DOE/CE/40735-2

**DEVELOPMENT OF A GRAVEL BED COMBUSTOR FOR A SOLID FUELED
GAS TURBINE**

For the period February 1, 1989 to June 30, 1991

by

Kenneth W. Ragland, Danny J. Aerts, and Carl A. Palmer
University of Wisconsin-Madison
Department of Mechanical Engineering
Madison, WI 53706

June 1992

prepared for:

THE U.S. DEPARTMENT OF ENERGY
Under contract No. DE-FG02-85E40735

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DEVELOPMENT OF A GRAVEL BED COMBUSTOR FOR A SOLID FUELED GAS TURBINE

ABSTRACT

Further work on a novel pressurized, downdraft combustor using aspen woodchips is reported for the period 2/89 to 6/91. The 42 cm i.d combustor was connected to a modified Allison 250-C20B gas turbine engine and operated for 250 hours. The performance of the combustor-turbine system is discussed. Deposits of ash on the turbine nozzles and rotors are identified and discussed. A dynamic simulation model for the combustor-turbine system is presented and used to investigate the control of the system. The highest net power output was 61 kW or 20 % of full power; the highest turbine speed was 75 % of the maximum speed; the highest mass flow was 50 % of the full power flow. The stability of the combustor must be improved before higher output and longer runs can be achieved.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

TABLE OF CONTENTS

	<u>page</u>
ABSTRACT	i
LIST OF FIGURES	iii
LIST OF TABLES	iii
ACKNOWLEDGEMENTS	iv
I. INTRODUCTION	1
A. Project Objectives	1
B. The Gravel Bed Combustor Concept	1
II. EXPERIMENTAL INVESTIGATIONS	3
A. Test Setup	3
B. Instrumentation and Controls	5
C. Combustor-Turbine Test Results	7
D. Discussion of Test Results	11
E. Turbine Deposits	15
F. Woodchip Drying	25
III. MODELING THE COMBUSTOR-TURBINE SYSTEM	27
A. Model Formulation	27
B. Model Verification	31
C. Model Performance	33
IV. CONCLUSIONS	38
V. REFERENCES	39
APPENDIX A. Instrumentation and Control Equipment	40
APPENDIX B. Summary of Test Data	42
APPENDIX C. Combustor-Turbine Test Comments.	45
APPENDIX D. Model Nomenclature	51

ACKNOWLEDGEMENTS

This project was sponsored by the U.S. Department of Energy under grant DE-FG02-85CE40735. Steve Waslo of DOE was the Program Manager. Andrew Baker, with the U.S.D.A. Forest Products Laboratory, advised us and supplied the woodchips. The Allison Division of General Motors provided the turbine. At Allison, Sy Ali, Tom Wright, Richard Wenglarz and others have provided much appreciated technical assistance. At the UW, Dr Mahendra Misra did the analysis of turbine deposition, Serdar Yeralan did the drying experiments, and John Wold, Dave Reinholt, Craig Hoerning and Steve Dingle assisted with the combustor-turbine tests.

I. INTRODUCTION

This report is for phase II of the Gravel Bed Combustor project. Phase I ran from Sept. 1, 1985 to Jan. 31, 1989 [Ragland and Aerts, 1989]. In Phase I, which used a 23 cm i.d. gravel bed combustor, the design and performance of the combustor were explored experimentally and with a computer model. A burning rate correlation was obtained at pressures up to 5 atm. Preliminary tests were conducted with a modified Allison model 250-C20B gas turbine. In Phase II a larger gravel bed combustor was built and used with the Allison gas turbine. The performance of the combustor-turbine system was explored experimentally and with a computer model.

A. PROJECT OBJECTIVES

The objective of phase II of the Gravel Bed Combustor project was to power a modified Allison model 250-C20B gas turbine with a 42 cm i.d. gravel bed combustor at a power level of 56 kW (75 hp) using woodchips as the fuel and without using additional hot gas cleanup. A target was to sustain this power level for a continuous 24 hour period. This was to be done in the house air mode with the compressor air dumped, and if possible, to switch over to the free standing, self-sustaining mode of operation. The purpose was to demonstrate the feasibility of the gravel bed combustor concept for a gas turbine. Additional objectives were to study the control of the system experimentally and using a computer model, and to study the ash deposition and erosion of the turbine blades.

B. THE GRAVEL BED COMBUSTOR CONCEPT

Biomass fuels are a significant energy option. Industrial and utility power plants which currently burn oil could in many locations switch to biomass fuels. Of all the biomass fuels, woodchips are the most easily produced and easily transported. Pulverized wood is not recommended because in contrast to coal, wood cannot be easily pulverized. Woodchip fuels are readily available in certain locations, cost effective, employ local people, and have low emissions. Wood is a renewable resource which naturally recycles the carbon dioxide in the combustion products. The ash from combustion can be reused as fertilizer.

Industrial power cogeneration can be done efficiently using a gas turbine to produce both electricity and process heat. Direct combustion offers a simpler and less expensive system than gasification or indirect combustion when using a gas turbine. Since the combustor is pressurized, the combustor should be as compact as possible, and should not produce excess particulates. Fluidized beds tend to generate excess ash due to attrition of the bed material. Updraft, packed bed combustors have relatively low intensity.

In this project a downdraft, packed bed combustor for a gas turbine is being developed. The combustor is designed to promote intense combustion in a thin reaction zone and to control particulate growth by using high excess air. The combustor consists of a magnesia and alumina gravel bed on top of which woodchips are fed. The heated air from the compressor (or heat exchanger in the house air mode) flows down through the woodchips (see Fig. 1), dries the woodchips near the top, helps devolatilize the woodchips further into the bed, and oxidizes the charred woodchips which are located in the region just above the gravel/woodchip interface. The pyrolyzed gases combust with the air and burn out in the char layer and in the gravel bed. The char burns at the gravel interface. Fine char particles entrained by the airflow are trapped and burned in the gravel bed. Ash is blown through the bed and the turbine. Combustion temperatures are kept low enough to avoid sintering the ash. Mineral matter in wood is in molecular form and the high excess air minimizes the particulate growth during combustion. The bed has a high thermal capacity that moderates temperature fluctuations.

In contrast to gas or liquid fuel fired combustors, the fuel burning rate in the woodchip-fired downdraft combustor is not determined by the fuel feed rate, but rather by the system variables of pressure, inlet temperature, and air flow rate. These system variables are in turn governed by the performance of the turbine and compressor. Instead of a throttle, load control is achieved by means of bypassing some air around the combustor, venting some of the compressor air, and with steam injection upstream of the combustor.

Figure 1. Gravel Bed Combustor Concept

II. EXPERIMENTAL INVESTIGATIONS

A. TEST SETUP

Experiments were conducted in our laboratory using a modified Allison model 250-C20B turbine (rated at 300 kW) loaded by a water brake and fired with a 42 cm i.d. gravel bed combustor using 2 cm aspen chips (see Fig. 2). Woodchips are fed continuously to the combustor by the horizontal auger. The conveyor and slidegate-lockhopper arrangement operate intermittently. Fuel level in the lockhopper is sensed sonically, while in the combustor, fuel level was sensed optically with a laser. When house air is used, the air is regeneratively heated to simulate heating by the compressor. The system is loaded with a water brake. In the self-sustaining mode the house air valve is closed, and the bypass and vent valves are used.

The 42 cm i.d. combustor was enlarged from the previous 23 cm i.d. setup. The size was determined using an experimentally determined burning rate correlation to match the lower portion of the turbine performance range at a load of 56 kW. This was the largest size combustor that could fit into the engine test room. The combustor system was designed for a maximum pressure of 7 atm. The main combustor section, shown in Fig. 1, is a carbon steel (SA-53) pressure vessel 0.95 cm thick lined with insulation and refractory. The steel is 61.0 cm o.d., 91 cm long and 109 cm high. The vertical section had 3.8 cm thick Ceraform 43 vacuum formed insulation and the horizontal section had 7.6 cm of insulation. Kricon 28XR refractory was 5.1 cm thick in the vertical section and 9.2 cm thick in the horizontal section. This gave a burning zone i.d. of 41.3 cm and a horizontal section i.d. of 25.5 cm. This was used for 63 tests, about 107 hours of operation.

Figure 2. Gravel Bed Combustor-Gas Turbine System

Refractory and insulation were then replaced and the inside area was increased slightly. The thickness of refractory in the vertical section was increased to give greater strength and the horizontal diameter was increased to reduce pressure drop. Insulation thickness was 2.55 cm in the vertical section and 7.6 cm in the horizontal. Refractory was 5.7 cm thick in the vertical section and 7.6 cm in the horizontal. This gave a burning zone i.d. of 42.6 cm and a horizontal i.d. of 28.7 cm.

The top 2 cm of the gravel bed were 8-10 mm magnesia pieces (Pyro-Mag KF-98 from National Refractory). The next 9 cm was a wedge shaped mixture of magnesia pieces and 16 mm alumina balls (T-1061 tabular alumina from Kaiser Chemical). Finally, 25 mm alumina balls (T-162 tabular alumina from Coastal Chemical) were used in the horizontal section. Two sets of 0.95 cm diameter alumina rods held the bed material in place. These were located at the end of the horizontal section of the main combustor section. (Inconel rods 1.27 cm diameter were used in the vertical section to hold the bed material for 11 of the last tests to get a shorter bed with less pressure drop.)

An outlet section of 40.6 cm o.d. carbon steel pipe, 0.95 cm thick and 45.7 cm long was located after the combustor section. This was lined with insulation and refractory. The inside was tapered from 25.4 cm i.d. at the combustor end to 15.2 cm i.d. at the turbine end. Four 2.5 cm dia. ports were spaced around the section to mix in bypass air. There were also connections for temperature, pressure and gas sampling probes. A 15.2 cm diameter stainless steel flexible pipe, 30.5 cm long connected the outlet section to the turbine inlet.

On top of the combustor section was a 27.3 cm pipe tee. The fuel feeder screw came in the side of this tee and the main air supply was connected to the top of the tee. Two sets of quartz windows were installed in the combustor 10 cm and 23 cm above the bed, similar to the previous setup. A light source on one side could be seen on the other side by the operator when fuel level was below the windows. Fuel feed was controlled to maintain fuel level between the windows. The lights were hard to see when burn through occurred and there was glowing in the combustor. For the last 17 tests a small helium neon laser was set up at the lower window to give a sharper, more distinctive signal. This worked very well.

The fuel feeder system was the same except that the lockhoppers were enlarged. Both sections were lengthened by 15.2 cm. This increased lockhopper volume from 18 L to 26 L and allowed higher fuel feeding rates required by the larger combustor.

A new air heater was built and used for the last 48 tests. The old air heater had too much pressure drop on the gas side. The exhaust fan could

not provide enough suction at higher loads to keep the turbine outlet negative, which resulted in smoke in the test room. The new air heater was a shell and tube heat exchanger with one gas pass and three air passes. The shell was 58.4 cm diameter and made from 0.091 cm thick stainless steel sheetmetal. The outside was wrapped with 2.5 cm thick Cerablanket and 5.1 cm thick Rigiflex FSK insulation. The air side had stainless steel inlet and outlet headers connected by 1.91 cm o.d., 1.66 cm i.d. stainless steel tubes. Each pass consisted of 42 tubes. This provided almost 4 times the air side cross section of the old air heater, decreasing the air supply pressure drop. The gas side open cross sectional area was almost 5 times greater than that of the old air heater, giving more exhaust suction at the turbine outlet.

A 5.1 cm ball valve was put in the house air line to provide increased air flow. Flanged, 7.6 cm ball valves were put in the compressor air outlet (vent) line and in the compressor to house air crossover line. A 3.8 cm ball valve was put in the bypass air line. Automax E600 electric actuators were put on all 4 valves, replacing pneumatic actuators, to get more accurate control.

Steam injection was added to the combustor for the last 43 tests. Saturated steam at 500 kPa was run through 2.7 cm pipe to the top of the combustor section. A control valve was used to adjust the steam flow from the control room. A steam trap was installed to remove condensate from the steam.

The gas turbine assembly was the same as in Ref. 1 except a larger oil cooler was installed in a water bath to keep the temperature down. A starter motor, which is discussed later, was added for several of the tests.

B. INSTRUMENTATION AND CONTROLS

Instrumentation included temperature, pressure, and flow rate measurements at the locations indicated in Fig. 3 and as summarized in Appendix A. All data was sampled and stored on a hard disk every 6 s. Temperature was measured at stations 1, 2, 3, 5, 8, 9, 10, 13, and 14 in Fig. 3. Pressure was measured at stations 0, 2-5, and 15. Flue gas was monitored for oxygen, carbon dioxide, carbon monoxide, and nitrogen oxide, and total particulates. On the turbine the torque, gas generator turbine speed (N1), power turbine speed (N2) and vibration, and gear box vibration were measured. Also a metal chip detector in the oil was used.

The feed rate of woodchips was determined in the following manner. An optical tachometer measured the rotation rate of the horizontal fuel auger. A calibration of woodchip flow versus auger speed was used. Also, the weight of the fuel hopper was measured continuously with a load cell and this was used as a check on the horizontal auger data.

C. COMBUSTOR-TURBINE TEST RESULTS

Ninety-eight combustor-turbine tests were run. The purpose of these tests was first to shake down the test rig, and then to investigate the performance of the system. A summary of key measurements for each run is given in Appendix B. The numbers shown in Appendix B are from the best part of each run. Startup typically required about 45 min. Steady state conditions were reached for only short periods of time as will be discussed below. The longest run (#285) lasted 7 hr and the highest power output level reached was 61 kW (81 hp). The turbine was run for a total of 202 hr, plus 52 hr were run on the turbine during the previous phase reported in Ref. 1. Operational comments regarding each run are summarized in Appendix C. As indicated by the comments, a variety of operational and equipment problems had to be overcome. The effect of bypass air, air preheat, steam injection, and fuel moisture were tested. The main goal was to try to achieve steady operation at increasingly higher levels and for increasingly longer run times.

All tests were run in the house air mode with the compressor air dumped to the atmosphere. The highest turbine speeds were 75 % of the maximum speed. The highest mass flows through the turbine were at 50 % of the rated full power flow. Bed exit temperature (T5, Fig. 3) was generally limited to 900°C to minimize ash deposition in the bed, and this was done by using high excess air. Note that the turbine temperature in Appendix B is T8, the inter-turbine temperature. The combustor inlet temperature (T3) from the heat exchanger was generally representative of the compressor outlet temperature (T2). The net power output is zero until the air flow reaches about 0.2 kg/s and then begins to increase rapidly with increasing air flow for a given temperature. Plots of net power versus air flow and fuel flow rate are shown in Fig. 4. Performance data plots from runs 266, 268, and 285 (Figs. 5, 6 and 7) are examples of operating under manual control and automatic control, and are discussed in detail in the next section.

Figure 4. Woodchip and Air Flow Rate Versus Net Turbine Power

Figure 5. Test Data From Run 266

Figure 6. Test Data From Run 268

Figure 7. Test Data From Run 285

D. DISCUSSION OF TEST RESULTS

The following topics will be discussed: combustor stability, gravel bed behavior, automatic control, fuel level control, steam injection, turbine vibrations, and switch-over to the free standing mode. In the next section ash deposition to the turbine blades is discussed.

Combustor Stability

The gravel bed combustor-turbine system is a sensitive, high gain system. The fuel burning rate is sensitive to changes in pressure, inlet air temperature and air flow rate. The reaction zone is about 2-3 cm thick and is located at the fuel-gravel interface. The combustor is operated near the lean limit. Perturbations in the flow conditions cause the reaction zone thickness to change, causing further changes in the system output, as seen in Figs. 5, 6 and 7. The response in the house air mode is to increase or decrease the inlet air flow either manually or automatically. However, in doing so the overall system response must be considered, as explained in section III. Perturbations may be due to a slow drift caused by heat exchanger changes or turbine speed changes, or rapid changes due to pressure fluctuations from operation of the lockhopper or perhaps local fuel bridging or changes in fuel properties. Investigation into the combustor stability is continuing.

Woodchips are fed into the combustor at the top and are swept downward by the inlet air. Small air jets are used to promote a uniform fuel depth. It is possible that at times the fuel bed is higher on one side than another and that this could cause combustor instability. Uniformity of the fuel feed needs to be verified with a video camera.

Gravel Bed Behavior

The refractory gravel bed supports the woodchips and allows burnout of the char and volatiles. The bed provides thermal inertia which reduces rapid turbine acceleration. Ash is deposited in the dead-end zones of the gravel while the main passages remain open. Deposition increases near stoichiometric conditions and hence the combustor is run lean. Potassium in the ash reacts with alumina bed material, and hence magnesia is used at the top of the bed. Alumina is less prone to damage from thermal shock than magnesia and is used for the lower portion of the bed. Bed pressure drop should be kept as low as possible and still provide for char burnout and thermal stability. There is no statistical evidence that bed pressure drop increases during a run, however after several runs the pressure drop did increase. Better control over the combustor is needed before the buildup of bed pressure drop can be assessed. In general pressure drop appears to increase when the combustor exit temperature exceeds 900°C.

Automatic Control

Automatic air flow control was used during some of the tests. Both carbon dioxide and bed outlet temperature were tried as inputs to the controller. Carbon dioxide gives a rapid indication of changes in combustor conditions, but fluctuates too rapidly at times. Combustor outlet temperature varies slowly (see Fig. 8). An optimum control system might use both carbon dioxide and temperature inputs. The controller was set for proportional and integral control. Since the overall system is sensitive to small changes, a vernier air flow control valve was added. The control system worked fine when the input signal fluctuations were not too large, but with large swings in combustion the controller had to be switched to manual operation.

Figure 8. Carbon Dioxide and Bed Outlet Temperature Control Signals

Fuel Bed Level

A Mikron 65EM optical pyrometer was mounted on top of the combustor to help control the fuel bed level. By looking down on the top of the bed through a quartz window, the pyrometer detected radiation when burn-through occurred. When this happened the horizontal auger speed was increased. The upper limit on the height of the fuel bed was set by interruption of a laser light. To keep a steadier fuel level in the combustor and to give greater combustion stability, we tried mounting an ultrasonic detector in the top of the combustor. A Sonin 30 distance meter did not have a large enough sensor area to detect a signal bouncing off woodchips. A Stanley Estimator 30-030 was then tried. It gave a reading from a layer of woodchips, and was tried several places inside the combustor. However, due to the geometry of the combustor we could not get a consistent reading. The signal would bounce back from an expansion in the pipe and would not read the fuel level further down. We plan to try a video camera next.

Steam Injection

Saturated steam at 500 kPa was injected above the fuel bed to try to control the swings in burning rate that were sometimes experienced. Normally air flow alone could be adjusted to control the burning rate. But if burning rate and temperatures increased rapidly, turbine speed would also go up, and adding more air to cool off the reaction zone would increase turbine speed even more. Using steam to cool the bed gave an independent control of bed temperature. From run 283, a steam flow of about 10% of the air flow caused a 3%/min decrease in the carbon dioxide level. Steam injection helped reduce the peaks in the burning rate, but it did not eliminate them. More precise control of the steam flow rate is needed in the future.

Turbine Vibration

Two accelerometers were mounted on the turbine to measure vibration - one on top of the gas producer turbine and the other on top of the gearbox. During many tests one or both of these would indicate greater than 2.5 cm/s vibration, which was the alarm point. Operation would continue if we did not have a turbine chip detector alarm or any other negative indication. Vibration increased at certain speeds, especially turbine vibration, but then dropped off as we passed to a higher speed (Fig. 9). Vibrations at low speeds were not considered serious. Vibrations at high speed were a cause for shutdown. Frequencies below 15 hz are not considered to be a problem. Cold air flow tests with a FFT analyzer showed that the greatest peaks were at less than 15 hz. Some peaks were at the speeds of the tachometer-generator gears, but there were only small peaks at speeds equal to N1 and N2. A frequency

filter was built which passed frequencies between 15 and 2000 hz, and this greatly reduced the number of high vibration alarms.

Figure 9. Turbine Vibrations for Run 260

Switch-Over to Free Standing Mode

One objective of the project was to operate in a self sustaining mode, with air from the compressor going to the combustor. During startup the compressor air was vented and compressed house air went to the combustor. After coming up to speed the vent valve was slowly closed to increase the compressor outlet pressure up to the combustor inlet pressure. If these could be equalized, then switch-over could be done. However, the compressor always went into surge as the vent valve was closed even though the air flow through the compressor was sufficient to match the air flow through the combustor (see Table 2).

It was decided to add an electric motor to the unit to boost compressor speed and allow switching over to self sustaining mode. A shaft and mounting bracket were made which attached to the turbine starter-generator pad and the turbine support stand. The motor was connected to the shaft by a HTD belt and pulleys. The motors, which were loaned by a local supplier at no charge, were 3 phase ac. The motor controller was a Wood's ETRAC AFC-2010-08 variable speed ac drive. Several size motors were tried culminating with a 7.5 kW motor which provided enough air to the combustor for startup, but at higher speeds the compressor still went into surge. The motor and drive shaft assembly were then removed. The conclusion was that the Allison 250-C20B engine has too small a surge margin for our combustor configuration.

Thinner Gravel Bed

For the last 11 tests the thickness of the gravel bed was reduced to 8 cm, and the bed was held in place by horizontal inconel rods. In this setup the gravel bed did not turn a corner, the pressure drop was reduced, and the gas flow was more uniform. It was hoped that the combustion might be more stable due to the more uniform air flow, and that there would be a better chance of achieving switch-over to the self-sustaining mode of operation due to the lower pressure drop. As it turned out, the combustion was not more stable, and eventually several of the inconel rods separated and a few pieces of gravel penetrated into the turbine. The first stage nozzle experienced severe erosion of the trailing edges, and the first stage rotor experienced severe erosion of the leading and trailing edges. Several bearings failed. The gas producer section of the turbine was no longer usable. The observed damage was due primarily to gravel penetrating the turbine.

E. TURBINE DEPOSITS

This section summarizes the results obtained thus far from various chemical analyses of ash samples taken from different stages of the turbine.

The first set of samples was obtained when the turbine was disassembled and inspected during June 1990 after 130 hours of operation. Yellow poplar chips were used during this period of operation. The second set of deposit samples was obtained in May 1991 after 122 hours using aspen chips.

Thickness of Turbine Deposits

The first inspection showed that in general the deposits were heavier on the nozzles than on the rotor blades. The deposits on the power turbine rotor blades were heavier compared to the deposits on the rotors in the first two stages. Also, the color of the deposits ranged from lighter green/gray in the upstream stages to dark green or brown in the power turbine sections. The nozzles and rotors cleaned up well with walnut shelling and did not show signs of erosion.

An attempt was made to quantify the second set of turbine deposits in terms of their thickness, and the measured values are reported in Table 1. Due to the complex contour of the turbine blades and due to the brittleness of the deposits, it was difficult to measure the thickness using calipers. For deposits that chipped off in flakes, the thickness was measured using an optical microscope. The rest of the approximate thicknesses reported in Table 3 were estimated and bracketed using a feeler thickness gauge. Again, the deposits were thicker on the nozzles than on the rotors.

Table 1. Thickness of Wood Ash Deposits in Different Stages of Turbine

1st Stage Rotor		~0.1 mm
2nd Stage Nozzle	Leading Edge	1.0 mm
	Trailing Edge	0.5 mm
2nd Stage Rotor	Front	~0.1 mm
	Back	< 0.1 mm
3rd Stage Nozzle		1.5 mm
3rd Stage Rotor	Front	0.15 mm
	Outer Rim	0.5 mm
4th Stage Nozzle	Leading Edge	1.6 mm
	Trailing Edge	0.2 mm
4th Stage Rotor	Back	~0.2 mm
	Front	~0.1 mm

Turbine Blockage

A measure of turbine flow area decrease from deposition can be given by the expression NAIN, normalized nozzle area index number [Kimura et. al., 1987],

$$\text{NAIN} = \frac{\frac{\dot{m}\sqrt{T}}{P}_{\text{turbine}}}{\frac{\dot{m}\sqrt{T}}{P}_{\text{clean turbine}}} \quad (1)$$

This equation assumes that the nozzle operates in an aerodynamically choked manner. Kimura et. al. used this index when studying coal combustion in a test stand that featured only the first stage turbine nozzle for studying deposition.

The NAIN has been calculated for all the steady-state test data following the overhaul of the turbine that occurred in June, 1990, and the results are shown in Fig. 10. The best-fit line ($r^2 = 0.56$) gives an area reduction rate of 4.2% per 1000 kg of wood burned. The results are presented as a function of cumulative wood burned because the tests were run at a variety of conditions, some at low load, and some at higher load. In terms of total hours, the NAIN decrease was 0.19% per hour. This reduction rate includes area reduction of all the stator and rotor stages, but is not at full load. By way of comparison, Kimura et al. found NAIN reduction rates of 0.35%/hr for residual oil and 0.17-0.50%/hr for Otisca coal-water mixture (50% solids, 0.8% ash, 4% sulfur, dry). This was at full load, but with only a single stage cascade of blades.

Figure 10. Turbine Normalized Area Index Number Versus Woodchips Burned

Chemical Analysis of Turbine Deposits

Various techniques used to analyze the turbine deposits included Electron Spectrometry for Chemical Analysis (ESCA) and Inductively Coupled Plasma Emission Spectroscopy (ICPES) to determine the elemental composition, and X-Ray Diffraction (XRD) for the identification of possible compounds present in the samples. Results of these analyses are presented in Figures 11 to 16. Deposits to the gravel bed were investigated in phase I and are not discussed in this report. The conclusion of the earlier work was that magnesium oxide gravel was best in the upper part of the bed and alumina oxide was best for the lower portion of the bed.

Results obtained from ICPES and XRD for the samples obtained during the first turbine overhaul are presented in Figures 11 and 12. Figure 11 shows the elemental composition of deposits, as determined by ICPES, in different stages of the turbine. It is seen from this figure that the deposits in the upstream stages are richer in alkali metals (potassium and sodium) and sulfur, whereas, those in the downstream stages show decreasing concentrations of both K and Na, while the proportions of calcium and magnesium are increasing. In addition to the elements listed above, iron and aluminum are the other elements present in the deposits. The amounts of Fe and Al are a maximum of 2.5% and 0.5% respectively, as observed in the last turbine stage. X-Ray Diffraction patterns of the deposits shown in Fig. 12 confirm the predominant amount of K and S and, in addition, show that these elements are present predominantly as potassium sulfate. Calcium and magnesium are present primarily as CaO and MgO respectively, though there appears to be some phosphates of both Ca and Mg present in the deposits. Iron and aluminum compounds seem to be present in quantities that are too low as they do not give a strong enough signal to be detected.

Figure 11. Elemental Composition of Ash Deposits in Different Stages of the Turbine - Yellow Poplar Fuel

Figure 12. X-ray Diffraction pattern of ash deposit taken from the stator before the power turbine. Compounds identified: 1. K_2SO_4 2. CaO 3. MgO 4. $Mg_3(PO_4)_2$ 5. $Ca_3Mg(SiO_4)_2$?

Chemical analyses of the second set of deposits (obtained during the second turbine overhall) are presented in Figures 13 to 16. Figure 13 shows the elemental composition of the deposits as determined by the ICPES. These results, in general, show that deposits on the upstream stages are richer in Ca and P compared to those in the downstream stages. The results also show that the relative amounts of K, Na and S are higher in the deposits on stationary parts (nozzles) compared to those on the rotating parts. From this figure, it appears that the relative amount of K increases in the downstream stages. This is not evident from the deposits on the nozzles, but becomes evident when the amounts in the deposits on the rotors in different stages are compared. This observation is important, as will be discussed in the next section, in support of one of the various phenomena of ash deposition.

X-Ray Diffraction results of the deposits are shown in Figs. 14 to 16. Figure 14 shows the results for the first stage nozzle, Fig. 15 for the first stage rotor and Fig. 16 for the fourth stage nozzle. In these figures, identification of the compounds that show strong peaks is based strongly on the results of elemental analysis by ICPES. It is seen from Fig. 14 that the most intense peaks are displayed by CaO , which agrees with the ICPES results showing higher amount of Ca. Other strong peaks displayed are those of MgO , K_2SO_4 , $Ca(OH)_2$ and $CaFe_4O_7$. Some of the weaker peaks indicate the possible presence of Mg_6MnO_8 , K_2O , K_3AlO_3 and $Ca_3(PO_4)_2$. Deposits on the first stage

rotor show more intense peaks of MgO followed by that of CaO (Fig. 15). These results again show the presence of K_2SO_4 and $Ca(OH)_2$. The weak signals in Fig. 15 are displayed possibly by calcium iron oxide ($CaFe_2O_5$) and calcium potassium phosphate ($KCaPO_4$). In the deposits on the fourth stage nozzle (Fig. 16) oxides of both calcium and magnesium and potassium sulfate are present. This figure also indicates a presence of potassium oxide, potassium magnesium phosphate and calcium iron oxide. Results of XRD analysis of the deposits on the intermediate stages were not much different from those of the deposits on the first stage. It is, however, interesting to note that the peaks corresponding to calcium hydroxide in Fig. 16 are not as strong as in Figs. 14 or 15, indicating that this compound is present in relatively much smaller quantity in the deposits on the fourth stage. The presence of calcium hydroxide in significant amount in the upstream stages of the turbine and its absence in the downstream stages probably accounts for the relatively higher percentages of Ca in the deposits in the upstream stages of the turbine.

Figure 13. Elemental Composition of Ash Deposits in Different Stages of the Turbine - Aspen Fuel

Figure 14. X-Ray Diffraction pattern of wood ash deposit on the first stage nozzle of gas turbine. Labels on the peaks correspond to: 1. CaO 2. MgO 3. K_2SO_4 4. $Ca(OH)_2$ 5. $CaFe_4O_7$ 6. Mg_6MnO_8 7. $Ca_2P_2O_7$ 8. K_3AlO_3

Figure 15. X-Ray Diffraction pattern of wood ash deposit on the first stage rotor of gas turbine. Labels on the peaks correspond to: 1. CaO 2. MgO 3. K_2SO_4 4. $Ca(OH)_2$ 5. $Zn_2Mn_3O_8$ 6. Mg_6MnO_8 7. $Ca_2Fe_7O_{11}$ 8. $CaFe_3O_5$ 9. $KCaPO_4$

Figure 16. X-Ray Diffraction pattern of wood ash deposit on the fourth stage nozzle of gas turbine. Labels on the peaks correspond to: 1. CaO 2. MgO 3. K_2SO_4 4. $KMg(PO_3)_3$ 5. $CaFe_3O_5$

Discussion

The presence of alkali metals in ash is of concern as they are thought to be responsible for initiating deposition. not only because alkali compounds generally have lower melting points, but also because their presence tends to lower the melting points of other compounds that otherwise would melt at higher temperatures. An example of the latter is $MgSO_4$ which dissociates without melting at 1120 °C to form MgO that has a melting temperature of 2850 °C. But, in the presence of K_2SO_4 , the $K_2SO_4 \cdot MgSO_4$ which could be formed melts at 750 °C. The molten compounds then adhere to turbine blades and provide a sticky layer on the blades to trap other solid particles. However, our measurements do not show $MgSO_4$ in the deposits, and hence this mechanism may not be occurring.

The analyses of the deposits in the second set of samples present a different picture. Results in Fig. 13 show higher proportions of Ca in the first stage, in contrast to higher percentage of K in Fig. 11. The difference between the two results is also evident in the trends of the relative amounts of K and Ca. Figure 13 shows an increase in the relative amount of K in downstream stages, while Fig. 11 shows a decreasing K percentage. The increasing trend of

K becomes more evident when Fig. 13 is redrawn as variation of ratios using calcium as a basis. This is shown in Fig. 17. The justification for replotting using Ca concentration as a normalizing factor is based on the stable nature of Ca compounds in wood ash and on the presumption that more information on the preferential deposition of various elements can be obtained on comparing the ratios with those in the parent wood.

Figure 17. Elemental Ratios (with respect to Calcium) of Ash Deposits on Different Stages of Gas Turbine - Aspen Fuel

Results presented in Figs. 11 and 13 show K/Ca to be greater than the ratio in parent wood, thus indicating a preferential deposition of potassium compounds. The difference in the observed trends in the two sets of results is attributed to the difference in the wood type used in the two sets of runs. Analyses of the ash formed at low temperatures from poplar and aspen show higher percentage of K (13.3%) and Ca (28.8%) in aspen ash compared to 7.9% and 25.7%, respectively, in poplar ash. One apparent explanation for the increasing proportions of K observed in Fig. 15 is suggested by the XRD results. These results indicate a presence of calcium hydroxide in significant amounts in the upstream stages and a decrease in the relative amount in the last stage. It appears that the calcium oxide formed after the dissociation of either calcium carbonate or calcium sulfate reacts with the water vapor present in the exhaust gas stream to form calcium hydroxide. This compound is present in a fused state at temperatures over 600 °C and gets deposited on relatively colder turbine surfaces. What is surprising however, is that if calcium hydroxide is being formed, what prevents the formation of potassium hydroxide when potassium oxides are being formed with the dissociation of potassium carbonate. This contradiction has been resolved to some extent by the chemical equilibrium analysis using STANJAN code to determine the relative amounts of hydroxides of calcium and potassium formed under combustion conditions. This analysis predicts the formation of both calcium hydroxide and potassium hydroxide in the presence of water vapor, but the amount of calcium hydroxide predicted is close to two orders of magnitude higher than that of KOH at lower temperatures.

The other reason for the difference in trends of Ca and K in Figs. 11 and 13 appears to be a hypothetical one at this time with some substantiation from the results of XRD analyses of low temperature aspen ash which show that potassium is present primarily as potassium carbonate. Dissociation of K_2CO_3 starting at about 800°C generates oxides of K that exist in vapor form at the dissociation temperatures. It is presumed that the potassium oxide vapors would condense on the relatively colder downstream stages of the turbine in increasing amount, thereby increasing the relative amount of K in the deposits. XRD results appear to support this hypothesis as they show some weak signals corresponding to the oxides of potassium. Due to the weak nature of the signals, little inference can be derived on the relative amounts of potassium oxides in different stages. On the other hand, at elevated temperatures, oxides of potassium are highly reactive and one would expect them to react with the products of combustion in the post-combustion region to form other compounds such as potassium carbonate or potassium hydroxide that then would initiate deposition. This, however, is not supported by the XRD results as they do not show significant presence of any potassium compound other than potassium sulfate.

Table 2. Drying Test Data for 2 cm Aspen Woodchips.

T (°C)	v(m/s)	MC _i (%)	t ₁ (min)	D*10 ⁸ (m ² /s)
60	0.5	10.2	12.	1.9
60	1.	6.5	12.	1.5
60	2.	7.2	6.	3.2
60	0.5	37.1	50.	0.7
60	1.	31.8	21.	1.7
60	2.	35.2	22.	1.7
<hr/>				
120	0.5	9.6	5.5	4.0
120	1.	10.2	4.0	5.7
120	2.	8.3	3.	6.9
120	1.	39.1	14.	2.7
120	2.	35.9	9.3	3.9
<hr/>				
180	1.	10.6	2.3	10.
180	2.	12.8	3.5	7.2
180	0.5	34.8	12.5	2.9
180	1.	53.3	9.	4.5
180	2.	35.9	6.	6.1
<hr/>				
240	0.5	16.2	5.	5.6
240	1.	18.1	5.	5.8
240	2.	18.	4.	7.2
240	0.5	50.1	10.	4.0
240	1.	53.1	7.	5.8

Drying in wood takes place by diffusion of water and water vapor across the cell walls [Adesanya, 1988]. The rate of diffusion is determined by the moisture gradient, the temperature of the wood, and the porosity of the wood species. We are assuming here that the moisture content is below the fiber saturation point so that capillary forces are not important. The governing equation for diffusion is,

$$\frac{d(MC)}{dt} = -D \frac{d^2(MC)}{dx^2} \quad (3)$$

and the solution for a slab (i.e., chip) is,

$$MC/(MC)_i = (8/\pi^2) \exp(-D t (\pi/2x)^2) \quad (4)$$

where x is the half-thickness of the chip. The time to reach 1 % moisture content is given by,

For the two turbines, the maps of corrected flow and efficiency as a function of corrected speed and expansion ratio are read through the use of spline fits. With these values, temperature drop and turbine work can be calculated in an analogous manner to the method for the compressor.

Figure 18. Compressor Map for Allison 250-C20B

The woodchip burning rate in the gravel bed combustor is not able to be set at a particular value, but rather is determined solely by external variables including combustor pressure, combustor inlet temperature, air flow rate, and wood moisture content. The actual temperature in the combustion zone also affects the combustion rate. Regression analysis of the steady state data from 223 combustor tests using the involved variables gives the relation (hereafter called the burning rate regression equation) of Eq. 9. The units are kg/hr for wood flow rate, m^2 for area, atm for pressure, K for temperature, kg/hr for air flow rate and the as-received basis for moisture content.

$$\dot{m}_{wood} = 0.95 A_{bed} P^{0.72} T^{1.03} \left(\frac{\text{air}}{\text{fuel}} \right)^{-0.81} (100 - \% \text{Moisture})^{0.46} \quad (9)$$

The form of the equation was developed to represent the physical processes occurring in the combustor. The air/fuel ratio is inversely related to the peak temperature in the combustor, which is operated lean. The pressure reflects the abundance of oxygen for the reactions and has a positive value for its power. The inlet air temperature influences the wood drying rate and initial pyrolysis rate, and also the final temperature. Reducing the moisture increases the burning rate. The correlation coefficient was $r^2 = 0.95$.

with a standard error of 12%. The percent error of the coefficients for $P, T, a/f$, and (100-%Moisture) are 3.4%, 7.5%, 4.0% and 14.3% respectively.

The gravel bed introduces a substantial thermal capacity into the system. To model the thermal energy transfer between the gravel and the combustion products flowing through the bed, the gas energy equation,

$$\frac{\partial T_f}{\partial t} = \frac{k_{ef}}{c_{pf}\rho_f} \frac{\partial^2 T_f}{\partial x^2} - \frac{\dot{m}}{\rho_f A_{bed} \epsilon} \frac{\partial T_f}{\partial x} - \frac{6\tilde{h}_p(1-\epsilon)}{\epsilon c_{pf}\rho_f d_p} (T_f - T_s) \quad (10)$$

and solid energy equation,

$$\frac{\partial T_s}{\partial t} = \frac{k_{es}}{c_{ps}\rho_s} \frac{\partial^2 T_s}{\partial x^2} + \frac{6\tilde{h}_p}{c_{ps}\rho_s d_p} (T_f - T_s) \quad (11)$$

were discretized using backwards time, centered space differencing together with the Thomas Algorithm. The effective conductivity and heat transfer coefficients were obtained from packed bed correlations [Wakao and Kaguei, 1982].

Pressure drop across the gravel bed was modelled using the mass flow rate through the bed, the inlet pressure and the gravel bed temperature profile. The Ergun equation [Ergun, 1952] provides the relationship between flow rate and pressure drop in a packed bed.

$$\frac{\Delta P}{L} = 150 \frac{(1-\epsilon)^2}{\epsilon^3} \frac{\mu v_{sup}}{d_p^2} + 1.75 \frac{1-\epsilon}{\epsilon^3} \frac{v_{sup}^2}{d_p} \quad (12)$$

This equation is applied to each slice of the discretized bed using the average of gas and solid phase temperatures to find the gas density. The pressure drop from each slice of the bed is then added up to find the total pressure drop across the gravel bed.

The relationship between valve capacity, percent open, pressure drop and flow rate for all control valves is given by their specification sheets. The pressure drop in all lines is assumed to be in the high Reynolds number region, where $\Delta P = K \rho v^2/2$, K being a constant for all flow rates.

When all the equations that describe the components are brought together by use of energy and mass balances in all the connecting lines, certain compatibility equations arise [Cohen et al, 1989]. For example, in steady state, the flow rate as read off the gas producer turbine map must equal the flow rate as read off of the power turbine map, that is,

$$\dot{m}_7 - \dot{m}_8 - E(1) = 0 \quad (13)$$

Here, $E(1)$ is an error variable that is less than a tolerance value (typically 10^{-4}) when the system of equations has been solved.

The transient equations for the turbomachinery are a direct extension of the steady state flow and work compatibility equations. In the transient situation, mass accumulates in an intercomponent volume when the two flows do not match. Using the perfect gas equation $m = PV/RT$, and neglecting the time dependence of T_8 ,

$$\dot{m}_7 - \dot{m}_8 - \frac{V_8}{R_{\text{gas}} T_8} \frac{dP_8}{dt} = E(1) = 0 \quad (14)$$

Work compatibility between the compressor and the gas producer turbine along the connecting shaft gives,

$$\Delta \dot{W} = \eta_{\text{shaft}} \dot{W}_{\text{turbine}} - \dot{W}_{\text{compressor}} \quad (15)$$

In steady state, $\Delta W = 0$. In the transient mode, Newton's second law gives,

$$\Delta \dot{W} - I_1 N_1 \left(\frac{2\pi}{60} \right)^2 \frac{dN_1}{dt} - E(3) = 0 \quad (16)$$

Here, I is the shaft moment of inertia. The last type of compatibility equation that arises is a momentum equation, where the pressure drop through the bypass line must equal the pressure drop through the combustor,

$$\Delta P_{\text{combustor}} - \Delta P_{\text{bypass}} = E(6) = 0 \quad (17)$$

Altogether there are two work compatibility equations applied to the two turbine shafts, two flow compatibility equations, and one momentum compatibility equation. The computational technique [Sellers and Teren, 1974] for solving the equations uses a Newton-Raphson technique and varies $\%N_1$, $\%N_2$, P_8 , CMV , $(m_3/(m_3+m_4))$ until all the compatibility equations are satisfied [$E(1)=0$]. For a steady-state solution all time derivatives are set equal to zero. A dynamic run of the program is started from either a non-steady state point given an initial gravel bed temperature profile, or from a steady state point. The former method is desirable for start-up testing. The latter method is useful for testing load changes and control strategies.

The computational stability of the program is assured (if the equations were linear) by the use of backwards differencing in all time derivatives, for example, $dP_8/dt = (P_{8i+1} - P_{8i})/dt$. The Newton-Raphson routine iterates in the $i+1$ time step using these derivatives until the dynamic compatibility

equations are satisfied. For each iteration, an inner subroutine calculates the bed temperature profile by the aforementioned finite difference technique. The time step of the program is variable, however the time steps are usually kept at or below the time lag of the control on the valves (about 5 s). Further details of the model implementation and application can be found in [Palmer, 1991].

B. MODEL VERIFICATION

Verification of the gravel-bed combustor, gas turbine system model SYSDYN was accomplished by a combination of means. First, the models for the turbomachinery and high-speed dynamics of the model were tested by running in jet-fuel mode and the results were compared to baseline data supplied by Allison Gas Turbines. Then, models for the gravel-bed combustor were verified by comparison of test data with the output of model subroutines. Finally, the gravel bed-gas turbine system was verified from experimental data in the house air mode. Further details of the model verification can be found in [Palmer, 1991].

In the jet-fuel configuration (no bypass line, jet fuel combustor instead of gravel bed combustor, and a transient energy equation added to the combustor) the model was run at several different fuel flow rates. The power turbine speed was kept at 100%. A pressure drop and heat loss similar to that of typical aerospace gas turbines was used. The horsepower from the model stays within 5% of the actual horsepower up through 90% compressor speed (above which the compressor map is extrapolated). For the dynamic mode, the verification is accomplished by comparing model results to Allison's specifications. The specification states that for a load decrease from takeoff power to ground idle, the time for 95% of the load change (or change in compressor speed) should not exceed 6 s. The model gives a time of 4.1 s for this maneuver. This is well within the maximum limit.

Both the wood burning rate and gravel bed thermal storage models were tested together by using only the combustor inlet temperature, pressure and air flow rate from the data. First, the burning rate regression (Eq. 9) is used and an energy balance is applied to the combustion to find the gravel bed inlet temperature. This temperature is a boundary condition needed for solving the differential energy (Eqs. 10-11) for the gravel bed. These equations then determine the bed outlet temperature, which is seen in Fig. 19. This figure shows that all the major features of the bed outlet temperature are modelled well.

The complete model in the house air mode has been verified by using the house air flow rate to determine all the other variables, such as burning rate, temperatures, pressures, flow rates, turbine speeds and output power.

The comparison of calculated power and actual power is given in Fig. 20. The gravel bed system has not been verified in self sustaining mode. Switch over from the house air mode to the self-sustaining mode has not yet been achieved experimentally because the compressor surges due to the higher pressure drop of the gravel bed. However, it is reasonable to assume that based on the results of the jet-fuel mode and the verification of the gravel bed subroutines, the model would give correct qualitative results for the self-sustaining mode.

Figure 19. Bed Outlet Temperature Using Burning Rate Equation to Find Inlet Temperature, Run 260

Figure 20. Comparison of Horsepower from Run 268 Data with Model

C. MODEL PERFORMANCE

Elsewhere [Palmer,1991], results for both the house air mode and the self-sustaining mode are presented in detail. The model showed that for the 42 cm i.d. combustor, the highest power attainable was 325 hp if the combustor pressure drop was 10% of the compressor pressure and the bypass was 0% corresponding to a turbine inlet temperature of 1240 K. Whereas if the pressure drop was 15%, then the maximum power was reduced to 140 hp. With 10% combustor pressure drop the model showed that switchover to the self-sustaining mode was possible when the power turbine reached 65% of maximum speed.

In this report a few results pertaining to the control of the self-sustaining mode are presented. The two main control variables for the system in self-sustaining mode are the vent and bypass valves. The first results presented show the response of the system to moving these valves starting from steady state. Then, a controlled load change will be presented.

The runs tested here start at the steady state point determined by the vent open 5% and the bypass valve open 50%. This corresponds to a power of 113 kW, compressor pressure of 4.89 atm, and flow rate of 1.17 kg/s. The initial combustion/gravel bed temperature is 1080 K. The 42.5 cm diameter gravel bed configuration is, from top to bottom: 2.5 cm depth of 0.84 cm average diameter MgO; 3.8 cm of 0.51 cm MgO; 5 cm of 1 cm Al_2O_3 ; 2 cross-hatched rows of 1.3 cm supporting rods.

The vent valve vents some of the compressor air to the environment. This has the effect of altering the pressure level in the system and moving the compressor farther from the surge line. Watching the surge margin is an important design and control consideration, because of the relatively high pressure drop in the gravel bed system. The vent flow should be kept to a minimum, however, as efficiency decreases with higher vent flow.

Fig. 21 gives the system response to opening the vent valve from 5% to 7%. The initial response is a quick decrease -- on the time scale of rotor dynamics -- in system operating level caused by lower mass flow through the turbines. The lower speed decreases the air temperature and pressure, as well as the air flow rate entering the combustor from the compressor. The lower combustor inlet pressure and temperature has a greater negative effect on the wood combustion rate than the positive effect that a lower airflow rate causes. The combustion products temperature drops quickly during the rotor dynamic phase. The operating level then falls steadily as the gravel bed outlet temperature starts to fall as the cooler combustion product temperature filters through the bed. This run illustrates that the two dominant time scales are the turbomachinery dynamics and the gravel bed energy storage dynamics. It

also shows the unstable drifting phenomena that is inherent in the gravel bed: when the bed is not operating at a steady state point, the system diverges slowly at first, and then more quickly once the gravel bed temperature begins to reflect the disturbance. Thus the combustor needs to be actively controlled.

The response of the system to a decrease in the vent setting from 5% to 3% open is the opposite of the last case where the vent was opened. The system operating level quickly increases in the time scale of the turbomachinery after the initial decrease in vent flow. Then the operating level continues to increase slowly at first and then accelerating after that, as the initial rise in combustion temperature filters through the bed.

The other main control variable for the gravel bed system is the bypass valve setting which determines the amount of the total flow rate from the compressor that enters the gravel bed and therefore has the closest relationship to the fuel flow control in a normal gas turbine for determining the system energy input. This example of a decrease in bypass valve setting starts from the same point as the last run. At 10 s, the bypass valve is closed at a rate of 1 %/s from 50% open to the final value of 45% open. At the beginning of the action, more of the total gas flow enters the gravel bed, and thus the fraction of hotter gas entering the bypass/bed exit mixing section at the bed exit increases. This increased energy in the turbine inlet gas accelerates the turbines (Fig. 22), which increases the total airflow and pressure. The wood burning rate does not change very much initially, as the increased combustor pressure and temperature, which tends to increase burning rate, is coupled with an increase in the combustor flow rate, which tends to decrease burning rate. As the burning rate does not change, and there is an increase in combustor air flow, this means the air/fuel ratio has increased, which lowers the adiabatic combustion temperature. The lower combustion temperature cools the gravel bed down, eventually filtering to the gravel bed exit, where the lower temperature causes the turbines to decelerate. The deceleration leads to a lower pressure and temperature in the combustor, which decreases burning rate, and further decreases combustion temperature. If no correcting control actions are taken, the system then decelerates all the way down to zero speed.

The above example shows the effect of the gravel bed heat storage. The initial increase is due to the thermal lag in the gravel bed. If there were no thermal storage in the gravel bed, an increase in combustor air flow would immediately decrease the combustion temperature, giving a turbine deceleration. So, when designing a control system, one must know the magnitude of the thermal lag to know how long the system will accelerate before decelerating. Also, the design must take into account the fact that the combustion history is stored in the gravel, and any major combustion temperature fluctuations will affect turbine dynamics after a time lag associated with the gravel bed temperature storage.

Figure 21.

Self-Sustaining System Response to
Opening Vent Valve

Figure 22.

Self-Sustaining System Response to
Closing Bypass Valve

For changing loads, the vent valve is used to control the carbon dioxide level while changing the bypass valve setting. The vent valve is used as the control variable because of the monotonic dynamic behavior seen in the previous examples: when the vent is closed, the system speeds up immediately, and continues to increase. The vent is used to control the carbon dioxide level because, in steady state, at any given vent setting, the carbon dioxide level is fairly constant for all bypass settings. Higher vent settings give higher steady state carbon dioxide levels. Because of the direct relationship the carbon dioxide level has to the combustion temperature, CO_2 is used as the variable to control. The automatic control used here is a simple proportionality constant between the difference in actual and desired carbon dioxide level, and the change in the valve setting.

$$\Delta(\% \text{OPEN VENT}) = K_P \text{ VENT} (\% \text{CO}_2 \text{ actual} - \% \text{CO}_2 \text{ set}) \quad (18)$$

The following example demonstrates increasing load in the self-sustaining system by decreasing the bypass setting while using the carbon dioxide level together with the vent setting to control the process. The dynamics of this run start at 10 s, where the bypass valve is closed from 50% to 45% open. The carbon dioxide set point is 5.5% and the automatic control proportionality constant $K_{P_{\text{vent}}}$ is set to 5. This value was picked because it is one of the lowest values that was fast enough to catch the swings of the system due to energy storage, but not so fast that it would accelerate the

turbines at what may be an unacceptable rate. From this point on, the bypass valve was decreased in a step change every 30 s by 5%, and the control system was allowed to respond to the changes. The bypass valve stops changing after it reaches its final value of 20% open.

The initial response of the control system after the first decrease in bypass setting is to close the vent valve somewhat to try to bring the carbon dioxide back to its set point of 5.5%. The combination of the higher fraction of air entering the combustor plus the vent valve closing has a double effect on accelerating the turbines (Fig. 23). This makes the carbon dioxide level shoot upwards past the set point, which forces the vent to start opening. This change in direction of the movement of the vent valve produces the little 'hump' on the speed curve. Just before the carbon dioxide is about to start decreasing, the next step change in the bypass setting occurs.

For each of the succeeding steps in the bypass valve, the combustion products temperature is hotter than the present gravel bed temperature (Fig. 24) so the system begins to drift upwards. The valve never needs to dip to as low a setting as during the initial step, because the increasing bed outlet temperature is contributing towards driving the carbon dioxide upwards towards its set point. After the last step change, there still are a few wiggles in the speed curve, as the gravel bed has been heated past its final steady state value, so the vent valve has to open to cool this down. The cooling is a little too strong, as the temperature dips under its final value. Eventually, the combustion temperature becomes stable at its final value, having reached steady state. This run is encouraging as the system did not diverge too high or too low from the start or ending points. The system power was increased by 56% fairly directly in a relatively (5 min) short period of time. Very fine control was needed on the vent valve setting, but the problems this raises can be overcome by properly sizing a lower capacity valve for this system. The step-by-step change in the bypass valve was used because attempts at faster bypass control movements, e.g. closing the bypass at 1%/s for 30 s, never let the system settle out. The system kept accelerating, from the flow switch through the hotter bed, meanwhile the control saw a low CO₂ level and also tended to accelerate the system. An optimized control system should include integral as well as proportional control.

Figure 23. Turbine Speed During Self-Sustaining Load Change by Closing Bypass Valve

Figure 24. Combustor Temperature During Self-Sustaining Load Change by Closing Bypass Valve

IV. CONCLUSIONS

A modified Allison 250-C20B gas turbine was connected to a 42 cm i.d. gravel bed, downdraft combustor which burned 2 cm aspen woodchips. No hot gas cleanup other than the gravel bed was used. Over 250 hours of testing was conducted on the combustor-turbine setup. All tests were in the house air mode with the compressor air dumped. The longest run lasted 7 hours and the highest net power output reached was 61 kW or 20 % of full power. The highest turbine speeds were 75% of the maximum speed, and the highest mass flows were 50% of the full power flow. The higher pressure drop of the gravel bed combustor compared to the conventional Allison combustor did not allow switch-over to the free standing mode. The stability of the combustor must be improved before higher output and longer runs can be achieved. The system is very sensitive to small changes in conditions and tends to drift off the set point. If the combustion stability can be improved, then the control system is expected to control the drift from the set point. Future work will study the fuel bed using a video camera to try to find the cause of the combustion instability.

Deposits of ash to the gravel bed are tolerable if the combustor exit temperature is held to 900°C. Deposits of ash to the turbine are of concern. Ash build up after 122 hours of operation was about 1 mm thick on the turbine nozzles and 0.1 mm to 0.2 mm thick on the rotors. The deposits consisted of calcium oxide, magnesium oxide, potassium sulfate and other compounds. Insitu cleaning of the turbine may be possible.

A dynamic simulation model of the gravel bed combustor-gas turbine system has been developed that follows the test data. The model is useful for system characterization, system scaleup, and development of control strategies. The model shows that the combustor-turbine system is a sensitive, high gain system which needs active control. Since the turbine load does not depend on the fuel feed rate, but rather depends on the operating conditions of the combustor, a control strategy is needed. As shown by testing and by the model, a combination of adjustments of the combustor bypass valve, compressor vent valve and steam injection can be used to control the system.

V. REFERENCES

Adesanya, V. et.al., "Drying Rates During High Temperature Drying of Yellow Poplar", *Drying Technology*, vol. 6, 1988, pp. 95-112.

Cohen H., Rogers G.F.C., and Saravanamuttoo H. I. H., 1989, *Gas Turbine Theory*, Third Edition, Longman Scientific & Technical, New York.

Ergun, Sabri, 1952, "Fluid Flow Through Packed Columns," *AIChE Chemical Engineering Progress*, Vol. 48, No. 2, pp. 89-94.

Kimura, S.G., Spiro, C.L., and Chen, C.C., 1987, "Combustion and Deposition in Coal-Fired Turbines," *Journal of Engineering for Gas Turbines and Power*, July, 1987, Vol. 109, no. 3, pp. 319-324.

Palmer, C. A., "Dynamic Simulation of a Solid Fuelled Gas Turbine System", Ph.D. thesis, The University of Wisconsin-Madison, May 1991.

Palmer, C. A. and Ragland, K.W., "Dynamic Simulation of the Gravel Bed Combustor Gas Turbine System", ASME Int'l Gas Turbine Congress, 91-GT-285, 8 p., June 1991.

Purnomo, "Model for a Downdraft Solid Fuel Combustor", Ph.D. thesis, The University of Wisconsin-Madison, 1988.

Purnomo, Aerts, D.J. and Ragland, K.W., "Pressurized Downdraft Combustion of Woodchips", *Twenty Third International Symposium on Combustion*, The Combustion Institute, 1990, pp. 1025-1032.

Ragland, K.W. and Aerts, D.J., "Development of a Gravel Bed Combustor for Solid Fueled Gas Turbine", DOE/CE/40735-1, May 1989.

Ragland, K.W., Aerts, D.J. and Palmer, C.A., "Evaluation of a Woodchip Fired Cogeneration System Using a Gravel Bed Combustor, 26th Annual IECEC, paper no. 910446, Aug. 1991.

Sellers J., and Teren F., 1974, "Generalized Dynamic Engine Simulation Techniques for the Digital Computer," AGARD-CP-151, Ustaoset, Norway, paper no. 24.

Wakao, N., and Kaguei, S., 1982, *Heat and Mass Transfer in Packed Beds*, Gordon and Breach, New York.

Yeralan, S., "Drying of Woodchips in a Packed Bed", M.S. thesis, The University Wisconsin-Madison, June 1991.

Appendix A. Instrumentation and Control Equipment.

Data Acquisition

Leading Edge model D computer, 640 k RAM, 30 MB hard drive.
 Metrabyte DAS-8 data acquisition system with three EXP-16 cards.
 Epson FX-85 dot matrix printer.
 Kensington Masterpiece Plus surge protector.
 Two digital timers, one Micronta #63-706, one West Bend #40007.

Temperature

Three Omega, type R probes, 3 mm o.d. inconel sheaths.
 Six Omega, type K probes, 3 mm o.d. 304 stainless steel sheaths.
 Four type K panel meters, Omega model 7055-K-2000.

Pressure

Schaevitz model P-3061 LVDT differential pressure transducer, 0-100 kPa.
 Five Omega model 242PC150G piezoelectric transmitters, 0-1000 kPa.
 Omega model PX95 piezoelectric transmitters, 0-700 kPa.
 Four Ashcroft Duragauge panel gauges, 0-700 kPa.
 Five Marsh panel gauges, three 0-200 kPa, two 0-700 kPa.
 Two Dwyer Magnehelic panel gauges, one 0-37 kPa, one -1 to +1 kPa.
 Ashcroft series C200 pressure switch set at 700 kPa.
 Two Sola power supplies, one 24 vdc #81-24-1801, one 5 and 9 vdc #83-81-2225.

Air, Steam and Water Flow Rate

Venturi flowmeter, 5.08 cm diameter.
 Four orifice plate flowmeters. Diameters 5.59 cm, 4.67 cm, 4.45 cm, 1.52 cm.
 Five Schaevitz model P-3061 LVDT differential pressure transducers. One 0-25 kPa, three 0-50 kPa, one 0-100 kPa.
 Two Jamesbury 7.6 cm, flanged, ball control valves.
 Two Jamesbury screwed ball control valves, one 5.1 cm, one 3.0 cm.
 Four Automax E600-12 electric valve actuators.
 Two Leeds & Northrup Electromax Vplus programmable controllers.
 Two Partlow MIC 2000 programmable controllers.
 Ball control valve, 1.3 cm, screwed.
 Worcester PM15S controller and 2039SN pneumatic actuator.
 Barber Colman model CP-8551 I/P converter.
 Two Barber Colman 1.9 cm control valves, one VB-9223, one VB-9263.
 Robertshaw model 2567, 1.9 cm pneumatic actuator.
 Barber Colman model MK4641, 1.9 cm pneumatic actuator.
 Robertshaw model 2390-501 pressure regulator.
 Two Watts Fluidair model R364-01AKPZ6 pressure regulators.
 Watts R119 pressure regulator.

Fuel Flow Rate

Sensotec SA-10D load cell system with two SA-BII cards and one SA-SD card.
 Three Sensotec model 43 load cells, 0-250 lbs.
 Cole-Parmer model 8203-20 Tachoprobe optical tachometer.
 Sonac 220 model 14 ultrasonic level detector.
 Helium-Neon laser, 15 mW.
 Four quartz windows in combustor, 1.2 cm dia.
 Dayton (0.37 kW) dc motor. Dayton SCR variable speed dc drive, model 2M171C.
 Five Dayton timer relays, two 6X603C, one 6X604C, one 5X828C, one 5X829C.
 Macromatic SS-50522-08 timer relay.
 Four control relays, three Magnacraft W88ACPX, one Dayton 5X827E.
 Sixteen toggle switches.

Nine indicator lights.
Mikron 65EM optical pyrometer.
Two Miller LA-53, 15.2 cm diameter air cylinders.
Two ASCO 8342 solenoids.
Four Microswitch HDLS limit switches.

Flue Gase Monitoring

Stainless, 0.95 cm o.d. and 0.64 cm o.d. tubing sample line.
Four 4.8 cm o.d. x 15.2 cm long stainless capped pipe, in styrofoam cooler ice bath.
Thomas diaphragm pump, model 707CM50.
Pyrex glass wool filter in 2.1 cm o.d. x 15.2 cm long stainless pipe.
Balston micro filter, 050-11-BH in model 95S6 housing.
Two Matheson series R7630 rotometers, tube 605, one with pyrex ball, one with steel.
Twelve teflon, .3 cm valves.
Two Horiba PIR-2000 infrared analyzers. CO₂ range 0-10%. NO range 0-2000 ppm.
Sensors series Five infrared analyzer for CO, range 0-2000 ppm.
Beckman model 7010 zirconium oxide analyzer for O₂, range 2.1-21%.
Calibration gases - 8.06% CO₂, 1820 ppm CO, 1076 ppm NO, 5.05% O₂.
G.C. Industries model GC401 CO alarm, set point 200 ppm.

Turbine Performance

Chip detector, two magnetic plugs and one light.
Two Globe Industries model 22A703 tachometer generators, 0-4200 rpm.
Two PCB Piezotronic model 308B accelerometers.
Two PCB Piezotronic model 480A08 integrating/amplifier units.
Two channel rms-to-dc converter, 0-5 vdc output.
Two channel low frequency filter, pass 15-2000 hz.

Particulate Monitoring

Stainless, 0.95 cm o.d. tubing sample line.
Schleicher & Schuell # 30 glass fiber filter paper.
R.A.C. Staksamplr pump and flowmeter.

APPENDIX B. Summary of Test Data- Average Values at Steady State

Test No.	Comb. Press. (atm)	Bed Drop (atm)	Comb. Air (kg/s)	Bypass Air (kg/s)	Air Fuel Ratio	CO2 (%)	Air Temp. (C)	Bed Exit (C)	Turb. Temp. (C)	N1 (%)	N2 (%)	Net Power (kW)	Total Time (hr)	Compressor Press. (atm)	Outlet Air (kg/s)	Outlet Temp. (C)
200	1.2	0.12	0.192	0.000	51.3	5.4	26	494	372	25.2	12.2	0.52	1.50	1.082	0.153	50
201	1.4	0.14	0.240	0.000	29.4	6.5	30	576	428	34.0	20.2	1.34	2.00	1.190	0.181	72
202	1.0	0.03	0.077	0.000		11.3	27	797	675	13.9	1.8	0.00	1.25	1.020		45
203	1.3	0.08	0.198	0.000	24.3	4.5	27	740	525	32.2	16.1	0.97	2.00	1.184	0.152	70
204	1.5	0.18	0.240	0.000	21.4	3.8	28	805	553	39.4	27.7	1.94	2.25	1.306	0.192	92
205A	1.2	0.11	0.198	0.000	33.8	5.5	25	426	343	26.8	12.4	0.52	3.25	1.116	0.135	51
205B	1.3	0.11	0.197	0.052	28.7	6.1	29	445	294	32.5	16.6	1.04		1.190	0.162	66
205C	1.6	0.20	0.254	0.046	31.7	7.8	31	537	362	41.5	29.7	2.16		1.340	0.205	95
206A	1.4	0.17	0.236	0.028	31.9	5.2	29	412	310	34.5	19.8	1.34	2.50	1.218	0.171	71
206B	1.7	0.20	0.276	0.052	33.5	7.0	33	519	330	43.8	33.0	2.54		1.388	0.215	105
207A	1.6	0.27	0.256	0.019	30.5	7.5	27	515	372	40.0	29.1	2.31	1.25	1.299	0.256	82
207B	1.8	0.23	0.281	0.052	29.1	7.0	29	563	366	46.3	38.3	3.43		1.435	0.307	102
208A	2.0	0.30	0.296	0.080	25.0	7.6	32	547	343	50.2	39.7	5.00	2.25	1.524	0.321	123
208B	2.2	0.35	0.328	0.121	29.3	7.4	35	569	305	57.1	47.2	7.61		1.701	0.368	155
209	2.0	0.35	0.294	0.092	22.4	8.4	34	603	345	51.6	46.5	4.40	2.00	1.578	0.343	128
210	1.3	0.11	0.162	0.055	25.0	7.5	28	627	338	30.5	15.9	0.89	3.00	1.150	0.185	62
211A	1.3	0.14	0.197	0.013	31.6	6.4	28	598	407	32.2	17.3	1.04	2.50	1.156	0.186	67
211B	1.5	0.18	0.215	0.052	26.4	7.1	29	652	383	38.4	27.1	1.86		1.252	0.236	82
212	1.5	0.21	0.216	0.015	31.2	6.8	33	669	459	36.9	25.4	1.72	1.50	1.231	0.222	79
213A	1.9	0.39	0.321	0.000	24.2	7.0	97	674	478	47.7	41.6	4.03	1.00	1.476	0.312	105
213B	2.4	0.41	0.416	0.005	26.6	7.2	109	780	504	62.1	65.6	7.76		1.905	0.381	173
214	2.3	0.35	0.404	0.014	21.9	6.8	107	590	461	58.5	59.6	6.64	1.50	1.810	0.370	153
215A	2.1	0.33	0.388	0.004	27.5	6.2	111	576	490	54.0	47.8	6.86	2.50	1.673	0.337	137
215B	1.8	0.24	0.367	0.027	37.9	2.7	87	384	343	45.1	36.8	3.36		1.408	0.274	113
216													0.50			
217A	2.1	0.35	0.358	0.003	23.0	6.7	105	581	474	48.5	46.9	5.07	1.50	1.340	0.710	109
217B	2.3	0.50	0.396	0.014	28.5	7.2	108	616	479	54.8	51.4	8.65		1.469	0.925	140
218	1.2	0.11	0.172	0.000	24.6	5.7	84	485	430	25.0	11.9	0.52	1.50	1.041	0.185	42
219	2.2	0.32	0.350	0.000	19.7	6.8	146	866	674	55.2	57.8	7.23	1.25	1.551	0.416	139
220A	1.9	0.27	0.361	0.000	31.8	4.1	104	614	475	47.4	43.0	4.70	2.00	1.449	0.291	113
220B	2.0	0.31	0.380	0.000	30.5	3.4	105	626	462	49.2	43.6	4.55		1.524	0.268	132
221A	1.8	0.26	0.317	0.000	26.6	4.0	110	668	506	43.3	37.0	3.50	1.75	1.361	0.277	97
221B	1.9	0.31	0.337	0.000	26.5	3.5	125	750	554	47.0	41.2	4.10		1.463	0.278	121
222	1.9	0.32	0.283	0.001	17.6	5.6	154	822	648	46.8	41.1	3.95	1.75	1.435	0.277	118
223													0.50			
224A	1.9	0.29	0.293	0.000	18.6	5.2	114	733	528	46.0	43.1	4.70	1.25	1.354	0.358	100
224B	2.6	0.37	0.377	0.079	19.6	5.3	103	822	483	61.4	57.4	14.77		1.735	0.482	168
225A	1.9	0.29	0.274	0.001	16.8	5.7	123	675	556	43.0	37.8	4.03	1.00	1.265	0.329	94
225B	2.4	0.38	0.340	0.030	14.6	6.5	126	855	580	58.0	55.0	11.33		1.633	0.450	155
226	2.0	0.29	0.295	0.000	17.3	5.4	112	712	506	46.0	42.5	4.92	1.00	1.340	0.355	106
227A	2.6	0.31	0.356	0.095	19.7	5.7	102	812	470	60.6	45.2	15.14	2.25	1.673	0.466	169
227B	2.5	0.28	0.324	0.141	19.3	5.2	86	750	380	59.9	42.8	13.42		1.653	0.448	178
227C	2.9	0.37	0.389	0.130	20.7	5.2	92	803	412	67.2	52.7	19.99		1.864	0.484	217
228													1.00			
229A	2.7	0.37	0.474	0.026	29.4	4.6	96	646	443	62.1	53.7	17.00	1.25	1.782	0.499	159
229B	2.8	0.38	0.430	0.109	19.3	5.0	87	684	396	64.5	56.4	18.87		1.878	0.509	175
229C	3.2	0.39	0.498	0.126	26.8	4.6	84	719	385	70.7	63.6	26.99		2.068	0.526	207
230	3.0	0.50	0.504	0.009	22.1	5.7	105	759	510	66.6	58.2	22.22	1.00	1.952	0.522	174
231A	2.5	0.35	0.424	0.014	23.5	5.1	92	687	434	56.8	47.2	11.26	1.00	1.639	0.471	129
231B	3.1	0.41	0.498	0.073	23.5	5.0	88	749	417	67.2	59.4	22.30		2.034	0.536	178
232	3.9	0.56	0.607	0.039	21.0	6.3	82	802	473	76.2	72.2	36.47	1.00	2.333	0.560	226
233													0.75			
234													1.00			
235													1.00			

Continued.

Test No.	Comb. Press. (atm)	Bed Drop (atm)	Comb. Air (kg/s)	Bypass Air (kg/s)	Air Fuel Ratio	CO2 (%)	Air Temp. (C)	Bed Exit (C)	Turb. Temp. (C)	N1 (%)	N2 (%)	Net Power (kW)	Total Time (hr)	Compressor Press. (atm)	Outlet Air (kg/s)	Temp. (C)
236													0.50			
237	2.1	0.24	0.387	0.000	20.4	5.2	104	802	473	51.2	42.8	8.20	1.25	1.218	0.426	95
238A	2.0	0.22	0.337	0.020	24.9	5.4	96	678	420	47.8	37.6	6.41	2.00	1.143	0.383	90
238B	2.3	0.24	0.382	0.057	24.6	4.9	90	723	386	55.9	48.8	11.26		1.259	0.461	119
238C	2.6	0.29	0.444	0.065	24.6	5.5	83	729	370	61.5	57.2	15.73		1.374	0.520	140
239A	2.6	0.37	0.500	0.000	31.4	2.6	126	892	565	62.0	57.4	16.33	1.75	1.367	0.522	138
239B	2.7	0.39	0.504	0.001	27.4	2.6	118	837	528	62.7	57.4	17.00		1.374	0.521	147
240	2.1	0.34	0.363	0.000	20.6	2.6	127	823	543	50.3	44.3	7.38	1.00	1.184	0.409	99
241													1.00			
242A	1.7	0.24	0.355	0.000	27.4	3.0	81	720	409	37.8	29.9	2.54	2.00	1.054	0.296	59
242B	1.9	0.28	0.401	0.000	28.2	2.6	95	809	475	44.6	38.9	4.77		1.129	0.356	77
242C	2.3	0.33	0.429	0.000	28.3	2.2	101	739	439	51.6	47.8	7.98		1.252	0.417	97
243A	2.0	0.29	0.324	0.000	23.6	3.1	110	754	497	46.6	38.4	5.82	1.50	1.129	0.373	82
243B	3.6	0.54	0.560	0.045	16.6	4.0	106	907	526	74.8	74.6	37.58		1.762	0.649	184
244A	1.9	0.28	0.369	0.000	27.3	4.2	94	690	451	44.8	38.6	4.85	2.00	1.163	0.343	76
244B	2.7	0.47	0.542	0.000	25.4	3.3	108	734	510	61.1	56.0	15.81		1.469	0.490	131
245	2.3	0.35	0.459	0.008	33.8	5.4	90	750	401	54.9	47.9	9.10	2.50	1.537	0.379	111
246	2.6	0.41	0.468	0.014	24.7	6.3	109	794	483	61.6	55.7	12.90	2.25	1.898	0.360	145
247	3.3	0.49	0.575	0.016	23.8	5.5	119	949	579	72.6	73.6	27.82	1.50	2.299	0.459	182
248	2.8	0.47	0.530	0.000	28.5	5.5	115	824	549	63.0	57.6	16.26	1.00	1.898	0.410	142
249A	3.1	0.49	0.535	0.002	23.3	6.4	119	861	554	67.9	64.6	22.52	2.25	1.946	0.477	162
249B	2.9	0.44	0.445	0.054	20.9	6.8	104	828	480	65.2	61.1	19.09		1.850	0.454	153
250	3.8	0.56	0.741	0.003	17.0	4.5	134	852	492	77.6	78.1	53.99	1.50	2.333	0.895	179
251													1.75			
252													3.00			
253	3.3	0.43	0.596	0.022	19.3		168		645	72.6	67.6	39.90	1.25	2.068	0.811	175
254B	2.7	0.44	0.468	0.040	17.8	4.8	156	860	568	63.4	64.2	20.66	2.25	1.673	0.683	138
254B	3.0	0.44	0.489	0.070	17.3	5.7	136	804	524	67.0	66.0	27.89		1.830	0.728	153
255													2.00			
256													1.25			
257	2.8	0.29	0.538	0.024	18.5	6.7	171	941	657	67.1	59.7	29.23	1.50	1.830	0.727	154
258A	3.4	0.46	0.706	0.028	21.6	5.4	138	894	560	74.8	69.2	48.92	2.00	2.163	0.827	184
258B	3.5	0.46	0.742	0.031	15.4	3.7	121	819	498	74.1	64.0	47.50		2.238	0.789	185
259	2.7	0.39	0.541	0.029	26.3	3.5	128	847	494	62.7	50.7	21.25	3.00	1.762	0.617	142
260	3.0	0.57	0.587	0.037	37.6	3.8	126	894	497	68.0	53.9	27.29	2.50	2.347	0.534	171
261A	3.0	0.46	0.538	0.000	25.3	2.6	139	900	531	66.8	54.4	24.61	4.25	2.354	0.498	165
261B	2.9	0.42	0.532	0.000	31.5	3.0	126	480	468	64.9	51.5	21.77		2.231	0.479	161
261C	3.2	0.43	0.543	0.000	22.2	3.4	137	975	530	67.9	56.3	28.56		2.340	0.556	170
262	4.0	0.55	0.624	0.000	19.0		164		648	78.4	73.9	59.06	1.75	2.952	0.664	220
263	2.5	0.26	0.508	0.000	31.9	4.2	130	764	485	61.7	48.1	19.16	3.75	2.109	0.528	146
264	2.8	0.27	0.557	0.020	31.7	4.1	117	716	446	62.4	53.2	23.34	3.75	2.163	0.624	140
265	2.8	0.29	0.522	0.041	28.7	5.4	126	795	468	61.7	47.3	22.89	3.25	2.102	0.649	136
266	3.1	0.33	0.563	0.071	27.2	6.1	118	750	438	65.6	54.5	30.50	4.00	2.381	0.666	153
267A	3.1	0.31	0.573	0.052	28.5	7.0	115	773	436	65.0	51.2	28.86	4.00	2.374	0.645	150
267B	3.0	0.41	0.528	0.079	21.1	5.5	112	751	423	62.3	46.6	23.34		2.218	0.603	144
268	4.1	0.59	0.674	0.026	24.8	6.9	126	821	508	73.8	64.5	53.47	2.75	2.980	0.763	192
269	2.4	0.12	0.440	0.011	21.8	5.9	130	708	460	55.5	40.6	15.81	3.75	1.925	0.524	118
270	3.4	0.21	0.602	0.041	23.8	7.1	129	779	495	69.6	57.2	40.64	3.25	2.673	0.707	171
271A	3.8	0.31	0.596	0.104	17.0	8.4	136	940	549	74.1	67.4	58.61	4.25	3.007	0.759	193
271B	3.5	0.29	0.575	0.102	19.9	7.1	121	816	472	69.9	58.0	43.48		2.687	0.694	174
272													3.00			
273													6.00			

Continued.

Test No.	Comb. Press. (atm)	Bed Drop (atm)	Comb. Air (kg/s)	Bypass Air (kg/s)	Air Fuel Ratio	CO2 (%)	Air Temp. (C)	Bed Exit Temp. (C)	Turb. Temp. (C)	N1 (%)	N2 (%)	Net Power (kW)	Total Time (hr)	Compressor Press. (atm)	Outlet Air (kg/s)	Outlet Temp. (C)
274A	2.9	0.27				7.2	141	823	515	58.8	44.1		4.50			132
274B	3.4	0.33				7.0	118	834	462	64.7	51.8					156
275													3.75			
276													2.75			
277													2.50			
278													3.00			
279													0.75			
280													0.50			
281													1.50			
282													1.00			
283													1.00			
284	3.1	0.29	0.465	0.068	18.8	4.8	135	809	541	61.9	50.8	27.67	3.75	2.088	0.735	123
285A	4.1	0.44	0.604	0.061	17.0	7.2	148	968	606	73.3	67.3	61.67	7.00	2.789	0.888	169
285B	2.4	0.27	0.350	0.052	22.5	4.9	152	777	533	50.8	36.1	10.44		1.639	0.539	93
285C	2.6	0.30	0.405	0.052	24.3	4.3	137	696	488	52.9	39.1	13.50		1.776	0.566	101
286													1.00			
287													0.50			
288													2.50			
289													0.75			
290													1.00			
291													1.50			
292													1.00			
293	2.0	0.07	0.390	0.000	31.7	3.9	129	722	531	47.0	32.9	8.05	4.00	1.544	0.283	93
294													1.50			
295													1.25			
296	2.8	0.04	0.551	0.000	32.6	4.3	120	727	469	58.3	44.2	22.22	1.75	2.061	0.568	131
297	1.9	0.15	0.336	0.000	21.0	4.6	166	839	560	46.6	33.0	7.61	4.00	1.558	0.430	94

APPENDIX C. Combustor-Turbine Test Comments.

TEST 200
New Refractory, 16.25" id.
New Bed.
No Preheat.
No Bypass Air.
No O₂, No FF, No HOP.

TEST 203
New Bed.
No Preheat.
Bypass Air.
Compressor Surge.
Conveyor Jammed.
No VT, No HOP.

TEST 206
No Preheat.
Bypass Air.
Compressor Surge.

TEST 209
No Preheat.
Bypass Air.
Compressor Inlet Screen.
Room Warm.
Low Air Supply Pressure.

TEST 212
Electric Air Heater.
Bypass Air.
Conveyor Jammed.

TEST 215
Clean Compressor.
Bypass Air.
Compressor Surge.
Room Hot.

TEST 218
New Bed.
New Air Valves.
No Bypass Air.
No Lockhopper Light.

TEST 201
No Preheat.
No Bypass Air.
Compressor Surge.
No O₂, No FF, No HOP.

TEST 204
No Preheat.
Bypass Air.
No VT.

TEST 207
No Preheat.
Bypass Air.
Conveyor Jammed.

TEST 210
New Bed.
No Preheat.
Bypass Air.

TEST 213
Air Preheater.
Bypass Air.
Compressor Surge.
Room Warm.
Oil Temperature High.

TEST 216
No Bypass Air.
Compressor Surge.
No Data Averaged.

TEST 219
No Bypass Air.
Room Hot.
Outlet Glowing.

TEST 202
No Preheat.
No Bypass Air.
Swings In Burning Rate.
Outlet Glowing.
No O₂, No HOP.

TEST 205
New Bed.
No Preheat.
Bypass Air.
No T₆.

TEST 208
No Preheat.
No Bypass Air.
Slide Gate Not Sealing
Room Hot.
Oil Temperature High.

TEST 211
No Preheat.
Bypass Air.
Conveyor Jammed.
Turbine Noise.

TEST 214
New Oil Radiator.
Bypass Air.
Compressor Surge.
Room Hot.
No VT.

TEST 217
Bypass Air.
Low Air Supply Press.
Room Hot.
Ran Out Of Wood.

TEST 220
Clean Turbine.
Bypass Air.
Compressor Surge.
Room Warm.
No VT.

TEST 221

Bypass Air.
Compressor Surge.
Ran Out Of Wood.
No VT.

TEST 224

New Top Of Bed.
Room Cooling Air Valve.
Bypass Air.
Room Hot.
Oil Temperature High.

TEST 227

Bypass Air.
Room Cooling Air.
Room Hot.
Vent Off Exhaust Duct.

TEST 230

Bypass Air.
Room Cooling Air.
High Vibration.
Chip Detector On.

TEST 233

No Bypass Air.
Swings In Burning Rate.
Conveyor Jammed.
Exhaust Duct Came Off.
No VT, No VG.
No Data Averaged

TEST 236

No Bypass Air.
Swings In Burning Rate.
No Data Averaged

TEST 239

Heat Tape On Air Lines
Bypass Air.
Swings In Burning Rate.
Outlet Glowing.
Overfill Lockhopper.

TEST 222

Bypass Air.
Compressor Surge.
Swings In Burning Rate.
Outlet Glowing.
No VT.

TEST 225

Vent Air To Exhaust.
Bypass Air.
Oil Temperature High.
Room Cooling Air.
Vent Off Exhaust Duct.

TEST 228

Venturi Flow Meter.
High Vibration.
Data System Problems.
No T2, No T4.
No Data Averaged

TEST 231

Bypass Air.
Room Cooling Air.
Room Hot.
Chip Detector On.
Exhaust Duct Came Off.

TEST 234

Bypass Air.
Room Cooling Air.
Out Several Times.
No VT, no VG.
No Data Averaged

TEST 237

New Bed.
No Bypass Air.
Compressor Surge.
High Vibration.
Chip Detector On.

TEST 240

Bypass Air.
Oil Leak.

TEST 223

No Bypass Air.
Swings In Burning Rate.
Chip Detector On.
No Data Averaged.

TEST 226

Oil Radiator In Water.
Bypass Air.
Room Cooling Air.
Burning In Screw Feeder
Blew Fuse.
No VG.

TEST 229

Bypass Air.
Room Cooling Air.
Room Hot.
Blew Fuse.

TEST 232

Bypass Air.
Room Hot.
Plastic Melted.
Overfill Lockhopper.
Chip Detector On.

TEST 235

No Bypass Air.
Room Cooling Air.
Lockhopper Cycle Off.
Room Warm.
Smoke In Room.
No Vt, No VG.
No Data Averaged

TEST 238

Bypass Air.
Compressor Surge.
Room Warm.

TEST 241

New Water Tank.
No Bypass Air.
High Vibration.
Chip Detector On.
Compressor Surge.
Low Supply Air Press.
No Data Averaged

TEST 242
Bypass Air.
Valve Swings In Burning Rate.
Burning In Screw Feeder.

TEST 245
New Bed.
Bypass Air.
Room Cooling Air
Low Supply Air Pressure.
Blew Fuse.
No T9.

TEST 248
Ceiling Fan.
Bypass Air.
Room Cooling Air.
Overfill Lockhopper.
Gas Sample Line Plugged.
Scope On Vibration.

TEST 251
Bypass Air.
Low Supply Air Pressure.
No VT.
No Data Averaged.

TEST 254
No Data Averaged
Bypass Air.
High Vibration.

TEST 257
New Bed.
Bypass Air.
Swings In Burning Rate.
Gas Sample Line Plugged.
Waterbrake VG.

TEST 243
Bypass Air.
Room Hot.
Outlet Glowing.
High Vibration.
Low Supply Air Pressure.

TEST 246
Bypass Air.
Compressor Surge.

TEST 249
Ceiling Fan.
Bypass Air.
Room Cooling Air.
Room Hot.
Low Supply Air Pressure.
Scope On Vibration.
No T4.

TEST 252
Bypass Air.
Swings In Burning Rate.
Burning In Screw Feeder.
Outlet Glowing.
High Vibration.
Slide Gate Not Sealing.
No VT.

TEST 255
Bypass Air.
Steam.
Turbine Noise.
No Data Averaged

TEST 258
Bypass Air.
Swings In Burning Rate.
Low Supply Air Pressure.
No T6, Waterbrake VG.

TEST 244
New Building Air
Bypass Air.
Chip Detector On.
Outlet Glowing.
Gas Sample Line Plug.

TEST 247
Bypass Air.
Smoke In Room.
Scope On Vibration.

TEST 250
New Air Heater.
New Bed.
Clean Turbine, Comp.
Bypass Air.
Outlet Glowing.
Smoke In Room.
No VT, No VG

TEST 253
Bypass Air.
High Vibration.
Overfill Lockhopper.
No T6, Lost T7.

TEST 256
Bypass Air.
High Vibration.
Turbine Noise.
Hot Spot On Combustor.
To T6.
No Data Averaged.

TEST 259
Optical Pyrometer.
Bypass Air.
Steam.
Swings In Burning Rate.
Overfill Lockhopper.
No T6, Waterbrake VG.

TEST 260
Bypass Air.
Steam.
Compressor Surge.
No T6.

TEST 263
New Refractory, 16.75" i.d.
New Bed.
Larger Gas Sample Line.
Bypass Air.
Steam.
High Vibration.
No F3.

TEST 266
Bypass Air.
Lockhopper Cycle Off.

TEST 269
New Bed.
Bypass Air.
Steam.
Auto Control.
Turbine Noise.
Conveyor Jammed.
Wood Not Falling.
Slide Gate Not Sealing.
No VT.

TEST 272
Bypass Air.
Steam.
Auto Control.
Overfill Lockhopper.
Conveyor Jammed.
No Data Averaged.

TEST 261
Bypass Air.
Steam.
Compressor Surge.
Swings In Burning Rate.
Slide Gate Not Sealing.
Lost T7.

TEST 264
New Air Filter.
Bypass Air.
Overfill Lockhopper.
Water On Floor.
Lost T7.

TEST 267
Bypass Air.
Tried Auto Control.
Lockhopper Cycle Off.
Overfill Lockhopper.
No VT.

TEST 270
Bypass Air.
Steam.
Auto Control.
Turbine Noise.
Ran Out Of Wood.

TEST 273
Bypass Air.
Steam.
Auto Control.
Turbine Noise.
Wood Not Falling.
No F1, F2, F3, or F4.
No Data Averaged

TEST 262
Bypass Air.
Swings In Burning Rate.
Burning In Screw Feed.
Compressor Surge.
Turbine Noise.
Overfill Lockhopper.
Smoke In Room.
Hot Spot on Combustor.
No F3, No T7.

TEST 265
Bypass Air.
Steam.
Swings In Burning Rate.
Lockhopper Cycle Off.
Overfill Lockhopper.
No VT.

TEST 268
Bypass Air.
Auto Control.
Overfill Lockhopper.
Ran Out Of Wood.
No VT.

TEST 271
Bypass Air.
Auto Control.
Outlet Glowing.
Room Hot.
Wood Not Falling.

TEST 274
Bypass Air.
Steam.
Auto Control.
Wood Not Falling.
No F2, No TR, No HP.

TEST 275
 Lockhopper Air Jet.
 Bypass Air.
 Steam.
 Auto Control.
 No F2, No TR, No HP.
 No Data Averaged.

TEST 278
 Starter Motor.
 Bypass Air.
 Steam.
 No Data Averaged

TEST 281
 Starter Motor.
 Bypass Air.
 Steam.
 Turbine Noise.
 No Data Averaged

TEST 284
 Starter Motor.
 Bypass Air.
 Swings In Burning
 Outlet Glowing.
 High Vibration.
 Turbine Noise.
 Overfill Lockhopper.

TEST 287
 Short Bed.
 Starter Motor.
 Bypass Air.
 Smoke In Room, Leak.
 No data averaged.

TEST 276
 New Bed.
 Air Deflector.
 Bypass Air.
 Auto Control.
 High Vibration.
 No F2, No HP.
 No Data Averaged

TEST 279
 Starter Motor.
 Bypass Air.
 Burning In Screw Feeder.
 No F2.
 No Data Averaged.

TEST 282
 Starter Motor.
 Bypass Air.
 Steam.
 Turbine Noise.
 No AMP.
 No Data Averaged

TEST 285
 Starter Motor.
 Bypass Air.
 Steam.
 Auto Control.
 Swings In Burning Rate
 Outlet Glowing.
 Burning In Screw Feeder
 Smoke In Room.
 Fire Alarm.
 Conveyor Jammed.
 Blew Fuse.
 Lost T8.

TEST 288
 New Combustor Top.
 Short Bed.
 Starter Motor.
 Bypass Air.
 Steam.
 Compressor Surge.
 No VT.
 No Data Averaged.

TEST 277
 New Gas Sample Probe.
 Bypass Air.
 Steam.
 Auto Control.
 Swings In Burning Rate.
 Outlet Glowing.
 High Vibration.
 No F2, No TR, No HP.
 No Data Averaged

TEST 280
 Three Data Boards.
 Starter Motor.
 No Bypass Air
 Steam
 No AMP, No CV3.
 No Data Averaged

TEST 283
 Starter Motor.
 Bypass Air.
 Steam.
 Turbine Noise.
 No Data Averaged

TEST 286
 New Short Bed.
 Used Laser.
 Starter Motor.
 Bypass Air.
 Leak At Flange.
 No VT, No PY.
 No Data Averaged.

TEST 289
 Short Bed.
 Starter Motor.
 Bypass Air.
 Swings In Burning Rate.
 Burning In Screw Feed.
 Outlet Glowing.
 Smoke In Room.
 No VT.
 No Data Averaged.

TEST 290
Short Bed.
No Bypass Air.
Burning In Screw.
Lockhopper Cycle Off.
Fire On Flex Pipe.
No PY.
No Data Averaged.

TEST 293
Old Combustor Top.
Short Bed.
No Bypass Air.
Steam.
Compressor Surge.
Outlet Glowing.
Smoke In Room.
Turbine Noise.
No F1, No VT, No T7.

TEST 296
Short Bed.
No Bypass Air.
Steam.
Auto Control.
Swings In Burning Rate.
Burning In Screw Feeder.
Turbine Noise.
Overfill Lockhopper.
No VT.

TEST 291
Short Bed.
No Bypass Air.
Smoke in Room, Leak
No F1, NO PY.
No data averaged.

TEST 294
Short Bed.
No Bypass Air.
Auto Control.
Smoke In Room.
High Vibration.
Turbine Noise.
No FF.
No Data Averaged.

TEST 297
New Bed, Alumina Rods.
Vernier Air Flow.
No Bypass Air.
Auto Control.
High Vibration.
Turbine Noise.
Chip Detector On.
Turbine Jammed.
Lost VT, Lost T7.

TEST 292
Short Bed.
No Bypass Air.
Steam.
Swings In Burning Rate.
Burning In Screw Feed.
Turbine Noise.
No F1, No VT.
No Data Averaged.

TEST 295
Short Bed.
No Bypass Air.
Smoke In Room.
Turbine Noise.
No data averaged.

APPENDIX D. Model Nomenclature

A	area [m ²]
c _p	specific heat at constant pressure [kJ/kg K]
CMV	compressor map variable []
d _p	gravel particle diameter [m]
D	diffusivity [m ² /s]
h	enthalpy [kJ/kg]
$\tilde{h}_p$	gravel-gas heat transfer coefficient [W/m ² K]
I	shaft moment of inertia [kg m ²]
k _{ef}	effective fluid thermal conductivity [kW/m K]
k _{es}	effective solid thermal conductivity [kW/m K]
K _{P VENT}	proportionality constant for vent valve control
L	length [m]
m	mass stored at station [kg]
$\dot{m}$	mass flow at station [kg/s]
N	actual speed of rotor [rpm]
%N	speed of rotor as percent of maximum [rpm/rpm]
%OPEN	valve setting
P	pressure [atm]
R _{cgas}	perfect gas constant for air (0.287) [kJ/kg K]
T	temperature [K]
T _f	temperature of gas in gravel bed [K]
T _s	temperature of solid in gravel bed [K]
t	time [s]
$\dot{W}$	power [kW]
v	velocity [m/s]
V	volume [m]
x	distance along gravel bed [m]
	ratio of specific heats
	gravel bed void fraction
	efficiency
	dynamic viscosity [kg/m s]
	gas density [kg/m ³]
Subscripts	
bed	gravel bed
bl	blowoff
c _{gas}	combustion products gas
comp	compressor
f	gas phase in gravel bed
s	solid phase in gravel bed
sup	superficial velocity