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HIGH EFFICIENCY WASTE TO ENERGY POWER PLANTS COMBINING MUNICIPAL SOLID WASTE AND NATURAL GAS OR ETHANOL

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ABSTRACT

A new WTE (Waste-to-Energy) power plant configuration combining municipal solid waste and gas turbines or landfill gas engines is proposed. The system has two objectives: increase the thermodynamic efficiency of the plant and avoid the corrosion in the MSW (Municipal Solid Waste) boiler caused by high tube metal temperatures. The difference between this concept and other existing configurations, such as the Zabalgarbi plant in Bilbao, Spain, is lower natural gas consumption, allowing an 80% waste contribution to the net energy exported or more. This high efficiency is achieved through four main steps: **1.** introducing condensing heat exchangers to capture low temperature heat from the boiler flue gases; the stack temperature can drop to 70°C; **2**. high steam temperatures in external superheaters using hot clean gases heated with duct burners; **3.** mixing the exhaust gases of a small gas turbine with hot air preheated in a specially designed heat exchangers. The resulting temperature of this gas mixture is almost the same as a standard gas turbine but with the flow similar to that of a large machine with a higher O_2 content; **4.** After the duct burner and heat exchangers, the oxygen content of the clean gas mixture is still high, nearly 18%, and the temperature is approximately 200°C. The gas is then used as combustion air to the MSW boiler such that all the energy stays in the system. The efficiency can be as high as 33% for the MSW part of the plant and 49% for the natural gas system. Since the natural gas consumption is almost ten times less than the existing designs, it can be replaced by landfill gas or gasified ethanol or biodiesel. Currently an 850 ton/day plant is being designed in Brazil in partnership with a large power company. Other advantages include, self generation of internal power and lower steam superheating temperatures in the MSW boiler. This concept can be used with any grate design.

1. INTRODUCTION

Conventional WTE plants burn waste on specially designed grates and the hot flue gases generate steam in a boiler. Due to the very corrosive nature of these flue gases, [1], the steam temperature and pressure are limited to 400°C / 40 bar resulting in low thermodynamic efficiencies, around 22%, for power generation. One way to overcome this difficulty is to combine a natural gas turbine with a waste incinerator in such a way that the superheated steam produced in the MSW boiler is further heated using the “clean” exhaust from a gas turbine in an external superheater. Many WTE plants have been built using this concept, the most important one being the Zabalgarbi plant, Figure 1. This power plant generates 100 MWe gross and the thermodynamic efficiency for the MSW portion of the fuel is approximately 30%. For natural gas the efficiency is around 50%. The disadvantage of this scheme is that 75% or more of the electric energy produced comes from natural gas. Although in some cases, this can be a good solution from an energy point of view, it is not as environmentally desirable since natural gas is a fossil fuel and contributes to global warming, cancelling the benefits of landfill diversion. Also natural gas prices can vary unpredictably and it may not be economical to dispatch such plants. However, WTE plants have to run with a high availability which poses additional problems to the grid operator.

2. OPTIMIZED COMBINED CYCLE – OCC

The proposed concept, named Optimized Combined Cycle - OCC, greatly reduces the amount of natural gas needed to increase the efficiency of MSW combustion. With OCC, 80% or more of the net energy comes from MSW allowing the natural gas to be replaced by fuels not commonly available in large amounts, including landfill gas or biogas from anaerobic digestion. Another possibility is to replace natural gas with gasified bio-fuels such as ethanol or biodiesel using the LPP Combustion, LLC, a Maryland-based company, process [2]. The efficiency of the MSW can reach values of more than 33% and the natural gas efficiencies are higher than a gas turbine if it was used in a standalone combined cycle without MSW. The natural gas efficiency approaches 50% even for small gas turbines around 5 MWe. The OCC (Optimized Combined Cycle) concept has other advantages such as being specially suited for high moisture MSW as well as for small incinerators using refractory walls. Nevertheless large waterwall boilers can employ the scheme with many advantages as discussed herein.

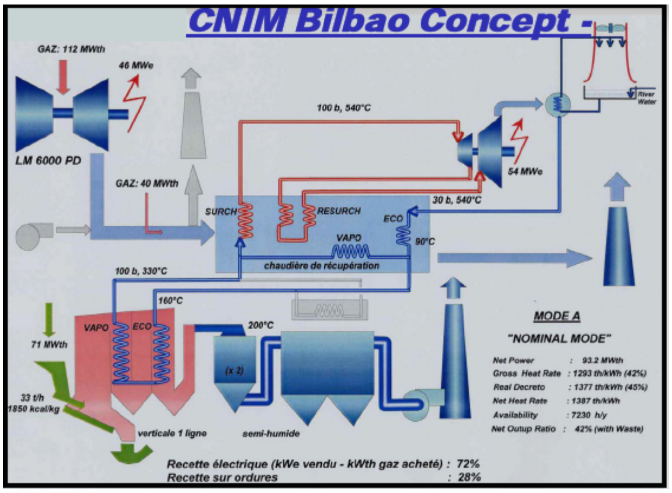

Fig. 1 – Zabalgarbi Plant Concept in Bilbao, Spain [4]

3. DESCRIPTION OF THE PROCESS

Consider Figure 2. The power is generated by one small gas turbine (10), a HP (High Pressure) steam turbine (17) and a LP (Low Pressure) steam turbine (18). The HP steam is superheated in the MSW boiler (6) up to a corrosion safe temperature and, optionally, to a higher temperature in the external superheater (3). Similarly the LP steam is reheated in (5) below 400°C first by MSW flue gas then further reheated in the external reheater (2). After the external superheater, (3) the flue gas is at temperature T2, above 400°C, and can be used in (13) to preheat the air, from (9), before being mixed with the gas turbine exhaust (Y). This has two effects: it reduces the amount of natural gas in the duct burners and increases the O_2 content of the gas turbine exhaust. After the air preheater (13), the flue gases from the gas turbine may preheat the boiler feedwater in the optional heat exchanger (25) and then be used as part of the combustion air in the MSW boiler.

Corrosion is avoided by using one or more external superheaters (2) and (3) heated by the clean gas exhaust coming from the gas turbine (10) mixed with preheated air at (9) and (13). This mixture is heated to temperatures between 600°C and 700°C, with duct burners (11) and (12) to adjust the steam superheating temperature. To increase the overall efficiency of the plant, the amount of natural gas used in the duct burners must be optimized, the steam cycle efficiency increased (higher pressure and temperature and reheating), the stack losses minimized by lowering the waste boiler flue gas temperature, and lowering the combustion excess air .

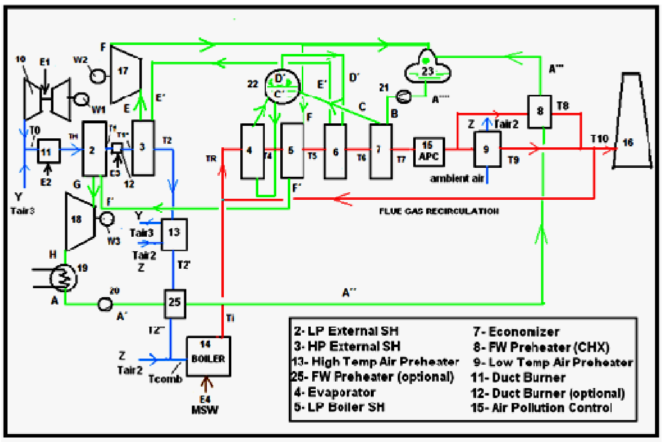

Fig. 2 – Optimized Combined Cycle Scheme

Since the flue gas temperature leaving the APC (Air Pollution Control) with dry scrubbers is 140 to 170°C, we can recover this energy using condensing heat exchangers (CHX) made of glass tubes, teflon tubes or teflon coated steel tubes, built by Swiss company Air Fröhlich [3]. Combustion air can be preheated to temperature Tair2 using a CHX (Condensing Heat Exchangers) air heater (9) and CHX economizer (8) used to preheat the feedwater close to the deaerator (23) temperature. In a good design, the stack (16) temperature can be as low as 70°C allowing not only the sensible heat recovery but also the latent heat from water condensing increasing the heat transferred from the waste combustion in the boiler (14) to the steam. The flue gas at T9 which is cooler and has a lower O_2 content can be partially recirculated as combustion air to control the waste combustion temperature and to reduce NOx formation in the MSW furnace. We can also run the plant without the gas turbine (10) by increasing the pure air flow Y, and natural gas duct firing (11) and (12) during maintenance periods. In this case, the amount of energy produced by the natural gas approximately matches the plant parasitic load and most of the energy exported by the plant will come from the waste. The natural gas efficiency will be lower since it is limited by the steam cycle efficiency, however, such a plant without the gas turbine would be a good solution if landfill gas can be utilized, particularly because it is generally available in limited quantities. This is also a good solution from an environmental point of view, because all the power produced will come from waste, including the plant parasitic load.

In some cases it is better to use a gas engine as opposed to a gas turbine. Gas engines differ from gas turbines with respect to their use in combined cycle applications in two ways: almost all the heat rejected in gas turbines goes to the exhaust flue gas. In gas engines, a substantial part of the heat loss occurs in the water cooling the cylinders. Thus we can introduce an additional feedwater preheater before or after the optional heat exchanger (25), to capture the heat from the engine cooling system to increase the efficiency of the plant which at the same time reduces the need for a heat sink to cool the engine. Gas engine exhaust has an O_2 content of 7-11%, compared to a gas turbines 13-16%. Mixing hot ambient air from heat exchanger (13) increases the O_2 content of the gas engine exhaust to that of a gas turbines exhaust, usually higher. In contrast with natural gas combined cycle plants, where only gas turbines are used, we can employ either gas engines or turbines, choosing the best solution for each particular case. This has special advantages for small machines, say below 2 MWe, where gas engines are more efficient than gas turbines.

In the proposed scheme, the combustion air for the MSW boiler is preheated between 200°C and 230°C and the O_2 content is close to 18%. This helps to reduce NOx formation and to vaporize the water in the MSW early in the combustion grate. This is particularly advantageous for high moisture waste that otherwise would require additional fuel to promote continuous combustion.

4. NUMERICAL RESULTS

The actual design of a WTE plant using OCC requires extensive calculations in order to optimize the parameters governing the project. Design requirements vary for different locations as well as MSW characteristics. For example, in Brazil, there is a tax cut in electricity sales for power plants up to 30 MWe. Although tipping fees are very low, under US$ 20/ton, power costs are higher than in the USA. Natural gas is almost twice the international price and must be reduced to a point in which the MSW efficiency is optimized with respect to economic feasibility. The small amount of natural gas needed opens the door for a WTE/gas plant 100% renewable, except for plastics, allowing the use of ethanol [2] or landfill gas.

To reach the optimum design point, we have developed specific OCC plant software making it possible to quickly run hundreds of cases, varying not only thermodynamic quantities but also plant configurations, MSW properties, as well as economic parameters. This software was validated (Annexes A and B) using the GateCycle computer program showing an almost perfect agreement between the two calculations for a particular case of OCC configuration.

To emphasize the advantages of the concept, Figure 3 represents a case where the Zabalgarbi MSW boiler, 792 TPD (metric tons per day) of 1,850 Kcal/Kg LHV (Low Heating Value) waste corresponding to 71 MWth, is combined with a 5.5 MWe General Electric (GE) GE5 gas turbine, instead of a GE LM6000 (46 MWe) as shown in Figure 1. The LM6000 has an open cycle efficiency of 41% while the GE5 value is 30.7%. In a pure combined cycle, General Electric lists the efficiencies as 51% and 43%, respectively. Considering that the natural gas efficiencies in the MSW/gas plant are the same as if the same amount of gas was used in a standard combined cycle plant, as described by Korobitsyn [1], we have:

Zabalgarbi → MSW apparent efficiency = 31.66%
Total Nat Gas consumption = 152 MWth

OCC → MSW apparent efficiency = 34.51%
Total Nat Gas consumption = 21.84 MWth

It can be seen that the natural gas needed decreases by a factor of seven and the MSW efficiency is almost 10% higher. The actual efficiencies for the OCC case can be calculated and are shown below:

OCC MSW actual efficiency = 32.65%
OCC Nat Gas efficiency = 49.06%

A natural gas efficiency of 49% on this scale, 21.84 MWth, is not achievable in any internal combustion machine available. Also, a pure combined cycle system for this amount is not economical and in practice, the maximum efficiency that can be obtained using gas engines this size is under 40%. Of course the natural gas consumption can be decreased with a corresponding lower value for the MSW efficiency as a function of the design requirements. For an apparent MSW efficiency of 30%, approximately 80% of the net power will come from waste. These results are summarized in Table 1.

	BILBAO PLANT ORIGINAL	BILBAO WITH OCC
TPD	792	792
GAS TURBINE(MWe)	46	5,5
PLANT GROSS POWER(MWe)	100	33,89
Nat Gas CONSUMPTION(MWth)	152	21,84
MSW APP EFFICIENCY	31,66%	34,51%
Nat Gas EFFICIENCY - CC	51,00%	43,00%
MSW ACTUAL EFFICIENCY	NA	32,65%
Nat Gas ACTUAL EFFICIENCY	NA	49,06%

Table 1 – Original Bilbao Plant x Same MSW boiler with OCC.

For this case, it is feasible to replace natural gas with landfill gas, gasified ethanol, or biodiesel [2]. We can use a smaller gas turbine, gas engine or just the duct burner depending on the economics and the availability of these fuels.

The Optimized Combined Cycle concept has been examined by the Austrian Patent Office in Vienna under the Patent Cooperation Treaty (PCT) International application No. PCT/BR 2008/000347. It has been given the statements of Novelty (N), Inventive step (IS) and Industrial applicability (IA).

POWER		ENERGY INPUT	
	MWe		MWth
GT or GE	5,500	GT or GE	17,915
HP st	4,555	Burner	3,923
LP st	23,835	TOT NG	21,838
TOTAL	33,890	MSW	70,992
Self Load	0,000	MSW eff	32,65%
Net Power	33,890	NG eff	49,06%
MSW Power	23,176	Overall eff	36,51%
NG Power	10,714	Ap MSW eff	34,51%

FLUE GASES				
	Kg/s		C	O2
mGT	19,546	TGT	572,7	13,30%
mA1	6,866	T0	528,6	15,12%
mA0	26,412	TH	650,3	13,99%
mA0*	26,490	T2	420,3	13,99%
mA2	32,438	T2air	120,0	20,43%
mAcomb	58,928	T3air	395,0	20,43%
mT7	65,92	T7	160,0	6,86%
mT8	33,22	T8	56,4	6,86%
mT9	32,70	T9	56,4	6,86%
mSTACK	65,920	T2'	353,4	13,99%
FGR	0,00%	Tcomb	228,3	17,48%

STEAM

POINT	PRESSURE (bar)	TEMP (C)	FLOW (KG/S)	ENTHALPY (KJ/KG)	ENTHALPY (BTU/LB)
A''	1,379	36,2	22,401	151,602	65,177
A'''	1,379	75,0	22,401	314,038	135,012
A''''	1,379	108,9	24,914	456,563	196,287
B	100,657	110,1	24,914	468,832	201,562
D'	100,000	311,0	24,172	2724,505	1171,326
E'	100,000	400,0	24,172	3096,093	1331,080
F	30,000	265,2	24,172	2899,521	1246,570
F'	30,000	400,0	22,401	3230,723	1388,961
G	30,000	540,0	22,401	3546,604	1524,765
H	0,060	36,2	22,401	2436,686	1047,586
A	0,060	36,2	22,401	151,469	65,120

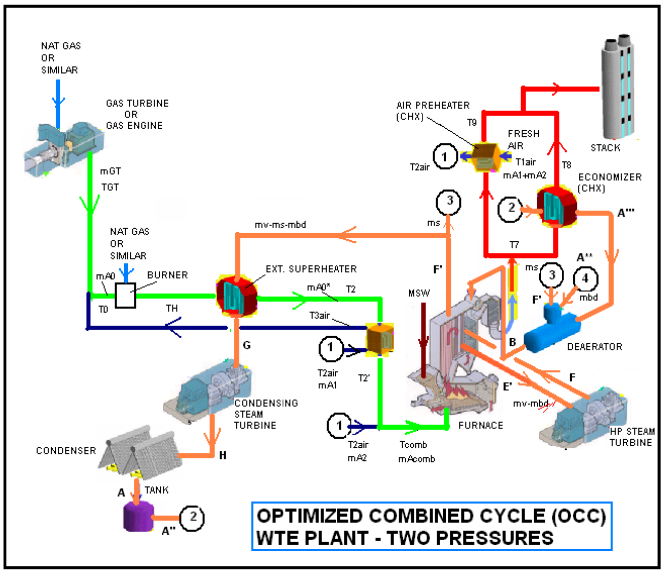

Fig. 3 - OCC Applied to Zabalgarbi Boiler.

4. CO_2 EMISSIONS

The next item to consider is how the use of fossil natural gas will affect the global warming related emissions. For Italian waste, Consonni et al [6] showed that the total carbon content is 27.6% and the renewable fraction is 16.0%, i.e., 58% of the total carbon is renewable. This seems to be true for several locations.

Consider a conventional WTE plant, without natural gas, burning 792 TPD of a 1.850 Kcal/Kg LHV, with the same carbon characteristics as the Italian waste, and a capacity factor of 90%. This corresponds to a thermal input of 71 MWth. With 22% efficiency, the total electric power produced will be 15.62 MWe. The annual fossil CO_2 emission from MSW burning would be:

CO_2 from MSW (fossil) = 792 x 365 x 0.9 x 0.116 x (44/12)

= 110,660 TPY (Tons per year)

Now consider the same MSW boiler with OCC consuming 21.84 MWth of natural gas (NG) and producing 33.89 MWe. Considering, for simplicity, that NG is equal to pure methane (CH4), burning one MWh of natural gas will produce 0.2 ton of CO_2. The annual CO_2 emission from NG would be:

CO_2 from NG in OCC=21.84 x 0.2 x 7884 = 34,437 TPY

Since the 21.84 MWth of NG spent would result in 33.89 - 15.62 = 18.27 MWe additional power, generating the same power using NG alone with 40% efficiency (maximum achievable for this amount), one would need to burn 18.27 / 0.4 =45.68 MWth of NG. This would result in 72,028 TPY of CO_2. The difference of 37,591 TPY of avoided CO_2 is due to the efficiency improvement of OCC. This corresponds to 34% of the CO_2 emissions of the fossil fraction of the MSW. If we replace natural gas with landfill gas or ethanol, this will increase to 65%. Additionally, the avoided methane from landfill diversion will correspond to approximately 338,000 TPY of CO_2 meaning that, even for the NG case, the annual net CO_2 sequestration would be 265,000 TPY of CO_2 for a 792 TPD WTE plant.

5. CONCLUSIONS

This process allows WTE to be feasible at very modest tipping fees. Developing Countries that could not afford the costs of landfill diversion will be able to stop burying their organic wastes. Also Europe, North America and Japan could benefit from this concept and apply the surplus of resources from lower tipping fees in other ways to mitigate global warming.

The OCC concept can be generalized to other types of thermal electric power plants such as sugarcane bagasse fuel for which the efficiency improvement can surpass 50% with very modest increase in the investment.

ACKNOWLEDGMENTS

I would like to express my gratitude and deepest admiration for Professor Nickolas J. Themelis, Chair of WTERT, who probably does not realize that the seeds he planted when he visited Rio de Janeiro in 2006 are about to germinate into large trees.

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[6] S. Consonni, M. Giugliano, M. Grosso, “Alternative strategies for energy recovery from municipal solid waste Part A: Mass and energy balances” - Waste Management 25 (2005) 123 135.

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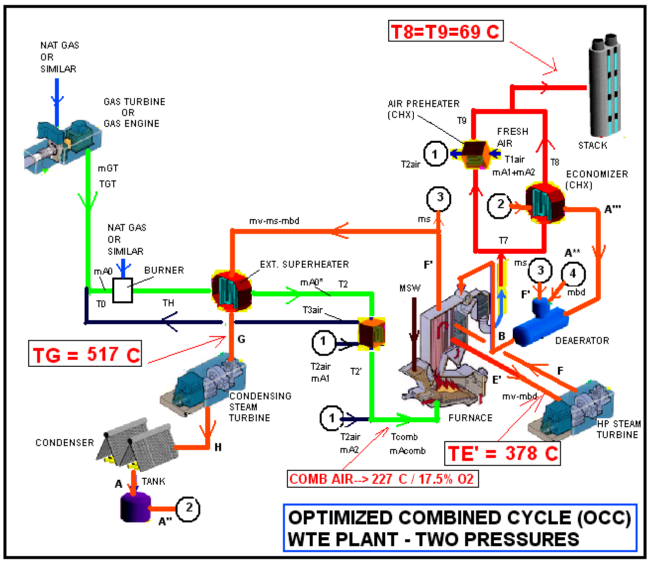
ANNEX A

PLANT SPECIFIC OCC MODEL



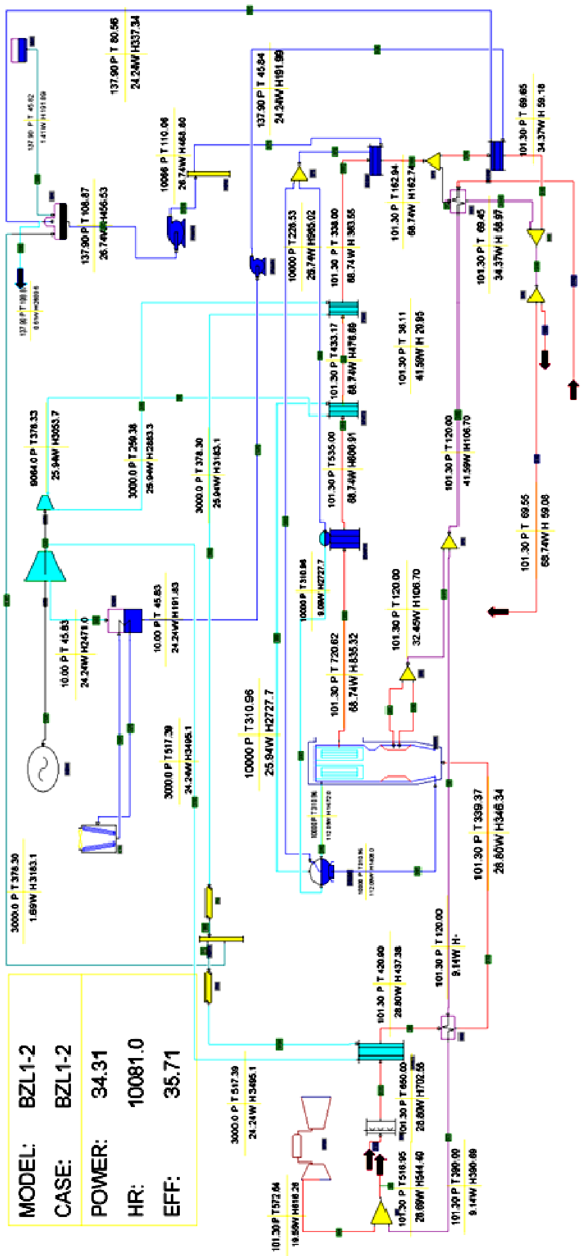
FLUE GASES				
	Kg/s		C	O2
mGT	19,546	TGT	572,7	13,30%
mA1	9,136	T0	516,9	15,53%
mA0	28,683	TH	649,8	14,30%
mA0*	28,775	T2	420,9	14,30%
mA2	32,450	T2air	120,0	20,43%
mAcomb	61,225	T3air	390,0	20,43%
mT7	68,71	T7	163,0	6,64%
mT8	34,02	T8	68,7	6,64%
mT9	34,68	T9	68,7	6,64%
mSTACK	68,708	T2'	340,3	14,30%
FGR	0,00%	Tcomb	226,5	17,50%

STEAM					
POINT	PRESSURE	TEMP	FLOW	ENTHALPY	ENTHALPY
	(bar)	(C)	(KG/S)	(KJ/KG)	(BTU/LB)
A"	1,379	45,8	24,246	191,963	82,529
A'''	1,379	80,6	24,246	337,346	145,033
A''''	1,379	108,9	26,740	456,563	196,287
B	100,657	110,1	26,740	468,832	201,562
D'	100,000	311,0	25,943	2724,505	1171,326
E'	90,640	378,3	25,943	3049,768	1311,164
F	30,000	259,0	25,943	2881,650	1238,887
F'	30,000	378,3	24,246	3180,860	1367,524
G	30,000	517,4	24,246	3495,703	1502,882
H	0,100	45,8	24,246	2468,723	1061,360
A	0,100	45,8	24,246	191,833	82,474

MSW						
TPD		850,000				
LHV		1849,8	Kcal/Kg	3329,0 BTU/lb		
% H2O		31,49%		Volatile Matter		40,07%
% Ashes		23,72%		Fixed Carbon		4,71%
% Fuel		44,78%				
Ult Anal	C		H	O	N	S
		23,34%	3,16%	17,83%	0,36%	0,10%
STEAM						
	bara		C	psia	F	
HP		100,00	378,33	1450,40	712,99	
LP		30,00	517,39	435,12	963,30	
Condenser		0,10	45,82	1,45	114,47	
Dearator		1,38	108,87	20,00	227,97	
Makeup Temp			25,00		77,00	
	Kg/s		lb/s			
HP flow		25,943	57,205			
LP flow		24,246	53,461			
HP isen eff		0,682				
LP isen eff		0,865				
POWER				ENERGY INPUT		
	MWe				MWth	
GT or GE		5,500		GT or GE	17,915	
HP st		4,297		Burner	4,632	
LP st		24,530		TOT NG	22,547	
TOTAL		34,327		MSW	76,191	
Self Load		0,000		MSW eff	31,04%	
Net Power		34,327		NG eff	47,36%	
MSW Power		23,650		Overall eff	34,77%	
NG Power		10,677				

ANNEX B

GATECYCLE OCC MODEL

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Date & Time of Last Run            10/16/09        12:05
Last Execution Status              Converged

Equipment ID: MSW1 Type: FBOILR Description: Fossil Boiler

                         Flow        Temperature Pressure     Enthalpy     Quality
Ports:                   kg/sec      C           kPa          kJ/kg        /x of CH
---------------------------------------------------------------------------------------
  Primary Air Inlet      0.0000      120.00      101.30       106.70       4
  Secondary Air Inlet    32.452      120.00      101.30       106.70       4
  Recycle Air Inlet      28.799      339.37      101.30       346.34       1.9983
  Flue Gas Outlet        68.736      720.62      101.30       835.32       0.0
  Evaporator Inlet       112.093     310.96      10000        1408.0       0.0
  Evaporator Outlet      112.093     310.96      10000        1672.0       0.2000
---------------------------------------------------------------------------------------

  Solid Fuel Flow                                9.84 kg/sec
  Oil Flow                                       0.0    kg/sec

  Main Inputs: ------------------------------------------------------------
  Boiler Load Method Flag                        Total Fuel Flow
  Desired Total Fuel Flow                        9.84 kg/sec
  Total Fuel Flow                                9.84 kg/sec

  Off Design Run Information: ---------------------------------------------
  Component was run in design mode

  Current Values: ---------------------------------------------------------
  LHV Heat Load                                  76132 kJ/sec
  HHV Heat Load                                  90488 kJ/sec
  Total Fuel Flow                                9.84 kg/sec
  Duty @ Furnace Walls                           29586 kJ/sec
  Duty @ Radiant SH                              0.0    kJ/sec
  Duty @ Radiant RH                              0.0    kJ/sec
  Current Heat Input / BFW                       789.13 kJ/kg
  BFW Flow                                       112.09 kg/sec
  Cur. Boiler Efficiency                         0.3295
  Cur. Reduc. Boiler Eff.                        0.2570
  Cur. Reduc. Firing Dens.                       1.20773
  Cur. Reduc. Sink Temp.                         0.4448
  Cur. Adiab. Flame Temp.                        1040.0 C
  Cur. Calc. Heat Rel. Rate                      77.67   kW/m2
  Cur. Stat. Heat Rel. Rate                      72.39   kW/m2
  Heat exchange              Furnace   Superheater Reheater
  Frac. from Radiation       0.8398    0.0         0.0
  Frac. from Convection      0.1602    0.0         0.0
  Overall Equiv. U(htc)      0.0443241 0.0         0.0 kJ/sec-m2-K

  Fuel Mix: ---------------------------------------------------------------
  Fuel Mix Method Flag                           Fraction of Total Fuel HHV
  Coal Fuel Input Fraction                       1.0
  Oil Fuel Input Fraction                        0.0
  Gas Fuel Input Fraction                        0.0

  Primary Combustion Air: -------------------------------------------------
  Pri. Air / Unit Weight Solid Fuel              0.0
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Last Execution Status              Converged

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                         Flow        Temperature Pressure     Enthalpy     Quality
  Ports:                 kg/sec      C           kPa          kJ/kg        /x of CH
  ---------------------------------------------------------------------------------------
  Gas Inlet              28.799      650.00      101.30       702.58       1.9983
  Gas Outlet             28.799      420.90      101.30       437.38       1.9983
  Steam Inlet            24.243      378.30      3000.0       3183.1       1.0
  Steam Outlet           24.243      517.39      3000.0       3495.1       1.0
  ---------------------------------------------------------------------------------------

  Main Inputs: ------------------------------------------------------------
  Superheater Method Flag                        Gas Outlet Temperature
  Desired Gas Outlet Temperature                 420.90 C
  Temperature                                    420.90 C
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