National Renewable Energy Laboratory
Innovation for Our Energy Future

Indirectly Heated Biomass Gasification

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PD_27_Bain

Overview

TIMELINE

- *Start date*: **July 2007**
- *End date*: **June 2009**
- *Percent complete*: **100%**

BUDGET

- Funding in FY08:

  $1,020,000
- Funding for FY09:

  $75,000

BARRIERS

Barriers
  Gasification efficiency
  Capital intensity
  Improved tar removal/reforming catalysts

Targets
  $1.60 / gge hydrogen in 2012
  $1.10 / gge hydrogen in 2017

PARTNERS

- Collaboration with the DOE Office of the Biomass Program (OBP) sponsored research at NREL
  - Gasification & tar reforming
  - OBP gasification data used in new correlation
  - New correlation to be used in OBP design models

Project Summary

Relevance	**To obtain new data on integrated gasification and processing to strengthen the technical basis for the 2012 ($1.60/gge) and 2017 ($1.10/gge) plant gate MYPP cost objectives for hydrogen produced via biomass gasification** Address efficiency, capital intensity, and reforming barriers Identified by NRC as a primary near term route for central hydrogen production
Approach	A three phase approach was used: 1) gasification, reforming, and shift reaction testing to produce a hydrogen-rich syngas, 2) material and energy balance modeling using updated gasifier correlations, and 3) updating capital costs, operating costs, and H2A economics
Technical Progress	Parametric gasification experimental testing complete Gasification / tar reforming / shift reaction proof of concept testing complete New gasifier yield correlation development complete ASPEN model and CAPEX/OPEX update complete Updated H2A economics spreadsheet complete

Objectives and Key Outcomes

Objective:

To experimentally update the technical & economic performance of an integrated biomass gasification-based hydrogen production process based on steam gasification

- Steam gasification
- Gas cleanup: tar & light hydrocarbon reforming
- Shift reaction

Key Outcomes Expected:

- Production of clean syngas
- Production of hydrogen-rich gas
- Development of updated yield and gas quality correlations
- Development of updated technoeconomic model
- Development of updated H2A model

Approach

Data Generation

- Parametric Gasification Testing
  - Performed using indirect steam gasifier
  - 2 feeds (oak, pine)
  - 3 temperatures (750, 850, 950°C)
  - 3 steam/biomass ratios
  - 20 kg/h biomass
- Tar reformer testing at a selected condition
- Slip-stream syngas processing at a selected condition
  - H_2S removal
  - High temperature shift

Process Modeling

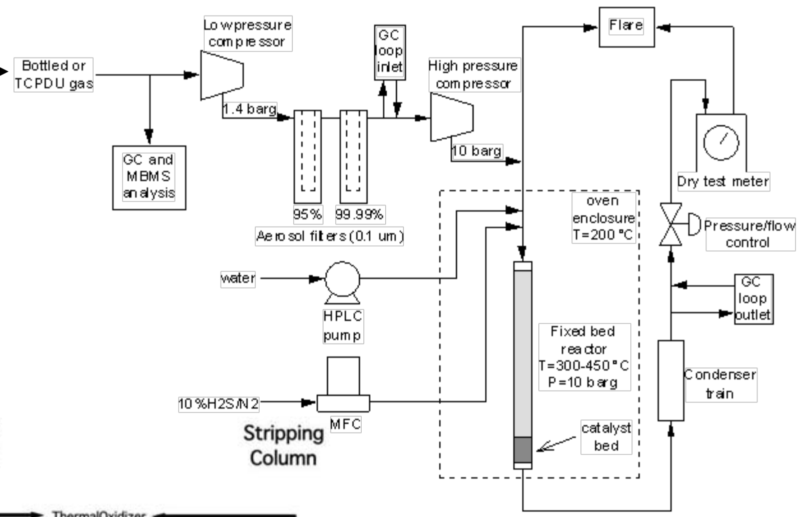
- Gasifier Correlation
  - Parametric data
  - Multivariate analysis (Unscrambler)
- ASPEN Analysis
  - ASPEN gasifier correlation FORTRAN block
  - ASPEN H2 integrated plant analysis
- EXCEL Summaries
- Comparison with 2005 Model

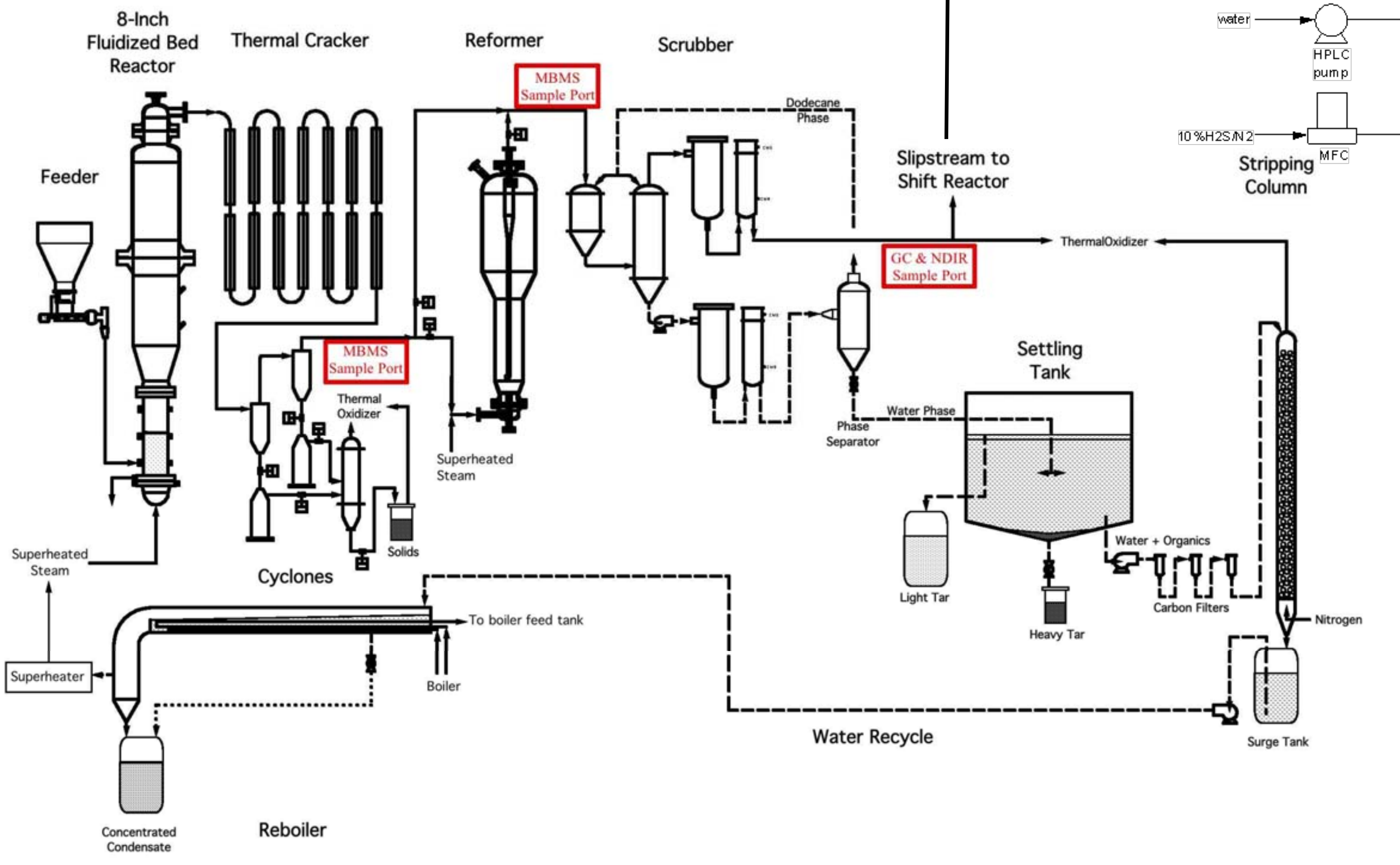
Economic Modeling

- Import of Process Modeling Results into H2A
- Comparison with Previous Results

NREL Thermochemical Process Development Unit & Slip-Stream Shift System

Experiments were performed using NREL’s 0.6 tonne per day pilot plant. A 10% slip stream was used for shift reaction experiments.



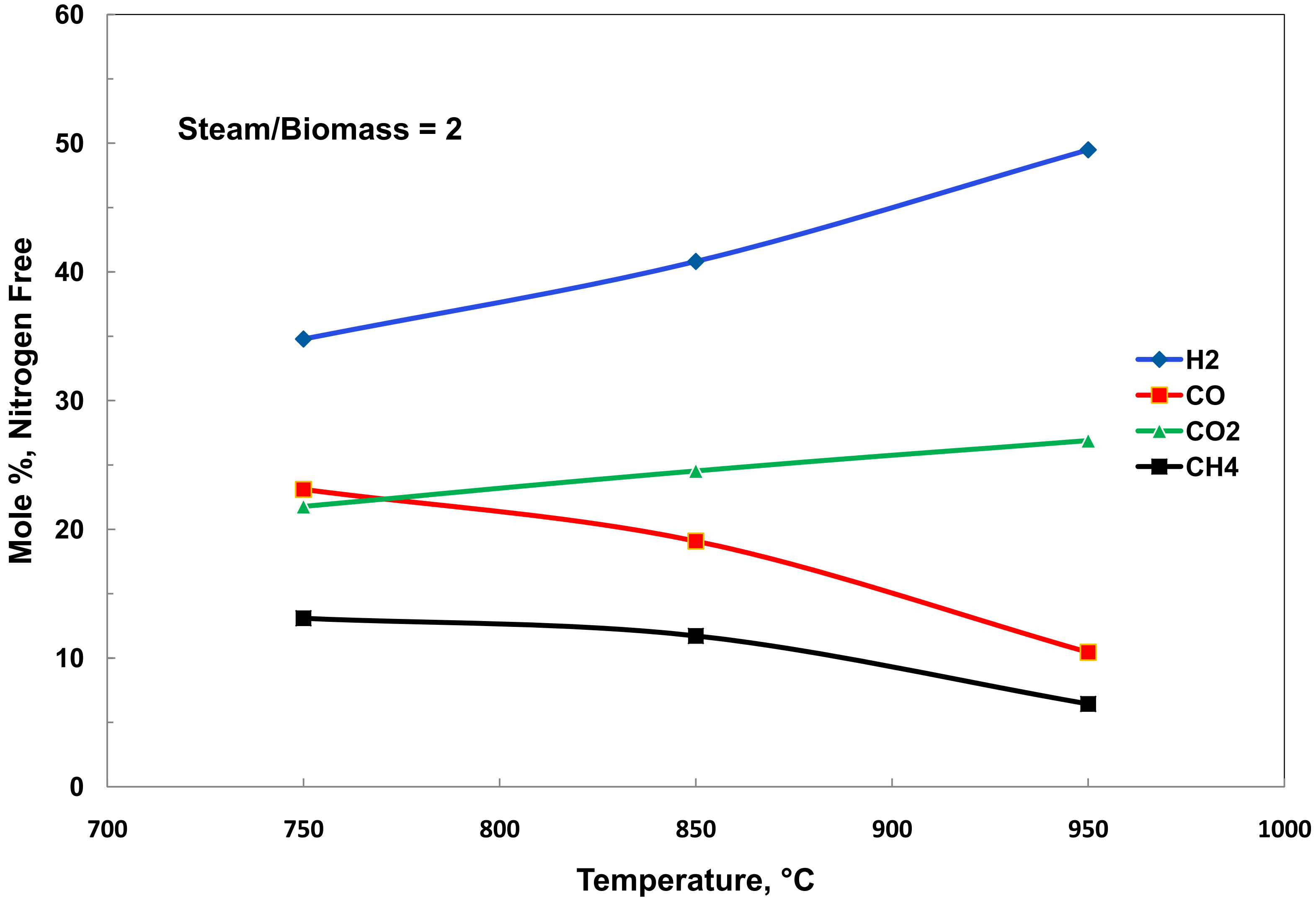


Typical Gas Composition Data

Feed	Oak	Oak	Oak	Pine	Pine	Pine
Temperature	750	850	950	750	850	950
Steam to Biomass Ratio	2	2	2	2	2	2
Gas Composition (vol%)						
H2	30.19	30.30	35.15	34.78	40.81	49.49
CO	27.94	28.30	25.48	23.10	19.08	10.45
CO2	21.17	20.45	20.76	21.78	24.55	26.91
CH4	12.82	13.70	13.11	13.10	11.73	6.44
He (tracer)	2.29	2.20	1.94	1.61	1.45	1.91
C2H6	0.00	0.00	0.00	0.00	0.00	0.00
C2H4	3.21	3.81	2.21	3.01	1.66	2.7
C2H2	1.21	0.47	0.01	1.16	0.24	0.0
C3H8	0.20	0.49	1.30	0.18	0.39	1.9
C3H6	0.48	0.10	0.00	0.46	0.09	0.0
1-C4H8	0.19	0.04	0.00	0.06	0.00	0.0
2-cis-C4H8	0.00	0.00	0.00	0.00	0.00	0.0
2-trans-C4H8	0.31	0.09	0.02	0.75	0.00	0.0
COS, ppm	1.66	2.08	0.00	0.00	0.00	0.0
H2S, ppm	0.00	61.26	60.88	0.00	24.00	21.0
H2:CO Ratio	1.08	1.07	1.38	1.51	2.14	4.7

Detailed gas and tar analyses were used to estimate both initial and reformed product gas composition, and percent conversion of components during reforming

Representative Gasification Data, Steam Gasification of Pine



Comparison of tar concentrations in raw oak- and pine-derived syngas for quantified species for experiments at 850°C and steam/biomass = 2

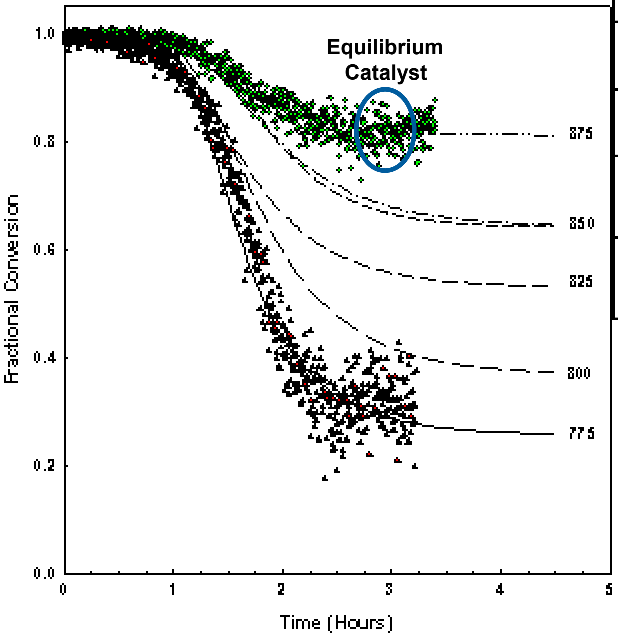
Species	*m/z*	*Tar Concentrations (mg/Nm^3 - wet basis)*	
		oak	*pine*
Benzene	**78**	**4860**	**4690**
Toluene	**92**	**1510**	**1540**
Phenol	**94**	**690**	**1090**
Cresol	**108**	**100**	**100**
Naphthalene	**128**	**1250**	**1310**
Phenanthrene	**178**	**390**	**570**
“other tar”	**80-176**	**2900**	**3190**
“heavy tar”	**180-400**	**2930**	**3590**
Total (>m/z 78)		**9770**	**11380**

Tar compositions and yields are comparable for oak and pine, indicating that for woody feedstocks, tar yield is a function of processing conditions, not feed.

Average concentrations (mg/Nm^3-dry basis) of pine-derived tars in raw and reformed gas.

Species	*m/z*	*Tar Concentrations (mg/Nm^3 – dry basis)*		
		Raw gas	*Reformed gas*	*Reduction % [a]*
Benzene	**78**	**11170**	**7880**	**29.4**
Toluene	**92**	**3650**	**230**	**93.7**
Phenol	**94**	**2200**	**60**	**97.3**
Cresol	**108**	**180**	**–**	**100**
Naphthalene	**128**	**2980**	**1090**	**63.4**
Phenanthrene	**178**	**1240**	**230**	**81.4**
“other tar”	**80-176**	**6300**	**240**	**96.2**
“heavy tar”	**180-400**	**6270**	**120**	**98.1**
Total (>m/z 78)		**22830**	**1960**	**91.4**

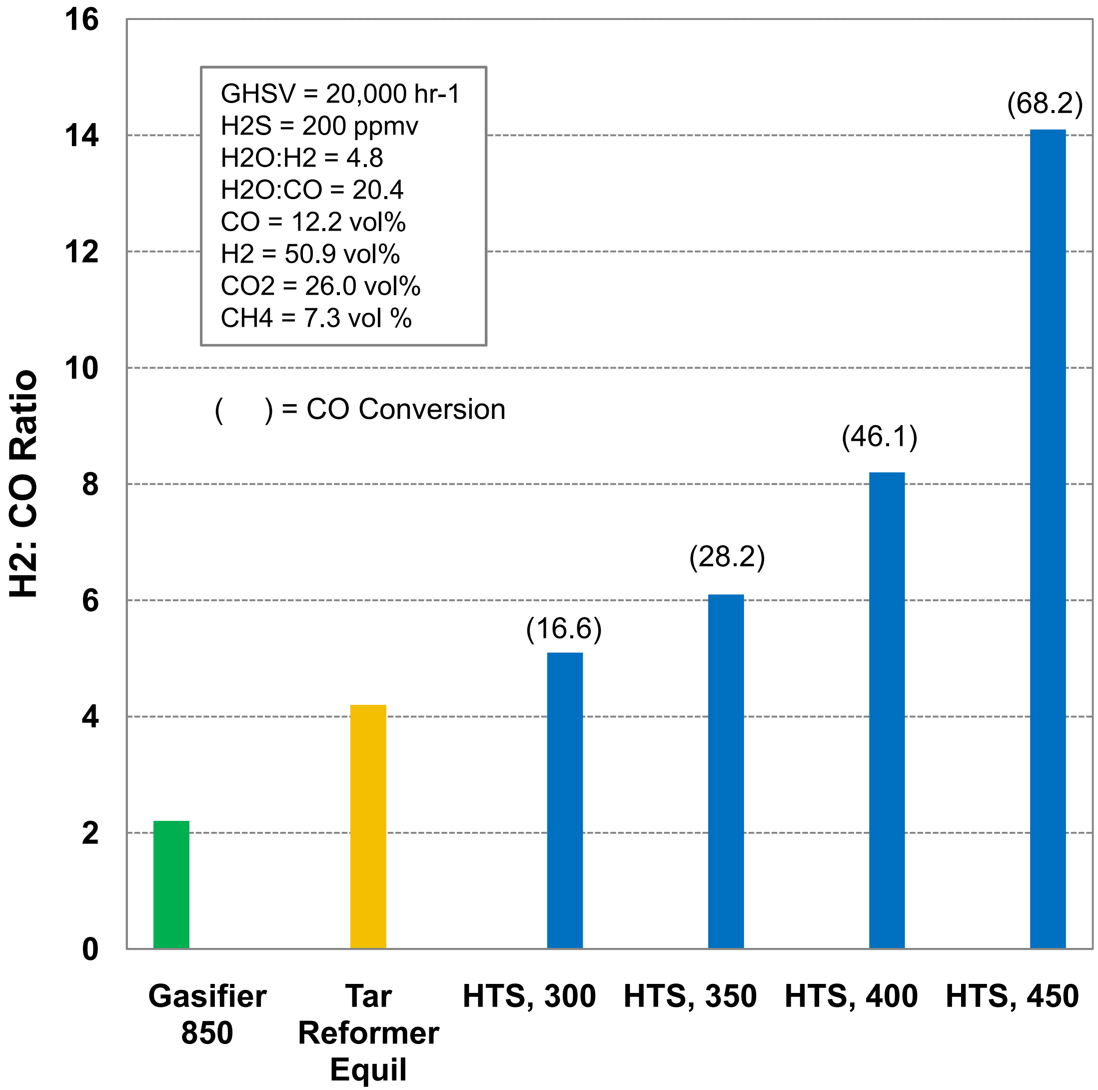
(a) % reduction – concentration basis not normalized for volume change



The equilibrium (deactivated) catalyst was effective in converting most tars other than benzene and naphthalene

Hydrogen:Carbon Monoxide Ratio
High Temperature Shift Reaction using Syngas

[Pine, 850°C, Equilibrium Tar Reforming Catalyst]



High temperature shift CO conversion similar to literature values achieved at 450°C

Multivariate Analysis of Parametric Gasification Data

Equation: $Y = a + \sum(b\cdot X + c\cdot X^2)_i$, where

Y = Component Value, [=] mole %, kg/kg feed, or mg/Nm^3, X = Independent Variable

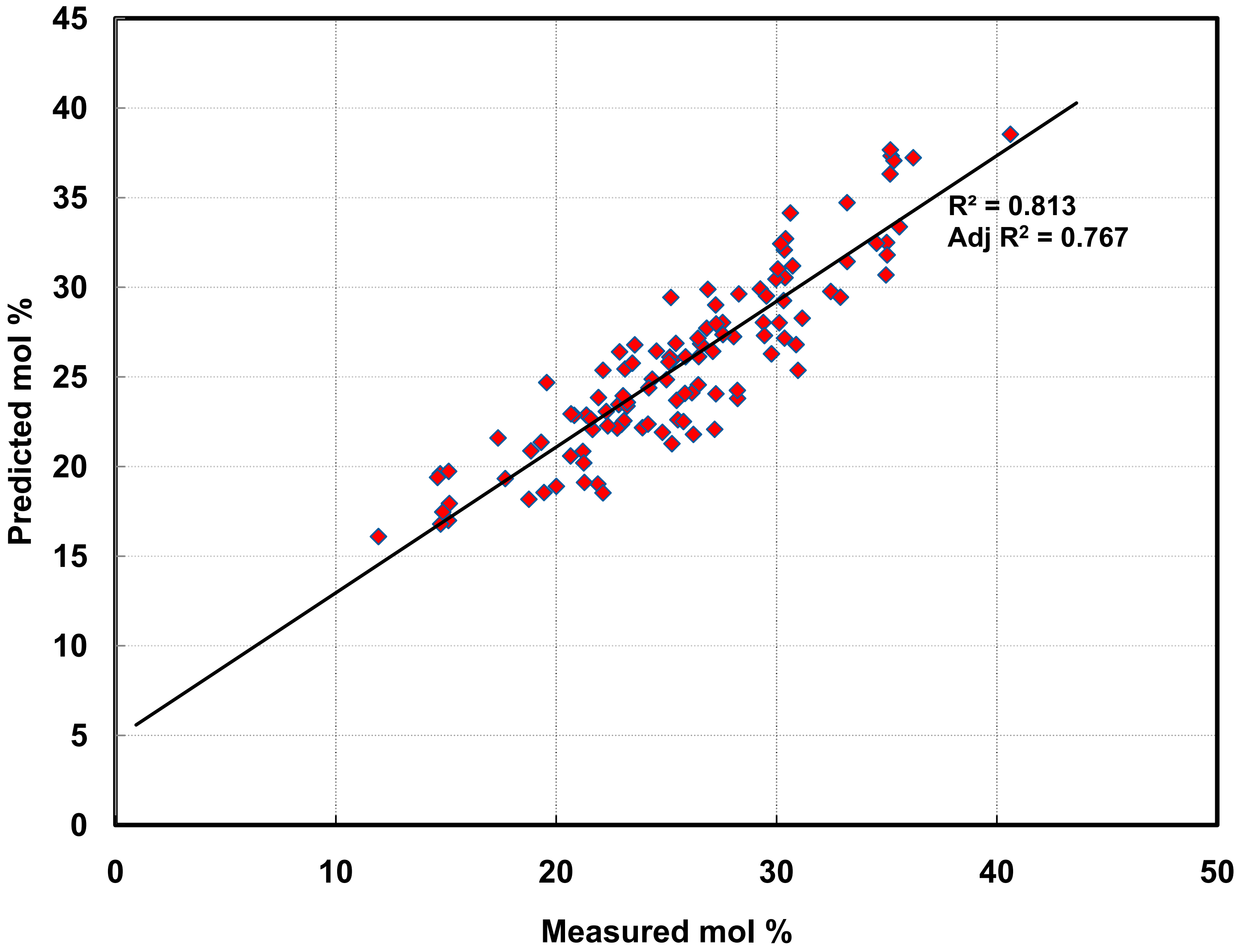
Independent Variables (X)

- Proximate Analysis (Moisture, Volatile Matter, Fixed Carbon), [=] wt%
- Ultimate Analysis (Carbon, Hydrogen, Oxygen, Nitrogen, Sulfur, Ash), [=] wt%
- Temperature (TC), [=] °C
- Steam to biomass ratio (SB)
- Residence Time (RT), [=] sec
- Interactions (TC:SB, TC:RT, SB:RT)

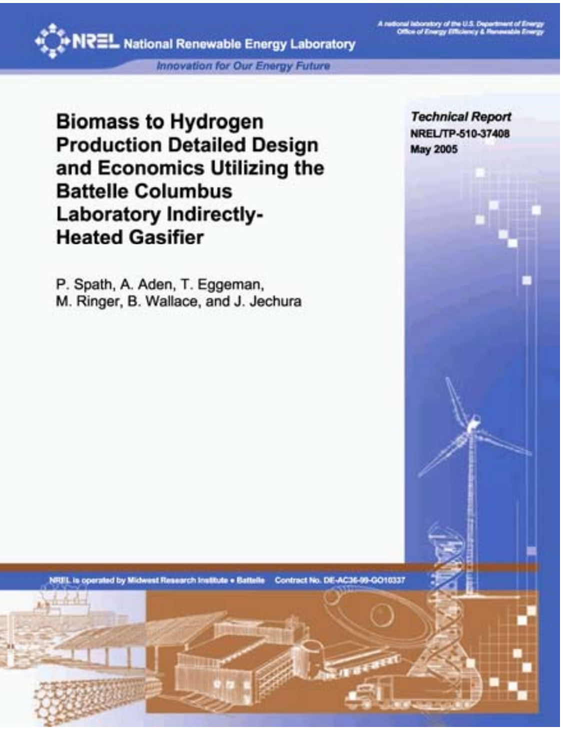
Component	NREL PDU Correlation	BCL PDU Correlation
Hydrogen	0.81	0.92
Carbon Dioxide	0.81	0.42
Carbon Monoxide	0.73	0.40
Methane	0.84	0.70
Acetylene	0.96	0.72
Ethylene	0.96	0.88
Ethane	0.72	0.85
Propane	0.90	
Propylene	0.95	
1-Butene	0.88	
2-c-Butene	0.71	
2-t-Butene	0.71	

Component	NREL PDU Correlation	BCL PDU Correlation
Hydrogen sulfide	0.85	
Benzene	0.97	
Toluene	0.83	
Phenol	0.83	
Cresols	0.94	
Naphthalene	0.98	
Phenanthrene	0.98	
Heavy Tar, MW > 180	0.55	
Total Tar, MW > 78	0.77	0.89
Char	0.74	0.66

Comparison of Predicted and Measured Hydrogen Concentration NREL PDU Correlation



Biomass to Hydrogen Block Flow Diagram



NREL National Renewable Energy Laboratory

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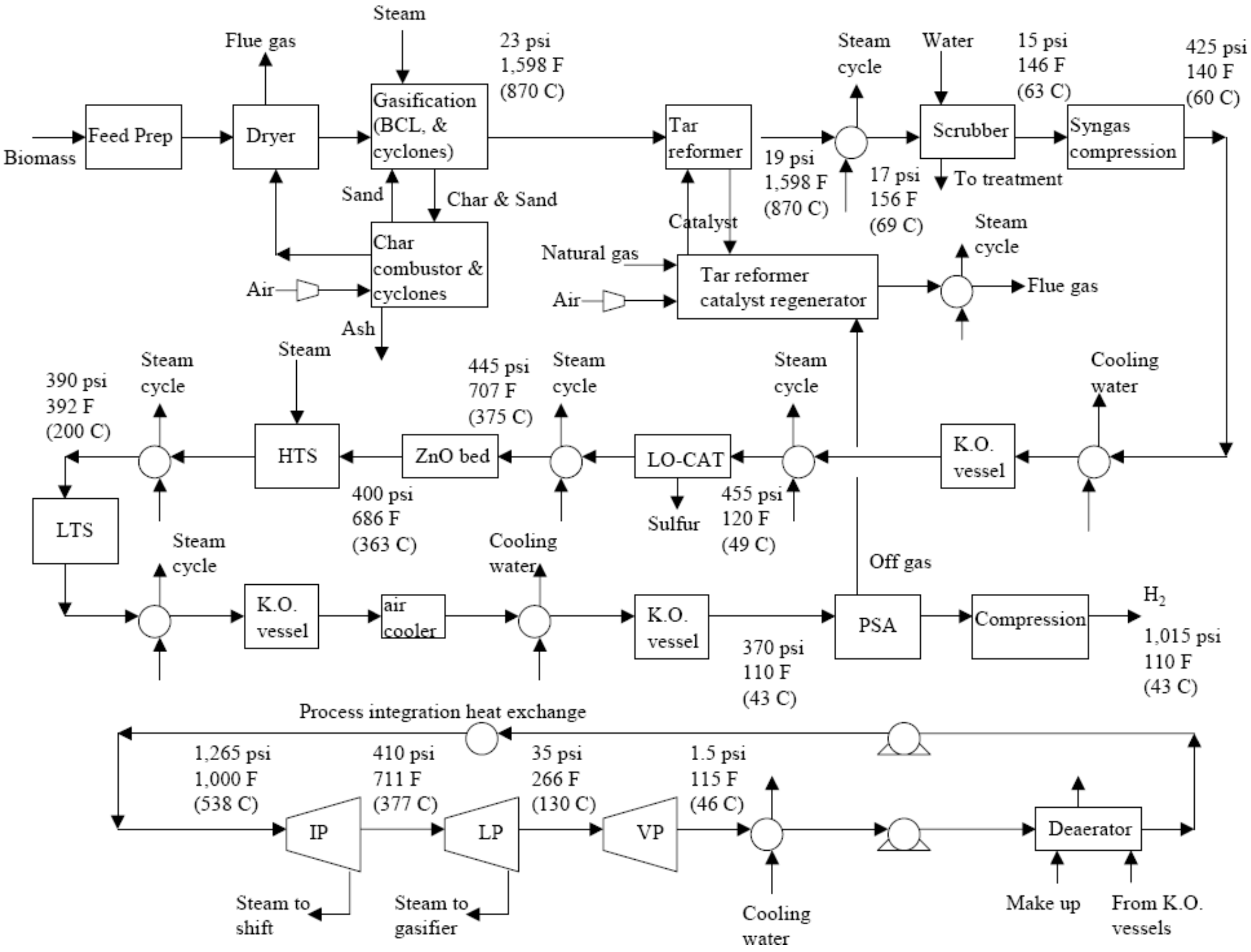
A national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy

Biomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly-Heated Gasifier

Technical Report
NREL/TP-510-37408
May 2005

P. Spath, A. Aden, T. Eggeman, M. Ringer, B. Wallace, and J. Jechura

NREL is operated by Midwest Research Institute • Battelle Contract No. DE-AC36-99-GO10337



(Spath et al, 2005)

H2A Model Cost Contribution Comparison

Cost Component	Existing (9-2008) H2A Model		Revised (3-2009) H2A Model	
	Cost Contribution ($/kg)	% of H2 Cost	Cost Contribution ($/kg)	% of H2 Cost
Capital Costs	0.50	34.12	0.47	31.47
Decommissioning Costs	0.00	0.05	0.00	0.04
Fixed O&M	0.20	13.61	0.19	12.47
Feedstock Costs	0.53	36.26	0.50	33.64
Other Raw Material Costs	0.10	6.86	0.08	5.41
Byproduct Credits	0.00	0.00	0.00	0.00
Other Variable Costs (including utilities)	0.13	9.11	0.25	16.99
Total	1.47		1.49	
Production Process Energy Efficiency	48.29%		49.00%	
Feedstock energy input (GJ)/kg H2	0.242		0.228	
Utility energy input (GJ/kg H2)	0.007		0.017	
Hydrogen energy output (GJ/kg)	0.120		0.120	
Byproduct energy output (GJ/kg H2)	0.000		0.000	

02D_Future _Central_Hydrogen_Production_via_Biomass _Gasification_version_2.1.2.xslm
http://www.hydrogen.energy/h2a_prod_studies_html (2/9/2009)

Process Summary

Gasifier or Process Variable	Existing ASPEN Model	Updated ASPEN Model
Gasifier Dry Gas Yield, Lbmol of dry gas/lb of dry feed	0.35	0.45
Gasifier H_2:CO molar ratio	0.57	1.31
Gasifier Gas Heating Value Btu/lb	Wet: 4,759 HHV 4,401 LHV Dry: 8,019 HHV 7,416 LHV	Wet: 4,283 HHV 3,899 LHV Dry: 6,104 HHV 5,557 LHV
Gasifier Char Yield, lb/lb of dry feed	0.22	0.10
Gasifier Efficiency	72.1% HHV 71.8% LHV	70.8% HHV 69.3% LHV
Overall Process Hydrogen Production	15,322 lb/hr (69.2 MMSCFD)	15,510 lb/hr (70.1 MMSCFD)
Electricity Purchased from Grid	22,361 kW (29,987 HP)	21,249 kW (28,496 HP)
Natural Gas	0.085 $Nm^3/kg\ H_2$	0.150 $Nm^3/kg\ H_2$
Wood price, 2005$, $/dry tonne	$60	$60
H2A Price, 2005 Dollars and Assumptions	$1.47	$1.49

Collaborations

- Collaboration with the DOE Office of the Biomass Program (OBP) sponsored research at NREL
  - Gasification & tar reforming
  - OBP gasification data used in new correlation
  - New correlation to be used in OBP design models

Proposed Future Work

- This project is complete

Summary

- The objective of the study was to update the technical and economic performance of hydrogen production via biomass steam gasification.
- Although the NREL gasifier yield correlations showed significant differences in char yield (NREL – 10%; BCL - 22%) the integrated process gasifier heat requirements and downstream unit operations (tar reforming and shift reaction) resulted in overall process performance for a 2,000 tonne per day plant that was very similar (NREL– 70.1 MMSCFD H_2; BCL – 69.2 MMSCFD H_2) and comparable costs (NREL – \$1.49/kg H_2; BCL - \$1.47/kg H_2).
- The new results verify conceptual process performance, based on independent pilot scale testing.
  - Parametric gasification tests were successfully performed using oak and pine at temperatures up to 950°C.
  - A new gasifier correlation was developed that includes biomass properties, temperature, residence time, and steam/biomass ratio. The correlation incorporates gasification data for other feedstocks obtained by Office of the Biomass Program research. The correlation includes a significant number of new yield components.
  - An updated ASPEN model, updated capital costs, and updated operating costs were developed.
  - An updated H2A model was developed that gave results comparable to the existing H2A model.
  - The produced syngas was used to generate a gas with high H_2 concentration in shift gas experiments. CO conversions comparable to literature values were obtained.
  - The objectives of the study were met.