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MTCI 90278-104

**Development of a Coal Fired Pulse Combustor for
Residential Space Heating**

**TECHNICAL PROGRESS REPORT
JULY - SEPTEMBER 1987**

Prepared For:

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PREFACE

A detailed description of the background technology application and Phase II Statement of Work for the development of a coal-fired pulse combustor for residential space heating was provided in the first quarterly report for the period October - December, 1986, report no. MTCI 90278-101. This material is omitted in this report.

The Phase I effort was nearing completion during this reporting period and a final report is in preparation. The configuration testing was completed early in the period and based upon results of the configuration tests, an optimized configuration for the experimental development testing was chosen. The refractory-lined chambers were fabricated and tested from mid-September through early October. The tandem unit was operated on DUC without support gas or excitation air for periods lasting from one to three hours. Performance was stable and turndown ratios of 3:1 were achieved during the first three-hour test.

A early commercial residential heating system configuration has been identified on the basis of the development testing conducted throughout the first phase of this effort. The development effort indicates that the residential unit goals are achievable with some additional product improvement effort to increase carbon burn-out efficiency, reduce CO emissions and develop a reliable and compact dry, ultrafine coal feed system (not included in the present effort).

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SECTION 1.0

PROGRAM DESCRIPTION AND WORK STATUS

1.1 PROGRAM DESCRIPTION

The systematic development of the residential combustion system is divided into three phases. Only Phase I is detailed here. Phase I constitutes the design, fabrication, testing, and evaluation of a pulse combustor sized for residential space heating. Phase II is an optional phase to develop an integrated system including a heat exchanger. Phase III is projected as a field test of the integrated coal-fired residential space heater. The program logic is depicted in Figure 1.

The objective of Phase I is to develop an advanced pulse coal combustor at the 100,000 Btu/hr scale which can later be integrated with a heat exchanger and controls to form a residential space heater. Phase I is comprised of four technical tasks which are described below.

The initial test fuels for the Phase I and II effort were expected to be coal slurries. However, it soon became obvious that the availability of the slurries during the development stage would be somewhat problematic and could become an impediment to maintaining progress and schedule. It was therefore decided, after discussions with the DOE Project Manager, to focus the Phase I and II effort upon the use of DUC and to consider the slurries for a product improvement activity in later phases of the program. This change will not affect the cost, schedule, or technical objectives of the Statement of Work.

TASK 1:

Task 1.1 Design of 100,000 Btu/hr pulse combustor

Although small pulse combustors (100,000 Btu/hr) have been built for natural gas and oil, none have been built for coal firing. Coal combustion requires more residence time than oil and gas. This is more of a factor for coal-mixtures, since the water needs to be evaporated first before the coal can burn. The design of the small pulse coal combustor should allow for the longer residence time requirements of slurry fuels, as well as the need for proper atomization of the slurry into the combustion chamber. In this regard, micronized coal slurries, such as the OTISCA coal slurry, may be better for small combustors since smaller coal particles would require less residence time for complete combustion.

Similarly, two chamber geometries will be designed and tested to arrive at a suitable combustor. With regards to the tail pipe, a single-tube tail pipe and multi-tube exhaust system will be designed for evaluation. A cyclone will also be designed to remove the particulate matter. In one case, the cyclone may be used as a second-stage combustor as well. All the components shall be made of metal and shall be capable of high temperatures. All accessories such as the slurry feeding system for the development unit will be specified.

FIGURE 1: PROGRAM LOGIC FOR THE DEVELOPMENT OF AN ADVANCED PULSED-COAL COMBUSTOR FOR RESIDENTIAL SPACE HEATING

An ignitor, pressure fluctuation monitoring sensor, temperature sensors, and other necessary control and monitoring instrumentation will be specified. SUR-LITE Corporation will be employed on a consulting basis for their expertise in ignitors and control instrumentation.

Task 1.2 Fabrication of a Pulse Coal Combustor

Pulse combustor components specified in the design in Task 1 will be fabricated and/or procured. Efforts will be made to utilize off-the-shelf components to the greatest extent possible. Kistler pressure transducer instrumentation will be used and a coal slurry pump and baghouse will be procured. During this stage of the program, arrangements will be made to obtain different types of coals. Initial test configuration will be set-up after completing the procurement. The combustor hardware will be assembled and unit operability determined.

Task 1.3 Testing the Pulse Coal Combustor

This is the major and most important task of this program. After completion of the set-up of the test unit, shake-down testing will be done to ensure safety during the regular test. The test plan developed under Task 1.1 shall consist of three major elements: 1) combustor geometry (including the tail pipe and aerodynamic valve) variations, 2) fuel types, and 3) controls evaluation. For the combustor geometry variations, two aerodynamic valves, two chambers and two tail pipes will be evaluated. In the case of the fuel types, first the combustor will be tested with natural gas and then with No. 2 fuel oil. Combustion air/fuel ratio, pressure boost, frequency, peak pressure variations, noise levels, temperatures and analysis of exhaust gases for O₂, N₂, CO, CO₂, and NO₂ will be performed. Combustion efficiency will be calculated. Then the unit will be tested on three coals, chosen in consultation with DOE. Table 1 provides the fuels test matrix. Particulate loading of the exhaust gases will be determined by the EPA method 5. Operational noise levels will be measured at various points in the laboratory.

In each test series, there will be a number of tests dictated by the variations in configurations to be tested. The test matrix does not give the details of the individual tests. In early testing series, some of the configurational variation may be found useless to pursue and such combinations will be eliminated in the later series. When feeding coal-based fuel to the pulse combustor, the particulates collected and flue gases will be analyzed to determine unburned carbon and combustion efficiency. MTCI will use gas chromatograph and instrumentation equipment already on-hand for gas analysis.

TABLE 1: Test Matrix - Phase I

<u>TEST SERIES NO.</u>	<u>FEED</u>	<u>CONFIGURATION EVALUATION</u>	<u>CONTROL EVALUATION</u>	<u>EMISSIONS MONITORING</u>
1.	Natural Gas	Yes	No	Yes
2.	#2 Fuel Oil	Yes	No	Yes
3.	Coal Fuel #1	Yes	Yes	Yes
4.	Coal Fuel #2	No	Yes	Yes
5.	Coal Fuel #3	No	Yes	Yes

Task 1.4 Evaluation and Selection of Optimum Configuration for Integrated Testing

The test data collected in Task 1.3 will be analyzed carefully. Based on the test results, an optimum configuration will be selected for further study as an integrated system in Phase II. This configuration will have the potential to meet or exceed the performance criteria and, in addition, will have the capability for fuel flexibility.

Whereas the emphasis in Phase I will be on the pulse combustor development, the emphasis in Phase II will be on testing and evaluating heat transfer/heat exchange equipment as integrated with the pulse combustor. Based on the level of success achieved during Phase I work, progressive development and testing of integrated combustor/heat exchanger subsystems will be performed.

1.2 STATUS

The Phase I effort was substantially completed during this period and a final Phase I report is being prepared. The last experimental run under the present Phase I effort was actually completed on October 8, 1987 but the data is reported here to provide a complete data set for the test series utilizing the optimized tandem development unit.

Development testing of the tandem units was completed early in the period. Three configurations for coupling of the units were evaluated. The technique chosen for the extensive optimization development testing was one in which the tailpipes were coupled at the exhaust plenum. The refractory chambers were fabricated, the system assembled and operated for a series of tests. The feasibility of wet ash collection was also verified. Four long-duration tests were completed (1-3 hours). In the first test, stable performance over a 3:1 turndown ratio was achieved with a carbon burn-out efficiency of 97.7 percent (based on ash analysis). Performance during all tests in the series was both stable and ran without support gas or excitation air.

Based on the performance of the units during both the preliminary configuration testing and the long-term optimization evaluation testing, an optimum configuration for the residential heating system was chosen for the Phase 2 effort. The key features include the tandem configuration with tailpipe coupling, refractory-lined conical combustors, automatic fuel biasing and a wet cyclone particulate trap.

SECTION 2.0

TECHNICAL DISCUSSION OF WORK COMPLETED DURING THE REPORTING PERIOD

The tandem configuration unit tests were completed during this period. Three different coupling techniques were evaluated empirically:

1) Coupling at the tailpipes by pointing the tailpipes towards each other and exhausting the flue gases into a common plenum or decoupling chamber, (Figure 2); 2) Coupling at the aerodynamic valves by pointing the aerodynamic valves towards each other (Figure 3). A common decoupling inlet plenum around the aerodynamic valves, and 3) Coupling the combustion chambers through an air feed Tee connecting to a single aerodynamic valve (Figure 4).

Coupling through the air feed Tee was found to be inoperable. This is evidently due to the fact that the flow resistance in the air feed Tee connecting each chamber was quite small. Thus, large quantities of combustion products were simply transported from one chamber to the next thereby dampening oscillations and extinguishing combustion. In the case of fuel phasing, the volumetric ratio of fuel to combustion products is quite small. Thus, only a small fraction of combustion generated products is necessary to provide the motive force for inducing phased fuel injection. In contrast, the volumetric ratio of combustion air to combustion products is relatively high. It is apparent that the quantity of combustion products required to induce sufficient quantities of combustion air is too large for coupling the chambers through a single aerodynamic valve.

The first and the second coupling techniques were successful in stabilizing a 180° phase lag (shift in pressure peaks) between the two combustors as observed by monitoring the peak-to-peak pressure fluctuations using a dual-trace oscilloscope. Stronger peaks or pulsations were observed in the case of aerodynamic valve coupling (Figure 2) than in the case of tailpipe coupling (Figure 1). Coupling of the aerodynamic valves provides a secondary benefit in that unburned coal particles or fuel vapors expelled during blowback are captured by the opposing valve. Although tailpipe coupling offers a similar advantage, loss of unburned coal in the air plenum is less desirable than in the exhaust pipes since a means for collecting fugitive particles in the air plenum (such as a cyclone) are less convenient and practical than those which may be considered at the exhaust exit. It was decided to further investigate the use of coupling at the aerodynamic valves as shown in Figure 2.

Tailpipe Length Variation: The tailpipe length strongly influences the frequency of operation (according to quarter-wave predictions). Sabnis and Lyman (1982), reported reductions in burn time of coal particles (1.3 mm diameter) of about 50 percent at a flow frequency of 54 Hz and only about 10 percent at 130 Hz.

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FIGURE 2:

TANDEM PULSE COMBUSTOR WITH COUPLED EXHAUST

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FIGURE 3:

TANDEM PULSE COMBUSTOR WITH COUPLED INLETS

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FIGURE 4:

TANDEM PULSE COMBUSTOR WITH COUPLED INLET

Prior tests indicated that observed over 92 percent combustion efficiency as measured by the carbon-in-ash method with the bare-metal tandem unit having a 68" long tailpipe. This corresponds to a frequency of 100 Hz. Increasing the tailpipe length to 140" thereby lowering the frequency to 50 Hz, suggested increases in the carbon burnout, even in a bare-metal unit. Hence, a longer tailpipe pulse unit was constructed.

Preliminary testing of the unit with aerodynamic valve coupling and a long tailpipe was carried out. Early test results indicated robust operation with high peak-to-peak pressures. Assembly of the unit was modified slightly to include the use of Tri-clover clamp fittings as an alternate to the band clamps employed in previous tests. The new fittings were used in order to reduce the leakage which had been troublesome in the past.

Additional testing revealed that the unit operated in a stable fashion only over a limited range of fuel firing rates. Furthermore, a consistent 180° peak pressure phase lag could not be sustained for prolonged periods. Instead, the phase lag appeared to float in a transitory fashion.

Based on these results, it was determined that a more comprehensive review of the existing data was necessary in order to better define the system configuration offering the greatest promise for efficient coal combustion for the present application.

The following conclusions have resulted from the experimental observations to date:

- A) In order to achieve high combustion efficiency, coal fuel must be properly phased during the combustion cycle. Therefore, some form of fuel phasing is necessary. This can be accomplished using a single combustor with a phase injector or by using a coupled tandem unit with a fuel biasing injector. Based on the experimental observations, the latter option is more easily controlled, simpler in design, and offers the best performance.
- B) Due to the combustion characteristics of coal, the optimum frequency of operation for coal fuels is less than that for gaseous fuels. This necessitates the use of longer tailpipes. The 140" tailpipe appears to result in an operating frequency which is consistent with the heat release rates for micronized coal. Furthermore, the additional tailpipe length offers a means for efficient heat transfer.
- C) Tandem combustor coupling can be accomplished by two primary means: (1) aerodynamic valve coupling, and (2) tailpipe coupling. Aerodynamic valve coupling is believed to be effective if sufficient thrust can be obtained as a result of high peak combustor pressure. However, it is now believed that for the small residential combustor which exhibits relatively low peak-to-peak pressures, tailpipe coupling is more effective over the entire range of turndown. Furthermore, since the residential unit operated with low ash coal in a non-slugging mode, ash erosion at the tailpipe coupling is not expected to be a problem.
- D) The chamber temperature for the bare metal unit is less than 2000°F. In order to improve the combustion performance, a combustor temperature of 2200°F is desirable. This will require the use of a refractory-lined combustion chamber.

The above conclusions derived from the experimental development tests resulted in the final design configuration to be used for extensive data evaluation and would include: 1) an advanced refractory chamber, (2) tandem unit operation, and (3) 140" tailpipes coupled at the exhaust plenum. The final design configuration is shown in Figure 5 (shown earlier as Figure 2).

Refractory-lined Chambers

Refractory-lined chambers were fabricated during this period. The purpose of the refractory lining is to elevate the combustor temperature to 2200°F. The tailpipes remain of bare metal construction. The shape of the combustor was unchanged from the advanced, conical, bare metal unit which was reported on previously. The conical refractory combustor form was cast in a cylindrical pipe which included a blind flange on one end for ease of inspection. The advanced refractory-lined residential chamber is depicted in Figure 6.

FIGURE 5: FINAL DESIGN CONFIGURATION

FIGURE 6: RESIDENTIAL ADVANCED CHAMBER
(Refractory Design)

The optimized, experimental, pulse combustion, test apparatus was fabricated shown in Figure 7. The unit consists of the following subcomponents: 1) a conical, refractory-lined combustor, 2) aerodynamic valves with tuned inserts and an intake plenum, 3) 140" resonance tailpipes coupled at an exhaust plenum, and 4) a wet cyclone particle trap. The primary objective was to collect performance data pertaining to the combustion of low ash, micronized dry coal. A secondary objective was to verify the feasibility of wet ash collection in a particulate cyclone.

Micronized Coal Tests

A series of test runs were conducted from mid-September through early October to monitor the performance of the optimized configuration on DUC fuel.

On September 21, 1987 the combustor was operated for a total period of approximately three hours. Of this period, DUC was fed for approximately two hours. The combustor operated in a stable manner without the benefit of support gas or excitation air over the entire coal feed period.

The coal feed rate was varied from 75,000 Btu/hr to 225,000 Btu/hr. Performance was stable over the full 3:1 turndown range. Typical combustor operating temperatures ranged from 2200°F to 2300°F with a mean combustor pressures of approximately 9" water column. A total of approximately 25 lbs of DUC fuel was fed during the test run.

Based on monitored oscilloscope waveforms, the two combustor chambers were running with a distinct 180° phase lag, as desired. This confirmed the successful operation of the fuel biasing injector for the tandem unit. It was noted, however, that the pulse waveforms decayed on a low frequency cycle which was characteristic of the coal screw feeder (approximately .5 - 1 Hz). This appears to be a result of non-uniform feeding by the screw feeder.

The non-uniform feed rate for the screw feeder is believed to negatively impact the performance of the unit. This is due to the fact that the pulse combustor is over loaded with fuel during some periods of the cycle, while it is starved at other times. Improvements to the feed system will eventually be required for the integrated system.

Fly ash samples were taken at two separate times during the run. The first sample was taken following prolonged operation at a firing rate of 150,000 Btu/hr. A second sample was taken after operation at 225,000 Btu/hr. Based on carbon in ash analyses, the carbon burnout efficiency at 150,000 Btu/hr was 97.7 percent. The carbon burn-out efficiency at the 225,000 Btu/hr rate diminished considerably to 84.7 percent. The low burn-out efficiency for the second sample seems to indicate that the maximum capacity of the pulse combustor was exceeded at the higher firing rate.

During this run, the pulse waveforms were monitored using both an oscilloscope and an A/D converter which digitalizes the pulse signal for analysis on a microcomputer. The pulse signal was digitalized with a 3000 Hz

FIGURE 7: OPTIMIZED RESIDENTIAL TEST APPARATUS

sampling frequency. The stored data was then processed using a Fast Fourier Transform (FFT) algorithm.

The FFT algorithm allows decomposition of the pulse waveform into its component frequencies. Figure 8 depicts the raw pulse signal over a .1 second sampling period. Figure 9 depicts the calculated frequency power spectrum for this pulse sample. The major peak in Figure 9 occurs at approximately 58 Hz. There also appears to be some lower frequency components. The FFT analysis has proven to be useful in quantifying the frequency response of the combustor to an extent unattainable from oscilloscope readings alone.

Decibel sound measurements were monitored 3 feet from the air intake plenum. The decibel reading was 84 dB. This reading is approximately equivalent to the background noise in the laboratory (coal feeder, air eductor, fans, etc.) indicating that the pulse combustor itself is operating well below 84 dB.

An important observation made during the coal test was that the red-hot zone of the tailpipe extended only a very short distance from the combustor. This is conclusive evidence that the bulk of the coal combustion is occurring in the refractory lined combustor. If hot incandescent coal particles were to have remained in the tailpipe, they would have radiated heat to the tailpipe walls thereby making them red-hot. Incandescent tailpipe regions of much longer lengths have been observed in tests performed by MTCI on other combustors where complete combustion was not attained in the combustion chamber. It is possible that the lack of unburned particles in the tailpipe for the current residential design may be a result of the efficient fuel phasing achieved by the tandem configuration.

A complete video recording of the test run was documented and is available for inspection.

A second coal run was performed on September 22, 1987. Coal was fed at a rate of 150,000 Btu/hr for a period of one hour. Observable combustor performance characteristics duplicated the previous run. The test was terminated because of a problem with the analytical gas sampling equipment.

A third test run was conducted on September 24, 1987. DUC was fed at a rate of 150,000 Btu/hr for a period of approximately one hour. The combustor temperature was typically 2300°F and exhibited a mean pressure of 9 inches water column. A value of 10,300 ppm of carbon monoxide was measured at the tailpipe exit with 2 percent oxygen on a dry basis. It should be noted that the oxygen concentration includes Argon since the gas chromatograph can not resolve these components. The Argon accounts for approximately one full percent of the 2 percent O₂ reading. Therefore, it is evident that the 10,300 ppm CO corresponds to near stoichiometric conditions. The measured carbon monoxide level at 3 percent oxygen was 6,570 ppm. No fly ash samples were collected during this run due to problems with the vacuum sampling pump.

FIGURE 8: PULSE COMBUSTOR ACOUSTIC SIGNAL

FIGURE 9: PULSE COMBUSTOR ACOUSTIC SIGNATURE

Another coal test run was conducted on September 30, 1987. The purpose of this test was to verify the feasibility of wet ash collection. A water quench spray was injected at the duct transition between the exhaust plenum and the cyclone. Water and ash is collected in a cyclone pump and then drained from an overflow tube. Fluid drained from the cyclone is then sampled to monitor the carbon burn-out efficiency.

Coal was fed at a rate of approximately 150,000 Btu/hr for a period of one hour. Measured carbon monoxide levels ranged from 2450 ppm to 3600 ppm during the course of the run. NO_x readings ranged from 200 ppm to 300 ppm (uncorrected).

Two separate ash samples were collected from the cyclone overflow tube. These samples were evaporated and then ashed to calculate the carbon burn-out efficiency. The two samples resulted in carbon burn-out values of 94.3 percent and 94.6 percent.

A final test run was made on October 8, 1987 during which DUC fuel was fed at a rate of approximately 131,000 Btu/hr for a period of two hours. The unit was operated with a wet cyclone condition as before. A fly ash sampling line was inserted downstream of the cyclone to estimate the cyclone particulate removal efficiency.

Virtually no detectable fly ash was collected in the downstream sampling port. This indicates that extremely high cyclone collection efficiencies were achieved. Four fly ash samples were collected from the tailpipe exit. Carbon burn-out efficiencies for these samples ranged from a low value of 89.8 percent to a high value of 92.4 percent. Fly ash samples from the wet cyclone drain yielded 90.6 percent carbon burn-out efficiencies.

Summary

Test runs conducted to date have achieved the following objectives:

- A) Unsupported coal combustion was confirmed
- B) A turndown ratio of 3:1 was verified (75,000 Btu/hr to 225,000 Btu/hr)
- C) Out-of-phase tandem combustor operation was confirmed
- D) Wet cyclone particle trap feasibility was verified
- E) Sound decibel level of tandem pulse combustor on coal is relatively low (less than background noise of 84 dB)

The test results indicate that carbon burn-out efficiencies of up to 97 percent are achievable in the present configuration. Typical carbon burn-out values for all runs ranged from 90-97 percent. It appeared that combustion performance diminished for later runs. The pulse combustor will be opened for inspection to determine whether any mechanical defects in the

refractory might explain the deteriorated performance. Table 1 summarizes the most recent test results.

Evaluation and Optimum Configuration Selection

The coal supplied by Energy International is from Upper Elkhorn-3 (UE3) seam. It has about 1.34 percent ash, 0.61 percent sulfur 36 percent volatile matter and a high heating value of 15,031 Btu/lb.

Initially, MTCI proposed to develop a coal-fired pulse combustor for residential space and/or water heating use, capable of firing both slurry fuels as well as dry fuels. Although the slurry fuels appeared to have a better potential for initial market penetration, we have now learned that the dry ultrafine fuel (DUF) has been used in certain European markets successfully (J.T. Bartis, 1985, EOS-TR-536-1, under DE-AC22-84PC72571).

In order to complete the coal combustion in small combustor volumes or short residence times comparable to oil or gas firing system, the coal particle size needed to be kept small. Hence, micronized or ultrafine coal feed is the likely fuel to be employed in the residential market. The micronized slurry fuel system needs more time for market penetration for establishing reliability, maintainability, etc. The dry ultrafine feed system usage in West Germany, and also in this country, testing by Ergon, Inc. support the basis for DUF application in residential sector. (From Burns and Roe Services Corp. report to DOE, Contract No. DE-AC22-84PC72571, May 1986.)

It is possible to use liquefied propane (LPG) or carbon dioxide for the transport of coal in dense phase from the storage container to the combustor. There is also the possibility of medium pressure natural gas (up to 30 psig available in the pipeline) as a transport gas. Most utility pipelines reduce the pressure just before the gas enters the house. With little change, 5 to 30 psig gas and the low pressure gas may be made available for the domestic use.

The present design configuration is believed to be easily adapted for application to packaged residential heating systems.

The unit is currently intended for operation on DUC fuels, however CWM may also be suitable. In the existing experimental system, DUC is fed by means of a screw feeder to a funnel. The funnel is connected to an air eductor which consumes modest quantities of air to convey the coal to the combustors. For the commercial product, alternate coal feeding means may be more economic, such as a small disk feeder. Development of small-scale, cost-effective, solids handling equipment is a prerequisite for market introduction of DUC-fueled heating systems.

TABLE 1:
SUMMARY OF RECENT EXPERIMENTAL RESULTS FOR
RESIDENTIAL PULSE COMBUSTOR

TEST DATE	<u>9/21/87</u>	<u>9/21/87</u>	<u>9/24/87</u>
CHAMBER CONFIGURATION	Conical Refractory Tandem/Tailpipe	Conical Refractory Tandem/Tailpipe	Conical Refractory Tandem/Tailpipe
GAS FEED, Btu/hr	None	None	None
COAL TYPE	DUC	DUC	DUC
FREQUENCY, Hz	58	58	58
MEAN PRESSURE, H ₂ O	9.0	9.5	8.0
CHAMBER TEMP., °F	2300	2250	2350
CARBON BURN-OUT, %	97.7	84.7	N/A
FLUE GAS (1):			
O ₂ %	6.5 (2)	N/A	2.0/3.0
CO, ppm	4860	N/A	10032/6750
NO, ppm	N/A	N/A	N/A
FLUE GAS (CORRECTED) (2):			
CO, ppm	6026	N/A	10032/6570
NO, ppm	N/A	N/A	N/A
TEST DATE	<u>9/30/87</u>	<u>10/8/87</u>	
CHAMBER CONFIGURATION	Conical Refractory Tandem/Tailpipe	Conical Refractory Tandem/Tailpipe	
GAS FEED, Btu/hr	None	None	
COAL TYPE	DUC	DUC	
FREQUENCY, Hz	58	58	
MEAN PRESSURE, H ₂ O	7.5	8.0	
CHAMBER TEMP., °F	N/A	N/A	
CARBON BURN-OUT, %	94.6	90.9	
FLUE GAS (1):			
O ₂ %	8.2 (2)	11.4 (2)	
CO, ppm	3220	>1000	
NO, ppm	200-300	200	
FLUE GAS (CORRECTED) (3):			
CO, ppm	4527	>1875	
NO, ppm	281-422	375	

-
- (1) Uncorrected Dry Gas Composition
(2) Air Leak Suspected in Sample Line
(3) Corrected to 3% O₂ (Dry Gas Basis)

Although CWM fuel handling may be easier under carefully controlled conditions, CWM usage has several significant shortcomings. First, CWM which is stored in unheated tanks is exposed to the risk of freezing resulting in defluidization. This poses an extreme reliability issue since CWM handling equipment depends entirely on maintaining proper fluidity. Furthermore, ageing, degradation, and corrosion are recognized as major barriers to widespread residential CWM usage. In contrast, DUC is much less sensitive to environmental factors. Consequently, transfer and storage equipment designed to handle DUC may ultimately be more reliable than that which is proposed for CWM.

Particulate Collection

The present design is envisioned to be integrated with a wet cyclone particle trap. Although the system design is not constrained to any single particulate removal system, the wet cyclone is thought to offer a simple and effective means for efficient particle removal.

The wet cyclone particle trap is depicted in Figure 10. The effluent flue gases from the tailpipe exhaust is quenched with a water spray. The moist flue gas then enters a conventional cyclone where the wet agglomerated ash particles stick to the cyclone walls. As a layer of wet particles accumulates to a sufficient thickness, it begins to flow down the cyclone wall toward the dipleg. From the dipleg, the wet particle stream is discharged to a sewer line or holding tank. Discussions with EPA officials have confirmed that power plant fly ash is presently considered non-toxic and is commonly incorporated into commercial products such as asphalt and cement. Early systems may be able to discharge directly into a sewer line.

The wet cyclone appears to be an ideal means for solids removal. Due to the extremely small sizes of the fly ash generated from combustion of micronized coal, dry cyclone systems are not capable of sufficiently high capture efficiencies. In contrast, the wet spray droplets serve to agglomerate ash particles thereby facilitating efficient collection. Furthermore, the annual rate of water consumption for the wet system is about 600 gallons per year.

Alternate dry collection means such as baghouses require more frequent maintenance, are prone to plugging causing excessive pressure drop, are more likely to result in dust emissions, and appear to be less suitable for residential applications.

An optimum configuration has been identified for the residential heating system. The optimum configuration includes the following key features:

- A) Tandem configuration
- B) Refractory-lined conical pulse combustor
- C) Intake air plenum
- D) Exhaust plenum with tailpipe coupling
- E) Automatic fuel biasing
- F) DUC coal feeder and pneumatic eductor
- G) Wet cyclone particle trap

FIGURE 10:
WET CYCLONE PARTICLE TRAP

The residential unit utilizes natural gas for start-up. Under normal operating conditions, the unit consumes only dry, ultrafine coal. The turndown ration is 3:1 with a maximum firing rate of 225,000 Btu/hr and a maximum combustor heat release rate of 3 MM Btu/ft³/hr. The ignition system consists of a spark ignitor and a pilot flame.

Figure 11 depicts a potential commercial embodiment for the optimized residential configuration. As can be seen, the entire pulse combustion apparatus is enclosed in an insulated furnace housing. The unit is arranged in a compact format and is expected to be approximately 6 - 7' tall and require a floor area of approximately 10 ft² excluding the coal hopper. A forced draft fan supplies circulation air to the housing. The air first passes through a finned tube exchanger and then, directed by internal baffles, passes over the resonance tubes and combustor before exiting as hot air to the end-user. It is estimated that approximately 80 percent of the heat is released from the resonance tubes and combustor, while only 20 percent of the heat is released in the final finned tube heat exchanger.

A typical material balance for this unit is summarized in Table 2. The projected economics for the residential heating system is summarized in Table 3.

In summary, a commercial residential heating system configuration has been identified based on the development tests conducted under this contract. The unit shows great potential for meeting the operational and performance target goals specified for these systems. The operational, environmental, and economic goals for single family, coal-fired, residential heating systems are repeated for information in Tables 4, 5, and 6, respectively.

Although the residential unit tested in this work indicates that the goals specified above are achievable, further work is necessary to: 1) increase carbon burn-out efficiency, 2) reduce carbon monoxide emission levels, and 3) develop reliable dry, ultrafine coal feed systems.

FIGURE 11:
EQUIPMENT LAYOUT FOR PHASE II
SYSTEMS INTEGRATION TESTS

TABLE 2:
MATERIAL BALANCE - RESIDENTIAL PULSE COMBUSTOR

FEED TYPE	:	DUF Coal (15,000 Btu/hr)
NOMINAL FIRING RATE	:	100,000 Btu/hr
CAPACITY FACTOR	:	15% (1315 hr/yr, 131.5 MMBtu/yr)
COAL FEED	:	8760 lb/yr
TOTAL REJECTED SOLIDS:		193 lb/yr (105 lb ash, 88 lb carbon)
WATER SPRAY	:	600 Gallon/yr

TABLE 3:
RESIDENTIAL UNIT PROJECTED ECONOMICS

		<u>COST \$</u>
Equipment and Materials:	Storage Bin	80.00
	Coal Feed System	350.00
	Pulse Combustor	200.00
	Heat Exchanger	40.00
	Ash Rejection System	120.00
	Furnace Enclosure	200.00
	Fans, Valves, Ignitors and Controls	380.00

	TOTAL MATERIALS	1370.00
Assembly Labor	: Mechanical (3 Manhours)	75.00
	Structural (3 Manhours)	75.00
	Electrical (4 Manhours)	100.00

	TOTAL LABOR	250.00
Overhead	: 40% of Manufactured Cost	648.00

	TOTAL	2268.00
		=====

TABLE 4:

OPERATIONAL GOALS FOR SINGLE-FAMILY RESIDENTIAL HEATING SYSTEMS

FUEL	Ash Content	: < 0.8 lb/MMBtu (1.2%)
	Sulfur Content	: < 0.5 lb/MMBtu (0.75%)
	Delivery	: < 5 per year
COMBUSTOR:	Firing Rate	: 100,000 Btu/hr
	Physical Size	: Maxium Height - 6 Ft
		Floor Area - 15 Ft ²
	Combustion Efficiency:	99%
	Energy Efficiency	: 75%
	Operation	: Automatic
	Solids Removal	: < 5 per year

TABLE 5:

ENVIRONMENTAL GOALS FOR RESIDENTIAL HEATING SYSTEMS

ITEM	EMISSIONS (lb/MMBtu)	PPMV (Typical)
Carbon Monoxide	.2	175
Methane	.1	150
Nitrogen Oxides	.5	265
Sulfur Oxides	1.0	380
Particulates	.1	

TABLE 6:

ECONOMIC GOALS FOR SINGLE-FAMILY RESIDENTIAL HEATING SYSTEMS

FUEL	: < \$	5/MMBtu
TOTAL INSTALLED COST:	< \$	3,500
ANNUAL MAINTENANCE	: < \$	120

SECTION 3.0

PLANNED ACTIVITY FOR THE NEXT PERIOD

Design and test activities are completed. The final report is being prepared and will be submitted to DOE for review, therefore, this is the final technical progress (quarterly) report to be submitted for this Phase.