SAWMILL, WOOD WASTE FUELLED, 100% RECUPERATED, 5 MW GAS TURBINE CO-GENERATION PLANT

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ABSTRACT

Sawmills in the Canadian province of British Columbia (BC) will soon be confronted with a collective wood waste disposal problem (bark, sawdust and shavings) of about 3 Million bone dry tonne/y at an average wet basis moisture content of about 45%. About 40 existing sawmill beehive burners presently incinerate this waste. Emissions from these beehive burners exceed current provincial particulate limits. Markets for the waste - board plants, sawdust digesters, charcoal plants, etc. - are limited. The economics of 25 to 50 MW wood-fired, steam power plants is poor. 6¢/kW.h is needed to finance a plant; the major utility offers 2¢/kW.h.

This paper describes a 3 MW to 5 MW, Nuovo Pignone PGT-5 co-generation plant fuelled by the 2000^{o}F (1093^{o}C) exhaust from a Heuristic EnvirOcycler, a two-stage, wood waste incinerator. The exhaust meets BC's particulate limit of 0.052 grains/dscf (120 mg/Nm^{3}). 37 to 65 Million Btu/h (39 to 68 GJ/h) of waste heat can be recovered from the system exhausts. In this application the PGT-5's external combustion chamber is replaced by a "recuperator", i.e., a high temperature, gas-to-air, heat exchanger.

Two variations of the basic system are examined. One features a larger than necessary EnvirOcycler to generate additional steam in the waste heat boiler. The other variation discusses heating 1550^{o}F (843^{o}C) air from the recuperator up to 1796^{o}F (980^{o}C) with natural gas. The extra power generated can cost as little as 1.9¢/kW.h.

INTRODUCTION

"Beehive burners", also known as "tee-pee" or "wigwam" burners, are large, conical, black iron incinerators used by sawmills to incinerate their wood waste. Some beehive burners can dispose of as much as 200,000 bone dry tonne/y at a moisture content of 45%, wet basis. The remaining 40 or so large BC beehive burners currently operate at the same emission levels they did decades ago. Unless extensive emission controls are installed pending BC environmental legislation will force their closure.

The use of beehive burners in BC in the late 1990's is contentious. Most medical authorities consider them to be a health concern. Beehive burners in the US Pacific Northwest were shut down in the early 1970's. Beehive burners continue to operate in BC despite efforts in most other industrialized countries to eliminate them due to their high level of emissions. However, during the last 20 years, BC beehive burners have become somewhat cleaner as more combustion air and better controls were installed.

Also during the last 20 years, in the US PURPA - the Public Utilities Regulatory Policies Act enacted by the Congress in 1978 in response to the sharp increase in the price of oil in the mid to late 1970's - came and went. A whole host of biomass power plants were built in the 1980's which took advantage of the 8 ¢/kW.h to 12 ¢/kW.h "avoided costs" utilities were forced to pay for power generated by these PURPA plants. In recent years deregulation of the US power industry has all but eliminated the PURPA rates. As a result, most of the PURPA biomass power plants have been shut down.

New environmental legislation was introduced in BC in 1993. A particulate limit of 120 mg/Nm^3, equivalent to 0.052 grains per dry standard cubic foot (grains/dscf), corrected to 8% oxygen by volume, was imposed by the Ministry of Environment (MoE) on all wood waste incinerators in the province. To date 40 of the smaller beehives have been shut down. However, the bulk of the last 40 beehive burners have yet to be shut down.

In an earlier paper on the EnvirOcycler (2nd Biomass Conference of the Americas, Portland OR, 1995) we showed that the cost of wood waste disposal in an MoE-compliant EnvirOcycler, was about CDN $7/wet ton. Displacing the cost of the sawmill's power and natural gas - for lumber drying and building heat - with energy recovered from an EnvirOcycler coupled to a recuperated gas turbine system, reduces the cost of waste disposal to about CDN $3/wet ton.

Developers are available to finance such systems. At the end of a finite period of time - 8 to 10 years - title to the system transfers to the sawmill. From that point onwards the sawmill is independent of natural gas and electricity price increases.

An innovative form of financing emerging today is the formation of joint ventures between developers connected to the utility business and sawmills. The joint venture operates the small co-generation plant, using sawmill labor, the developer markets the surplus power and the developer and sawmill share in the profits. This type of financing seems to be spurred by CO_2 offsets in the post-Kyoto era.

The major obstacle to these solutions being implemented in BC is the forest products industry's difficulty in accepting the fact that a "tipping fee" must be paid for each ton of wood waste disposed. Up until now the industry has been able to burn its wood waste in beehive burners at minimal cost.

RECUPERATED GAS TURBINE

In a typical axial gas turbine air is induced into the gas turbine's compressor, pressurized and led to either an annular combustion chamber or to a series of parallel, cylindrical combustion chambers. There, fuel is injected and burned. The mixture of fuel products of combustion and compressor discharge air is blended down to the design turbine inlet temperature (TIT). The hot, pressurized mixture expands through the turbine. The turbine does work and drives the compressor and the generator.

In a recuperated gas turbine, the combustion chamber is replaced by an external, high temperature, heat exchanger, i.e., a "recuperator". In this case, pressurized, compressor discharge air is routed, at right angles to the turbine centerline, to and through the tubes of the external recuperator, where it is heated up to an elevated temperature compatible with the metallurgy of the tube materials, and then routed back to the turbine inlet.

The 2000^{o}F (1093^{o}C) EnvirOcycler "flue gas" serves as the energy source to heat the compressor discharge air up to the TIT. The "flue gas" is delivered to the top of the shell side of the recuperator. It is then drawn down, cross-flow-like, over the air filled tubes, under the action of an induced draft fan.

Some gas turbine manufacturers supply their machines with external combustion chambers already mounted at right angles to their turbine centerlines. These gas turbines readily lend themselves to being recuperated. The 5 MW, Nuovo Pignone PGT-5, manufactured in Italy, is one such machine. It is fitted with a single external combustion chamber. Its design TIT is 1796^{o}F (980^{o}C). The recuperated PGT-5, with TIT's ranging from 1500^{o}F(816^{o}F) to 1796^{o}F (980^{o}C), is the subject of this paper.

The 5 MW, MAN GHH, THM 1203, a gas turbine generator set manufactured in Germany, is a similar machine. It is fitted with 2 external combustion chambers. Its TIT is 1661^{o}F (905^{o}C). MAN also manufactures a larger version of the 1203: the 10 MW, THM 1304.

Solar, in the US, has manufactured recuperated versions of its Saturn and its Centaur gas turbines. The recuperated Saturn was a nominal 800 kW machine while the recuperated Centaur, TIT = 1660^{o}F (905^{o}C), was a nominal 3.1 MW machine. Both machines had axial combustion chambers. Solar developed a set of flanged "outs" and "ins" for each machine. These were specially designed castings, one to guide compressor air out from the compressor and up to a "compressor discharge flange"; the other to guide hot turbine inlet air from a "turbine inlet flange" into the annulus leading to the turbine nozzle ring.

Sulzer-Escher Wyss manufactures a 5 MW, Type 3 gas turbine generator set in Switzerland which is fitted with 4 long, cylindrical combustion chambers, the axes of which are parallel to the turbine centerline, bolted to the outside of the machine. These combustion chambers are readily accessible. The Type 3 machine, therefore, is suitable for recuperation. Its design TIT is 1778^{o}F (970^{o}C).

Dresser-Rand manufactures a 1.8 MW, generator set in Norway with a radial compressor/turbine and an external combustion chamber. Its design TIT is 1526^{o}F (832^{o}C).

Finally, Allison in the US, is in the final stages of developing a 4 MW version of its 501, the KM, with a single external combustion chamber. Its TIT is 1935^{o}F (1057^{o}C).

THE HEURISTIC ENVIROCYCLER

The Heuristic EnvirOcycler is a two-stage combustor which was developed by Heuristic Engineering in the late 1970's. The EnvirOcycler gasifies wet wood waste (or any other suitable biomass) in a very large first stage of gentle updraft gasification. The first stage features an A-frame grate. "Producer gas", formed in the first stage, is vigorously burned in the EnvirOcycler's second stage: a cyclonic, double vortex, combustion chamber located immediately above the first stage. Ash is removed from two troughs, one on either side of the A-frame grate, at the bottom of the first stage.

When burning normal sawmill wood waste, particulate in the EnvirOcycler's, typically, 2000^{o}F (1093^{o}C) discharge is guaranteed to not exceed the BC MoE's limit of 120 mg/Nm^3 (0.052 grains/ dscf). This limit is more stringent than the EPA's limit for incinerators of 0.080 grains/dscf (Code of Federal Regulations, Title 40, Part 60, Subpart E -Standards for Incinerators, §60.52). It should be noted that many US jurisdictions have tighter particulate limits.

Because of restrictive "Boiler Branch" regulations, BC sawmills generally stay clear of steam and steam plant personnel. A typical BC, wood-fired, 25,000 lb/h, 150 psig (11.34 tonne/h, 10.2 bar) boiler requires about 7 steam plant personnel to staff the boiler 7 days/week. These include a 2nd class chief, 3rd class shift engineers and 4th class helpers. However, steam generated in a waste heat boiler only requires the presence of a 4th class chief (the equivalent of a millwright with some steam training) on staff and one boiler operator on shift, who can also attend to other duties.

Earlier versions of the EnvirOcycler have been in continuous service in the forest products industry for over 17 years. During that time two 45 Million Btu/h (47.5 GJ/h) units have each been direct firing a rotary dryer in a waferboard plant in the US Midwest. Also during this period a 27.5 Million Btu/h (29 GJ/h) unit has been direct firing two dry kilns in a pole treating plant in the US Southeast; this plant started out as sawmill. Until about a year ago, when its whole tree chip supplier retired, a hospital in Newfoundland, operated a 10 Million Btu/h (10.6 GJ/h) unit which fired a 6000 lb/h (2.72 tonne/h) firetube boiler.

With the EnvirOcycler's very large grate, temperatures on the grate surface typically do not exceed 1200^{o}F (649^{o}C). As a result, the vaporization of potassium - boiling point 1400^{o}F (760^{o}C) - and sodium - boiling point 1616^{o}F (880^{o}C) - from potash and soda in wood ash , does not occur. Rather, these alkalies stay in the EnvirOcycler's first stage and are removed by its built-in ash removal system. Alkali deposits in boilers co-fired by EnvirOcyclers burning biomass (wood or agricultural waste) are greatly reduced .

The EnvirOcycler can also be used to dispose of rice husks. One 27.5 Million Btu/h (29 GJ/h) unit operated in a parboil rice plant in the US Southeast for over 10 years. It direct fired a waste heat boiler as well as a parboil rice dryer.

A major problem with rice husk combustors is the very high silica content of its ash (about 22%). With high grate temperatures the naturally porous and absorbent silica converts to the crystalline form known as tridymite, which is an environmental concern. If inhaled for prolonged periods of time tridymite can lead to silicosis. The trydimite transition temperature is about 1600^{o}F (871^{o}C). Therefore, with its low grate temperature, the porous form of silica does not convert to the crystalline trydimite form in an EnvirOcycler.

In addition to wood and agricultural waste, the EnvirOcycler is also suitable for the disposal of various mixtures of shredded MSW (municipal solid waste) - particularly for communities of under 250,000 people, municipal sewage sludge, shredded tires and shredded industrial wastes such as carpet waste, auto fluff, etc. Power to operate small waste-to-energy plants on outlying landfill sites can be self-generated and process steam can be recovered using the recuperated PGT-5 systems described below.

EnvirOcycler Ratings

The EnvirOcycler is rated according to the total enthalpy in its products of combustion with respect to a reference temperature of 77^{o}F (25^{o}C). Thus, a 60 Million Btu/h (63 GJ/h) EnvirOcycler discharges a stream of, say, 2000^{o}F (1093^{o}C) products of combustion, the total enthalpy of the component gases of which - carbon dioxide, water vapor, oxygen and nitrogen - with respect to a datum of 77^{o}F, is 60 Million Btu/h. The assumption is made that the water in the EnvirOcycler's products of combustion (water brought in by the solid waste as well as water of combustion) remains in the vapor state, even at 77^{o}F. This assumption is really not restrictive since it is differences in enthalpy during a heat transfer process that are of interest.

PGT-5/ENVIROCYCLER SYSTEMS WITH VARYING TURBINE INLET TEMPERATURES

Figures 1 is a schematic which shows 2000^{o}F (1093^{o}C) EnvirOcycler products of combustion of 45% moisture content (wet basis) wood waste routed to a recuperator coupled to a Nuovo Pignone PGT-5 gas turbine generator set. The TIT is 1550^{o}F (843^{o}C) The air flow induced into the compressor is noted. So is the calculated size of recuperator required to heat the compressor air up to 1550^{o}F (843^{o}C) as is the calculated amount of power produced, assuming a generator efficiency of 95%.

Making the assumption that the recuperator exhaust (EnvirOcycler products of combustion) is at the same temperature as the turbine exhaust (air), Figure 1 shows the size of the EnvirOcycler required to transfer the necessary heat to the recuperator. It also shows the amount of sensible heat recoverable in a, say, waste heat boiler from both exhausts - the turbine and the recuperator - assuming the boiler stack temperature is 350^{o}F (177^{o}C). Finally, Figure 1 shows the amount of 45% moisture content "BC Interior" wood waste (a mixture of spruce, pine and fir) each EnvirOcycler must consume to deliver its rated output, as well as the weight flows of the products of combustion delivered to the recuperator.

The 1550^{o}F (843^{o}C) information contained in Figure 1 is tabulated in Table I. Table I includes similar information for four other TIT's: 1500^{o}F (816^{o}C), 1600^{o}F (871^{o}C), 1700^{o}F (927^{o}C) and the design temperature of 1796^{o}F (980^{o}C).

Table I also lists the amount of 50 psig (3.40 bar), saturated steam produced in the waste heat boilers assuming a feedwater temperature of 180^{o}F (82^{o}C). The air flows, the compressor discharge temperatures, the compressor discharge pressures and the turbine exhaust temperatures for each TIT were supplied by Nuovo Pignone. Nuovo Pignone also supplied values for the power generated at each TIT. These power figures were slightly higher than the calculated figures shown (by 4.5% ± 1.5%). For the purposes of this paper the differences are not considered to be significant.

The Effect of Turbine Inlet Temperature on Output and Recuperator Cost

An investigation of the cost of the recuperator as a function of TIT was made. TIT's of 1600°F (871°C), 1550°F (843°C) and 1500°F (816°C) were evaluated. High temperature heat exchanger manufacturers design for a creep rupture life of about 100,000 hours (11.4 y). With that in mind and with the range and cost of alloys available today, the most cost effective TIT appears to be 1550°F (843°C)

1,550°F Recuperated PGT- 5 with additional steam generation

The 1550°F (843°C) schematic shown in Figure 2 is a variation of the schematic of Figure 1. Figure 2 shows a 100 Million Btu/h (105.506 GJ/h) EnvirOcycler replacing the 78.423 Million Btu/h (82.741 GJ/h) EnvirOcycler shown in Figure 1. As before, 136,312 lb/h (61.831 tonne/h) of 2000°F (1093°C) products of combustion are supplied to the 50.281 Million Btu/h (53.049 GJ/h) recuperator. However, since the larger EnvirOcycler generates 173,815 lb/h (78.842 tonne/h) of products of combustion, the surplus 37,503 lb/h (17.011 tonne/h) is now routed to a new "blend chamber". There, 72,638 lb/h (32.948 tonne/h) of blend air is added to form a 110,141 lb/h (49.960 tonne/h) mixture whose temperature is 825°F (440°C), the same temperature as that of the recuperator exhaust. The 110,141 lb/h (49.960 tonne/h) mixture transfers an additional 13.819 Million Btu/h (14.580 GJ/h) to the boiler for a total of 55.148 Million Btu/h (58.185 GJ/h).

1,550°F Recuperated PGT- 5 / Natural Gas Top Up

Figure 3 is another variation of the Figure 1 schematic. Figure 3 shows a natural gas burner in the duct conveying 1550°F (843°C) air from the recuperator to the PGT- 5 turbine inlet. Sufficient natural gas is burned to raise the temperature of the mixture of compressor discharge air and natural gas products of combustion up to the "design" temperature of 1796°F (980°C). By so doing the output of the PGT- 5 is raised from 3.791 MW to 5.178 MW, an increase of 1.387 MW.. An estimated 13.368 Million Btu/h (14.104 GJ/h) of natural gas heat release is required.

In addition to increasing the power output, the natural gas top up raises the turbine exhaust temperature from 825°F (440°C) to 974°F (523°C). The modest increase in turbine mass flow (531 lb/h or 241 kg/h of natural gas), and the larger temperature difference of the turbine "air" across the waste heat boiler, combine to increase the heat transferred to the boiler by the turbine exhaust from 23.067 Million Btu/h (24.337 GJ/h) to 30.640 Million Btu/h (32.327 GJ/h).

The heat transferred by the 825°F (440°C) recuperator exhaust remains the same at 18.262 Million Btu/h (19.268 GJ/h) . Therefore, the total heat transferred to the waste heat boiler increases to 48.902 Million Btu/h (51.594 GJ/h) from the 41.239 Million Btu/h (43.510 GJ/h) shown in Figure 1, a gain of 7.663 Million Btu/h (8.084 GJ/h).

Incremental cost of electricity when topping up with natural gas. As indicated above, burning 13.368 Million Btu/h (14.104 GJ/h) of natural gas downstream from the 1550°F (843°C) recuperator results in the generation of an additional 1.387 MW and the recovery of an additional 7.663 Million Btu/h (8.084 GJ/h) of waste heat. It is interesting to calculate the incremental cost of this power both neglecting and considering the contribution of the waste heat.

At an assumed natural gas price of $3/Million Btu, the cost for 8400 h (one year) of 13.368 Million Btu/h of natural gas is 13.368 * $3 * 8400 = $336,874. The extra electrical energy generated during that year is 1,387 * 8400 = 11,650,800 kW.h. Therefore the incremental cost per kW.h is $336,874 ÷ 11,650,800 = 2.89¢/kW.h.

If the additional heat transferred to the waste heat boiler is valued at, say, $2/Million Btu, then over 8400 h, the extra heat/steam is worth 7.573 * $2 * 8,400 = $127,226. If the value of the steam recovered is deducted from the $336,874 spent for natural gas then the cost per kW.h reduces to ($336,874 - $127,226) ÷ 11,650,800 = 1.80¢/kW.h.

CONCLUSIONS

- 3 MW to 5 MW wood waste fuelled recuperated, gas turbine plants discussed in this paper are technically feasible, environmentally benign, and in some cases, economically viable.
- The heat source - the Heuristic EnvirOcycler - burns sawmill wood waste with emissions guaranteed to not exceed the BC MoE particulate limit of 0.052 grains/dscf (120 mg/Nm^3). Its relatively low first-stage temperatures precludes the vaporization of corrosive potassium or sodium, which are retained in the ash.
- Gas turbines with external combustors are more appropriate for recuperation than turbines with internal combustion chambers.
- A current obstacle to the implementation of these self generating. load-displacing, small power plants in the BC forest products industry is sawmill resistance to the payment of tipping fees

ACKNOWLEDGEMENT

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Table I

Nuovo Pignone PGT-5 Recuperated Gas Turbine Generator Set
The recuperator is heated by the 2000°F (1093°C) products of combustion of 45% moisture content wood waste consumed in the various Heuristic EnvirOcyclers listed below.
Assumptions: ΔP_{Inlet} = 0.426 psi (300 mm H_2O); $\Delta P_{recuperator}$ = 5.00 psi (0.34 bar); ΔP_{Outlet}= 0.142 psi (100 mm H_2O)
$T_{Boiler\ Stack}$ = 350°F (177°C)

T_3 - °F (°C) Turbine Inlet	1500(816)	1550(843) Fig.1	1600(871)	1700(927)	1796(980)	1550(843) Fig. 2	1796(980) Fig. 3
P_2 - psia (bara)	124 (8.44)	126 (8.57)	128 (8.71)	131 (8.91)	134 (9.12)	126 (8.57)	126(8.57)
T_2 - °F (°C)	565 (296)	569 (298)	573 (300)	580 (304)	587 (308)	569 (298)	569 (298)
T_4 - °F (°C)	795 (424)	825 (440)	855 (457)	916 (491)	974 (523)	825 (440)	974 (523)
Turbine $W_{Air\ Flow}$ Lb/h (tonne/h)	193,968 (87.983)	193,950 (87.975)	193,932 (87.967)	193,896 (87.951)	193,860 (87.934)	193,950 (87.975)	194,481 (88.216)
Power – MW	3.513	3.791	4.070	4.632	5.178	3.791	5.178
$Q_{Recuperator}$ 10^6 Btu/h (GJ/h)	47.791 (50.422)	50.281 (53.049)	52.782 (55.688)	57.858 (61.044)	62.748 (66.202)	50.281 (53.049)	50.281 (53.049)
$Q_{EnvirOcycler}$ 10^6 Btu/h wrt 77°F (GJ/h wrt 25°C)	72.814 (76.823)	78.423 (82.741)	84.335 (88.978)	97.306 (102.664)	111.133 (117.252)	100.000 (105.506)	78.423 (82.741)
Natural Gas Burner 10^6 Btu/h wrt 77°F (GJ/h wrt 25°C)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	13.368 (14.104)
$Q_{Turbine\ exhaust}$ 10^6 Btu/h wrt 350°F (GJ/h wrt 177°C)	21.575 (22.763)	23.067 (24.337)	24.565 (25.918)	27.626 (29.147)	30.556 (32.238)	23.067 (24.337)	30.640 (32.327)
$Q_{Recuperator\ exhaust}$ 10^6 Btu/h wrt 350°F (GJ/h wrt 177°C)	15.846 (16.718)	18.262 (19.268)	20.924 (22.076)	27.186 (28.683)	34.377 (36.270)	18.262 (19.268)	18.262 (19.268)
$Q_{Blend\ chamber\ exhaust}$ 106 Btu/h wrt 350°F (GJ/h wrt 177°C)	n.a.	n.a.	n.a.	n.a.	n.a.	13.819 (14.580)	n.a.
$Q_{"Waste"\ Heat}$ 10^6 Btu/h wrt 350°F (GJ/h wrt 177°C)	37.421 (39.481)	41.329 (43.605)	45.489 (47.994)	54.812 (57.830)	64.933 (68.508)	55.148 (58.185)	48.902 (51.595)
50 psig sat'd $W_{Steam\ Flow}$ lb/h (tonne/h)	36,289 (16.461)	40,078 (18.179)	44,113 (20.010)	53,154 (24.110)	62,968 (28.562)	53,479 (24.280)	47,422 (21.510)
$W_{Wood\ Waste}$ lb/h (tonne/h) @ 45% mc	19,174 (8.697)	20,650 (9.367)	22,211 (10.075)	25,625 (11.623)	29,266 (13.275)	26,333 (11.944)	20,650 (9.367)
EnvirOcycler $W_{Gas\ Flow}$ lb/h (tonne/h)	126,555 (57.405)	136,312 (61.831)	146,581 (66.489)	169,130 (76.717)	193,151 (87.613)	173,815 (78.842)	136,312 (61.831)

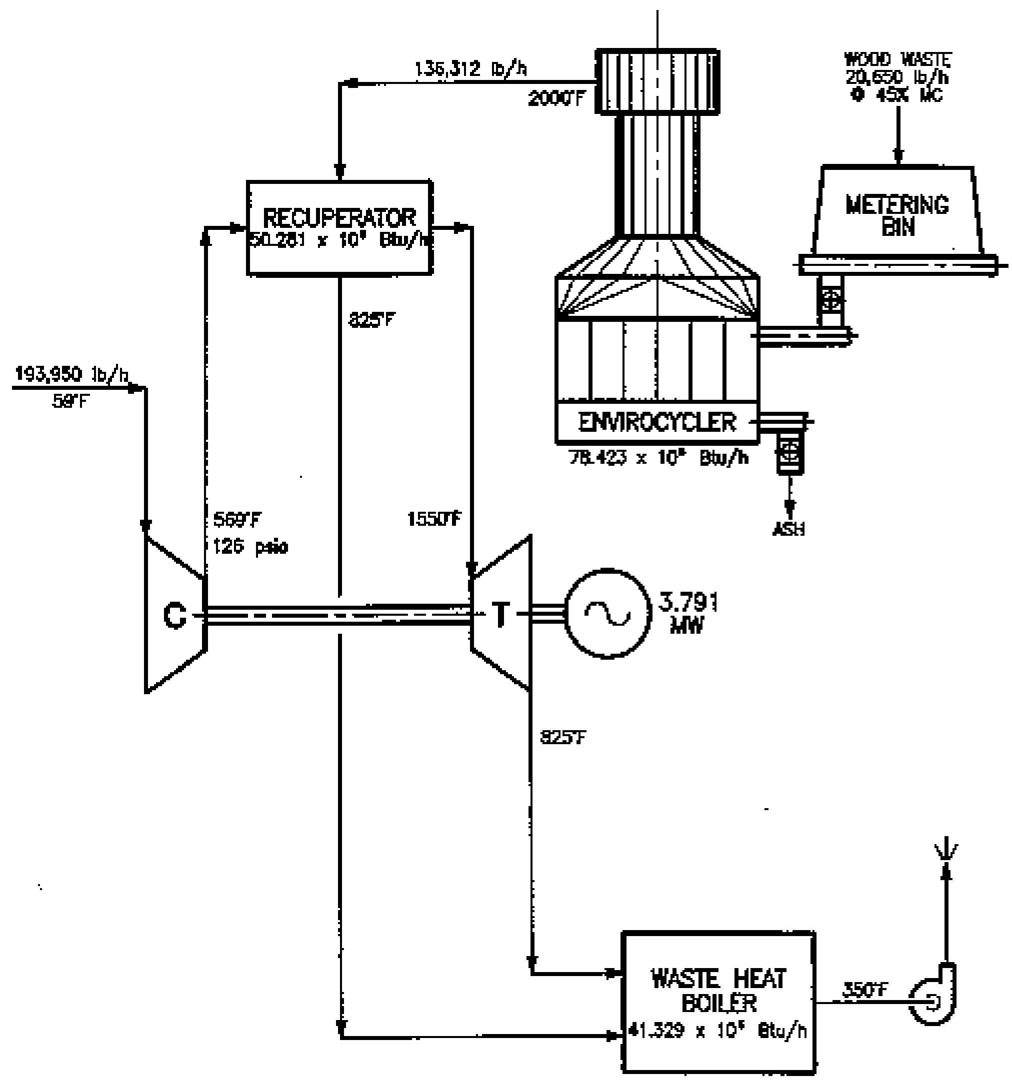

FIGURE - 1

100% WOOD WASTE FUELLED, RECUPERATED, PGT 5
TURBINE INLET TEMPERATURE = 1550°F

Heuristic Engineering Inc.

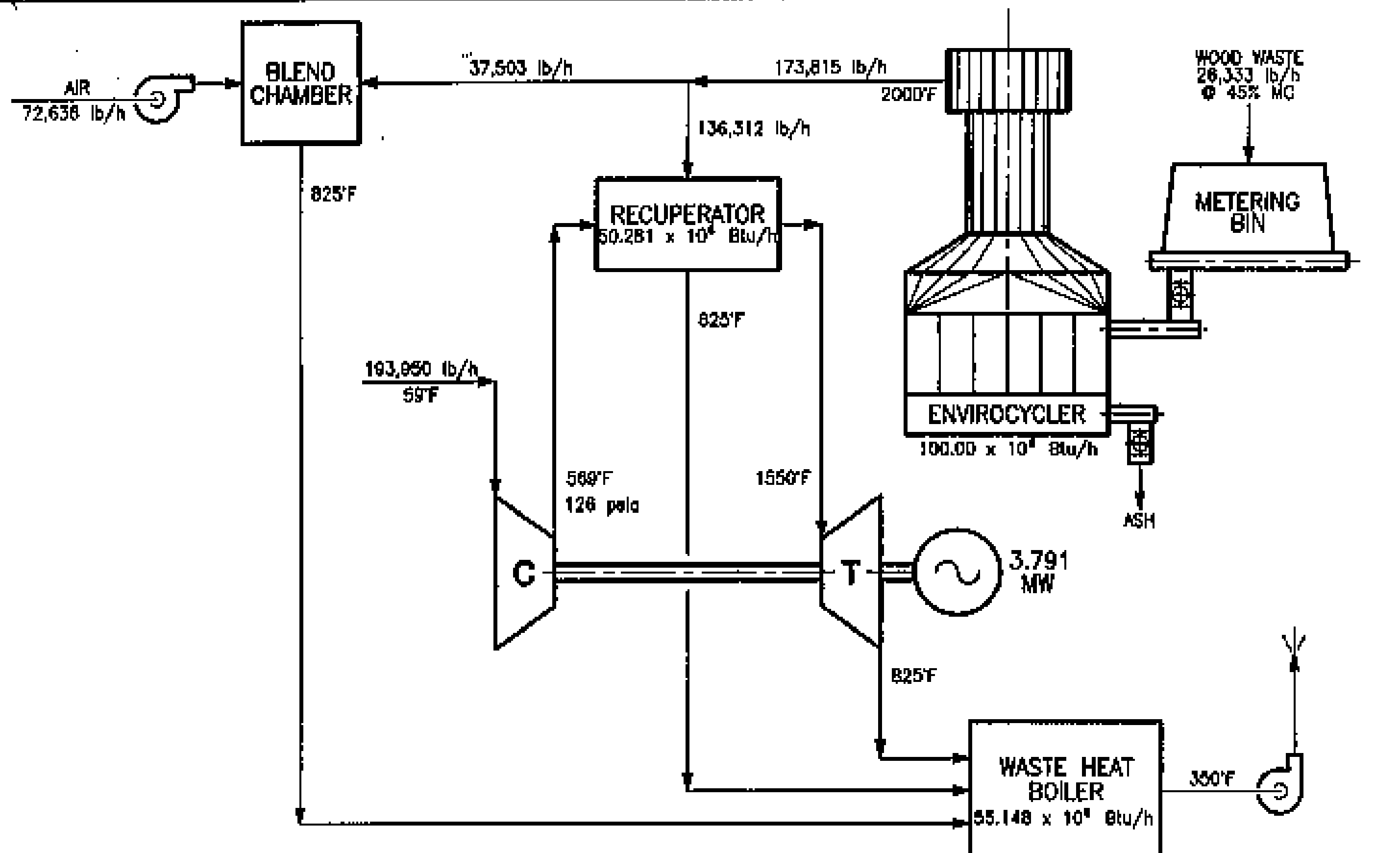

FIGURE - 2

100% WOOD WASTE FUELLED, RECUPERATED, PGT 5 WITH LARGER THAN NECESSARY ENVIROCYCLER FOR ADDITIONAL STEAM GENERATION

Heuristic Engineering Inc.

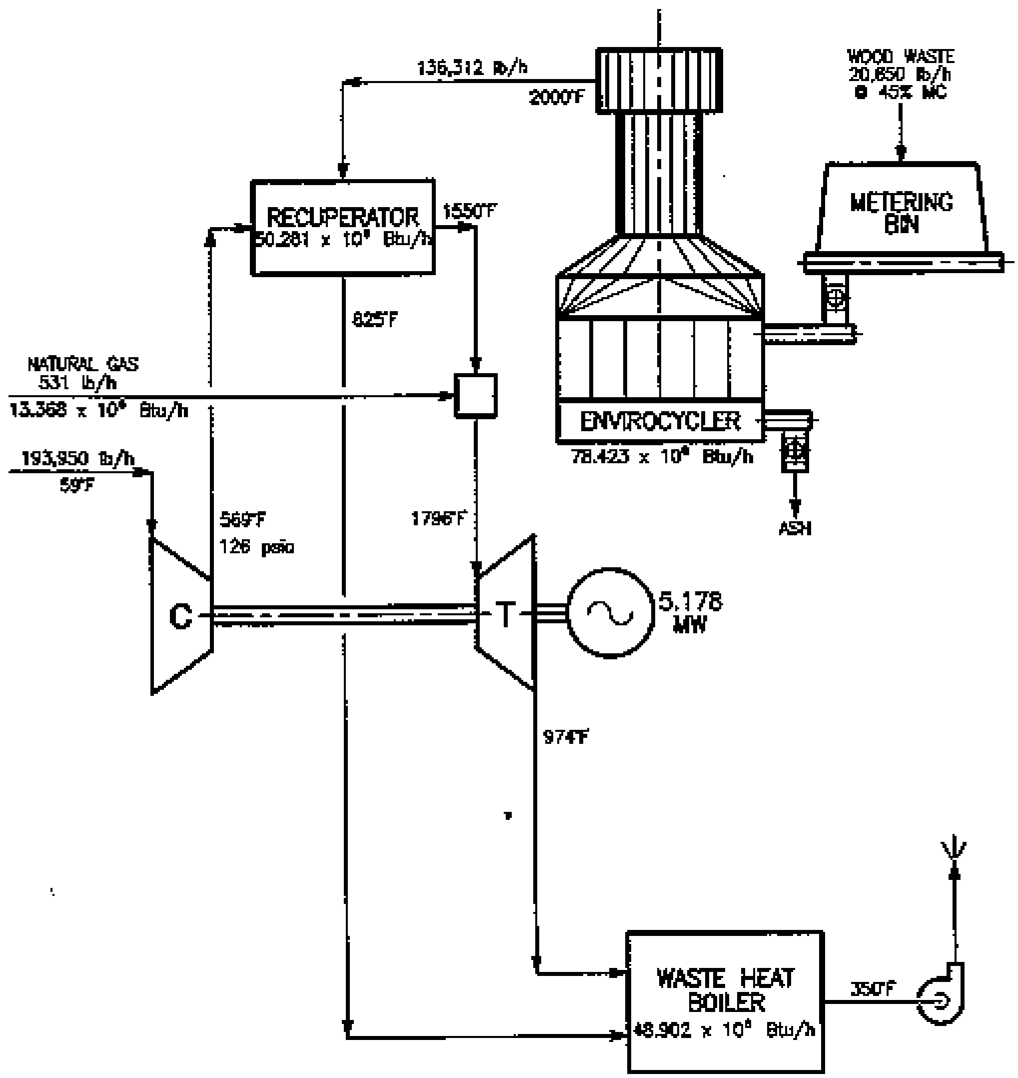

FIGURE - 3

100% WOOD WASTE FUELLED,
RECUPERATED, PGT 5 WITH NATURAL GAS
'TOP UP' TO GENERATE MAXIMUM POWER.
TURBINE INLET TEMP. RAISED FROM 1550°F TO 1796°F

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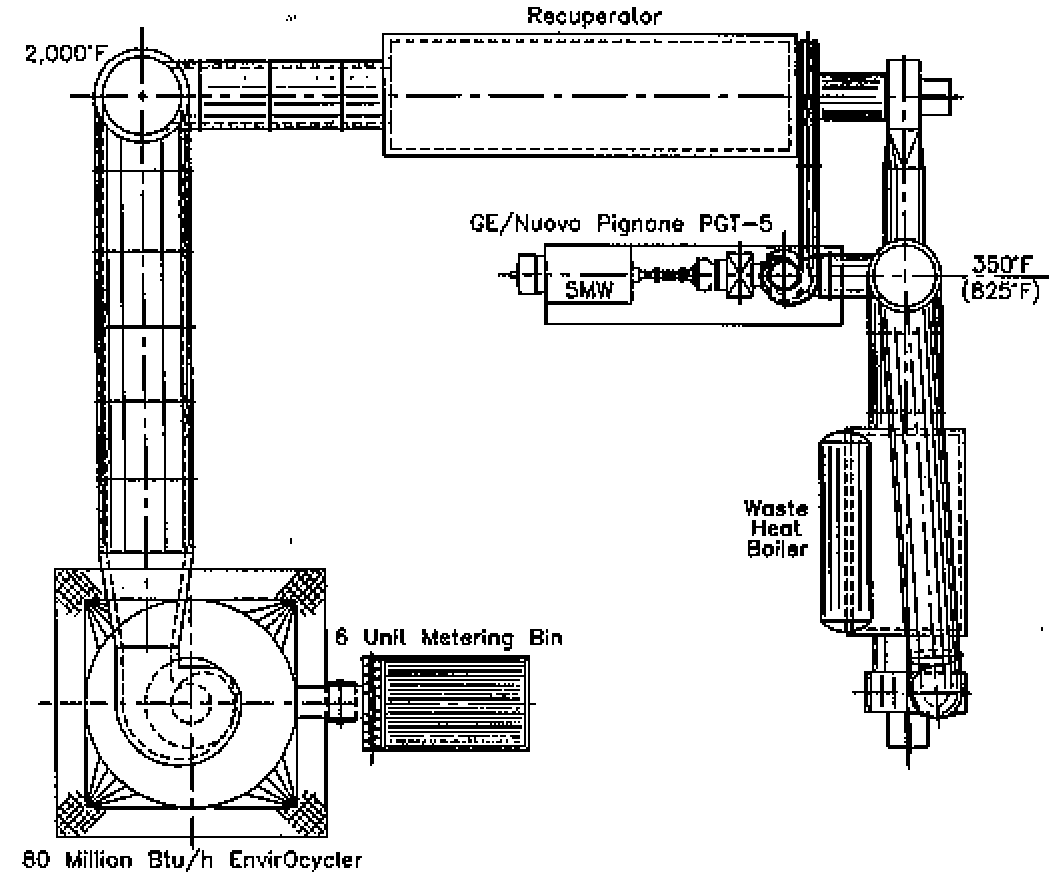

80 MILLION Btu/h ENVIROCYCLER
FUELLING A PGT-5 RECUPERATED
GAS TURBINE SET - SHEET 1

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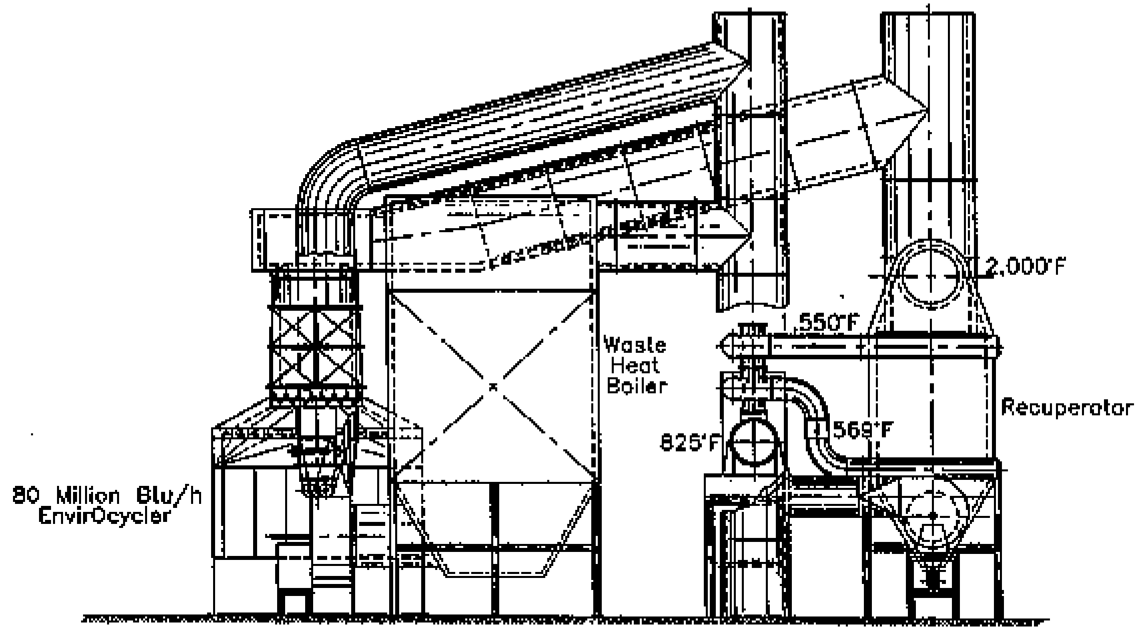
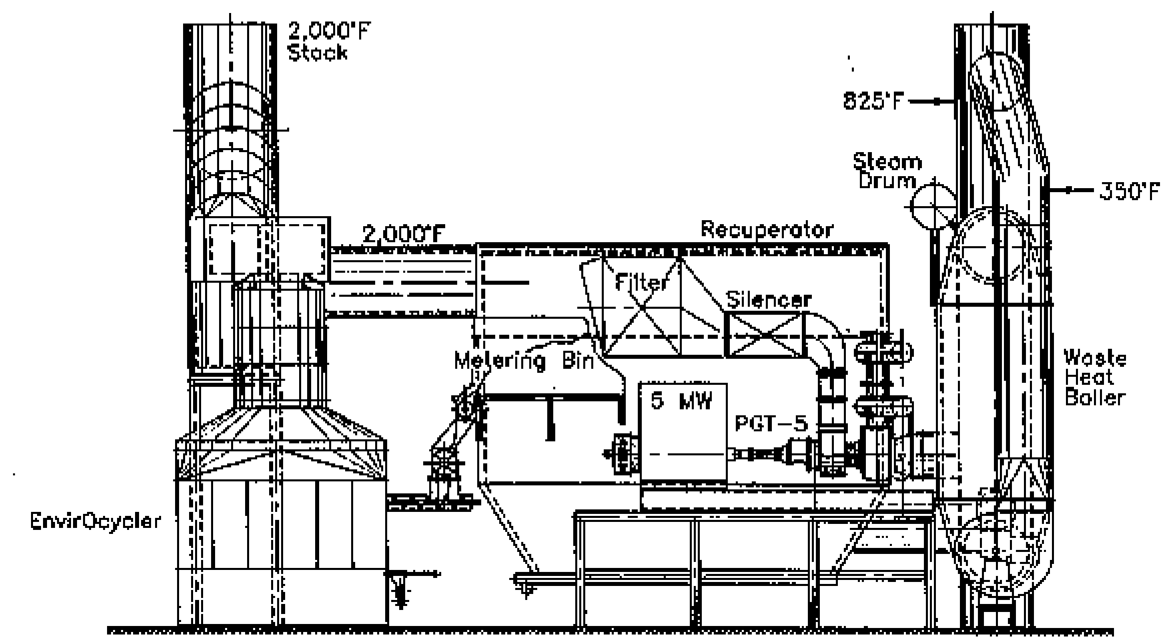


80 MILLION Btu/h ENVIROCYCLER FUELLING A PGT-5 RECUPERATED GAS TURBINE SET - SHEET 2

Heuristic Engineering Inc.



80 MILLION Btu/h ENVIROCYCLER FUELLING A PGT-5 RECUPERATED GAS TURBINE SET - SHEET 3

Heuristic Engineering Inc.