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The use of biomass fuels for power generation and process hot water and steam is an important aspect of cultural and economic development of many Pacific Rim countries, even including portions of some technologically advanced countries. Much of this biomass will be burned in relatively small combustors of the order of one to ten million Btu per hour in fluid bed combustors. While there is significant emission potential with biomass fuel, the relatively small size of the equipment provides certain advantages in obtaining adequate emission control. The specific design of a 3 million Btu per hour fluid bed combustor is described, and items such as furnace sizing, cyclone selection, and back end treatment of the flue gas is discussed. This particular application is to provide high temperature heat to an "externally fired" gas turbine for power generation (200 kw net), with optional waste heat available for steam, hot water heating or steam driven chillers. The unit described is being installed in a lumber mill in Georgia (USA) for EPA evaluation, and several others are being considered for installation in the Caribbean and Pacific islands areas.

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EMISSION CONTROL OF SMALL FLUIDIZED BED COMBUSTORS UTILIZING BIOMASS FUELS

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ABSTRACT

The use of biomass fuels for power generation and process hot water and steam is an important aspect of cultural and economic development of many Pacific Rim countries, even including portions of some technologically advanced countries. Much of this biomass will be burned in relatively small combustors of the order of one to ten million Btu per hour in fluid bed combustors. While there is significant emission potential with biomass fuel, the relatively small size of the equipment provides certain advantages in obtaining adequate emission control. The specific design of a 3 million Btu per hour fluid bed combustor is described, and items such as furnace sizing, cyclone selection, and back end treatment of the flue gas is discussed. This particular application is to provide high temperature heat to an "externally fired" gas turbine for power generation (200 kw net), with optional waste heat available for steam, hot water heating or steam driven chillers. The unit described is being installed in a lumber mill in Georgia (USA) for EPA evaluation, and several others are being considered for installation in the Caribbean and Pacific islands areas.

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INTRODUCTION

Electric power generating biomass plants have always represented a challenge for the designers. This is particularly so in small sizes of the order of a few hundred kilowatts of electrical power, because of the conflicting requirements of keeping the equipment simple, while still attempting to meet current concepts of being low polluting devices.

As a quick review of the current situation, there are still areas of the world where there is little or no electrification. Often, because of population sparsity or geographical obstacles there is little anticipation that these areas will ever be provided electric power as part of a distribution system connected to central power plants. Where electricity is to be provided it is and will be provided by diesel generator sets which consume up to 0.1 gallons of fuel per kilowatt hour generated. Even at heavily subsidized costs of $1 per gallon the fuel cost is 10 cents per kilowatt hour. In many locations where delivered diesel prices are $2 to $4 per gallon, the cost of electrical power can be prohibitive. In many of the outlying areas, this constitutes a clear incentive to develop biomass fueled systems.

This paper concentrates mostly on the combustion portion of a well known, but seldom used concept of using an externally fired gas turbine as the prime mover for the generation. The advantages of such a system is no water requirements whatsoever along with no boiler water treatment equipment, low pressures, and ease of replacement/overhaul of the prime mover.

Other challenges not detailed in this paper, but mentioned in passing, are those involving much higher operating temperatures than those associated with steam systems, necessitating the use of aerospace type alloys. Also required are unique control systems to regulate the biomass fuel flow, and controls and safety valves to insure the safety of a gas turbine with a large thermal mass connected.

The specific fluid bed/turbine system discussed herein is commercially offered by ENERGEO, Inc., San Francisco, California. The unit has the trade name "AGRIPOWER" and is fabricated in modules and assembled at manufacturing sites for shipment to the location of end use for quick installation and operation with little site preparation. The 200 kilowatt electrical unit comes on two skids which conform to shipping container and highway sizes. Because essentially no onsite construction is normally required, the unit can be operating within a week.

The trial installation at a lumber mill in Georgia is being funded by the U.S. Environmental Protection Agency, the U.S. Department of Energy, the U.S. Department of Defense, and the Tennessee Valley Authority.

DESCRIPTION OF FURNACE

Figure 1 is a schematic representation of the fluid bed and radiant furnace. It contains all the elements relating to the combustion of biomass fuels for the power system. Also, it is important to keep in mind that though simple in concept, the conditions selected for the combustion process have evolved from numerous studies and experiments which have been directed toward maximizing the electrical power output from an externally fired gas turbine cycle, while at the same time emphasizing simplicity.

As a generic type this combustor can be classified as a "bubbling" fluid bed operating at atmospheric to slightly subatmospheric pressure (negative draft furnace). Due to the fuel type currently being commercialized (wood) the distribution of air is one third to the fluid bed and two thirds to the secondary air. This is almost in proportion to the fixed carbon to volatiles in the fuel (24% and 72% respectively). Because of the large amount of secondary air, and the velocity of injection (200 - 300 ft/sec), the entire furnace can be modeled as a well stirred reactor. The mean residence time of the reactants in the furnace is approximately four seconds, and also would be the residence time calculated from the point of fuel injection.

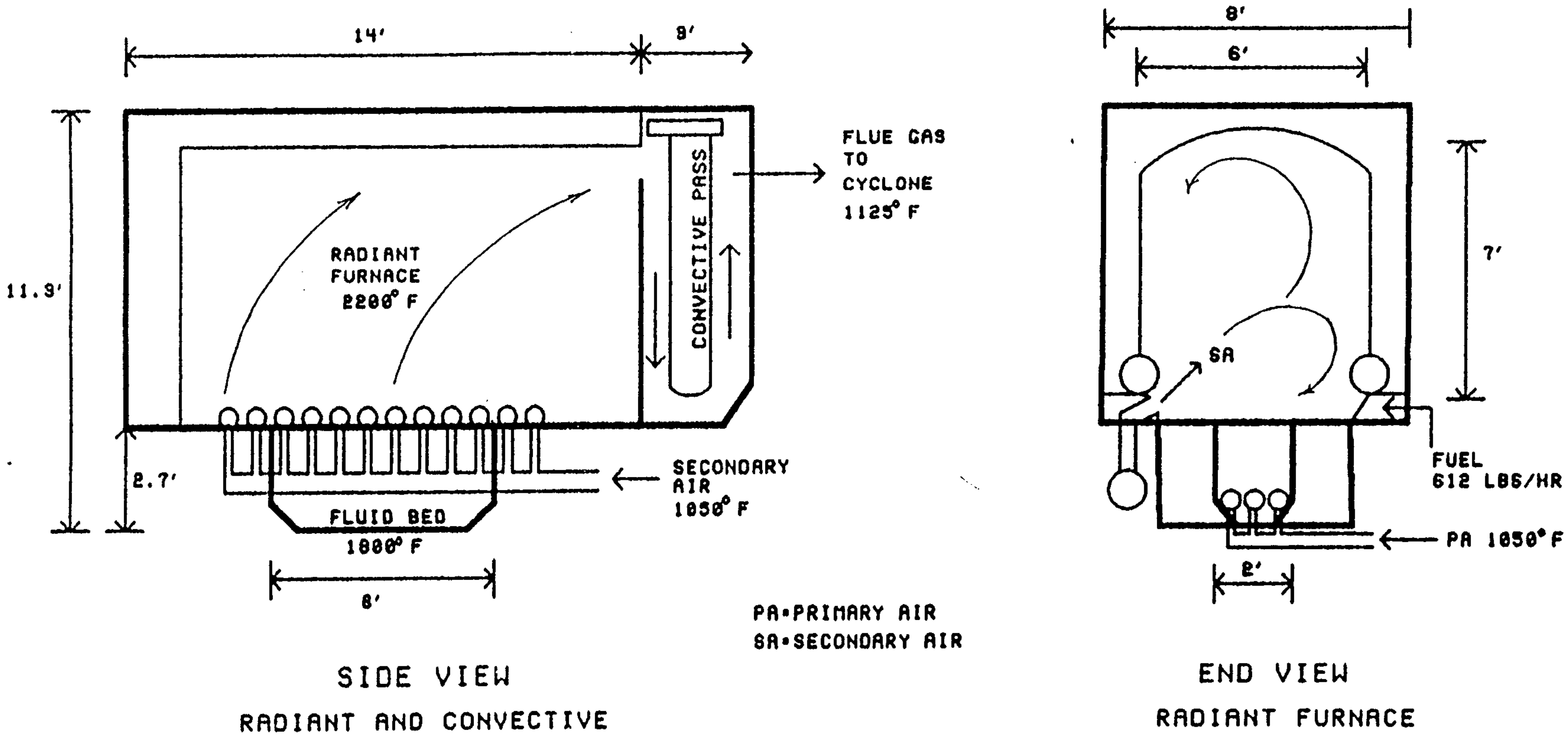

FIGURE 1. AGRIPOWER 200 KW FURNACE AND FLUID BED SCHEMATIC

The radiant furnace is designed to operate in the 2200°F to 2400° F range. The bed will operate at lower temperatures, closer to 1800° F. These temperatures are higher than those commonly used in larger installations, and is due primarily to the requirement of obtaining 1600° to 1650° F temperatures on the pressurized air side back to the gas turbine. The bed material is a refractory sand, capable of withstanding high temperatures without fusing. Also it should be noted that this is approximately a 2:1 scale up from a previous experimental fluid bed/furnace/gas turbine cycle. Actual operating data on this design is not yet available, as the unit is now scheduled to begin operation in the spring of 1995.

It should be noted that operating temperatures chosen for wood fuel are not conducive for sulfur capture by limestone (1550° F process), and are not recommended for fuels containing silica, such as rice hulls. For these fuels, reduced bed temperatures, and furnace temperatures are required, which can be obtained by heat absorbing elements within the bed, changes in excess air, and possible changes in the turbine peak operating temperature.

NO_x Control

Nitrogen oxides are formed by both of two mechanisms. One is the direct conversion of gaseous nitrogen at high temperatures to nitrogen oxide, and the other is the conversion of organic nitrogen to nitrogen oxide. Although in this design it is expected that all of the nitrogen oxides may come from the fuel nitrogen, it is still worthwhile to review the thermal NO_x formation.

Figure 2 shows the nominal lower heating value of the candidate wood fuel versus moisture content. Typical ranges for moisture content are from 30% to 70% water on a dry fuel basis. At 50% moisture the LHV is approximately 5000 Btu/lb of fuel (dry fuel plus water). The fuel analysis is presented as Table 1, and represents both a specific wood and a "typical" wood.

TABLE 1 - WOOD FUEL ANALYSIS

CARBON %	49.89
HYDROGEN %	6.00
OXYGEN %	42.96
SULFUR %	.04
NITROGEN %	.11
ASH %	1.00
HHV, BTU/LB DRY	8700
MOISTURE % DRY	45
VOLATILES % DRY	72
FIXED CARBON % DRY	24

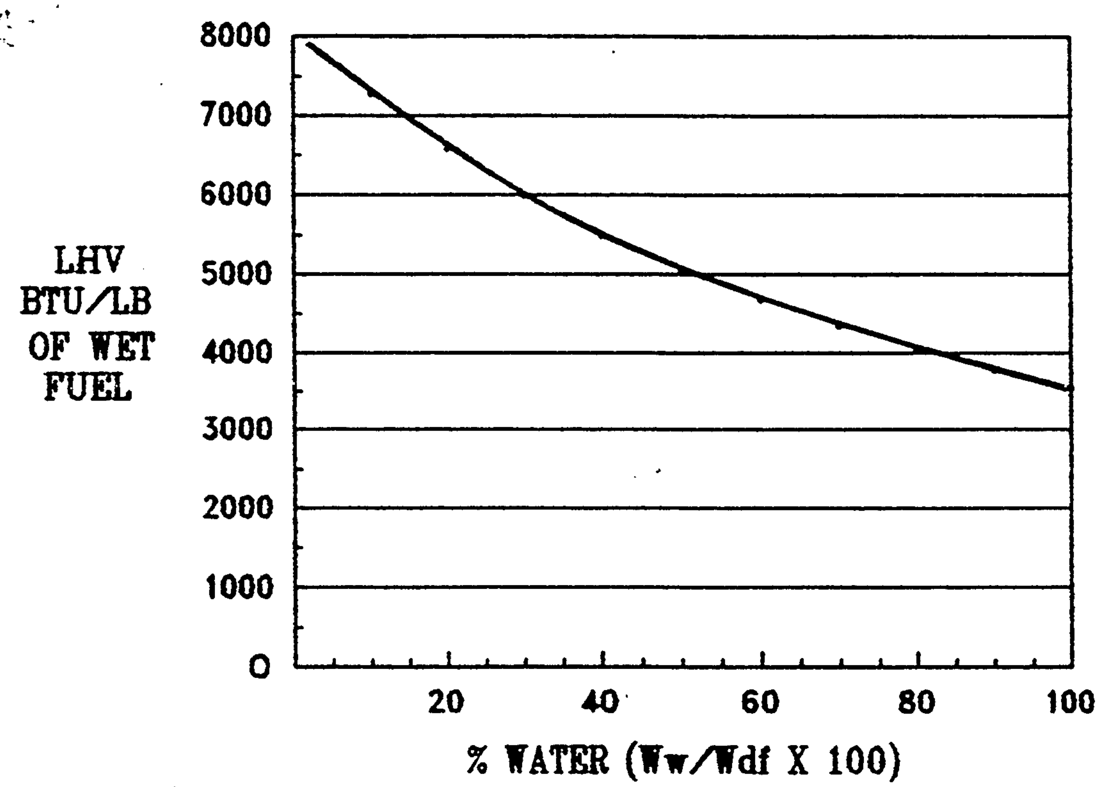

FIGURE 2. NOMINAL LOWER HEATING VALUE OF WOOD FUEL VERSUS WATER CONTENT

From the fuel analysis (composition and moisture content) a calculation of flame temperature versus equivalence ratio can be made for the conditions of adiabatic heat release, and also the present case of a well stirred reactor with significant heat transfer. For ease of calculation, the nondissociated temperatures are shown, which means that the no heat loss case is higher than would be measured, but does not affect the calculation of the furnace temperatures with heat loss, since these are in the range where dissociation is not significant. For the existing design, Figure 3 presents these idealized calculations showing both the adiabatic case and the actual design case with significant heat loss. With the intended heat extraction from the furnace to the turbine cycle, and at equivalence ratios of from 1.2 to 1.5, temperature of the "well stirred reactor" will range from 2350° F to 2150° F.

Following the calculation of temperature, an equilibrium NO_x calculation can be made at the temperatures, and excess O_2 represented by the fuel composition and equivalence ratio. Without heat loss, very high equilibrium NO_x theoretically could exist, and even with heat loss equilibrium values of around 500 ppm could exist if formed. These values are shown in Figure 4.

To determine actual thermal NO_x, rates of formation need to be calculated and applied to the residence time in the furnace. These values are shown in Figure 5, for the heat loss case, and even at the lowest equivalence ratio formation rates of less than 1 ppm per second are calculated from the standard Zeldovich mechanism. However, it should be noted that if well stirred conditions do not occur throughout the radiant furnace, formation rates of localized areas could approach 3000 ppm/sec.

Fuel nitrogen originated NO_x represents another source of NO_x emissions. In this case, the process conditions are not so favorable and the current literature suggests conversion ratios of from 18% to 55% of the fuel nitrogen to nitrogen oxides. At .11% nitrogen in the fuel, 100% conversion would be 320 ppm, and optimistically a 20% conversion will occur, but still result in emissions of 64 ppm (.08 lbs/million Btu of higher heating value), or about .4 lbs per hour. This is still an area of concern, and will be monitored during the startup tests.

For higher nitrogen fuels, a two stage convective section with ammonia injection at a 1750° F window could be considered, but equilibrium values of NO_x at an equivalence ratio of 1.5 would be around 125 ppm. This sets a lower limit on the NO_x reduction available with thermal deNO_x methods. Further reduction would require selective catalytic reduction, and potential difficulties with catalyst plugging by flyash. Selective catalytic reduction could be accomplished after a bag house if the combustor flue gas was reheated to 700° F by the turbine exhaust.

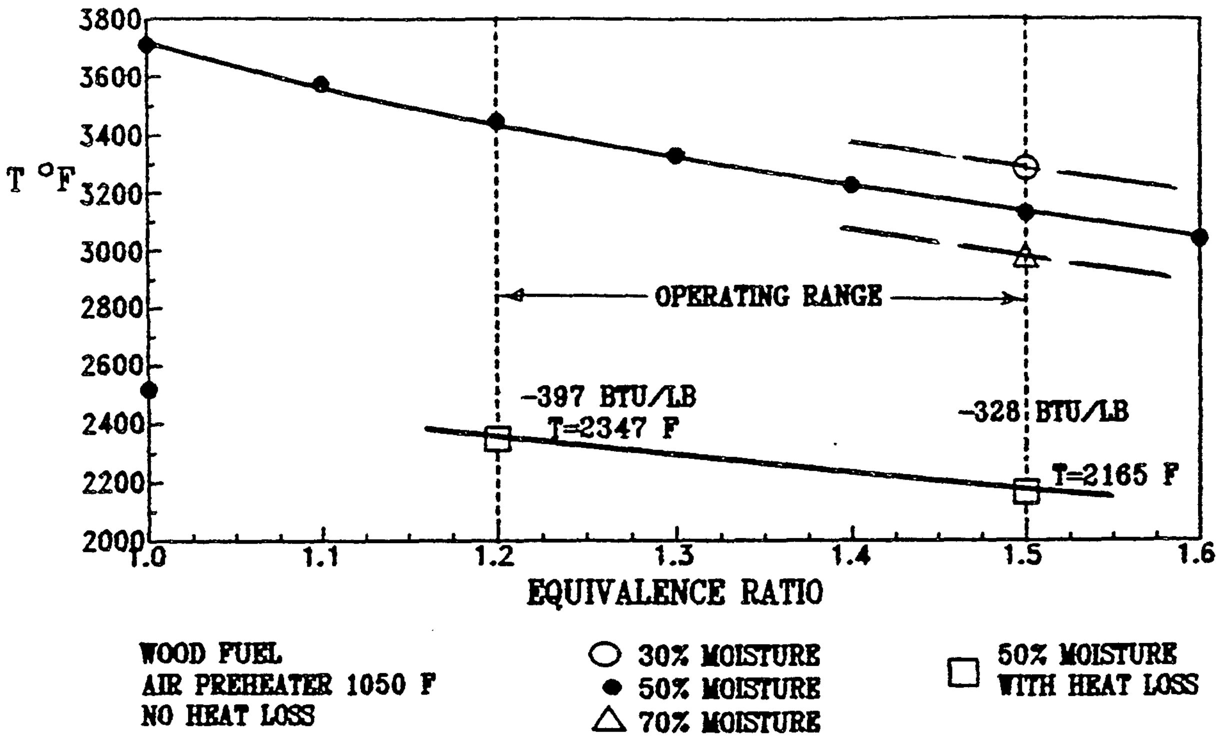

FIGURE 3. APPROXIMATE FLAME TEMPERATURE VERSUS EQUIVALENCE RATIO

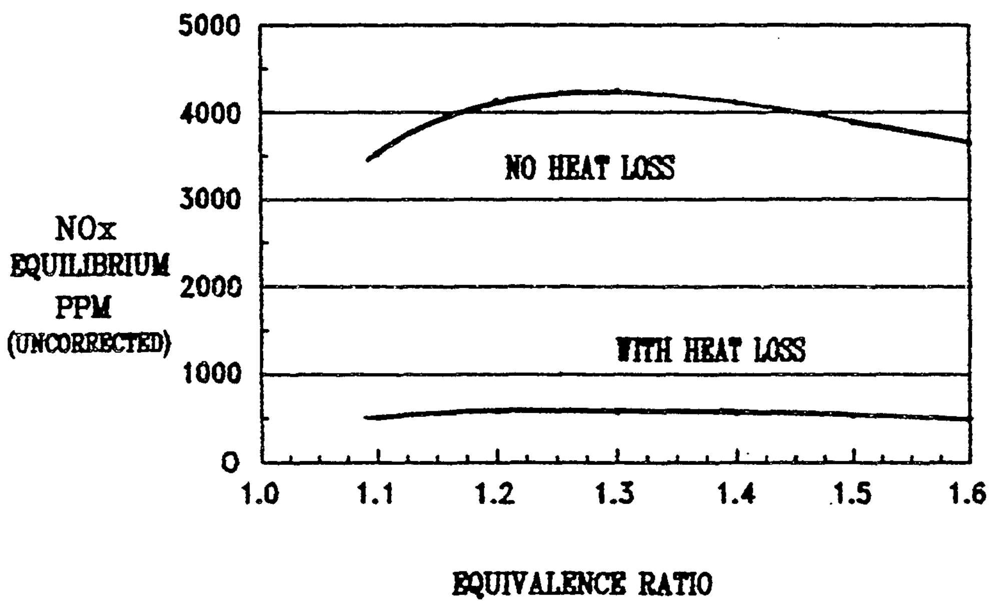

FIGURE 4. THEORETICAL EQUILIBRIUM NOx VERSUS EQUIVALENCE RATIO WOOD FUEL, 50% MOISTURE

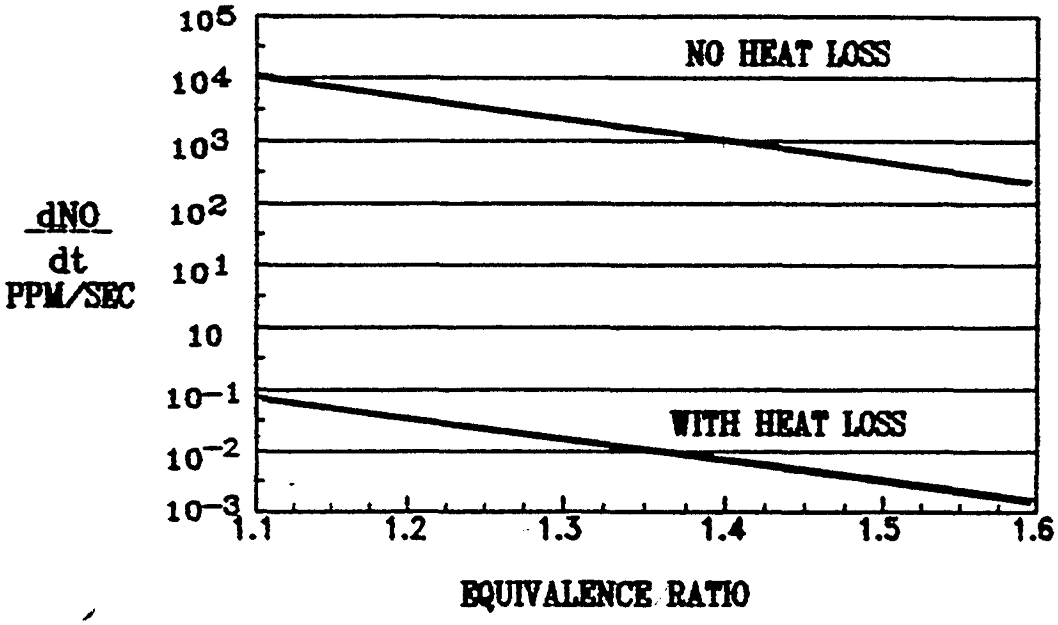

FIGURE 5. THEORETICAL NOx FORMATION RATE VERSUS EQUIVALENCE RATIO

VOLATILE ORGANIC COMPOUNDS AND UNBURNED HYDROCARBONS

The long residence time (4 sec) and high temperature (2200° F) minimize problems associated with unburned hydrocarbons, or any form of organic compounds being emitted. In the unlikely event these did occur, the design lends itself to the addition of a refractory chamber pass following the furnace and prior to the convective section to add to the residence time at high temperature. Since the system is constructed in modules, and velocities are low, refractory blanket material could be used for this component as well as its current use in the furnace.

PARTICULATE CONTROL

Particulate control is accomplished primarily by a moderate pressure drop (7 in. H_2O) cyclone operating with geometric parameters to give an overall pressure drop of 8 times the velocity head. Temperature at this point in the cycle is approximately 1125° F, and the cyclone is stainless steel sheet construction.

For the design wood fuel the ash content is 1% of the dry fuel. The cyclone utilized has a capture efficiency approaching 90% so that the final particulate emissions are approximately .12 lbs per hour or approximately .04 lbs/10^6 Btu. Elutriation of the fluid bed material (high alumina content refractory sand) also contributes to the particulate material. The bed is approximately two feet by six feet by 18 inches deep and contains approximately 1800 lbs of material. A loss rate of 1% per day will contribute another .02 lbs/10^6 Btu emitted if the cyclone capture rate is 90% for this material also.

In the event that greater particulate reduction is required the overall cycle has been designed such that the stack temperature is 400° F, which allows the installation of a low cost bag-house. This may also be desirable if the plant is close to habitation where PM_{10} (particles less than 10 microns) is a concern. The 400° F temperature is also required if the induced draft fan design and power consumption is to be reasonable.

SULFUR EMISSIONS

Sulfur level in the candidate wood fuel is .04%. This converts to .092 lbs of SO_2 per million Btu or 50 ppm in the flue gas. This will result in approximately .28 lbs per hour SO_2 emissions. It is expected that bed temperatures will be well above the 1550° F considered optimum for limestone capture, so that the sulfur emissions will be essentially unabated. For higher sulfur fuels a "dry" scrubber would need to be installed after the air preheaters. This would provide an added advantage of dropping the flue gas temperature slightly and reducing the load on the induced draft fan.

OVERALL CYCLE CONSIDERATIONS

The overall cycle is shown in Figure 6. The turbine system operates with an "open" Brayton cycle using a fluid bed combustor and several heat exchangers to heat compressed air and drive a turbine generator set. The turbine generator set including the compressor is a Solar "Spartan" set and recuperator packaged for this application by Alturdyne of San Diego, California. The balance of the system was designed by ENERGEO and HB Energy, and fabricated by PMC Production in Sacramento, California. A turbine combustor (diesel fired) included in the system is used for startup and may be used to supplement the biomass fuel for maximum output if restricted bed temperatures are required or for trim control of the turbine. Also the turbine exhaust from the recuperator is clean, hot air (500° F) which can be used in a variety of processes.

There are two primary flow circuits in the process. The power cycle (turbine cycle) and a combustion cycle. The compressed air turbine cycle begins with the intake of ambient air through filters by the compressor which is direct powered by the turbine. The air is

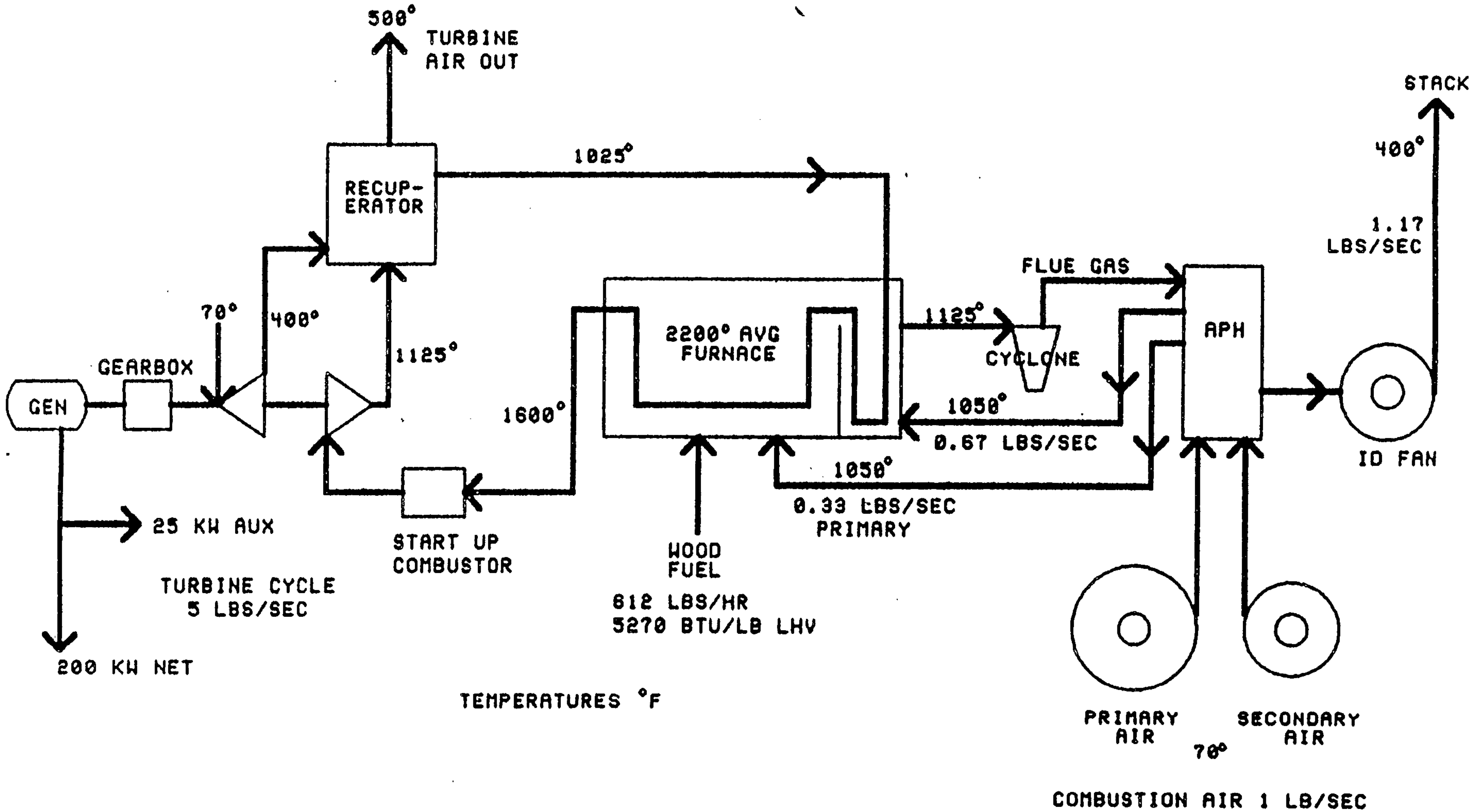

FIGURE 6. OVERALL SYSTEM CYCLE

compressed to four atmospheres with resultant heating to about 400° F and passes through a recuperator which transfers over half the heat from the power turbine exhaust to the compressed air. From the recuperator the air passes to the convective section of the furnace, and then to the radiant section of the furnace. Each contributes approximately equally to the temperature rise of the air. The heated, compressed air then passes through the inline turbine combustor, and may receive additional heat, and then to the power turbine which is coupled to the compressor and the electrical generator. The turbine exhaust then passes through the recuperator and exhausts to the atmosphere or through lower temperature heat recovery devices such as water distillation units.

The combustion circuit uses two air fans to provide preheated air to the fluid bed (primary air) and to the furnace above the bed (secondary air). Biomass fuel is supplied to the furnace by a feed hopper and screw conveyors. Two screws located in the bottom of the hopper regulate the flow of fuel to a third screw which injects the fuel above the fluid bed. The temperatures both in the bed and above the bed may be regulated to limit potential problems associated with the ash. After giving up energy to the compressed air through the radiant and convective heat exchangers the combustion gases pass through a cyclone for removal of the fly ash. From the cyclone the flue gases are used to preheat the combustion air streams via the air preheaters. An induced draft fan exhausts the flue gases to atmosphere, and is controlled to maintain a slight negative pressure in the furnace above the bed. An optional baghouse may be installed downstream of the induced draft fan.

The motors for the screw conveyors and all fans are variable speed as part of system control. Feedback from the power output of the electrical generator and the inlet to the power turbine are used to regulate the amount of fuel supplied to the furnace. Key furnace temperatures are used to control the combustion air supply. Individual controllers are used for each principal control loop. The individual controllers are supervised by a digital computer providing overall control of the system. In the event of a computer failure, the individual controllers can operate independently.

Design specifications for the Georgia lumber mill installation call for consumption of 612 pounds per hour of fuel with a lower heating value of 5270 Btu/lb on a wet basis with 45% moisture - % moisture defined as 100 x (wet weight of sample - dry weight of sample)/(dry weight of sample). Start up fuel for the gas turbine combustor is preferably No. 1 Diesel Fuel, and a flow rate of approximately 10 to 12 gallons per hour is required for the start up, electrical synchronization with the power grid, and operation of the fans and screw feeder to bring the fluid bed up to temperature. After the unit is running on biomass, the diesel fuel is cut off entirely, and so long as the unit is synchronized to a large grid, speed control is not required and the screw feeder will be controlled by turbine inlet temperature set point.

ALTERNATE SYSTEMS AND CONSEQUENCES

Although an optimized system for wood fuel has been presented, and the emission characteristics examined, it is by no means certain that this system is universal for all size ranges and all fuels.

Fuels containing low melting point ash, such as rice hulls may require reduced temperatures to avoid the formation of "clinkers" in the bed, and glass deposits on the convective tubes. This would require that the turbine air leaving the furnace be at a reduced temperature, and thus the power turbine output would be reduced, unless the in line combustor were utilized with a premium fuel. This partially defeats the purpose of the biomass fueled system, but may still be a good solution, since the premium fuel could be used as a "topping" fuel whenever maximum power was required.

Even with well behaved biomass fuels, high nickel alloys are required for the radiant furnace, and the higher temperature portion of the convective section. This may be an excellent application for the ceramic tube materials which are emerging from research and edging toward commercialization. Pressures are relatively low, and the temperatures are not extreme for ceramics.

More open convective section designs would be beneficial, but heat transfer efficiency drops as gas velocity drops. Lower cost alloys would allow more maintenance friendly designs.

Though not directly related to the combustion process, one of the most exciting developments in small power systems is the "shaft speed" alternating current generator. By computer controlled solid state electronics, in phase ac power can be generated without the generator being physically in phase with the system. This means that with high speed turbines such as the Spartan (shaft speed 37057 rpm) the gearbox with its attendant weight and complexity can be eliminated. Accurate speed control is not required and from that sense reduces the impact of control system inputs. These devices have been perfected for generators up to 300 kW and are now undergoing commercial evaluation. It is anticipated that future ENERGEO products will incorporate this technology.

Because of the thermal energy contained in the waste heat streams - flue gas and turbine exhaust recuperator exit - several auxiliary devices can be coupled to the system. These include possible fuel drying, water distillation or purification, water heating; and steam for uses such as food processing, chillers, and air conditioning systems. Since these devices would be running off a waste heat stream, high efficiency is not required for the initial introduction of these improvements.

SUMMARY

The externally fired gas turbine cycle presents many challenges to the designers of such systems. The ability to burn fuel of any quality, independent of the gas turbine process air requirements is too tempting an area to ignore. Virtually any fuel is a candidate - wood, agricultural waste, coals, trash, etc.

Good understanding of materials, and imagination in designing the heat exchange elements are essential. This is an area which is totally open to innovation.

Combustion generated emissions, will always be of major concern for fluid bed combustors. The operating temperature windows are not always optimum for reduction of the pollutants under consideration, as bed temperatures may be above those utilized for limestone sulfur capture. Excess air requirements for temperature control, may be contrary to that for NO_x control. The fluid bed material itself constitutes an additional particulate load on clean up equipment.