FutureGen -Tomorrow's Clean Energy
Interactive and Combined Economic Drivers

Resoure:	**Fossil Fuels: Gas, Oil and Coal** **Biomass: Wood, AG and Waste Products**
Power Fuels:	**Stationary: Carbon and Carbon Carriers** **Transportation: Hydrogen and Hydrogen Carriers**
Converters:	**High Efficiency**
Environment:	**Reduced CO2 Emission: Sequestration**

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An Innovative Highly Efficient Combined Cycle Fossil and biomass Fuel Power Generation and Hydrogen Production Plant with Zero CO_2 Emission

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By

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March 2003

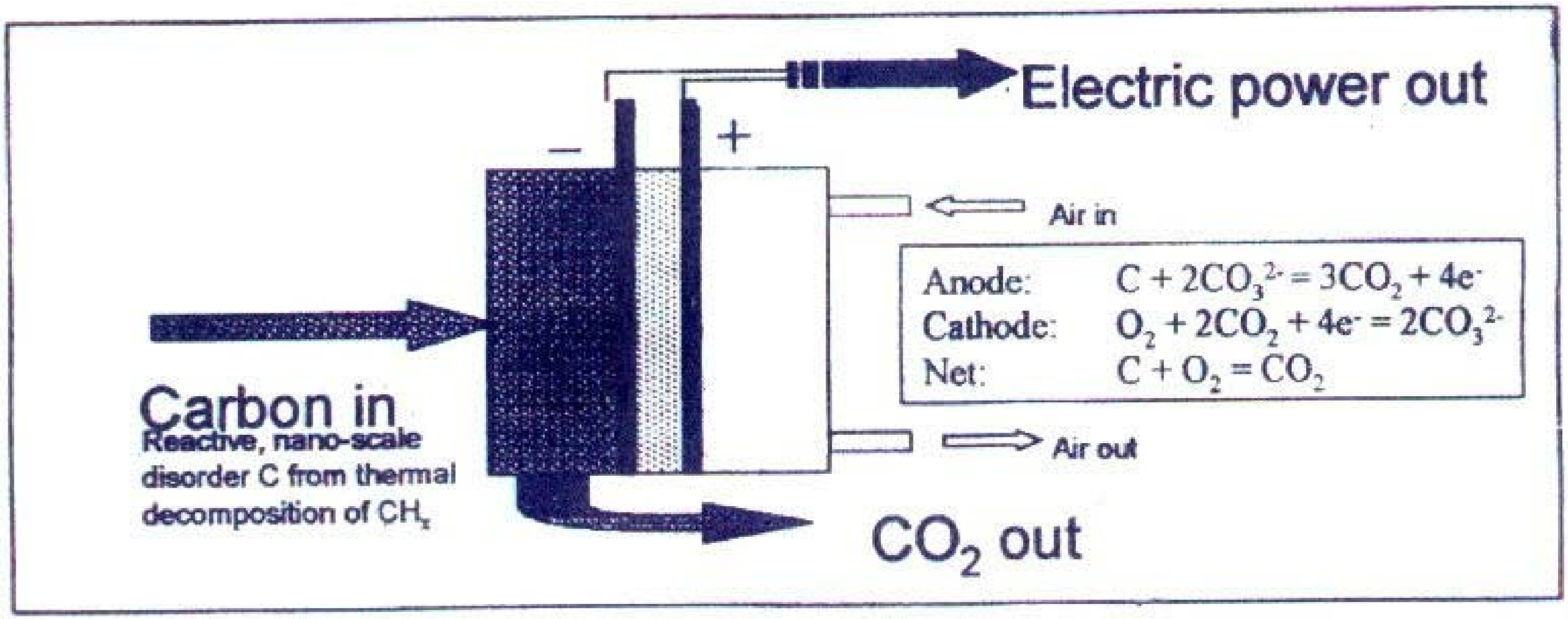

Figure 1. Direct Carbon Fuel Cell with Molten Carbonate Salt Electrolyte at 750° – 800°C

Benefits of a Carbon Fuel Cell

•Utilizes all the Carbon Energy in Fossil Fuels Directly and Efficiently

•The Thermodynamic Efficiency of a Carbon Fuel Cell is 100%;
Entropy Change is zero $\Delta F/\Delta H = 1.002$ (25-1000°C)

•The Thermodynamic Efficiency of a Hydrogen Fuel Cell is only 70%;
Entropy Change is Large $\Delta F/\Delta H = 0.700$ at 1000°C

•The Activity of the C Fuel and CO_2 Product is Unity
Allows Full Utilization of C Fuel in One Pass.
The Activity of the H_2 Fuel and H_2O Product in a Hydrogen-Fuel Cell is Less than Unit Resulting in Only 80% Utilization in One Pass

•A Molten Salt (Carbonate) Carbon Fuel Cell Operating at 750°C Has Achieved 86% Thermodynamic Efficiency

•Power Densities of 1 Kw/m^2 has been Achieved

•Concentrated CO_2 is Evolved at the Anode Ready for Sequestration

•O_2 from Air is Consumed at the Cathode Forming Carbonate Ion which is Transported through the Molten Salt Electrolyte to the Anode

Processes for Conversion of Fossil Fuels and Biomass to Carbon

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1. **Thermal Black – from Natural Gas**
2. **Furnace Black – from Oil**
3. **Petroleum Coke – from Residual Oil**
4. **Hydrocarb Process – from Coal and Biomass Hydrogenation followed by Thermal Decomposition of Methane**
5. **Plasma Black – from Fossil Fuels and Biomass**

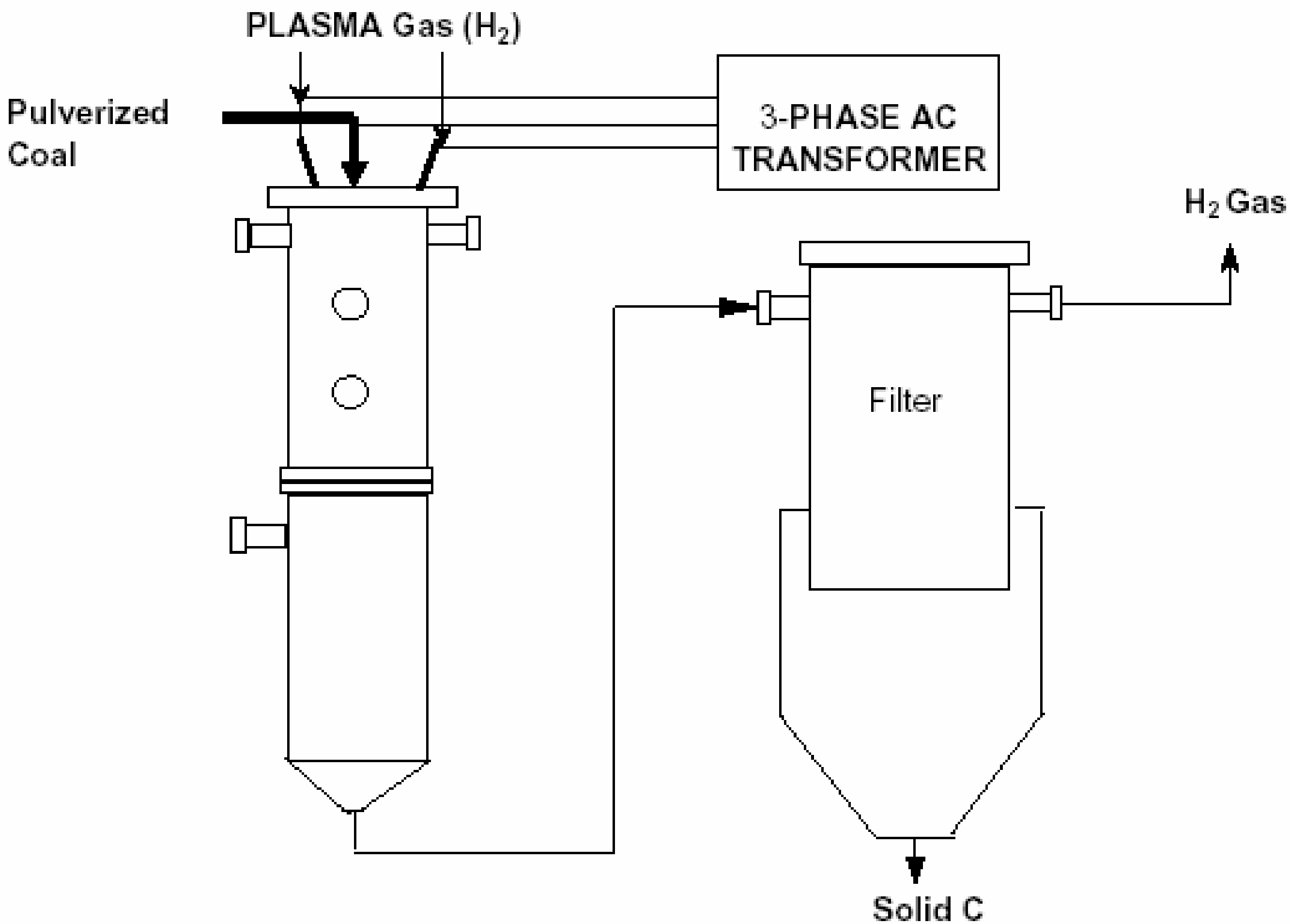
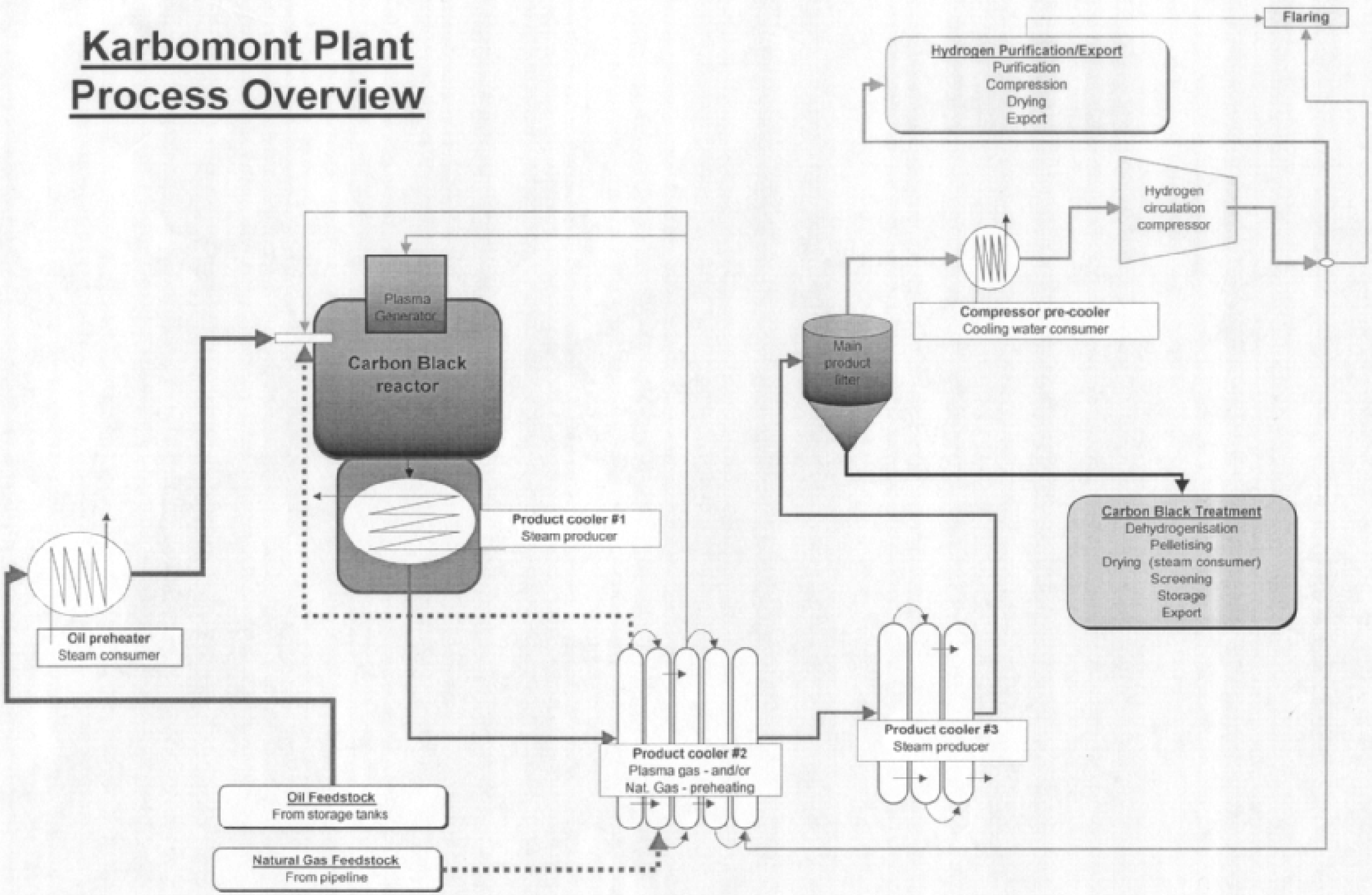
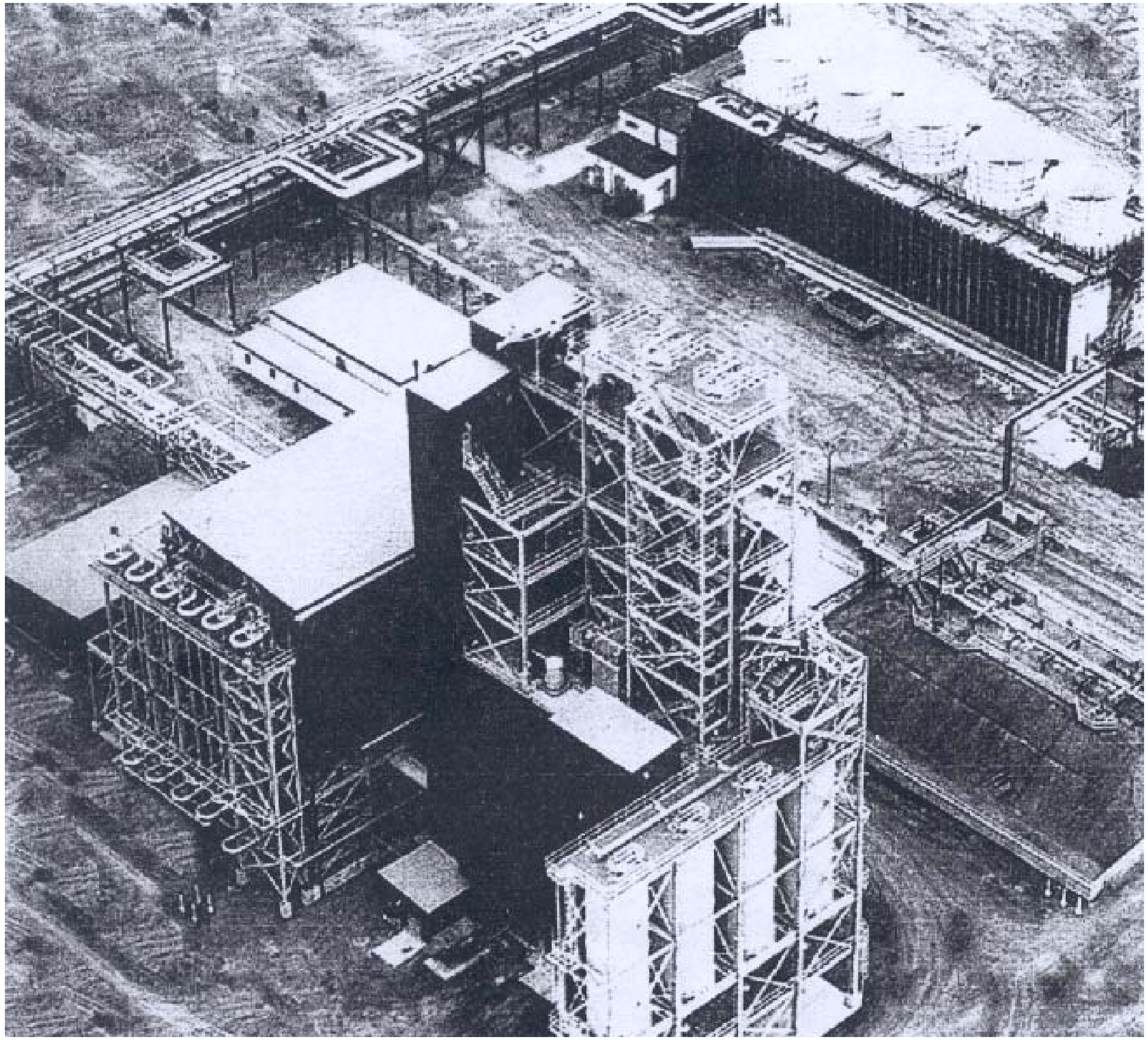


Figure 2. THE HYDROGEN PLASMA BLACK REACTOR

Karbomont Plant Process Overview





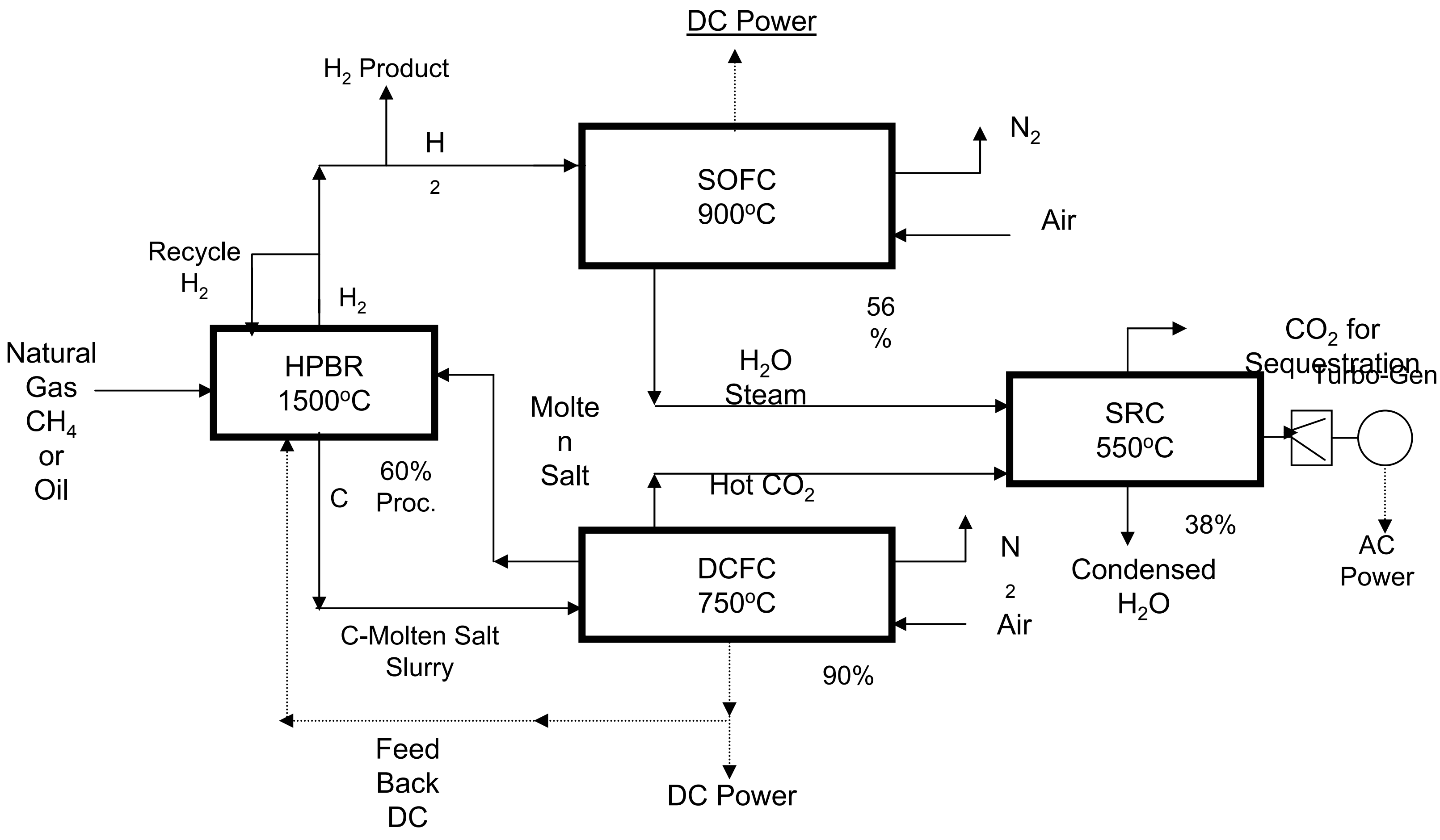
Aerial view of the $65 million Karbomont Montreal-East facility, producing 20,000 T/year CARBON BLACK and 2500 million cubic ft/year HYDROGEN – operating on natural gas and oil. (We are proposing to operate this process with coal after performing bench scale research with a laboratory palsma arc.)

Benefits of Hydrogen Plasma Black Reactor (HPBR)

1. Hydrogen Plasma is very efficient in cracking carbonaceous fuels to carbon, hydrogen and CO.
2. The reactor is flexible operating with different fuel feedstocks and is modular in design.
3. Thermal reaction temperatures of approximately 1500°C is readily achieved.
4. Thermal Decomposition (cracking) Conversion is complete in one pass.
5. Best way of injecting enthalpy into the system and removing carbon:
   - No heat transfer surface
   - No combustion gases
6. Process Efficiency reaches 60% based on enthalpy of cracking.
7. Thermal Efficiency to products, C, H and CO reaches >90%.

Benefits of Matching Hydrogen Plasma Black Reactor (HPBR) with Direct Carbon Fuel Cell (DCFC)

1. The efficient generation of electrical energy from carbon in the DCFC can be supplied to and efficiently used in the HPBR.
2. The carbon efficiently generated in the HPBR can be efficiently used in the DCFC.
3. The fluid molten carbonate electrolyte in the DCFC can be effectively used to capture the carbon from the hydrogen stream in the HPBR.
4. The high temperature enthalpy in the HPBR (1500°C) can be conserved in the DCFC (800°C)
5. Modular design of the HPBR can be matched with the modular design of the DCFC.
6. The hydrogen from the HPBR can either be used in the SOFC for power generation or sold for the hydrogen fuel market.



<u>HPBR - Hydrogen Plasma Black Reactor</u>

Natural Gas $CH_4 = C + 2H$

Oil $CH_{1.7} = C + 0.85\ H_2$

<u>DCFC - Direct Carbon Fuel Cell</u>

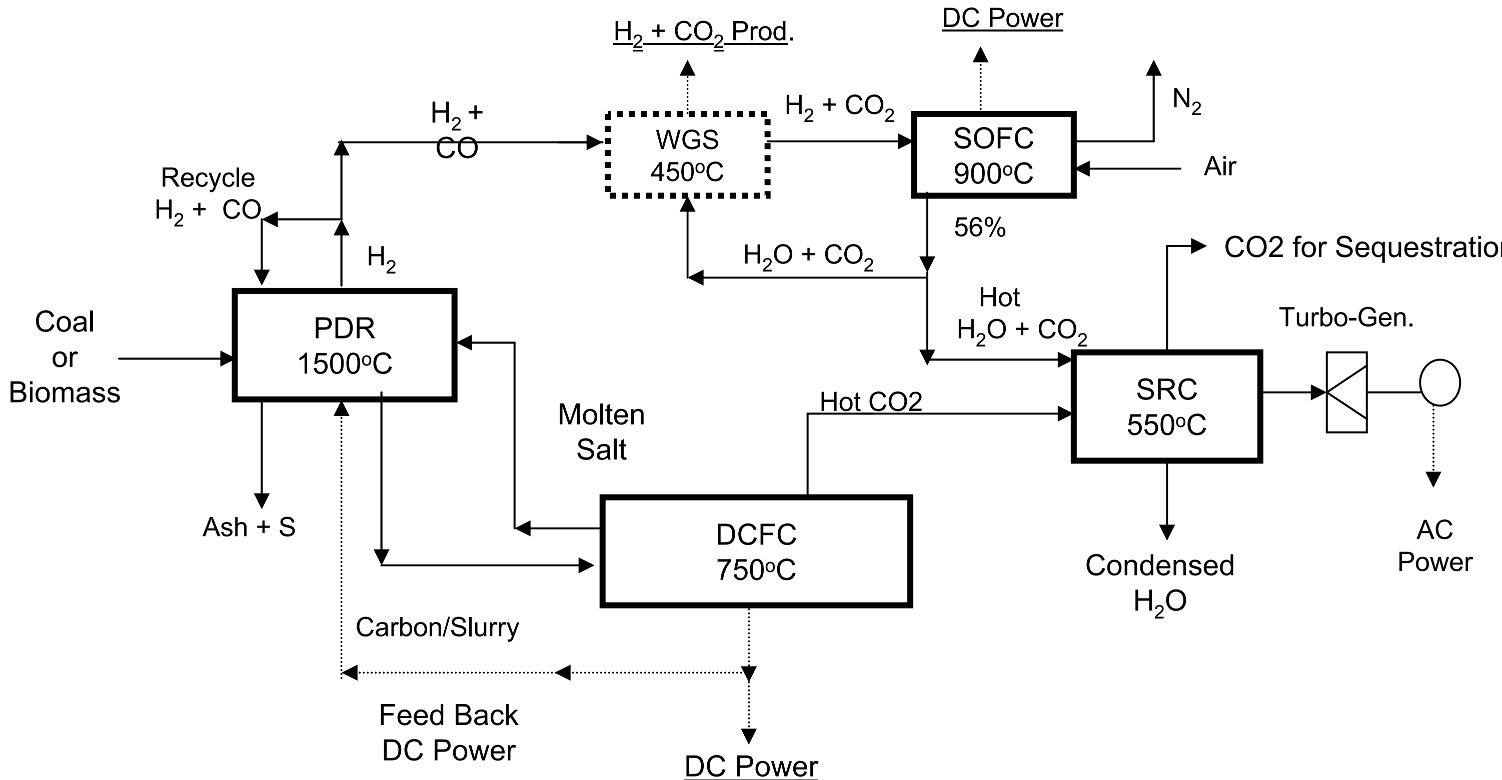
$C + O_2 = CO_2$ ($CO_3^=$ Ion Transport)

<u>SOFC - Solid Oxide Fuel Cell</u>

$H_2 + 1/2\ O_2 = H_2O$ ($O^=$ Ion Transport)

<u>SRC - Steam Boiler Rankine Cycle</u>

Figure 3 - 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. 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

Combined Cycle Fossil and Biomass Fuel Power Generation and Hydrogen production

Unit		Max. Efficiency %
HPBR –	Hydrogen Plasma Black Reactor Converts FF to hydrogen and Carbon	Proc. Eff. 60
DCFC –	Direct Carbon Fuel Cell Converts Carbon to Electric Power	90
SOFC –	Solid Oxide Fuel Cell Converts Hydrogen to Electric Power	56
SRC –	Steam Rankine Cycle Converts Steam to Electric Power	38

Table 5
Electrical Power Production in the HPBR/DCFC/SOFC/SRC Combined Power Cycle Plant
Thermal Efficiency Evaluation and CO_2 Emission
Basis: -1 gmol of Fuel

Fuel Feedstock		Natural Gas	Crude Oil	N. Dakota Lignite Coal	Kentucky Bitum. 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 All Energy Values in Kcal/gmol fuel						
Unit	Eff. %					
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	0.610	0.955	0.833	(0.986)**
CO_2 Reduction from conventional 38% SRC cycle - %		48.7	56.5	54.4	53.6	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 CO2 emitted from power cycle, however, because of the photosynthesis of biomass there is a zero net emission of CO_2.

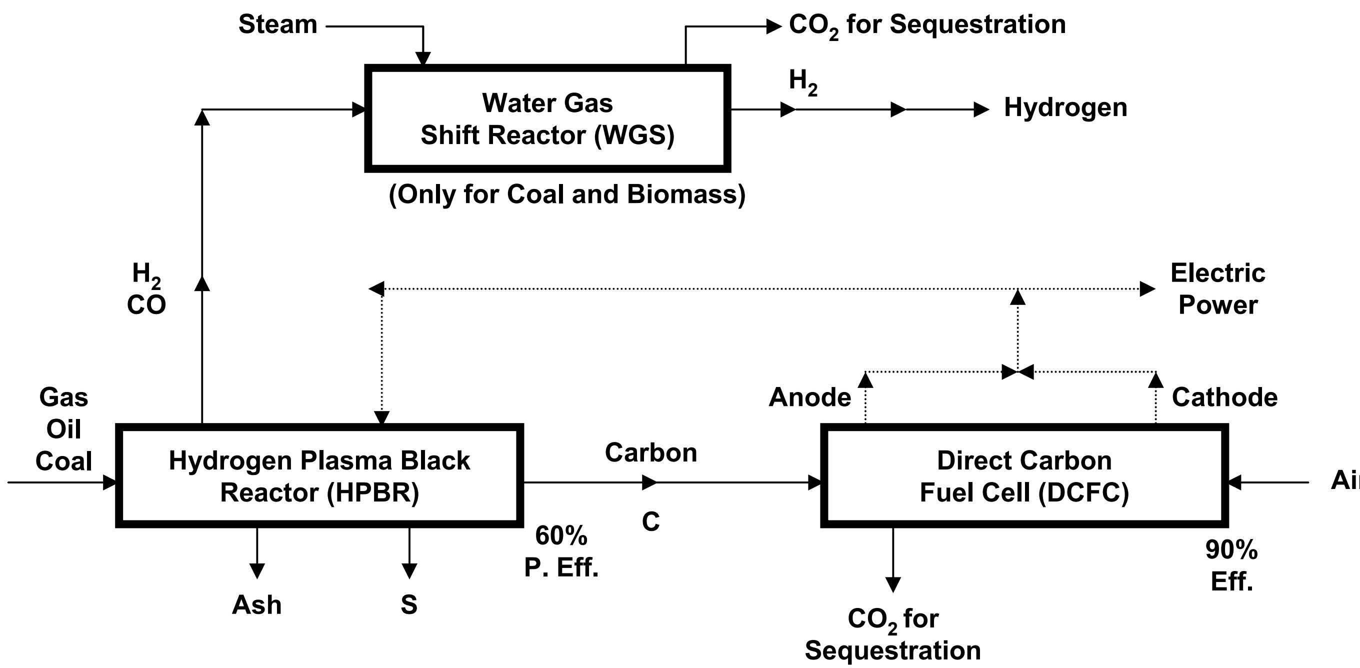
Very High Efficiency Combined Cycle Fossil and Biomass Fuel Power Generation HPBR/DCFC/SO FC/SRC

Fuel	HHV Thermal Efficiency -%	CO_2 emission * Reduction -%
Natural Gas	74.1	48.7
Crude Oil	84.1	56.5
N. Dakota/Lignite Coal	83.3	54.4
Kentucky Bituminous Coal	81.8	53.6
Biomass -Wood	69.5	(100.0)

*CO_2 Reduction from Conventional Steam Plant at 38% HHV Efficiency

Innovative High Efficiency Power and Hydrogen Generation Fossil Fuel Combined Cycle

Hydrogen Plasma Black Reactor (HPBR) in Combination with Direct Carbon Fuel Cell (DCFC)



Total Thermal Eff. H_2 + Power = >90%

Table 6
Hydrogen and Electrical Power Production in the HPBR/DCFC/SRC Combined Cycle Plant
Energy and Thermal Efficiency Distribution between Hydrogen and Electrical Power Production

Fuel Feedstock	Natural Gas	N. Dakota Lignite Coal	Biomass (Wood)
Electricity Production (from DCFC only)			
Electrical Energy Kcal(e)/gmol fuel	54.6	58.3	13.5
Hydrogen Production			
Thermal energy in H_2 Kcal(t)/gmol fuel*	136	42.2	87.
HHV of Fuel Feedstock Kcal(t)/gm mol	212	110.3	112.8
Thermal Efficiency			
Electricity Production - %	25.8	52.9	12.0
Hyrdrogen Production - %	64.2	38.3	77.1
Total Efficiency - %	90.0	91.2	89.1

*HHV of hydrogen = 68 Kcal/mol

Advanced High Efficiency Hydrogen and Electric power Production

HPRB/DCFC/SRC Combined Cycle

Fuel	Hydrogen Production Efficiency %	Electric Power Efficiency %	Total Efficiency %
Natural Gas	64.2	25.8	90.0
N. Dakota/Lignite Coal	38.3	52.9	91.2
Biomass (wood)	77.1	12.0	89.1

Combined Cycle Fossil and Biomass Fuel Power Generation and Hydrogen production

Unit		Max. Efficiency %	Capital Cost Range -$/KW Min.	Max.
HPBR –	Hydrogen Plasma Black Reactor Converts FF to Hydrogen and Carbon	Proc. Eff. 60	300	400
DCFC –	Direct Carbon Fuel Cell Converts Carbon to Electric Power	90	500	900
SOFC –	Solid Oxide Fuel Cell Converts Hydrogen to Electric Power	56	500	600
SRC –	Steam Rankine Cycle Converts Steam to Electric Power	38	1000	1300

Integrated Combined Cycle Plant – Preliminary Cost Estimate
Electricity and Hydrogen Production
Feedstock - Lignite Coal (17 MMBTU/ton - MF Montana)

Unit Capital Cost Estimate		
	$1200/KW	$800/KW
Thermal Efficiency	%	%
Electricity Production	52.9	52.9
Hydrogen Production	38.3	38.3
Total Efficiency	91.2	91.2
Capital Cost Distribution (Prorated)	$/KW	$/KW
Plasma Reactor[1]	600	384
Carbon Fuel Cell[2]	500	348
Water Gas Shift[3]	40	42
Contingency	60	16
Total Unit	1200/KW	$800
Combined Hydrogen and Electricity Production Cost	Mills/KWhr	Mills/Khr
Lignite at $12.40/ton	2.73	2.73
Fixed Charges @ 20% of Capital/annum	34.29	22.86
O&M at 15% of FC	5.14	3.43
Total	42.16	29.02
Hyrdogen Price		
$/MMBTU	= $12.35	8.50
$/MSCF	= $4.00	2.73
$/gal equivalent gasoline	= $ 1.48	1.00

1) Estimate based on Karbomont Plant max. 50% and min. 30% of $1100/KW total plant.
2) LLNL report UCRL - SC146774 (Jan. 2002). $900/KW prorated.
3) WGS estimate at $100/KW(t) prorated based on H_2 production.

Integrated Combined Cycle Plant – ICCPH
Electricity and Hydrogen Production – Preliminary Cost Estimate
Feedstock – Lignite Coal (17 MMBTU/ton - MF Montana - $12.40/ton)

H_2 Production Cost as a Function of Electricity and Capital Cost

Electricity	Capital Cost	Hydrogen Cost			
Mills/KWhr	$/KW	Mills/KWhr	$/MMBTU	$/MSCF	$/gal. Equiv.
42.16	1200	42.16	12.35	4.00	1.48
29.02	800	29.02	8.50	2.73	1.00
62.80	1200	13.65	4.00	1.29	0.48[1]
50.00[2]	945	13.65	4.00	1.29	0.48[1]
50.00[2]	800	0.00	0.00	0.00	0.00

1) DOE Target H_2 cost for Future Gen Project = 0.48/gal. Equiv. = $4/MMBTU.

Note H_2 cost from K-T coal gasification plant = 38.34 mills/KWhr = $11.23/MMBTU = $1.36/gal.

<u>CO_2 emission reduction</u> of ICCPH plant from coal gasification = 37% based on hydrogen alone.

<u>Similarly CO_2 emission reduction</u> of ICCPH from conventional coal power plant = 58% based on electricity alone

2) 50 mills/KWh is cost of electricity from a lignite conventional Rankine Steam Cycle Plant at 38% efficiency.

Summary of Economic and Environmental Parameters for Integrated Combined Cycle Plants (ICCP) HPBR/DCFC/SOFC/SRC

Electricity Production Only

I Max Range of Capital Cost

Feedstock	Thermal Efficiency % (HHV)	Capital Cost $/KW(e)	Fuel Cost $/MMBTU	Electricity Prod. Cost Mills/KWh(e)	CO_2 Reduction %[1]
Natural Gas	74.1%	$1000	$2.00	42.07	48.7%
			4.00	51.28	"
			6.00	60.49	"
Petroleum	84.1	1100	4.17 ($25/bbl)	55.40	54.8
Bituminous Coal	81.8	1300	1.00 ($25/ton)	46.84	53.5
Lignite Coal	83.3	1300	0.73 ($12.40/ton)	45.66	54.4
Biomass (wood)	69.5	1200	2.00	49.25	100.0[2]

II Min. Range of Capital Costs

Feedstock	Thermal Efficiency % (HHV)	Capital Cost $/KW(e)	Fuel Cost $/MMBTU	Electricity Prod. Cost Mills/KWh(e)	CO_2 Reduction %[1]
Natural Gas	74.1%	735	2.00	33.36	48.7
			4.00	42.57	"
			6.00	51.78	"
Petroleum	84.1	740	4.17	43.12	54.8
Bituminous Coal	81.8	800	1.00 ($25/ton)	30.44	53.5
Lignite Coal	83.3	800	0.73 ($12.40/ton)	29.28	54.4
Biomass	69.5	785	2.00	35.61	100.0[2]

1) CO2 reduction per unit electricity produced compared to a conventional Steam Rankine Cycle at 38% efficiency.
2) Biomass generated by photosynthesis from CO_2 emitted, no net CO2 increase to atmosphere.

Summary of Economic and Environmental Parameters for Integrated Combined Cycle Plants (ICCP) HPBR/DCFC/SOFC/SRC and Comparison with Conventional Combined Cycle Plants
Electricity Production Alone - Feedstock Coal and Biomass

Feedstock	Process	Thermal Efficiency % (HHV)	Unit Capital Cost Min.-Max Range \$/KW(e)	Fuel Cost \$/MMBTU	Electricity Min. - Max Mill/Kwh(e)	CO_2 Emission Reduction %[1]
Bituminous Coal	ICCP	81.8	800 – 1300	1.00 (\$25/ton)	30.44-46.84	53.5 73.1%[2]
Bituminous Coal	Conventional IGCC	55.0	1000	1.00 (\$25/ton)	38.21	30.9
Lignite Coal	ICCP	83.3	800 – 1300	0.73 (\$12.40/ton)	29.28-45.66	54.5 76.7%[2]
Lignite Coal	Conventional IGCC	55.0	1000	0.73 (\$12.40/ton)	37.39	30.9
Biomass Wood	ICCP	69.5	785 – 1200	2.00	35.61-49.25	100.0[3]

1) $\%CO_2$ emission reduction per unit of electricity produced compared to a conventional Steam Rankine Cycle Plant at 38% efficiency.
2) CO_2 emission reduction of ICCP compared to conventional IGCC.
3) Biomass generated by photosynthesis from an equal amount of CO_2 emitted from the ICCP, results in a not zero emission of CO_2.

CONCLUSIONS

- **The Hydrogen Plasma Black Reactor (HPBR) is an efficient Fossil Fuel and Biomass Converter supplying carbon for the highly efficient Direct Carbon Fuel Cell (DCFC).**
- **The Integrated Combined Cycle (ICCPH) for hydrogen and Electricity production can reach into 90% thermal efficiency.**
- **The ICCP for electricity using hydrogen in a Solid Oxide Fuel Cell (SOFC) and carbon in the DCFC can reach into the 70 to 80% thermal efficiency which is double that of conventional steam plants.**
- **A major environmental benefit of ICCPH is that the CO_2 emission is significantly reduced in some cases by as much as 77% compared to conventional power and hydrogen production plants.**
- **Within the range of current costs of fossil fuel and projected capital cost of fuel cells, the estimated ICCP production costs are lower that with current conventional hydrogen and power plant costs. The co-product feature of ICCPH allows flexibility in marketing competition between hydrogen and electricity.**