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**DEVELOPMENT AND TESTING OF A COMMERCIAL-SCALE
COAL-FIRED COMBUSTION SYSTEM - PHASE III**

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TABLE OF CONTENTS

1. INTRODUCTION	1
2. PROJECT STATUS	7
2.1 SYSTEM INTEGRATION	7
2.2 SHAKEDOWN TESTING	7
2.3 COMPONENT DESIGN	7
3. PLANNED ACTIVITIES	24
4. SUMMARY	25

LIST OF ILLUSTRATIONS

1.1	Process Flow Diagram	4
1.2	Work Breakdown Structure for Entire Project	5
2.1	Boiler Installation	8
2.2	Transition Chamber Installation	9
2.3	Baghouse Installation	10
2.4	System Tests Configuration – Combustor Test Series	11
2.5	Combustor/Transition Chamber Assembly	12
2.6	Slurry Production Facility Coal Grinding Stand	13
2.7	Slurry Production Facility Mixing Stand	14
2.8	Prefilm Airblast Atomizer	17
2.9	Effect of Air/Liquid Ratio and Liquid Viscosity on Twin-Fluid Atomizer Performance	18
2.10	VSA Atomizer with Narrow Spray Angle	20
2.11	VSA Atomizer with Intermediate Spray Angle	21
2.12	VSA Atomizer with Wide Spray Angle	22
2.13a	Slurry Droplet Distribution with the Variable-Spray-Angle Atomizer	23
2.13b	Slurry Droplet Distribution with the Modified Delavan Delta Atomizer	23

LIST OF TABLES

1.1 Performance Goals 3

2.1 Variable-Spray-Angle (VSA) Atomizer Features 16

1. INTRODUCTION

Coal is the most plentiful energy resource in the United States, and in 1987 it provided approximately one third of the quads of total energy consumed in the United States. Its use, however, has been largely restricted to utility power generation since World War II for environmental and economic reasons.

Within the commercial sector, oil and natural gas are the predominant fuels used to meet the space-heating needs of schools, office buildings, apartment complexes, and other similar structures. In general, these buildings require firing rates of 1 to 10 million Btu/hr. The objective of this program is to demonstrate the technical and economic viability of a coal-fired combustion system for this sector.

The development program includes all aspects of the process, from fuel selection and preparation to pollution control and waste disposal. In attempting to restore coal to small users such as residential and commercial space heating, it is important to recognize that fuel form is an important consideration because of its impact on handling and emissions. Ease of handling is an important criterion at the small sizes since complex equipment will add greatly to the overall system costs. Furthermore, manpower is not available to perform manual functions or keep complex equipment working. Emission levels, if not currently regulated, can be expected to be regulated at low levels in the future. The levels considered acceptable will be reduced over time, following the current environmental trends. Preparation and use of a coal-water slurry fuel can aid in meeting these criteria. Coal-water slurry use eliminates the need for dry pulverized coal with its attendant handling and dusting problems as well as its explosive potential. In addition, coal-water slurry is amenable to coal washing since coal cleaning technologies are generally water-based processes requiring fine grinding of the coal. For these reasons, the program objective will be met through the development of a coal-water slurry fired system.

Although the coal-water slurry fuel in commercial practice will be manufactured by coal companies or fuel suppliers at regional facilities and transported to the user much as is done today with oil, the program includes the construction of a slurry production facility. In this way, all aspects of the fuel's use – from coal selection to combustion properties – can be evaluated and an economic evaluation of the process can be carried out.

The commercial-scale coal-water slurry (CWS)-fired space heating system will be a scale-up of a CWS-fired residential warm-air heating system developed by Tecogen under contract to the Department of Energy, Pittsburgh Energy Technology Center. This system included a patented nonslagging combustor known as IRIS,

for Inertial Reactor with Internal Separation. This combustion technology, which has demonstrated high combustion efficiency using CWS fuels at input rates of 100,000 Btu/hr, will be scaled to operate at 2 to 5 million Btu/hr. Along with the necessary fuel storage and delivery, heat recovery, and control equipment, the system will include pollution control devices to meet targeted values of NO_x, SO₂, and particulate emissions. In general, the system will be designed to match the reliability, safety, turndown, and ignition performance of gas or oil-fired systems. Table 1.1 summarizes the performance goals of the system. Figure 1.1 is a process flow diagram for the system.

The successful development and future marketability of the heating system require a strong, dedicated team with expertise in a broad range of areas including coal-water slurry preparation, coal combustion, pollution control, component manufacture, and systems integration. Such a team has been assembled and includes the following organizations: Tecogen, Donlee Technologies, AMAX Coal, and Southern Illinois University.

Tecogen is the prime contractor and is responsible for overall program management, combustor development, and integration of the subsystem components and installation of the system at the field test site. AMAX has extensive experience in coal-water slurry preparation and serves as the principal coal supplier. Donlee Technologies is responsible for the boiler/heat exchanger design and manufacture. Donlee has over 70 years' experience in the commercial boiler business and is a potential commercializer of the technology. Southern Illinois University is the host for the field test portion of the program. The heating system will provide space heating at the SIU Coal Research Center.

The development program has been divided into 3 stages covering a time span of 39 months. During the first stage, which covers 14 months, the program will focus on component development. The second stage, which covers a 10-month period, will focus on proof-of-concept testing. The final stage covers a 15-month period and will focus on testing all the components as an integrated system in an actual installation. Figure 1.2 gives the work breakdown structure for the program.

This report documents the work carried out in the fourth quarter of the program. Activities focused on the construction of the major system components and assembly of these components into Tecogen's test facility in preparation for preliminary system and proof-of-concept testing. Component design testing of the combustor was conducted to verify combustor scale-up.

TABLE 1.1
PERFORMANCE GOALS

• Thermal Input	– 4 million Btu/hr
• Thermal Efficiency	– >80%
• Combustion Efficiency	– >99%
• Emissions	– 1.2 lb SO ₂ /MMBtu
0.3 lb NO _x /MMBtu
0.03 lb Part./MMBtu
• Turndown	– 3:1
• Ignition	– Fully automatic startup with system purge and ignition verification
• Reliability/Safety	– Comparable to oil-fired commercial boilers
• Ash Removal	– Dust free and automatic or semi-automatic
• Routine Maintenance	– Less than one manhour per day and an additional two manhours per week
• Service Life	– >20 years

Figure 1.1 Process Flow Diagram

Figure 1.2 Work Breakdown Structure for Entire Project

Prior to this fourth quarter work, activities were focused on overall system definition and component design. Combustor scaling laws were developed to allow for an extension of the data base that has been established with the residential combustor and to provide guidelines for the scale-up of this combustor technology to larger sizes. In particular, particle separation, reaction rate kinetics, pressure drop, and residence times were evaluated.

2. PROJECT STATUS

During the fourth quarter of this program, most of the program activities were related to installation of the major system components. A hot shakedown test of the combustor/transition chamber assembly was also completed.

2.1 SYSTEM INTEGRATION

The major system components were placed in position at Tecogen's Waltham facility where system and proof-of-concept testing will be conducted. Figures 2.1 through 2.3 show the boiler, transition chamber, and baghouse being moved into position. Installation of the combustion air system, fuel oil and slurry delivery systems, and combustor cooling system was completed. Exhaust piping between the transition chamber and an existing water-quench exhaust system has been installed to allow combustor operation independent of the heat recovery boiler and fabric filter. This mode of operation will be utilized for initial system tests and for testing new slurry formulations and evaluating combustor operating parameters. A schematic of the test setup is shown in Figure 2.4 and a photograph of the fully piped and instrumented combustor/transition chamber assembly is shown in Figure 2.5.

Work continued on the integration of the slurry preparation facility components. Figures 2.6 and 2.7 are photographs of the equipment. Figure 2.6 shows the coal grinding stand, which includes a storage hopper, screw feeder, and pulverizer, and Figure 2.7 shows the mixing stand, which includes the collection cyclones and mixing tank.

2.2 SHAKEDOWN TESTING

A hot checkout test of the combustor/transition chamber was made utilizing fuel oil. All systems operated satisfactorily. Fuel oil introduction through the slurry atomizer was evaluated. Stable combustion and uniform heatup were achieved with all the fuel oil introduced through the slurry atomizer. This arrangement eliminates the need for multiple fuel nozzles for system warmup and oil-fired operation.

2.3 COMPONENT DESIGN

A variable-spray-angle externally mixed twin-fluid atomizer was designed and built. The atomizer design is an extension of the twin-fluid coal water slurry (CWS) atomizer technology developed under the previously funded CWS-Fired Residential Warm Air Heating System Program. The atomizer operating conditions

Figure 2.1 Boiler Installation

Figure 2.2 Transition Chamber Installation

Figure 2.3 Baghouse Installation

Figure 2.4 System Tests Configuration
Combustor Test Series

TF125 292

Figure 2.5 Combustor/Transition
Chamber Assembly

Figure 2.6 Slurry Production Facility
Coal Grinding Stand

Figure 2.7 Slurry Production Facility
Mixing Stand

can be set to provide the wide cone angle required of the radial top-center-firing configuration of the commercial-scale system. This atomizer uses two perpendicular atomizing streams to shear the CWS into a thin unstable ligament sheet that breaks up into small droplets external to the atomizer.

The external atomization feature of this nozzle prevents erosion and allows for a large CWS passageway which minimizes the head that the CWS pump must produce. In addition to providing fine atomization due to the high shear that is imparted by the two perpendicular atomizing streams, by varying the flow rate of each of these streams, the spray angle can be changed on-line without any mechanical modifications to the atomizer. Table 2.1 lists the features of the atomizer.

In designing the VSA atomizer, an analogy was made with Prefilming Airblast atomizers which are used for fuel injection in aircraft and industrial gas turbines. In a prefilming airblast atomizer (shown schematically in Figure 2.8) the liquid to be atomized is first spread out into a thin continuous sheet and then exposed on both sides to high velocity air. Lefebvre¹ derived a general correlation that takes into account fluid properties, velocity, geometry, and the air/liquid mass ratio on Sauter Mean Diameter (SMD). SMD is the diameter of a droplet whose ratio of volume to surface area is equal to that of the entire spray sample. This relationship is:

$$\begin{aligned} \text{SMD} = & 0.073 \left(\frac{\sigma_L}{\rho_A U_A^2} \right)^{0.6} \left(\frac{\rho_L}{\rho_A} \right)^{0.1} D_p^{0.4} \left(1 + \frac{1}{\text{ALR}} \right) \\ & + 0.015 \left(\frac{\mu_L^2 D_p}{\sigma_L \rho_L} \right)^{0.5} \left(1 + \frac{1}{\text{ALR}} \right) \end{aligned} \quad (2.1)$$

where σ is surface tension, ρ is density, μ is viscosity, U is the flow velocity, D_p is the diameter of the prefilming lip, ALR is the air/liquid mass ratio, and the subscripts A and L are for air and the liquid being atomized, respectively.

Either one of the two terms in equation 2.1 dominates, depending on the properties of the fluid being atomized. For fluids with low viscosity such as water or distilled light fuel oils such as kerosene, the first term in equation 2.1 dominates. However, for viscous fluids such as heavy fuel oil and CWS, the second term dominates. The effects of ALR and fluid properties are shown in Figure 2.9 for

¹Lefebvre, A.H., quoted in Energy, Combustion, and Environment, Chigier, N., ed., McGraw-Hill, Inc., 1981.

TABLE 2.1

VARIABLE-SPRAY-ANGLE (VSA) ATOMIZER FEATURES

- **Spray Angle Adjustable On-Line by Controlling Atomizing Air Flow**
 - **Allows Compensation for Slurry Atomizing Characteristics**
- **Low Slurry Pressure**
- **External Mix/Low Wear**
- **Low Atomizing Air Flow**
- **Water or Air Cooled**
- **Operates on Both Slurry and Heating Oil**
- **Simple Construction/Low Cost**

Figure 2.8 Prefilm Airblast Atomizer
(See Footnote 1)

Figure 2.9 Effect of Air/Liquid Ratio and Liquid Viscosity On Twin-Fluid Atomizer Performance

water, number 6 fuel oil (at 210°F), and CWS for viscosities ranging from 100 to 600 centipoise.

In making the analogy between a prefilming airblast and the VSA atomizer one should be sure to consider that due to the perpendicular orientation of the atomizing streams, the VSA imparts higher shear and as such it is expected that the coefficients of the two terms in equation 2.1 may be different; however, for design purposes this equation is sufficient. The interesting feature of Figure 2.9 is that there is only a marginal increase in atomizer performance as the ALR is increased above 0.5 and for this reason this value was chosen as the design point to size the axial and radial air nozzle dimensions.

Figures 2.10 through 2.12 show the variation in spray angle which can be achieved by varying the atomizing air flows. These photographs were taken with the atomizer operating with water at a flow rate equivalent to 5 MMBtu/hr. Figure 2.13a shows a typical CWS particle size distribution for the variable-spray-angle (VSA) atomizer and Figure 2.13b shows a similar impact scatter plot for a modified fuel oil atomizer operating with slurry.

TF35-292N

Figure 2.10 VSA Atomizer with Narrow Spray Angle

TF36-292N

Figure 2.11 VSA Atomizer with Intermediate Spray Angle

TF37 292N

Figure 2.12 VSA Atomizer with Wide Spray Angle

Figure 2.13a Slurry Droplet Distribution with the Variable-Spray-Angle Atomizer
(380 lb/hr Slurry, 0.45 Air/Slurry Ratio)

Figure 2.13b Slurry Droplet Distribution with the Modified Delavan Delta Atomizer
(380 lb/hr Slurry, 0.35 Air/Slurry Ratio)

3. PLANNED ACTIVITIES

A series of tests will be performed to provide preliminary evaluation of component and system performance, identify key operating variables and their ranges, and establish appropriate operating conditions for subsequent proof-of-concept testing.

The tests will be made in a stepwise approach to allow for focused attention on individual components and subsystems prior to the operation of the fully integrated system. Three series of tests will be performed: combustor, heat recovery/emissions control, and integrated system. In addition to these tests, operation of the slurry facility will be carried out to demonstrate the operation of the slurry plant and to provide slurry for the test program.

The combustor tests will extend the data base on combustor performance generated during component design testing. During the component design tests, combustor design and scale-up were verified and preliminary data on combustor performance were obtained. These tests were made with the combustor firing directly into a water-quench exhaust system.

In the combustor tests, the combustor will be operated in conjunction with the transition chamber. Combustion gases from the transition chamber will then be sent to the water-quench exhaust system as discussed in Section 2.1. This series of tests will therefore allow evaluation of such system components and subsystems as the combustion air system, fuel oil and slurry delivery system, combustor cooling system, and transition chamber.

With the completion of the combustor test series, reliable operation of the combustor will have been achieved, thereby allowing focused attention on the operation of the boiler and emission control equipment. For these tests the products of combustion leaving the transition chamber will be directed to the boiler inlet.

With all major system components tested and evaluated, the system will be operated as an integrated system. Over 100 hours of integrated system tests are scheduled.

The slurry production facility will also be operated during the preliminary system tests. A series of component shakedown tests will be conducted to verify the operation of the individual components. In particular, the coal feeder will be calibrated and the pulverizer operated to determine coal grind at certain operating conditions. Once all components are operational and calibrated, slurry will be produced. Tests to determine slurry stability and viscosity will be made. The slurry facility will be operated as needed to supply slurry for the system tests.

4. SUMMARY

During the fourth quarter of the program, activities focused on the construction of the major system components and assembly of these components into Tecogen's test facility in preparation for preliminary system and proof-of-concept tests. An initial shakedown test of the combustor/transition chamber assembly was conducted which demonstrated that all equipment and subsystems are ready for preliminary system testing.

A variable-spray-angle external-mix atomizer was designed and built. This atomizer is expected to operate with low wear, low pump pressure, and low atomizing fluid flow while providing operation flexibility through its ability to control the spray pattern angle. Preliminary tests with water and slurry have shown that the atomizer produces a finer droplet size than previously tested.

System tests to evaluate component and system performance, identify key operating variables and their ranges, and establish appropriate operating conditions for subsequent proof-of-concept testing will be conducted during the next reporting period.

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