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Alternative Fuel for Gas Turbines**

April 1991

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DEVELOPMENT OF BIOMASS AS AN
ALTERNATIVE FUEL FOR GAS TURBINES

J.T. Hamrick

Aerospace Research Corporation
5454 Jae Valley Road, SE
Roanoke, Virginia 24014

G.F. Schiefelbein, PNL Project Manager

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EXECUTIVE SUMMARY

A program to develop biomass as an alternative fuel for gas turbines was started at Aerospace Research Corporation in 1980. The research culminated in construction and installation of a power generation system using an Allison T-56 gas turbine at Red Boiling Springs, Tennessee. The system has been successfully operated with delivery of power to the Tennessee Valley Authority (TVA). Emissions from the system meet or exceed EPA requirements. No erosion of the turbine has been detected in over 760 hours of operation, 106 of which were on line generating power for the TVA. It was necessary to limit the turbine inlet temperature to 1450°F to control the rate of ash deposition on the turbine blades and stators and facilitate periodic cleaning of these components. Results of tests by researchers at Battelle Memorial Institute - Columbus Division, give promise that deposits on the turbine blades, which must be periodically removed with milled walnut hulls, can be eliminated with addition of lime to the fuel. Operational problems, which are centered primarily around the feed system and engine configuration, have been adequately identified and can be corrected in an upgraded design. The system is now ready for development of a commercial version.

A major consideration in the use of biomass is its low density, which results in high shipping costs. One method of profitably using biomass as a fuel is to generate power near the location at which it is produced and transmit the power through available power grids to the point of use. The biomass burning gas turbine system at Red Boiling Springs, Tennessee represents such a method. The facility is located adjacent to a 69,000 volt Tennessee Valley Authority power transmission line. A contract was negotiated for sale of power to the TVA.

The U.S. Department of Energy (DOE) provided support only for the evaluation of wood as an alternative fuel for gas turbines. However, the system appears to have high potential for integration into a hybrid system for the production of ethanol from sorghum or sugar cane. During the course of

the research program on wood, the increasing emphasis on the use of oxygenated fuels to improve air quality coupled with the prominence of the global warming problem led Aerospace Research to increasingly focus on use of sugar cane and sweet sorghum bagasse as the renewable fuels of choice for gas turbines. At the conclusion of the DOE test program independent tests were conducted by Aerospace using sugar cane bagasse as a gas turbine fuel. The test results and potential for this application are discussed in the main body of this report.

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1.0 INTRODUCTION

In 1980, Aerospace Research corporation initiated a research program to develop biomass as an alternative fuel for gas turbines under sponsorship of the U.S. Department of Energy. The U.S. Public Utility Regulatory Policies Act (PURPA) of 1978 provided a financial incentive to develop small 15 to 20 megawatt gas turbine generating systems operating on alternative fuels. Sawdust and other woodwastes from sawmills and similar wood processing operations represent an under-utilized energy resource in many areas of the country. Increasing concerns over potential pollution of ground water supplies is leading to restrictions being placed on the landfill disposal of such wastes in many locations. Utilizing these wastes as fuel for gas turbine power generating systems will eliminate the disposal problem and provide electrical energy from a renewable resource capable of recycling carbon dioxide emissions.

The gas turbine system appears to have high potential for integration into a hybrid system for the production of ethanol from sorghum or sugar cane. The U.S. Department of Energy provided support only for the evaluation of wood as an alternative fuel for gas turbines. However, tests using sugar cane bagasse as fuel were conducted independently by Aerospace Research Corporation. The results of these tests and a discussion of the potential of this application are addressed in a separate section of this report.

Preliminary test results with direct firing of biomass in a Garrett IE831-200 gas turbine and possible application of biomass as an alternative fuel in an Allison model 501-K gas turbine were presented in reference (1). A brief summary of these tests is included in this report as a convenience to the reader. Based on the results obtained in these preliminary tests, a larger scale gas turbine power generating system was constructed and installed at Red Boiling Springs, Tennessee. An Allison model T-56 gas turbine, the military version of the model 501K engine, modified for use with biomass, was used in the system. A contract was negotiated with the Tennessee Valley Authority for their purchase of power generated by the system. The system was installed in 1984 and operation at low speed was started in January of 1985. During the period from January 1985 to December 1989 a wide range of

developmental problems were encountered and solutions were either implemented or methods of implementation were determined. Tests were performed with two biomass fuels; initially with wood and later with sugar cane bagasse.

Based upon results of previous research at the Coal Utilization Research Laboratory (CURL) (2) with coal, a turbine inlet temperature of 1450°F was targeted as the possible maximum. At 1450°F the rate of deposition on the turbine blades is low enough, and the deposits of an adequately soft consistency, to allow periodical removal with milled walnut hulls. The rate of deposition and hardness of the deposits become excessive at higher temperatures. Analyses of the deposits were made by researchers at the Pacific Northwest Laboratory and tests were conducted at Battelle Memorial Institute, Columbus Division which showed promise that additives can reduce or prevent deposits.

It is the purpose of this report to acquaint the reader with the system and system hardware and present the research results. A month by month log of events after operation commenced is presented in Appendix A.

2.0 BACKGROUND INFORMATION

Gas turbines operating in a combined cycle mode or with steam injection are potentially the most efficient of any heat-power systems. Thermal efficiencies range from 33 to 40 percent even in systems as low as 5 to 10 megawatts in output. Combined cycle technology has been proven with gas and oil burning systems. The extension of the gas turbine capability to burn biomass provides a very attractive combination of low capital cost, low operating cost, and low environmental impact. In addition, systems in the 15 to 30 megawatt range which use on the order of 500 to 1000 tons of green biomass per day can be supplied from forest waste or crop residues with a maximum hauling distance of 10 to 20 miles in most areas. The generation of power in this manner, in which the power grid is used to wheel power, eliminates the need for long distance hauling, provides an outlet for local wood wastes and supplies local jobs.

A decision to pursue research on direct firing of biomass in gas turbines was based upon the success of researchers at the British Coal Utilization Laboratory (2) in cleaning gases from coal combustion with single large cyclones in series. Research results from work performed in Australia (3) were used in designing combustors. The coal fired gas turbine research performed at the Australian Aeronautical Research Laboratories (3) from 1948 until approximately 1970 is the most comprehensive work for which recent reports have been issued. The brown coal that was used in their research is similar in ash content and heating value to wood. The results obtained in tests with both brown and black coal in direct fired, open cycle gas turbines can be applied in biomass fired gas turbine research. EPA-funded research work was done with a municipal waste fired pressurized fluidized bed and a two shaft gas turbine (4) from 1970 to 1975. The results from that effort were similar to some of the early results obtained by the Australians.

3.0 IE831-200 GAS TURBINE TESTS

At Aerospace Research Corporation a wood burning gas turbine system was assembled and operated using a Garrett IE831-200 gas turbine rated at 400 kw. This work has been reported in detail previously (1) and will only be reviewed briefly here to provide overall project continuity.

3.1 IE831-200 GAS TURBINE SYSTEM TEST SUMMARY

A view of the IE831-200 system is shown in Figure 1. The wood feed bin with conical shaped lower section is located at the top. Located directly below the feed bin is the housing containing the combustion chamber, and at the bottom of the photograph, the housing containing three stages of cyclone separators. The housings and connecting ducts were constructed of low carbon steel and internally insulated to maintain wall temperatures below 600°F. The maximum temperature of the air leaving the compressor was approximately 600°F and the maximum temperature of the gases leaving the combustion chamber was approximately 1500°F. The ability to vent variable portions of air between the compressor and the combustion chamber allowed a wide range of operating conditions to be explored.

3.1.1 Wood Fuel

The primary fuel was yellow pine sawdust passed through a hammermill fitted with a 1/4 inch screen. Secondary fuel consisted of yellow pine chips pulverized green to pass a 3/4 inch screen, dried to 20-25 percent moisture, and further pulverized to pass a 1/2 inch screen.

3.1.2 Wood Feed System

Initially, wood was metered into the combustion chamber from the wood feed bin by means of an auger with the bin maintained at the same pressure as the combustor by using a side stream from the compressor. This proved unsatisfactory. Heat from the combustor repeatedly caused fires in the feed bin after the system was shut down. The auger was subsequently replaced by a series of rotary valves.

FIGURE 1. View Showing Small IE831-200 Wood Burning Gas Turbine System.

3.1.3 Combustion Chamber

The 21 ft. long combustion chamber housing can be seen just below the wood feed bin in Figure 1. Air from the compressor was ducted to the bottom of the combustion chamber, up through an outer annulus and into the burner located at the top of the chamber. The combustion gases were ducted from the bottom of the chamber to the inlet of the cyclones.

3.1.4 Cyclone Filters

The cyclone housing initially contained three cyclones (later reduced to two cyclones) connected in series and wrapped with high temperature insulation. The cyclones were patterned after those developed by the Coal Utilization Research Laboratories (2). Each cyclone was equipped with an ash collection chamber, lock hopper for ash removal and appropriate valving and pneumatic conveyance to remove ash during gas turbine operation. Gases from the final cyclone were ducted to the turbine inlet.

3.1.5 Gas Turbine

To install the Garrett IE831-200 turbine in the wood burning system, the oil fired turbine combustor and housing were removed and replaced by ducting carrying hot gases from the cyclone. The rated continuous shaft output of the gas turbine at 80°F and sea level was 500 hp. Running at that level, the velocities of the gases relative to the turbine buckets at the exit were on the order of 1400 ft/sec. The relative velocity could be reduced by dumping air at a vent valve ahead of the combustor, thereby reducing the turbine rotation speed. At zero generator output, 23,000 rpm and 1450°F turbine inlet temperature, the velocities relative to the turbine buckets at exit were on the order of 800 ft/sec. Thus, the IE831-200 was capable of serving as a research vehicle to cover nearly the full range of turbine relative velocities for existing gas turbines.

The major difference in the control of a gas turbine operating on wood and one operating on oil is a greater response time to changes in fuel flow for the wood burning system due to the relatively large volumes of the combustor, cyclone and associated ducting. Compensation for a sudden loss of load was made by opening the vent valve ahead of the combustor to reduce

system pressure and opening a bypass valve, allowing compressor air to cool the combustion gases prior to entering the turbine.

3.1.6 System Startup

The system was started on propane gas and shifted to wood fuel at approximately 21,000 rpm. Because the electric starter could only be operated for a short period, it was best to start the engine with wood containing eight percent or less moisture in order to establish a flame pattern as rapidly as possible. The engine could be operated at any speed during the tests since the generator was not connected to a commercial power system.

3.1.7 Summary Test Results

After operation for 210 hours, the Garrett IE831-200 gas turbine was disassembled for inspection. There were moderate hard deposits on the first two stages of the turbine. Photographs of the three stages before and after cleaning are shown in Figures 2, 3, and 4. There was no detectable erosion or corrosion of either turbine blades or stators. Operation of the gas turbine was continued for a total of 575 hours at 14,500 to 35,000 rpm with pine wood and propane at 1200° to 1450°F turbine inlet temperature without incident. A second IE831-200 engine was also operated for 365 hours. It was not disassembled for inspection. Only third stage turbine blades were visible. They showed no evidence of erosion and negligible deposits.

First Stage Stators Before Cleaning

First Stage Stators After Cleaning

First Stage Turbine Before Cleaning

First Stage Turbine After Cleaning

FIGURE 2. Views Of First Stage Turbine And Stators Of Garrett IE831-200 Engine After 200 Hours Operation At 1350 - 1450°F Gas Inlet To Engine.

Second Stage Stators Before Cleaning

Second Stage Stators After Cleaning

Second Stage Turbine Before Cleaning

Second Stage Turbine After Cleaning

FIGURE 3. Views Of Second Stage Turbine And Stators Of Garrett IE831-200 Engine After 200 Hours Operation At 1350 - 1450°F Gas Inlet To Engine.

Third Stage Stators Before Cleaning

Third Stage Stators After Cleaning

Third Stage Turbine Before Cleaning

Third Stage Turbine After Cleaning

FIGURE 4. Views Of Third Stage turbine And stators Of Garrett IE831-200 Engine After 200 hours Operation At 1350 - 1450°F Gas Inlet To Engine.

Figure 1: Initial stage of the process.

Figure 2: Intermediate stage of the process.

Figure 3: Final stage of the process.

Figure 4: Comparison of the results.

Figure 1: Initial stage of the process.

Figure 2: Intermediate stage of the process.

4.0 T-56 GAS TURBINE SYSTEM DESCRIPTION

As a result of the 831-200 test results discussed above, a decision was made to design and build a preprototype system using an Allison T-56 gas turbine rated at 3000 kw. The system was built and tested in Roanoke Virginia and subsequently installed at Red Boiling Springs, Tennessee, an area with large sawdust surpluses. A contract was signed with the Tennessee Valley Authority for sale of the power generated by the system. A schematic diagram of the 3000 KW system is shown in Figure 5. An overall view indicating individual components of the 3000 KW system installed at Red Boiling Springs is shown in Figure 6.

Incoming sawdust in forty-foot trailers is weighed and dumped by a hydraulic dumper. The sawdust is conveyed by belt to a green wood bin shown at the right in Figure 7. Wood from the green wood bin is fed through a rotary valve to an auger which conveys the wood to the drier inlet as shown in Figure 8. Sawdust leaving the drier passes through a hammermill and on to the dry wood storage bin shown in Figure 6. Wood from the dry wood storage bin is fed through a flexible auger to a live bottom metering bin, located on top of the combustor and thence through rotary valves into the combustor. The hot combustion products produced in the combustor pass to a hot gas cyclone where ash is removed from the gases before they are admitted to the gas turbine. Electrical power produced by the generator attached to the gas turbine is conducted through appropriate switching equipment to the transformers shown in Figure 9 where it is stepped up to 69,000 volts for delivery to the TVA grid. The oil circuit breaker and metering station is shown in Figure 10.

4.1 PRELIMINARY CONSIDERATIONS

A number of considerations were involved in the selection of the type of gas turbine to be utilized in the facility and its operating mode. These are discussed in the following subsections.

FIGURE 5. Schematic Diagram Of Wood Fueled 3000 KW Gas Turbine System

FIGURE 6. 3000 KW Gas Turbine System At Red Boiling Springs

FIGURE 7. View Of Green Wood Bin And Drier

FIGURE 8. Overhead View Of Drier And Feed Arrangement

FIGURE 9. Transformers For Stepping Up Power From Generated 4160 Volts To 69,000 Volts For Delivery To TVA

FIGURE 10. Oil Circuit Breaker And Metering Station

4.1.1 Turbine Selection

For a number of reasons the General Motors - Allison T-56 gas turbine is the most favorable one for use in a wood burning gas turbine power generation system. The reasons for its selection are:

- 1) It is the only 3000 kw axial flow compressor engine manufactured in the United States that can be easily adapted to a combustor that is offset from the compressor and turbine.
- 2) The axial flow compressor in the T-56 engine has a wide surge margin that allows use of water/steam augmentation in the combustor.
- 3) The engine, being an aircraft engine currently in production is widely available, both new and used.
- 4) The 3000 kw output of the engine is in the range that is compatible with wood supplies available in many areas.
- 5) It is a single shaft engine which allows speed control by the power grid.
- 6) The turbine section of the engine can be removed and replaced in four hours or less.

The maximum temperature at which blade endurance was tested at the Coal Utilization Research Laboratory (2) was 1500°F. It was reported that cooling of the blade surfaces to 1350° to 1450°F appeared to be a viable method of reducing corrosion to acceptable rates in pressurized fluidized bed powered turbines.

4.1.2 Theoretical Analysis; Water/Steam Injection

To derive rated power from the T-56 gas turbine with an average turbine inlet temperature of 1400°F requires injection of water or steam into the hot gases during or at the end of the combustion process. Water injection into turbines in Australia (3) was reported by J.C. Wisdom of Australia as early as 1958. Calculations were made to determine power output and efficiency for the T-56-15 gas turbine with and without water or steam. Performance of the T-56-15 model more closely approaches the performance the 501-KB commercial version of the engine than does the T-56-9 version that is being used in the wood burning program. Computations were made (6) with varying amounts of injected water and steam. The results of the calculations for steam injection

are shown in Figure 11 for turbine inlet temperatures of 1400°F, 1450°F, and 1500°F. Results are shown for water injection in Figure 12. The computer printouts for the theoretical performance shown in Figures 11 and 12 are included in (6). All of the steam that is needed for injection can be generated by routing the exhaust gases through an eighty percent efficient waste heat boiler. Results with steam injection by Allison (7) in the 501 KB gas turbine and water injection in the 3000 kw wood burning system have proven the effectiveness of the method. As can be seen in Figures 11 and 12, there is substantial improvement in system efficiency with the use of steam as opposed to water.

FIGURE 11. T-56-15 Gas Turbine Performance With Steam Injection

FIGURE 12. T-56-15 Gas Turbine Performance With Water Injection

4.2 T-56 GAS TURBINE SYSTEM DESIGN AND CONSTRUCTION

Design of the T-56 wood fueled gas turbine generating system was based on extensive review of prior efforts from the literature and operating experience gained from the testing program with the IE831-200 engine.

4.2.1 Site Selection and Construction

Site evaluation was limited primarily to the eastern part of the U.S. because of communication and travel considerations. The policies and plans of power companies regarding the use of renewable fuels were greater factors than site suitability. Of the many power companies contacted, only the Tennessee Valley Authority and the Virginia Electric and Power Company openly encouraged placement of renewable energy installations in their areas. Based upon the ratio of rates paid for power to the cost of wood, the Red Boiling Springs site in the TVA service area was selected. There were approximately 35 sawmills in the Red Boiling Springs area, while the nearest large scale user of sawdust was located 120 miles away. Hauling sawdust that distance netted the seller approximately two dollars per ton. Contracts for sawdust at \$5.00 per ton were signed with local sawmills. A ten year contract for the sale of power was signed with the TVA. The five acre site selected was located adjacent to the right-of-way for a 69,000 volt distribution line within the city of Red Boiling Springs. A road into the site with provisions for weighing trailer trucks, unloading and turn around were completed early in 1983. In successive order the foundations for electrical gear, an office building, sawdust storage building and the gas turbine system were completed. Weigh scales with 50 tons capacity and a truck dumper were installed. The gas turbine system was fabricated at Aerospace Research's Roanoke, VA shops and transported to Red Boiling Springs site for assembly.

4.2.2 Wood Fuel Supply

Timber growth in the Red Boiling Springs area consists primarily of tulip poplar and red and white oak. There is little or no pine timber. Most of the approximately thirty five sawmills in the area use circular single saw blades with replaceable teeth. Some area plants engaged in pallet manufacture use band saws to produce the thin pallet boards. The fine sawdust produced by the band saws was found to be difficult to feed with rotary valves, therefore, procurement of sawdust from these plants was avoided. A characterization of typical Red Boiling Springs sawdust fuel, performed by Pacific Northwest Laboratory, is shown in Table 1.

TABLE 1.
CHARACTERIZATION OF RED BOILING SPRINGS
WOOD FUEL (SAWDUST)

ULTIMATE ANALYSIS Mass %, Dry Basis, (a)		ASH COMPOSITION Mass %, As Oxides, (b)	
Carbon	45.5	SiO ₂	52.8
Hydrogen	6.0	CaO	17.0
Nitrogen	2.1	K ₂ O	6.4
Oxygen (by diff.)	46.7	Al ₂ O ₃	3.9
Ash	1.7	Fe ₂ O ₃	2.2
		MgO	2.2
		P ₂ O ₅	1.0
		SO ₃	1.0
		Na ₂ O	NA
(a) Carbon, hydrogen, nitrogen analysis by CHN analyzer		TiO ₂ , MnO ₂ ,	< 1.0
		BaO, CuO,	
		ZnO, NiO,	
		SrO, Cr ₂ O ₃	
(b) Analysis by inductively coupled plasma spectrometry			

4.2.3 Wood Feed Preparation

Incoming sawdust in forty-foot trailers is first weighed and then dumped by a hydraulic dumper. The sawdust is conveyed by belt to the green wood bin shown at the right in Figure 7. Wood is fed from the green wood bin to an auger that conveys the sawdust to the drier inlet through a rotary valve. An overhead view of the drier arrangement is shown in Figure 8.

Sawdust moves across the drier screen and through a rotary valve to an auger that conveys the dried sawdust to the hammermill. The hammermill reduces wood chunks and stringers to a size that will pass a screen with quarter-inch diameter perforations before it is conveyed to the dry wood bin shown in Figure 6. Referring to Figure 6, the sawdust which has been dried to a 20 to 25 percent water content is conveyed from the dry wood bin by a

flexible auger to the live bottom bin and then through the rotary valves to the combustor.

The incoming sawdust varies in the amount of bark stringers, board chunks, knots and saw teeth contained in the mix. A large magnet was installed to capture saw teeth and other tramp metal. For this test program suppliers with the fewest large scraps were favored. The sawdust particles range from approximately 1/32 inch to 1/16 inch cubes for oak to 1/16 to 3/32 inch cubes for poplar. For actual commercial systems a method of eliminating large scraps, perhaps with a hogger, will be required. Freshly cut sawdust contains 35 to 50 percent moisture, depending on the season, but can increase to 60 percent if stored in the open subject to rain. This moisture content not only increases the dryer loading but also results in freezing problems in the winter. Under cover storage is a necessity for operations in the Red Boiling Springs area.

4.2.4 Wood Feed System

It was recognized at the outset that feeding solids from atmospheric pressure into a high pressure combustor would require a significant R&D effort. In previous solids fueled gas turbine research (3)(4)(5), feeding of fuel into the combustor had been accomplished with rotary valves serving as pumps. Consideration was given to use of lock hoppers, but the experience of Yellott et al. (5) with batch systems, together with adverse experience with pressurized hoppers in early research at Aerospace Research Corporation, led to a decision to use rotary valves. Yellott et al. reported the following on batch systems research for the Locomotive Development Committee program.

"At the outset of the L.D.C. program, it appeared that pressurizing of either crushed or pulverized coal could be handled by some form of batch system, such as a lock hopper, or a twin-tank arrangement. A conventional sandblast lock hopper was tested with the Dunkirk Pilot Plant but this was not satisfactorily because the crushed coal would not flow freely through the poppet valves from the upper to the lower chambers.

A slide-valve lock hopper was built and tested with some success at Johns Hopkins. A pressurizer of similar design was used

at the beginning of the Fontana tests. The slide valves of the device were actuated by pneumatic power pistons which were controlled by a rotating timer. More than 2000 lb/hr of crushed coal could be delivered into a storage tank against 120 psig, and the large valve opening allowed the coal to discharge freely.

When the lock hopper was used in large scale combustion tests, it was found that pressure fluctuations were caused by the opening and closing of the valves. These pressure changes caused the coal feed rate to vary, which in turn started pressure surges in the combustor. A sudden pressure rise in the tank compacted the coal and usually reduced the feed rate because of bridging. A sudden fall in pressure could cause the coal to flood through the screw. Experience taught that even the best batch system was not likely to be satisfactory in a variable-pressure system such as a gas turbine."

In addition to the problem with pressure fluctuations there is another problem in feeding directly from pressurized hoppers. In early tests with the Garrett engine at Aerospace Research Corporation sawdust was metered by means of an auger directly into the combustion chamber from a pressurized bin. Even though the bin was depressurized at shutdown, any wood that was left in the bin ignited causing severe problems. Rotary valves provide an advantage in that they can be cleared of sawdust on shutdown to provide a fire screening buffer between the combustion chamber and sawdust bin.

In the Australian research (3) no mention was made of any unusual difficulty with the rotary valve in feeding crushed coal to the combustor of the Ruston gas turbine. However in that system the compressor outlet pressure, for an output shaft speed of 1250 rpm, was only 49 psig. For the system being operated by Yellott et al. (5) the pressure was 75 psig, and difficulty was encountered in feeding with a single valve, which led to the consideration of using multiple valves in series for the wood feed system. No mention was made of difficulties experienced with rotary valves in the CPC program (4). That research was performed with a Ruston gas turbine which featured low compressor outlet pressure.

In their description of the rotary valve the Australians (3) referred to it as a fuel pressurizing pump. Yellott et al (5) referred to it as a rotary pump. The term rotary valve is in more general use throughout the United States and that is the term used in this report. The radial vanes of the valve, in effect, convey the fiber particles from a zone of low pressure to a zone of high pressure without an action that is normally considered as one of pumping.

Based on the above background and test results with the 831-200, the decision was made to employ a rotary valve feeder. In a survey of rotary valve manufacturers no off-the-shelf valve was found that could deliver dry sawdust at the needed 150 psig pressure. Rotary valves designed and fabricated by Aerospace Research Corporation were tested on the 831-200 system with good results. It was estimated that four valves stacked in series would be needed for the T-56 system. Bench testing the valves at a pressure differential of approximately 90 psig indicated that they would perform satisfactorily.

4.2.5 Combustion Chamber

The combustion chamber was designed on the basis of results with the 831-200 system and earlier research by the Australians (3). Pile up of wood particles at the combustor inlet for off-design wood flows in earlier work with horizontal chambers led to the decision to introduce the wood downward in a vertical chamber. A schematic of the firebrick lined combustor is shown in Figure 13.

There was no secondary combustor in the 831-200 system. As a result, any unburned char moved into the first cyclone and burned, overheating the cyclone walls. The degree of overheating grew worse with increasing water content in the wood. As a result of the experience with the 831-200 system it was decided to swirl the exhaust products from what would be the primary combustor into a secondary combustor, as shown in Figure 13.

As can be seen from the schematic, air from the compressor enters an annulus at the top of the secondary combustor and flows around the outside of the firebrick to the primary combustor. One benefit from this arrangement is the cooling of the firebrick from the back side with the 650°F air supplied by

the compressor, increasing the life of the firebrick. Figure 13 shows locations at which water was injected into the combustor.

FIGURE 13. Schematic Diagram Of The 3000 KW Combustor

4.2.6 Cyclone Filter

The hot combustion products move to the hot gas cyclone where ash is conveyed from lock hoppers at the bottom of the hot gas cyclone to the ash cyclone. In the coal experiments at the Coal Utilization Research Laboratory (2) three cyclones in series were used in the cascade test rig. It appeared from the CURL data and the results obtained in the IE831-200 system that two cyclones would be required in the T-56 system. The system was initially fitted with two cyclones mounted in series and tested.

4.2.7 T-56 Gas Turbine

The cleaned gases are ducted to the T-56 gas turbine shown in Figure 14. The pipe above the gas turbine is supported by a yoke on springs that rest on the stanchions. The center section arrangement for ducting the compressed air

out of the compressor and the hot gases back into the turbine is shown in Figure 15.

FIGURE 14. Detailed View Of The T-56 Turbine

FIGURE 15. Transition Section For Accommodation Of The External Combustor For The T-56 Turbine

4.2.8 Starting System

The power take off to drive the gear box and generator is located at the compressor end of the gas turbine. An Oldsmobile 455 engine with hydramatic transmission is used to rotate the gas turbine during warm up and to assist in starting. The drive arrangement is shown in Figure 16. Power is transmitted

FIGURE 16. Drive Arrangement For Start Assist And Warm Up

through eight V-belts to a shaft with an overrunning clutch and disk clutch. The generator field is shorted and the generator used as a motor during starting of the gas turbine.

4.2.9 Power Transmission

The facility is located adjacent to a 69,000 volt Tennessee Valley Authority power transmission line. The generated power is conducted through appropriate switching equipment to the transformers shown in Figure 9. The oil circuit breaker and metering station is shown in Figure 10.

5.0 T-56 GAS TURBINE SYSTEM TEST RESULTS WITH WOOD

The nature of any system is that all of its components must function with the degree of performance needed to produce the desired end result. In most of the tests the weakest link in the system proved to be the mechanism for feeding wood into the burner for which the pressure was on the order of 130 psig. As can be seen from the month-to-month log in Appendix A, there were other operational problems, most of which were resolved to the extent needed to achieve two to four hour runs on line with the Tennessee Valley Authority. The major basic problem is one of deposits on the turbine blades.

5.1 SYSTEM COMPONENT PERFORMANCE

Experimental results with the starting system, rotary valve feeder, combustion chamber, cyclone filter, gas turbine, sawdust drier, and the overall system are discussed in the following subsections.

5.1.1 Sawdust Drier And Conveyors

The vibrating fluidized bed dryer has proven to be a basically sound selection for drying sawdust in this application. Improvement can be made in the structural design. The main structural problem has been with bolt failure, including the bolts that hold the vibrators onto each side of the drier. The perforated plate, across which the fluidized sawdust moves, was made of hot rolled steel and the diameter of the perforations becomes smaller due to rust. The holes have to be cleaned out periodically. The drier was sized to dry sawdust containing 45 percent water (wet basis) to approximately 25 percent. The hardwood sawdust from the local sawmills absorbs and retains approximately 60 percent water when exposed to rain. An initial problem with drier capacity was corrected by changes in the baffling in the drier and passages in the flow ducting.

There were two areas of difficulty with the conveyors. Freezing immobilized the chain and bar conveyor in the bottom of the green wood bin and the green wood screw conveyors at temperatures near zero °F. Because of the infrequency of such cold temperatures at Red Boiling Springs, no changes have been made to solve the problem. Chunks of wood occasionally cause jamming of

the augers that distribute wood overhead in the green wood bin and in the auger between the green wood bin and drier. Screening out the chunks at the green wood bin outlet and more discrimination in choosing sawdust suppliers has greatly reduced the frequency with which the problem occurs.

5.1.2 Wood Feed And Rotary Valves

In operation of the system at Red Boiling Springs, seals on the rotary valves proved to be a major problem. Seal materials, whether plastic or metallic lasted only two to twenty hours with the system operating at synchronous speed. A wide variety of valve sizes and configurations were evaluated. A favorable factor with rotary valves is the absence of fires after shut down. A schematic view of an eight vane rotary valve is shown in Figure 17.

FIGURE 17. Schematic Of A Rotary Valve With Eight Wiper Blades

The abrasiveness of wood was grossly underestimated in the initial designs. It was determined after testing many configurations and materials

that wood particles trapped between two sealing surfaces with no give in position for either surface would quickly abrade one or both surfaces, spoiling the seal. The sealing configuration that has proven best at this point is one in which spring loaded seals consisting of one half inch thick bars of a special nylon material are mounted in slots at the edges of the vanes shown in Figure 17. Because of the give in the spring loaded seals, trapped particles can move out without damaging the sealing surfaces, and compensation for normal wear is provided by the free movement of the seals. Initial problems occurred with powdered wood packing into the slots and binding the seals. Tapering the bars appears to have corrected the problem. While this configuration appears to have provided a solution to the problem, running over hundreds of hours will be needed for full evaluation.

Initial problems encountered with the rotary valve feeding system led PNL to commission a preliminary design study for an alternate feeding system which is discussed in appendix F.

5.1.3 Combustion Chamber

Overall, there have been few problems with combustor performance. One problem arose from inadvertent piling of sawdust at the bottom of the primary combustor. At low pressure piled sawdust burns very slowly. At the 135 psig pressure in the combustion chamber it burns very rapidly. In this instance as the gas turbine reached operating speed on startup the piled sawdust burned so rapidly that it caused overheating of all components downstream of the combustor, badly damaging the cyclone, ducting, and turbine. After devising many measures to prevent inadvertent sawdust piling and detection of piling, it was discovered that opening the four two-inch dump valves in the duct between the compressor and combustor would suffice to prevent overheating, if piling did occur. A second problem arose from burning sawdust with water content exceeding approximately 25%. With sawdust exceeding a 25% water content, the amount of char entering the secondary combustor was excessive. The char burning on the walls caused the temperature to exceed the melting point of the ash, causing molten ash to pile on the floor of the secondary combustor.

Figure 13 shows locations at which water was injected. Untreated water was used in the tests to determine if the mineral fallout from the water would be removed in the cyclone. Significant increases in power output were achieved with injection at both locations, but the mineral particles proved too small to be removed in the cyclone. They passed through the cyclone and caused excessive depositions on the turbine blades. Deionized water will be required when water injection is used.

5.1.4 Cyclone Filter

The system was initially fitted with two cyclones mounted in series and tested. So little ash was collected in the second cyclone that it was eliminated. A single cyclone has functioned well. Results of emission tests by Battelle-Columbus are provided in Appendix C. The maximum particulate concentration was 33 parts per million and the maximum particle size was 2.6 μm . No erosion of the turbine can be expected from particles below 5 μm in size and none was experienced. However, contrary to the experience at CURL where little deposition was evidenced on the cascade of blades after 1000 hours of testing, there were excessive deposits on the stators and blades of the T-56 gas turbine after only 26 hours of operation. These deposits, from burning oak wood, will be discussed further in the analysis of results section.

5.1.5 T-56 Gas Turbine

The retrofit of the T-56 engine worked well except for problems with the compressor inlet bearing oil seal, surging of the compressor on shutdown, and bypassing of compressed air.

The compressor inlet bearing oil seal is the labyrinth type which depends upon the 6th stage air pressure to prevent leakage of oil into the compressor inlet. The oil seal arrangement is shown in Figure 18. The arrangement works well when the engine is operating at rated speed, but not for prolonged operation at low speed. During operation as an aircraft engine on jet fuel, the T-56 engine reaches rated speed in sixty seconds. With the external combustor and cyclone filter the engine must be operated for fifteen minutes to one hour at low speed for warm up. During that time the pressure generated by the lubrication pump exceeds the pressure generated at the sixth compressor

FIGURE 18. Oil Seal Arrangement For The T-56-9 Engine

stage, resulting in leakage of oil into the compressor. Any leaked oil is then centrifuged to the wall, collecting in the cavities of the bleed valves shown on the compressor in Figure 6. Upon three occasions, oil that had collected in the bleed valve cavities caught fire during compressor surge at shutdown, severely damaging the compressor blades. It was only after the third occurrence that the source of the problem was determined and corrective action taken. One action was to remove the oil with a water wash after warm up and the second was elimination of compressor surge.

Since the high temperature synthetic oil used to lubricate the gas turbine is water soluble, it can be diluted or washed out by spraying water into the compressor inlet. Water spray nozzles were installed upstream of the compressor inlet, and water was sprayed into the compressor inlet after system warm up during the startup procedure. In addition to elimination of the oil, a procedure was set up for elimination of surge at shutdown. Four two-inch ball valves were installed on the air delivery pipe to the combustion chamber which allowed the air pressure between the compressor and combustion chamber to be vented. The objective of venting is two fold. First, venting is used to prevent overspeeding of the gas turbine in the event of an electrical fault on the TVA line, which would result in automatic removal of the load on the gas turbine. Second, opening of the four valves at shutdown eliminates surging of the compressor. Venting at the valves was made a routine part of the shutdown procedure. No compressor fires have occurred since the foregoing procedures were adopted.

Some problem was encountered with the turbine transition section shown in Figure 15. Some bypassing of compressed air into the turbine occurs due to leakage at the turbine inlet and around the peripheries of the turbine stators. There is a slip joint between the six delivery ducts in the transition section (Figure 15) and the first stage stators of the turbine. Air leakage in the remaining stators occurs primarily through the openings between stator sectors. These sectors are segmented to allow for expansion upon heating. In the conventional engine this leakage is less prominent because of the lower pressure drop across the combustor. The main effect of

the leakage is to reduce the aerodynamic efficiency of the turbine and to reduce the effective turbine inlet temperature.

5.1.6 Starting System

The starting system as described previously includes the 455 Oldsmobile engine, automatic transmission, belt drive, overrunning clutch, disk clutch, generator, and synchronism check relay. The automatic transmission is needed to ease the load on the engine as it starts rotation of the 10,000 lb generator rotor and gas turbine. When warm up of the system is completed and power is applied to the generator operating as a motor, the overrunning clutch allows the generator and gas turbine to move up in speed without overspeeding the Oldsmobile engine before the disk clutch is released. An overspeed trip on the engine ignition circuit is set to prevent overspeeding of the engine as the disk clutch is released. As the gas turbine takes over and drives the generator, the generator field is unshorted and the fuel adjusted to achieve synchronous speed. A synchronism check relay prevents the closing of the generator-to-line high voltage contactor until the generator phase and frequency matches that of the TVA Grid. The starting system has functioned well in the foregoing described manner. To reduce the time required to achieve synchronism an injection system, that injects diesel fuel into the combustor, was added to provide a more precise trim for speed control. Once the generator-to-line relay is closed the oil trim is discontinued and the speed of the generator and gas turbine is controlled by the TVA grid. The wood feed control then functions only to control the turbine inlet temperature.

6.0 OVERALL SYSTEM TEST RESULTS WITH WOOD

The system was operated on wood for a total of 760 hours, 106 of which were on line with the Tennessee Valley Authority. Data from typical runs with and without water injection are provided in Table 2.

At the low combustor outlet temperature of 1471 F with water injection the power output is more than double that with no water and a combustor outlet temperature of 1494 F. Based upon the turbine exhaust gas temperature (EGT) of 621 F for the run with no water the effective turbine inlet temperature was 1240 F which means that the gases at 1387 F entering the engine inlet duct are diluted by leakage of compressor air into the turbine. A similar situation exists for the run with water injection except that with water injection there is an advantage in that the water or steam injected into the combustor increases the flow through the turbine, reducing the effect of compressor air leakage. Measurement of the wood feed for the run with water injection was possible because the rotary valve configuration did not include a vent as shown in Figure 16. All of the wood from the calibrated live bottom bed passed through the rotary valve to the combustor. For the run with no water the rotary valve configurations had been changed to include the vents on the two upper valves. With the vent some of the sawdust is discharged back to the dry wood bin and not measured.

After approximately 26 hours of operation at a turbine inlet temperature of 1450°F the gas turbine power output starts to decline due to deposition and the turbine must be cleaned with milled walnut hulls. An alternative method of cleaning is with high pressure water sprays. Both methods have been used. Regardless of the cleaning method, the turbine must be periodically removed, partially disassembled, and cleaned. The total hours between removals has not been firmly established but is on the order of 180 hours. For both future research and commercial operation a spare turbine is needed to accommodate the cleaning process. A turbine can be replaced in four or less hours, but cleaning can require 17 hours or more. It is probable that periodic cleaning will be required even if fuel additives successfully reduce the severity of the deposition problem. At turbine inlet temperatures above 1500°F the rate of turbine deposition was so great that sustained runs could not be made.

Start up, operation and shut down of the system is currently performed manually by an experienced operator. The continued presence of the operator is required. Enough of the operating parameters and critical factors have been identified to allow design and fabrication of an automatic control system. Programming of an automatic control system will be necessary for commercialization.

TABLE 2. Typical Test Results from Operation of T-56 Gas Turbine

<u>Measurement Location</u>	<u>Run With Water Injection</u>	<u>Run Without Water Injection</u>
Ambient Temp. °F	51	56
Compressor Outlet, °F	646	597
Combustor Outlet, °F	1471	1494
Cyclone to Engine Duct, °F	1387	1326
Exhaust Gas Temperature (EGT), °F	665	621
Turbine Inlet Temperature (From EGT)*, °F	1273	1204
Gas Turbine Speed, RPM	14195	14195
Compressor Outlet Pressure, PSIG	128	120
Turbine Inlet Pressure, PSIG	118	108
Pressure Loss, percent	7	9
Air Flow, lbs/sec	34	34
Wood Feed, lbs/hr	5500	-*
Water Injection Rate, GPM	12	0
Power Output, KW	1600	700

* Explanation contained in Discussion Of Results, page 35.

7.0 T-56 SYSTEM TEST RESULTS WITH SUGAR CANE BAGASSE

Early in the wood fueled gas turbine research program, Aerospace Research Corporation was approached by representatives from Brazil regarding the use of sugar cane bagasse as a gas turbine fuel. The production of alcohol fuel from sugar cane juice, which results in a large surplus of bagasse, is a major factor in the Brazilian economy.

Although the U.S. Department of Energy provided support only for the evaluation of wood as an alternative fuel for gas turbines, the system appears to have high potential for integration into a hybrid system for the production of ethanol from sorghum or sugar cane.

Sorghum and sugar cane have the highest conversions of solar energy into biomass of any of the species in the plant kingdom, substantially greater than trees. Sweet sorghum can be grown throughout the United States as well as the tropic and temperate zones of the earth. The sorghum grain can be used for fermentation or food. Sweet sorghum and sugar cane juices are readily converted to alcohol by yeast fermentation and the remaining bagasse can be used as a fuel for gas turbines. By using the bagasse as a fuel for a power generating gas turbine, the income from power sales would be available to substantially improve the economics of producing the alcohol. With the use of bagasse as a fuel for gas turbines generating power it is possible for the income from power sales to reduce the cost of alcohol well below that for gasoline. The high volume, high temperature exhaust gases from the turbine could be used to concentrate the juice, make alcohol, dry the bagasse or generate steam for injection into the turbine.

Growth of sugar cane and sorghum on the 66.4 million acres of land taken out of production in the U.S. between 1981 and 1988 could supply enough energy to generate approximately one third of the power now consumed in the U.S. At the current rates paid by power companies in several states for power generated with renewable fuels 25.4 billion gallons of alcohol can be produced as a by-product of power production.

Recently, the Minnesota Legislature funded \$512,000 in that state for research on sweet sorghum as an alternative crop for fuel alcohol, livestock

feed, and fuel for electrical power generation. The state of California has set aside \$140,000 to assist farmers in experimenting with sweet sorghum as an alternative crop, and a joint resolution was passed by the California Senate requesting that farmers be permitted to grow energy crops on the 3,084,714 acres now out of production and costing in excess of \$285,560,000. Agriculture researchers at Virginia Polytechnic Institute and State University are in their ninth year of research on sweet sorghum as an alternative crop for feed and energy.

During the course of the research program on wood, the increasing emphasis on the use of oxygenated fuels to improve air quality coupled with the prominence of the global warming problem led Aerospace Research to focus on use of sugar cane and sweet sorghum bagasse as the renewable fuels of choice for gas turbines. Therefore, Aerospace Research elected to conduct independently funded tests using sugar cane bagasse as a gas turbine fuel.

Tests were performed with sugar cane bagasse to determine the following:

- a) Required Modifications to the Sawdust Conveying System
- b) Drying Characteristics
- c) Burning Characteristics
- d) Extent of Deposition on Turbine Blades

Sugar cane bagasse for the test trials was provided by M. A. Patout & Sons, Ltd., Jeanerette, Louisiana. Because of the long hauling distance from the source of the bagasse in Louisiana to Red Boiling Springs, testing was limited to a single trailer load of approximately 1500 cubic feet of bagasse. The material, as received, had been ground into a combination of particles that ranged from powder size to stringers approximately four inches in length. The green particles with 52 to 56 percent moisture did not pour freely like green sawdust and tended to form clumps when packed. The dried, pulverized material, which had a bulk density of approximately 9.3 lbs/per cubic foot (dry basis), more closely resembled sawdust in its consistency, but included small stringers.

7.1 REQUIRED MODIFICATIONS TO THE SAWDUST CONVEYING SYSTEM

The major difference in conveying sawdust as opposed to bagasse resulted from the stringers in the bagasse. All ledges and other projections in the

conveyors where the stringers could lodge and cause bridging or jamming had to be eliminated. Ducting sizes into and out of the drier will have to be made larger due to both the stringiness and lower bulk density of bagasse. Pneumatic and belt conveyors have proven most reliable. Augers have tended to jam, especially those set on an incline and delivering bagasse upward.

7.2 DRYING CHARACTERISTICS

The fluidized bed drier worked well with the sugar cane bagasse. Based upon test results the drying time for bagasse is approximately one fourth that for an equal volume of sawdust. On that basis a single fluidized bed drier will be capable of simultaneously drying the bagasse needed for operation of the system during the harvest period and the bagasse to be stored for operation during the remainder of the year.

7.3 BURNING CHARACTERISTICS

During feeding through the rotary valves and combustion of the bagasse, there was no detectable change from burning sawdust except for a lower temperature on the wall of the secondary combustor. As the hot gases leave the primary combustor and swirl into the secondary combustor any unburned particles are centrifuged to the wall where they finish burning and heat the walls. With bagasse the temperature of the gas at the wall was 1600°F whereas with wood under the same conditions it would have been 1800°F. This result indicates that more nearly complete combustion of bagasse took place in the primary burner.

7.4 EXTENT OF DEPOSITION ON TURBINE BLADES

After 10 hours of running at 25 to 75 percent of rated engine speed and 1400 to 1450°F turbine inlet temperature there appeared to be no difference in deposition rate between wood and bagasse. The deposits were powdery and could be cleaned off with milled walnut hulls. Sorghum rind and pith samples supplied by Virginia Tech and sugar cane bagasse samples supplied by Louisiana State University were analyzed by researchers at the Battelle Pacific Northwest Laboratory. The results are provided in Table 3.

Except for conveyor problems due to stringiness the sugar cane bagasse, served as well as sawdust or better throughout the system. The faster drying rate for bagasse is a favorable factor in view of the need to dry bagasse for storage of a year round supply. The more nearly complete combustion in the primary combustor as indicated by the lower wall temperature in the secondary combustor will result in longer life for the firebrick lining in that portion of the burner.

The higher than normal ash content for the sugar cane bagasse could have resulted from extended exposure of the material to the weather before its selection as sample material.

**TABLE 3. Elemental Analysis of Sugarcane And Sorghum Feedstock Samples
(wt%, as received)**

<u>Element</u>	<u>Sorghum Rind</u>	<u>Sorghum Pith</u>	<u>Sugar Cane Bagasse</u>
Carbon	44.8	44.0	42.6
Hydrogen	5.48	5.28	5.10
Nitrogen	1.28	0.83	0.59
Oxygen (a)	44.9	46.2	37.9
Calcium	0.215	0.145	0.882
Potassium	0.559	0.500	0.354
Potassium	0.559	0.500	0.354
Silicon	0.818	0.986	2.94
Magnesium	0.210	0.136	0.124
Sulfur	0.117	0.086	0.073
Iron	0.049	0.075	0.152
Aluminum	0.072	0.108	0.29
Phosphorus	0.093	0.070	0.034
Manganese	0.004	0.004	0.070
Sodium	0.008	0.012	0.098
Chromium	ND	0.002	0.007
Barium	0.002	0.007	0.004
Nickel	0.001	NO	0.005
Zinc	0.006	0.006	0.008
Boron	0.002	0.002	0.002
Titanium	0.007	0.012	0.015
Strontium	0.006	0.0005	0.003
Copper	0.002	0.002	0.002
moisture (by TGA)*	5.8	6.1	5.8
fixed carbon (b)	0.9	0.3	1.4
ash	3.5	3.7	13.8

ND = not detected

(a) by difference, $100 - (C+H+N+ash) = \text{Oxygen}$

(b) believed low due to suspected air leakage

* TGA = Thermogravimetric Analysis

8.0 DISCUSSION OF RESULTS

A discussion of the performance of system components and recommendations for changes in future systems follows.

8.1 SAWDUST DRIER AND CONVEYORS

The problem of mechanical failures on the drier and the problems encountered with rust on the perforated plate can be corrected by improved design. The current arrangement in which a blower pulls the turbine exhaust through the cyclone and dryer probably can be changed to eliminate the exhaust blower. The pressure from the turbine exhaust is adequate to move the gases through the dryer. A smaller blower will be needed to supply ambient air to mix with and cool the turbine exhaust gases before they enter the dryer.

With the difficulties encountered with auger conveyors as opposed to belt conveyors, it is recommended that belt conveyors be used where possible and that a pneumatic conveyor be used to move the dried fuel to the live bottom bin that meters the fuel to the rotary valves.

8.2 WOOD FEED AND ROTARY VALVES

There are at least two advantages provided by spring loaded high density nylon seals in the rotary valves. The first is that the seal can move and allow wood particles to pass across the sealing surface without cutting into and abrading it. The second is that there is no momentary excess load on the motor that drives the rotor due to particles wedging under the sealing surfaces.

Of the three valves now on the system, only two are carrying a pressure load. Due to heat transfer from the combustor to the bottom valve, plastic seals soften and fail. Graphite seals have proven ineffective. As a result, the bottom valve in the series of three serves only as a fire stop and heat shield for the valves above it. The main problem with the two upper valves has been equalizing the pressure drops across them. That is a function of the effectiveness of the seals and the diameters of the air vents in the valve casings. The approximate location of each air vent is shown in Figure 17.

Reliable long-term operation of the feed system should be a major goal of any future program.

8.3 COMBUSTION CHAMBER

The combustion chamber has functioned well. An excess of carbon monoxide which was detected in the exhaust gas analyses as reported by Battelle in Appendix C appears to have been caused by a large leak around the dome of the primary combustor. The leak has been eliminated, but further exhaust gas analyses have not been made. Continuous monitoring of carbon monoxide should be carried out on a commercial version.

8.4 CYCLONE FILTER

The initial decision to perform research on wood burning gas turbines was based on results obtained with coal by the Coal Utilization Research Laboratories at Leatherhead, England. In tests extending to 1000 hours in a coal fired system using cyclone filters there was no significant erosion or corrosion of blades. The inlet temperature to the blades was 1450°F. It was concluded that for wood fired gas turbines it might be necessary to restrict the turbine inlet temperature to 1450°F. Thus far there has been no evidence of corrosion or erosion of turbine blades after operation at 1450°F, indicating that cyclone is effectively removing abrasive particles.

8.5 T-56 GAS TURBINE

The major problem encountered with the turbine has been one of deposits from the inorganic constituents of wood ash forming on the turbine blades and other turbine components. After operation at 1450°F inlet temperature the blades are easily cleaned with milled walnut hulls or a high pressure water spray. After operation at turbine inlet temperatures much in excess of 1450°F, the deposits appear to sinter and the blades are much more difficult to clean. Therefore, it is anticipated that for the immediate future the inlet temperature will be restricted to 1450°F. To produce 3000 kw at 1450°F turbine inlet, either water or steam injection into the combustor will be required. The main difference in using water rather than steam is that the overall thermal efficiency is 4 to 6 points lower with water than it is if the

turbine exhaust is used to generate the steam. The use of steam or water reduces the effect of leakage from the compressor air side to the turbine gas side in the transition section since the water or steam is injected on the hot gas side.

In view of the possibility that it may be necessary to restrict the turbine inlet temperature to 1450°F, calculations were made to determine the effect of compressor and turbine efficiencies on overall thermal efficiency with changing turbine inlet temperature. The results are shown in Figure 19. The maximum turbine inlet temperature for continuous operation of the T-56 engine without turbine blade cooling is 1700°F. With restriction to 1450°F there is a difference of 3.6 points in gas turbine efficiency when operating with a compressor efficiency of 0.80 and turbine efficiency of 0.82. With an increase to 0.86 compressor efficiency and 0.88 turbine efficiency the difference drops to 2 points. As the turbine will last considerably longer at 1450°F, a loss of 2 points in efficiency could be a viable trade off for longer turbine life. From standpoint of the T-56 engine performance the loss in power output is a more significant factor. Figure 20 shows the air flow rates required to maintain 3000 kw at various compressor and turbine efficiencies over a range of turbine inlet temperatures. At an inlet temperature of 1450°F, compressor efficiency 0.82, and turbine efficiency 0.84, 53 lbs of air per second would be required compared to the normal 34 lbs per second required at an inlet temperature of 1700°F. Water or steam injection can make up the loss in power where water is available.

Because of the requirement for high power to weight ratios needed for aircraft engines, developers strive for high turbine inlet temperatures and high compressor pressure ratios that can be sustained for take off and short power bursts during military maneuvering. For sustained power at cruise conditions, the operational temperatures and pressure ratios in those engines are much lower. For stationary engines that must have long life for economical reasons, turbine inlet temperatures in the 1450° to 1500°F range are much more practical.

The assistance of personnel at Battelle PNL and Columbus was sought in attacking the deposition problem. Work by both laboratories, which is in the preliminary stage, points toward sulfur and potassium in the wood ash as the

FIGURE 19. Performance For Gas Turbines With 3000 Kw Output at 59°F And 29.92 In. Hg. Ambient With 10-1 Compression Ratio Over a Range of Temperature And Component Efficiencies.

FIGURE 20. Air Weight Flow Requirements For Gas Turbines With 3000 Kw Output at 59°F And 29.92 In. Hg. Ambient With 10-1 Compression Ratio Over a Range of Temperature And Component Efficiencies.

main culprits. Results of particle analysis work by PNL are presented in Appendix D and combustion research results with fuel additives by Battelle Columbus in Appendix E. The possibility of eliminating deposits by adding lime to the fuel is encouraging. The importance of the work should not be underestimated due to its having been placed in the Appendix. That placement affords an easy identification of the researchers and their approaches toward solving the problem.

Aside from the problems caused by the turbine blade deposits, the main problems are oil leakage into the compressor and air leakage into the turbine. It would not be good industrial practice to require continued use of the compressor water wash after warm up to clear leaked oil from the compressor in future installations. To avoid the requirement, the engine manufacturer can replace the labyrinth seal with a positive seal.

Air leakage into the turbine from the compressor at the transition section delivery ducts and at openings in the stators in the amount of approximately 5.3 lbs/sec reduces the engine output available for a given turbine inlet temperature. For example, the turbine inlet temperature must currently be restricted to 1450 F to prevent hardening of the deposits on the stator and turbine blades. With leakage through the delivery ducts and leakage into the downstream stages, the effective turbine inlet temperature is reduced. As shown in Table 2 the exhaust gas temperature of 665 F corresponds to a turbine inlet temperature of 1273 F rather than the measured temperature of 1387 F entering the engine. A new design configuration for the transition section, that eliminates the leakage, has been prepared and is ready for implementation.

8.6 STARTING SYSTEM

The synchronous generator in the present system does not have amortisseur windings that allow impressing full line voltage on the field for start up while using the generator as a motor. Westinghouse engineering advised use of 1000 volts maximum on the field. Transformers supplying 830 volts were installed for that purpose. Newly built generators will need to be equipped with amortisseur windings.

The oil trim required with an automatic speed control which is currently used for synchronizing the system to lock into the power-grid would not be necessary with use of an automatic synchronizing relay. The action of the synchronism check relay now in use is not rapid enough to compensate for the imprecise control of speed with wood alone.

9.0 CONCLUSIONS

1. It has been demonstrated that an Allison T-56 gas turbine can be successfully operated on biomass and deliver power to a public utility.
2. Operation at the target turbine inlet temperature of 1450°F was achieved.
3. The power output at 1450°F turbine inlet temperature can be significantly increased by injection of water or steam, but the water must be treated for this use.
4. Emissions from the system meet EPA requirements for gas turbines.
5. The use of lime or other additives shows promise of reducing or eliminating the deposits on the turbine blades.
6. Tests with sugar cane bagasse show it to be equal or superior to sawdust as a fuel for gas turbines.
7. Programming of an automatic control system for start up, operation and shut down is needed for commercialization.
8. The system is ready for development of a commercial version.

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APPENDIX A

MONTH BY MONTH LOG OF EVENTS ON
OPERATION OF THE T-56 GAS TURBINE SYSTEM

APPENDIX A

MONTH BY MONTH LOG OF EVENTS ON OPERATION OF THE T-56 GAS TURBINE SYSTEM

1985

- January - Operated 3000 kw system at low speed with propane gas. Retrofitted Air Force T-56 engine for backup use. TVA Contract modified for use of TVA grid power for starting.
- February - System was operated with wood to check out full system including dryer - System awaiting installation of reverse metering by TVA.
- March - Modification of spare rotary valve completed. Continued work on Air Force Engine - ARC designed center section 90 percent complete.
- April - Reverse metering installed and power applied to generator operating as motor. Gas turbine run at 11,000 rpm.
- May - The system was severely overheated by sawdust piled on the floor of the primary combustor. The system was repaired and put back in service using the Air Force engine.
- June - The system was operated with the Air Force T-56 engine at speeds up to 13,845 rpm but speed could not be increased because of insufficient wood feed.
- July - System was run with variations in the rotary valve feeder which feeds sawdust into the combustor at 130-150 psi.
- August - System was operated at rated speed for 35 minutes. During shut down the first oil fire in the compressor partially melted stages 5 through 9 of compressor blades. The fire was caused by oil which leaked into the compressor through the front compressor oil seal. Work on a 16-inch rotary valve continued. Power was generated in the induction mode.
- September - 16-inch rotary valve feeders being installed.
- October - 16-inch rotary valve feeder and newly overhauled compressor installed.
- November - Overhauled compressor bearing failed due to lack of oil. (Overhauler failed to provide orifice for oil flow to rear compressor bearing). Backup rotary valve with 12 vanes being constructed. (Previous valves used 8 vanes.)

December - Rupture disk actuated prematurely and damaged the combustor outlet dome due to sudden decompression. The system had accumulated 140 hours of operation at all engine speeds.

1986

January - Turbine blades failed on the T-56 gas turbine. New rupture disk configuration installed.

February - Allison 501 KG engine repaired and reinstalled. Fire at tenth stage damaged the compressor. Indication that turbine inlet temperatures above 1450 F may be a problem.

March - Study of blade cleaning. Newly overhauled T-56 turbine ready for installation.

April - Repaired turbine installed and tested with ports in bottom valves of 5th and 10th stage in attempt to prevent compressor fires. Speed control being installed.

May - Ran system at synchronous speed using new control for synchronization. Openings in cyclone causing hot spots. Continued problems with fibrous seals in rotary valves.

June - Hard coating of ash above 1450 F turbine inlet temperature. Problems with cyclone overheating. Life of rotary valve seals in question.

July - Repaired cyclone ready for installation. Springs installed in combustor inlet and outlet bonnets. Installed additional oil coolers. Ceramic coatings tested on stators.

August - Installed repaired cyclone. Ceramic coating eroded away in three hours of operation. Installed second turbine from Air Force.

September - Exterior burner section redesigned and fabrication started. Operation on line for 17 hours. Tests at 1400, 1450, 1550, 1650 for three hours duration. Ran with water injection. Water injection a viable augmentation measure.

October - Small problem with controls.

November - Changes in external combustor midsection to reduce internal bypassing of compressor air completed. Problems encountered with getting on line.

December - Capped outlet stack to provide higher pressure across dryer. Only 12 minutes required to get on line after supplying current to Generator. New transition section greatly reduces temperature drop. Estimate 43 gpm of water required to produce 2800 kw of

power. Problems with dryer. More tests of packing material in valves without success.

1987

- January - Design and initiation of fabrication of new rotary valve with all metal seals. 29 accumulated hours on line.
- February - New Valve 90% complete. Dryer becoming decreasingly effective. Holes require opening in perforated plate. Emissions report received from Battelle. 38 hours on line.
- March - Sawdust containing 35-45% moisture was tested in the system with result that excessive slagging occurred in the secondary combustor. 464 accumulated hours on wood. Revised rotary valve with metallic seals were tested and modified. 24 hour intervals for turbine cleaning determined. 55 accumulated hours on line. Pressure applied to prevent erosion of valves in ash lock hoppers. Turbine partially disassembled for cleaning by scraping after 179 accumulated hours on wood.
- April - Air Force Engine compressor blade seals failed causing compressor to surge. Blade cleaning program started with water-blast system setup at Roanoke. 62.5 accumulated hours on line.
- May - Casing of T-56 Engine Compressor removed to determine cause of low pressure - stator seals crumbled away. Blade cleaning program proceeding according to plan. 400 accumulated hours on wood. 62.5 accumulated hours on line.
- June - 16.5 hours on metal seals of rotary valve without failure. Air Force engine no longer operable. Series II engine supplied by Navy. Air Force engine being modified at Roanoke. Water wash system being fabricated. Tests run on hot stators quenched with water.
- July - Trailer dumper for unloading trailer loads of sawdust being fabricated in Roanoke. Navy T-56-A-426 Engine installed at Red Boiling Springs - Run for 9.5 hours. Fabrication of waterblast cleaning system almost complete. Wood sample analysis furnished by PNL. 71.5 accumulated hours running on wood.
- August - Near disastrous explosion in T-56 engine supplied by Navy. Trailer dumper installed. System damage incurred by explosion being repaired. Second Air Force Engine being repaired at Roanoke.
- September - Compressor Fire problem assessed - Fire extinguishing system needed. Dump valves moved away from engine. Second Air Force Engine delivered to Red Boiling Springs. 509 hours on wood. 72.5 total hours on line.

- October - Navy supplied gas turbine which exploded disassembled and inspected at Roanoke. Metal in compressor tie bolt had fatigued and failed at final thread on the bolt. Dye on partial fracture showed crack had been missed on preassembly inspection.
- November - Completed installation of second Air Force engine at Red Boiling Springs and finished repair of damage to the remainder of the system. Prepared fire extinguishing system for installation. Further evaluation of water spray blade cleaning system. Study of possible new insulating techniques for cyclone and piping.
- December - Operated repaired T-56 Air Force Engine. Determined that compressor was too worn for use. Spare compressor requested from Air Force. Fire extinguisher system installed. Installed rotary valve with metallic seals.

1988

- January - Attempted repairs on compressor of second Air Force T-56 engine unsuccessful. Air Force gave notice of shipment of spare engine parts.
- February - Spare engine parts received from Air Force. Compressor being prepared for replacement on engine at Red Boiling Springs.
- March - Replaced compressor on second Air Force engine with one received from Air Force. Analysis of blade deposits by PNL indicates potassium sulfate is major contributor to turbine blade deposition. Corrective measures studied. Instituted water wash of compressor after warm up to prevent compressor fires caused by oil leakage through labyrinth seals. Also instituted practice of dumping compressor air through all four of the two-inch ball valves immediately upon shut down to prevent surge. Rupture disk removed from system. The contract with PNL-DOE ends March 31.
- April - Wear on rotary valve metallic seals indicates that they will not be satisfactory - other sealing methods being studied. Further testing of water spray cleaning method partially successful.
- May 1988 - Testing of system with modified rotary valves using spring
to activated nylon seals -- most successful to date. Testing with
May 1989 fuels from different mills and upgrading of drier occupied most of time. Water injection tests showed that the particle fall out from untreated water cannot be collected in the cyclone. Deionizing of water will be required.

APPENDIX B

RESULTS OF EMISSIONS MEASUREMENTS FOR
GARRETT IE831-200 GAS TURBINE OPERATING ON WOOD AND PROPANE

5050 DEER CREEK ROAD
COLUMBUS, OHIO 43260
TELEPHONE (614) 488-6224
FAX (614) 488-6224

January 12, 1983

Mr. Gary Schiefelbein
Pacific Northwest Laboratories
Battelle Boulevard
Richland, Washington 99352

Dear Gary:

Revision of September 9, 1982 Letter

This letter report will serve to summarize the results of the wood combustion emissions measurements taken at the Aerospace Research Corporation facility in Roanoke, Virginia during the week of August 23, 1982. Joe Hamrick and his associates were very cooperative during the measurement program, in providing access ports and support as requested.

Conclusions

The Andersen impactor data show that 80-90 percent of the particle mass is less than 0.5 μm in dia. Results show that the particulate loading entering the turbine for all three runs is in the range of 0.004 to 0.006 gr/dscf.

Objective and Procedure

The objective of the emission measurements was to determine the mass concentration and particle size distribution of the particulate wood combustion products entering the gas turbine.

Figure 1 shows the flow schematic of the wood combustor and sampling system used for these measurements. The system pressure was used to push the gas sample through stainless tubing nominally 0.5 inch in diameter and approximately 15 ft long. The gas temperature in the sample line was maintained above the dew point (about 350 F) by bleeding a portion of the stream withdrawn through this tubing to the atmosphere. Due to the relatively low flow through the impactor, it was heated with electric tape to maintain temperatures at ~ 350 F. The gas was then passed through condensers at approximately 32 F and then the volume was measured with a test gas meter and an orifice with associated manometer. Because the impactor could not be operated at the duct pressure, a flow control valve was used upstream of the impactor. Table 1 shows the turbine operating conditions during the sampling period. Although maximum values are tabulated, these variables remained relatively stable during the sampling periods. The fuel being burned was bark-free yellow pine saw dust, purchased locally.

FIGURE 1. SCHEMATIC DIAGRAM OF SAMPLING SYSTEM
USED FOR PARTICULATE LOADING MEASUREMENTS

TABLE 1. TURBINE OPERATING CONDITIONS

Fuel: Bark-free yellow pine sawdust

	Run #1	Run #3	Run #4
Turbine Inlet temp. (upper) F	1481	1408	1507
Turbine Inlet pressure, psig	27.1	42.1	24.0
Engine Speed, rmp	29,540	34,320	28,080

Maximum Aerospace recorded turbine operational data obtained during sampling period. These values remained relatively stable during the sampling periods.

Table 2 is a summary of the data obtained for 3 runs. Run #2, as indicated, was not used due to insufficient sample volume. Run #1 is a mass measurement test, used to determine the approximate length of time necessary to obtain suitable measureable mass on the stages using the Andersen cascade impactor. The sampling rate for Run #1 was 2.35 acfm at ambient conditions as opposed to a nominal sampling flow rate of 0.5 to 0.7 acfm through the impactor. The data from Runs 3 and 4, then, have been used to determine this size consist of particulates in the combustion product stream entering the turbine. Figure 2 shows the size distribution and is plotted as percent of mass greater than the stated size in micrometers.

An attempt was made to determine the mass and particle size of the solids in the combustion products entering the 1st cyclone. However, the sample probe was plugged. It appeared that combustion was not entirely completed at the 1st cyclone inlet. Relatively large hot embers were observed blowing out of the sample probe during an attempt to unplug the probe. Sampling at this point in the system was terminated, then, due to the inability to maintain gas flow due to the plugging.

The possibility of losing some of the particulate via thermal deposition on the sample line wall was considered. Theoretical calculations were made using average sample line wall temperatures and velocities to determine order of magnitude losses that may occur. Table 3 shows that at a temperature differential of ~ 800 F using a 15 ft long 0.5 inch dia sample probe one could lose by thermal deposition as much as 50 percent of the sampled particulate at a sampling rate of 0.2 scfm for 0.5 μ m particles. The loss drops to 24 percent at 0.5 scfm.

TABLE 3. THEORETICAL WALL LOSSES

Particle Size, μ m	Flow Rate, scfm	Percent loss
0.5	0.2	49.9
	0.5	23.9
5.0	0.2	30.5
	0.5	13.7
Conditions: 0.5 dia probe, 15 ft long 800 F differential at 30 psig		

TABLE 2. SAMPLING DATA

Date	8-24	8-25	8-26
Run No.	1	3	4
Clock Time	1344-1517	1200-1434	1332-1718
Sample time, min.	93	154	226
Sample vol., dcf	220.7	72.4	110.8
Gas meter temp., F	106	92	83
Bar. press., in. Hg	29.15	28.90	29.20
Condensate, grams	204.4	50.0	133.0
Sample vol., dscf	201.2	67.1	105.5
Sample rate, dscfm	2.19	0.43	0.46
Stack gas moisture, percent	8.6	10.1	9.8
Stack gas pressure, psig	26	45	26
Particulate collected, mg	82.0	18.0	29.0
Particulate conc., gr/dscf	0.006	0.004	0.004
mg/Nm ³	13.9	9.3	9.3

ARC operational problems resulted in insufficient sample collection to obtain mass determination for Run #2.

FIGURE 2. SIZE DISTRIBUTION OF SUSPENDED PARTICLES

Flow rates for Runs 1, 3 and 4 are listed in Table 2 as 2.19, 0.43 and 0.46 dry standard cubic ft respectively. Therefore, based on the data presented in Table 3 it appears that at most 24% of the material sampled could have been lost to the walls.

Operational limitations on site required that the sample pressure be reduced before the sample entered the cascade impactor. The consensus of Battelle's particle dynamics specialists was that particle break up and alteration in passing through the throttling valve would not be significant. In future measurements, however, it is recommended that the particulate sample be obtained with the impactor operating at stream pressure to avoid this possible source of error. The cut-off size for each impactor stage must then be corrected for density effects.

Recommendations

It is recommended that in the planned continued operations of the turbine several variables be investigated to determine their effects on mass concentrations and size distributions of the resulting suspended particles entering the turbine. The variables of interest are:

- size of fuel particles entering combustor
- moisture content of wood fuel
- fuel firing rate (go to full turbine rating if possible)
- specie of wood (at least one hard wood to be included).

Inclusion of these variables into the continuing test program should have minimal effect on the costs of continued operation of the unit.

In any subsequent measurements of particle size and loading, it is recommended that the sampling program be modified to include:

- dilution cooled sample, or the use of a high-temperature impactor
- shorter sampling line for the impactor, to minimize the line losses
- impactor operation at the elevated pressure in the turbine inlet duct, to eliminate possible particle break up in the throttling valve
- measurement of particle loading leaving the complete unit, including any device applied downstream of the turbine.

Mr. Gary Schiefelbein
Pacific Northwest Laboratories

8

January 12, 1983

Summary

The low particle mass loading and small particle sizes observed in these brief tests indicate the turbine erosion may be less of a problem than had been anticipated. A reasonable rough rule-of-thumb objective of mass loadings (<5 ppm of particles >5 μm) has apparently been met. If these particulate loadings can be maintained at full turbine power with a variety of wood fuels, the erosion should be low. No measurements were made relative to the ash metal deposition and possible corrosion effects within the turbine.

Yours very truly,

Paul R. Webb
Fuels and Combustion Section

PRW:jeb

xc: Joe Hamrick
S. Friedrich

APPENDIX C

RESULTS OF EMISSIONS MEASUREMENTS FOR
ALLISON T-56 GAS TURBINE OPERATING ON WOOD

TOPICAL REPORT

ILA B-M8155-A-K

on

WOOD-FIRED TURBINE EMISSIONS MEASUREMENTS

to

PACIFIC NORTHWEST LABORATORIES
Richland, Washington

January 20, 1987

by

Paul R. Webb

BATTELLE
Columbus Division
505 King Avenue
Columbus, Ohio 43201

TOPICAL REPORT
on
WOOD-FIRED TURBINE EMISSIONS MEASUREMENTS
to
PACIFIC NORTHWEST LABORATORIES
January 20, 1987

SUMMARY

Particulate mass, particle size distribution, and gaseous emissions were measured from the wood combustor-turbine system at the Red Boiling Springs facility during the week of December 15, 1986. The facility operating log indicated that the combustor was operating at 2800 lbs per hour of mixed oak and poplar with bark containing about 20 percent water. Total mass throughput of the turbine was 126,000 lb/hr. The fuel heat input is calculated at 19.52×10^6 Btu/hr based on 6970 Btu/lb. Particulate mass entering the turbine is 0.017 gr/dscf with 77.5 percent of the particles being less than $1.2 \mu\text{m}$; 100 percent being less than $2.6 \mu\text{m}$. Gaseous emission measurements indicated significantly high CO levels ($8.8 \text{ lb}/10^6 \text{ Btu}$) indicating possibly poor mixing during combustion. NO_x and SO_2 levels are relatively high (0.36 and 0.93 lb per 10^6 Btu , respectively, but are within Federal EPA limits⁽¹⁾, 0.7 and $1.2 \text{ lb}/10^6 \text{ Btu}$, respectively.

Background

The wood-fired gas turbine receives its energy from the combustion of wood chips, including bark, which is trucked into the Red Boiling Springs facility. The as-received wood has about 45 percent moisture. About 15-20 percent of the combustion gas leaving the gas turbine is used to dry the wood chips to about 15 percent moisture. The compressor

section of the turbine is initially driven by an internal combustion engine to develop sufficient combustion air pressure to operate the wood combustor. After sufficient temperature increase, the internal combustion engine is shut down and the system is self contained solely from the exhaust gases of the wood combustor. One cyclone is used to remove ash from the hot gas before entering the turbine. The operating conditions, supplied by Mr. Joseph Hamrich of Aerospace Research Corporation, are as follows:

Wood Feed Rate	2800 lb/hr
Wood Moisture	~ 20 percent
Wood Type	Approximately 50 percent each of Oak and Poplar with bark
Turbine Inlet Temp., F	1350 - 1400 F
Turbine pressure	115 - 120 psig
Mass throughput	35 lb per second.

Sampling Equipment

The sampling equipment used for collecting ash for mass determination was a 47 mm stainless steel filter holder. The filter material was fiberglass which had been cut to fit the filter holder, desiccated, and weighed prior to collecting the ash sample. The filter holder was connected to a 0.5 inch diameter stainless steel tube 24 inches long which was inserted into the stack through a packing gland and gate valve. Figure 1 is a flow diagram showing the sampling location and geometry of the wood combustor. The gas flow rate through the filter was controlled to maintain the filter temperature above the dew point of water. The gas was then passed through glass condensers at 32 F to remove the water before passing through a dry gas meter for volume determination. The inlet and outlet temperature of the gas meter was monitored so that gas volumes could be corrected to standard conditions of 70 F and 29.92 inches of Hg.

FIGURE 1 FLOW DIAGRAM OF WOOD COMBUSTOR AND GAS SAMPLING SYSTEM USED FOR PARTICULATE AND GASEOUS EMISSION MEASUREMENTS

Sampling for particle size distribution incorporated an Andersen impactor which was placed in a pressure vessel. The 47 mm stainless filter was removed from the system and replaced with the Andersen impactor. The pressure vessel is equipped with a pressure gage, thermocouples, and valves. The combustion gases are allowed to vent to the atmosphere prior to sampling. This allows the impactor to reach a temperature which is above the dew point of water so that condensation, which could alter the size distribution, will not occur during particle sampling. The impactor body temperature is measured independent of the gas temperature. The particles which enter the impactor are collected on pre-weighed filter media which are then desiccated and reweighed to determine the mass collected on each stage. There are seven stages of impaction plus a back-up filter. The size distribution is a function of actual cubic feet per minute through the impactor which is a function of the impactor gas temperature and pressure.

The combustion gases were sampled to determine concentration of NO_x , THC, SO_2 , O_2 , CO_2 , and CO. The following is a list of the analyzers used for these measurements:

Beckman Model 402	Total Hydrocarbons
Beckman Model 955	Nitrogen Oxides
Teledyne	Oxygen
Horiba Model PIR-2000	Carbon Monoxide
Horiba Model PIR-2000	Carbon Dioxide
Horiba Model PIR-2000	Sulfur Dioxide.

The instruments were calibrated with standard calibration gases before and after emission sampling.

The system pressure was used to push the combustion gases through a 47 mm absolute filter to remove particulate. The gases then passed through a heated Teflon sample line which was controlled to 300 F for the determination of NO_x and THC's. A needle valve was used to control the flow to maintain gas temperature to the Teflon® sample line at 250-300 F.

Combustion emissions were also measured from the outlet of the wood dryer. A vacuum pump was used to draw a sample from the dis-

charge duct of the dryer. The gas then passed through the gas monitoring system for determination of NO_x, THC, CO, CO₂, O₂, and SO₂.

Gaseous Emissions

Table 1 shows gaseous emissions data from the turbine inlet and the wood combustor outlet.

Table 1. Combustion Gas Composition

	NO _x	THC	SO ₂	CO	O ₂	CO ₂
	PPM				Percent	
Turbine Inlet	35	15	65	1300	19.5	3.0
Wood Dryer Outlet	20	65	65	1400	20.5	2.0
	lb/hr					
Turbine Inlet(a)	6.0	0.84	15.5	135.3		
Wood Dryer Outlet(b)	0.6	0.70	2.7	25.7		
Total Emissions	6.6	1.54	18.2	161.0		
Wood-Burning Boiler(c)(1)	54.1	21.7	3.0	79.2		
	lb/10 ⁶ Btu					
Total Emissions	0.34	0.08	0.93	8.3		
Federal EPA(2)	0.70	--	1.20			
Wood Burning(c) Boiler(1)	0.15	0.06	0.01	0.96		

(a) Based on 85 percent of mass vented to atmosphere from turbine exit, lb/hr

(b) Based on 15 percent of mass passing through wood dryer to atmosphere, lb/hr

A report by the Proctor and Gamble Company on emission from a wood-burning boiler⁽¹⁾ has been used for comparison with the Red Boiling Springs data. The SO₂ emissions are significantly higher than that reported by Proctor and Gamble (P&G). The sulfur content of wood is known to vary, but these data are higher than what one would expect, although they do fall within the EPA guideline of 1.2 lb per 10⁶ Btu. NO_x is also a factor of 2 higher than P&G's results on a lb per 10⁶ Btu basis. This may be attributable to firing conditions and related temperatures in the combustion zone. CO is also high and may also be related to poor mixing in the combustor.

Particulate Emissions

Particulate emissions as shown in Table 2 ranged from 0.0151 gr/dscf to 0.0173 gr/dscf. These emissions are about half of the mass concentrations found during the test performed at the Roanoke facility made in October of 1984. This may be attributable to different firing rates and different fuels.

The particle size data shown in Table 3 are similar to those data obtained from the Roanoke facility. As indicated, 77.5 percent of the particles on a mass basis were less than 1.2 μ m.

The rule-of-thumb guidelines of less than 5 ppm of particles greater than 5 μ m for turbine application is still being met. However, based on EPA emission factors from the literature survey⁽²⁾, particulate emissions are still a factor of 2 high; 0.1 lb per 10⁶ Btu compared to Red Boiling Springs data of 0.22 lb per 10⁶ Btu.

After the sampling was completed, the sample probe was removed from the stack. A very distinct deposit was observed on the probe in line with the gas flow. A photograph of this deposit is presented as Figure 2. This deposit is similar to deposits found on superheater tubes in coal-fired boilers. Figure 3, which is a copy of a page from

Table 2. Sampling Data

	12-19	Date 12-19	12-19
Run No.	1	2	3
Clock Time	1115-1140	1158-1230	1237-1306
Sample Time, min.	25	32	29
Gas Meter Temp., F	48	53	58
Bar Press in. Hg	29.48	29.48	29.48
Condensate, grams	13.6	21.9	23.5
Sample Vol., dscf	24.41	27.64	33.68
Stack Moisture, percent	2.6	3.6	3.2
Stack Pressure, psig	118	118	118
Total Particulate Mass Collected, mg	27.5	27.1	37.4
Particulate Conc.			
gr/dscf	.0173	.0151	.0171
ppm	33	29	33
lbs per hour	4.2	3.7	4.2
lbs per 10 ⁶ Btu	0.22	0.19	0.22

Table 3. Size Distribution

Conditions: 0.16 acfm, 300 F, 118 psig				
Stage	mg	percent	Cumm percent	μm
5	1.3	4.8	100.0	2.6
6	2.7	10.0	95.2	1.6
7	2.1	7.7	85.2	1.2
Filter	21.0	77.5		

"Steam", shows a boiler tube deposit along with an elemental analysis. It is suggested that the deposit found on the Red Boiling Springs sample probe be analyzed for potential corrosive materials and to determine what ash components may be causing the deposition. It can be assumed that the deposit found on the sample probe will also deposit on the stationary blades of the turbine. Although the mass of the particles are sub-micron, diffusion is apparently taking place which is allowing deposit accumulation. This accumulation, depending on the composition may cause corrosion when operating on a relatively long-term basis. Break-away of the deposit may also cause an out-of-balance condition and create excessive turbine vibration and/or blade damage.

Noise Measurements

A General Radio Model 1945 Community Noise analyzer was taken to Red Boiling Springs to monitor the noise level. A General Radio sound level calibrator was used to calibrate the Community Noise Analyzer. Calibration specifications from the analyzer were not obtainable. A set of data were taken with and without the turbine in operation,

FIGURE 2

Fig. 25 Transverse sections of corroded tubes from secondary superheater platens.

temperature alloys and until methods are developed for avoiding corrosion at higher steam temperatures.

General characteristics of corrosion

External corrosion of superheaters and reheaters is concentrated on the upstream side of the tube, as shown in Fig. 25. The greatest metal loss usually occurs on the 10 and 2 o'clock sectors of the tubes and it tapers off to little or none on the back side of the tubes. The corroded surface of the tube is highly sculptured by a shallow macropitting type of attack. The amount of corrosion, as measured by reduction in tube wall thickness, varies considerably along the length of the tube, depending on local conditions, i.e., the position of the tube in the bank or platen, the proximity of sootblowers, the composition of ash deposits and, most importantly, the gas and metal temperatures.

The corrosion rate is a nonlinear function of metal temperature (Fig. 26). The corrosion of both chrome-ferritic and 18Cr-8Ni stainless steels increases sharply above a temperature of 1150F, passes through a broad maximum between 1250 and 1350F, and then decreases rapidly at still higher temperatures.

The highest corrosion rates are generally found on the outlet tubes of radiant superheater or reheater platens opposite retractable sootblowers. Values ranging from 50 to 250 mils/year have been observed on 18Cr-8Ni stainless steel tubes under these adverse conditions.

Fig. 26 Effect of temperature on corrosion rate.

When similar high-temperature surfaces (1100-1175F) are arranged in convection tube banks so they are shielded from direct furnace radiation and sootblower action, corrosion rates are much lower, ranging between 5 and 20 mils/year.

Corrosive ash deposits

Corrosion is rarely found on superheater or reheater tubes having only dusty deposits. It is nearly always associated with sintered or slag-type deposits that are strongly bonded to the tubes. Such deposits consist of at least three distinct layers. The outer layer, shown diagrammatically in Fig. 27, constitutes the bulk of the deposit and has an elemental composition similar to that of fly ash. Though often hard and brittle, this layer is a porous structure through which gases may diffuse. Innocuous by itself, it plays an important part in the formation of an intermediate layer that contains the corrosive agents.

The intermediate layer, frequently called the white layer, is a white-to-yellow colored material which varies in thickness from $\frac{1}{32}$ to $\frac{1}{4}$ in. It usually has a chalky texture where corrosion is mild or nonexistent but is fused and semi-glossy where corrosion is severe. In the latter condition this layer is difficult to remove as it is so firmly bonded to the corroded surface beneath.

Upon heating in air, the intermediate layer melts around 1000F and slowly discolors and hardens into a hard mass resembling rust. Chemical analyses of this layer show that it contains higher concentrations of potassium, sodium and sulfur than does the parent coal

Fig. 27 Analyses of typical ash deposit from 18Cr-8Ni superheater tube.

but the situation was discussed with BCD's acoustic engineer and the data were deemed unusable due to a probable bad microphone on the analyzer. The analyzer is a relatively simple device to use and the sound level noise data could be obtained during any future trip to the facility.

Conclusion

The mass loading and particle size are acceptable for turbine application, however, particulate accumulation is still a major problem for long-term operation. Particulate emissions exceed Federal EPA regulations. The gaseous emissions for NO_x and SO_2 are less than Federal EPA emission standards, although SO_2 is higher than expected. CO emissions are very high and need to be reduced.

Recommendations

It is recommended that the deposit which was collected on the sample probe be analyzed for any potential corrosive materials. Additional tests to characterize the wood ash will help understand the deposits on the turbine blades and lead to combustion system improvements to overcome this problem as well as identify and provide solutions for potential problems as fuel sources, and thus, ash constituents vary in the future. The relatively high CO could be reduced by better mixing of the fuel and combustion air.

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APPENDIX D

ANALYSIS OF WOOD FUEL AND TURBINE DEPOSITS

APPENDIX D

ANALYSIS OF WOOD FUEL AND TURBINE DEPOSITS

Prepared by G. F. Schiefelbein and Associates
Pacific Northwest Laboratory

Early in 1986, after short periods of continuous operation of the T-56 turbine at Red Boiling Springs on sawdust fuel, it became apparent that hard deposits were forming on the blades and other turbine components, particularly if the turbine was operated at inlet temperatures above 1450°F. A study of possible turbine blade cleaning methods was initiated and a series of samples representing the sawdust fuel, combustion ash removed by the cyclone and turbine blade deposits were taken and sent to Pacific Northwest Laboratory (PNL) for analysis. The results of these analyses are discussed later.

Later in 1986, after the facility had achieved a degree of operational stability, personnel from Battelle Columbus Division performed on-site emissions measurements at the facility (Appendix C). The results of the emissions measurements indicated that the cyclone continued to provide effective particulate removal. The total particulate mass entering the turbine was found to be 0.017 gr/dscf with 77.5 percent of the particles being less than 1.2 μm and 100 percent being less than 2.6 μm . However, two results of these tests were unusual. First, relatively high levels of sulfur dioxide (SO_2) were measured in the cyclone off-gas stream to the turbine. The SO_2 level was higher than could be accounted for by the sulfur present in the wood. Second, during the emission tests performed by Battelle, a deposit formed on the sample probe used to obtain the gas samples. No deposit formation had occurred during similar sampling operations performed on the IEB31-200 turbine system four years earlier.

Spark source mass spectrographic analysis of the probe deposit by Battelle determined that the major components were potassium and calcium with smaller amounts of magnesium, aluminum and sulfur present. Table D.1 shows the results of an analysis performed by PNL on a "grab sample" of sawdust fuel

microanalytical instrument (CHN analyzer); ash was determined by heating the sample at 750°C in a muffle furnace; trace inorganic constituents of the ash were determined by inductively coupled plasma-atomic emission spectrometry (ICP-AES). The results of the analysis are fairly typical of that expected for a hardwood fuel. The distribution of carbon, hydrogen, nitrogen and oxygen is typical of a woody material. The ash level is slightly higher than is typically reported for wood. The values for sulfur and other trace elements are in the range expected for a hard wood. The sulfur level found in the wood does not explain the relatively high level of sulfur dioxide found by Battelle during emissions measurements. An x-ray diffraction analysis of the wood showed little evidence of crystalline material and there was no evidence of the potassium sulfate or calcium carbonate found in the analysis of the first turbine blade deposit sample (Table D.4). Apparently, these materials do not exist as such in the wood samples but form later during or after the combustion process.

Based on Battelle's emission measurements, 18.1 lb of SO₂ was released from the wood combustion system while burning 2800 lb/hr of wood containing 20% moisture. In order to generate this amount of sulfur dioxide, assuming all the sulfur was converted to the gaseous phase, the wood feed would have had to contain about 0.4 wt% sulfur. This was approximately 20 times more than was found in the analysis of the "RBS wood" sample.

In an effort to determine the source of the high sulfur values, a series of samples of input materials to the process were taken and sent to PNL for analysis. The results of these analyses are shown in Table D.2. The first three columns represent analyses of sawdust from three different suppliers to the facility. The next three columns represent samples taken from the sawdust storage pile, dried sawdust and the dryer fines stream. A sample of Virginia pine similar to that used in the initial tests with the IE831-200 turbine was included to determine if there were any differences in elemental composition between the Virginia pine and the Tennessee hardwoods that could account for the deposition taking place at Red Boiling Springs. Analyses were also performed on samples of the fuel oil used for heating and "trim control" during startup and the original "RBS wood" shown in Table D.1.

From the data shown in Table D.2, it is apparent that the fuel oil has a much higher sulfur content than the wood samples. The sulfur content of the fuel oil could account for the high levels of SO_2 encountered during Battelle's emission measurements. While fuel oil was not being burned at the time the emission measurements were made, SO_2 may absorb on surfaces of the system during startup and gradually desorb during periods of operation on wood fuel.

It is also apparent from the data in Table D.2 that there are marked differences between the Virginia pine and Tennessee hardwoods in both silicon and alkali content. The alkali (potassium and calcium) content of the hardwoods is two to five times greater than that of the pine. The samples exhibit a wide range of silicon content. The silicon content of the sample labeled "Green Dust From Storage" may be an anomaly since it is much higher than any of the other samples.

Comparisons of the elemental composition of the "RBS wood", ash collected in the cyclone and several turbine deposits are shown in Table D.3. The samples were collected during different periods, so it is not possible to perform an elemental material balance using them. However, a couple of observations are readily apparent. First, except for sulfur, the elemental composition of the ash collected in the cyclone is generally consistent with that of the wood feed. Second, the values for sulfur and potassium found in the turbine deposits are much higher than found in the wood feed or cyclone ash. A selective migration of these materials through the system appears to be taking place. Whether these materials transfer through the system in a volatile form or as very small particles is open to speculation. The mechanism of transfer is certainly a subject worthy of further investigation.

It is also interesting to note that the sulfur content of the deposits appears to be decreasing with time. The reason for this is not known. Possibly, sulfur was absorbed on the walls of the system during periods of heavy fuel oil use during initial "shakedown" activities and has gradually desorbed during subsequent operations on wood.

In Table D.4, brief discussions of the results of x-ray diffraction analysis on three of the turbine deposit samples are presented. This

analytical technique is useful for determining the molecular composition of the crystalline phases of the samples. Relatively small portions (less than 30%) of the deposit samples were crystalline in nature, the bulk of the samples being amorphous. In the first deposit sample taken (9/86), potassium sulfate represented approximately 60% of the crystalline phase; the balance being predominately calcium carbonate. The crystalline phase of the second deposit sample taken (04/87) contained approximately 50% potassium sulfate, 30% fairchildite and 20% calcium carbonate. The crystalline phase of the third deposit sample taken (7/88) consisted of 50-60% calcium carbonate, 20-30% potassium sulfate and 10-20% spurrite. The shift in relative concentrations of potassium and calcium in the crystalline phase of third sample, compared to the two previous samples, is consistent with the elemental analysis data shown in Table D.3. Calcium has replaced potassium as the most abundant element present in the third deposit sample when compared to the two previous samples. The sulfur content is also lower in the third sample.

BENCH SCALE COMBUSTION STUDIES

The deposit analyses discussed above represent, at best, an initial attempt to define the turbine deposition problem encountered at the Red Boiling Springs facility. The results of the few samples analyzed raise more questions than they answer.

- What is the mechanism for the apparent selective migration of sulfur and potassium through the cyclone to the turbine?
- Are these species transported as solid or liquid aerosols or in the vapor state? Studies of the combustion of peat indicate that the concentration of vapor-phase alkali metals present in the flue gas is strongly dependent on both operating temperature and pressure as well as chlorine content of the feedstock (A).
- Are the K_2SO_4 and $CaCO_3$ found in all the turbine deposits transported as such or are these compounds formed by elemental reactions on surfaces within the turbine?
- Is deposit formation a function of potassium and calcium content and independent of sulfur content?
- What is the rate of deposition within the turbine and how does it vary with elemental composition of the wood feedstock and combustion conditions?

- What effect does sintering time at elevated temperature have on the strength of the deposits? Both sintering time and temperature are known to have an impact on the strength of fly ash deposits formed in coal fired boilers (B).
- Most importantly, can the deposition be controlled or eliminated by manipulation of operating conditions or the addition of additives to the combustion zone or hot combustion gas stream? Additives such as dolomite and kaolinite have been employed to reduce both the strength and extent of deposits formed in both oil and coal fired boilers (B,C).

While a more comprehensive sampling program at the Red Boiling Springs facility is desirable, obtaining answers to the questions raised above would be difficult at such a large facility. Therefore, PNL initiated a study at Battelle Columbus Division which utilized a small bench scale combustor in an attempt to answer some of the questions raised. The results of a limited number of experiments performed by Battelle are discussed in Appendix E.

The bench scale combustion test facility utilized by Battelle was capable of duplicating the combustion conditions of the Red Boiling Springs facility except in regard to pressure. The bench scale combustor was operated at atmospheric pressure. Summarizing the results obtained by Battelle, they were unable to obtain deposits on probes placed in the combustion gas stream after 20 hours operation on wood obtained from RBS. When RBS wood and about 25% fuel oil (containing 1.18% sulfur) were co-fired, a deposit was obtained after 10 hours of firing. It should be noted that the sulfur content of the fuel oil used by Battelle in these tests had a sulfur content over five times greater than the sulfur content reported for the fuel oil used at Red Boiling Springs (Table D.2). In a final set of experiments, RBS wood and fuel oil were co-fired with lime added to the fuel mixture. Sufficient lime was added to the fuel to provide a calcium/sulfur molar ratio of about 3/1. With the lime added to the fuel mixture, no deposition occurred. The results of these initial bench scale tests suggest that the deposition problem may be significantly reduced or eliminated by the addition of lime or other additives. Unfortunately, no further bench scale tests were performed due to a decision by DOE to discontinue further support for the Red Boiling Springs wood fueled gas turbine project.

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TABLE D.1.

CHARACTERIZATION OF RED BOILING SPRINGS
WOOD FUEL (SAWDUST)

ULTIMATE ANALYSIS		ASH COMPOSITION	
Mass %, Dry Basis, (a)		Mass %, As Oxides, (b)	
Carbon	45.5	SiO ₂	52.8
Hydrogen	6.0	CaO	17.0
Nitrogen	2.1	K ₂ O	6.4
Oxygen (by diff.)	46.7	Al ₂ O ₃	3.9
Ash	1.7	Fe ₂ O ₃	2.2
		MgO	2.2
		P ₂ O ₅	1.0
		SO ₃	1.0
		Na ₂ O	NA
(a) Carbon, hydrogen, nitrogen analysis by CHN analyzer		TiO ₂ , MnO ₂ ,	< 1.0
		BaO, CuO,	
		ZnO, NiO,	
		SrO, Cr ₂ O ₃	
		(b) Analysis by inductively coupled plasma spectrometry	

TABLE D.2. ANALYSES OF RED BOILING SPRINGS TURBINE FUELS

(ppm-dry basis* except as noted)

Component	Sawdust Suppliers			RBS Sawdust			Other Samples		
	Macon Hardwood	Clark Poplar	Jones Oak	Green Dust From Storage	Dried Dust Pulverized	Dryer Fines	Virginia Pine	RBS Fuel Oil	RBS Wood**
silicon	940	3370	1070	9360	1800	2980	<310	<290	4940
calcium	1133	2810	4685	1680	2230	2915	764	12	2330
potassium	917	764	1103	902	1002	1395	392	<9	1136
sulfur	98	185	149	69	131	267	129	2190	168
iron	38	125	54	413	157	923	45	4	293
manganese	68	41	53	56	46	67	62	<3	65
titanium	<9	32	15	86	25	25	12	<11	50
zinc	6	2	2	4	35	160	9	6	11
chromium	<4	<4	<4	<4	3	6	<4	<5	5
copper	3	3	2	2	3	3	2	2	3
nickel	<1	<1	<1	1	<1	3	<1	<1	3
phosphorus	<310	<370	<420	<380	<300	<350	<270	<170	<190
chlorine	<44	<37	<41	<32	<33	<38	<38	<42	<40
rubidium	<1	<1	4	2	2	2	<1	<1	1
lead	<2	<2	<2	<2	<2	2	<2	<2	<2
moisture, % as received	35.2	44.6	37.1	39.9	14.0	19.4	48.8	--	--
ash, % dry basis	0.33	1.11	0.98	1.62	0.72	2.09	0.20	--	1.68

* Elemental analyses by scanning x-ray fluorescence spectrometer. Values cited as < indicate the level that would have been detectable above background noise at the time a particular value was determined.

** As received basis. Same sample identified as RBS Wood in Table D.1.

TABLE D.3. ELEMENTAL ANALYSES OF RED BOILING SPRINGS ASH SAMPLES
(As Oxides, wt. %)

Element	RBS Wood Fuel	Cyclone Ash	Turbine Deposits				03/89*
			09/86	04/87	07/88	#1**	#2***
CaO	17.0	19.7	19.4	22.0	33.4	21.4	30.1
K ₂ O	6.4	7.2	35.1	31.7	17.3	29.2	15.3
SO ₃	1.0	0.5	25.8	15.6	10.9	11.2	5.8
SiO ₂	52.2	50.4	4.1	5.2	8.1	2.9	5.4
MgO	2.2	2.3	0.7	1.3	2.4	2.1	3.0
Fe ₂ O ₃	2.2	3.1	1.2	1.2	2.3	1.1	1.6
Al ₂ O ₃	3.9	4.6	0.8	0.9	1.6	0.5	1.0
P ₂ O ₅	1.0	1.4	1.4	0.9	1.2	0.8	1.0
MnO ₂	0.5	0.6	0.2	0.4	0.5	0.5	0.6
Na ₂ O	NA	1.4	---	1.2	0.6	0.6	0.6
Cr ₂ O ₃	0.04	0.2	2.6	0.3	0.4	0.5	0.3
BaO	0.3	0.2	0.1	0.1	0.2	0.2	0.2
NiO	0.05	0.1	0.1	0.1	0.2	0.1	0.1
ZnO	0.09	0.2	2.0	0.6	0.1	0.5	0.4
B ₂ O ₃	---	0.3	0.9	0.6	0.6	0.3	0.6
TiO ₂	0.5	0.6	0.04	0.06	0.1	0.02	0.05
SrO	0.06	0.07	0.05	0.06	0.09	0.06	0.09
CuO	0.01	0.05	0.09	0.10	0.09	0.04	0.05
CdO	---	---	0.04	0.02	---	---	---

All analyses performed by inductively coupled plasma-atomic emission spectrometry

NA = Not analyzed

--- = Concentration below limits of detection

* Samples taken after operation with water injection (non-deionized water)

** #1. Tan-gray powder removed from turbine blades

*** #2. Gray crusted particulate deposit removed from turbine entrance

TABLE D.4. X-RAY DIFFRACTION ANALYSES OF TURBINE BLADE DEPOSITS

Sample No.	Description
09/86	Crystalline material represented between 10 and 20% of this sample, the balance being amorphous. The crystalline portion consisted of approximately 60% potassium sulfate (K_2SO_4), the balance being predominately calcium carbonate ($CaCO_3$). Traces of spurrite [$Ca_5(SiO_4)_2CO_3$] were probably present.
04/87	The crystalline portion of this sample consisted of approximately 50% potassium sulfate (K_2SO_4), 30% fairchildite [$K_2Ca(CO_3)_2$] and 20% calcium carbonate ($CaCO_3$). As with sample 9/86, much of this sample was amorphous.
07/88	The crystalline phase of this sample was found to consist of 50-60% calcium carbonate ($CaCO_3$), 20-30% potassium sulfate (K_2SO_4) and 10-20% spurrite [$Ca_5(SiO_4)_2CO_3$]. Additional weak lines indicated the possible presence of additional minor crystalline phases but none were strong enough to be identified.

APPENDIX E

WOOD ASH EVALUATION TASK

TASK COMPLETION REPORT

on

WOOD ASH EVALUATION

to

BATTELLE PACIFIC NORTHWEST LABORATORY

March 1, 1989

TASK COMPLETION REPORT

on

WOOD ASH EVALUATION

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INTRODUCTION

Ash deposition in combustion systems has been a continuing problem for many years. Much of the work related to this problem has been aimed at large fuel users such as utilities and, thus, has focused on improvements in the use of coal and other fossil fuels. These studies on coal systems have identified some particularly troublesome mixtures of compounds that increase the potential for deposits to form. These mixtures occur in the form of low melting point eutectics that greatly reduce the temperature at which the ash components sinter or become tacky. As fuel sources are expanded to include renewable fuels such as wood or other biomass materials, existing data bases for fossil fuels will need to be expanded. An understanding of ash chemistry will be useful in generating and interpreting the expanded data base.

New technologies for combustion and power generation are being developed that will use these renewable biomass resources. The distribution of ash constituents in biomass materials is significantly different than in fossil fuels. Hence, the data base that exists for coal ash and oil ash may not be applicable to biomass materials. In particular, the greater alkali metal content of biomass ashes can promote the formation of the low temperature eutectics.

This task was undertaken to begin to develop such a data base while solving a specific problem encountered at Aerospace Research in the wood fired gas turbine work at Red Boiling Springs, Tennessee.

BACKGROUND

Operation of a gas turbine is generally considered possible only with liquid or gaseous fuels due to the close tolerances on blades and generally higher temperatures of metal surfaces compared to boilers. When using solid fuels in a turbine, the ash content and composition of the fuels and the operating conditions must be controlled closer.

Aerospace Research has been developing a combustion system that will allow direct firing of wood in a gas turbine. This application should yield favorable overall heat rates for power generation. Initial testing on the system was conducted at a small scale in Roanoke, Virginia. As problems with particulate emissions were anticipated, Battelle Columbus conducted a series of sampling tests on the experimental turbines in Roanoke beginning in 1982. These tests were conducted while using a variety of wood feedstocks as well as one test using manure as a feed stock. The sampling activities focused mainly on particulates, but also measured gaseous products of combustion (CO , CO_2 , SO_2 , NO_x , THC, and O_2).

Results of these tests showed that the particulates produced were primarily smaller than 1 micron in size, and that mass loadings were in a range from 0.004 to 0.23 gr/dscf.

Analysis of these results along with the combustion tests performed by Aerospace Research led to a decision to scale-up the system to a small commercial scale. Consequently, wood combustors and turbines were installed at Red Boiling Springs. Operations at Red Boiling Springs have resulted in deposits of material forming on surfaces downstream from the combustor. On a sampling visit to RBS, Battelle noticed similar deposits on the water-cooled sample probes that were used. Later examination in Columbus revealed that these deposits were similar to boiler deposits studied earlier by Battelle and others. This observation led to the conclusion that a similar type of study might be conducted for the RBS deposits.

Prior to this evaluation, the deposits were characterized chemically by use of Inductively Coupled Plasma Spectrometry and Spark Source Mass Spectrometry. These analyses, although providing a chemical analysis of the deposits, did not provide any information as to the origin of the deposits or possible solutions to the problem. In order to suppress the formation of

these deposits, combustion temperatures have been limited to levels below design temperatures. Such a temperature limitation, however, severely limits process efficiencies.

A reliable method of determining the origin of the deposits and more importantly a method for eliminating them then was necessary. The study conducted provided data on the mechanism of formation and suggested several alternatives that could be used as control methods.

The analytical tests performed by PNL and BCD on samples of ash and deposits have shown "typical" wood ash character. These show that basically all of the species present in the parent wood can occur in the ash. The sulfur present in the ash demonstrates a significant amount of capture by the wood ash components. This capture, while helping reduce atmospheric emissions, further complicates the deposition picture. Binary mixtures of K_2SO_4 , Na_2SO_4 , $CaSO_4$, and $MgSO_4$ have very low melting points as shown in the table below. Ternary mixtures can add to the problem and complex sulfate, e.g., $Na_3Fe(SO_4)_3$, have even lower melting points. Some success in alleviating the potential for fouling has been achieved by adding small amounts of additives have been successfully added with the fuel in coal systems. The mechanisms here are typically either (1) complexing the compounds to form metal silicates or other compounds with high melting points or (2) inhibiting the formation of an intermediate form such as SiO to eliminate the problem.

TABLE 1. POSSIBLE EUTECTIC FORMS IN AN ASH SYSTEM

Eutectic	Melting Point, F
$\text{MgSO}_4 \cdot \text{Na}_2\text{SO}_4$	1240
$\text{MgSO}_4 \cdot \text{K}_2\text{SO}_4$	1380
$\text{Na}_2\text{O} \cdot \text{SiO}_2$	1500
$\text{CaSO}_4 \cdot \text{SiO}_2$	1590
$\text{CaSO}_4 \cdot \text{Na}_2\text{SO}_4$	1683
$\text{Na}_2\text{SO}_4 \cdot \text{K}_2\text{SO}_4$	1530
$\text{K}_2\text{O} \cdot \text{SiO}_2$	985
$\text{Na}_3\text{Fe}(\text{SO}_4)_3 \cdot \text{K}_3\text{Fe}(\text{SO}_4)_3$	1030

OBJECTIVES

The program was designed to address three major objectives. These were:

- (1) Identify the physical state and composition of the ash as it leaves the combustion zone.
- (2) Identify whether deposits are formed from vapors or fine particulates.
- (3) Investigate methods for control of deposits through combustion modifications and/or additive injection.

A fourth objective was to determine the source of sulfur in the deposits at RBS and to identify their fate was initially considered less critical than the other objectives. As will be discussed below, the deposition problem hinged on the presence of sulfur in the system and thus was the critical parameter in the ability to recreate the deposits formed at RBS and control them.

PROGRAM PLAN

In order to achieve these objectives, the following six tasks were conducted:

- Task 1. Literature Survey
- Task 2. Detailed Determination of Time-Temperature History in RBS Combustor
- Task 3. Combustor Preparation
- Task 4. Combustor Operation
- Task 5. Combustion Modifications
- Task 6. Sample Analysis

Experimental Operation

Experiments run under this program were conducted using Battelle's Bench-Scale Laboratory Combustor which is illustrated in Figure 1. The unit is designed to fire small quantities of fuel under a controlled time and temperature history. The ash produced then can be collected and analyzed for composition and physical characteristics. Ash cooling rates can be easily modified in the unit as the combustion zone is fired externally with natural gas. This allows simulation of various combustion intensities (within a range of about 25,000 to 100,000 Btu/ft³/hr) to allow the effect of process changes to be easily evaluated.

Experimental Conditions

Operating conditions within the ARC combustor and turbine entrance were duplicated to the extent possible within the Bench-Scale Combustor. Since the combustor is an atmospheric pressure unit, the combustion intensities present in the high pressure ARC combustor were simulated by adjusting the natural gas firing rate on the exterior of the Bench-Scale Unit reaction tube. Other parameters recreated were temperature, carbon oxide and oxygen concentrations, and gas inlet and blade temperatures. Consistency of conditions when compared with the ARC data was confirmed by the fact that the physical and chemical properties of the flyash produced in the Bench-Scale Unit were nearly identical to those generated by the ARC combustor.

FIGURE 1. BENCH SCALE COMBUSTOR

RESULTS

Task 1. A detailed literature search was conducted on practical and technical information on ash deposition and on wood firing. The data showed that even a small quantities of non-wood ash components such as sulfur can lead to deposition problems. Similar deposition problems are not encountered when firing boilers on wood alone.

The total sulfur content of the fuel also has a bearing on the tendency for formation of deposits. This data then suggested that the fate or source of the sulfur compounds in the RBS deposits should be of primary importance in the overall task experimental plan.

An annotated bibliography of the references used is included in the appendix.

Tasks 2 through 6. These tasks comprised the experimental component of the program. Data was obtained from ARC on the turbine combustor conditions and was used as the basis for simulation in the Bench-Scale Unit. A small wood feeder capable of feed rates on the order of 2 pounds per hour was installed on the unit to provide a match between the firing rate and combustion intensity desired for the simulations. The feeder could reproducibly and reliably feed wood to the unit over extended times.

Wood samples from RBS were used in the tests as a further attempt to accurately reproduce the conditions present in the gas turbine combustor.

When firing neat (as received) ARC wood turbine fuel, the Bench-Scale unit was successful in recreating most ARC turbine combustion conditions. To our surprise *no ash deposition occurred even when tests over 20 hours were conducted.* At this point in the program, we realized that two very significant differences between the Bench-Scale Unit operation and the RBS operation existed. These were the total system pressure and the fact that the RBS combustor is preheated by cofiring the wood with distillate oil. As the bench-scale unit is an atmospheric pressure unit we decided to further investigate the effect of cofiring oil with the wood fuel. The literature search results also supported the validity of this approach.

Fuel oil was cofired in the next experiments at a level of 25% or less on a heating value basis to simulate the RBS conditions. An ash deposit formed after 10 hours of operation that was similar in character to the RBS

deposits. The similarity was verified by mineralogical analysis. When oil was removed from the wood firing, the deposit potential disappeared.

A final set of experiments was made to determine if the deposits formed when firing wood and oil could be controlled with additives. A simple and readily available additive is lime. A calcium to sulfur ratio (Ca/S) of 3 was selected as a baseline condition for the determination. The calcium source used was technical grade pulverized lime. Lime was admixed with the wood fuel and then cofired with the fuel oil in the same ratio as the previous tests. The RBS thermal and chemical conditions were again maintained during these tests.

When lime was added to the fuel, the deposit did not form with tests continued over an extended period of time. Additional tests should be run to determine the lowest level at which the deposition potential can be eliminated.

CONCLUSIONS AND RECOMMENDATIONS

In summary, deposits similar to those found in the RBS turbine were reproduced *only* when cofiring wood and oil. This indicates that the startup procedure at RBS has a significant if not critical part in the formation of ash deposits in the RBS turbine. Deposits which form can be eliminated by the inclusion of additives that retard the formation of low temperature eutectics with the ash materials. One such material shown to be effective in this regard is lime.

Additional wood and biomass ash evaluations should be conducted to (1) broaden the data base on deposition potential, (2) identify potential fouling fuels, and (3) identify additional low cost additive that might be used to reduce fouling potential of these fuels. If significant amounts of biomass fuels are to be used as gas turbine fuels, the effect of pressure, which was outside the scope of this evaluation, should also be investigated in more detail.

APPENDIX

FINAL REPORT

RESEARCH SUMMARY

Project Title: Wood Ash Evaluation

Contract Number: ILA-B-M8155-A-K

Contracting Organization: Battelle Columbus Division

Project Manager: M. A. Paisley 614/424-4958

Principal Investigator: J. J. Reuther 614/424-7916

RESULTS AND PROGRESS

The objective of this program was to identify the parameters that may cause and could mitigate the unwanted ash deposition in the Aerospace Research Corporation (ARC) wood-fired gas turbine. The approach used consisted of a critical literature review and selected combustion experiments from which information regarding the causes and effects of wood ash deposition in turbines were derived.

The Battelle Bench-Scale Combustor (BBSC) was operated in a manner that simulated, as much as practicable, the deposit-prone combustion environment of the ARC turbine. When firing the actual ARC wood fuel that gave rise to deposition problems (Table 1), the BBSC recreated the chemical emissions and the gas inlet temperatures of the ARC turbine (Table 2). That this experimental device essentially simulated the thermochemical environment of the ARC turbine was confirmed by determining that the physicochemical characteristics of the flyash generated by the BBSC were nearly identical to those generated by the ARC turbine (Table 3).

When firing neat ARC wood turbine fuel, the BBSC was successful in recreating most ARC turbine combustion characteristics, except the most important one: ash deposition (Table 4). That is, no ash deposition occurred when firing the BBSC with neat wood, even after ultralong combustion durations (20+ hours). At this point in the program, it was realized that the BBSC simulation was different from actual ARC wood-fired turbine conditions in two possibly significant ways. First, the ARC turbine was typically fired at superatmospheric pressure. Second, the ARC turbine was preheated not by firing neat wood, as the BBSC is, but by cofiring petroleum with the neat wood. Because the BBSC could not be fired at superatmospheric pressure in its current configuration, it was decided to determine the significance upon ash deposition of cofiring the BBSC with oil and wood.

Deposits formed upon cofiring the BBSC with about 25 percent or less fuel oil and wood (Table 4), while recreating the same baseline combustion characteristics of neat wood firing (Table 2). The deposit appeared within 10 hours of operation, or less.

Mineralogical analysis of the resulting trace ash deposit revealed that it was similar to that formed on ARC turbine blades.

The last set of experiments conducted consisted of determining whether additives could be used to control the observed ash deposition taking place in the BBSC when cofiring oil and wood. When pulverized technical-grade lime was admixed with the oil/wood dual fuel, such that the molar calcium/sulfur (Ca/S) ratio was about 3, and fired, no ash deposition occurred (Table 4). Baseline thermal and chemical combustion conditions (ARC turbine-like) were also maintained during these additive tests (Table 2). Experiments were not conducted to determine the lowest Ca/S ratio at which ash deposition would occur with sorbent addition.

In summary, ash deposits did not form when firing neat wood, did form when cofiring fuel oil with raw wood, and did not form when cofiring fuel oil with wood that had been admixed with a calcium sorbent (Table 4).

Practical and technical information from the vast literature on ash deposition and on wood firing confirmed that these results were not unique and provided a plausible explanation for them.⁽¹⁻¹⁶⁾ First, it is known that ash deposition is usually not a problem when firing boilers on wood alone, but is a problem when cofiring fuel oil with wood.^(2-4,10) Second, it is also known that the total sulfur content of the fuel being fired has an influence on the tendency for ash deposition to occur.^(8,12) Because adding fuel oil to wood did more to change the total sulfur content of the fuel than to change most other chemical properties (increased sulfur 40-fold), it strongly appeared, albeit via circumstantial evidence, that it was the cofiring of oil with the wood that resulted in the ash deposition problem. Third, and finally, there is precedent for using added calcium to lower the deposition tendencies of pulverized coal.^(13,16)

The obvious parameter that was not accounted for in Battelle experiments or in the rationalization of the data, was combustor operating pressure. Because the technical literature on the effect of superatmospheric pressure on ash deposition is scarce, it is recommended that high-pressure combustion tests be conducted using the BBSC to confirm whether or not this prerequisite turbine-operating parameter plays a critical role in ash deposition, or if the ARC ash-deposition problem can be solved by not cofiring oil with wood.

TABLE 1. PROPERTIES OF FUELS FIRED IN BATTELLE BENCH-SCALE
COMBUSTOR SIMULATION OF AEROSPACE RESEARCH
CORPORATION WOOD-FIRED TURBINE

Fuel Property	ARC Turbine Wood ^(a)	Fuel Oil
Heating Value (dry, Btu/lb)	8,230	19,005
<u>Ultimate Analysis (dry, weight %)</u>		
Carbon	49.53	85.41
Hydrogen	5.71	11.23
Nitrogen	0.70	0.71
Sulfur	0.03	1.18
Oxygen	42.55	1.44
Ash	1.48	0.03
<u>Mineral Analysis of Ash (dry, weight %)</u>		
Silica, SiO ₂	39.25	38.80
Alumina, Al ₂ O ₃	5.33	1.30
Titania, TiO ₂	0.52	8.15
Ferric Oxide, Fe ₂ O ₃	4.14	11.65
Lime, CaO	32.40	8.70
Magnesia, MgO	2.80	1.80
Potassium Oxide, K ₂ O	9.20	--
Sodium Oxide, Na ₂ O	0.46	9.50
Sulfur Trioxide, SO ₃	3.09	15.0
Phos. Pentoxide, P ₂ O ₅	1.50	
Vanadium Oxide, V ₂ O ₅	--	5.10

(a) Supplied to Battelle by the Aerospace Research Corporation.

TABLE 2. ARC WOOD-TURBINE COMBUSTION CONDITIONS SIMULATED BY THE BATTELLE BENCH-SCALE COMBUSTOR^(a)

Combustion Characteristic	ARC Wood-Fired Turbine	Battelle Bench-Scale Combustor
Turbine Inlet Temperature (F)	1350-1400	1350 ± 50
Oxygen Concentration (%)	19.5	19.0 ± 0.5
Carbon Dioxide Concentration (%)	3.0	3.0 ± 0.25
Carbon Monoxide Concentration (ppm)	1300	1350 ± 50
Nitrogen Oxides Concentration (ppm)	35	40 ± 10
Sulfur Dioxide Concentration (ppm)	65	75 ± 20
Turbine Inlet Pressure (psig)	24-42	1

(a) Webb, P. R., "Wood-Fired Turbine Emissions Measurements", Topical Report from Battelle Columbus Division to Battelle Pacific Northwest Laboratories on ILA-B-M8155-A-K, April 20, 1987.

TABLE 3. BATTELLE BENCH-SCALE COMBUSTOR SIMULATION OF
FLYASH FROM ARC WOOD-FIRED TURBINE

Flyash Property	ARC Wood-Fired Turbine Flyash ^(a)	Battelle Bench-Scale Combustor Flyash
<u>Mineral Constituent (dry, weight %)</u>		
Silica, SiO ₂	47.49	37.07
Alumina, Al ₂ O ₃	4.89	4.58
Titania, TiO ₂	0.57	0.47
Ferric Oxide, Fe ₂ O ₃	3.44	4.73
Lime, CaO	28.78	30.64
Magnesia, MgO	3.78	3.34
Potassium Oxide, K ₂ O	5.00	7.96
Sodium Oxide, Na ₂ O	0.36	0.41
Sulfur Trioxide, SO ₃	0.37	0.50
Phos. Pentoxide	1.67	1.44
Strontium Oxide, SrO	0.09	0.09
Barium Oxide, BaO	0.25	0.21
Manganese Oxide, Mn ₃ O ₄	0.68	0.59
Undetermined	2.63	7.97
<u>Ash Fusion Temperatures (Reducing, F)</u>		
Initial Deformation	2200	2195
Softening	2260	2245
Hemispherical	2310	2290
Fluid	2340	2325

(a) Supplied to Battelle by the Aerospace Research Corporation.

TABLE 4. DEPOSITION TENDENCIES OF BATTELLE TEST FUELS

Fuel Fired	Sulfur (%)	Deposit Formation?
ARC Wood	0.03	No
Fuel Oil	1.18	No
ARC Wood + Fuel Oil	0.15	Yes
ARC Wood + Fuel Oil + Lime	0.15	No

ANNOTATED BIBLIOGRAPHY

Project Title: Wood Ash Evaluation

Contract Number: ILA-B-M8155-A-K

Contracting Organization: Battelle Columbus Division

Project Manager: M. A. Paisley 614/424-7958

Principal Investigator: J. J. Reuther 614/424-7916

Given below is a chronological bibliographic listing of technical papers relevant to the task entitled "Wood Ash Evaluation", conducted at Battelle Columbus Division for Battelle Pacific Northwest Laboratories under ILA-B-M8155-A-K. Each bibliographic listing is followed by comments on how specific information or results given in that particular document were of technical value to the wood ash research program.

1. Zicherman, J. B. and Thomas, R. J., "Analysis of Loblolly Pine Ash Materials", Paper 3574, Journal Series of the North Carolina State University Agricultural Experiment Station, Holzforchung Bd. 26, H. 4, pp. 150-152 (1972).

This document provides mineralogical data on the ash constituents of pine, one of the wood fuels fired in the Aerospace Research gas turbine of Red Boiling Springs, Tennessee.

2. Hupa, M., Karlsson, K. H., and Skrifvars, B., "Deposit Formation in Boilers with Combined Firing of Fuel Oil and Bark", Paperi ja Puu 7, 1-5 (1976).

This document discusses the propensity of wood and wood cofired with oil to form deposits in boilers. Whereas neat wood firing is deposit-free, the cofiring of oil with wood is deposit-prone. Preliminary evidence is provided to support a possible explanation for this no/yes behavior, which implicates sulfur in the oil as the constituent that actively promotes deposition by wood ash.

3. Hupa, M., "Deposit Formation in Boilers Fired with Bark Alone or in Combination with Other Fuels", Paperi ja Puu 8, 1-7 (1977).

This document is a continuation of the research reported in Reference 2 here, and provides detailed information supporting the speculation that it is the sulfur in a cofired-fuel that promotes deposition upon wood combustion.

4. Hupa, M., Eriksson, B.-E., and Klingstedt, G., "A Rapid Method for Investigation of Ash Deposition in Boilers", Paperi ja Puu 11, 1-4 (1978).

This paper is the third in a series, along with References 2 and 3 here, to provide information on why deposition may occur upon cofiring wood and oil but does not occur when firing wood alone. Scanning electron microscope data are used to identify sulfur associated with the oil as the catalyst for deposition from wood flames.

5. "Wood", Steam/Its Generation and Use, 5-21,22, 39th Ed., Babcock & Wilcox (1978).

This document provides analyses of wood bark and wood ash for a variety of species, including pine, oak, spruce, and redwood.

6. Schwleger, R., "Power from Wood", Power, 5-1-32 (1980).

This document provides a comprehensive review on wood firing, with particular emphasis on how physicochemical wood properties influence combustion performance. Included in various data compilations are the ash constituents of various species of wood.

7. Oglesby, H. S. and Blosser, R. O., "Information on the Sulfur Content of Bark and Its Contribution to SO₂ Emissions When Burned as a Fuel", Journal of the Air Pollution Control Association 30, 769-772 (1980).

This document provides data on the amount and partitioning (wood/bark) of sulfur in wood fuels. Included in the paper as secondary information are ash analyses for several wood species, including jack pine, birch, maple and hemlock.

8. Bryers, R. W., "Influence of Mineral Matter in Coal on Steam Generator Conversions", American Flame Research Committee/International Flame Research Foundation Symposium: Conversion to Solid Fuels, Paper 1:1-66 (1982).

This paper comprehensively reviews the impact of mineral matter in oil and coal on the tendency of solid fuels have deposition problems upon combustion in boilers, and summarizes the empirical indices that have been developed to predict these tendencies, most of which include a sulfur term.

9. Brizzolara, L. G., "Retrofitting Biomass Burning Equipment To an Existing Gas/Oil Burning Plant", American Flame Research Committee/International Flame Research Foundation Symposium: Conversion to Solid Fuels, Paper 27:1-12 (1982).

The document provides information on how the combustion properties of gas and oil compare with those for pulverized wood. Also provided are ash deformation temperatures for various wood fuels, including pine, fir, hemlock, and "waste" woods.

10. Huppa, M. and Backman, R., "Slagging and Fouling During Combined Burning of Bark with Oil, Coal, Gas or Peat", International Conference on Fouling of Heat Exchanger Surface (1982).

This document reviews and updates the information presented in References 2-4 here, and provides compelling experimental evidence that the sulfur originating in cofired-oil causes wood flames to generate deposits when neat wood flames do not. Also discussed is the inability of MgO additive to reduce deposition problems when cofiring wood and oil.

11. Osman, E. A. and Goss, J. R., "Ash Deformation and Fusion Temperature Models for Wood and Agricultural Residues", American Society of Agricultural Engineers, Paper 83-3550 (1983).

This paper provides extensive numerical information on the mineralogical constituents of biomass fuels, including wood, as well as empirical correlations for predicting the ash deformation temperatures of these fuels. Of all (9) ash constituents considered, sulfur ranked fourth in its negative influence on deformation temperature.

12. Blackwell B., MacCallum, C., Helminen, P., MacKay, W., Pope S., Holmes, G., and Wong, J., "Preparation of Wood for Combustion", Report 173-G-297 to the Canadian Electrical Association by Sandwell and Company Limited (1984).

A comprehensive review of how physicochemical wood properties determine and control wood combustion characteristics. Highlighted are the results of References 2-4, and 10 here that the cofiring of wood and fuel oil can result in a significant increase in deposit formation relative to firing either wood, or oil, alone.

13. Goetz, G. J., Mirolli, M. D., and Eskinazi, D., "Fireside Consequences of Furnace Limestone Injection for SO₂ Capture", American Society of Mechanical Engineers Paper 84-JPGC-APC 10 (1984).

The intent of this paper was to provide information on how the use of limestone injection in boilers for SO₂ control impacts ash deposition tendencies. Data are provided that demonstrate that limestone injection reduces deposit buildup when firing various pulverized coals.

14. Ragland, K. W. and Baker, A. J., "Mineral Matter in Coal and Wood- Implications for Solid Fueled Gas Turbines", Central States Section Combustion Institute Proceedings: Combustion Fundamentals and Applications, pp. 117-122 (1987).

This technical paper briefly discusses how mineralogical characteristics of various solid fuels, including wood, influence the tendency for these fuels to have slagging and fouling problems in gas turbines upon combustion.

15. Yeakel, J. D. and Finkelman, R., "A New Model for Predicting the Fouling Deposit Weight of Coal", American Chemical Society Division of Fuel Chemistry Preprints 33, 91-102 (1987).

This paper presents an empirical correlation that predicts the weight of fouling deposits upon the combustion of coal. Ash constituents that were highly correlated in the regression model included sulfur content and calcium-to-sulfur ratio.

16. Anderson, R. J., Richards, G. A., Logan, R. G., and Meyer, C. T., "Combustion/Deposition of Coal-Derived Fuels", Proceedings of the Annual Coal Fuel Heat Engines and Gas Stream Cleanup Systems Contractors Meeting, pp. 123-131, U.S. Department of Energy Morgantown Energy Technology Center (1988).

This paper provides experimental data demonstrating that the addition of calcium effectively lowers the sticking coefficients of slag deposits upon simulated coal-fired combustion turbine conditions, which may result in reduced deposits.

APPENDIX F

REPORT OF DESIGN STUDY OF ALTERNATE WOOD FEED SYSTEMS

AT RBS CORP., RED BOILING SPRINGS, TN

REPORT OF DESIGN STUDY
OF
ALTERNATE WOOD FEED SYSTEMS
AT RBS CORP.
Red Boiling Springs, TN

July 21, 1986

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July 17, 1986

REPORT OF DESIGN STUDY
OF
ALTERNATE WOOD FEED SYSTEMS
AT RBS CORP.
Red Boiling Springs, TN

THE PURPOSE of this study was to develop alternate methods of feeding wood to the RBS Combustor, to provide that the feeding equipment is placed on the ground and away from the heat, and to achieve as uniform a feed rate as practical.

THE BACKGROUND for this study consists of problems of capacity and operation of the 4 Rotary Valves designed by Hamrick, and installed in series atop the combustor. (Reference, TRM Letter March 21, 1986 re: valve flanges.)

It is my understanding that the recently revised valves have been operating fairly well in the limited use of the past few months.

However, it is well recognized that if the feed system with the meter bin and the valves (or valve) could be installed at ground level, supplying the wood to the bin, maintenance would be improved, as well as removing the feed system from exposure to heat.

These matters have been the subject of a great deal of discussion, particularly since the fall of 1985.

THE THREE BASIC FEEDING PROBLEMS are present in the RBS system:

- A) Overcoming the pressure differential;
- B) Accurate, uniform and variable metering rate;
- C) Delivering or injecting into the reactor.

This study investigates a variety of solutions to these problems.

FUEL REQUIREMENTS to generate 3 MW of electricity are:

132 lbs/min. of 10% M. sawdust
= 11 CFM of sawdust at 12 lb/C.F.

This dry sawdust will have a fuel value of approximately 8100 BTU/lb., and have a solid wood content of approximately 40%, with 60% of the volume as air or "gas void".

UNIFORMITY OF FEED RATE is of the greatest importance, especially to a suspension firing system with a total residence time of 2-3 seconds. The $\frac{1}{2}$ second pulses of a rotary valve result in finite "blobs" of fuel being introduced into the combustor or air stream. We have seen this for years in high pressure conveying systems fed with a rotary valve in which these "blobs" of wood chips are still intact even after traveling $\frac{1}{2}$ mile and around many bends.

TWO CONVEYING METHODS of delivering the dried sawdust from the ground to the combustor are available:

1) A PRESSURIZED VERTICAL SCREW (Screw Conveyor Corp. 9" Type G) would convey the fuel 25 feet vertically as well as serving to isolate the feed system from heat. Metering would be done on the ground to the vertical screw. Turning the screw at 250 RPM, the fuel would be delivered in approximately $\frac{1}{2}$ second pulses. Such a screw would cost approximately \$26,000, and could be fed with either the Meter Bin/Lockhopper or the Rotary Valve systems. In both cases, provision for a supply of cooled displacement and leakage air would have to be made. This would amount to 12 to 60 ACFM, but would not require the compressor. This air is required to prevent backflow of hot gases from the combustor. This equipment would cost:

E.P. Adams Co. SAF-53 Aftercooler w/6" Separation	\$ 2,800
Piping & Fittings	400
Pressurized Vertical Screw	<u>26,000</u>
EQUIPMENT -	\$29,200

This would require approximately 25 gpm of 80° or cooler water and the screws would require a total of 15 HP.

2) A PNEUMATIC CONVEYING SYSTEM in combination with one of the metering options shown in DRWGS 506.4-01 and -02 would allow the greatest versatility.

The 600° F., 150 psi, GT compressor air would have to be cooled to approximately 100° F. and a 5 HP blower installed to increase the pressure of approximately 225 ACFM by about 3 psi to overcome the conveying line resistance and provide a positive ΔP for lockhopper and rotary valve operation.

No rotary valve would be required at the combustor since the check valve would prevent any backflow in case of a rupture in the feed system.

The equipment to supply the cooled, compressed 225 ACFM would be:

Aftercooler #194-N, w/8" CY-C Separator	
E.P. Adams Co.	\$6,533
Sutorbuilt 5 MV Blower	1,246
5 HP TEFC Motor & Cplng	350
150 psi Enclosure	3,100
Pipe, Fittings	<u>500</u>
EQUIPMENT ONLY -	\$11,729

This system would require 81 gpm of 80° F. or cooler water and consume 5 HP for the blower.

This system would allow a separate location - up to 150' - for the metering/valve functions.

LOCKHOPPERS vs. ROTARY VALVES are the subject of many differing opinions, so we shall present both systems as applied to RBS.

LOCKHOPPERS, as shown on top of the Meter Bin in Sketches -01 & -02, intermittently pass a specific charge of material into the high pressure Meter Bin as follows:

- 1) Fill L.H. with top valve open.
- 2) Close top valve.
- 3) Pressurize L.H. from external source to balance Meter Bin Pressure (150 psi).
- 4) Open lower valve, releasing charge into Meter Bin.
- 5) Close lower valve and vent 150 psi to atmosphere.
- 6) Open top valve - repeat cycle.

From full scale tests, and from three years of experience of IGT using our design to feed a 300 psi gasifier with 18" and 24" valves, we know the system works well, and can operate on a 2 minute total cycle.

Initially we used modified Fabri Valves on the IGT system but they proved inadequate at the 300 psi pressure. They were replaced by a new valve that we designed specifically for dry fuel lockhopper service, which has proven very satisfactory. These valves will only open on balanced pressure, the gate moves on machined ways and is lifted to seal, thus avoiding scraping the seal surfaces. Wipers keep the top surfaces clean.

The maximum fuel demand rate is 11 CFM (132 lb/min). The L.H. cycle is 2 min., thus the capacity is required to be 22 C. F. Allowing some margin makes it 24 C.F.

When the Lockhopper is full of 12 lb/C.F. dry sawdust, the solid wood content of the sawdust is 40% or 8.8 C.F., leaving 15.2 C.F. of gas in the voids. To pressurize this gas to 150 psi (10 ATM) requires 152 SCF of 150 psi air from the cooled, compressed source. When the charge is dropped into the Meter Bin, this solid wood is displaced by 150 psi gas in the Meter Bin, leaving the L.H. charged with 24 ACF of 150 psi gas or 240 SCF.

Based on a 2 minute cycle, the average demand is 12 ACFM, which is vented to atmosphere with each cycle.

The L. H. method is the most efficient in terms of conserving vented gas. In our 450 psi gasifier feeder design for Framatome in France (which is being commissioned this summer, 1986) we use two parallel 24" L.H.'s to increase capacity, provide redundancy and to conserve vent gas even more by cross-venting.

Lockhoppers do require a Meter Bin to take up the intermittent charges and to provide variable rate fuel metering.

The equipment costs of the Lockhopper system shown are:

2 - Miles Lift Gate Valves -	\$ 68,000
Precharge & Lockhoppers	6,300
Meter Bin, Screws w/V.S. Drive	43,000
Piping, Valving	<u>2,500</u>
EQUIPMENT -	\$ 119,800

ROTARY VALVES or airlocks operate by continuously transferring material from one zone to another in pockets between vanes, one or more of which "seal" to the barrel either by very close tolerances or by lip seals in contact with the barrel.

They should never be used to meter biomass fuels out of a bin, but only as pressure isolating airlocks.

Characteristically, backflow or venting losses through the valves are of three types:

Pocket Loss - in which each empty pocket carries high pressure gas around and vents it to atmosphere (or the feed device). Cross-venting from the high to the low pressure sides can salvage approximately 40% of this pocket loss.

Vane Leakage - is a function of the quality of the vane-to-barrel seal or clearance and gradually deteriorates during operation, requiring seal renewal or vane build-up and eventually re-machining the barrel and re-chroming.

In high differential pressure valves, the rotor shaft deflection cannot be completely eliminated and must be accounted for in setting the clearances. Heat also has a profound effect on these clearances.

End Rotor or End Bell Leakage is similar in nature to Vane Leakage but is not subject to the same deflection problems.

PRESSURE RATINGS are described for two conditions:

INTERNAL pressure rating is the pressure that the body of the valve must withstand - the system pressure to atmosphere.

DIFFERENTIAL pressure is the difference in pressure across the rotor.

Obviously it is more difficult to design and construct rotary valves for high differential pressures with their high bearing loads, shaft/rotor deflections, seal problems.

A prime example of this is Young Industrial, who make Class 150 and 300 psi Internal Pressure Rotary Valves - with a maximum of 15 psi differential pressure - see Appendix A. They are not interested in making anything over 15 psi ΔP .

The Beaumont Birch prints and literature are unusual in providing good descriptive data.

We have tested a number of rotary valves for leakage at lower pressures, 3-10 psi, and have collected as much data as possible on high pressure valves. All manufacturers are very reluctant to quote leakage figures because conditions, materials, temperatures and maintenance vary so widely.

MULTIPLE ROTARY VALVES conserve pocket losses and reduce differential pressure levels in the same way as cross-venting. They still, however, require the same internal pressure capability as the system, 150 psig in this case. There are risks in too much dependence on reduced ΔP , especially in the primary and secondary stages. A rotor or body loss can subject adjacent valves to the full ΔP and potential failures. In any case, all the valves must be designed for full system internal pressure and maximum ΔP .

Gas losses for multiple valves can be estimated as shown in Appendix B "Rotary Valve Calculations". Leakage is estimated as the sum of pocket loss and rotor and vane clearance leakage. Pockets are filled with material for only half a revolution. Since material fills one half of the pocket, total gas voiding is equal to three quarters of the valve displacement per revolution. After the material is discharged, vanes are filled with air at a pressure near conveying line pressure. A 1.5 CFR feeder rotating at 15 RPM, discharging into a line at 150 psig would have an estimated pocket volume air leakage of 15 ACFM (170 SCFM). Adding valves or cross-venting reduces pressure drop across the valves so that pocket leakage at the high pressure valve can be reduced to as little as 3 ACFM (32 SCFM).

High pressure air flowing through radial and axial clearance spaces between the valve rotor and its housing cause additional leakage. Clearance leakage is estimated by considering the valve as a rectangular orifice. Rotor and vane tip clearances describe orifice area, while a discharge coefficient is used, together with pressure drop, in an orifice equation for less than critical flow.

Hamrick's existing stack of four valves has demonstrated that a 35 psig drop across each valve is workable. For the valve described above, clearance leakage for a 35 psig ΔP may be 23 ACFM compared with 75 ACFM for a 150 psig ΔP . There is little information to confirm actual clearance leakage with sawdust at high pressures

over time. Few manufacturers will quote valve performance based on these conditions. Seal and rotor designs differ between manufacturers. However, pocket loss added to clearance leakage estimated in this manner has been close to actual losses we have measured on the test stand.

VANE TIP SEALING is done by three methods: machined tips, adjustable tips, and tapered rotor. Low pressure valves often use Teflon, rubber or nylon seal strips on the vane tips, some adjustable. Most rotary valves depend on close machine tolerances, in the order of .003" to .007".

Ingersoll-Rand, Beloit and Beaumont Birch use adjustable metal knives at the tip, which are carefully set to provide the tightest clearances when operating in the hot steamy digester atmosphere.

The Bauer valve depends on its tapered rotor to adjust clearances to accommodate both wear and temperature.

Generally, any plastic tip material does not last long with wood products. Dry sawdust is surprisingly abrasive, and when combined with hot backflow gases, as in the recent RBS situation, these nylon tip seals will probably have a limited life.

SIZING A ROTARY VALVE and selecting a speed are very critical. Using RBS as an example, we need to charge 11 C.F./minute of dry sawdust from atmospheric pressure into a 150 psi combustor. To avoid excess wear from the fuel and preclude jamming, we use a 50% pocket loading. Therefore, we need to displace 22 CFM in the valve.

In selecting a valve for long service we need to stay under 20 RPM. Rotary valves are sized on the basis of CFR - or net cubic feet of displacement per revolution. Thus, dividing 22 CFM by 20 RPM we get a minimum CFR of 1.1.

Now we must bring to bear the several variables such as:

- Flow ability of the fuel,
- Accuracy of the 11 CFM,
- Potential future rate changes,
- Expected wear, failures,
- Available sizes in pressure range.

Taking all of the variables into consideration, a valve with a CFR of 1.5 turning at 15 RPM would be a good choice.

The present RBS valves have an approximate CFR of 1.5 but if my information is correct they are turning faster, thus incurring more wear and venting more gas.

PULSES OF FUEL as a result of vanes/minute in a rotary valve can be evened out with the screw shown on -02. This triple flighted screw produces approximately 5 pulses/second and the dead zone further diminishes the pulse effect. This problem is obviously exacerbated by using an excessively large valve such as the IMPCO or Bauer, and necessitates a secondary metering function.

Since the dry fines almost literally "explode" in milliseconds, it is mandatory to provide as uniform a feed rate as possible.

If the vane or pulse frequency is about 1/8 second or less, it is not as necessary to even out the flow. The Meter Bin or Secondary Meter provides these fast pulse rates and when properly fed to a pneumatic system, it also helps even out the flow.

One method of nominally increasing the "pulse rate" is to add more vanes. Above 10 vanes it becomes a matter of diminishing returns since the pocket loading/unloading time is substantially diminished. Very large valves can use more vanes. 10 vanes also provide an opportunity to have at least 2 if not three vanes sealing at all times, which helps the leakage problem and places somewhat less emphasis on very tight clearances or sliding vane tips.

Increasing rotational speed not only affects loading/unloading but increases wear and usually increases pocket loss due to lower pocket loading.

Another method to help disperse the discrete pulses produced by a rotary valve or screw is to introduce one or more baffles in the drop chute to break up the free fall of a pocket load.

MANUFACTURERS of rotary valves are generally described and listed in Appendix A. Those making high pressure units were especially sought and the most likely candidates for the RBS application are:

C. E. BAUER - Div. COMBUSTION ENGINEERING

Springfield, Ohio 513) 390-3400

Mr. John Lemmon, Engineer - Jack Schaefer, Sales

Sizes: - 12 x 14 x 24, CFR 1.86

150 psi - Δ P & Internal

Wt. 5600 Lbs.

\$ 100,000

Poss. Recond. Avail.

- 18 x 20 x 33 CFR 9.0

150 psi - Δ P & Internal

Wt. 13,000#

\$ 170,-200,000

Cast steel w/ s/s overlay on wear/corrosion parts, replaceable barrel liner, stellite vane tips, tapered rotor for adjustment.

SPROUT-WALDRON

Muncy, PA - 717) 546-8211

Larry Wilson

In addition to a complete line of Standard Pressure rotary valves they have:

- 30 x 22 - CFR 6

150 psi Internal - 130 Δ psi

Wt. 9,000 #

\$ 125,000

(Operating at "Kiln Gas" gasifier)

- Will build same rating in

a) 20 x 18 - CFR 2.5

\$ 100,000

b) 16 x 14 - CFR 1.4

\$ 90,000

They are interested in working with us on this project.

BEAUMONT-BIRCH

Pennsauken, NJ - 609) 663-6440

Mrs. Judith Stelian - Mark Chalmers

Provides a wide variety of sizes and for special applications, including coal gasification.

STANDARD - 12" S.T.T. MARK II
 Approx. 18x18 - CFR 2.5
 75 psi Internal, 40 ΔP
 w/ Teflon Seals \$ 22,000

SPECIALS -
 a) - 12" S.T.T. MARK III
 18x18 - CFR 2.2
 150 psi Internal - 50 ΔP
 Est. \$ 30,000

b) - 12" S.T.T. MARK IV
 18x18 - CFR 1.9
 150 psi Internal - 150 ΔP
 Est. \$ 65,000

c) - 12" S.T.T. MARK V - ESTIMATE
 18x18 - CFR 1.9
 150 psi Internal - 75 ΔP Est. \$ 40,000

This firm is interested in these special applications. Of these options, the use of 2 - 75 ΔP valves is probably the best commercial choice, as well as being the least cost.

Other Possibilities

Beloit has a 75 psi internal pressure digester valve but is not too interested in special valves.

Ingersoll-Rand/IMPCO has three larger high pressure sizes but is not interested in smaller units.

Young Industries has 150 & 300 psi internal pressure valves as standard - and also Hi Temp - but does not build over 15 psi ΔP.

SYSTEMS COMPARISONS

- A) THE EXISTING SYSTEM at RBS consists of 4 RBS 12" Rotary Valves in series sitting atop the furnace, with fuel metered out of a multiscrew bin.

There are some very serious problems with this arrangement:

EXPOSURE TO HEAT - Their location atop the furnace exposes the valves unnecessarily to heat. Maintenance is also delayed by having to cool before working on them.

ACCESSIBILITY - The high location of both the meterbin and the valves greatly complicates inspection and maintenance.

Removing the bin and valves to ground level would:

- 1) Eliminate heat exposure;
- 2) Facilitate access to valves and bin, at a lesser cost, and reduce repair time and cost;
- 3) Provide a reasonable level of safety.

B) VERTICAL SCREW / METER BIN / LOCKHOPPER

Ref. Sketch -03

Equipment Only:

2-New Miles Lift Gate Valves	\$68,000
Precharge & Lockhopper	6,300
Meter Bin w/ Screws, V.S. Drive	43,000
Injector Screw & Drive	12,000
Vertical Screw (less Injector)	14,000
Aftercooler SAF-53 N, w/ 6" Cycl.	2,800
Piping, Valves, etc.	<u>3,500</u>

Total \$ 149,600

Note: If remodeled IGT Valves
were used, \$58,000 could be deducted

[Alternate \$ 91,600]

C) VERTICAL SCREW/METER BIN/ROTARY VALVESEquipment Only:

3 - Beaumont 12" STT valves	\$ 90,000
Meter Bin w/ Screws, Drive	43,000
Injector & Drive	12,000
Vertical Screw (less Injector)	14,000
Aftercooler SAF-53 N	2,800
Piping, Valves	<u>2,500</u>
	\$ 164,300

(If 2 - 75 Δp Rotary Valves used)

[Alternate \$ 154,300]

D) VERTICAL SCREW/ 3 ROTARY VALVES

Based on Beaumont quote of 50 Δ P/valve and using existing fuel metering bin relocated, and secondary meter/injector.

Equipment Only:

3 - Beaumont 12" STT Valves	\$ 90,000
Vertical Screw w/Modified Injector	30,000
Aftercooler SAF-53 N w/ 6" Cycl.	2,800
Piping, Valves, etc.	<u>1,500</u>
	\$ 124,300

(If 2 - 75 Δ P Rotary Valves used)

[Alternate \$ 114,300]

E) PNEUMATIC CONVEYING/METER BIN/LOCKHOPPEREquipment Only:

Aftercooler #194-N	\$ 6,600
Sutorbuilt 5 MV Blower	1,300
5 HP TEFC Motor	350
150 psi Enclosure	3,100
Pipe Fittings	<u>500</u>

TOTAL PNEUMATIC CONVEYING: \$ 11,850

Meter Bin w/ Screws, Drive	\$ 43,000
Lockhoppers	6,300
2 - New Miles Valves	68,000
Valves, Piping	<u>1,500</u>

Added \$ 118,800

TOTAL \$ 130,650

Note: If IGT Valves used:

[Alternate \$ 72,650]

F) PNEUMATIC CONVEYING/METER BIN/ROTARY VALVESEquipment Only:

Pneumatic Conveying	\$ 11,850
Meter Bin	43,000
3 - Beaumont Valves	90,000
Valves, Piping	<u>1,000</u>
TOTAL	\$ 145,850

G) PNEUMATIC CONVEYING/ 3 ROTARY VALVES

Requires external metering to valves

Pneumatic Conveying	\$ 11,850
Secondary Meter	10,000
3 - Beaumont Valves	<u>90,000</u>
TOTAL	\$ 111,850

Note: If a single 12" Bauer Valve is used
(at \$100,000) in place of the
3 - Beaumont Valves (\$90,000),
add \$10,000 to above figures -

[Alternate \$ 121,850]

OR If two 75 AP Beaumonts were used,
deduct \$10,000 -

[Alternate \$ 101,850]

SUMMARY OF COSTS

USING THE VERTICAL SCREW

B)	-	With Meter Bin & Lockhopper	\$ 149,600
		[or w/IGT Valves	\$ 91,600]
C)	-	With Meter Bin & 3 Rotary Valves	\$ 164,300
		[or w/ 2- 75# ΔP Valves	\$154,300]
D)	-	With Secondary Meter & 3 Rotary Valves	\$ 124,300
		[or w/ 2 - 75# ΔP Valves	\$114,300]

PNEUMATIC CONVEYING

E)	-	With Meter Bin & Lockhopper	\$ 130,650
		[if IGT Valves used -	\$ 72,650]
F)	-	With Meter Bin & 3 Rotary Valves	\$ 145,850
		[w/ 2 - 75# ΔP Valves	\$135,850]
G)	-	With Secondary Meter & 3 Rotary Valves	\$ 111,850
		[w/ 2 - 75# ΔP Valves	\$101,850]

NOTES:

These costs are estimates based on actual costs or preliminary supplier quotations, but they do not include any contingencies, installation, or engineering.

All rotary valves, vessels and piping are in compliance with the ASME PRESSURE VESSEL CODE, SECTION VIII, DIVISION 2, which would be the case in any commercial installation.

All of these systems will meet the operating requirements.

CONCLUSIONS:

- 1) It is interesting to note the relatively narrow cost spread across the 6 options.
- 2) If two or more rotary valves are used, the combined pocket and leakage losses are comparable to that of the lockhopper.
- 3) The lockhopper has fewer wearing elements and would require less maintenance.
- 4) Option G with rotary valves and pneumatic conveying is least cost and has the advantage of greater capacity if needed, as well as uniform flow.
- 5) The vertical screw has more wearing parts than the pneumatic system and has a lower "pulse rate" - 1/4 sec.
- 6) Any of the pneumatic options will have a higher "pulse rate" - more uniform flow.
- 7) The 80 gpm water requirements for cooling pneumatic conveying air may be a problem. There is an option of reducing this to about 30 gpm by using an air precooler, with added cost (about \$5,000).

RECOMMENDATIONS

- 1) Proper safety provisions must be made at the RBS plant - and not just be limited to the valves/bin situation.
- 2) Investigate availability of 80 gpm of cooling water, also 30 gpm.
- 3) Based on 2) results, select either D) or G).
- 4) Request formal quotes from Sprout-Waldron, Beaumont, Bauer, and anyone else interested - for valves in the 1.5 - 2. CFR range:
 - a) (3) 150 psi internal - 50 psi ΔP
 - b) (2) 150 psi " - 75 psi ΔP
 - c) (1) 150 psi " -150 psi ΔPand for quantities that would include spares and projected future requirements.
- 5) Move the Meter Bin and Feed System to ground level in any event.
- 6) The above steps would only be taken if it is determined that all of the other components in this relatively sophisticated power generation system are operable and reasonably maintainable.

Thos. R. Miles

SCHEMATIC - RBS 3 MW PLANT
WITH 3 ALTERNATE FEED METHODS
USING PNEUMATIC CONVEYING

THOMAS R. MILES CONSULTING DESIGN ENGINEERS 3473 S.W. Arrowwood Lane, Portland, Oregon 97235 Area 391 392 5181	
DES <i>TRM</i> CHK Date <i>7/11/84</i> Scale <i>SCHEM</i>	SCHEMATIC - RBS 3 MW PLANT WITH 3 ALTERNATE FEED METHODS FOR RUS CORP. RED BOLLING SPRINGS, TN 5064-01

5475 S. W. ARROWWOOD LANE
PORTLAND, OREGON 97225
503/292-2919

SAF-S3. AFTER COOLER

VERTICAL SCREWLIFT W/ ROTARY VALVES
OR LOCK HOPPER / METER BIN

506.4-03

TRM

APPENDIX A - ROTARY VALVES

An extensive search was initiated to determine who is offering various types of rotary valve, especially high pressure units. Rotary Valves, or Airlocks (sometimes called Feeders) fall into 4 pressure classes and several special use classes:

- 1) Very Low Pressure - up to 1 psi - light gauge with flexible rubber tips. For low pressure conveying in agriculture, dusts, etc.
- 2) Standard Pressure - 1-10 psi (some to 15 psi) fabricated or cast construction, general purpose. In this range internal and differential pressures are about the same. Majority of sales are in this class.
- 3) Medium Pressure - up to 20 psi
- 4) High Pressure - 20-75 psi differential pressures with internal pressures to 600 psi. Virtually all are custom above 15 psi ΔP .
- 5) Very High Pressure - 75 to 150 psi differential pressures. Three manufacturers offer standard valves in, variously, 24, 30, 36, and 42 diameter Rotors, S/S Construction, Cross Vented. Many in use in feeding continuous digesters in pulp mills, CFR starts at 7.0, prices are \$175,000 to \$220,000.
- 6) Special Wood Chip and Biomass handling valves, Standard Pressure and contain knife to cut fiber and avoid jams. 2 principal sources.
- 7) Special High Temperature and/or High Pressure Valves for Coal Gasification and Chemical Processing.
- 8) Will build custom valves for high differential pressures.

(Appendix A - Rotary Valves, continued)

The following list of Rotary Valve suppliers offer equipment in the classes noted:

CLASS	SUPPLIER	TELEPHONE
4,5	BELOIT - Jones Div. - W. Office: Digester Valves - Jack Connon 18, 24, 30 - 75 psi	503) 255-5330
5	BAUER, C. E., West Coast office, Beaverton OR 150 psi, Pulp Digester Feeders, CFR 2.+ Ike Thomsen	503) 641-3086
2,3,4,8	BEAUMONT BIRCH - Pennsauken, NJ Mrs. Judith Stelian, Mark Chalmers Std to 75 psi, CFR to 2.5, wide variety, will build to suit.	609) 663-6440
1,2,3	CARTER-DAY - Minneapolis, MN Conveying, Dust Systems	612) 781-6541
1,2	COLT-ON, MAC - Sabetha, Kansas General Purpose - 2 CFR - Dave Remmers	913) 284-2196
2	DETROIT STOKER - Monroe, Michigan Ash Handling to 1 CFR	
2,3	DUCON FLUID TRANSPORT - King of Prussia, PA Mostly Ash Systems, 18" max. diam., CFR to 1.5	215) 337-3770
1,2	FLOTRONICS - Minneapolis, MN	
2	FULLER - Catasauqua, PA Fuller-Kinuron Dry Powder Pump, Rotary Valves	

(Appendix A - Rotary Valves, continued)

CLASS	SUPPLIER	TELEPHONE
2	GENERAL RESOURCES - Hopkins, MN General Applic. CFR to 4.5	612) 933-7474
5	INGERSOL-RAND (IMPCO) - Vancouver, WA Manfred Durek Fred Emmerling, Nashua, NH Pulp Digester Valves - 150 psi, CFR 9. +	206) 573-5211 603) 886-5604
5	KAMYR - Glens Falls, NY	
2	MEYER, Wm. - Skokie, IL Jerry Domke, Bill Meyer General Applic. - CFR to 49.5	312) 463-5127
1,2	PRATER - Chicago, IL General Conveying	312) 652-6200
2,3	PREMIER PNEUMATICS - Salina, Kansas General Conveying	913) 825-1611
2,6	PSI CONVEYING GROUPS, 5895 SW Jean Road Lake Oswego, OR Wood Chip Conveying, w/knife	503) 635-3746
2,6	RADER COMPANIES Wood Chip Conveying, w/knife, sizes to 72x72	
2	SCHICK - Kansas City, MO General Conveying	816) 861-7224
2,3,6	SEMCO SYSTEMS - Houston, TX Gen'l Convey. - Chip Feeder w/knife	713) 869-3583

(Appendix A - Rotary Valves, continued)

CLASS	SUPPLIER	TELEPHONE
2,3,4,5,8	SPROUT WALDRON - Muncy, PA Larry Wilson General Conveying Will build Hi Pressure	717) 546-8211
1,2	WESTERN PNEUMATICS - Eugene, OR Wood Chip Systems	
2,3,4	YOUNG INDUSTRIES - Muncy, PA Roy Schwartz Hi Temp or Hi Internal Pressures	717) 546-3165

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