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Development of a Coal Fired Pulse Combustor for Residential Space Heating

TECHNICAL PROGRESS REPORT JANUARY - MARCH 1987

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PREFACE

A detailed description of the background, technology and application, and 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 1986 - December 1986. This material is omitted in this report.

The development test activities during this period focused upon the following units:

- o Residential Unit (Lockwood/SNECMA design)
- o Bare Metal Advanced Chamber Combustor
- o Refractory Lined Advanced Chamber Combustor.

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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 Phases I and II are 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 3-1.

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 1-1: PROGRAM LOGIC FOR 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 baghouse will be procured. During this stage of the program, arrangements will be made to obtain different types of coal slurries. 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 tailpipe 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 coal fuels, chosen in consultation with DOE. Table 1-1 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 above 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 1-1: Test Matrix - Phase I

TEST SERIES NO.	FEED	CONFIGURATION EVALUATION	CONTROL EVALUATION	EMISSIONS MONITORING
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 development test activities during this period focused upon the following units:

- o Residential Unit (Lockwood/SNECMA design)
- o Bare Metal Advanced Chamber Combustor
- o Refractory Lined Advanced Chamber Combustor.

The residential unit (scaled-down feasibility unit) was fired on gas, no. 2 fuel oil, and coal (micronized Pittsburgh no. 8). The maximum firing rate on gas was 180,000 Btu/hr with a turndown of 3:1 to 60,000 Btu/hr. The startup runs with no.2 oil was satisfactory but steady state operation was terminated due to problems with the oil feed system and the tests were converted to coal operation utilizing the modified MTCI biomass feeder. The combustor was operated on coal for short periods of time between 54,000 - 154,000 Btu/hr within the limits of the modified biomass feeder performance. This was a temporary measure to permit testing of the combustors until the coal feed issue was resolved.

Bare metal and refractory lined combustor tests were conducted with the original feasibility unit modified to incorporate the advanced chamber designs. The evaluation of the advanced chamber design performance and operation will provide the design data required for the design and fabrication of the scaled-down units for this program. The bare metal chamber achieved a sustained boost pressure of 16 inches of water, the refractory lined chamber 18 inches of water when operated in the tuned combustor configuration. A detailed discussion on those tests and ancillary activities is provided in the following section, Technical Discussion of Work Completed during the Reporting Period.

SECTION 2.0

TECHNICAL DISCUSSION OF WORK COMPLETED DURING THE REPORTING PERIOD

Tasks 1.1 (design of advanced 100,000 Btu/hr pulse combustor) and Task 1.2 (fabrication of pulse combustors) were essentially completed during the last period. Design modifications and subsequent fabrication activities resulting from tests on the advanced chamber designs and ancillary subsystems eg. aerodynamic valves, fuel feeders, and acoustic decouplers; will be implemented under Task 1.3, development testing.

Most of the testing conducted during the early part of this period was with the modified Hanby design pulse combustor with expanding tail pipe as shown in Figure 2-1. In this modified Hanby configuration, autoaspiration of air was achieved with a 1.875" diameter venturi as the flow diode (Figure 2-2) in the aerodynamic valve, and the tail pipe length was varied between 63" to 70". When coal feed was started, the chamber temperature climbed from about 1978°F to over 2400°F (which was the limit of the Type K thermocouple that was used for measurement). The frequency was in the vicinity of 67 to 70 Hz. The small variation of frequency resulted from variations in the gas temperature in the combustor.

The analysis of coal used is given in Table 2-1. It is a micronized Pittsburgh #8 coal with a nominal size of 10 microns.

Coal combustion increased the pressure boost and the dynamic pressure oscillation in the combustor indicating sufficient heat release in phase with the dynamic pressure oscillation in the modified Handy combustion chamber. Coal feed was implemented using an eductor system (Figure 2-3) with a screw feeder metering the coal into the eductor system funnel. The coal flow metered into the eductor funnel by the screw feeder possessed periodic changes in flow rate. This was reflected in the variation of the dynamic pressure amplitude. The frequency of the coal feed variation was in the order of two cycles per second; therefore, it did not couple with the resonant operating frequency of the combustor. This test condition, however, provided excellent verification of the combustor's load following capability. The heat release rate, as evident by the variation of the dynamic pressure amplitude variation and the combustor's sound pressure level, responded faithfully to the periodicity in the coal feed. The latter was due to the characteristics of the screw feeder used to feed the coal into the eductor funnel.

Until dry micronized and pulverized coals with less than 1% ash and corresponding slurries are received from Energy International, MTCI will use the medium-ash micronized coal that MTCI has on hand.

FIGURE 2-1: MODIFIED HANBY DESIGN PULSE COMBUSTOR

FIGURE 2-2: VENTURI DIODE INSERT

TABLE 2-1: ANALYSIS OF MICRONIZED PITTSBURGH #8 COAL

<u>PROXIMATE ANALYSIS</u>	<u>% WEIGHT</u>	
	<u>AS RECEIVED</u>	<u>DRY BASIS</u>
Moisture	1.62	XXXX
Ash	12.99	13.20
Volatile	37.64	38.26
Fixed Carbon	<u>47.75</u>	<u>48.54</u>
	100.00	100.00
Btu/lb	12650	12858
Sulfur	2.43	2.47
Alk. as Na-O	----	0.22

SULFUR FORMS

Pyritic Sulfur	1.56	1.59
Sulfate Sulfur	0.01	0.01
Organic Sulfur	0.86	0.87

<u>FUSION TEMPERATURE OF ASH</u>	<u>REDUCING</u>	<u>OXIDIZING</u>
Initial Deformation	2150°F	2550°F
Softening (H=W)	2550°F	2700+°F
Softening (H=1/2W)	2600°F	2700+°F
Fluid	2700°F	2700+°F
Silica Value	73.67	
Base: Acid Ratio	0.26	
T ₂ SO Temperature	2600°F	

<u>ULTIMATE ANALYSIS</u>	<u>% WEIGHT</u>	
	<u>AS RECEIVED</u>	<u>DRY BASIS</u>
Moisture	1.62	XXXXX
Carbon	70.00	71.15
Hydrogen	4.90	4.98
Nitrogen	1.23	1.25
Chlorine	0.14	0.14
Sulfur	2.43	2.47
Ash	12.99	13.20
Oxygen (diff)	<u>6.69</u>	<u>6.81</u>
	100.00	100.00

TABLE 2-1: ANALYSIS OF MICRONIZED PITTSBURGH #8 COAL (CONTINUED)

<u>MINERAL ANALYSIS OF ASH</u>	<u>% WEIGHT IGNITED BASIS</u>
Silica, SiO_2	50.37
Alumina, Al_2O_3	25.59
Titania, TiO_2	1.12
Ferric Oxide, Fe_2O_3	16.78
Lime, CaO	0.68
Magnesia, MgO	0.54
Potassium Oxide, K_2O	2.12
Sodium Oxide, Na_2O	0.29
Sulfur Trioxide, SO_3	0.56
Phos. Pentoxide, P_2O_5	0.09
Strontium Oxide, SrO	0.01
Barium Oxide, BaO	0.08
Manganese Oxide, Mn_3O_4	0.00
Undetermined	<u>1.77</u>
	100.00
Fouling Index	0.08
Slagging Index	0.64

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FIGURE 2-3: COAL FEED SYSTEM

These developmental tests explored the performance of the residential unit (Figure 2-4) on gas, #2 fuel oil and micronized coal firing.

Maximum firing rate on gas was found to be around 180,000 Btu/hr with the gas injector design used. (A simple 1/4" tube in the aerodynamic valve.) higher gas firing rate with this injector design caused the combustor frequency to drop from 180 to 70 Hz. The theoretical design frequency of the combustor ranged from 180 to 200 Hz based on estimated average gas temperature and the dominant resonance mechanism (Helmholtz vs. quarter wave frequency). Firing rate of up to 400,000 Btu/hr is possible with better gas injectors which induce better mixing. The lowest firing rate with the simple 1/4" tube injector was approximately 60,000 Btu/hr. Thus, turn down of the unit was 3:1 with this inexpensive gas injector. Since gas would normally be used for start-up, this injector scheme and location were judged adequate.

In addition, tests with #2 fuel oil were conducted to evaluate this fuel option for start-up. No combustor modification was required and the operation of the combustor was in general satisfactory. Nevertheless, problems were encountered with the oil feed system which did not permit steady-state operation. Based on the test experience in those runs when the feed system operated satisfactorily over short periods of time, a decision was made to move to coal fired testing and a conclusion was reached that the combustor design is capable of operation on #2 fuel oil for start-up without modifications of the combustor design. Heat up rate of the combustor with oil firing was approximately half of that for natural gas. This was attributed to the higher flame luminosity with oil firing. In these tests, coal was initially conveyed with air from a modified MTCI biomass feeder which is pressurized to 3 - 5 psi. The 1/4" stainless steel tubing which was initially used was plugged. This was followed by employing an atmospheric Vibrascrew feed system with an eductor and 3/8" stainless tubing to convey the coal. Flow rate measurements were made by a Micromotion true mass flow meter. Using the mass flow meter, the conveying air was measured at .22 lbs/minute (13.2 lbs/hr). The coal/air mixture flow rate fluctuated from .29 lbs/minute to .42 lbs/minute with some periodicity (53,760 Btu/hr - 153,600 Btu/hr). The period was approximately half second which was characteristic of the screw feeder performance.

The combustor was operated on coal for five minutes while data was being acquired. The frequency of operation was between 167 - 180 Hz, O₂ was at 11.2 percent, SO₂ was at 600 ppm and NO_x at 280 ppm, CO at 2000+ ppm and CO₂ at nine percent. No attempts were made to optimize the coal injector and combustor performance until the coal feed issue was resolved.

The present residential size pulse combustor unit (100,000 Btu/hr) is small and is designed to operate at high frequency (approximately 180 Hz). As a result, the residence times are in the order of 10 to 20 milliseconds at full firing rate. Due to the short residence time, pulverized coal with a top size of over 100 mesh (150 microns) may not be an acceptable fuel. This is due to the need for high heat release in phase with the dynamic pressure

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FIGURE 2-4: RESIDENTIAL SIZE PULSE COMBUSTOR

amplitude at the higher frequency and the short overall residence time. Lower frequency/longer residence time designs will be explored later in the program. In the lower frequency units, which would have a long tailpipe, the tailpipe would be employed for heat exchange.

Because of the intermittent load demand, slagging operation does not appear practical at this time for the residential unit. The low-ash coal in the micronized dry form can be expected to be a viable fuel supply in the future. It is available as dry ultra fine coal (DUC) in W. Germany in bins for residential and commercial uses. (Ref: Market and Equipment Performance Analysis for the Application of coal based fuels - Commercial and Small Industrial Application, Burns & Roe, DOE/PETC, DE-AC22-84PC72571, May 1986).

At this stage, micronized coal fuel is the preferred fuel for residential application. Since dry-ash rather than slag or molten ash is to be expected as the combustion residue, refractory lined combustor chamber and tail pipe may not be needed. Although MTCI will investigate all the options, the above is based on test experience obtained thus far in the program.

The activities under this task were then focused on the advanced chamber fabrication and test to acquire design data at the 1 - 2 MMBtu/hr size before scale-down.

Two chambers of the advanced chamber design were fabricated during this reporting period. One was a bare metal unit fabricated by metal spinning (mold machined) and a refractory-lined unit was casted of the same configuration. The chamber design with the dimensions delineated is shown in Figure 2-5. Cylindrical extensions for the chambers at the maximum diameter were also made from bare metal and refractory casting. These extensions are intended to provide significant increases in chamber volume with little increase in chamber length. This part of the program is shared with the industrial retrofit unit development activity. Bare metal tail pipes and aerodynamic valves were also fabricated for the two advanced chambers.

A. Bare Metal Advanced Chamber Combustor Tests:

These tests were conducted to tune the basic combustor configuration before tests are conducted on the refractory-lined chamber. The combustor design test unit is shown in Figure 2-6. Initially, the aerodynamic valve length was six inches, which provided poor performance. The aerodynamic valve length was then increased to 11 inches providing fair performance at a tail pipe length of 45 inches. This was followed by adjusting the telescoping tail pipe length during operation to tune the combustor. The tuned combustor configuration was achieved at an overall tail pipe length of 52.5". Maximum boost pressure was 20 inches of water and sustained boost pressure of 16 inches was attained. During the combustor tuning tests the frequency varied between 125 - 80 Hz with the tuned combustor operating at 80 Hz.

FIGURE 2-5: MTCI ADVANCED CHAMBER CONFIGURATION

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FIGURE 2-6: TEST COMBUSTOR CONFIGURATION (ADVANCED CHAMBER DESIGN)

Additional tests were carried out with the bare metal Lockwood pulse combustor to evaluate phased coal feed into the chamber to improve combustion. Continuous coal feed results on some half of the coal enter the chamber when no combustion is taking place. Although this coal burns partially in the chamber and tail pipe, it does not burn as completely as when phased with the combustion pulse. Heat released during this low pressure portion of the cycle tends to dampen pulsations. An interim solution was to try another diameter for phase injector tube, connecting the phase injector to the chamber.

The phase chamber would then be at a somewhat lower pressure than the coal feed line (preferably about the same pressure as the combustion chamber) so coal would only enter the chamber during the low pressure half of the cycle. This would result in improvement of the combustion of the coal. The phase chamber was also used to preheat the coal with gases from the combustion chamber but the temperature in the pulse chamber was too low to be effective.

The test data indicated better combustion with the interim phase injector as compared to without the phase injector. The combustor also operated much smoother and with healthier pulses. With the phase injector the support gas was completely turned off. One test with the phased feed flow injector was made without using support gas. It operated satisfactorily.

Another test without the phase injector but with an electronic preheat device was also restricted. The heater consisted of 20 feet of 3/8" tubing with an electric resistance heater. The heater was heated up to 550°F but this provided too much back pressure for the eductor used to feed the coal. The coal feed rate was limited to four lbs/hr instead of seven-to-eight lbs/hr of coal. The combustion was 94% but required full gas support and was not satisfactory due to the sporadic feed rate.

The test results indicated that phase injection will be effective in the combustion of dry coal. The interim phase feed injector was not expected to provide the eventual of solution for complete combustion. But based on the data from these tests, the use of tandem combustor should be highly effective for complete combustion. Coal would only feed to the chamber during the low pressure portion of the pulse cycle. A design for this chamber will be generated next period. The test activity was then focused on the refractory-lined chamber unit. The refractory-lined chamber is made for coal firing.

B. Refractory-Lined Advanced Chamber Combustor Tests:

Based on the test experience with the modified Hanby chamber design and other design calculations, a venturi diode was designed and installed in the aerodynamic valve of the refractory-lined chamber. The dimensions of the venturi diode insert is shown in Figure 2-7.

A number of gas injectors were tested and an optimum design was selected. In this design the gas is injected in the aerodynamic valve in a flow pattern prescribing a sheath perpendicular to the flow of air in the valve. The gas injection location was one inch upstream of the chamber/valve interface. This provided a gas injector scheme which would not interfere with axial coal injection through the aerodynamic valve. This is illustrated in Figure 2-8.

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FIGURE 2-7: VENTURI DIODE INSERT

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FIGURE 2-8: COAL AND GAS INJECTION

Tuning the combustor with the refractory-lined chamber with natural gas firing resulted in an aerodynamic valve length of 10.75" with the venturi diode insert and a tail pipe length of 66.5". The frequency of operation was approximately 70 Hz. Typical operation at 18.25 SCFM (1,095,144 Btu/hr) of natural gas provided peak-to-peak dynamic pressure of 2.5 psi, 18 inches sustained pressure boost in the chamber, chamber exhaust temperature of 2,100°F and self-aspiration of combustion air.

Tests were then run with coal firing. A maximum feed rate of 20 lbs/hr of coal was tested (256,000 Btu/hr). This feed rate was injected using the Vibrascrew feeder and an eductor (Process Systems Model 264PPC, 1/2" eductor) conveying the coal through a specially designed injector, as shown in Figure 2-8. In this injector, the axial flow of air and coal is deflected by a disc to fan the flow in a sheath perpendicular to the aerodynamic valve air flow, thus promoting good mixing. The gas flow during these tests was initially maintained at a minimum of five SCFM (317,223 Btu/hr). We should note that the turn-down of the refractory-lined chamber in the range tested was satisfactory (3.5:1). In these tests the maximum firing rate was limited not by the combustor but by the gas line pressure available in the laboratory (15 psi).

With coal firing, the chamber exhaust temperature climbed to 2850°F. Boost pressure, however, dropped to nine inches due to the reduced overall firing rate as expected. The combustor, however, appeared to operate satisfactorily but required more coal feed rate to achieve higher dynamic pressure and boost in order to eliminate the gas completely. Work on coal feed problems became a must; thus, an attempt was made to accelerate the delivery of a coal feeder ordered January 27, 1987 which is relatively inexpensive (Reliaflow feeder for \$2,635). This feeder is capable of feeding coal from 10 - 100 lbs/hr. The combustor performance on coal firing appeared to be satisfactory.

C. Support Equipment Design and Test:

In this area a number of items needed attention. First is the aforementioned coal feed problem. Other laboratories were contacted to secure an adequate feeder which could be used in the interim in support of test activities until the new feeder is authorized by DOE. The Reliaflow feeder was on order and accelerated delivery was sought.

In addition, an intake air plenum was needed but was put aside until the basic combustor design was tuned and operated on coal. This plenum was designed, fabricated and installed in the test facility. A forced combustion air fan was also installed due to recommendations by Sur-Lite for operational flexibility and safety reasons. This was completed by the end of this reporting period.

SECTION 3.0

PLANNED ACTIVITY FOR THE NEXT PERIOD

Developmental testing of pulse combustors will continue next period with initial emphasis on completing the testing of the modified feasibility unit with refractory lining. The concept of a Tandem Pulse Combustor System will be explored and, if feasible; designed, fabricated and tested. It may then be appropriate to use the phased coal injector continuously feeding each combustor of the tandem unit alternately and enhance combustion system efficiency.

Two residential sized advanced chambers will be fabricated and may be configured in tandem if the analysis indicates that efficiency can be enhanced by phased injection. These units will initially be fired separately. A scrubber for better control of off-design operation emissions will be installed.