TECHNICAL PROGRESS REPORT
August - October 1988

For:

U.S. Department of Energy
Morgantown Energy Technology Center

Under:

DOE Contract No. DE-AC21-88MC20069
Pulse Atmospheric Fluidized Bed Combustion

By:

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October 1988
This second Quarterly Technical Progress Report presents the results of work accomplished during the period July 25 through October 30, 1988 under Contract No. DE-AC21-88MC25069 entitled "Pulsed Atmospheric Fluidized Bed Combustion (PAFBC).

The overall objective of the program is the development of a pulsed atmospheric fluidized-bed combustion (PAFBC) technology to burn coal and to provide heat and steam to commercial, institutional, and small industrial applications at a reasonable price in an environmentally acceptable manner. The program scope consisted of two tasks; the first was to establish preliminary feasibility by the use of theoretical and state-of-the-art information. The task was completed during the first quarter of the contract period and a topical report entitled, "Pulsed Atmospheric Fluidized Bed Combustion (PAFBC) - Preliminary Feasibility Study" was prepared as a "decision point to proceed" deliverable in accordance with the terms of the contract. The first quarterly progress report therefore also covered the contract activities subsequent to the approval of the feasibility study and the decision to proceed with the Task 2 effort. As the initial quarterly technical progress report, that document also included a subsection on background which has been omitted in this second quarterly technical progress report.

Progress during this period accelerated rapidly. The site for the installation of the PAFBC was completed. All of the system components, including the fabrication of the furnace, were also completed. Additional component testing and inspection was also completed. By the end of this period the AFBC was completely assembled and installed at the site adjacent to the MTCI facility and shakedown tests were initiated.
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SECTION 1.0
PROJECT DESCRIPTION AND WORK STATUS

1.1 PROGRAM DESCRIPTION

The overall objective of the program is to develop the pulsed atmospheric fluidized-bed combustion (PAFBC) technology to burn coal and to provide heat and steam to commercial, institutional, and small industrial applications at a reasonable price in an environmentally acceptable manner.

Significant advancements have taken place regarding the design and operation of AFBC units of 50,000 - 100,000 pounds steam per hour capacity, but the potential of AFBC technology has not been fully investigated for small-scale applications. The AFBC technology has a tremendous market potential in small-scale installations of less than 50,000 pounds steam per hour equivalents. These smaller units meet the needs for process heat, hot water, low-quality steam, and space heating for a wide variety of uses. Currently, oil- and natural gas-fired equipment are being used for these applications. Due to the large difference between the prices of these fuels and coal, a coal-fueled AFBC technology engineered for these small-scale applications has the potential of being very competitive. A successful coal-fueled system will not only be less expensive, but will also lessen the nation’s dependence on foreign oil and open up new markets for domestic coal.

The technical characteristics of systems which can meet the objectives for entering these market sectors with packaged air heaters and boilers requires an AFBC technology that can supply process heat, process steam, hot air, and hot water for small industries, commercial and residential buildings, warehouses, hospitals and other such users. These small units must produce clean energy from high sulfur coals at competitive prices. Innovative
concepts and advanced AFBC systems having the following characteristics are needed to meet this objective:

- High combustion efficiency
- High SO$_2$ capture capacity
- Low NO$_x$ emissions
- Reliability, maintainability and safety of operations equivalent to oil- and gas-fired packaged systems
- Compatibility with conventional heat and steam distribution and control technology
- Cost competitiveness with gas- and oil-fueled systems
- Capacities in the ranges of 1,000 - 10,000 lbs. steam per hour equivalent.

The scale-down of large systems will probably not meet these requirements and there is therefore a need for:

- Simplification of system configurations and methods of control
- Improvements in system start-up capability and load following
- Enhanced system throughput with adequate pollution control and cost reduction.

1.2 TASK DESCRIPTIONS

**Task 1: Feasibility**

**Subtask 1.1: Evaluation** - The Contractor shall perform evaluation of state-of-the-art information on atmospheric fluidized-bed combustor (PAFBC) technology and pulsed combustion of coal. The Contractor shall review relevant published data and evaluate it for use in the feasibility study. Data on coals, sorbents, SO$_2$ and NO$_x$ control, characteristics of fluidized-bed coal combustors, pulsed combustion of coals, regeneration of spent sorbents, steam generation, ash disposal, and other aspects shall be used to formulate a design basis for the study.
Subtask 1.2: Market Analysis - For the new technology, the Contractor shall identify potential markets for generating heat and steam for different uses and shall make projections on the increased use of coal. The Contractor shall assess the competition from oil- and gas-fired units.

Subtask 1.3: Conceptual Design and Cost Estimate - Using the design basis formulated in Subtask 1.1, the Contractor shall develop a conceptual design of a PAFBC system that will produce 1,000 lbs/hr of steam equivalent. The Contractor shall prepare a preliminary cost estimate and shall compare the cost of the proposed system with the cost of oil- and gas-fired units currently in use.

Subtask 1.4: Test Plan for Task 2 Work - The Contractor shall identify problematic aspects of the technology and develop a test plan to resolve the problems through theoretical and experimental approaches. The Test Plan shall be submitted to the DOE/Contracting Officer's Technical Representative (COTR) for review and approval.

Subtask 1.5: Task 1 Topical Report - A Topical Report shall be prepared summarizing the PAFBC package boiler concept. The report shall include market, technical, design and cost information developed under Subtasks 1.1, 1.2, and 1.3, and the Test Plan developed under Subtask 1.4. The report shall include a review of the coal/sorbent feed, ash handling and cleanup systems, and the sensitivity of these factors on environmental system capital and operating and maintenance costs. The report shall also address the system's potential for meeting the following criteria and provide the material required to proceed to the performance of Task 2:

- The PAFBC combustor and controls technology must be competitive with gas-/oil-fired technology and scaleable to the 1,000 lb/hr steam equivalent range.

- The solids handling problems must be amenable to automated dust-free operation.
Overall emissions (SO₂, NOₓ, and particulates) must be comparable to those of conventional gas/oil-fired equipment.

The PAFBC system must require no operating or maintenance skills beyond those needed to operate equivalent gas/oil-fired equipment.

A significant market potential must exist for the integrated PAFBC technology.

**Task 2: Laboratory-Scale Development and Testing**

The testing specified in these subtasks will be conducted in accordance with the approved Test Plan.

**Subtask 2.1: Design, Procurement, and Construction of an Atmospheric Fluidized-Bed Combustor** - The Contractor shall design, procure, and build a fluidized-bed system with the following features:

- Capacity: 1,000 lbs steam/hr
- Fluidizing Velocity: 5 - 10 ft/sec
- Sorbent: Precalcined dolomite or limestone
- Coal: Bituminous/Sulfur Content: 2 - 4%
- Temperature of Operation: 1400 - 1750°F

**Subtask 2.2: Coal Combustion Tests in the PAFBC System** - The Contractor shall carry out coal combustion tests under a range of conditions as set forth in the approved Test Plan to establish baseline performance data. Tests shall be carried out under the following conditions:

- Superficial Velocity: 5 - 10 ft/sec
- Temperature: 1400 - 1750°F
- Pressure: Near Atmospheric
- Mode of Operation: Batch with respect to sorbent and continuous with respect to coal
- Coal: Bituminous/Sulfur Content: 2 - 4%
Sorbent: Precalcined dolomite or limestone
Ca/S: 2 - 4

The Contractor shall use the test data to optimize operational parameters with respect to fluidization velocity, sorbent/coal ratio, temperature of operation, combustion efficiency, steam generation, NO\textsubscript{x} control and sulfur capture, and establish optimum operational parameters and baseline performance data.

**Subtask 2.3: Modification of PAFBC System for Pulsed Combustion of Coal** - The Contractor shall modify the PAFBC system by the incorporation of a pulse combustor that supplies pulsed effluent gas to fluidize the bed. The needed modifications and the geometry of the pulsed PAFBC combustor shall be as determined under Subtask 1.3 study.

**Subtask 2.4: Operation of the Pulsed PAFBC Without Coal** - The Contractor shall operate the fluidized-bed combustor in the pulsed mode to establish fluidization parameters under pulsing conditions and determine the effect of pulsations on fluidization velocity, bed expansion, and particle elutriation at optimum conditions for fluidization under pulsed conditions.

**Subtask 2.5: Coal Combustion Tests in the PAFBC System** - The Contractor shall carry out coal combustion tests under a range of conditions established under Subtasks 2.1 and 2.4, generating test data to evaluate operability, performance and pollution control efficiency of the PAFBC system, and optimization of design and operational parameters.

**Subtask 2.6: Technical, Environmental, and Economic Assessment** - The Contractor shall perform technical, environmental, and economic evaluations based on experimental data generated under Subtasks 2.2, 2.4, and 2.5.
1.3 SUMMARY STATUS

All effort during this period was devoted to the completion of the assembly and installation of the PAFBC. The site, adjacent to the MTCI building which was chosen for the installation of the PAFBC, was completed. All of the ancillary components that were purchased and/or renovated were tested. The program pace accelerated rapidly as soon as the fabrication of the furnace was completed and delivered to MTCI.

The assembly and installation of the system was completed and installed at the test site. Some additional safety features were included in the system to avoid accumulation of any unburned gases in the freeboard section during operation. A start-up burner system for the baseline tests was also installed in the main combustion air stream. A delivery of a high sulphur coal from Island Creek Coal Company, as well as calcium grits, was received and shakedown as well as cold-flow tests were initiated. Data from the initial set of cold-flow tests are being analyzed in order to initiate the development of an integrated design for the pulse combustor.
SECTION 2.0
TECHNICAL DISCUSSION OF WORK COMPLETED DURING THE REPORTING PERIOD

The fabrication, assembly and installation of the Atmospheric Fluidized Bed Combustor (AFBC) System was completed during this reporting period. Figure 1 shows the AFBC system layout. Shakedown tests of the unit were initiated as well as cold-flow pilot tests for development of the pulse combustor’s integrated design. The following discussion provides the details of the system components and the initial tests.

The Combustor Section

Primary combustion air is supplied through a 4-inch C.S. manifold to the pipe grids located beneath the fluidized bed. Air is introduced into the bed through approximately 100 orifice nozzles per tube which are uniformly spaced, both circumferentially and longitudinally, around the pipe grids. Boiler tubes are mounted within the bed to maintain the bed temperature between 1500°F - 1600°F. The primary combustion air blower is of a positive displacement variety. The air flow rate to the AFBC is controlled by a blow-off vent valve. Due to high noise level at the air blower vent valve, a silencer is mounted at its exit to reduce the noise level by expanding the airflow from a 2-inch pipe into a 40-gallon C.S. tank. Figure 2 shows a schematic of the silencer.

As a combustor safety feature, a pilot flame has been placed slightly above the bed in order to avoid the accumulation of any unburned gases in the freeboard section. Figure 3 shows a schematic of the 8,000 Btu/hr pilot burner. A pre-mixed mixture of gas and air enters the burner tube and an electrical spark plug ignites the mixture. A flame holder has been positioned to keep the flame source inside the tube. A thermocouple is placed downstream of the flame holder in order to verify existence of the flame.
FIGURE 1: AFBC SYSTEM LAYOUT
FIGURE 2: SCHEMATIC OF THE SILENCER
FIGURE 3: SCHEMATIC OF THE PILOT BURNER
All of the designated ports were placed on the furnace body to prepare the furnace for pouring the two layers of refractory inside the furnace walls. V-shape anchors 4" long were prepared and welded to the furnace walls in order to hold the refractory layers in place. The curing period for the refractory layers was about one week.

The in-bed steam coils have been fabricated and were placed inside the furnace before pouring the refractory, for ease of installation. The pipe grid air distributor is also completed and will be installed after the refractory has been poured. Figure 4(a), shows a photograph of the AFBC furnace structure without the freeboard section. Figure 4(b) shows the AFBC furnace freeboard section.

A 1-inch solids draw-off valve has been placed in the furnace section to maintain the bed level at the desired height. The draw-off valve is slanted to allow gravity overflow of the bed solids to a sealed collection drum.

In addition, a screw-type solids sample valve has been placed on the furnace wall. The sample valve will allow monitoring of the bed carbon inventory level during a test run. Figure 5 shows a schematic of the sample valve.

Coal and Limestone Feeding System

The coal and limestone will be fed at a single port above the fluidized bed. The coal and limestone will be pre-mixed at a ratio of Ca/S of 2 in a 3'x 2'x 4' C.S. live bottom hopper and will be fed by screw feeder into the combustor. Because of high temperatures in the fluidized bed combustor, a 1 ft screw extension made of stainless steel 304 material has been ordered which will be mounted on the main C.S. screw. In addition, the screw barrel will be water-cooled to prevent significant pyrolysis and agglomeration within the screw flights.
FIGURE 4(A): THE AFBC FURNACE STRUCTURE

FIGURE 4(B): THE AFBC FREEBOARD SECTION
FIGURE 5: SCHEMATIC OF THE SAMPLE VALVE
Flue Gas/Heat Exchange System

The combustion gases exit the fluidized bed combustor at a temperature of 1600°F - 1700°F. An induced draft fan maintains a suction draft for the flue gases. The hot gases, containing fly ash and elutriates, enter a stainless steel cyclone. The solids entrained in the flue gas will be collected in a stainless steel drum. The flue gas exiting the cyclone is then cooled to approximately 300°F as it passes through the water spray quench system before it is vented to the atmosphere.

Start-Up Burner

A 500,000 Btu/hr gas burner is installed in the main combustion air stream which will preheat the air to about 1200°F before it enters the fluidized bed furnace. The air from the main air blower is supplied to the burner through a bypass line and gate valve that will control the air flow to the burner. Figure 6 shows a schematic of the start-up burner system. During start-up, the burner will be down-fired into the bed while maintaining low-velocity fluidization conditions in order to distribute heat uniformly throughout the bed. As the bed temperature reaches 1000°F, the start-up burner will be shut off and coal and limestone will be fed into the bed. The start-up gas burner will be controlled manually; however, it will include a gas shut-off valve which will be actuated in the case of a flame-out or bed over-temperature condition. Figure 7 is a photograph of the installed burner.

Control Panel

The AFBC control panel has been fabricated and final instrumentation connections and checkout were completed. The control panel includes all necessary flow controllers, temperature and pressure monitors, ignitor switches and alarms.
FIGURE 7: GAS-FIRED BURNER FOR INITIAL BED HEAT UP
Stack Gas Monitoring Equipment

Oxygen, carbon monoxide and combustibles will be monitored using a portable Teledyne. NO\textsubscript{x} and SO\textsubscript{2} will be monitored using a Horiba analyzer. Flue gases may also be analyzed using a Microsensor gas chromatograph. Sample ports will be located in the freeboard, cyclone exit, and stack.

Test Site

The preparation work of the outdoor test site for the PAFBC system was completed. Water, gas, air, and electricity lines have been supplied to the test site. Figure 8 shows the completed outdoor test site at the MTCI facility prior to installation of equipment. Work has also been completed on refurbishing the second Roots blower for combustion air. Figure 9 shows the Roots blower (type 710 AF) being installed at the test site.

Figure 10 shows the AFBC furnace in place at the MTCI facility test site. Figures 11(a) and 11(b) show the steam drum for the AFBC system with liquid level switch installed and all the necessary plumbing completed. A 2 HP electric motor with a 4" diameter impeller liquid pump and 2 ft of net positive suction head has been selected for the boiler circulation water. Figure 12 shows the plot plan for the AFBC system. The system has been configured in a compact arrangement and occupies approximately 100 square feet of floor space. Additional space also has been provided for the future installation of a convection section that would replace the quench system currently located at the exit of the fluidized bed combustor.
FIGURE 8: AFBC OUTDOOR TEST SITE AT MTCI FACILITY
FIGURE 9: ROOTS BLOWER (TYPE 710 AF) INSTALLED AT THE TEST SITE
FIGURE 10: ATMOSPHERIC FLUIDIZED BED COMBUSTOR
AT THE MTCI TEST FACILITY
FIGURE 11: STEAM DRUM FOR THE AFBC SYSTEM
FIGURE 12: PLOT PLAN FOR THE AFBC SYSTEM
**System Instrumentation**

A total of 12 thermocouples have been placed in the bed section of the AFBC at different heights and locations in order to monitor the bed temperature. Also, thermocouples have been placed in the expansion section and the freeboard section.

In-bed pressure taps have been placed at one-foot intervals in order to monitor the bed depth and fluidization characteristics. A valve has been placed at the inlet of two of the steam coils in order to control the amount of heat extracted from the bed. Flue gas will be analyzed for NO\textsubscript{x}, SO\textsubscript{2}, CO\textsubscript{2}, O\textsubscript{2} and unburned carbon after the cyclone. Thermocouples have been placed at several different locations to monitor the flue gas temperature.

**Pulse Combustion Design**

Two separate pulse combustor configurations are being considered for testing in the pulse-enhanced FBC concept. In the first configuration, a single tailpipe from the pulse combustor will be immersed in the fluid bed. The tailpipe will be shrouded by an annular draft tube as described in previous reports. In the second configuration, multiple resonance tubes are employed to more evenly distribute combustion gases within the bed.

*Figure 13* shows the multiple tube pulse combustor design for the AFBC system. The pulse combustor is designed for a firing range from 200,000 Btu/hr to 500,000 Btu/hr. The pulse combustor will operate at a quarter wave frequency in the range of 40 to 50 Hz. The combustion chamber is refractory lined in order to control the heat losses and promote rapid combustion. The refractory thickness is optimized to avoid slagging conditions. A thrust augmenter is employed to pump combustion air into the pipe grids to help bed fluidization. There is a total of 12 3/4-inch SS 304 tubes which will penetrate into the bed. An 80-gallon carbon-steel tank has been purchased to be used as a steam drum.
50,000 BTU/HR PULSE COMBUSTOR FOR PAFBC SYSTEM

FIGURE 13: DESIGN OF THE AFBC MULTI-TUBE PULSE COMBUSTOR
Figure 14 shows a photograph of the steam drum. The tank has been sand blasted inside in order to clean all the rusts and corroded surfaces. To assure that a minimum water level is maintained in the drum, a liquid level switch has been purchased. The liquid level switch is composed of two stainless steel electrodes, which are placed vertically inside the steam drum at a low and a high level, and a dual function relay.

Process

Figure 15 shows the process flow diagram for the PAFBC system. Fluidization air is supplied by the Roots blower (type 710 AF). Air flow rate is controlled by a vent valve placed at the exit line of the blower. The initial start-up bed will be limestone particles, with an average diameter of 1.5 mm. Coal and limestone will be fed mechanically with a screw feeder at a desired ratio of Ca/S=2 into a single screw feeder, which will feed the coal and limestone mixture into the bed. The flue gases exit the furnace at about 1600°F and enter into a cyclone. A stainless-steel cyclone has been designed for and built at MTCI. Figure 16 shows the sketch of the cyclone. Afterwards, the cyclone flue gas is directed to a 10" stainless-steel pipe furnished with a water spray to cool down the flue gases, which are then vented to the atmosphere.

Coal-Combustion Tests in the AFBC System

A series of shakedown tests have been performed on the AFBC system to check the system operation and also to debug the system. Additional shakedown tests will be performed on the AFBC system without the bed to further cure the refractory walls of the furnace. During the next period, hot fluidization tests will be performed to characterize the AFBC with solids. Coal combustion tests will be conducted in late November to gather baseline data for the AFBC system. Later, the AFBC will be retrofitted with a pulse combustor to compare performance in the PAFBC.
FIGURE 14: STEAM DRUM FOR AFBC SYSTEM
FIGURE 15: PROCESS FLOW DIAGRAM FOR THE PAFBC SYSTEM
FIGURE 16: DRAWING OF THE AFBC CYCLONE
Four tons of high sulfur coal (-1/4" x 0) have been obtained from Island Creek Coal Company for PAFBC tests. Cold flow fluidization tests were conducted to characterize the fluidization properties of the bed material. Four tons of high calcium grits have been purchased. The chemical composition of the grits is shown in Table 1. Table 2 shows the particle size analysis for these particular grits.

Figure 17 shows the pilot fluidization test result performed on the limestone grits #9. The bed dimensions for the pilot apparatus are a scale-down of the actual AFAC furnace.

As shown in Figure 16, the minimum fluidization velocity is approximately 2.5 ft/sec. This corresponds reasonably well with the calculated value of 2.9 ft/sec. Extrapolation to the hot conditions of the operating AFBC yield an expected fluidization velocity of approximately 2.0 ft/sec. Thus, at full load, the AFBC will operate at two to three times the minimum fluidization velocity. Figure 18 shows the test set-up for the pilot test.

Modification of AFBC to Pulsed AFBC

The benefits of incorporating a pulse combustor in the AFBC have been discussed at some length in previous monthly reports and in the Phase I report under this program. Briefly, these benefits include: (1) the ability to burn fines directly in the pulse combustor, thus avoiding excessive elutriation during overbed feeding, (2) the ability to recycle ash to the pulse combustor to complete carbon burn-out and enhance combustion efficiency, (3) increase reactivity of bed by reducing bubble growth and stimulating turbulence, (4) improving system responsiveness and reducing start-up time, and (5) reducing parasitic fan power requirements.
TABLE 1:
CHEMICAL COMPOSITION OF THE GRITS #9

CHEMICAL COMPOSITION - (typical)

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<thead>
<tr>
<th></th>
<th>Chemical Formula</th>
<th>Weight (%)</th>
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<tbody>
<tr>
<td>Calcium Carbonate</td>
<td>CaCO₃</td>
<td>98.0%</td>
</tr>
<tr>
<td>Magnesium Carbonate</td>
<td>MgCO₃</td>
<td>0.6%</td>
</tr>
<tr>
<td>Silicon Dioxide</td>
<td>SiO₂</td>
<td>0.2%</td>
</tr>
<tr>
<td>Aluminum Oxide</td>
<td>Al₂O₃</td>
<td>0.1%</td>
</tr>
<tr>
<td>Ferric Oxide</td>
<td>Fe₂O₃</td>
<td>0.25%</td>
</tr>
</tbody>
</table>

TABLE 2:
PARTICLE SIZE ANALYSIS OF THE GRITS #9

SCREEN SIZE

<table>
<thead>
<tr>
<th>MESH NO.</th>
<th>AVERAGE DIAMETER (MICRONS)</th>
<th>% WEIGHT RETAINED ON THE SCREEN</th>
</tr>
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<tbody>
<tr>
<td>6</td>
<td>-</td>
<td>0</td>
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<tr>
<td>10</td>
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<td>725</td>
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<td>PAN</td>
<td>300</td>
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FIGURE 17: COLD AIR FLUIDIZATION TEST ON LIMESTONE
(AVERAGE DIAMETERS, 1.6 mm)
FIGURE 18: TEST SETUP FOR PILOT FLUIDIZATION TEST
In addition, it is now believed that the pulse combustor can be utilized to create long-range circulation patterns within the bed that will enhance mixing of large coal particles during the early pyrolysis flame stage. This may significantly enhance combustion performance for certain fuels.

According to a research study conducted by the Babcock & Wilcox research group on the effect of fuel characteristics on Atmospheric Fluidized Bed Combustor performance, medium- to large-sized coal particles have a tendency to float on the top of a conventional bubbling fluidized bed due to buoyancy forces. When the coal is first introduced, it begins to burn with a visible pyrolysis flame which extends into the freeboard section. This phenomena increases NO\textsubscript{x} production in the vicinity of the flame and releases sulfur gases into the freeboard where sulfur capture is minimal. In the PAFBC system a pulse combustor will be mounted on the top of the fluidized bed furnace with a single tailpipe immersed into the fluidized bed. The flue gases will exit the tailpipe with sufficient velocity to create a circulating flow pattern as shown in Figure 19. This causes the coal particles to be circulated within the bed and prevent buoyant burning at the surface.

A series of cold flow pilot tests were performed in order to obtain an optimum location of the tailpipe in relation to the bed and to investigate the range of the flow velocities which will promote the desired circulating phenomena.

Data from the cold flow tests are being analyzed to develop designs for the pulse combustor to be used in the initial PAFBC tests. A preliminary design for the single tailpipe pulse combustor is shown in Figure 20.
FIGURE 19: SCHEMATIC OF THE CIRCULATING FLOW PATTERN WITHIN THE BED
FIGURE 20: SCHEMATIC OF THE PULSE COMBUSTOR FOR THE AFBC SYSTEM
SECTION 3.0
PLANS FOR NEXT PERIOD

With the completion of the procurement, fabrication and delivery of components for the pulsed AFBC program, progress accelerated rapidly. The installation of the unit at the test site and initiation of shakedown tests should now begin to approach the revised program schedule. The original schedule was revised because of the delay in initiating work on Task 2 and the delay in delivery and fabrication of parts.