2.3 HYDROGEN FUEL PLANT – 1112°F (600°C) MEMBRANE

Utilizing the revised assumptions for the HSD, updated plant concepts were prepared for HSD operation at 1112°F (600°C). The initial plant design was modified to determine the impact of the revised assumptions and of changing the operating temperature of the HSD to 1112°F (600°C) equilibrium. This concept utilizes the same hot gas desulfurization and particulate removal upstream of the HSD along with a modern non-ATS (conventional) gas turbine in the CO_2-rich stream. Table 2-7 provides the design basis established for the plant.

Table 2-7
Design Basis for Baseline Hydrogen Fuel Plant
1112°F (600°C) Membrane

Hydrogen Fuel Production Facility Parameter	Hydrogen Fuel Production Facility Plant Design Basis
Coal Feed	Pittsburgh No. 8, <10% ash
Limestone Sorbent	None
Gasifier	Oxygen-blown Destec with second stage adjusted for 1905°F output
Hot Gas Temperature	1905°F
Gasifier Outlet Pressure	1000 psia
Ambient Conditions	14.7 psia, 60°F
Hot Gas Desulfurization	Yes, 1100°F
Sulfur Recovery	Sulfuric acid
Ceramic Candle Filter	Before HSD
Hydrogen Separation	H_2 separation device Shell and tube configuration 95% separation 99.5% pure H_2 Zero sulfur 20 psia hydrogen compressed to 346 psia
Separated Gas	CO shifted to 1112°F equilibrium 5% of fuel value in gas 950 psia
Separated Gas Utilization	Combustion with oxygen Steam injection conventional turbine expander
CO_2 Product Pressure	19.4 psia
Hydrogen Utilization	346 psia offsite
Auxiliary Power Block	Conventional turbine expander
Plant Size	Maximum H_2 production from 2,500 tpd dry gasifier Excess power sold offsite

2.3.1 PROCESS DESCRIPTION

A block flow diagram of the plant is shown on Figure 2-4. The flows and state points on the attached process flow diagram (Figure 2-5) result from the heat and material balance for the plant. Key process components included in the plant are a Destec high-pressure slurry-feed gasifier, the ETTP HSD, and the transport reactor for desulfurization. The high-pressure syngas produced in the gasifier is quenched to 1905°F as a result of adjustments in the second stage of the gasifier. The hot raw gas is cleaned of larger particulates in a cyclone and then is cooled in a firetube boiler to 1100°F. A hot gas cleanup system consisting of a transport reactor desulfurizer and a ceramic candle filter removes sulfur and particulates from the fuel gas stream. Sulfur is recovered as sulfuric acid.

For this case, both steam and water are added to cool the syngas while ensuring adequate water content for the high-temperature shift reaction to occur at the lower HSD inlet temperature. The gas enters the HSD at 605°F and leaves the HSD at 1112°F as a result of the exothermic shift reaction. The hydrogen produced from the HSD is 99.5 percent pure. It goes through a HRSG and then is compressed to 346 psia.

Figure 2-4
Block Flow Diagram
Baseline Hydrogen Fuel Plant
1112°F (600°C) Hydrogen Separation Device

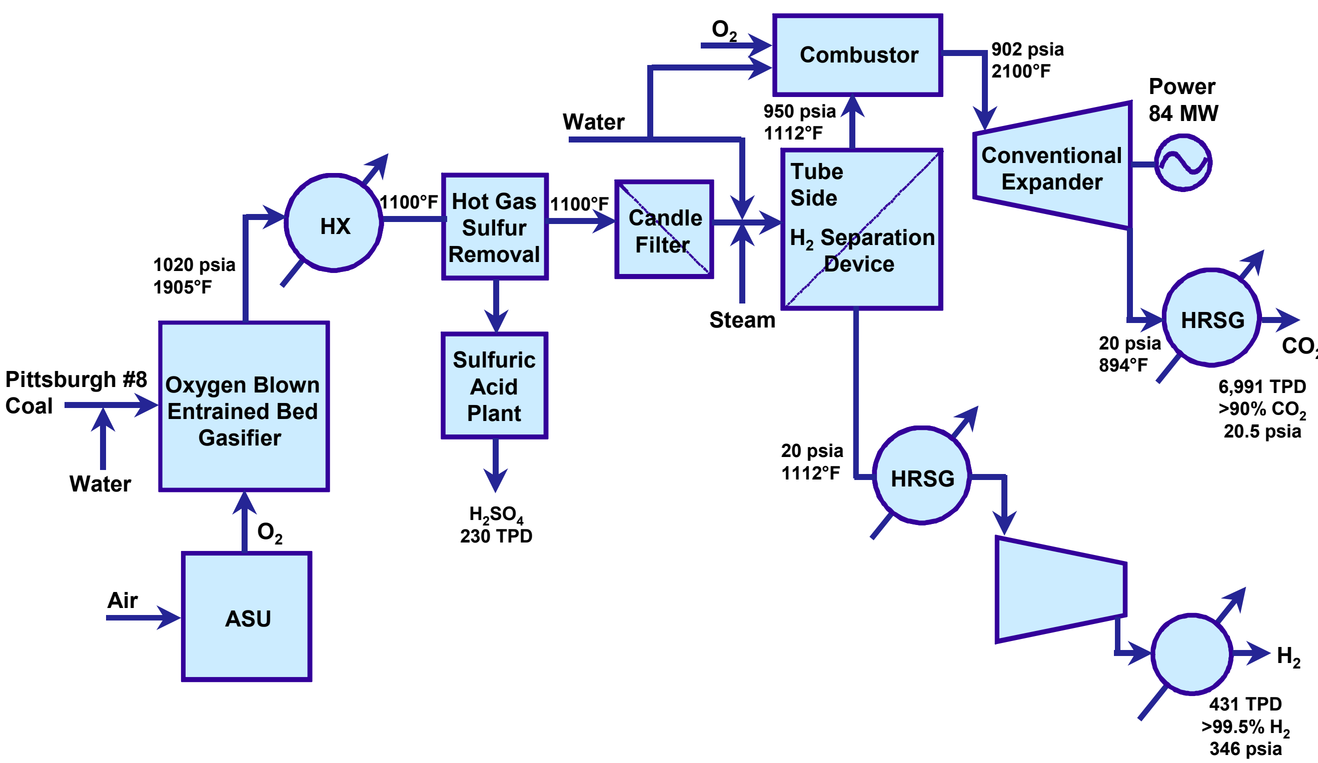
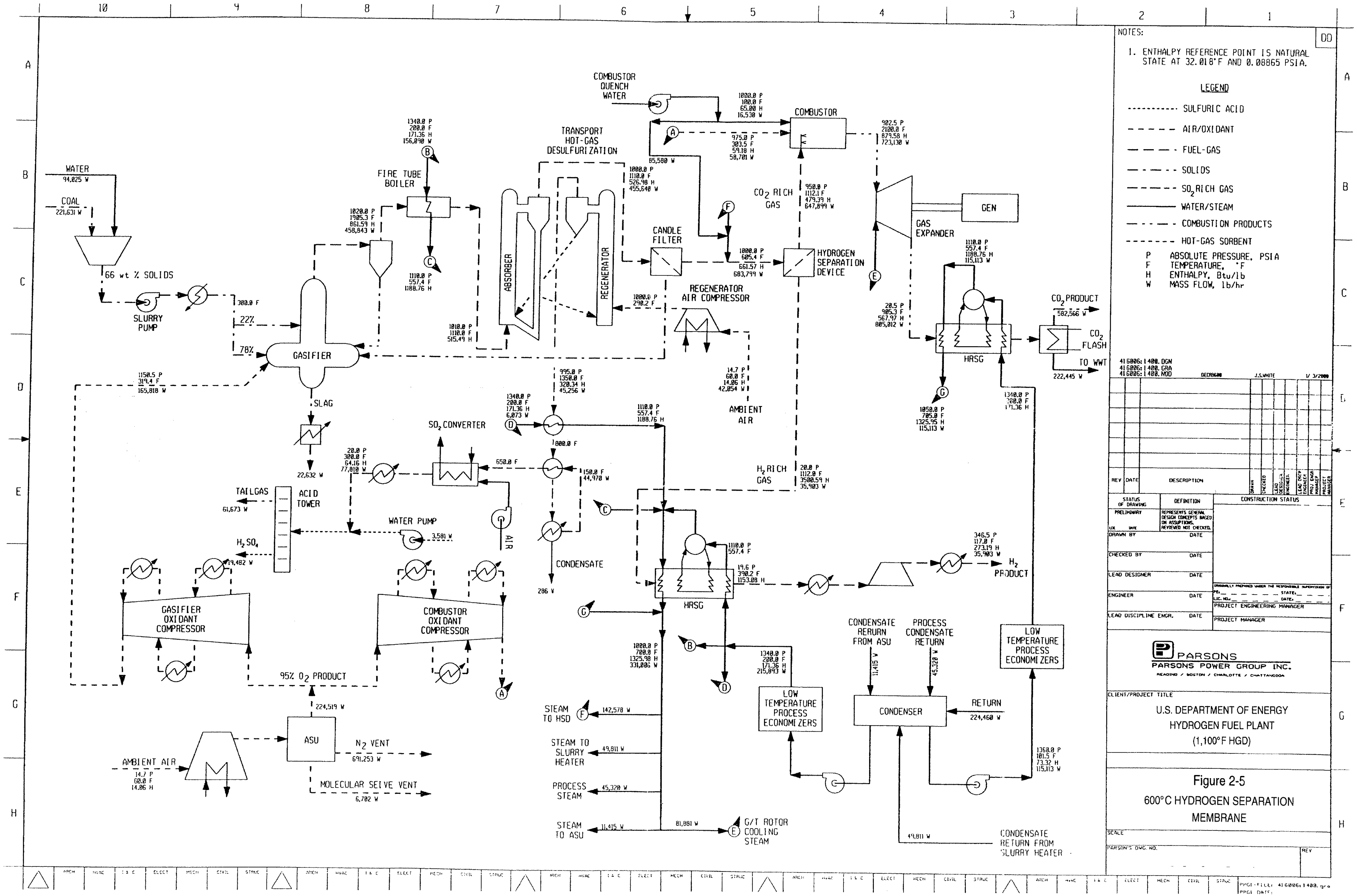


Figure 2-5


NOTES:
1. ENTHALPY REFERENCE POINT IS NATURAL STATE AT 32.018°F AND 0.08865 PSIA.
LEGEND
SULFURIC ACID
AIR/OXIDANT
FUEL-GAS
SOLIDS
SO_2 RICH GAS
WATER/STEAM
COMBUSTION PRODUCTS
HOT-GAS SORBENT
P ABSOLUTE PRESSURE, PSIA
F TEMPERATURE, °F
H ENTHALPY, Btu/lb
W MASS FLOW, lb/hr
WATER
COAL
66 wt % SOLIDS
SLURRY PUMP
GASIFIER
SLAG
FIRE TUBE BOILER
TRANSPORT HOT-GAS DESULFURIZATION
ABSORBER
REGENERATOR
REGENERATOR AIR COMPRESSOR
AMBIENT AIR
COMBUSTOR QUENCH WATER
COMBUSTOR
CANDLE FILTER
CO_2 RICH GAS
HYDROGEN SEPARATION DEVICE
GAS EXPANDER
GEN
HRSG
CO_2 PRODUCT
CO_2 FLASH
TO WWT
SO_2 CONVERTER
ACID TOWER
TAILGAS
H_2SO_4
WATER PUMP
AIR
CONDENSATE
H_2 RICH GAS
H_2 PRODUCT
GASIFIER OXIDANT COMPRESSOR
COMBUSTOR OXIDANT COMPRESSOR
95% O_2 PRODUCT
ASU
N_2 VENT
MOLECULAR SEIVE VENT
STEAM TO HSD
STEAM TO SLURRY HEATER
PROCESS STEAM
STEAM TO ASU
G/T ROTOR COOLING STEAM
LOW TEMPERATURE PROCESS ECONOMIZERS
CONDENSATE RERURN FROM ASU
PROCESS CONDENSATE RETURN
CONDENSER
RETURN
CONDENSATE RETURN FROM SLURRY HEATER
PARSONS
PARSONS POWER GROUP INC.
U.S. DEPARTMENT OF ENERGY
HYDROGEN FUEL PLANT
(1,100°F HGD)
Figure 2-5
600°C HYDROGEN SEPARATION MEMBRANE

The CO_2-rich gas leaving the HSD at 950 psia contains about 5 percent of the fuel value of the inlet syngas stream. This gas goes to the gas turbine combustor with which oxygen is injected to convert CO and hydrogen to CO_2 and H_2O, respectively. Both steam and water are injected into the combustor to moderate the temperature to 2100°F. The hot gas is expanded to 20 psia and 905°F through the conventional gas turbine expander to produce 84 MW electric power. The gas is cooled in a HRSG, and the steam produced is combined with other steam produced from cooling the hydrogen for process applications. There is no power produced from steam. The CO_2 product is cooled to 100°F, dried, and sent offsite.

Table 2-8 presents the performance summary for the plant, and Table 2-9 identifies the plant power requirements. Table 2-10 is the plant water balance.

Table 2-8
Performance Summary

Coal Feed	221,631 lb/h
Oxygen Feed (95%)	224,519 lb/h
Hydrogen Product Stream	35,903 lb/h
CO_2 Product Stream	582,566 lb/h
Sulfuric Acid Product	19,482 lb/h
Gross Power Production	84 MW
Auxiliary Power Requirement	77 MW
Net Power Production	7 MW
Effective Thermal Efficiency (ETE), HHV	80.4%

Table 2-9
Auxiliary Power Load, kW

Gasifier Auxiliary Oxygen Compressor	10,300
Combustor Oxygen Compressor	4,000
ASU Air Compressor	30,900
Gasifier Slurry Pumps	190
Water Spray Pump	400
Boiler Feedwater Pumps	510
Coal Handling	210
Slag Handling	530
Regenerator Air Blower	2,960
Gas Turbine Auxiliary	400
Hydrogen Compressor	25,690
Miscellaneous Balance of Plant	750
Total Auxiliary Load	**76,840 kW**

Table 2-10
Plant Water Balance

Water Source	
Makeup Water	198,150 lb/h
Recycled from Stack Condenser	222,445 lb/h
Water Consumption Point	
Boiler Feed	224,460 lb/h
Gasifier Coal Slurry Preparation	94,025 lb/h
Shift Water	85,580 lb/h
Quench	16,530 lb/h

2.3.2 EFFECTIVE THERMAL EFFICIENCY

For comparative purposes and to arrive at a figure of merit for the plant design, an ETE was derived for the plant performance based on HHV thermal value of hydrogen produced and offsite power sales, divided by the fuel input to the plant. The formula is:

$$ETE = \frac{\text{(Hydrogen Heating Value + Electrical Btu Equivalent)}}{\text{Fuel Heating Value (HHV)}}$$

$$ETE = \frac{35{,}903 \text{ lb } H_2\text{/h x } 61{,}095 \text{ Btu/lb} + 7{,}060 \text{ kW x } 3{,}414 \text{ Btu/kWh}}{221{,}631 \text{ lb coal/h x } 12{,}450 \text{ Btu/lb}}$$

$$ETE = 80.4\%$$

2.4 HYDROGEN FUEL PLANT – 572°F (300°C) MEMBRANE

Utilizing the revised assumptions for the HSD, updated plant concepts were prepared for HSD operation at 572°F (300°C) to determine the impact of lowering the operating temperature of the HSD. The plant design basis is shown in Table 2-11.

Table 2-11
Design Basis for Baseline Hydrogen Fuel Plant
572°F (300°C) Membrane

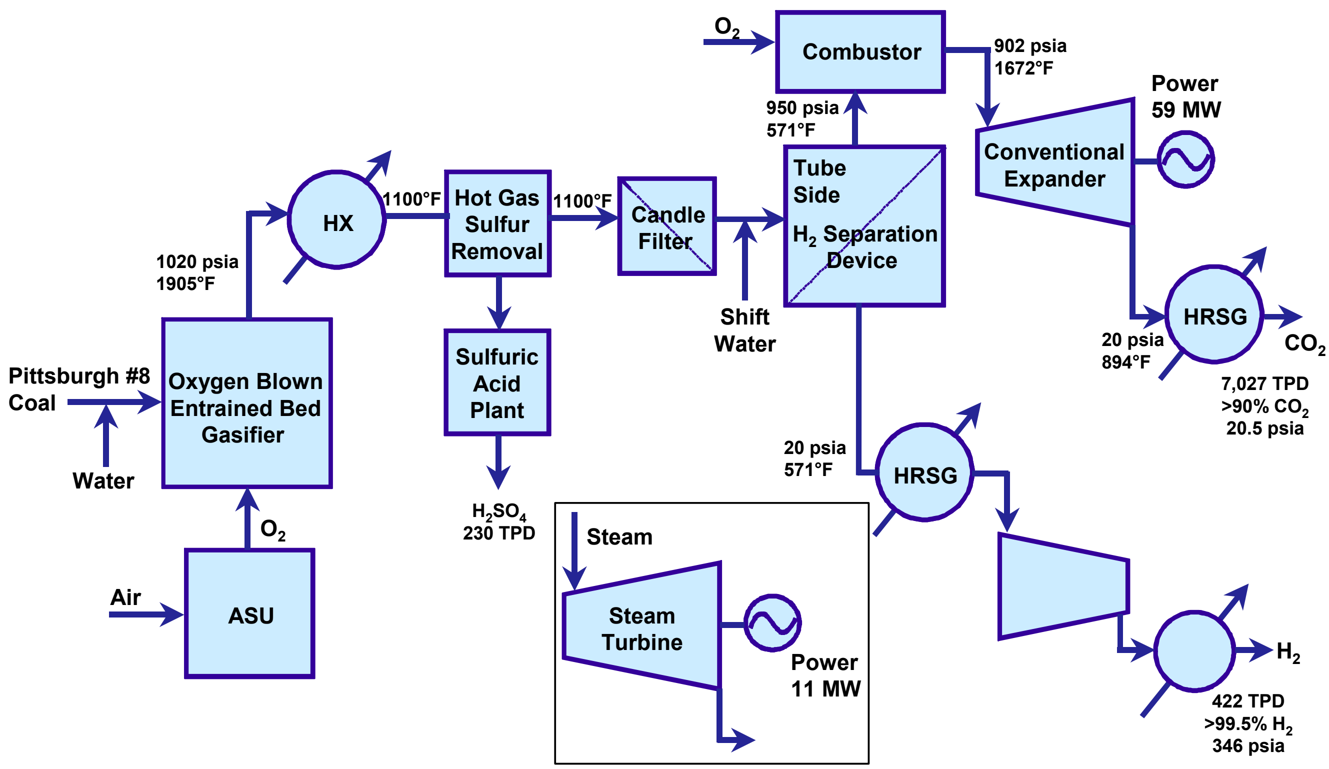
Hydrogen Fuel Production Facility Parameter	Hydrogen Fuel Production Facility Plant Design Basis
Coal Feed	Pittsburgh No. 8, <10% ash
Limestone Sorbent	None
Gasifier	Oxygen-blown Destec with second stage adjusted for 1905°F output
Hot Gas Temperature	1905°F
Gasifier Outlet Pressure	1000 psia
Ambient Conditions	14.7 psia, 60°F
Hot Gas Desulfurization	Yes, 1100°F
Sulfur Recovery	Sulfuric acid
Ceramic Candle Filter	Before HSD
Hydrogen Separation	H_2 separation device Shell and tube configuration 95% separation 99.5% pure H_2 Zero sulfur 20 psia hydrogen compressed to 346 psia
Separated Gas	CO shifted to 572°F equilibrium 5% of fuel value in gas 950 psia
Separated Gas Utilization	Combustion with oxygen Steam injection conventional turbine expander
CO_2 Product Pressure	19.4 psia
Hydrogen Utilization	346 psia offsite
Auxiliary Power Block	Conventional turbine expander
Plant Size	Maximum H_2 production from 2,500 tpd dry gasifier

2.4.1 PROCESS DESCRIPTION

A block flow diagram of the plant is shown on Figure 2-6. The flows and state points on the attached process flow diagram (Figure 2-7) result from the heat and material balance for the plant.

For this case, only water is added to cool the syngas, ensuring adequate water content for the high-temperature shift reaction to occur at the lower HSD inlet temperature. The gas enters the HSD at 404°F and leaves the HSD at 571°F as a result of the exothermic shift reaction. The hydrogen produced from the HSD is 99.5 percent pure. It goes through a HRSG and then is compressed to 346 psia.

Figure 2-6
Block Flow Diagram
Baseline Hydrogen Fuel Plant
572°F (300°C) Hydrogen Separation Device



The CO_2-rich gas leaving the HSD at 950 psia contains about 5 percent of the fuel value of the inlet syngas stream. This gas goes to the gas turbine combustor with which oxygen is injected to convert CO and hydrogen to CO_2 and H_2O, respectively. Since gas exits the combustor at 1672°F, it is not necessary to add steam or water to moderate the temperature. The hot gas is expanded to 20 psia and 782°F through the conventional gas turbine expander to produce 59 MW electric power. The gas is cooled in a HRSG, and the steam produced is combined with other steam produced from cooling the hydrogen for process applications. This plant has excess steam, which is used to produce 11 MW power. The CO_2 product is cooled to 100°F, dried, and sent offsite.

Figure 2-7

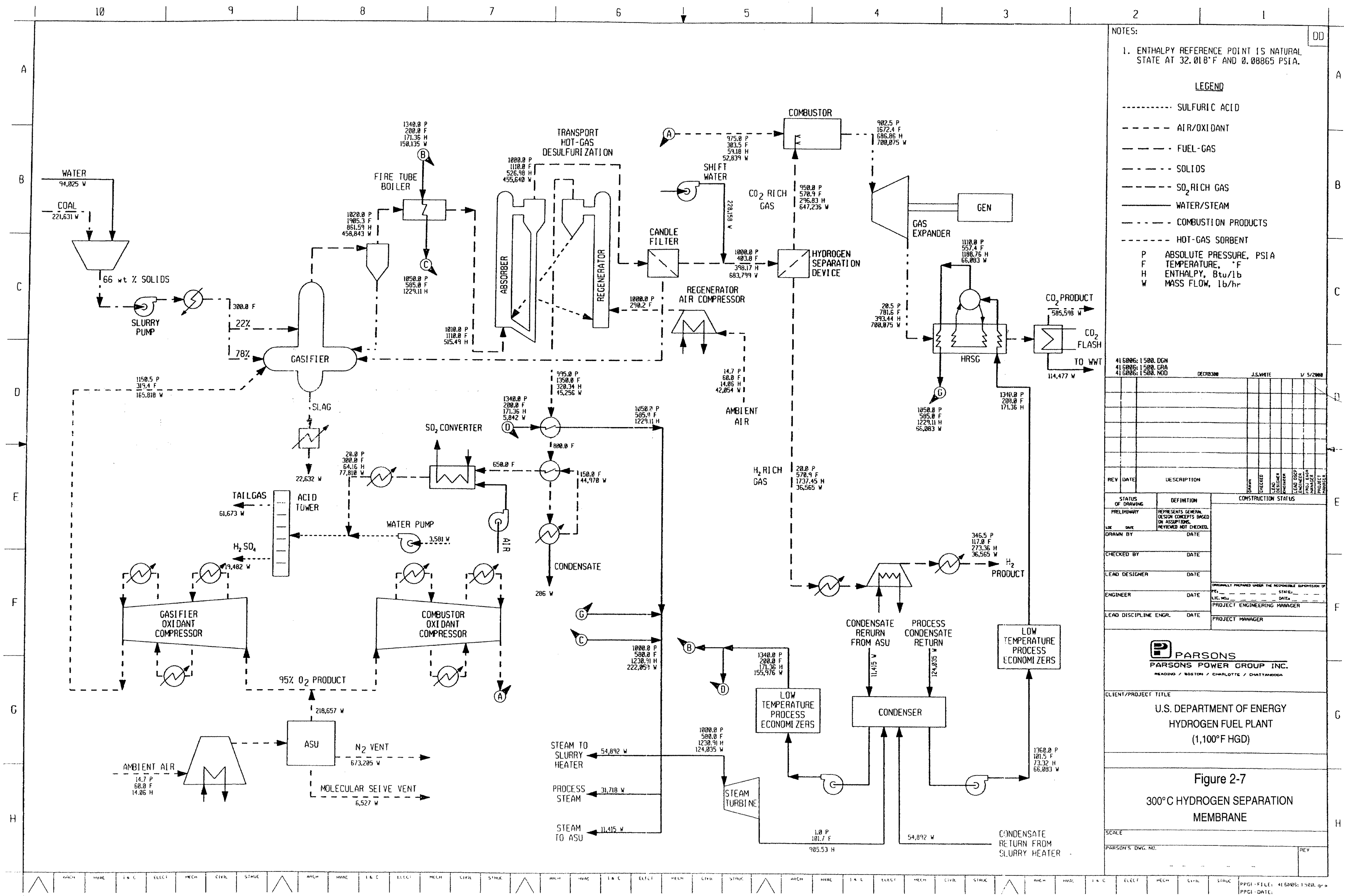

NOTES:
1. ENTHALPY REFERENCE POINT IS NATURAL STATE AT 32.018°F AND 0.08865 PSIA.
LEGEND
SULFURIC ACID
AIR/OXIDANT
FUEL-GAS
SOLIDS
SO2 RICH GAS
WATER/STEAM
COMBUSTION PRODUCTS
HOT-GAS SORBENT
P ABSOLUTE PRESSURE, PSIA
F TEMPERATURE, °F
H ENTHALPY, Btu/lb
W MASS FLOW, lb/hr
WATER
COAL
66 wt % SOLIDS
SLURRY PUMP
GASIFIER
SLAG
FIRE TUBE BOILER
TRANSPORT HOT-GAS DESULFURIZATION
ABSORBER
REGENERATOR
CANDLE FILTER
REGENERATOR AIR COMPRESSOR
AMBIENT AIR
SHIFT WATER
CO2 RICH GAS
COMBUSTOR
HYDROGEN SEPARATION DEVICE
GAS EXPANDER
GEN
HRSG
CO2 PRODUCT
CO2 FLASH
TO WWT
H2 RICH GAS
H2 PRODUCT
SO2 CONVERTER
TAILGAS
ACID TOWER
H2SO4
WATER PUMP
AIR
CONDENSATE
GASIFIER OXIDANT COMPRESSOR
COMBUSTOR OXIDANT COMPRESSOR
95% O2 PRODUCT
ASU
N2 VENT
MOLECULAR SEIVE VENT
AMBIENT AIR
STEAM TO SLURRY HEATER
PROCESS STEAM
STEAM TO ASU
STEAM TURBINE
LOW TEMPERATURE PROCESS ECONOMIZERS
CONDENSATE RERURN FROM ASU
PROCESS CONDENSATE RETURN
CONDENSER
CONDENSATE RETURN FROM SLURRY HEATER
PARSONS
PARSONS POWER GROUP INC.
U.S. DEPARTMENT OF ENERGY
HYDROGEN FUEL PLANT
(1,100°F HGD)
Figure 2-7
300°C HYDROGEN SEPARATION MEMBRANE

Table 2-12 presents the performance summary for the plant, and Table 2-13 identifies the plant power requirements. Table 2-14 shows the plant water balance.

Table 2-12
Performance Summary

Coal Feed	221,631 lb/h
Oxygen Feed (95%)	218,657 lb/h
Hydrogen Product Stream	36,565 lb/h
CO_2 Product Stream	585,598 lb/h
Sulfuric Acid Product	19,482 lb/h
Gas Turbine Gross Power	59 MW
Steam Turbine Gross Power	11 MW
Auxiliary Power Requirement	76 MW
Net Power Production	(6 MW)
Effective Thermal Efficiency (ETE), HHV	80.3%

Table 2-13
Auxiliary Power Load, kW

Gasifier Auxiliary Oxygen Compressor	10,300
Combustor Oxygen Compressor	3,200
ASU Air Compressor	29,220
Gasifier Slurry Pumps	190
Water Spray Pump	400
Boiler Feedwater Pumps	340
Coal Handling	210
Slag Handling	530
Regenerator Air Blower	2,960
Gas Turbine Auxiliary	400
Steam Turbine Auxiliary	400
Cooling Tower	890
Hydrogen Compressor	26,180
Miscellaneous Balance of Plant	750
Total Auxiliary Load	**75,970 kW**

Table 2-14
Plant Water Balance

Water Source	
Makeup Water	nil
Recycled from Stack Condenser	114,477 lb/h
Water Consumption Point	
Gasifier Coal Slurry Preparation	94,025 lb/h
Sulfuric Acid Water	3,581 lb/h
Shift Water	16,530 lb/h

2.4.2 EFFECTIVE THERMAL EFFICIENCY

For comparative purposes and to arrive at a figure of merit for the plant design, an ETE was derived for the plant performance based on HHV thermal value of hydrogen produced and offsite power sales, divided by the fuel input to the plant. The formula is:

$$ETE = \frac{\text{(Hydrogen Heating Value + Electrical Btu Equivalent)}}{\text{Fuel Heating Value (HHV)}}$$

$$ETE = \frac{36{,}565 \text{ lb } H_2\text{/h x } 61{,}095 \text{ Btu/lb} - 5{,}510 \text{ kW x } 3{,}414 \text{ Btu/kWh}}{221{,}631 \text{ lb coal/h x } 12{,}450 \text{ Btu/lb}}$$

ETE = 80.3%

2.5 HYDROGEN FUEL PLANT – 1112°F (600°C) MEMBRANE AND 80 PERCENT HYDROGEN TRANSPORT

The baseline plant design having 600°C HSD equilibrium was modified to determine the impact of less than optimum performance from the membrane. It was assumed that only 80 percent of the syngas was recovered as hydrogen, with the rest being utilized in the topping cycle to generate electricity. The plant design basis is shown in Table 2-15.

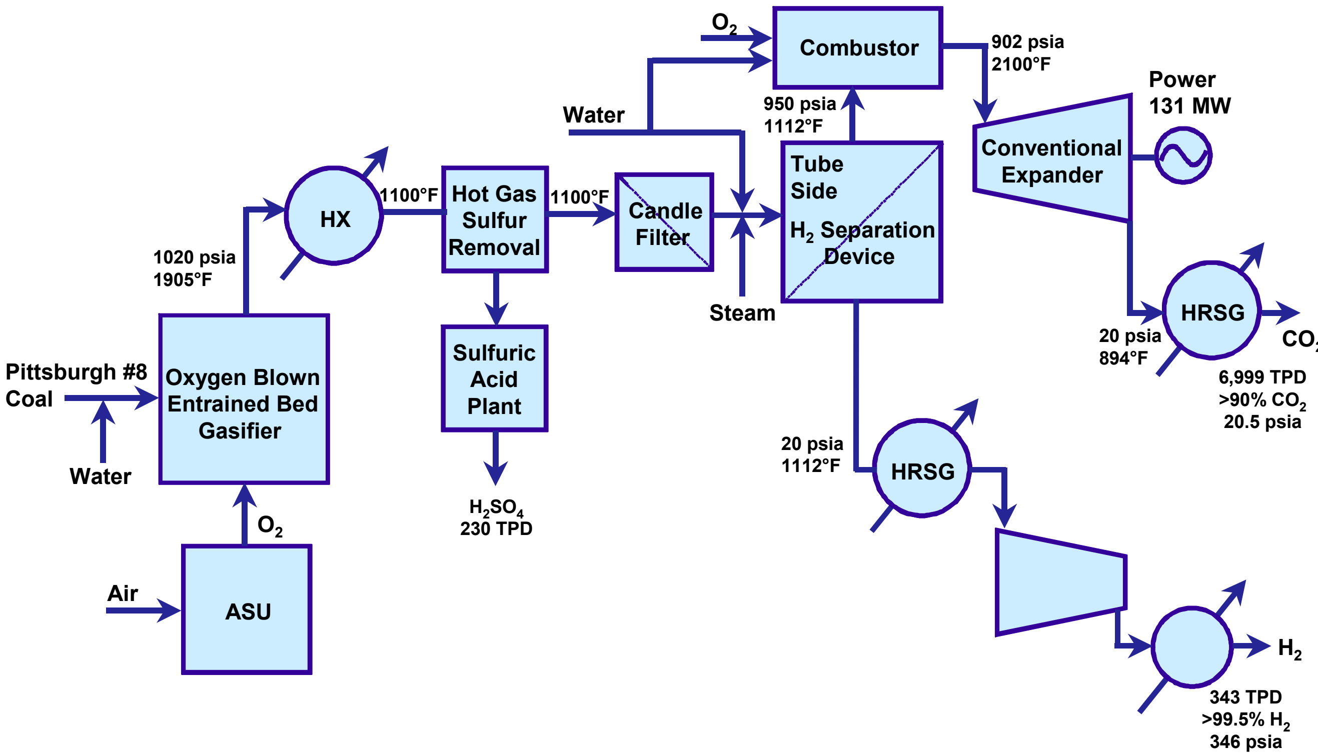
Table 2-15
Design Basis for Baseline Hydrogen Fuel Plant
1112°F (600°C) Membrane and 80 Percent Hydrogen Transport

Hydrogen Fuel Production Facility Parameter	Hydrogen Fuel Production Facility Plant Design Basis
Coal Feed	Pittsburgh No. 8, <10% ash
Limestone Sorbent	None
Gasifier	Oxygen-blown Destec with second stage adjusted for 1905°F output
Hot Gas Temperature	1905°F
Gasifier Outlet Pressure	1000 psia
Ambient Conditions	14.7 psia, 60°F
Hot Gas Desulfurization	Yes, 1100°F
Sulfur Recovery	Sulfuric acid
Ceramic Candle Filter	Before HSD
Hydrogen Separation	H_2 separation device Shell and tube configuration 95% separation x 0.8 99.5% pure H_2 Zero sulfur 20 psia hydrogen compressed to 346 psia
Separated Gas	CO shifted to 572°F equilibrium ~ 1.2 x 5% of fuel value in gas 950 psia
Separated Gas Utilization	Combustion with oxygen Steam injection conventional turbine expander
CO_2 Product Pressure	19.4 psia
Hydrogen Utilization	346 psia offsite
Auxiliary Power Block	Conventional turbine expander
Plant Size	Maximum H_2 production from 2,500 tpd dry gasifier

2.5.1 PROCESS DESCRIPTION

A block flow diagram of the plant is shown on Figure 2-8. The flows and state points on the attached process flow diagram (Figure 2-9) result from the heat and material balance for the plant. Key process components included in the plant are a Destec high-pressure slurry-feed gasifier, the ETTP HSD, and the transport reactor for desulfurization. The high-pressure syngas produced in the gasifier is quenched to 1905°F as a result of adjustments in the second stage of the gasifier. The hot raw gas is cleaned of larger particulates in a cyclone and then is cooled in a firetube boiler to 1100°F. A hot gas cleanup system consisting of a transport reactor desulfurizer and a ceramic candle filter removes sulfur and particulates from the fuel gas stream. Sulfur is recovered as sulfuric acid.

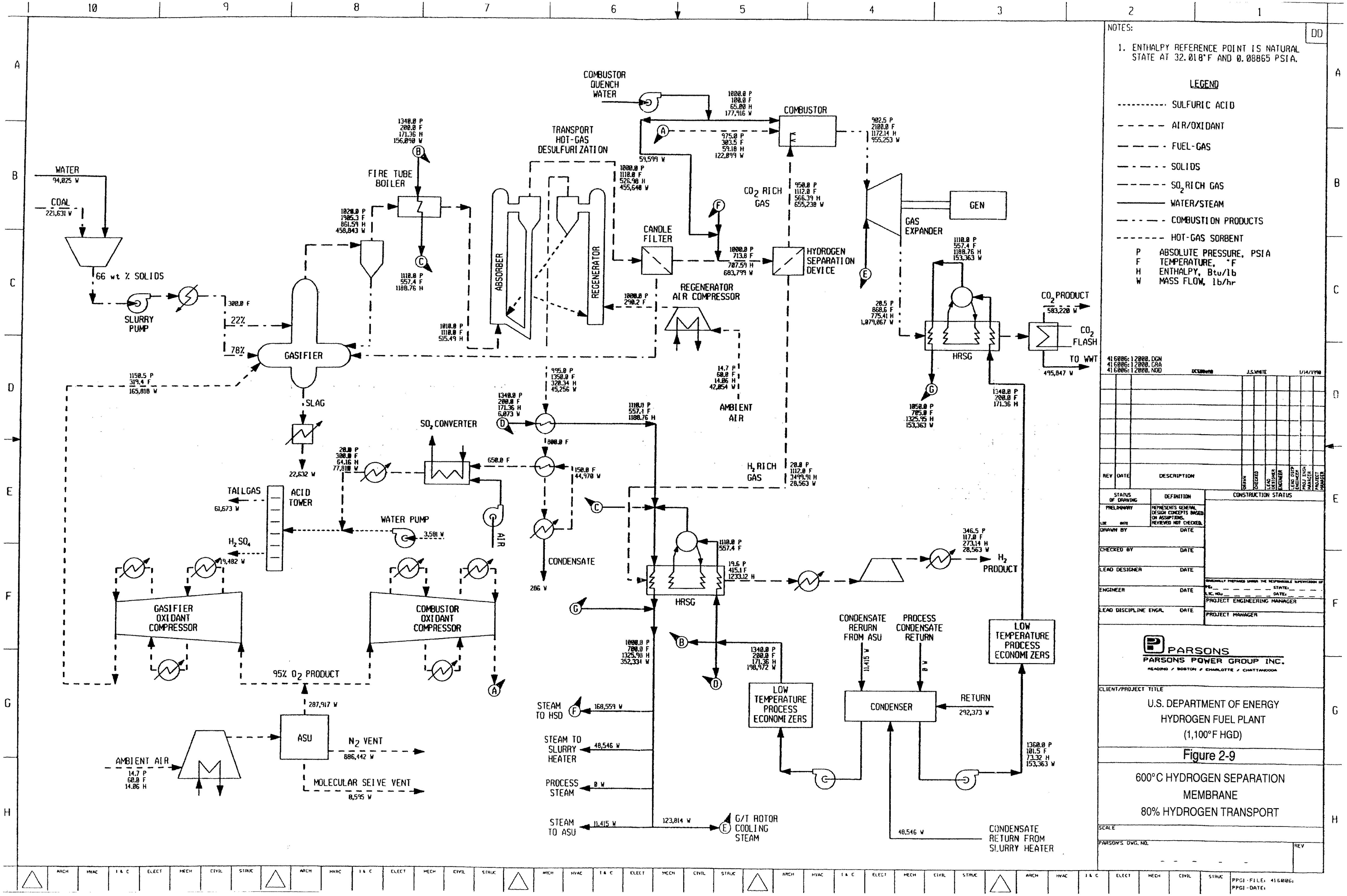
Figure 2-8
Block Flow Diagram
Baseline Hydrogen Fuel Plant
1112°F (600°C) Hydrogen Separation Device at 80 Percent Hydrogen Transport



For this case, both steam and water are added to cool the syngas while ensuring adequate water content for the high-temperature shift reaction to occur at the lower HSD inlet temperature. The gas enters the HSD at 605°F and leaves the HSD at 1112°F as a result of the exothermic shift reaction. For modeling purposes, 20 percent of the syngas bypasses the HSD, resulting in reduced hydrogen flow. Hydrogen produced is still 99.5 percent pure. It goes through a HRSG and then is compressed to 346 psia.

The CO_2-rich gas leaving the HSD at 950 psia contains more than the previous 5 percent of the fuel value of the inlet syngas stream. This gas goes to the gas turbine combustor with which oxygen is injected to convert CO and hydrogen to CO_2 and H_2O, respectively. A larger oxygen plant is needed to fire this gas. Both steam and water are injected into the combustor to moderate the temperature to 2100°F. The hot gas is expanded to 20 psia and 905°F through the conventional gas turbine expander to produce 84 MW electric power. The gas is cooled in a HRSG, and steam produced is combined with other steam produced from cooling the hydrogen for process applications. There is no power produced from steam. The CO_2 product is cooled to 100°F, dried, and sent offsite.

Figure 2-9


NOTES:
1. ENTHALPY REFERENCE POINT IS NATURAL STATE AT 32.018°F AND 0.08865 PSIA.
LEGEND
SULFURIC ACID
AIR/OXIDANT
FUEL-GAS
SOLIDS
SO2 RICH GAS
WATER/STEAM
COMBUSTION PRODUCTS
HOT-GAS SORBENT
P ABSOLUTE PRESSURE, PSIA
F TEMPERATURE, °F
H ENTHALPY, Btu/lb
W MASS FLOW, lb/hr
WATER
COAL
66 wt % SOLIDS
SLURRY PUMP
GASIFIER
SLAG
FIRE TUBE BOILER
TRANSPORT HOT-GAS DESULFURIZATION
ABSORBER
REGENERATOR
COMBUSTOR QUENCH WATER
COMBUSTOR
CANDLE FILTER
CO2 RICH GAS
HYDROGEN SEPARATION DEVICE
REGENERATOR AIR COMPRESSOR
AMBIENT AIR
GAS EXPANDER
GEN
HRSG
CO2 PRODUCT
CO2 FLASH
TO WWT
SO2 CONVERTER
TAILGAS
ACID TOWER
H2SO4
WATER PUMP
AIR
CONDENSATE
H2 RICH GAS
H2 PRODUCT
GASIFIER OXIDANT COMPRESSOR
COMBUSTOR OXIDANT COMPRESSOR
95% O2 PRODUCT
ASU
N2 VENT
MOLECULAR SEIVE VENT
AMBIENT AIR
STEAM TO HSD
STEAM TO SLURRY HEATER
PROCESS STEAM
STEAM TO ASU
G/T ROTOR COOLING STEAM
LOW TEMPERATURE PROCESS ECONOMIZERS
CONDENSATE RERURN FROM ASU
PROCESS CONDENSATE RETURN
CONDENSER
RETURN
CONDENSATE RETURN FROM SLURRY HEATER
PARSONS
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U.S. DEPARTMENT OF ENERGY
HYDROGEN FUEL PLANT
(1,100°F HGD)
Figure 2-9
600°C HYDROGEN SEPARATION
MEMBRANE
80% HYDROGEN TRANSPORT

Table 2-16 presents the performance summary for the plant, and Table 2-17 identifies the plant power requirements. Table 2-18 is the plant water balance.

Table 2-16
Performance Summary

Coal Feed	221,631 lb/h
Oxygen Feed (95%)	287,917 lb/h
Hydrogen Product Stream	28,563 lb/h
CO_2 Product Stream	583,220 lb/h
Sulfuric Acid Product	19,482 lb/h
Gross Power Production	131 MW
Auxiliary Power Requirement	83 MW
Net Power Production	48 MW
Effective Thermal Efficiency (ETE), HHV	69.2%

Table 2-17
Auxiliary Power Load, kW

Gasifier Auxiliary Oxygen Compressor	10,300
Combustor Oxygen Compressor	7,340
ASU Air Compressor	38,480
Gasifier Slurry Pumps	190
Water Spray Pump	400
Boiler Feedwater Pumps	550
Coal Handling	210
Slag Handling	530
Regenerator Air Blower	2,960
Gas Turbine Auxiliary	400
Hydrogen Compressor	20,440
Miscellaneous Balance of Plant	750
Total Auxiliary Load	**82,550 kW**