The Benefits of SOFC for Coal-Based Power Generation

October 30, 2007

Disclaimer

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Executive Summary

The Department of Energy's Office of Fossil Energy's Coal and Power Systems program has a set of aggressive technology goals set forth to advance coal-fired power generation power systems. The Department's fuel cell program known as the Solid State Energy Conversion Alliance (SECA) directly addresses the goals highlighted in red.

By 2010, coal-fired power systems will have the following characteristics:

- 45-50% efficiency
- 99% SO2 removal
- NOx emissions < 0.01 lb/MMBtu
- 90% Hg removal

By 2012, these coal-fired power systems will improve:

- 90% CO2 capture
- < 10% increase in the cost of electricity (COE) with carbon sequestration

By 2015, further improvements include:

- Multi-product capability (e.g. power and H2)
- 60% efficiency

A primary reason the Department's SECA program has focused on the solid-oxide fuel cell (SOFC) is its very unique synergism with coal plant integration.

The importance of carbon capture and storage for coal power plants together with the development of new low-cost solid oxide fuel cell technologies asks the question of what impact SECA fuel cells will have on the cost, efficiency, and environmental performance of advanced coal power plants and if SECA fuel cells integrated with a coal gasification process known as an Integrated Gasification Fuel Cell Cycle (IGFC) addresses carbon capture in an effective way.

To address this issue, a number of systems analyses were conducted to determine the benefits of SOFC systems integrated with coal gasification. These analyses, which are based on the methodology developed for the DOE Cost and Performance Baseline for Fossil Energy Plants, permits the Department to quantify these impacts. The analyses underlying this analysis include detailed system study, detailed analyses of SOFC module costs, as well as recent system tests of SOFC stacks under development in the Department's SECA program. For the near-term analyses targeting 50% Higher Heating Value (HHV), commercially available or proven technologies for all plant sections but the SOFC were assumed. For analyses targeting 60% HHV, use was made of results expected from the Department's Coal R&D program synergizing with incorporation of SECA fuel cells as the primary power generator.

Benefit of SOFC Systems

The Primary Benefit of an Integrated Gasification Fuel Cell Cycle is a large increase in efficiency coupled with the SOFC's unique and fundamental characteristic that it transfers oxygen to the fuel without directly mixing the fuel with the air.

The large increase in efficiency substantially results from the simple fact that the fuel cell converts chemical energy to electrical energy without an intermediate heat production to electrical energy conversion step. In addition, although not really any different than the bottoming of a gas turbine with a steam cycle, the SOFC's waste heat that is produced can be recovered to produce additional electrical energy or used for plant integration, such as steam production.

Increased Efficiency – Why is this Important

Cost-of-Electricity - higher efficiency reduces plant capital cost.

- Smaller Power Plant -- High efficiency means a smaller power plant. This leads to a reduction in capital cost which compounded by the financial considerations associated with the construction period is a major component of the ultimate cost-of-electricity.

- Reduced Emissions – Higher efficiency translates to reduced emissions of product gas such as carbon dioxide and unwanted by-products such as mercury and sulfur that require removal and appropriate disposal. Reduced emissions mean smaller systems and parasitic power requirements to mitigate emissions reducing cost-of-electricity.

- Conserves Fuel – Higher efficiency conserves fuel which translates to reduced cost-of-electricity and extension of coal reserve availability.

Synergism with a Coal Plant – How SECA Fuel Cells Fit

Cost-of-Electricity – synergism with a coal plant reduces plant capital cost, especially when capturing carbon.

- The SOFC is a unique power generator and combines what are normally separate plant stages in one device. In addition to producing electrical power directly from chemical energy without an intermediate heat step the SOFC also performs additional important functions in the same device eliminating the need for separate equipment and further reducing cost-of-electricity.

    - Oxygen Separation Membrane - The SOFC electrolyte permits the flow of oxygen to the fuel but does not permit electrons to travel in the reverse direction. This is essential to the function of the SOFC but also permits keeping the fuel and air separate. This leaves only CO_2 and water in the fuel stream allowing easy capture by condensing the water.

    - Water Gas Shift Reactor – The SOFC fuel electrode (anode) will "shift" CO to CO_2 by reaction with water producing H_2. This eliminates the need to shift CO to CO_2 in a separate reactor.

- Steam Reformer – The SOFC fuel electrode (anode) will reform methane and to some degree higher hydrocarbons to CO and H_2.

The SOFC produces steam when the separated O_2 and hydrogen react; the steam reacts with methane on the fuel electrode producing CO and H_2; the CO is shifted on the fuel electrode producing H_2 and CO_2 leaving a stream of CO_2 and H_2O which can be easily separated. It does all this while producing very efficient electrical energy.

In summary, given that the materials used and construction of the SOFC are selected solely for optimizing power production; the oxygen separation, water gas shift and steam reforming comes free.

Higher Methane Fuels - Why is this Important

- SECA fuel cells can use high methane fuels and capture carbon.
  - Higher methane fuels are important because the lower the gasification temperature the higher the gasification efficiency; less energy is lost to keep the reactor hot. When carbon capture is required, there is one drawback; lower temperature gasification also produces more methane which will carry carbon passed all the systems designed to capture the carbon before it mixes with air for combustion. The SOFC with it's free of charge and internal oxygen separation, water gas shift and steam reforming will permit use of high methane fuels and the resulting higher efficiency gasification while still capturing greater than 90% of the carbon.
  - One additional efficiency enhancing feature comes with the high methane. The methane also reduces the amount of air required to cool the SOFC because the steam reforming occurring inside the SOFC (rather than in a separate external reactor) consumes heat. This significantly reduces one of the only significant losses to SOFC efficiency; compressing the air.

The discussion and systems analysis included in the attached report describes Integrated Gasification Fuel Cell (IGFC) plants that will achieve over 60% efficiency (based on HHV); a significant improvement compared with current state-of-the-art pulverized coal plants.

Cost of Electricity

Though SOFC initially suffered from high projected capital cost (as high as $4500/kW about 10 years ago), state-of-the-art stack technologies developed under SECA have reduced stack costs to below $300/kW[1]. Further improvements will reduce that cost to $100/kW.

To put this in the context of advanced coal-based power systems, an estimate was developed for the levelized cost electricity (LCOE) from gasification-based power generation platforms being developed by DOE's Office of Fossil Energy. Table 1 presents five power platforms under both a

[1] Complete stack cost based on current performance in small systems, but assuming production at >100 MW/yr

"no CO2 capture" and a "with CO2 capture" configuration. Each case contains data on efficiency, capital cost, fixed O&M, and variable O&M and a calculated levelized cost of electricity.

Table 1. Cost Impact of State of the Art Advanced Coal Power Systems

Levelized Cost of Electricity from Advanced PC, IGCC, and IGFC Power Plants, With and Without CO2 Capture and Storage										
	Baseline Power Systems					Scaling Factor	Advanced Power Systems With CO2 Capture, Compression and Storage				
	SPC from Baseline	**GEE from Baseline**	**Adv IGCC**	**atm IGFC**	**press IGFC**		**SPC from Baseline**	**GEE from Baseline**	**Adv IGCC**	**atm IGFC**	**press IGFC**
Information Source	1	1	2	3	4		1	1	2	3	4
Efficiency	**39.1%**	**38.2%**	**45.0%**	**49.0%**	**62.0%**		**27.2%**	**32.5%**	**40.2%**	**42.8%**	**57.3%**
% of Power from Steam Cycle	100%	39%	39%	26%	2%		100%	37%	37%	26%	2%
% CO2 Capture	0%	0%	0%	0%	0%		90%	90%	90%	100%	100%
O2 Requirement (lb O2/lb dry coal)	0.00	0.89	0.89	0.80	0.52		0.00	0.89	0.89	0.80	0.52
Capital Cost, $/kW net	**1,575**	**1,813**	**1,688**	**1,663**	**1,443**		**2,870**	**2,390**	**2,169**	**1,991**	**1,667**
coal handling*	97	141	123	114	93	0.85	122	166	139	131	103
ASU*	0	287	250	212	120	0.85	0	342	286	247	134
gasifier*	0	426	383	362	311	0.65	0	498	434	416	344
gas clean up*	229	203	177	164	134	0.85	302	239	199	189	147
combustion turbine/ fuel cell	0	187	188	296	392	0.85	0	238	238	339	424
boiler	510	0	0	0	0	0.65	660	0	0	0	0
HRSG	65	89	89	65	8	0.80	70	99	99	75	10
steam turbine	204	105	105	75	8	0.85	232	116	116	86	10
CO2 capture*	0	0	0	0	0	0.65	837	175	153	0	0
CO2 compression	0	0	0	0	0	0.85	0	68	57	59	46
Other	470	375	375	375	375	NA	647	449	449	449	449
Variable O&M*, cents/kWh	0.49	0.65	0.55	0.51	0.56		0.94	0.81	0.53	0.49	0.55
CO2 Costs, cents/kWh	0.00	0.00	0.00	0.00	0.00		0.75	0.63	0.51	0.30	0.23
Fixed O&M, $/kW/yr	25.2	35.3	35.3	43.9	47.8		37.4	43.7	43.7	51.5	55.4
Fuel Costs, cents/kWh	1.57	1.61	1.36	1.25	0.99		2.26	1.89	1.53	1.43	1.07
LCOE, cents/kWh	**6.3**	**7.8**	**7.1**	**7.0**	**6.2**		**11.6**	**10.6**	**9.2**	**8.5**	**7.3**

* cost per kWh for adv IGCC and IGFC cases estimated to be proportional to the change in efficiency from the GEE baseline.

Appendix A – Systems Analysis

This section presents systems analyses of IGFC combined cycles. Each case includes a system description, process flow diagram, and mass/energy balance tables.

Mature IGFC Combined Cycle Cases with a Pressurized SOFC – 60% Efficient

A description of the cases that are capable of achieving at least 60% net system efficiency (coal HHV basis) are provided as Case 1 and Case 2. Although these analyses were done independently of one another, both use an advanced catalytic gasifier and pressurized fuel cell. The analyses in Table A.1 indicate what efficiencies are expected when advances in NETL's fuel cell and gasification programs are merged to provide synergistic benefits. Both cases either capture CO_2 emissions, or produce a concentrated CO_2 stream (greater than 90% on a dry, molar basis) through novel process design.

Table A.1 - Mature IGFC Combined Cycle Cases (60% Efficient)

Case	Source	Efficiency	Description
1	SAIC	62%	Pressurized fuel cell Advanced catalytic gasifier
2	J. Thijssen, LLC	62%	Pressurized fuel cell Advanced catalytic gasifier

Near-Term IGFC Combined Cycle Cases with an Atmospheric SOFC – 50% Efficient

A description of the cases capable of achieving the Office of Fossil Energy's 2010 Power Systems goal of 45-50% net system efficiency are provided as Case 3 and Case 4. These configurations are unique due to their ability to obtain high efficiency (relative to conventional power generation) while using strictly commercially available technology. No advanced unit operations were assumed in the development of these configurations. Both Case 3 and Case 4 either capture CO_2 emissions, or produce a concentrated CO_2 stream (greater than 90% on a dry, molar basis) through novel process design.

Table A.2 - Near-Term IGFC Combined Cycle Cases (50% Efficient)

Case	Source	Efficiency	Description
3	NETL	49%	Atmospheric fuel cell
4	J. Thijssen, LLC	52%	Atmospheric fuel cell

Comparison Cases

For reference, comparison cases are presented in Case 5, 6, and 7. Case 6 is a state-of-the-art PC plant (27% efficient) and Case 7 is a state-of-the-art IGCC plant (33% efficient); both indicative of what efficiency could be achieved with today's commercial technology. Both of these plants capture 90% of carbon emissions. These two cases should be evaluated against the IGFC configurations shown in Table A.2; all use strictly commercially available technology, however the IGFC combined cycles obtain much higher system efficiency, while still capturing carbon emissions. Case 5 describes a mature IGCC plant (45% efficient) that does not include carbon capture.

Table A.3 - Comparison Cases

Case	Source	Efficiency	Description
5	Noblis	45%	Mature IGCC, no CO_2 capture
6	NETL	27%	State-of-the-art PC with CO_2 capture
7	NETL	33%	State-of-the-art IGCC with CO_2 capture

A.1 Case 1: Pressurized SOFC IGFC Combined Cycle (62% Case, SAIC)

This section describes a coal-fired fuel cell power plant that can achieve a net AC power efficiency of 62% (coal HHV basis). This result is based on a detailed process simulation using ChemCad. The system uses an advanced catalytic gasifier, a pressurized SOFC, an advanced, humid gas cleanup system, and oxy-combustion of the anode off-gas. A process flow diagram is shown in Figure A.1 and the corresponding stream table is Table A.5.

The gasifier chosen for this application is an advanced catalytic coal gasifier. This model produces syngas having high methane content and consumes less oxygen than other gasifiers. The cryogenic air separation unit is designed to produce 95% pure oxygen for use in the gasifier and the oxy-combustor. The syngas humid gas cleaning section removes particulate matter, halides, and sulfur in a series of unit operation steps. This produces a warm (293ºC), humid, sulfur-free syngas that is the fuel for the SOFC stack.

The SOFC fuel cell model assumes 85% fuel utilization, a stack temperature rise of 300ºC (600ºC inlet/900ºC outlet), and a voltage of 0.8 V. These operating parameters are consistent with what is currently being reported by SECA Industry Teams. The fuel cell operating pressure is assumed to be 270 psia, representative of the pressure used in large industrial, turbine expanders.

Turbine expanders recover energy from the cathode off-gas and the anode oxy-combustion gas streams. Waste heat from the fuel cell anode oxy-combustion gas and the cathode off-gas streams is recovered in a sub-critical steam Rankine cycle.

A comprehensive auxiliary power load list was compiled based on the results of the ChemCad simulation. A summary of the power produced and system efficiency is shown below.

Table A.4 – SAIC Pressurized SOFC IGFC Combined Cycle Power Production Summary

SAIC Pressurized SOFC IGFC Combined Cycle	
Fuel Cell Power	397,900 kW
Turbine Expander Power	238,900 kW
Steam Cycle Power	12,500 kW
Parasitic Power	-126,623 kW
Net Power Produced	522,682 kW
Coal Power Fed	840,957 kW
SOFC Inverter Efficiency	96%
Net System Efficiency	62%

This configuration shows a fuel cell combined cycle's ability to achieve high system efficiency using advanced technologies. This configuration produces a sequestration-ready CO_2 product stream, achieving approximately 90% purity once the moisture is condensed out through cooling. The only cost required to sequester CO_2 would be the additional compressors required.

Figure A.1 - SAIC Pressurized SOFC Combined Cycle

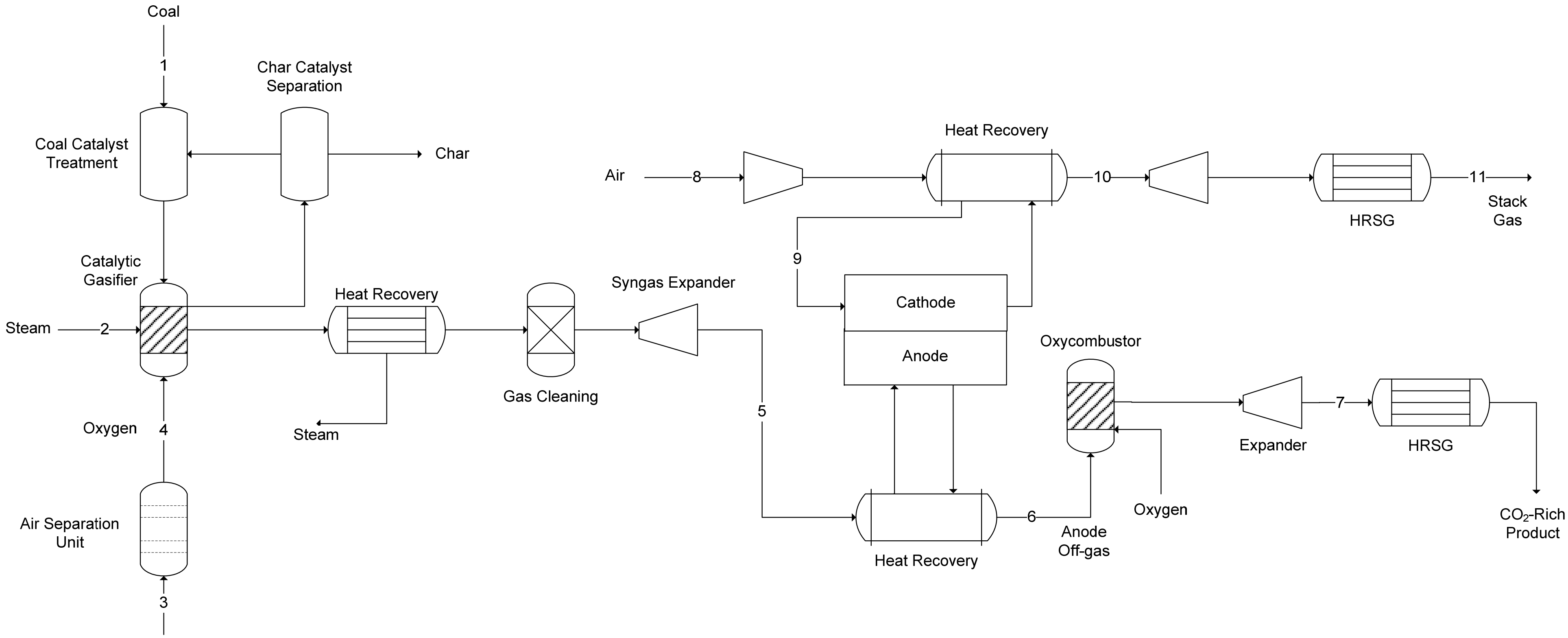

Table A.5 - SAIC Pressurized SOFC Combined Cycle Stream Table

Stream	1	2	3	4	5	6	7	8	9	10	11
Flow (lb/h)	228,420	330,000	503,000	64,421	643,782	992,544	1,041,205	1,840,000	1,840,000	1,491,211	1,491,211
Temperature (°F)	59	580	59	272	561	1418	255	59	1100	1318	255
Pressure (psia)	1100	1100	14.7	1050	275	267	15.3	14.7	287	281	15.2
Vapor Fraction		1	1	1	1	1	1	1	1	1	1
Enthalpy (MMBtu/h)	-146.07	-1866.10	-21.99	2.57	-2337.30	-3889.80	-4656.70	-80.46	403.75	408.28	-6.69
Component mole %											
H_2					12.5	4.7	0.0				
CH_4					17.0	0.0	0.0				
H_2O		100.0	1.0		39.1	59.2	63.9	1.0	1.0	1.3	1.3
CO					5.0	3.1	0.0				
CO_2					21.5	29.4	32.5				
N_2			77.2	0.2	4.7	3.5	3.5	77.2	77.2	93.1	93.1
Ar			0.9	0.3	0.1	0.1	0.1	0.9	0.9	1.1	1.1
NH_3					0.051500	0.000795	0.000000				
HCN					0.005821	0.000000	0.000000				
HCl					0.000092	0.000069	0.000069				
H_2S					0.000006	0.000004	0.000000				
COS					0.000000	0.000000	0.000000				
SO_2					0.000179	0.000133	0.000138				
O_2			20.8	99.5	0.0	0.0	0.0	20.8	20.8	4.4	4.4

A.2 Case 2: Pressurized SOFC IGFC Combined Cycle (62% Case, J. Thijssen, LLC)

This section describes a coal-based fuel cell power plant that can achieve a net AC electric efficiency of 62% (coal HHV basis) with high pressure CO_2 capture and virtually all power coming from the SOFC. These results are based on a detailed heat and mass balance and reactor modeling. Salient characteristics of the system include a low-temperature catalytic gasifier, a conventional solvent-based syngas sweetening system (Selexol), a pressurized SOFC with anode gas recycle to the gasifier, a hot-air turbine for cathode-side pressure recovery and no air separation unit at all. A process flow diagram is shown in Figure A.2, and the corresponding stream table is Table A.6.

The gasifier is a catalytic coal gasifier functionally similar to that proven in the 1980s by Exxon in a demonstration plant and currently being developed by GreatPoint Energy. This analysis uses the SOFC's hot anode tailgas exclusively to provide heat and oxidant, thus avoiding the use of oxygen altogether and achieving a high cold-gas efficiency (>90%). The gasification reaction is thermally balanced by choosing the appropriate operating points of the gasifier and the fuel cell, and by removing CO_2 from the gas stream. A small purge stream (5-10% depending on inert concentrations) is removed from the recycle and mixed with the spent cathode air.

The SOFC fuel cell model assumes 70% fuel utilization, a stack temperature rise of 200ºC (650ºC inlet/850ºC outlet), and a cell voltage of 0.8 V, while operating at 35 bar; except for the pressure, not particularly challenging operating conditions for today's SOFC. Cathode air is provided by a compressor.

A comprehensive auxiliary power load list was developed and checked against the DOE Baseline IGCC analyses. A summary of the power produced and system efficiency is shown below in Table A.6.

Table A.6 - J. Thijssen, LLC Pressurized SOFC ICFC Combined Cycle Power Production Summary

J. Thijssen, LLC Pressurized SOFC IGFC Combined Cycle	
Fuel Cell Power	400,376 kW
Compressor/Expander Power (net)	131,670 kW
Steam Cycle Power	0
Parasitic Power	-140,937 kW
Net Power Produced	376,661 kW
Coal Power Fed	609,960 kW
SOFC Inverter Efficiency	96%
Net System Efficiency	62%

This configuration shows that by judicious integration of a catalytic gasifier, a high-efficiency system can be developed that produces CO_2 in a concentrated form from a high-pressure Selexol process. The system reduces the chemical process units to the fuel cell, the gas sweetening system, and the low-temperature gasifier, eliminating the need for an air separation unit, shift reactors, and a high temperature gasifier.

Figure A.2 - J. Thijssen, LLC Pressurized SOFC IGFC Combined Cycle

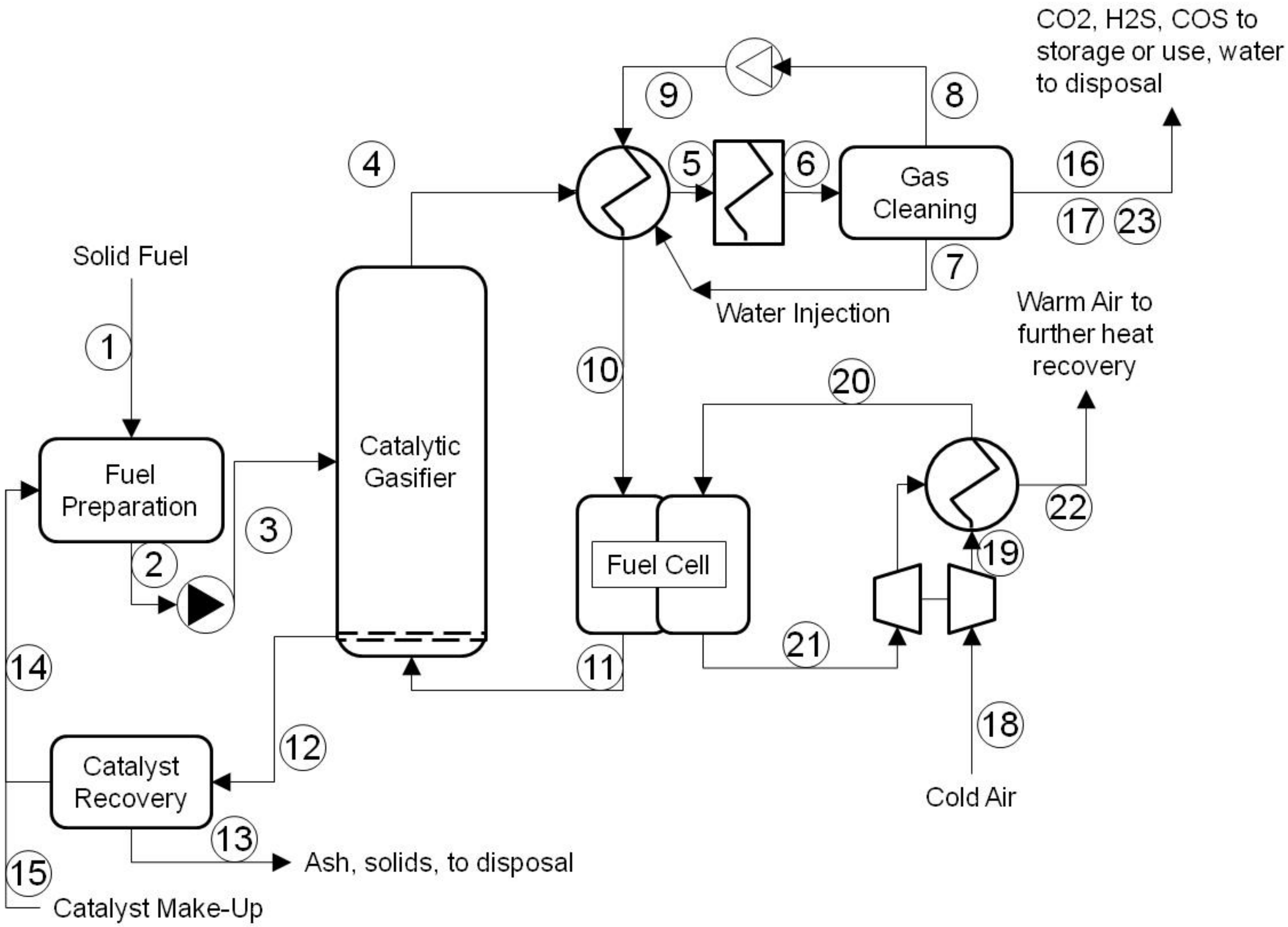

Table A.7 - J. Thijssen, LLC Pressurized SOFC IGFC Stream Table

Stream	1	2	3	4	5	6	7	8	9	10	11	12
Flow (kg/s)	22.5	24.75	24.75	102.84	102.84	102.84	29.6	25.13	25.13	54.8	96.0	6.16
Temperature (ºC)	25	50	50	714	203	125	60	60	127	625	850	714
Pressure (bar)	1	1	35	35	35	35	35	35	35	35	35	35
Enthalpy (kJ/s)	-7.88E4	-2.03E5	-2.03E5	-8.27E5	-9.27E5	-9.41E5	-4.36E5	-1.14E5	-1.12E5	-4.38E5	--9.23E5	-5.49E4
Component Mass Flow												
Coal / Char (DAF)	17.26	17.26	17.26									1.73
Ash	2.18	2.18	2.18									2.18
Catalyst		2.25	2.25									2.25
H_2				1.38	1.38	1.38		1.38	1.38	1.38	1.61	
O_2												
N_2				2.52	2.52	2.52		2.52	2.52	2.52	2.52	
H_2O				33.5	33.5	33.5	29.6	1.56	1.56	31.2	53.4	
CO_2				48.2	48.2	48.2		2.41	2.41	2.41	31.9	
CO				6.47	6.47	6.47		6.47	6.47	6.47	6.62	
CH_4				10.8	10.8	10.8		10.8	10.8	10.8		
H_2S				0.62	0.62	0.62						

Stream	13	14	15	16	17	18	19	20	21	22	23	
Flow (kg/s)	4.14	2.25	0.225	0.62	45.8	263.6	263.6	263.6	232.0	232.0	3.9	
Temperature (ºC)	25	25	25	40	40	25	370	650	941.6	60	40	
Pressure (bar)	1	1	1	1	1	1	35	35	35	1	1	
Enthalpy (kJ/s)	-5.80E5	-2.38E4	-2.38E3	-9.41E3	-4.09E5	1.97E-5	9.40E4	1.75E5	1.13E5	-1.22E5	-0.57E5	
Component Mass Flow												
Coal / Char (DAF)	1.73											
Ash	2.18											
Catalyst	0.23	2.25	0.225									
H_2												
O_2						61.1	61.1	61.1	18.2	18.2		
N_2						202.5	202.5	202.5	202.5	202.5		
H_2O									6.79	6.79	3.9	
CO_2					45.8				4.22	4.22		
CO												
CH_4												
H_2S				0.62								