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CWS-FIRED RESIDENTIAL WARM-AIR HEATING SYSTEM

Quarterly Report for the Period August 1, 1988 – October 31, 1988

By
J. Balsavich, F.E. Becker and L.A. Smolensky

December 1988

Work Performed Under Contract No. DE-AC22-87PC79650

Tecogen Inc.
A Subsidiary of Thermo Electron Corporation
Waltham, Massachusetts

MASTER

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TABLE OF CONTENTS

1. INTRODUCTION	1
2. WORK PERFORMED DURING THE FIRST QUARTER OF THE SECOND PHASE OF THE PROGRAM	2
2.1 DESIGN OF FINAL LABORATORY PROTOTYPE FURNACE	2
2.2 FABRICATION AND ASSEMBLY OF FINAL PROTOTYPE COMPONENTS INTO COMPLETE FURNACE	9
2.3 FURNACE TESTING AND EVALUATION	9
2.3.1 Supersonic CWS Atomizer Testing	10
2.3.2 Combustor Performance Testing	10
2.3.3 Effect of IRIS Liners on System Performance	13
2.3.4 Bag Filter Testing	21
2.4 MANUFACTURING AND OPERATING COST EVALUATION	23
3. SUMMARY STATUS ASSESSMENT AND FORECAST	23

LIST OF ILLUSTRATIONS

2.1	Photograph of CWS Warm-Air Furnace System Testing Facility	3
2.2	Schematic of Second-Generation Furnace Facility	4
2.3	Third-Generation Furnace Arrangement No. 1	5
2.4	Third-Generation Furnace Arrangement No. 2	6
2.5	Third-Generation Furnace Arrangement No. 3	7
2.6	Third-Generation Furnace Arrangement No. 4	8
2.7	Effect of Excess Air on Combustion Efficiency	12
2.8	Percent Carbon Dioxide in Products of Combustion	14
2.9	Precombustor Wall Temperature as a Function of Time	15
2.10	Effect of Excess Air on NO _x Emissions	16
2.11	Effect of Excess Air on SO ₂ Emissions	17
2.12	Water Loop Heat Recovery Breakdown	20
2.13	Bag Filter Pressure Drop as a Function of Time	22
2.14	First CWS-Fired Manufacturing Prototype	24

LIST OF TABLES

2.1	Performance Tests with Supersonic Atomizer	11
2.2	Performance Tests with Different Liner Arrangements	18
2.3	Cost of Materials for the IRIS Combustor and CWS Atomizer	25
2.4	Cost of Purchased Components Associated with the CWS-Firing Processes .	26

1. INTRODUCTION

The objective of the CWS-Fired Residential Warm-Air Heating System program is the development of an economically viable coal-water slurry fueled furnace that is competitive with current oil and natural gas systems. This report summarizes the results of the first quarter of Phase II.

During the first phase of the program, the major focus of the work concentrated on the development of the major system components. The Phase II work entails the integration and refinement of these components to function as a complete residential furnace installation.

During this report period, testing and evaluation of the second-generation furnace continued. The program is ahead of schedule, and the process of design integration of all the major components is proceeding smoothly. In particular, design and fabrication of a third-generation furnace were done as was a preliminary manufacturing cost evaluation.

The third-generation furnace is considered the final laboratory prototype, after which a manufacturing prototype will be designed and built. Tecogen Inc. and its manufacturing partner, Yukon Energy Corporation, have already begun to discuss various design arrangements for this first manufacturing prototype.

2. WORK PERFORMED DURING THE FIRST QUARTER OF THE SECOND PHASE OF THE PROGRAM

2.1 DESIGN OF FINAL LABORATORY PROTOTYPE FURNACE

The design of the final laboratory prototype furnace (the third-generation furnace) is based on modifications made to the previous, second-generation model. A photograph and schematic diagram of the second-generation model are presented in Figures 2.1 and 2.2.

Both the third-generation furnace and the second-generation furnace employ the same major individual components and the same basic design principles, although the design arrangements for these furnaces are different. The design arrangements considered for the third-generation furnace are depicted in Figures 2.3 to 2.6. The furnaces are all 4.8 ft high and have the following respective footprints:

<u>Arrangement</u>	<u>Floor Space, ft²</u>
1	12.1
2	13.5
3	14.5
4	15.0

Arrangement 1 is the most compact and was selected for further development. Arrangement 2 is also rather compact; however, it comprises a horizontal type heat exchanger, and fouling may cause a problem for this heat exchanger.

The third-generation furnace as well as the second-generation furnace includes the following primary components and subsystems:

- The IRIS combustor with two partitions forming two precombustion chambers
- Shell-and-tube heat exchangers
- Bag-type ash collection subsystem
- Primary ash collection box
- Fuel delivery subsystem comprising the CWS storage tank with agitator and peristaltic tank
- Air-assist atomizer with air compressor
- Fuel ignition subsystem

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Figure 2.1 Photograph of Second-Generation Furnace

Figure 2.2 Schematic of Second-Generation Furnace Facility

1. Baghouses
2. Air Handling Unit
3. Blower, Pump and Control Box
4. Heat Exchanger
5. Primary Ash Collector
6. Combustor

Figure 2.3 Third-Generation Furnace Arrangement No. 1

1. Air Handling Unit
2. Baghouses
3. Primary Ash Collector
4. Combustor
5. Heat Exchanger

Figure 2.4 Third-Generation Furnace Arrangement No. 2

Figure 2.5 Third-Generation Furnace Arrangement No. 3

- 1. Combustor
- 2. Primary Ash Collector
- 3. Heat Exchanger
- 4. Baghouses
- 5. Air Handling Unit

Figure 2.6 Third-Generation Furnace Arrangement No. 4

All these components and subsystems had been described in detail in the final report DE-AC22-87PC79650-8 for the first phase of the program.

Although the basic design principles remain unchanged for the second- and third-generation furnaces as well as for the individual components and subsystems in these furnaces, some differences between the furnaces can be noticed. The most important differences are:

- The third-generation furnace (Figure 2.3) is designed as a stand-alone heating furnace. It incorporates the air handling unit (No. 2 on figure) and blower, pump, and control box (No. 3 on figure) as part of the furnace. In contrast, the second-generation furnace was designed more as an experimental unit for which modifications could easily be made. For example, the air handling unit, pump, and blower were not integrated into the unit.
- The second-generation furnace employs a single baghouse. In the third-generation furnace, a dual-baghouse design was chosen. In this design, the products of combustion can be alternated from one baghouse to the other. In this manner, the bag filters in one house can be cleaned while it is off-line. In the second-generation IRIS combustor, it was found that since the combustor pressure drop is so low, any attempt to clean the bag filters by air pulsing tended to blow coal particles back through the combustor and out the air inlet. Therefore, it is much easier to clean the bag filters when the baghouse is off-line.

2.2 FABRICATION AND ASSEMBLY OF FINAL PROTOTYPE COMPONENTS INTO COMPLETE FURNACE

It was mentioned that fabrication and assembly of the final prototype components into the second-generation furnace was accomplished during the first phase of the program, and now fabrication of individual components for the third-generation furnace has begun. Specifically, Tecogen Inc. began fabrication of the new IRIS combustor shell (No. 6 on Figure 2.3), shell-and-tube heat exchanger (No. 4 on Figure 2.3) and baghouses (No. 1 on Figure 2.3) for the furnace arrangement shown.

Final assembly of the individual components into the third-generation furnace is planned to take place once most of the experiments scheduled for the second-generation furnace have been completed. In this case, we will minimize the number of modifications required for the third-generation furnace and still will have at least 6 to 7 months of the life-cycle testing for this furnace.

2.3 FURNACE TESTING AND EVALUATION

Testing of the system shown in Figures 2.1 and 2.2 allows us to analyze the effect of some component modifications on the system performance and obtain data characterizing the behavior and reliability of the unmodified components and

subsystems (for example, fouling characteristics for the heat exchanger and bag filters, reliability of the peristaltic pump, etc.)

The particular objectives of this quarter's testing were:

- Development of the new type of CWS atomizer with lower atomizing air consumption.
- Studying the effect of different types of IRIS liners on system performance.
- Obtaining fouling characteristics of the bag filters.

2.3.1 Supersonic CWS Atomizer Testing

The atomizer used in the first phase of this program was annular in design, with CWS flowing in the central tube while atomizing air flowed in the annular passageway around the CWS tube. This atomizer was designed to operate at best, under sonic conditions. Under normal operating conditions this atomizer required 50 lbm/hr of atomizing air to shear the CWS into droplets that would burn in the IRIS combustor. This atomizing air flow rate translated up to 4.7 pounds of air per pound of CWS that was being atomized. With the new supersonic design, a converging/diverging section has been incorporated in the annular air passage to obtain supersonic velocities and provide higher shear between the air and the CWS.

As a result of a series of six performance tests, the supersonic atomizer worked extremely well, providing a much higher degree of atomization than had been previously obtained while significantly reducing the amount of atomizing air that was required. The atomizing air consumption was reduced to about 1.68 pounds of air per pound of CWS.

2.3.2 Combustor Performance Testing

A series of six performance tests was conducted with the supersonic atomizer (results shown in Table 2.1). The tested IRIS combustor has air inlets in each precombustion chamber and is thus capable of operating as a two-stage combustor. For the series of tests shown in Table 2.1, the air inlet to the lower precombustor was blocked in an effort to obtain baseline single-stage combustion data. In this mode of operation, all the combustion air entered the upper precombustion chamber, where the supersonic atomizer was situated at the top section of the air inlet. This series of tests was conducted for amounts of excess air ranging from 11.3 to 45.2 percent.

The effect of excess air on combustion efficiency while the unit operates in the single-stage mode is plotted in Figure 2.7. In referring to Figure 2.7, it can be seen that as the amount of excess air is decreased, the combustion efficiency, as determined by

TABLE 2.1
PERFORMANCE TESTS WITH SUPERSONIC ATOMIZER

Case	CWS Flow Rate (lbm/hr)	Input Rate (Btu/hr)	Atomizing Air Flow (lbm/hr)	CO ₂ (Excess Air) (Percent)	lbm Atomizing Air lbm CWS	Combustion Efficiency (Percent)	Test Duration (hr)
1	12.75	124,465	30.66	14.3 (26.4)	2.40	98.38	3.18
2	10.54	102,900	29.7	14.6 (23.8)	2.82	98.51	3.13
3	10.72	104,630	29.7	13.6 (32.7)	2.77	98.93	2.77
4	11.54	112,680	29.7	12.4 (45.2)	2.57	98.91	2.17
5	10.74	104,860	29.9	16.3 (11.3)	2.78	95.61	1.03
6	11.17	109,030	18.7	13.8 (30.8)	1.68	98.39	1.60

Figure 2.7 Effect of Excess Air on Combustion Efficiency

analysis of ash collected in the baghouse, decreases. It appears from the figure that the maximum combustion efficiency occurs at slightly over 30-percent excess air, with a combustion efficiency of 98.93 percent. Though the efficiency drops with decreasing excess air (95.61 percent at 11.3 percent excess air) the flame is extremely intense and stable. It would be expected that with secondary air injection, combustion efficiency would increase.

Combustor operating stability was also evaluated with the supersonic atomizer. Figures 2.8 and 2.9 show the percent carbon dioxide in the products of combustion and the precombustor wall temperature as a function of time. These plots are obtained from Case 6 of Table 2.1 and represent the lowest atomizing-air-to-CWS ratio tested to date (1.68 pounds of air per pound of CWS). In referring to Figures 2.8 and 2.9, it can be seen that both the precombustor wall temperature and the amount of carbon dioxide in the products of combustion remain very stable throughout the time that the unit was operated with CWS. The two large drops in carbon dioxide resulted at 10 and 20 minutes into the test when the access port on the top of the combustor was opened so that flame characteristics could be observed.

During the series of six performance tests with the supersonic atomizer, both NO_x and SO_2 measurements were taken several times for each particular test. These emissions were converted to an lbm/MMBtu basis and are presented in Figures 2.10 and 2.11, respectively. In referring to Figure 2.10, it can be seen that as the amount of excess air is increased, the amount of NO_x increases, reaching a maximum at about 40-percent excess air. This change of NO_x with excess air is quite dramatic; at about 9-percent excess air, the single-stage IRIS combustor produces about 0.29 lbm/MMBtu, whereas when the amount of excess air is increased to about 40 percent, the combustor produces 0.68 lbm/MMBtu, or 2.3 times more NO_x . Though for single-stage operation, NO_x levels are lower at lower values of excess air, it is not desirable to operate the combustor under these conditions since combustion efficiency decreases at the lower values of excess air.

In Figure 2.11, the amount of SO_2 produced is plotted as a function of excess air. For the sake of consistency, the y axis scale of Figure 2.11 was chosen to be the same as that for Figure 2.10. In referring to Figure 2.11, it can be seen that for single-stage operation, there appears to be no significant variation of SO_2 with excess air, at least of the same magnitude that is present for NO_x .

2.3.3 Effect of IRIS Liners on System Performance

During this quarter, a series of five tests was conducted on the furnace to study the effect of the IRIS liners on system performance. The results of these tests are presented in Table 2.2. Cases 1 and 2 were performed with silicon carbide liners in the lower precombustor section of the furnace. Hastalloy alloy 188 was used in the upper

Figure 2.8 Percent Carbon Dioxide in Products of Combustion

Figure 2.9 Precombustor Wall Temperature as a Function of Time

Figure 2.10 Effect of Excess Air on NO_x Emissions

Figure 2.11 Effect of Excess Air on SO₂ Emissions

TABLE 2.2
PERFORMANCE TESTS WITH DIFFERENT LINER ARRANGEMENTS

Case	Input Rate (Btu/hr)	Excess Air (Percent)	Precombustor Wall Temp., °F		Emissions lbm/MMBtu		Combustion Efficiency (Percent)	Liner Arrangements		
			Upper	Lower	SO ₂	NO _x		Upper Precombustion Chamber	Lower Precombustion Chamber	Main Combustor
1	101,525	32.7	2,075	---	0.550	---	99.7	Hastalloy Alloy 188	Silicon Carbide	Hastalloy Alloy 188
2	106,590	33.7	2,100	---	0.542	---	99.3	Hastalloy Alloy 188	Silicon Carbide	Hastalloy Alloy 188
3	112,360	27.3	1,966	2,155	0.539	0.747	96.7	Hastalloy Alloy 188	Hastalloy Alloy 188	Removed Insulation and Liner
4	98,300	27.3	2,022	2,140	0.562	0.626	98.5	Hastalloy Alloy 188	Hastalloy Alloy 188	Hastalloy Alloy 188
5	115,980	35.6	1,920	2,166	0.575	0.821	98.3	Hastalloy Alloy 188	Hastalloy Alloy 188	Hastalloy Alloy 188

precombustor and in the main combustion chamber. For these tests, combustion efficiencies based on analysis of ash collected in the bag filters were 99.7 and 99.3 percent, respectively. Although combustion performance was completely satisfactory, it was found that the silicon carbide liners were prone to slag buildup. This has not been the case with the metallic Hastalloy liners. Although some limited slagging may be occurring on the metallic liners during actual operation, it is possible that upon cooldown, it simply breaks off and is no longer visible.

Since the Hastalloy liners are not subject to slagging, a series of tests was conducted using liners made of this material in the lower as well as in the upper precombustor. This was done for Cases 3, 4, and 5 of Table 2.1. For Case 3, in addition to having a Hastalloy in the lower precombustor section, the high temperature liner and insulation layer was removed from the main combustion chamber directly below the lower precombustor. The purpose of this was twofold: first, to determine how much the main combustion chamber contributes to carbon burnout and second, to obtain heat transfer data from the hot gases to the cold walls. Because these walls were cold at that point, the combustion process would tend to be frozen; therefore, the combustion efficiency obtained is a reflection of how well the precombustor performs.

For this particular case, a combustion efficiency of 96.7 percent was obtained, based on analysis of ash collected in the bag filter. This indicates that there is only a small contribution by the main combustion chamber to overall carbon burnout; however, a hot main combustion chamber is still needed to raise the combustion efficiency to desirable levels.

In terms of heat transfer performance, by having the main combustion chamber uninsulated, much higher heat fluxes could be obtained due to this section having both high convective and radiative components. This can be seen in Figure 2.12, which shows the heat recovered in the water loop. Figure 2.12 is broken down to show the contribution by the combustor, which is mostly from the main combustion chamber, and the heat exchanger. As shown in Figure 2.12, the combustor recovers more than twice the amount of heat the heat exchanger does.

Since the available area for heat transfer in the main combustion chamber is one-tenth of what it is for the heat exchanger, this section is a fairly efficient heat transfer surface. In comparison, heat fluxes in the uninsulated main combustion chamber are on the order of $12,400 \text{ Btu/hr-ft}^2$, while in the heat exchanger fluxes are on the order of 670 Btu/hr-ft^2 . This translates into an overall heat transfer coefficient for the main combustion chamber of $9.4 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$, compared to $2 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$ in the heat exchanger.

Though the combustor operated with the main combustion chamber uninsulated, the combustion efficiency did fall off by a few points. In order to raise the efficiency up

Figure 2.12 Water Loop Heat Recovery Breakdown

to the previous levels, the main combustion chamber was insulated and a new liner made of Hastalloy alloy 230 was installed. Alloy 230 was used since it typically costs 1/3 less than alloy 188.

Two tests (4 and 5 in Table 2.1) were conducted with the IRIS combustor using all-metallic liners. The main difference between these tests is that Test 4 used the standard CWS that has been used throughout the program, namely UE3-116-MCW-F and Test 5 used a higher-ash CWS known as UE3-198-CWF-F. The UE3-198-CWF-F contained coal with 2.71 percent ash as opposed to 1.35 percent in the UE3-116-MCW-F. The higher ash fuel burned with a combustion efficiency of 98.3 percent, which was similar to the low ash CWS, which yielded a combustion efficiency of 98.5 percent when operating at close to the same conditions.

2.3.4 Bag Filter Testing

The main purpose of the bag filter tests conducted this quarter was to obtain data on the pressure drop characteristics of the residual fly ash produced from burning CWS prepared with micronized, deep-cleaned coal, and to see how it affects bag filters.

The bag filters used in this testing were standard bags made of a blend of Teflon and glass fibers needled into a woven scrim known by the trade name "Tefaire." Seven bags, each 36 inches long and 3.563 inches in diameter, were tested. This provided a 20.1 ft² collection area, and under normal operation conditions translated into an air to cloth (A/C) ratio of about 1.8 fpm.

Figure 2.13 shows how the filter pressure drop increased as a function of time. For the particular case shown in Figure 2.13, the unit was operated at an input rate of 105,000 Btu/hr with a combustion efficiency of 99.7 percent (as determined from analysis of the collected ash on the bags).

For a bag filter, pressure drop can be determined by the following:

$$P = (K_0 + K_1 W) V_s$$

where V_s is the filtering velocity (A/C), W is the dust loading on the bags at any given time, K_0 is a constant dependent on the pressure drop of the clean bag material, and K_1 is a constant related to the resistance of the material being collected. The value of K_0 for the Tefaire bags used in this work was measured at 0.00827 in. w.c./fpm. From the data in Figure 2.13, the value of K_1 for this ash was found to be on the order of 19 in. w.c.-ft²/fpm-lbm. From the literature we've found that this value is fairly typical of many dusts in the particle size range between 2 and 20 microns.

Figure 2.13 Bag Filter Pressure Drop as a Function of Time

2.4 MANUFACTURING AND OPERATING COST EVALUATION

The "Manufacturing and Operating Cost Evaluation" (Task 2.50), is divided into two parts. The first part of this task was completed this quarter and included a preliminary cost evaluation of the first manufacturing prototype. The second part of the task is scheduled for the last quarter of the phase, when a more accurate cost evaluation will be carried out.

The cost was evaluated for the design concept depicted in Figure 2.14. The furnace system comprises the IRIS CWS-fired combustor (No. 4 in Figure 2.14) and its auxiliary equipment; a closed-loop water circulation system with a water pump and hot water/air heat exchanger coil (No. 1 in Figure 2.14) to cool the IRIS combustor (No. 6 in Figure 2.14); a primary ash collector (No. 7 in Figure 2.14); and a gas/air heat exchanger (No. 9 in Figure 2.14).

The concept is based on modifying the basic Yukon stoker-type wood-coal furnace to operate with the IRIS combustor on CWS fuel. One difference between the original Tecogen design and this concept is that the original design used a compound flue gas-to-water and water-to-circulating air heat exchanger loop, while this design mainly uses a direct flue gas-to-circulating air heat exchanger.

The cost analysis was done in cooperation with Yukon Energy Corporation and used an incremental cost approach. In this fashion, the base cost of the Yukon furnace was defined and the incremental cost of the CWS combustor and components were added. In this way, uncertainty regarding the total cost is mainly associated with the unique CWS components. Later in this phase, more exact costs will be estimated based on detailed design drawings done in cooperation with Yukon. This design will make use of Yukon's 25 years of expertise in the design of residential furnaces.

The components that are essentially the same for the original and modified Yukon furnace are the fan for the air handling unit, the furnace housing, the ash collection box, the insulation, the flue-gas-to-circulation-air heat exchanger, and the control system components.

By factoring out these component costs in the original Yukon furnace (base cost), the cost evaluation task for the first manufacturing prototype becomes one of adding to the base cost the costs of the IRIS combustor, peristaltic pump, CWS atomizer with air compressor, and hot water/air coil with water loop circulation pump.

The evaluated cost of the materials S_m and components S_p associated with the CWS-firing processes are indicated in Tables 2.3 and 2.4:

- 1. Warm Air
- 2. Cold Air
- 3. Air Filter
- 4. IRIS Combustor
- 5. Combustion Air
- 6. Water Cooled Combustor Walls
- 7. Ash Collecting Box
- 8. Air Fan
- 9. Flue Gas/Air Heat Exchanger

- 10. Discharged Flue Gases
- 11. Hot Water/Air Coil

Legend:
 ———→ Air
 - - - - -→ Flue Gases and Combustion Air

Figure 2.14 First CWS-Fired Manufacturing Prototype (Preliminary Concept)

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TABLE 2.3
COST OF MATERIALS FOR THE
IRIS COMBUSTOR AND CWS ATOMIZER

Items	Cost (\$)
1 Cast Iron Combustor Shell	60
2 Hastalloy Alloy 230 (1/16 in. Thick) Liners	88
3 Silicon Carbide Partitions	57
4 Combustor Insulation	14
5 Main Combustor Chamber Liners (14 ga 304 SS)	28
6 CWS Atomizer Material	6
TOTAL, S_M	253

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TABLE 2.4
COST OF PURCHASED COMPONENTS
ASSOCIATED WITH THE CWS-FIRING PROCESSES

Items	Cost (\$)
1 Fixed Speed Peristaltic Pump 900-0490	33
2 Air Compressor	84
3 Heat Exchanger Coil	35
4 Water Loop Circulation Pump	36
TOTAL, S_p	188

$$S_m = \$253$$

$$S_p = \$188$$

For the considered types of furnaces, labor cost can be calculated as:

$$S_L = 0.4 S_m = 0.4 \times 253 = \$101$$

and overhead expenses are:

$$S_0 = S_L = \$101$$

Taking into consideration the known cost of the remaining unchanged components $S_u = \$550$ we can determine the manufacturing cost of the CWS-fired residential warm-air heating system:

$$S = S_m + S_p + S_L + S_0 + S_u = \$1193$$

For residential appliances, the selling price to the customer is typically 1.75 times the manufacturing cost. Thus, we could expect a selling price of approximately \$2,100.

3. SUMMARY STATUS ASSESSMENT AND FORECAST

During this report period, testing and evaluation of the second-generation furnace assembly (which comprises all the major system components) continued. Emphasis was placed on integrated system performance and value engineering. Work also began on the design and fabrication of a third-generation prototype furnace. In cooperation with Yukon Energy Corporation, a preliminary cost evaluation was accomplished.

During the next quarter, testing of the second-generation furnace will continue and fabrication of the third-generation furnace will be completed. Plans will also be made for more detailed design and cost analysis of the manufacturing prototype unit.

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