A HIGHLY EFFICIENT COMBINED CYCLE FOSSIL AND BIOMASS FUEL POWER GENERATION AND HYDROGEN PRODUCTION PLANT WITH ZERO CO_2 EMISSION

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ABSTRACT

An advanced combined cycle for fossil and biomass fuel power generation and hydrogen production is described. An electric arc hydrogen plasma black reactor (HPBR) decomposes the carbonaceous fuel (natural gas, oil, coal and biomass) to elemental carbon and hydrogen. When coal and biomass feedstocks are used, the contained oxygen converts to carbon monoxide. Any ash and sulfur present are separated and removed. The elemental carbon is fed to a molten carbonate direct carbon fuel cell (DCFC) to produce electrical power, part of which is fed back to power the hydrogen plasma. The hydrogen produced is used in a solid oxide fuel (SOFC) cell for power generation and the remaining high temperature energy in a back-end steam Rankine cycle (SRC) for additional power. Any CO formed is converted to hydrogen using a water gas shift reactor. The plasma reactor is 60% process efficient, the direct carbon fuel cell is up to 90% thermally efficient, the solid oxide fuel cell is 56% efficient and the steam Rankine cycle is 38% efficient. Depending on the feedstock, the combined cycles have efficiencies ranging from over 70% to exceeding 80% based on the higher heating value of the feedstock and are thus twice as high as conventional plants. The CO_2 emissions are proportionately reduced. Since the CO_2 from the direct carbon fuel cell and the water gas shift is highly concentrated, the CO_2 can be sequestered to reduce emission to zero with much less energy loss than required by conventional plants. Alternatively, the combined cycle plants can produce hydrogen for the FreedomCAR program in combination with electrical power production at total thermal efficiencies greater than obtained with fossil fuel reforming and gasification plants producing hydrogen alone.

INTRODUCTION

The impact factors for electrical power generation are the economy and the environment. Fuel efficiency is a prime factor for reducing cost of electrical power generation and reducing emissions of pollutants. This paper presents a power cycle utilizing fossil or biomass fuel, which maximizes efficiency of conversion of fuel energy to electrical power and consequently reduces CO_2 emissions accordingly. With sequestration, zero CO_2 emission is achieved with a minimum of loss of power.

Hydrogen Fuel Cell

The most efficient thermal to electrical conversion device is the electrochemical fuel cell. It can convert the free energy of oxidation of fossil fuel to electrical energy in one step without moving parts. (Faraday's Law $\Delta F = nfe$). The problem is to match the fuel with an electrolyte

that would produce the optimum electrochemical effect. The most advanced fuel cells operate with a clean elemental hydrogen fuel. For power generation the most advanced and efficient fuel cell developed to date has been the high temperature solid oxide fuel cell (SOFC).[1] The oxide electrolyte (transfers oxygen ions to the hydrogen) is a ceramic (stabilized zirconia) which operates at temperatures in the range of 900-1000^{o}C, yielding a power efficiency of up to 56%.[1] For transportation purposes, the polymer electrolyte membrane (PEM) appears to be the preferred fuel cell electrolyte. The current U.S. administration has declared the hydrogen powered fuel cell automobile (The FreedomCAR) [2] to eventually replace the gasoline powered internal combustion engine.

Carbon Fuel Cell

The problem with the utilization of fossil fuels and biomass for fuel cells is that the predominant element is carbon. Thus, it becomes necessary to convert the carbon to hydrogen, which can be accomplished by reaction with water (steam) resulting in the emission of the carbon as CO_2, which is a prime greenhouse gas. However, recently a fuel cell has been under development, which utilizes elemental carbon.[3,4] A schematic of the direct carbon fuel cell is shown in Figure 1. The electrolyte is a molten carbonate salt which transfers carbonate ions from the oxygen cathode to the anode where it reacts with the carbon fuel particulates dispersed in the molten salt and forms CO_2 in high concentration. The cell operates in the range of 750^{o}C to 800^{o}C. The unique feature of this fuel cell based on the direct oxidation of carbon to CO_2 is that the theoretical efficiency of conversion of the enthalpy (heating value) of the carbon to electricity can be 100%. This is because the entropy of oxidation of carbon is zero ($\Delta S = 0$) and thus the enthalpy of oxidation equals the free energy ($\Delta H = \Delta F$). This is not the case for the hydrogen fuel cell because the entropy of oxidation of hydrogen is such that the theoretical thermal efficiency can only be 70%. ($\Delta F/\Delta H = 0.70$ for H_2 oxidation). Efficiencies of 85% to 90% have already been obtained in laboratory carbon molten salt fuel cells at power densities sufficient for stationary power production (0.8 kW/m^2). An additional advantage of the cell is that the product CO_2 emerges from the anode side of the cell at 100% concentration ready for sequestration. The critical factor in this development is to produce a carbon having good reactive properties, i.e., small particle size and active surface properties.

Conversion of Fossil Fuels to Carbon and Hydrogen

The problem of the application of fossil fuels for powering fuel cells is to process the hydrocarbons in fossil fuels to produce elemental hydrogen and elemental carbon. This can be accomplished by thermal cracking (decomposition) and pyrolysis processes. For example, the well-known method of producing carbon black is to heat methane (natural gas) in a firebrick furnace to temperatures of between 800oC to 1400oC, which decomposes the methane to carbon, and hydrogen.(5) This is a discontinuous process in which two tandem furnaces are alternately heated for cracking the methane. Other processes have also been developed in which some partial combustion of the fuel is used to provide the endothermic heat of reaction required to crack the hydrocarbon. The problem of designing a continuous reactor is to be able to heat the fossil fuel to high temperatures (>800oC) and to extract and separate the carbon from the H2, CO and CO2 gases in a continuous manner. It has been suggested that carbon can act as a catalyst in thermally decomposing methane.(9) Hydrogenation processes have also been developed to produce methane from fossil fuels which is subsequently decomposed to carbon and hydrogen, part of which is recycled to provide the hydropyrolysis reaction.(4)

Plasma Black Process

Recently, hydrogen plasma has been developed which accomplishes a continuous fossil fuel cracking process. This process has originally been developed to produce carbon black from natural gas and oil on a commercial scale.[6] This development appears to be ideal for cracking fossil fuels and biomass to carbon and hydrogen. Temperatures of the order of 1500°C are achieved in the hydrogen plasma between the carbon electrodes where the fossil fuels are introduced. At these temperatures, the hydrocarbons are completely cracked to carbon and hydrogen in one pass. Any oxygen in the fuel, as in coal and biomass (wood), is converted to carbon monoxide (CO). A simplified schematic of the plasma reactor is shown in Figure 2. A full-scale plasma black plant producing 30,000 tons per year of carbon black and 2,500 billion cu. ft. of hydrogen per year has been built and operated outside of Montreal [7] on both natural gas and heavy oil feedstocks. The process efficiency has been found to be very high (>50%).

The main problem with the plasma decomposition process is the need for electrical power. Supplying conventional electric power generated from fossil fuel by the steam Rankine Cycle (SRC) is at most 38% efficient, which means that the overall fuel to product cycle efficiency of utilizing the plasma process is degraded. However, if the direct carbon fuel cell (DCFC), is used, the electric power generated from carbon produced by the plasma, can be increased to as high as 90% efficiency. Furthermore, the carbon formed in the plasma reactor is of a quality suitable for the molten carbonate cell. There is, thus, a good match between the hydrogen plasma black reactor (HPBR) and the direct carbon fuel cell (DCFC) for producing electric power and/or hydrogen and maximizing the power cycle efficiency.

The Hydrogen Plasma Black Reactor (HPBR) with Direct Carbon Fuel Cell (DCFC) and Solid Oxide Fuel Cell (SOFC) Combined Power Cycle

Flow sheets for the HPBR/DCFC/SOFC combined cycle electric power generation system are developed in Figure 3 for natural gas and oil and Figure 4 for biomass and coal. In the Karbomont plasma black reactor, the gases are cooled by means of a water-cooled coil directly under the concentric tubular electrodes where the DC arc is struck. The carbon is separated from the gases after further cooling in bag filters. It is proposed for the DCFC power cycle, that the molten carbonate salt (Li/K) at 750°C be circulated in a section below the carbon arc electrodes in direct contact with the hydrogen in an entrained fashion to scrub the carbon particulates out of hydrogen stream. The carbon then becomes dispersed in the molten carbonate. The molten salt is then circulated between the HPBR and DCFC. Because of the high temperature, all types of feedstock can be completely decomposed to hydrogen and carbon and CO. From data presented by Karbomont[7] it is estimated that the process efficiency can be as high as 60% of the thermal decomposition energy of the feedstock. The particulate carbon dispersed in the molten salt is converted to CO_2, which emerges from the anode compartment of the cell at 100% concentration. The DCFC can operate at up to 90% efficiency producing the electricity. The hydrogen from the HPBR is sent to a solid oxide fuel cell (SOFC) as shown in Figure 2 where thermal to electrical efficiencies up to 56% can be obtained. In the case of coal and biomass as shown in Figure 4 where oxygen is present in the feedstock, in addition to hydrogen, CO is formed. For power production, the H_2 and CO hot gas from the HPBR is sent directly to the SOFC. Oxygen ion is transmitted through the SOFC ceramic membrane and oxidizes the CO and H_2 to CO_2 and H_2O with the production of DC power. Alternatively, CO can be converted to additional hydrogen in an energy neutral water gas shift (WGS) reactor with recycled steam and then sent to the SOFC for DC power production. WGS is preferred when

hydrogen production for the market is preferred. The CO_2 can be removed from the hydrogen by pressure swing adsorption (PSA) or by scrubbing with MEA. The ash and sulfur present in the coal and biomass will either be separated by density difference in the HPBR or in the effluent hydrogen stream.

To complete the cycle in both Figures 3 and 4, a backend steam Rankine cycle (SRC) is used to convert the high temperature heat capacity remaining in the CO_2 and H_2O emitted from the fuel cells into AC power. There is no combustion in the boiler; however, there is a heat exchanger boiler to raise high-pressure steam from water to 550^{o}C and 68 atm to drive the turbo-generator. The efficiency is equivalent to a conventional steam Rankine cycle plant at 38% efficiency.

Energy Efficiency of the HPBR/DCFC/SOFC/SRC

The energy efficiency for conversion of the thermal energy in the fossil fuel feedstock to electrical energy is thermodynamically evaluated as follows. The compositional and thermodynamic energy functions of a series of coal and biomass feedstocks derived from handbook data[8] and private sources are given in Table 1. Additional thermodynamic data for other carbonaceous feedstocks are given in Table 2, which includes the natural gas and oil feedstock. Based on the stoichiometries of the various feedstocks, the enthalpy or heat of reaction for each of the unit operations of the power cycle are given in Tables 3 and 4 for natural gas and oil and for coal and biomass feedstocks, respectively. The HHV thermal efficiency of the power cycle is then calculated based on the following equation.

$$\% \text{ Thermal Efficiency} = \frac{\text{Net Enthalpy to Electrical Energy}}{\text{HHV of Fuel}} \times 100$$

Net Enthalpy to Electrical Energy = Enthalpy for DCFC + Enthalpy for SOFC + Enthalpy for. SCR – Enthalpy for HPBR

$$\text{Enthalpy for DCFC} = n_C \, E_{DCFC} \, \Delta H_{DCFC}$$

$$\text{Enthalpy for SOFC} = n_{H2} \, E_{SOFC} \, \Delta H_{SOFC}$$

$$\text{Enthalpy for SRC} = E_{SCR} \left[(1 - E_{DCFC}) \, n_C \Delta H_{DCFC} + (1 - E_{SOFC}) n_{H2} \Delta H_{SOFC} \right]$$

ΔH = Enthalpy of reaction Kcal/gm.mol
HHV = Higher Heating Value of fuel = Enthalpy of combustion
E = Thermal efficiency
Proc. E_{HPBR} = Process efficiency of decomposition energy in plasma.
n_C = gm.mol of carbon. Basis is n_C = 1.0 for fuel feedstock
n_{H2} = gm.mol of hydrogen produced in HPBR and WGSR
DCFC = Refers to Direct Carbon Fuel Cell
SOFC = Refers to Solid Oxide Fuel Cell
HPCR = Refers to Hydrogen Plasma Black Reactor
SRC = Refers to Steam Rankine Cycle
WGSR = Refers to Water Gas Shift Reactor

Table 5 then gives the breakdown of energy generation for each unit of the HPBR/DCFC/SOFC/SRC combined power cycle, based on the data and efficiencies given in the previous tables. The highest combined cycle efficiency is obtained using oil as feedstock at 84.1%. This is more than twice the efficiency of the 38% that is currently obtained with a steam Rankine cycle. Lignite coal results in a high efficiency of 83.3% with bituminous coal somewhat less at 81.3% efficiency. Biomass and natural gas indicate the lowest efficiency but still high, in the order of twice the efficiency of the conventional SRC plant at 76.3 and 74.1%, respectively. It appears that the reason these two feedstocks are lower in efficiency is because of the larger amount of energy required to decompose these feedstocks compared to the oil and coal and the higher hydrogen content, which goes to the SOFC at a lower efficiency than the carbon fuel cell. This has been confirmed for oil compared to natural in the Karbomont plant.[7]

The CO_2 emission in lbs CO_2/kWh(e) is also given in Table 5. The values are proportionately a function of the feedstock and the thermal efficiency. The lowest emissions at 0.53 lb CO_2/kWh(e) is obtained with natural gas and that is because natural gas has the highest hydrogen content of all the fuels. Because the CO_2 is emitted from the DCFC and the steam boiler after water condensation, at essentially 100% concentration, no energy is needed to separate CO_2 from nitrogen as is required by the flue gas from a conventional fuel combustion steam plant for purposes of sequestering the CO_2 in order to obtain zero emission. However, in order to sequester CO_2 in deep saline water aquifers or in depleted oil or gas wells or in the ocean, it is necessary to compress and/or liquefy the CO_2. It takes an equivalent of about 0.112 kWh(e) of electrical energy to separate and liquefy 1 lb of CO_2.[9] About 58% of the energy is in the separation by absorption/stripping with a solvent such as MEA and 42% is for the liquefaction of the separated CO_2. Thus, the energy required to sequester CO_2 from a conventional natural plant is 12.4% of the energy generated. With the combined cycle plant this is reduced to 2.5%. For a lignite coal plant the conventional plant sequestering energy consumption is as much as 23.0% of the power plant output. With the above combined cycle plant this is reduced to 4.0%. These reductions constitute considerable savings in energy and production cost of electrical power to achieve zero CO_2 emission.

Combined Hydrogen and Electrical Energy

Because of the advent of the FreedomCAR program, the above combined cycle plants can be configured to produce both hydrogen and electric power. The solid oxide fuel cell, which converts the hydrogen to electricity, is eliminated and only the DCFC produces electricity from the carbon formed in the HPBR. The WGSR converts any CO formed in the HPBR into additional hydrogen. Figure 5 shows the power and hydrogen combined cycle plant and Table 6 gives an evaluation of the energy and thermal efficiency distribution between the hydrogen and electrical production for three feedstocks. Hydrogen production is shown in terms of its higher heating value (HHV = 68 kcal/gmol). It is interesting to note that the total efficiency for hydrogen and electricity production is greater than for electricity production alone. This is because electricity production from hydrogen in the SOFC is only efficient to the extent of 56% whereas if you count hydrogen in terms of its thermal energy content, the total efficiency is maximized. Of course what really counts is what the market is willing to pay for hydrogen gas versus electrical power. It is also interesting to note that production of hydrogen by conventional natural gas reforming is 78.5% efficient and from bituminous coal by gasification it is 63.2% efficient.[10] The combined cycle plants presented in this paper thus offer much higher efficiency

in the nineties for combined hydrogen and power production with corresponding reduction in CO_2 emission.

It should be noted that maximizing efficiency reduces cost of fuel towards the production cost of both electrical power and hydrogen. What is equally important, from an economic point of view, is the capital investment. Based on an earlier study on combined cycle plants using direct carbon and solid oxide fuel cells, a conservative estimate of the unit capital investment in terms of $/kW(e), was found to be competitive with conventional plants for different feedstock.[4] The main difference between the earlier and the current study is that conversion of feedstocks to carbon and hydrogen was performed with thermal decomposition processes, (pyrolysis and hydropyrolysis reactions) instead of the hydrogen plasma black process. As a result, the current study yielded higher electrical power efficiencies and should result in lower capital investment. A definitive study must also take into account the size and capacity of the various units in the combined cycle plant.

CONCLUSION

The combined cycle plant which utilizes a hydrogen plasma black reactor (HPBR) to produce carbon from fossil fuel feedstocks for a direct carbon fuel cell (DCFC) and hydrogen for a solid oxide fuel cell (SOFC) and with a backend steam Rankine cycle plant (SRC), yields electrical power plant efficiencies ranging from over 70% to exceeding 80% based on higher heating values. These plants are more than twice as efficient as conventional steam Rankine cycle plants. Consequently, the CO_2 emissions are less than half that of conventional steam plants. The CO_2 emission from the DCFC and the water gas reactor is highly concentrated. To achieve zero CO_2 emissions, the CO_2 can be sequestered with much less energy loss than required from the flue gas of conventional steam plants. The combined cycle plants can be configured to produce hydrogen for the FreedomCAR program in conjunction with electrical power at total thermal efficiencies much greater than obtained with fossil fuel reforming and gasification plants. This study confirms that further development of this concept appears warranted.

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Composition and Thermodynamics of the Feedstocks Used in this Study

Feedstock	Biomass Wood	Bituminous Kentucky Coal	Lignite N. Dakota Coal	Sub Bituminous Wyodak Coal	Alaska Beluga Coal	Sewage Sludge
Composition (wt%)						
C	45.86	67.02	43.37	49.95	49.33	28.55
H	5.27	4.54	2.78	3.51	4.00	4.09
O	36.07	7.22	13.97	12.58	15.56	16.03
H_2O	11.67	8.60	30.10	26.40	21.78	9.82
Ash	0.66	8.34	8.30	6.03	8.67	36.53
S	0.04	2.85	0.81	0.60	0.12	1.36
N	0.43	1.43	0.67	0.93	0.54	3.62
Heating Value (Higher)						
(BTU/lb-MF)	-8800.0	-13650	-10254	-11730	-11082	-5510
(kcal/kg-MF)	-4888.9	-7583.3	-5696.7	-6516.7	-6156.7	-3061.1
Heat of Formation (kcal/kg-MAF)	-1214.4	183.0	-593.0	-461.7	-584.9	-1769.7
Heat Capacity (kcal/kgMF/^{o}C)	0.570	0.315	0.315	0.315	0.315	0.250

MAF Moisture Ash Free
MF Moisture Free

Table 2
Thermodynamics of Various Carbonaceous Feedstocks

Feedstock	Stoichiometric Formula[1]	Heat of Combustion[2] (Kcal/Mole) HHV	LHV	Heat of Formation[2] (Kcal/Mole)	Heat of Cracking[2] Cracking Products[3]	(Kcal/Mole)
Natural Gas	CH_4	-212	-192	-18	$C(s) + 2H_{2(g)}$	+18
Petroleum Medium Crude Resids, Tar, Sands, Shale	$CH_{1.7}$	-149	-141	-3	$C(s) + 0.85H_{2(g)}$	+3
Wood (Biomass)						
Sawdust	$CH_{1.44}O_{0.66}$	-105	-98	-38	$C(s) + 0.06H_{2(g)} + 0.66H_2O_{(\ell)}$	-7
Pine (12% Moisture)	$CH_{1.44}O_{0.66}$	-127	-120	-16	$C(s) + 0.06H_{2(g)} + 0.66H_2O_{(\ell)}$	-29
MSW and Paper Waste						
Rubber						
Styrene-Butadiene (Synthetic)	$CH_{1.15}$	-142	-136	+9	$C(s) + 0.58H_{2(g)}$	-9
Natural Rubber (Isoprene)	$CH_{1.6}$	-144	-136	-5	$C(s) + 0.8H_{2(g)}$	+5
Coal						
Bituminous	$CH_{0.8}O_{0.08}$	-116	-112	-5	$C(s) + 0.32H_{2(g)} + 0.08H_2O_{(\ell)}$	-1
Lignite	$CH_{0.8}O_{0.22}$	-113	-109	-8	$C(s) + 0.18H_{2(g)} + 0.22H_2O_{(\ell)}$	-7

(1) Representative formulae, based on unit atom of carbon in feedstock. Specific samples will vary in composition.

(2) All heats of combustion, formation, and cracking (at 298.2°K) are based upon one gram-mole of feedstock containing one gram-atom of carbon. HHV represents higher heating value and LHV is lower heating value.

(3) Note cracking products in this table are to H_2 and H_2O, whereas at high temperature the cracking products are to CO and H_2 as shown in Table 3.

Table 3
Natural Gas or Oil Fired Combined Cycle Hydrogen Plasma Black Reactor (HPBR)
With Direct Carbon Fuel Cell (DCFC) and Solid Oxide Fuel (SOFC) and
Backend Steam Rankine Power Generation (SRC)
Enthalpy and Efficiency of Unit Reactions

Unit and Reactions	$\Delta H_{298.2}$ Kcal/gmol	Efficiency %
HPBR – Hydrogen Plasma Black Reactor – 1500°C-atm		
Natural gas $CH_4 = C + 2H_2$	+18.0	Process 60
Oil $CH_{1.7} = C + 0.85H_2$	+ 3.0	Process 60
DCFC – Direct Carbon Fuel Cell – 750°C-atm		
$C + O_2 = CO_2$ ($CO_3^=$ ion transport)	-94.0	Thermal 90
SOFC – Solid Oxide Fuel Cell – 900°C-atm		
Hydrogen: $H_2 + 1/2\ O_2 = H_2O$ ($O^=$ ion transport)	-68.0	Thermal 56
SRC – Steam Rankine Cycle – 550°C-68 atm		
$H_2O_{(\ell)} = H_2O_{(g)}$ (Steam Pressure)	Remaining ΔH	Thermal 38

Table 4
Coal and Biomass Fueled Combined Cycle
Hdrogen Plasma Black Reactor (HPBR)
With Direct Carbon Fuel Cell (DCFC) and Solid Oxide Fuel (SOFC) and
Backend Steam Rankine Power Generation (SRC)
IPFC
Enthalpy and Efficiency of Unit Reactions

Unit and Reactions	? $H_{298.2}$ Kcal/gmol	Efficiency %
HPBR – Hydrogen Plasma Black Reactor – 1500°C-atm		
Lignite Coal: $CH_{0.77}O_{0.24} = 0.76\ C + 0.24\ CO + 0.385\ H_2$	+3.6	Process 60
Kentucky Bit Coal: $CH_{0.81}O_{0.08} = 0.92\ C + 0.08\ CO + 0.4\ H_2$	+4.8	Process 60
Biomass: $CH_{1.38}O_{0.59} = 0.41\ C + 0.59\ CO + 0.69\ H_2$	+12.7	Process 60
WGS – Water Gas Shift – 450° C		
Lignite: $0.24\ CO + 0.24\ H_2O = 0.24\ CO_2 + 0.24\ H_2$	0	Conversion 100
Bituminous: $0.08\ CO + 0.08\ H_2O = 0.08\ CO + 0.08\ H_2$	0	Conversion 100
Biomass: $0.59\ CO + 0.59\ H_2O = 0.59\ CO + 0.59\ H_2$	0	Conversion 100
DCFC – Direct Carbon Fuel Cell – 750°C-atm		
Carbon: $C + O_2 = CO_2$ ($CO_3^=$ ion transport)	-94.0	Thermal 90
SOFC – Solid Oxide Fuel Cell – 900°C-atm		
Hydrogen: $H_2 + 1/2\ O_2 = H_2O$ ($O^=$ ion transport)	-68.0	Thermal 56
SRC – Steam Rankine Cycle – 550°C-68 atm		
$H_2O_{(\ell)} = H_2O_{(g)}$ (Steam Pressure)	Remaining ? H	Thermal 38

Table 5
Electrical Power Production in the Integrated Plasma Fuel Cell IPFC Combined Power Cycle Plant
Thermal Efficiency Evaluation and CO_2 Emission
Basis: -1 gmol of Fuel

Fuel Feedstock		Natural Gas	Petroleum	N. Dakota Lignite Coal	Kentucky Bituminous Coal	Biomass Wood
Molar Composition (MAF)		CH_4	$CH_{1.7}$	$CH_{0.77}O_{0.24}$	$CH_{0.81}O_{0.08}$	$CH_{1.38}O_{0.59}$
Plasma Decomp. Products Mole/Mole Fuel						
C		1.0	1.0	0.76	0.92	0.41
CO		-	-	0.24	0.08	0.59
H_2		2.0	0.85	0.39	0.41	0.69
Ash, S, N (wt%)		-	~1.0	9.8	12.6	1.1
Enthalpy of Decomposition Kcal/gmol		+18.0	+3.0	+3.6	+4.8	+12.7
Electrical Energy Generation <u>All Energy Values in Kcal/gmol fuel</u>						
<u>UnitEff. %</u>						
DCFC	90	84.6	84.6	64.3	77.8	34.7
SOFC	56	76.2	32.4	23.8	18.7	48.7
SRC	38	26.3	13.3	9.8	8.8	16.2
HPBR	60 - Consumed -30.0		-5.0	-6.0	-8.0	-21.2
Net Electricity Generation, Kcal(e)		157.1	125.3	91.9	97.3	78.4
HHV of Fuel, Kcal(t)		212.0	149.0	110.3	119.0	112.8
Heat Exch. for Preheat* Kcal(t)		14.8	16.2	7.7	6.5	18.9
Thermal Efficiency - %		74.1	84.1	83.3	81.8	69.5
CO_2 Emission, Lbs/kWh(e)		0.531	0.666	0.908	0.857	(1.064)**
CO_2 Reduction from conventional 38% SRC cycle - %		48.7	54.8	54.4	53.5	100.0

HPBR = Hydrogen Plasma Black Reactor
DCFC = Direct Carbon Fuel Coal
SOFC = Solid Oxide Fuel Cell
SRC = Steam Rancine Cycle

* This is the amount of heat unconverted from high temperature gas and can be used to preheat the incoming feed to reactor temperature by heat exchange.
**For biomass this is the amount of CO_2 emitted from power cycle, however, because of the photosynthesis of biomass there is a zero net emission of CO_2.

Table 6
Hydrogen and Electrical Power Production in the Integrated Plasma Fuel Cell (IPFC)
Combined Cycle Plant Energy and Thermal Efficiency Distribution for
Hydrogen and Electrical Power Production

Fuel Feedstock	Natural Gas	Petroleum	N. Dakota Lignite Coal	Kentucky Bit. Coal	Biomass (Wood)
Electricity Production (from DCFC only)					
Electrical Energy Kcal(e)/gmol fuel	54.6	79.6	58.3	69.8	13.5
Hydrogen Production from HPBR					
Thermal energy in H_2 Kcal(t)/gmol fuel*	136	57.8	42.2	33.4	87.0
HHV of Fuel Feedstock Kcal(t)/gm mol	212	149.0	110.3	119.0	112.8
Thermal Efficiency					
Electricity Production - %	25.8	53.4	52.9	58.7	12.0
Hyrdrogen Production - %	64.2	38.8	38.3	28.1	77.1
Total Efficiency - %	90.0	92.2	91.2	86.8	89.1

*HHV of hydrogen = 68 Kcal/mol

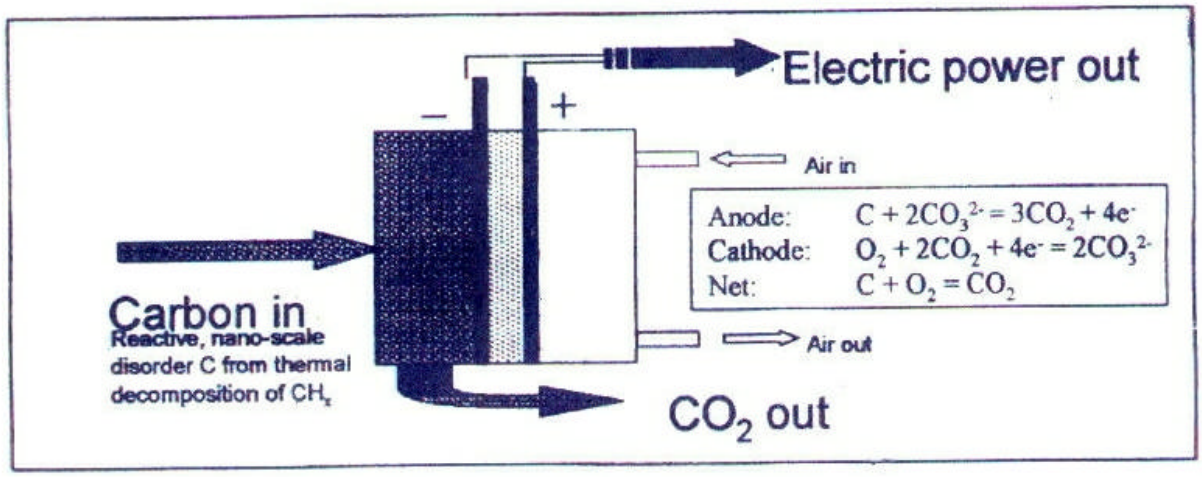


Figure 1. Direct Carbon Fuel Cell with Molten Carbonate Salt Electrolyte at 750° – 800°C

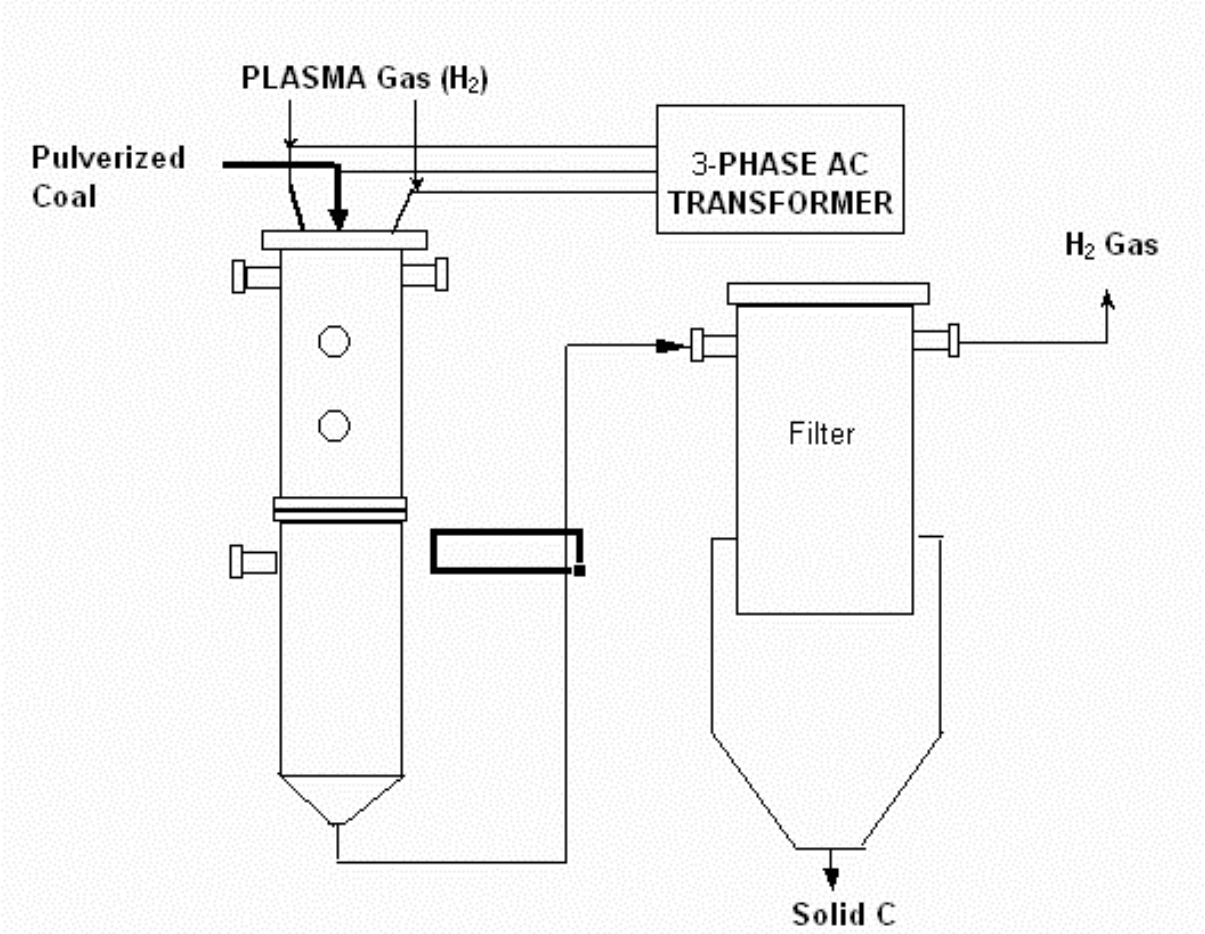
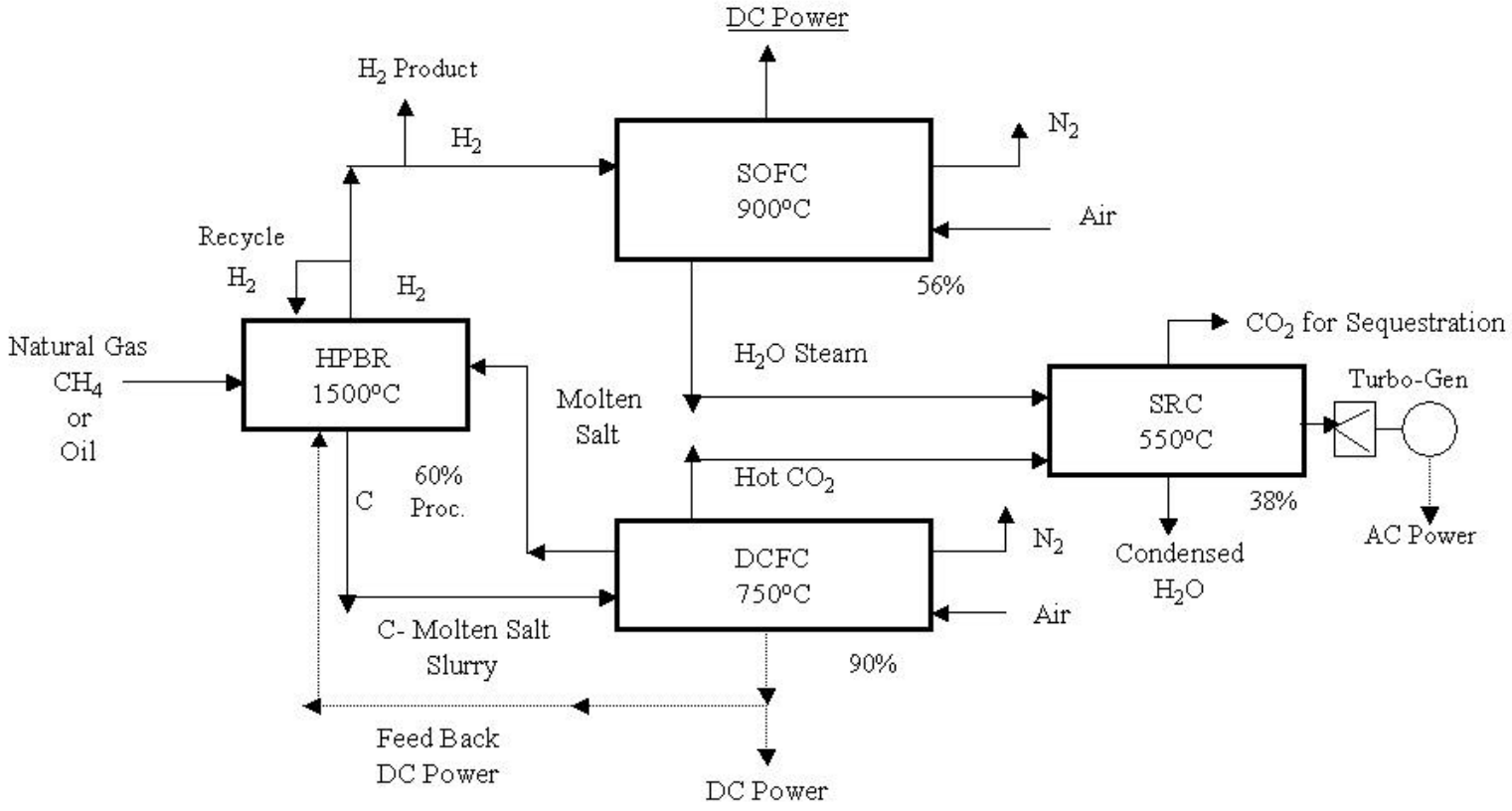
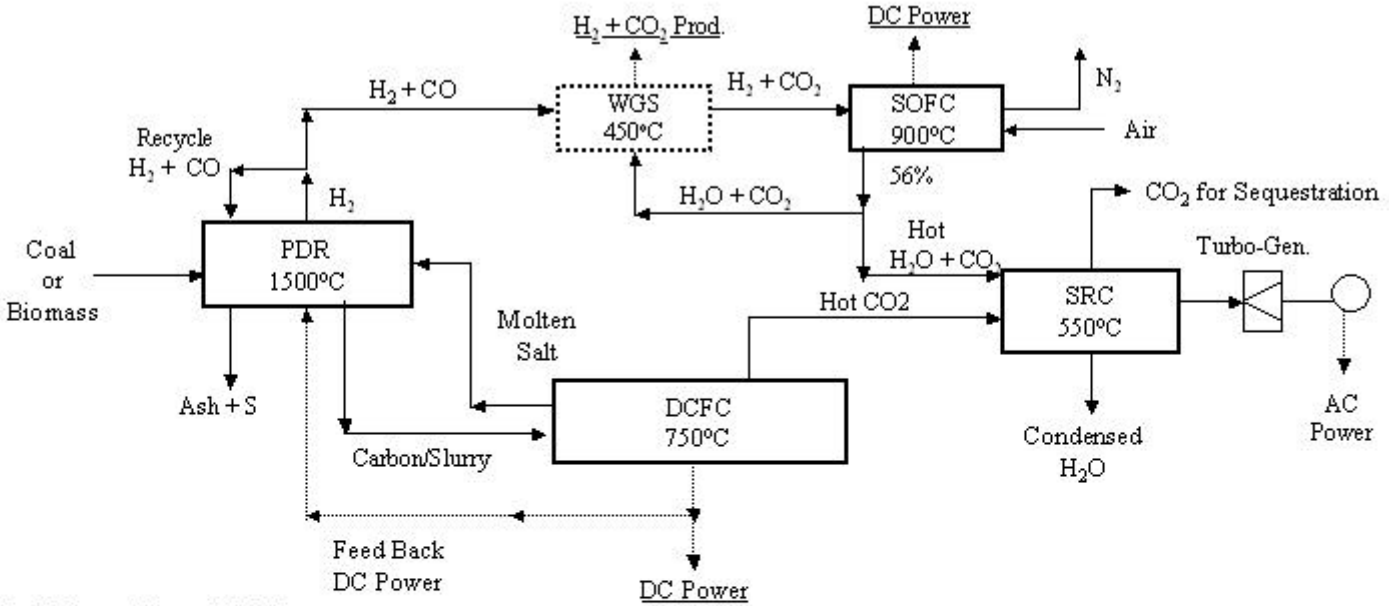


Figure 2. THE HYDROGEN PLASMA BLACK REACTOR



HPBR – Hydrogen Plasma Black Reactor
Natural Gas $CH_4 = C + 2H$
Oil $CH_{1.7} = C + 0.85\ H_2$
DCFC - Direct Carbon Fuel Cell
$C + O_2 = CO_2$ ($CO_3^=$ Ion Transport)
SOFC - Solid Oxide Fuel Cell
$H_2 + 1/2\ O_2 = H_2O$ ($O^=$ Ion Transport)
SRC - Steam Rankine Cycle

Figure 3 – Intergrated Plasma Fuel Cell (IPFC) Plant Natural Gas or Oil Fueled Combined Cycle Hydrogen Plasma Black Reactor (HPBR) with Direct Carbon Fuel Cell (DCFC), Solid Oxide Fuel Cell (SOFC) and Backend Steam Rankine Cycle (SRC) Power Generation



HPBR - Hydrogen Plasma Black Reactor
Lignite Coal $CH_{0.77}O_{0.24} = 0.76C + 0.24\,CO + 0.385\,H_2$
Kentucky Bit. Coal $CH_{0.81}O_{0.08} = 0.92\,C + 0.08\,CO + 0.40\,H_2$
Biomass: $CH_{1.38}O_{0.59} = 0.41\,C + 0.59\,CO + 0.69\,H_2$
WGS - Water Gas Shift
Lignite $0.24\,CO + 0.24\,H_2O = 0.24\,CO_2 + 0.24\,H_2$
Bituminous $0.08\,CO + 0.08\,H_2O = 0.08\,CO + 0.08\,H_2$
Biomass: $0.59\,CO + 0.59\,H_2O = 0.59\,CO_2 + 0.59\,H_2$
SOFC - Solid Oxide Fuel Cell
$H_2 + 1/2\,O_2 = H_2O$ (High Transport)
DCFC - Direct Carbon Fuel Cell
$C + O_2 + CO_2$ ($CO_3^=$ Ion Transport)
SRC - Steam Boiler Rankine Cycle

Figure 4. Integrated Plasma Fuel Cell (IPFC) Plant Coal or Biomass Fueled Combined Cycle Plasma Composition (PDR) with Direct Carbon Fuel Cell (DCFC), Hydrogen Solid Oxide Fuel Cell (SOFC) Backend Steam Rankine Cycle (SRC) Power Generation