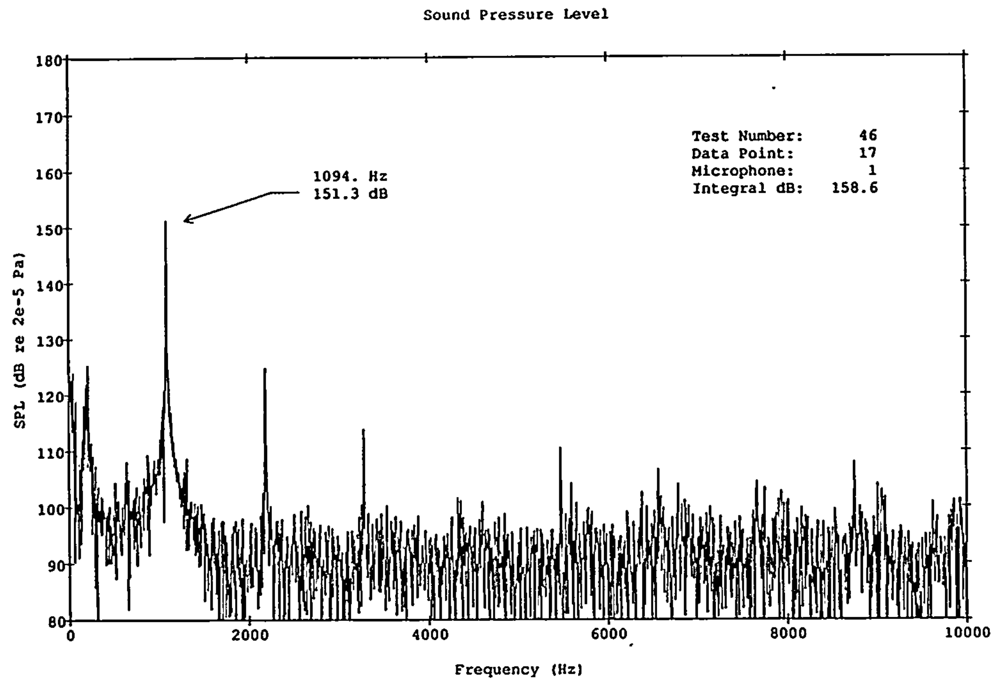


Figure 24. Sound Pressure Level vs. Frequency with 1000 Hz Pulse Combustor Tuned In.

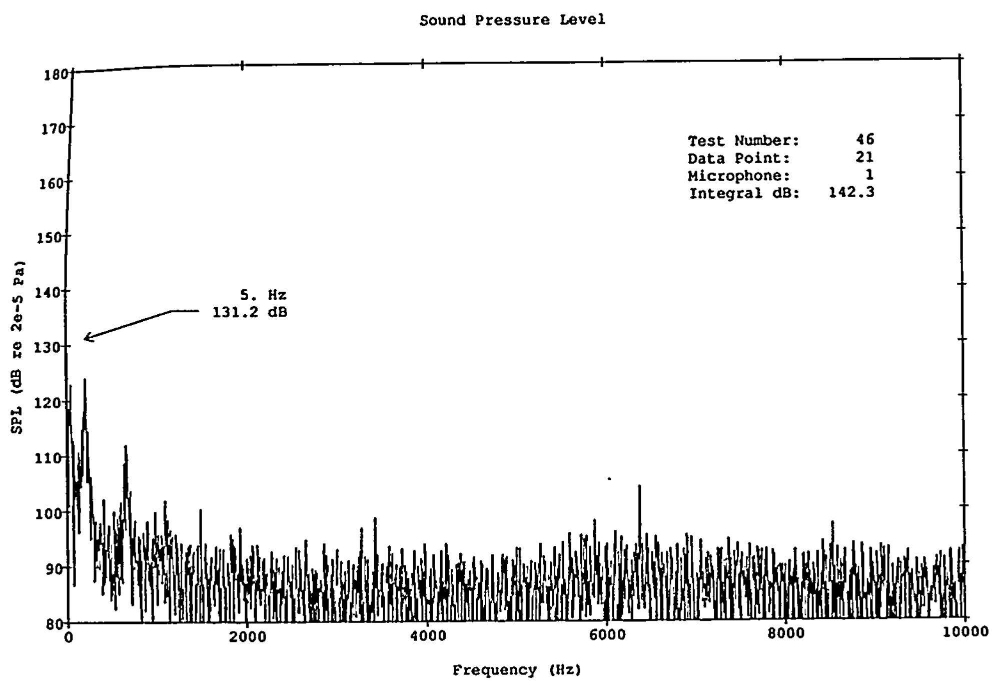


Figure 25. Sound Pressure Level vs. Frequency with 1000 Hz Pulse Combustor Tuned Out.

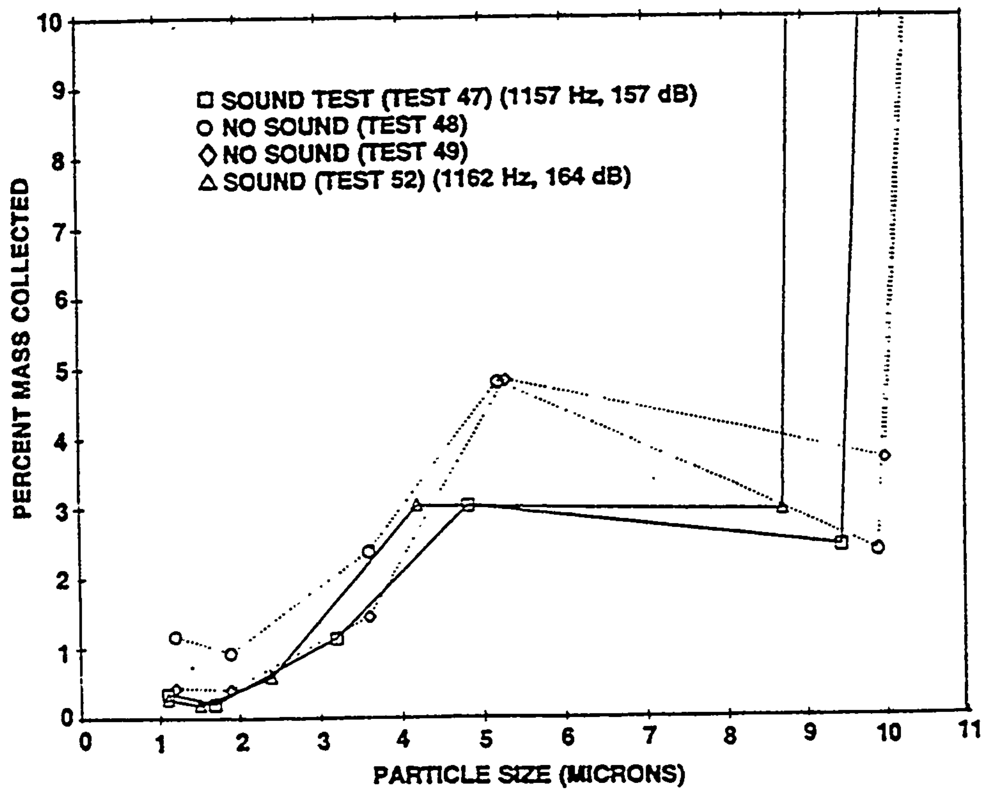


Figure 26. Particle Size Distribution Data From Tests 47, 48, and 49.

3.2.3 Low Frequency Testing

Once all low frequency facility modifications were completed, testing began with the nominal 150 Hz pulse combustor. System modifications included the addition of piping to redirect the gas flow from an upward path to a downward course. Heavy insulation was also installed on the piping because heat loss was too great between the first and second sampling probes. In addition, the ash feed system was moved to the top of the chamber and the first sample probe was reinstalled at the bottom of the agglomeration chamber.

MTCI fabricated, tested, and delivered two low frequency (150 Hz and 550 Hz) pulse combustors. System characterization and ash feeding tests were completed with the 150 Hz combustor, resulting in SPLs as high as 190 dB at 171 Hz. Originally, a glow plug, rather than a sparkplug was used as the combustor ignition source. Complications associated with the use of glow plugs are described in the Test Results section. A third ultra low frequency pulse combustor was also fabricated by MTCI to be tested in the agglomeration facility. The specified frequency of 63 Hz, for this combustor, was based upon prior test results.

Low frequency agglomeration tests (150-600 Hz) were performed with ash feeding only at the 150 Hz level. Preliminary agglomeration data, using the 150 Hz combustor, appear promising. No tests were performed on the 500 Hz pulse combustor, as lower frequency pulse combustors showed more promising results. A ultra-low frequency combustor (63 Hz) was built and delivered. No testing was performed on the 63 Hz combustor as it was delivered at the end of the contract.

3.2.3.1 Low Frequency Pulse Combustor Characterization

MTCI's low frequency combustor (Figure 27) is designed to produce the maximum sound pressure level (SPL) output at around 170 Hz and required the overall length of the unit be increased from 30 inches for the 510 Hz unit to 60 inches (Refs. 3&4). The design, operating principles, and physical characteristics are generally the same as the previous high frequency combustors. Starting with the 500 Hz combustor, all have natural gas injected into the combustion chamber through a central gas injector tube instead of through a gas manifold located around the inlet to the combustor.

The virtues of a pulse combustor firing natural gas at high pressure were demonstrated by the tests and some of the benefits are:

- Super combustion intensity (volumetric heat release rate exceeding 10 MMBtu/ ft^3/hr)
- High intensity acoustic field in the combustion chamber (peak-to-peak pressure was about 45 psi at 70 psig static pressure with a near triangular wave form)
- High combustion efficiency (hydrocarbon emissions of less than 50 ppm even with water quenching just downstream of the tailpipe exit)
- Low NOx emissions (less than 25 ppm at a temperature of 2300°F)

The central fuel injector solved the stability problems with this combustor design by improving the mixing of the fuel and air. The factory testing of the combustor is summarized in Table 7 and shows sound pressure levels around 180 dB at low pressures. The frequency spectrum at the highest static pressure tested (Figure 28) shows a maximum sound pressure level (SPL) of 179 dB. The oscilloscope showed a peak-to-peak pressure of 45 psi which translates into approximately 198 dB which is extremely beneficial from an agglomeration standpoint.

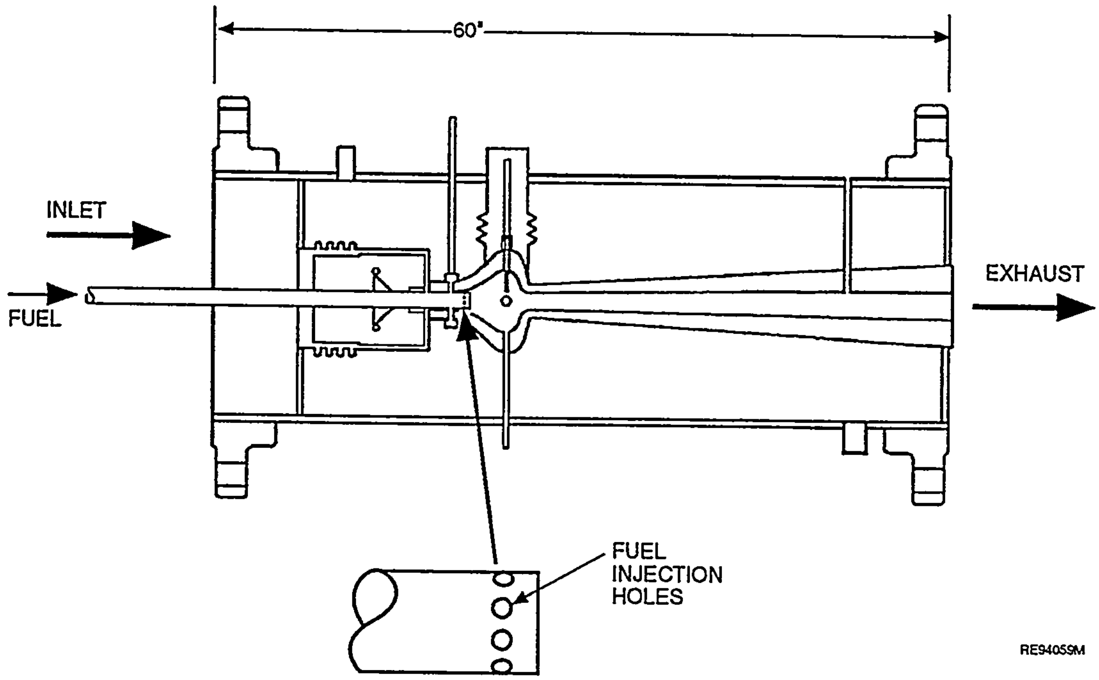


Figure 27. Cross-Section of Low Frequency Pulse Combustor

Table 7. Laboratory Test Results of Low Frequency Pulse Combustor (Ref. 4)

Air Plenum Static Pressure (psig)	0	11	20	30	40	54	70
Gas Firing Rate (kBtu/h)	166	345	507	604	750	837	993
Combustion Chamber Temperature (F)	1,785	1,949	2,032	2,070	2,175	2,201	2,309
Combustion Chamber Pressure (psig)	0	10	19.5	29	38	50	68
O_2 at the Exit of Tail Pipe (%)	6.3	4.2	2.6	2.2	2.3	4.2	3.6
NOx at the Exit of Tail Pipe (ppm)	15	14	22	27	27	22	25
Hydrocarbons at the Exit of Tail Pipe (ppm)	16	1	3	19	66	26	49
Frequency (Hz)	144	166	168	176	174	184	180
Sound Pressure Level (dB)	178	179	177	178	177	178	179

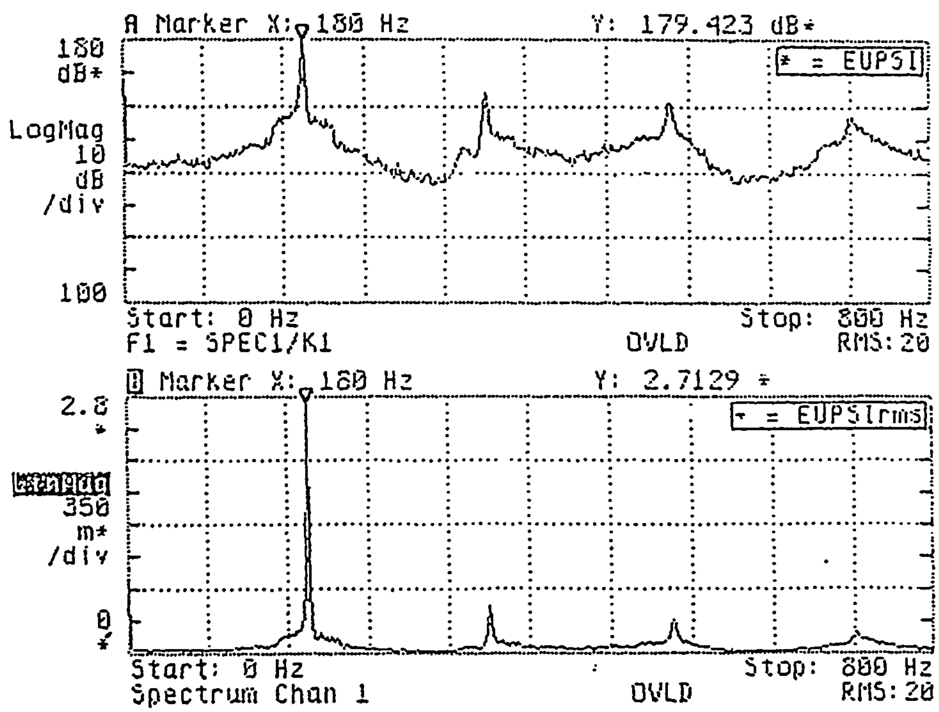
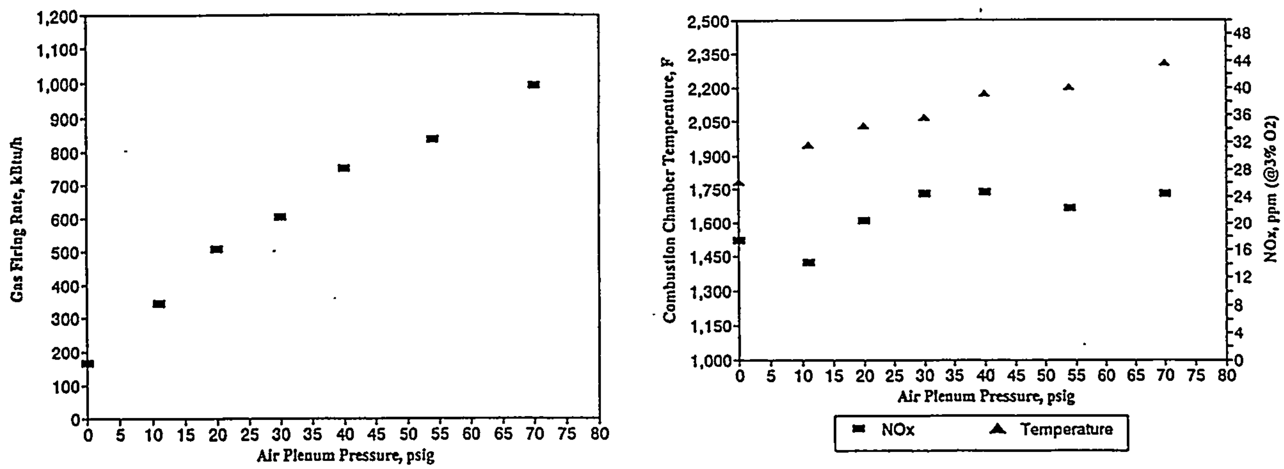


Figure 28. Typical pressure fluctuation in combustion chamber (68 psig. Gas firing rate: 993 kBtu/h) (Ref. 4).

The gas firing rate (Figure 29A) increased at less than a linear rate with air plenum static pressure and verified that stable operation in the 1 MMBtu/hr firing rate plateau at the design pressure of 135 psig could be accomplished. The temperature (Figure 29B) increases with static pressure due to an increase in firing rate. The heat release rate is higher but the heat loss rate does not keep pace and therefore the temperature rises. The NOx emissions remained below 25 ppm when corrected to 3% O_2 and are well below the regulated value of 30 ppm. These results indicate that the complex NOx production is minimal compared to conventional burners.



A. Gas Firing Rate with Air Plenum Static Pressure

B. Combustion Chamber Temperature and NOx at the Exit of Tail Pipe

Figure 29. Combustion Performance of the Low Frequency (150 Hz) Pulse Combustor (Ref. 4)

The frequency at which the maximum sound pressure level occurs, increases with the system pressure while the maximum SPL amplitude, as indicated by the spectrum analyzer, remains nearly constant (Figure 30). The increase in frequency is attributed to the increase in tailpipe temperature and in turn the speed of sound. The pressure amplitude is also seen to increase significantly with system pressure although the measured dB level does not. This suggests that for a given design and enclosure, there exists a peak acoustic energy per unit area. Nevertheless, the increase in pressure amplitude with system pressure is a good sign for acoustic agglomeration from enhanced displacement.

3.2.4.3 Test Results

Once the hardware configuration changes were made to convert the up flow high frequency test setup to the down flow low frequency flow pattern checkout of the system began. Three ash runs were made at each of the four test conditions listed in Table 4 using TVA ash mixture (50 percent fly and 50 percent char ash).

The usual minor startup problems were experienced and can be generally categorized as: (1) location of the pulse combustor fuel injector, (2) replacing plastic pressure transducer instrumentation lines that were failing or leaking, (3) pulse combustor light off problems, glow plug reliability and catastrophic failures leading to eventual replacement with a spark ignitor, (4) general wiring and checkout with movement of hardware required by the new test configuration, (5) instrumentation inconsistencies that had to be resolved, (6) water leaks in the cooling jackets, (7) general facility malfunctions including regulated power that failed the data acquisition monitors and air supply system upgrades resulting in extended outages, (8) cooling air injection and development for adequate mixing, (9) ash feeder motor gradual decline and failure and (10) developing and revising the current operating procedures to correspond to the new test configuration.

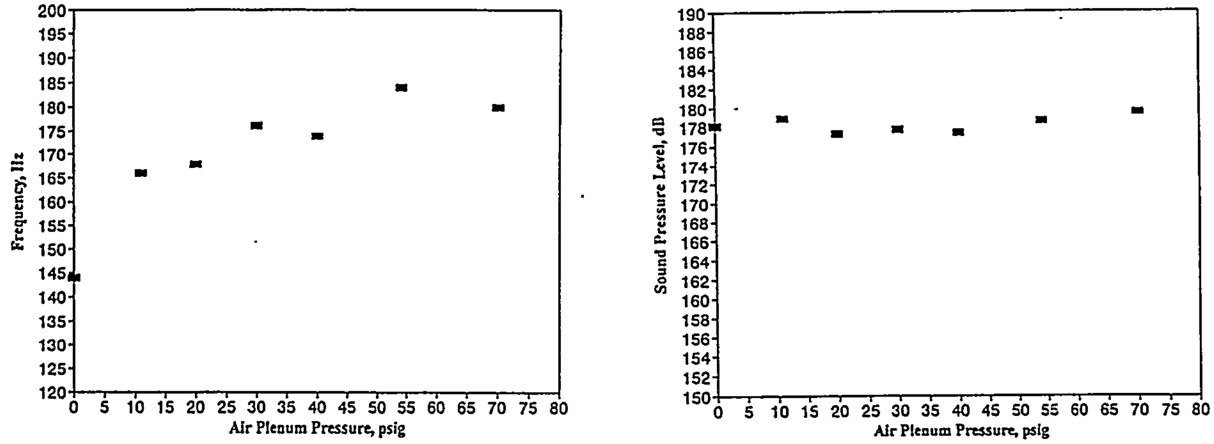


Figure 30. Acoustic Performance of the Low Frequency Pulse Combustor (Ref. 4)

Since the preheat combustor was eliminated for the low frequency testing, there was no way to perform sound-no sound comparison tests on ash agglomeration. This is because the sound generating pulse combustor now served to heat the air into the chamber. A no sound test would mean a cold test. Thus, the determination of ash agglomeration within the chamber are much more difficult to determine for the low frequency test series.

Once ash runs were attempted, the major problem became ash plugging the sample lines. On occasion, residual ash in the sample line or chamber would result in the sample line plugging to the point where no flow could be drawn through. A great deal of effort was invested to determine and resolve this problem. Procedurally, all the sample lines, ash feeder lines, and chamber were cleaned after each run to prevent any accumulation of ash in the lines.

Excessive water found in the sample lines after testing would cause the ash to form a paste that would eventually plug the line and prevent the ash particles from reaching the sampler. The source of the water was determined to be from condensing water vapor as a byproduct of combustion as all the water cooling jackets were hydrostatically tested and no leaks were found. The sample line from the chamber to the cyclade was several feet long and contained several sharp ninety degree bends that would trap the ash and cause a blockage of the line. After several minutes of sampling, the sample flow would start decreasing and the proper flows to the Cyclade™ could not be maintained. The probable cause is that the bends would cause the water ash mixture in the line to centrifuge the particles out to the wall where they would begin sticking and accumulating. As the ash accumulated, it would reduce the relatively hot sample flow through the line and eventually the would be low enough that the downstream tubing would begin to cool. As the tubing cooled, moisture from the combustion gasses would condense in increasing quantities eventually forming a solid plug in the line.

To correct the problem, a larger and heavily insulated line with very long radius bends was installed and the operating procedure changed to heat up the sample line to over 250°F before starting the ash flow to avoid condensing in the line. In addition a small bore butterfly shutoff valve at the entrance to the Cyclade™ was replaced with a larger bore ball valve to further reduce line restrictions. These changes resulted in fairly consistent ash flow into the Cyclade™ from test to test.

Once ash flow was consistently maintained to the Cyclade™, the problem became the apparent low quantities of ash that were being collected. With a sample flow of 0.5 acfm and an ash loading of 6 grams/scf, a 20 minutes sample should yield 60 grams of ash in the Cyclade™ (0.5 acfm x 6gr/acfm x 20 min). Most of the ash runs resulted in 50 milligrams to 1.5 grams of ash collected in the Cyclade™. Some of the total ash was also dropping out of the gas stream in the long sample line from the chamber to the Cyclade™. These quantities amounted to generally 5 grams that could be blown out of the line and captured in a Balston filter.

On only one ash run (Check-Out Test#108) were significant quantities of ash collected. In that test, over 55 grams of ash were collected in the Cyclade™ in a single thirty minute run. These results are close to the amounts expected but were never duplicated in any run before or after this test. Some effort went into explaining the reason this one run was so successful in collecting ash but none was ever found.

Several questions arise as a result of the large amounts of ash found in the sample line. namely, (1) are the ash particles depositing in the line biasing the Cyclade™ results?, (2) Are particles selectively depositing in the line by size criteria and never reaching the Cyclade™?; (3) And is the Cyclade™ sample representative of the particle size distribution in the chamber? To help resolve these questions, cold ash runs were made at each pressure and ash loading to obtain data on the size distribution collected in the Cyclade™ without heat or acoustic agglomeration. This problem was never fully resolved when testing was terminated the end of June 1994.

The location of the ash sampling probe was moved about seventeen inches above the centerline of the chamber exhaust port where it was originally located. The results were somewhat marginal but it appeared that the amount of sample collected increased slightly. Further work is required to determine if the ash concentration across the entire width of the chamber is constant or if the initial ash injection is causing large ash distribution fluctuations across the flow stream.

In general, testing at the low pressures was much more difficult than at high pressures because the system and controls were set up for the high pressure operation. At low pressure, the unit had to be control in the 0-10% range of the controllers where the response is generally not linear and extremely sensitive.

Ash testing was performed with only the TVA ash mixture so that the resulting test matrix shown in Table 8 consists of four test points. Three ash runs were obtained at each of the four test conditions listed. Representative sound pressure level/frequency plots (Figures 31 and 32) show that the test conditions at the 135 psig pressures were 193.1 dB at 210 hertz and are similar to the low pressure tests which had a maximum sound pressure level of 193.4 dB at around 205 hertz. The data, when all plotted on the same graph (Figure 33), shows three distinct accumulation of peaks in the sound pressure levels. Tests 107, 108, and 111 all peak around 181 hertz while tests 116 and 117 peak around 195 hertz and the final group of tests 112, 114, 118, 119, 120, 121, and 122 all peak around 205-215 hertz. There appears to be no significant difference in the magnitude of the sound pressure levels between the tests and the low pressure maximum amplitudes are almost identical with the high pressure results. The maximum sound pressure level was 196.2 dB for the high pressure (135 psig) tests and 193.4 for the low pressure tests (35 psig).

It is interesting that the peak sound pressure level shifted to higher frequencies as the testing progressed. The only explanation is that the operating points varied somewhat in actual fuel/air ratios. As test experience was gained, the optimum operating points for combustor stability were found and used repeatedly towards the end of the test sequence. The optimum operating point, was characterized by stable combustor operation towards the high end of the operating fuel air ratios. The fuel air ratio would slightly affect the sound pressure level and frequency at which the peak occurred and the beginning tests were at the low end of the permissible fuel air ratio while the later tests were at the high end (see Figures 34A and 34B). Pressure could also affect the frequency at which the peak sound pressure level would occur, but the data shows no systematic variations in pressure that would explain these results. Also the peak frequencies are about the same for the low and high pressure tests indicating that this result is not pressure dependent.

An interesting phenomena is the spread of the low frequency sound pressure levels seen in Figure 33A. The initial sound pressure levels in the 0 to 150 hertz band range from 120 dB to 160 dB but still all peak in the 180-215 hertz range within 176 to 197 dB. The lowest initial curve (around 120 dB) peaks at 193 dB at 205 hertz while the highest curve also peaks at around 193 dB and 210 hertz. Therefore, the initial amplitude of the sound pressure level in the low frequencies is no indication of the peak amplitude. Whether the amplitude at these lower frequencies has any effect on the agglomeration of the ash particles has not been determined.

The average sound pressure levels for the high pressure tests were on average, higher than at the low pressure. The average sound pressure level for all the high pressure tests was 193.9 dB with a standard deviation of 2.2 dB and 187.0 dB with a standard deviation of 6.7 dB for the all the low pressure tests. In general, the low pressure tests were harder to control and small variations in test pressure or other test operating conditions would produce greater changes in the test results. But, in general, the lower sound pressure level at the low pressures is consistent with the preliminary combustor tests and agree with the theory.

Table 8. Low Frequency Test Matrix Performed

Test	LF-1	LF-2	LF-3	LF-4
Ash Residence Time (s)	3	3	3	3
Ash Loading (gr/scf)	6	12	6	12
System Pressure (psig)	35	35	135	135
System Temperature (F)	1600	1600	1600	1600
Ash Type	TVA	TVA	TVA	TVA

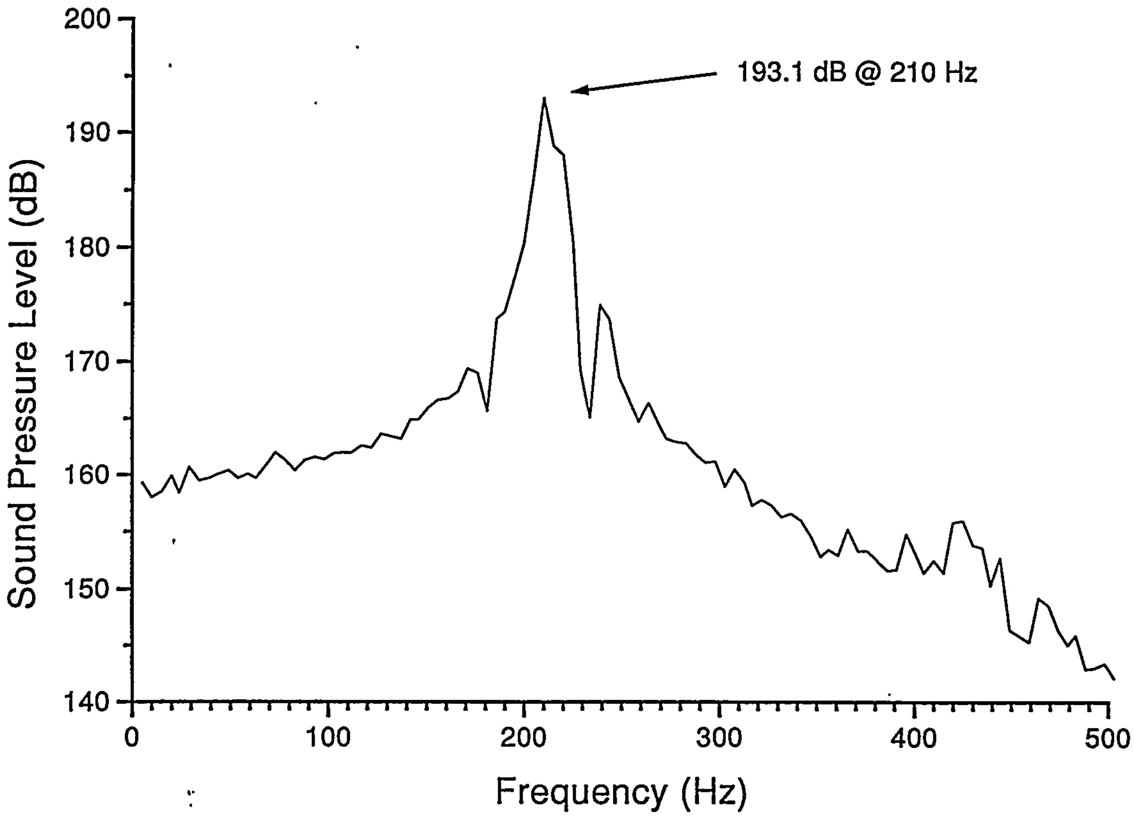


Figure 31. Typical SPL/Frequency Response for High pressure Test (135 psig, Test #114, Microphone #1.

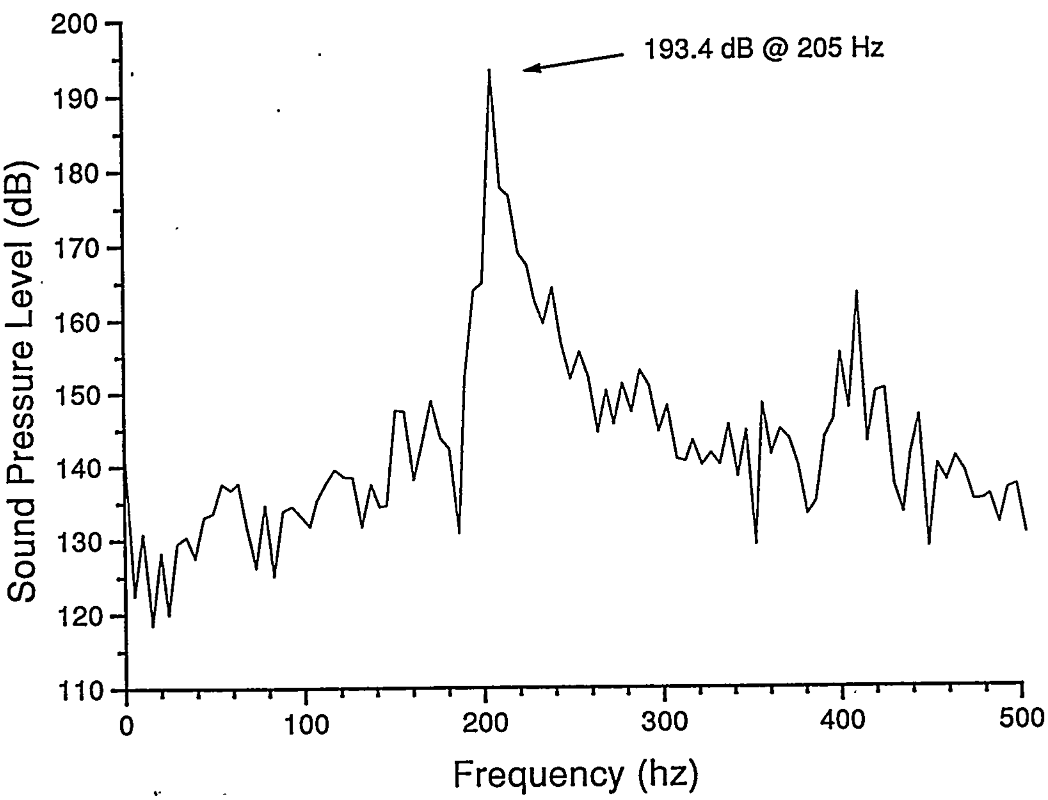


Figure 32. Typical SPL/Frequency Response for Low Pressure Test (35 psig, Test #116, Microphone #1.

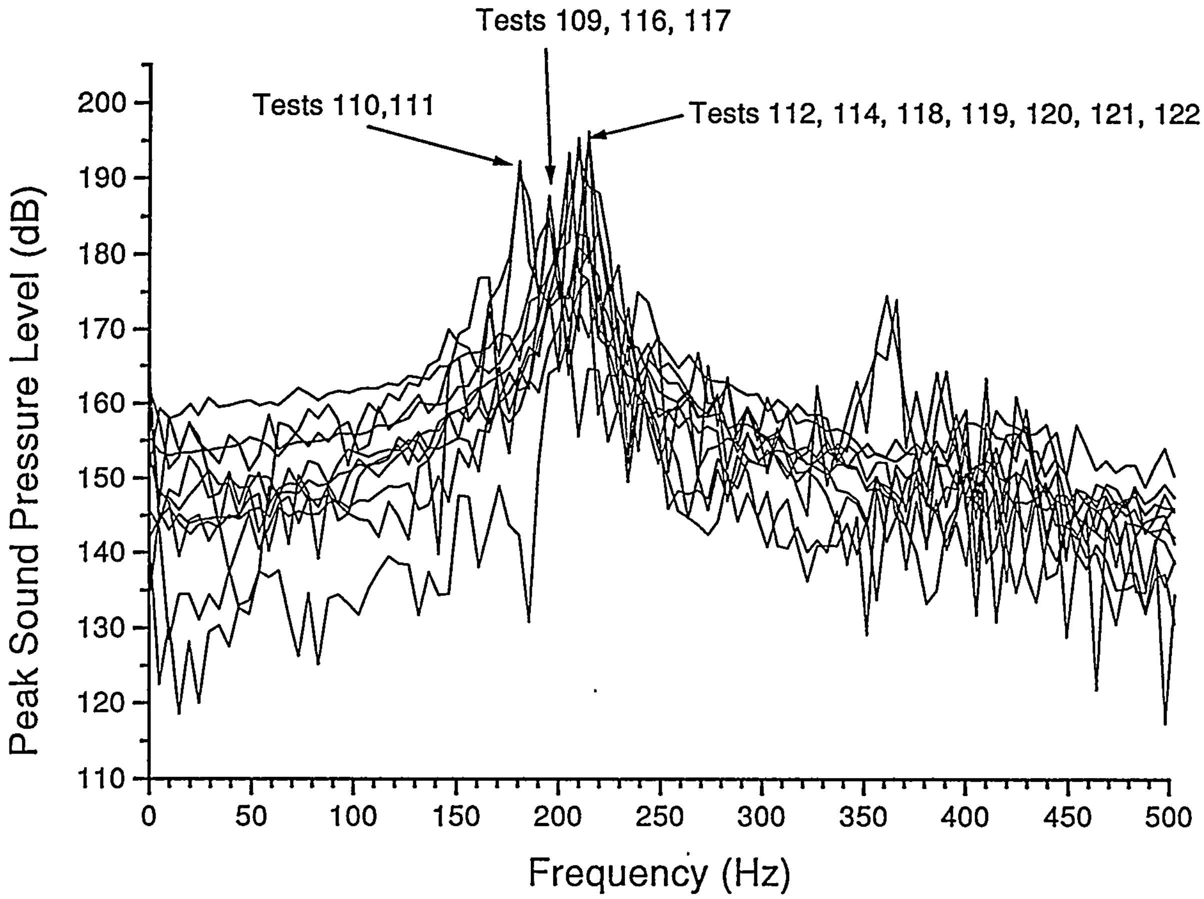
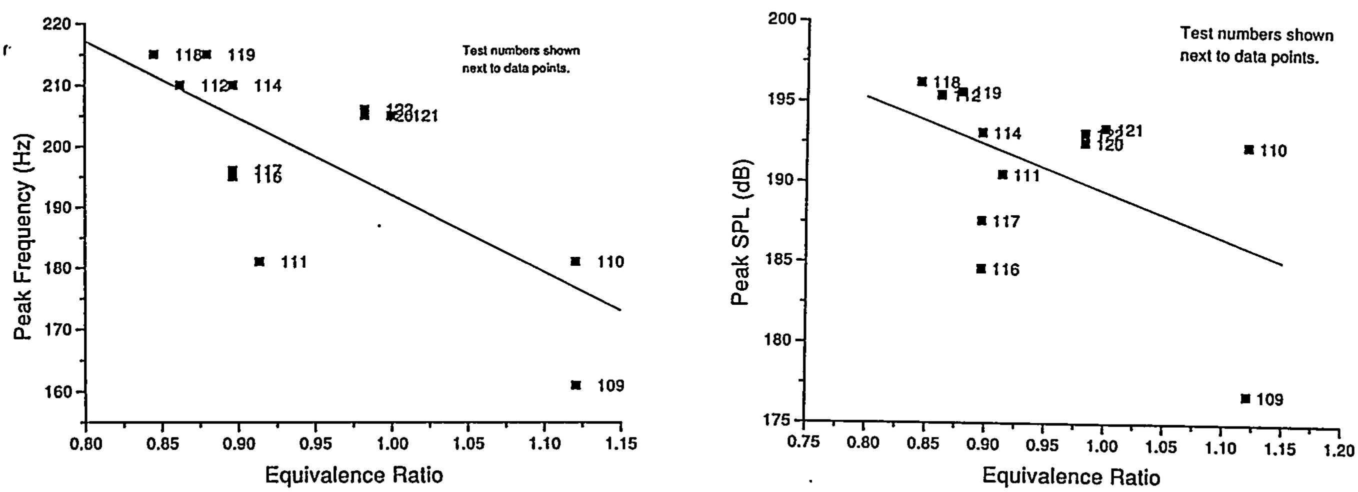


Figure 33. All Data Plotted Showing Multiple Frequencies at which Maximum SPL Occurs



(A) (B)

Figure 34. Effect of Equivalence Ratio on (A) Peak Frequency and (B) Peak Sound Pressure Level (SPL).

The test had four microphones equally spaced along the length of the chamber. Microphone #4 (at the bottom of the chamber) malfunctioned during the initial checkout runs. It was removed and sent to the factory were it was found to un-repairable. It was never replaced.

Typical data from microphone #1 (at the top) and #2 (third one down) and #3 (two thirds down) plotted in Figure 35 for Test #119. The peaks are coincident at a frequency of 215 hertz with the amplitude of microphone #1 at 195.6 dB and microphone #2 at 193.9 dB and 125.3 dB for microphone #3. Microphone #3 also appears to be failing and the lower sound pressure levels may be more a result of this deterioration rather than a physical characteristic of the system.

A secondary and much lower amplitude peak occurs at twice the frequency of the main peak. Thus, secondary spikes are seen at around 360 to 420 hertz. The amplitude is at least 20 dB lower and generally not much above 170 dB. A plot of frequencies further out (Figure 36) shows that a minor peak occurs at even multiples of the first peak frequency (2x, 4x, 6x, ... 430hz, 860 hz, 1290 hz...) and a major peak at odd multiples of the first peak frequency (3x, 5x, 7x,... 545 hz, 1075 hz, 1505 hz,....).

Microphone #3 was also reading bad electrically and all data is deemed not of good quality and should be used with caution. This may be a continuation of earlier problems with the electrical connections or the transducer is failing similar to microphone #4. The connections were re-examined and cleaned with no improvement in the signal output. The microphone reads but the amplifier indicates the connection is marginal at best.

The maximum sound pressure levels, the overall sound pressure level, and the frequency at which they occur for each of the tests is summarized in Table 9. The overall sound pressure level is an integration of the SPL over the frequency range and the relationship between the peak and overall SPL is shown in Figure 37 where the overall value is generally around 7-11 dB higher than the peak.

The low frequency testing on the 150 hertz pulse combustor consisted of twelve test runs, three at each of the two pressures and two ash flowrates as summarized in Table 9 (Tests #109-122). In addition, one run at each of the pressures and ash flowrates was made cold (no combustor and acoustic environment) as a calibration (Tests #123-126).

The data in Table 10 was combined and averaged by test type and plotted as Figure 38. Test #113 was aborted when the ash feed line plugged after reaching steady state conditions and preparing to flow ash. After this occurrence, a set of valves were installed in the line to allow cleaning without shutting the combustor and test down. The data from Test #115 was omitted because the Cyclade™ "O"-ring sealing stage nine was found broken after the test and ash all over the inside of the canister. It can be concluded that significant ash escaped the Cyclade™ and the results were not valid.

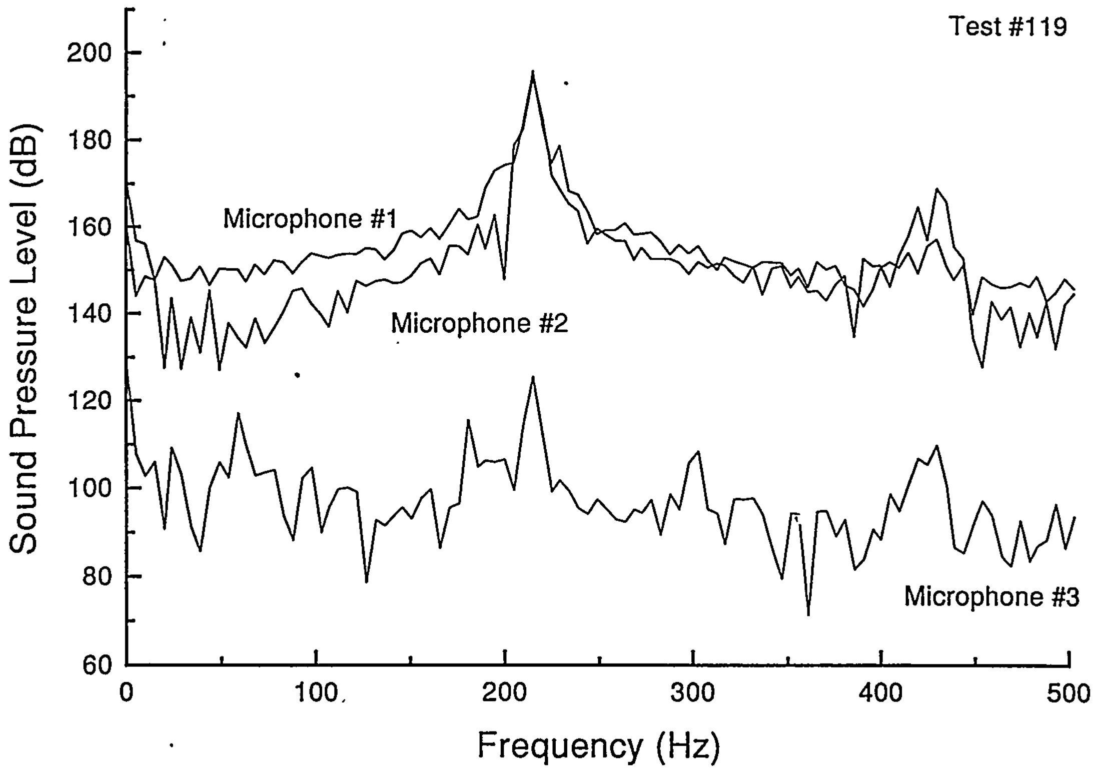


Figure 35. SPL Viarations in Microphone Data

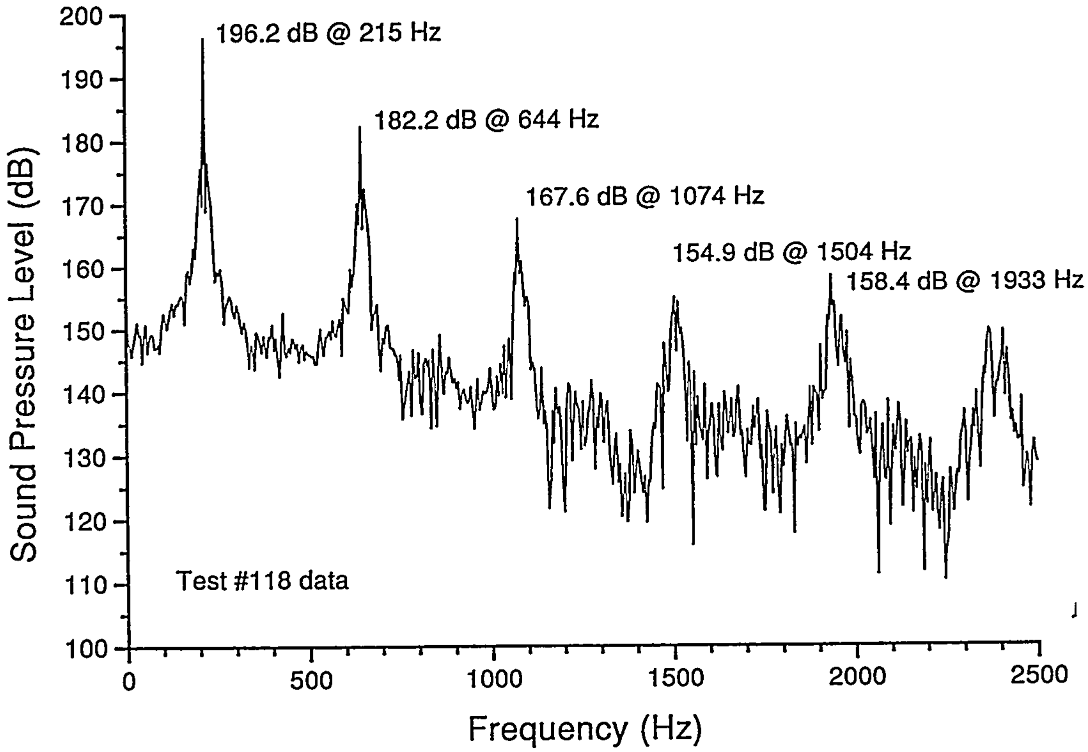


Figure 36. Harmonic Sound Pressure Level Peaks

Table 9. Acoustic Levels During Low Frequency Testing (Microphone #1 Data)

Test No.	Maximum SPL (dB)	Frequency (Hz)	Test Pressure (psig)	Test No.	Maximum SPL (dB)	Frequency (Hz)	Test Pressure (psig)
109	176.8	161	35	117	187.6	195	35
110	192.3	181	135	118	196.2	215	135
111	190.5	181	135	119	195.6	215	135
112	195.4	210	135	120	192.5	205	35
114	193.1	210	135	121	193.4	205	35
116	184.6	195	35	122	193.1	205	35

Table 10. Summary of Low Frequency Ash Testing

Test No.	Pressure (psig)	Ash Loading (gr/scf)	Run Time (Min:Sec)	Total Sample (grams)	Cyclade Stage 9 (%)	Cyclade Stage 1 (%)	Cyclade Stage 2 (%)	Cyclade Stage 3 (%)	Cyclade Stage 4 (%)	Cyclade Stage 5 (%)	Cyclade Filter (%)
109	35.0	11.96	6:06	0.17	76.90	16.38	0.00	4.83	1.89	0.00	0.00
110	129	12.16	12:27	2.05	98.19	0.81	0.07	0.10	0.05	0.12	0.65
111	137.7	12.32	6:04	0.26	92.18	4.63	0.87	0.84	0.99	0.49	0.00
112	135.5	12.72	14:10	0.42	98.92	0.19	0.26	0.19	0.02	0.38	0.02
114	135.8	6.17	21:28	0.23	96.38	0.44	0.17	0.17	0.83	2.01	0.00
116	36.5	6.19	30:24	0.16	90.27	0.44	1.39	3.79	1.07	3.03	0.00
117	36.2	15.48	20:04	2.03	76.59	6.41	10.22	0.27	0.39	0.16	5.97
118	137.0	6.77	20:03	0.18	80.46	2.62	2.45	8.72	3.93	1.65	0.17
119	134.4	5.02	20:07	1.22	89.49	2.01	5.06	2.35	0.76	0.33	0.00
120	37.0	6.44	20:05	0.28	51.51	1.62	8.25	22.44	9.06	7.13	0.00
121	37.3	12.05	20:04	0.31	91.55	1.96	0.26	0.46	0.82	3.83	1.11
122	34.9	6.27	20:10	0.18	59.75	5.73	7.21	12.33	6.06	8.31	0.61
123 cold	135	11.58	20	0.99	85.60	2.81	3.93	3.84	2.04	1.14	0.64
124 cold	135	6.20	20	1.06	95.87	1.85	0.55	1.01	0.38	0.22	0.11
125 cold	35	6.72	20	0.18	50.48	5.46	20.51	14.76	5.01	3.10	0.68
126 cold	35	12.48	20	0.23	40.25	3.98	16.50	18.89	8.36	8.45	3.58

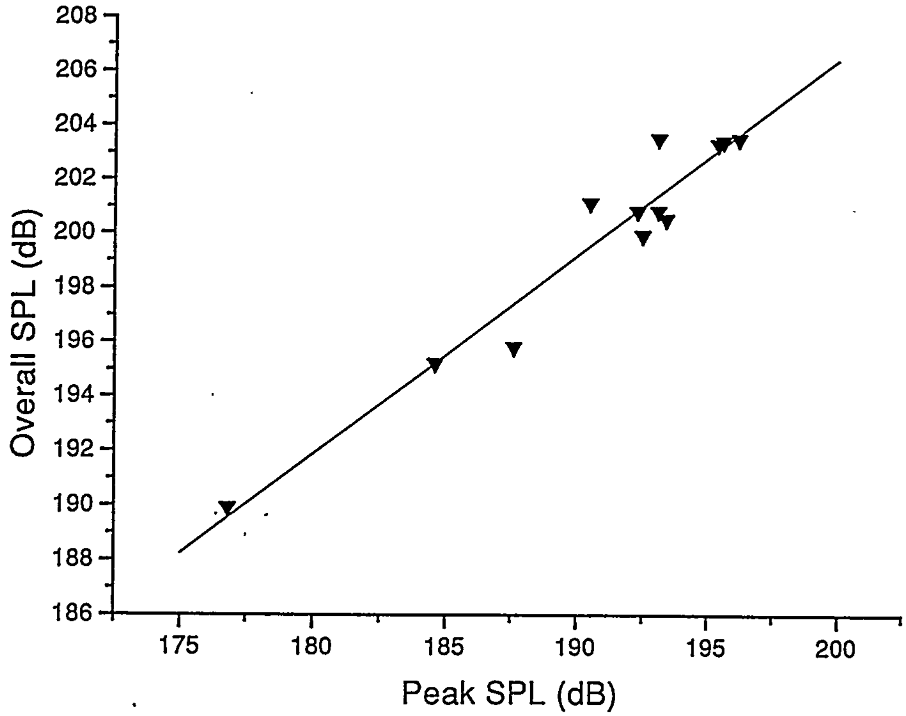


Figure 37. Relationship Between Peak and Overall Sound Pressure Levels

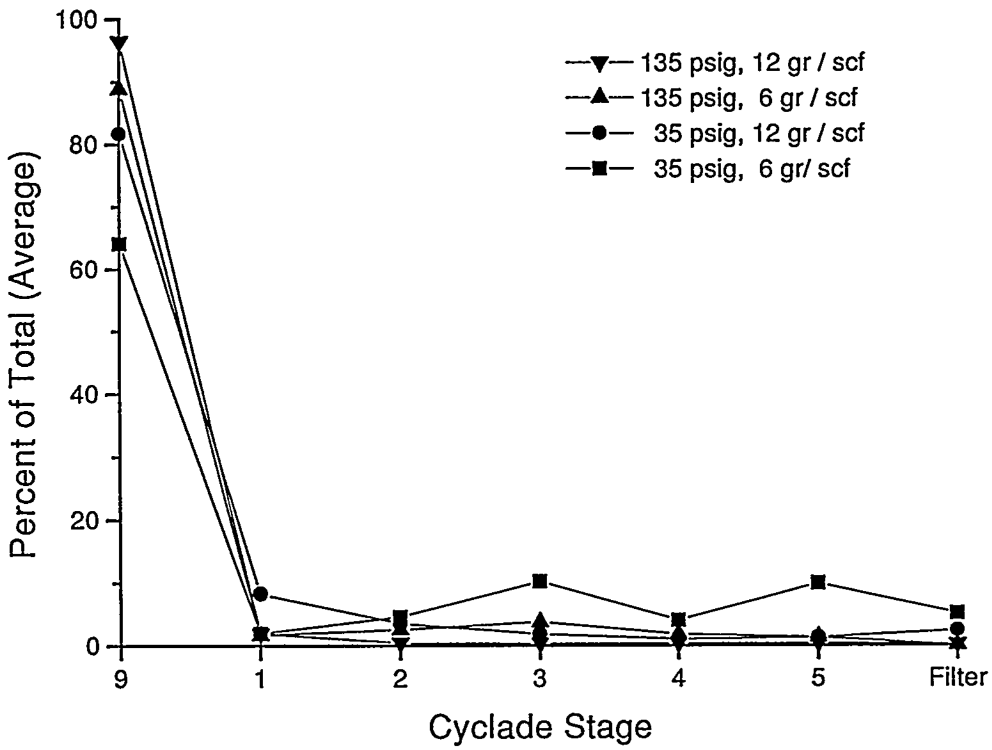


Figure 38. Summary of Averaged Ash Distribution Results for Each of the Four Major Test Conditions.

One would expect that the cold ash runs (Tests 123-126) would have about the same Cyclade™ particle size distribution results. As seen from the data, the Stage 9 (largest size particles) show a definite decrease in mass collected (about half) for the two low pressure runs (Tests 125-126) and a marked increase in the Stage 2-5 collection amounts. This result was unexpected and both tests were re-run with the same results. Since the Cyclade™ classifies by aerodynamic size rather than physical size, one must conclude that the effects of passing the same ash through the Cyclade™ varies with density. This is the only variation possible since the flowrate is the same, the pressure drop through the Cyclade™ and hence the velocities must be different between the high and low pressure runs. However, the mean particle size collected in each stage of the Cyclade™ is only dependent upon it temperature and flowrate, both of which are nearly the same for the two pressures tested. The flowrate is controlled by adjusting the pressure drop across a downstream valve so that the pressure drop across and flowrate through the Cyclade™ should be about constant. The one major difference in the cold runs is that at ambient temperatures, the density of the air is higher and the air supply system could not supply the air required to equal the chamber velocities during a hot test. Thus, the velocity and flowrates through the chamber is much less than in the hot tests. The sample flow to the Cyclade™, however, was constant.

The ash test data are further reduced and are plotted versus the mean particle size, in microns, in Figures 39-42 for each of the tests and shown together for comparison in Figure 43. Figure 39 shows that the particle size distribution for the 135 psig 12 gr/scf case rises sharply after 5 microns for all tests. In contrast, the 135 psig, 6 gr/scf data shown in Figure 40 has a spike in the 3 to 5 micron range for all three tests. The 35 psig data is much more scattered and more difficult to interpret. The 35 psig data at 12 gr/scf (Figure 41) shows an increasing trend from the 1 micron size all the way above 8 microns if the average value of all the tests is used. This is in contrast to a fairly flat curve from 1 to 5 microns and then steadily rising above 5 microns for the higher pressure case.

The low pressure low ash loading data is also somewhat scattered but there is a definite peak in the 3-5 micron size range (Figure 42) similar to that seen in the high pressure results (Figure 40). There also seems to be a definite distinction in the data with respect to pressure and a lesser differentiation in the results with respect to ash loading. The ash loading effects are essentially non existent for the low pressure tests but at high pressure, the lower ash loading appears to have increasing mass at the smaller size ranges. This indicates that the agglomeration is less effective at the lower pressure levels as more of the mass is contained in the smaller particles.

The data is again plotted in Figure 44 as a cumulative ash weight percentage distribution with particle size. The general trend is for better agglomeration and lower mass contained in the smaller particle sizes for the higher pressures compared with the lower pressure tests. Also, better agglomeration is seen for ash flowrates of 12 gr/scf than with 6 gr/scf. The low pressure data has different cutoff points for mean particle size in the Cyclade at the lower pressures and different temperatures as seen from the figure.

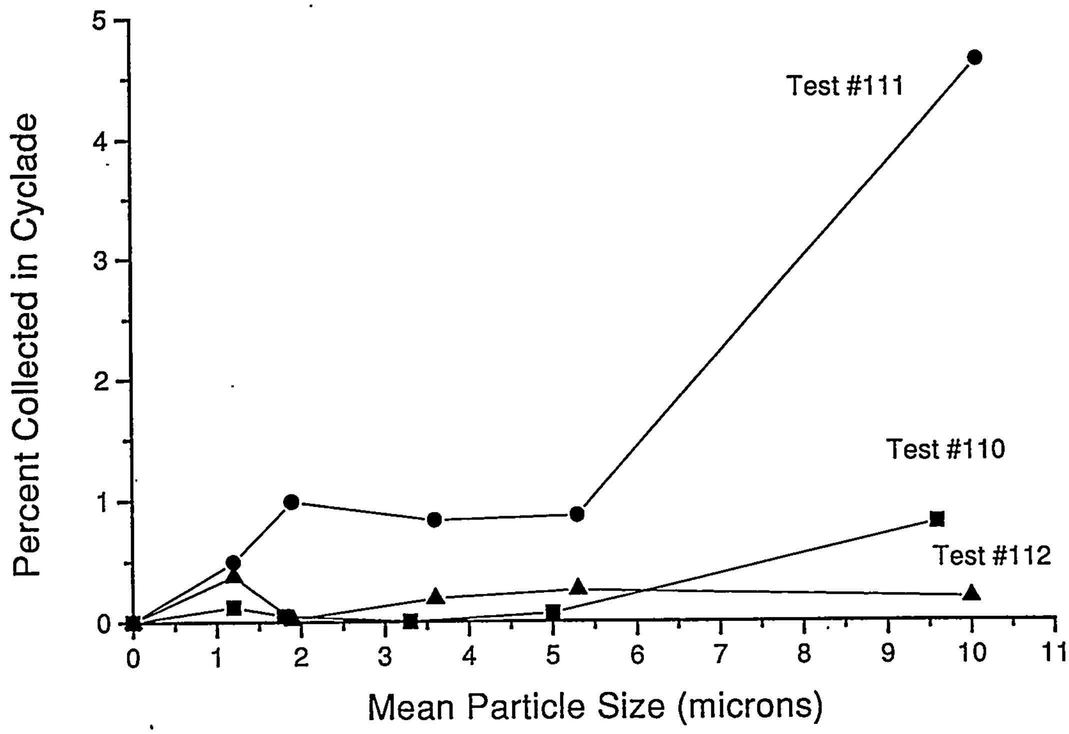


Figure 39. Low Frequency Test Results for 135 psig 12 gr/scf Tests

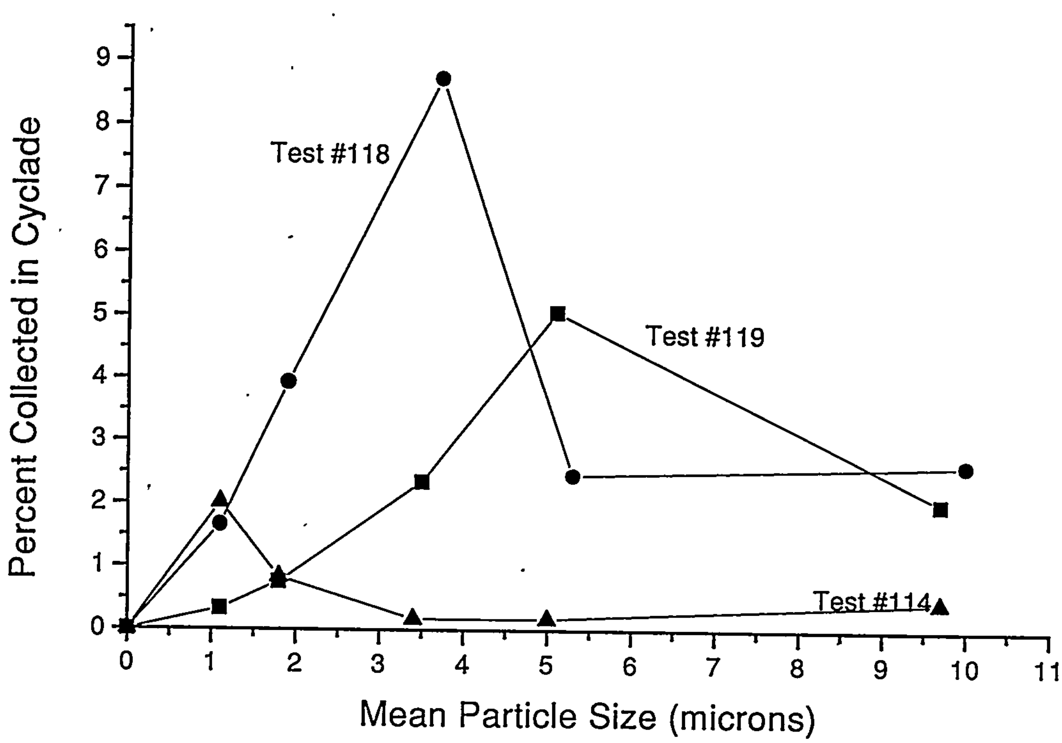


Figure 40. Low Frequency Test Results for 135 psig, 6 gr/scf

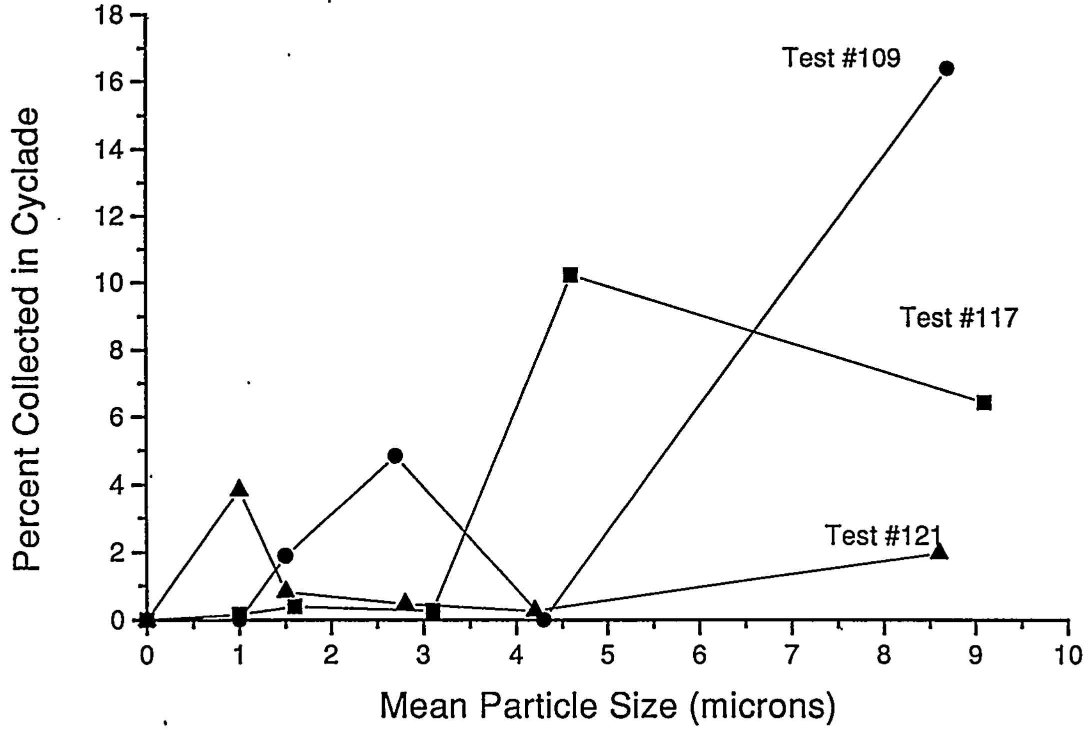


Figure 41. Low Frequency Test Results for 35 psig, 12 gr/scf

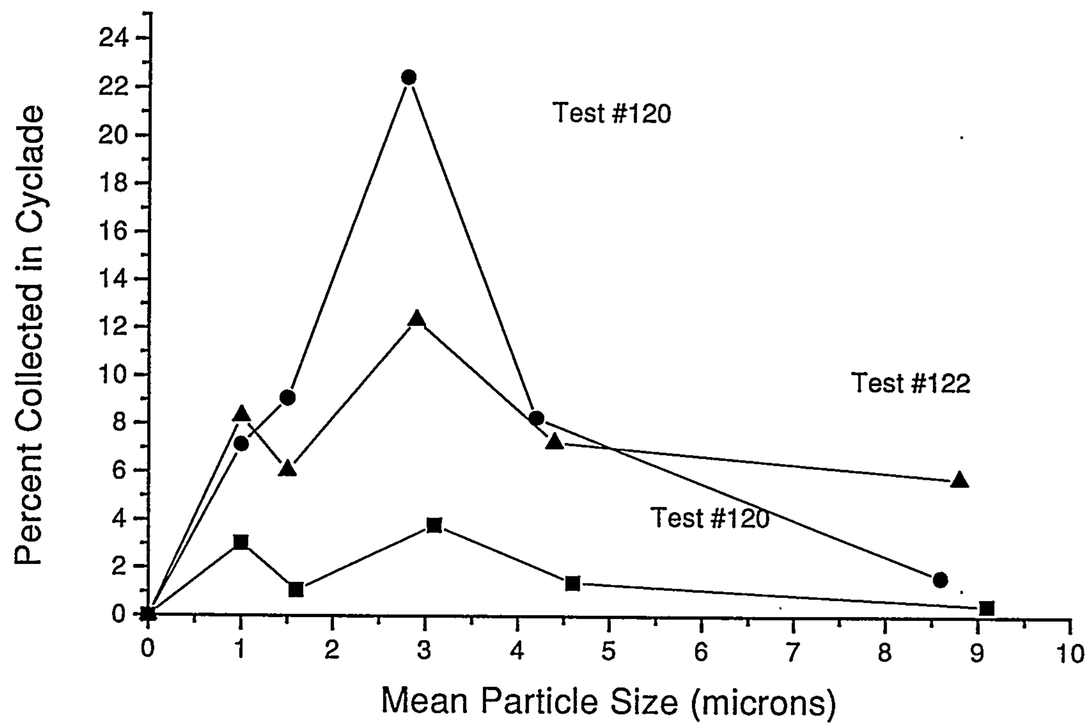


Figure 42. Low Frequency Tests Results for 35 psig, 6 gr/scf

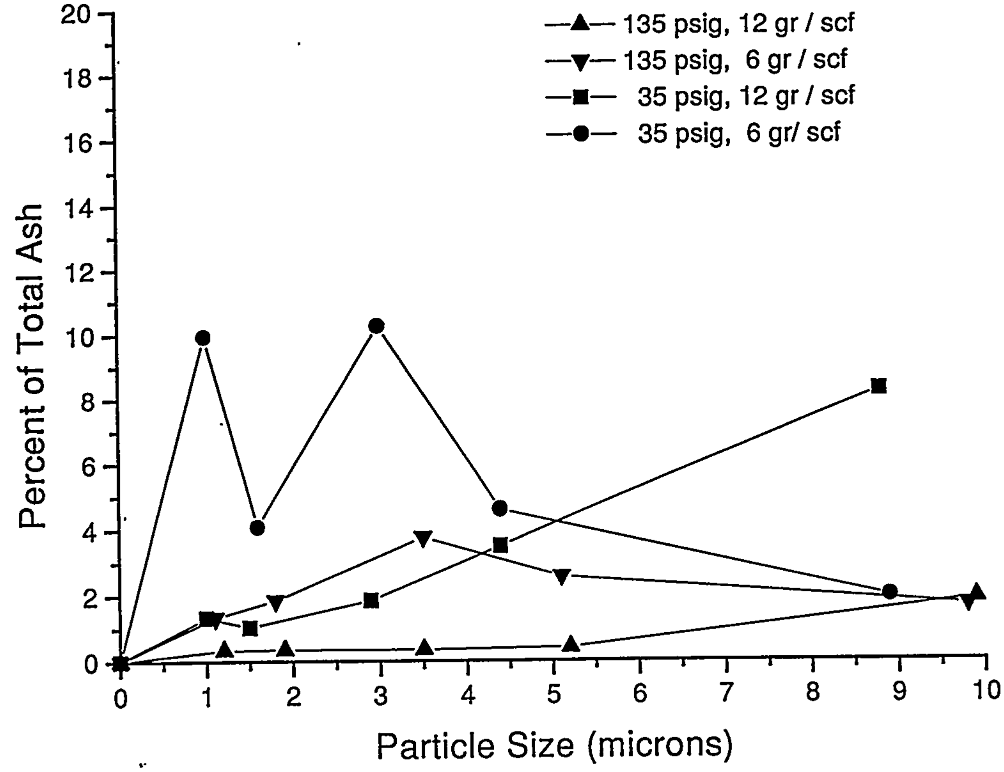


Figure 43. Averaged Percent of Ash Collected in Cyclade by Particle Size for Each of the Four Low Frequency Test Conditions.

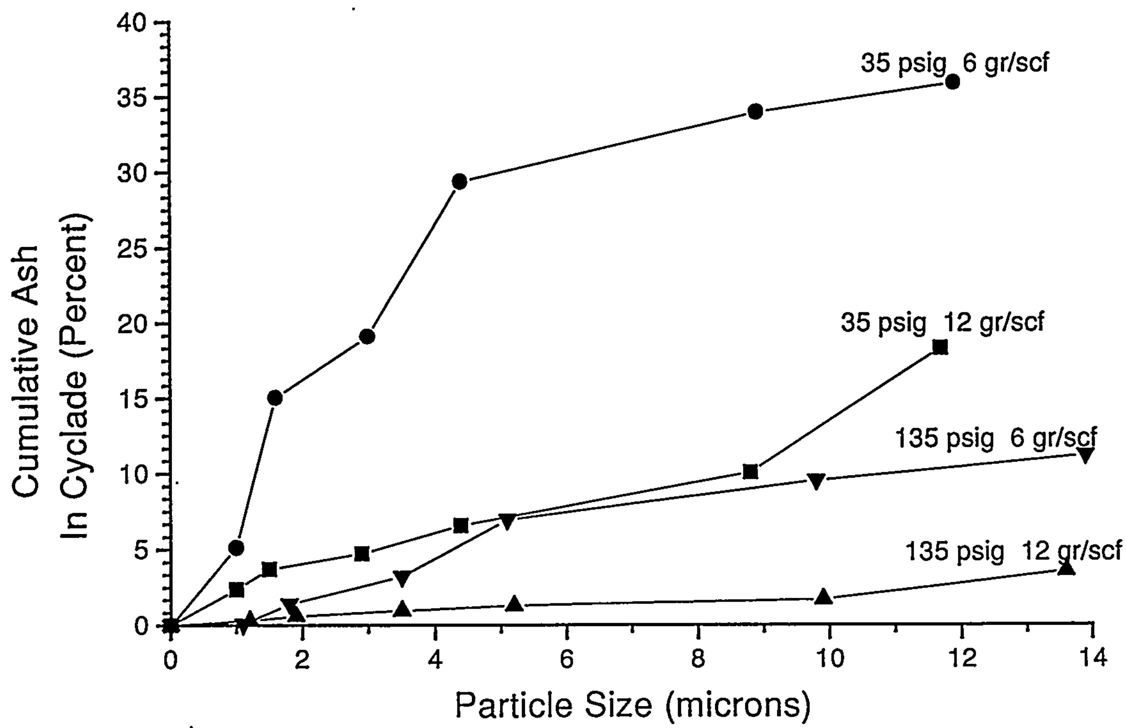


Figure 44. Cumulative Ash (By Weight) in Cyclade

The test results show much higher mass percentages for all the various micron size ranges than present in the "as-received" ash. This is an indication that the ash found in the sample line is the larger particle sizes dropping out of the flow stream. Since 85 percent of the ash mixture is over ten microns in size, the small particle sizes are essentially a small portion of the whole. If the large particles were not reaching the Cyclade™, then the apparent proportion of the smaller sizes would increase as seen in the data. For instance, if particles in the 4 to 5 micron range are two percent of the total, then the Cyclade™ would measure 2 grams in a 100 gram sample. Now if the larger particles drop out in the sample line (assume 80 grams for the purposes of illustration) then the two gram sample collected in the Cyclade™ in the 4 to 5 micron range is now ten percent of the total Cyclade™ sample(2/20). This is what the data is showing. The Cyclade™ percentage proportion of the sample is generally much larger than in the original ash mixture indicating the loss of the larger particles in the sample line. Therefore, only comparative analysis of the results is possible and quantitative analysis is not accurately possible.

The unanswered question is whether or not the large particles dropping out in the sample line affects the conclusions made from Figure 44. Certainly, the amount of ash collected in the first stage of the Cyclade (Stage 9) affects the percentage amounts in the other stages and hence the level shown in the graphs. However, since the flowrate through the Cyclade is the same for all tests, one can assume that the amounts of ash being collected in the sample opening should be the same for the same ash flows. The velocities and temperatures in the sample line should also be comparable and therefore the size of the particles dropping out in the line should be equivalent for each test pressure and ash flow.

The missing data are the (1) connection between the loss of particulates in the sample line on the results presented, and (2) the ash distribution in the chamber. The chamber ash flow was not mapped and the consistency and distribution across the chamber was not measured. More importantly is if the ash flow distribution in the chamber changes with ash flowrate or system pressure.

This assumption has not been verified for the testing reported on here and therefore the quality of the data is still suspect because of the large amounts of ash left in the sample line after the test. Testing to verify if the only the larger or smaller particles were selectively being deposited in the line and affecting the Cyclade™ results was not performed because the testing was terminated. The solution to the problem of ash dropping out in the sample line is to close couple the sampler and probe and reduce the line length to just the cooling jacket (about two feet).

3.2.3.3 Other Low Frequency Testing Issues

Other significant problems that occurred during checkout prior to testing were facility related and not directly involved with the measurement or collection of ash.

Ash Feeder Motor - Early in the testing, the ash feeding system was plagued with inconsistent and sporadic operation of the augur system. During some tests, the motor would not turn and indicated a power overload. The packing was loosened and this would alleviate the problem temporarily before the motor would seize again. Finally the packing was loosened to the point where the ash blew out past the packing into the atmosphere.

The motor would not turn with any sort of pressure on the shaft and one could stop it by hand. The motor was removed and electrical tests showed serious internal winding problems. The motor was then replaced with a new unit and there were no more ash feeding problems associated with the augur or feed system.

Glow Plug - Glow plugs, similar to those used for starting diesel engines, were used during the initial checkout runs of the low frequency agglomerator testing and proved very satisfactory. It was noticed that the glow plug would fail after several runs as indicated by an open circuit in the electrical loop. However, upon achieving operating conditions and rig stabilization for an ash run, the glow plug would rupture and shoot several feet across the top of the building. This was both a personnel and safety hazard as the tube was glowing red hot while being propelled at high velocity through the air. The glow plugs, although advertised as high temperature items, were meant to be cooled by a water jacket present in a diesel engine and not for uncooled operation. Air blast cooling was provided to the outside of the glow plug from shop air supply but that only prolonged the life of the plug from 1 to 4 hours before failure and did not solve the problem. Even if the plug survived the test intact, the electrical circuitry inside failed during any long exposure to high temperatures. The supply of glow plugs rapidly dwindled and are very expensive to replace.

The solution was to revert back to special long reach spark plugs that would place the spark in the same location as the hot tip of the glow plug. These units were built in house and would last several runs before requiring re-gapping the points or replacing the metal tip that would sometimes burn off. Two spark plugs were built so that there was always a spare and any failures would not impact the testing schedule. Once the proper depth of the plug was determined, these units worked extremely well and were good for 4-5 runs before requiring refurbishing. These plugs would also glow red hot on the outside and were cooled by directing a jet of shop air on the outer case. There were no light off or operational problems encountered after going to the spark plugs. Any failure to light the combustor was a direct result of the spark receiving heat damage from the previous runs and once the backup was installed the unit lite off the first time. The failed plug was then rebuilt immediately and held as a back up.

Fuel Tube - Combustion problems were also experienced when the flame relocated at the chamber inlet rather than in the combustion chamber. This sudden change in operating behavior was caused when the fuel injection broke off while running ash at steady state and preparing to sample. The fuel distribution, or injection tube, consists of a stub tube with numerous small holes around the circumference serving a fuel injector. It is located just inside of the combustion chamber where it mixes with the incoming air (see Figure 27). Once the injector broke off, the fuel would jet through the combustion chamber and without the proper mixing would not burn until it reached the agglomeration chamber where mixing would lean out the fuel/air mixture and allow burning to occur. The first indications of a problem was a rapid rise in the inlet gas temperature to the agglomeration chamber. This temperature is normally maintained around 1650°F by injecting cooling air at several ports around the chamber circumference. When the fuel injection tube broke off, the chamber inlet temperature rapidly rose to 2000°F and was continuing to increase. The unit was turned off because there was insufficient cooling air available to reduce and maintain the chamber inlet temperature below the design operating limit of 1700°F.

Subsequent attempts to re-light the combustor were unsuccessful and finally by adjusting the fuel/air ratio sufficiently the combustor was again started. However, the combustion characteristics were completely different than before in that the flame could not be maintained in the combustion chamber but would immediately jump down into the agglomeration chamber upon any attempt to increase operating pressure or power level. The full system was thoroughly checked and the disappearance of the inlet fuel injector discovered. The quarter inch tube was fastened to a half inch support tube with three spot welds that had broken off from fatigue at the point of the spot welds. The broken fuel tube then dropped through the combustor and agglomeration chamber and was found on the chamber floor.

The fuel distribution was re-attached and testing continued. Subsequent tests indicate that the tube must have been cracked for some time before breaking completely off and allowing fuel out the partial rupture. This conclusion was reached when the combustor operation was vastly different and improved following the repair. The operating stability of the system was also greatly improved and the noise level increased from about 160 dB to around 190 dB as seen in Figure 45. Also the noise spectrum had a sharp spike rather than a broad rounded peak that was evidenced prior to the repair. This is not seen in this figure but was noticed on the Rockland Scientific Corporation System/90 Model 9040 dual channel FFT signal analysis workstation that was on line and displaying the frequency spectrum for two microphones in real time during the tests.

3.2.4 <u>Ultra Low Frequency Testing</u>

It has been suggested that the agglomeration of particles increases even further at lower frequencies. Hence, the design and testing of an ultra low frequency pulse combustor was planned, built, but not tested because of budget constraints. The combustor is a natural gas fired unit with a firing rate of 1 MMBtu/hr. The frequency of the pulsations is around 68 Hz with a sound pressure level of 170 dB (at atmospheric pressure). The unit (Fig. 46) is designed to mount on the current test rig in place of the 150 hertz combustor (Ref. 5).

3.3 PHASE III - COMMERCIALIZATION PLAN

The initial contract called for an engineering and economic evaluation of the acoustic agglomeration system and a commercialization plan. This was also to include a balance of plant study of a second generation PFBC system with a coal fired pulsed topping combustor providing the acoustic energy for the acoustically enhanced cyclone system. Part of this task was to review the second generation PFBC systems developed by Foster Wheeler and M.W. Kellogg and the development work done by MTCI on the coal fired pulse topping combustor. Solar was also going to generate data on the effects of vitiated air on a coal fired pulse systems. These items along with the entire balance of plant study was eliminated from the program. The commercialization plan was also eliminated since Solar does not intend to enter the market as a supplier of hot gas clean-up devices. The initial motivation for Solar to perform this program was for a backup gas clean-up device for the coal fired gas turbine. However, a company policy decision to eliminate the coal fired gas turbine program also eliminated the need and desire for commercializing this product as it was not included in the product plan of the company.

Figure 45. Changes in Agglomeration Chamber SPL After Fixing Fuel Tube

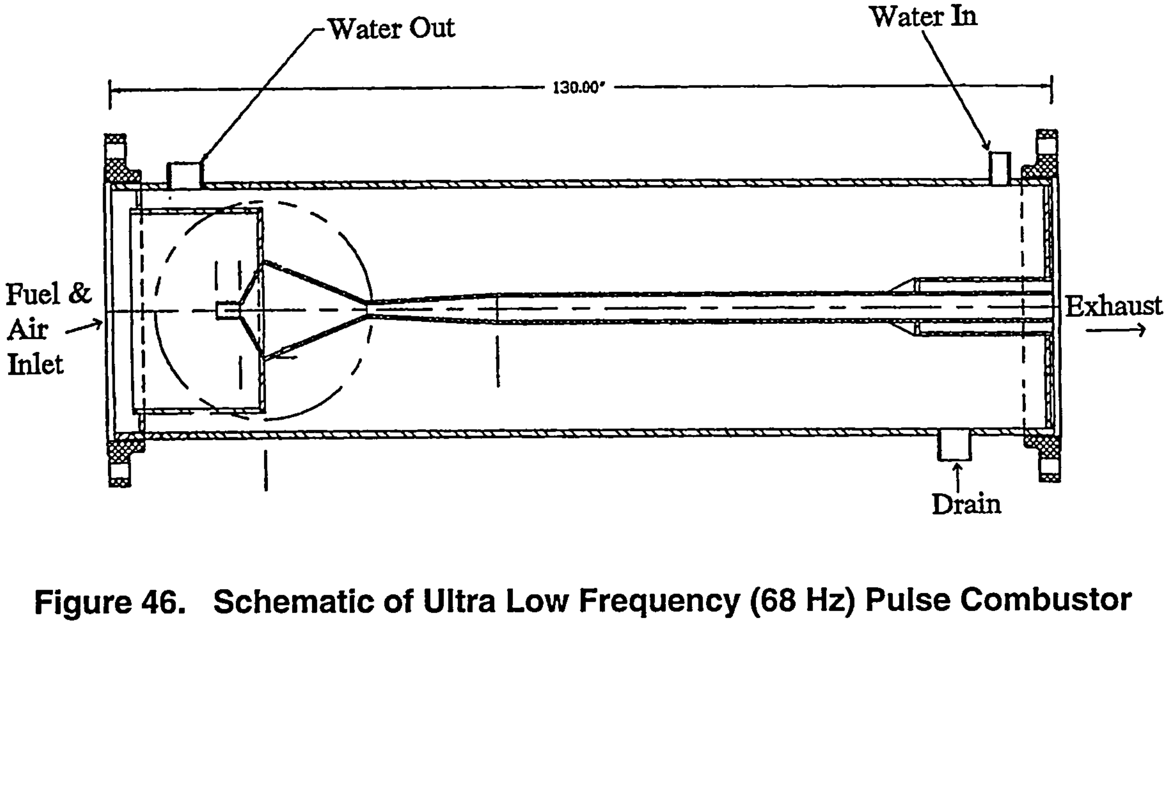


Figure 46. Schematic of Ultra Low Frequency (68 Hz) Pulse Combustor

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CONCLUSIONS & RECOMMENDATIONS

Pulse combustors have been proven as an acceptable method of providing the acoustic environment necessary for the agglomeration of ash to take place. High sound pressure levels were most easily achieved with low frequency pulse combustors (150 Hz nominal).

During high frequency testing performed with a 1000 Hz pulse combustor, data revealed that in an active sound field, the percentage of small particles is decreased through agglomeration, resulting in larger particles which are more likely to be cleaned by conventional means. Further testing is required to determine whether the reduction in the small micron mass fraction with the operating, acoustic sound source is truly significant.

Problems encountered with low frequency testing precluded any definitive conclusions from being reached. The large ash particles in the gas stream were dropping out in the sample line and the uncertainties associated with the collected amounts make it virtually impossible to conclude the effects and the extent of agglomeration that may exist in the chamber during low frequency exposure. Further test hardware improvements and verifications are necessary to reach significant conclusions.

Qualitatively, however, it appears from the data that some agglomeration is taking place in the low frequency testing. The agglomeration is more at the high pressure (135 psig) than at the lower pressure (35 psig) and more at the high ash loading (12 gr/scf) than at the low ash loading (6 gr/scr).

Pulse combustor ignition was a major concern at the onset of low frequency testing. However, it was determined after much testing, that ignition was about the same using either a glow plug or spark plug. However, the expense and durability of the glow plugs make them much less desirable for any commercial application. The spark ignitors would last several through tests before being rebuilt while the glow plugs were only good for one test.

5.0

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