

Innovation for Our Energy Future

Indirectly Heated Biomass Gasification

Richard L. Bain June 12, 2008

PD 29

This presentation does not contain any proprietary, confidential, or otherwise restricted information



NREL is operated by Midwest Research Institute • Battelle



Timeline

- Project start date: July 2007
- Project end date: September 2008
- Percent complete: 33%

Budget

- Total project funding \$1,100,000
- Funding received in FY07 \$500,000
- Funding for FY08 \$600,000

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 sponsored research at NREL
 - Gasification & tar reforming



MYPP Objective

By 2012, reduce the cost of hydrogen produced from biomass gasification to \$1.60 / gge at the plant gate (<\$3.30 / gge delivered).

By 2017, reduce the cost of hydrogen produced from biomass gasification to \$1.10 / gge at the plant gate (\$2.10 / gge delivered).

DOE (2007). "Hydrogen, Fuel Cells & Infrastructure Program Multi-Year Research and Demonstration Program," p 3.1-1.



Objective 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
- Hydrogen sulfide removal
- Shift reaction
- Hydrogen separation
- Key Outcomes Expected:
 - Production of clean syngas
 - Production of high-purity hydrogen
 - Development of updated yield and gas quality correlations
 - Development of updated technoeconomic model



Milestones

Month/Year	Milestone
Jun-08	Complete initial gasification and hydrogen production testing
Jun-08	Complete initial ASPEN modeling and H2A modeling
Sep-08	Complete parametric gasification/shift reaction testing for two biomass feeds
Sep-08	Complete ASPEN model update and revised H2A estimate



Approach



Experimental System



Typical Gasification Results

Gasification of Oak, NREL TCPDU Steam/Biomass = 2





Tar Reforming Experiments



 $X_{A} = \frac{e^{k\tau(a_{s1} + (1 - a_{s1})e^{-\psi t})}}{1 + e^{k\tau(a_{s1} + (1 - a_{s1})e^{-\psi t})}}$

Bain, R. L., D. C. Dayton, D. L. Carpenter, S. R. Czernik, C. J. Feik, R. J. French, K. A. Magrini-Bair and S. D. Phillips (2005). "An Evaluation of Catalyst Deactivation During Catalytic Steam Reforming of Biomass-Derived Syngas," *I&ECR*, 44, p 7945-7956.

NREL National Renewable Energy Laboratory

Tar Reforming Experiments





Gasifier / Reformer Performance

Oak Gasification: NREL TCPDU Nov-Dec 2007

Run Order: 4 5 13 14 Run Code: 97095 InDe1 97095b InDe2 OK_HY_97095 OK_NREL32b_InDe1 OK_HY_97095b OK_NREL32b_InDe2 H2 33.74 50.46 39.15 49.91 CO 24.45 12.18 18.37 13.91 CO2 19.93 23.64 23.45 13.91 CO2 19.93 23.64 23.45 13.91 CO2 19.93 23.64 23.45 13.91 CO2 24.45 11.06 13.91 14 N2 0.00 0.00 0.00 0.00 0.00 C2H4 2.12 0.17 1.66 tar analyses are used to estimate both initial and reformed product gas composition, and percent conversions of C3H6 0.00 0.000 0.000 C3H6 0.00 0.000 0.000 0.000 0.000 0.000 0.000 Case C4H8 0.00 0.000 0.000 0.000 0.000 0.000 0.000 0.000 Closure 95.99 92.21 96.42	Uuit		Janoi				•,•					_
Run Code: 97095 InDe1 97095b InDe2 OK_HY_97095 OK_NREL32b_InDe1 OK_NREL32b_InDe2 H2 33,74 50,46 39,15 49,91 CO 24,45 12,18 18,37 13,95 13,95 CO2 19,93 23,64 23,45 13,95 13,95 CH4 12,59 4,62 11,06 13,95 14,91 N2 0,00 0,00 0,00 0,00 0,00 0,00 Re(tracer) 1,86 1,07 1,66 Detailed gas and tar analyses are used to estimate other initial and tar analyses are used to estimate other initial and reformed product gas composition, and percent conversions of C3H6 0,00 0,00 0,000	Run Order:		4			5		13			14	
OK_HY 97095 OK_NREL32b_InDet OK_HY 97095 OK_NREL32b_InDet H2 33.74 50.46 39.15 49.91 CO 24.45 12.18 18.37 13.05 CO2 19.93 23.64 23.45 13.05 CH4 12.59 4.62 11.06 13.06 N2 0.00 0.00 0.00 0.00 C2H6 0.00 0.00 0.00 0.00 C2H4 2.12 0.17 1.66 tar analyses are used to estimate both initial and reformed product gas composition, cos C3H6 0.00 0.00 0.00 0.00 0.00 2-cis-C4H8 0.00 0.00 0.00 0.004 conversions of components during reformed product gas composition, and percent conversions of components during reforming Closure 95.99 92.21 96.42 0 toluene 393 0 326 6874 phenol 46 29 39 52 toluene 393 0 324	Run Code:		97095			nDe1		97095b			InDe2	
H2 33.74 50.46 39.15 49.91 CO 24.45 12.18 18.37 13.66 CO2 19.93 23.64 23.45 13.66 CH4 12.59 4.62 11.06 13.66 N2 0.00 0.00 0.00 0.00 C2H6 0.00 0.00 0.00 0.00 C2H4 2.12 0.01 0.00 0.03 used to estimate C3H8 1.25 0.07 0.99 used to estimate both initial and 1-C4H8 0.00 0.00 0.00 0.00 2/4/4 gs composition, CS3 0.0000 0.000 0.00 0.00 0.00 gs composition, CC4H8 0.02 0.00 0.004 0.004 gs composition, Closure 95.99 92.21 96.42 conversions of conversions of Components 0 0 0 0 0 0 0 phenanthrene 7383 42 1834 0 52 52 52		OK_HY_	97095	OK_N	REL32b_Ir	De1	OK_HY_9	97095b	OK	_NREL32b	_InDe2	
CO 24.45 12.18 18.37 13.05 CO2 19.93 23.64 23.45 CH4 12.59 4.62 11.06 N2 0.00 0.00 0.00 Leftacer) 1.86 1.07 1.69 C2H6 0.00 0.00 0.00 C2H4 2.12 0.17 1.66 C3H8 1.25 0.07 0.99 C3H6 0.00 0.00 0.00 CoS 0.0000 0.000 0.00 CoS 0.0000 0.000 0.00 Cos 0.0000 0.000 0.000 Cos 0.0000 0.000 0.000 Cos 0.0000 0.000 0.000 Cos 0.0000 0.0040 0 Cos 0.0000 0.0040 0 Cos 0.0058 0.0006 0.0040 Cos 0 0 0 phenal 46 29 39 cresols 0 0 0 "teatar'(H2		33.74		:	50.46		39.15			49.91	
CO2 19.93 23.64 23.45 CH4 12.59 4.62 11.06 N2 0.00 0.00 0.00 He (tracer) 1.86 1.07 1.69 C2H6 0.00 0.00 0.00 C2H4 2.12 0.17 1.66 C2H2 0.01 0.00 0.00 C3H8 1.25 0.07 0.99 C3H6 0.00 0.00 0.00 1-C4H8 0.00 0.00 0.00 2-cis-C4H8 0.02 0.00 0.00 COS 0.0000 0.0000 0.0291 H2S 0.0058 0.0006 0.040 Closure 95.99 92.21 96.42 toluene 393 0 326 phenol 46 29 39 cresols 0 0 0 naphthalene 2383 442 1834 phenonthrene 792 0 535 "total tar' (minus 78) 718 72 5250 52	CO		24.45			12.18		18.37			13 95	
CH4 12.59 4.62 11.06 N2 0.00 0.00 0.00 N2 0.00 0.00 0.00 N2 0.00 0.00 0.00 C2H6 0.00 0.00 0.00 C2H4 2.12 0.17 1.66 C2H2 0.01 0.00 0.03 C3H6 0.00 0.00 0.00 C3H6 0.00 0.00 0.00 C4H4 2.5 0.07 0.99 C3H6 0.00 0.00 0.00 C4H8 0.00 0.00 0.00 2-cis-C4H8 0.02 0.00 0.00 COS 0.0000 0.0000 0.000 Cos 0.0000 0.0000 0.000 Cos 0.0000 0.000 0.000 phenol 46 29 39 cresols 0 0 0 Tear (mg/Nm3-wet) reformer or finitial conv.* sample time (min) maphthalene 728 72 520 52 <td>CO2</td> <td></td> <td>19.93</td> <td></td> <td>:</td> <td>23.64</td> <td></td> <td>23.45</td> <td></td> <td></td> <td></td> <td></td>	CO2		19.93		:	23.64		23.45				
N2 0.00 0.00 0.00 0.00 He (tracer) 1.86 1.07 1.69 Detailed gas and tar analyses are used to estimate 0.00 C2H4 2.12 0.17 1.66 tar analyses are used to estimate 0.00 0.00 C3H6 0.00 0.00 0.00 0.00 0.00 tar analyses are used to estimate 0.01 C3H6 0.00 0.00 0.00 0.00 0.00 0.00 1.64H8 0.00 0.00 0.00 0.00 2.32 2.33 2-cis-C4H8 0.00 0.000 0.000 0.0291 gas composition, and percent conversions of components during reformer in reformer or (initial) reformer in conversions of components during reforming Closure 95.99 9.2.21 96.42 0 0 toluene 393 0 326 0 0 0 naphthalene 2383 42 1834 0 0 52 "theat tar' (ninus 78) 7188 72 5250 52 52 "total tar' (ninus 78) 1417 0 824 0 52	CH4		12.59			4.62		11.06				
He (tracer) 1.86 1.07 1.69 C2H6 0.00 0.00 0.00 C2H4 2.12 0.17 1.66 C2H2 0.01 0.00 0.03 C3H8 1.25 0.07 0.99 C3H6 0.00 0.00 0.00 1-C4H8 0.00 0.00 0.00 2-cis-C4H8 0.02 0.00 0.00 COS 0.0000 0.000 0.0291 H2S 0.0058 0.0000 0.0040 Closure 95.99 92.21 96.42 Column reformer in reformer out (initial) reformer in conversions of conversions of conversions of tar (mg/Nm3-wet) reformer out (initial) reformer in reformer out benzene 7785 280 6874 during reforming benzene 792 0 535 0 0 othertar" (as 128) 2157 0 1691 0 52 intital conv.* sample time (min) sample time (min) 52 <td>N2</td> <td></td> <td>0.00</td> <td></td> <td></td> <td>0.00</td> <td></td> <td>0.00</td> <td></td> <td></td> <td></td> <td></td>	N2		0.00			0.00		0.00				
C2H6 0.00 0.00 0.00 0.00 C2H4 2.12 0.17 1.66 tar analyses are C2H2 0.01 0.00 0.03 used to estimate C3H8 1.25 0.07 0.99 used to estimate C3H6 0.00 0.00 0.00 0.00 2-cis-C4H8 0.00 0.00 0.00 0.00 2-cis-C4H8 0.00 0.000 0.000 0.000 2-cis-C4H8 0.00 0.000 0.000 0.000 COS 0.0000 0.0006 0.0040 gas composition, and percent Closure 95.99 92.21 96.42 conversions of tar (mg/Nm3-wet) reformer out (initial) reformer in reformer out (initial) reformer out (initial) phenol 46 29 39 other is tag other is tag phenol 46 29 39 other is tag other is tag "totat tar" (as 178) 718 72 5250 <td< td=""><td>He (tracer)</td><td></td><td>1.86</td><td></td><td></td><td>1.07</td><td></td><td>1.69</td><td></td><td></td><td>_</td><td></td></td<>	He (tracer)		1.86			1.07		1.69			_	
C2H4 2.12 0.17 1.66 tar analyses are C2H2 0.01 0.00 0.03 used to estimate C3H6 0.00 0.00 0.00 0.00 C3H6 0.00 0.00 0.00 0.00 1-C4H8 0.00 0.00 0.00 0.00 2-cis-C4H8 0.00 0.000 0.00 gas composition, CSS 0.0000 0.0000 0.0291 and percent CSore 0.0058 0.0006 0.0040 and percent Closure 95.99 92.21 96.42 conversions of tar (mg/Nm3-wet) reformer in reformer out (initial) reformer in reformer in conversions of conversions of tatring reforming 0 0 0 0 0 0 oluene 393 0 326 0 0 0 phenalthrene 792 0 535 52 52 ''total tar'' (as 178) 1417 0 824 0 52 ''total tar'' (as 178) 1417 0 824	C2H6		0.00			0.00		0.00				Detailed gas and
C2H2 0.01 0.00 0.03 tar analyses are C3H6 1.25 0.07 0.99 used to estimate C3H6 0.00 0.00 0.00 0.00 1-C4H8 0.00 0.00 0.00 0.00 2-cis-C4H8 0.02 0.00 0.00 0.00 2-trans-C4H8 0.02 0.00 0.00 0.00 COS 0.0000 0.000 0.0291 and percent Cos 0.0000 0.0006 0.0040 and percent Cos 0.0058 0.0026 6874 toluene 393 0 326 phenol 46 29 39 cresols 0 0 0 mapthtalene 722 0 52 'toter tar' (as 128) 2157 0 1691 0 'total tar' (minus 78) 7188 72 5250 'total tar' (minus 78) 1837 97.8% 9 <tr< td=""><td>C2H4</td><td></td><td>2.12</td><td></td><td></td><td>0.17</td><td></td><td>1.66</td><td></td><td></td><td>•</td><td>tar analyses are</td></tr<>	C2H4		2.12			0.17		1.66			•	tar analyses are
C3H8 1.25 0.07 0.99 Used to estimate C3H6 0.00 0.00 0.00 both initial and 1-C4H8 0.00 0.00 0.00 efformed product 2-cis-C4H8 0.02 0.00 0.00 gas composition, 2-trans-C4H8 0.02 0.00 0.000 gas composition, COS 0.0000 0.0000 0.0001 gas composition, COS 0.0058 0.0006 0.0040 conversions of Cosure 95.99 92.21 96.42 conversions of benzene 7785 280 6874 during reforming toluene 393 0 326 during reforming phenol 46 29 39 during reforming other tar" (as 128) 2157 0 1691 0 "totat tar" (minus 78) 7188 72 5250 52 thenauter benzene naphthalene methane methane InDe# initial conv.* sample time (min) sample time (min) T1107-12/07 2	C2H2		0.01			0.00		0.03				tal allaryses are
C3H6 0.00 0.00 0.00 0.00 0.00 1-C4H8 0.00 0.00 0.00 0.00 0.00 2-cis-C4H8 0.00 0.00 0.00 0.00 0.00 COS 0.0000 0.000 0.000 0.000 0.000 0.000 COS 0.0000 0.0000 0.0040 0.001 and percent Cosure 95.99 92.21 96.42 conversions of conversions of tar (mg/Nm3-wet) reformer in reformer out (initial) reformer in reforming benzene 7785 280 6874 during reforming bluene 393 0 326 during reforming phenol 46 29 39 during reforming other tar" (as 128) 2157 0 1691 0 "heavy tar" (as 178) 1417 0 824 0 "total tar" (minus 78) 7188 72 5250 52 "total tar" (minus 78) 150.3% 95.6% 97.3% 9 S:B=2 50.0%	C3H8		1.25			0.07		0.99			ι	used to estimate
1-C4H8 0.00 0.00 0.00 0.00 reformed product 2-cis-C4H8 0.02 0.00 0.00 0.00 reformed product 2-trans-C4H8 0.02 0.000 0.000 0.02 gas composition, COS 0.0006 0.0040 0.02 and percent conversions of Closure 95.99 92.21 96.42 conversions of components tar (mg/Nm3-wet) reformer out (initial) reformer or components during reforming toluene 393 0 326 o o o phenol 46 29 39 o o o resols 0 0 0 o o o wheavy tar" (as 128) 2157 0 1891 o o "total tar" (minus 78) 7188 72 5250 52 52 total tar" (minus 78) 150.3% 95.6% 97.3% 9 8 S:B=2 56.0% 95.6% 97.3% 8 8 S:B=2 50 </td <td>C3H6</td> <td></td> <td>0.00</td> <td></td> <td></td> <td>0.00</td> <td></td> <td>0.00</td> <td></td> <td></td> <td></td> <td>both initial and</td>	C3H6		0.00			0.00		0.00				both initial and
2-cis-C4H8 0.00 0.00 0.00 0.00 2-trans-C4H8 0.02 0.00 0.00 0.00 COS 0.0000 0.0000 0.0040 and percent Closure 95.99 92.21 96.42 conversions of tar (mg/Nm3-wet) reformer in reformer out (initial) reformer in reformer in conversions of benzene 7785 280 6874 during reforming oluene 393 0 326 otherautic (antital) conversions of phenol 46 29 39 otherautic (antital) conversions otherautic (antital) other tar" (as 128) 2157 0 1691 0 otherautic (antital conv.* sample time (min) "total tar" (minus 78) 7188 72 5250 52 52 total tar" (minus 78) 1 50.3% 97.8% 9 9 S:B=2 56.0% 95.6% 97.3% 8 8 5 S:B=2	1-C4H8		0.00			0.00		0.00				
2-trans-C4H8 0.02 0.00 0.00 0.00 COS 0.0000 0.0000 0.0291 and percent H2S 0.0058 0.0006 0.0040 conversions of Cosure 95.99 92.21 96.42 conversions of tar (mg/Nm3-wet) reformer in reformer out (initial) reformer in reformer in reformer out (initial) reformer in reformer of conversions of benzene 7785 280 6874 during reforming other and the conversions 0 326 393 0 326 phenol 46 29 39 39 0 6874 other anthrene 792 0 535 0 0 0 "heavy tar" (as 128) 2157 0 1691 0 0 0 "total tar" (minus 78) 7188 72 5250 52 52 Methane benzene naphthalene methane 97.8% 9 8 S	2-cis-C4H8		0.00			0.00		0.00			r	eformed product
COS 0.0000 0.0000 0.0291 gate components, and percent H2S 0.0058 0.0006 0.0040 and percent Closure 95.99 92.21 96.42 conversions of tar (mg/Nm3-wet) reformer in reformer out (initial) reformer in reformer out (initial) conversions of conversions of toluene 393 0 326 0	2-trans-C4H8		0.02			0.00		0.00			C	las composition
H2S 0.0058 0.0006 0.0040 and percent Closure 95.99 92.21 96.42 conversions of tar (mg/Nm3-wet) reformer in reformer out (initial) reformer out (initial) <t< td=""><td>COS</td><td></td><td>0.0000</td><td></td><td>0.</td><td>.0000</td><td></td><td>0.0291</td><td></td><td></td><td>3</td><td></td></t<>	COS		0.0000		0.	.0000		0.0291			3	
Closure 95.99 92.21 96.42 conversions of components during reformers during reforming tar (mg/Nm3-wet) reformer in 7785 280 6874 conversions of components during reforming benzene 7785 280 6874 conversions of components benzene 7785 280 6874 conversions of components benzene 393 0 326 phenol 46 29 39 cresols 0 0 0 naphthalene 2383 42 1834 phenonthrene 792 0 1691 0 "total tar" (as 128) 2157 0 1691 0 "total tar" (minus 78) 7188 72 5250 52 total tar" (minus 78) 70.3% 97.3% 9 9 11/07-12/07 2 56.0% 97.3% 9 S:B=2 R500=700 I 56.0% 97.3% 8 S:B=2 R500=700 I 56.0% 97.3%	H2S		0.0058		0.	.0006		0.0040				and percent
tar (mg/Nm3-wet) reformer in reformer out (initial) reformer in reformer of components benzene 7785 280 6874 Components toluene 393 0 326 during reforming phenol 46 29 39 during reforming cresols 0 0 0 0 naphthalene 2383 42 1834 phenanthrene 792 0 535 "other tar" (as 128) 2157 0 1691 0 "heavy tar" (as 178) 1417 0 824 0 "total tar" (minus 78) 7188 72 5250 52 total tar" (minus 78) 7188 72 5250 52 total tar" (minus 78) 7188 97.3% 9 9 11/07-12/07 2 56.0% 97.3% 9 8 S:B=2 8 9 66.0% 97.3% 8 8 S:B=2 9 9 <t< td=""><td>Closure</td><td></td><td>95.99</td><td></td><td>9</td><td>92.21</td><td></td><td>96.42</td><td></td><td></td><td></td><td>conversions of</td></t<>	Closure		95.99		9	92.21		96.42				conversions of
tar (mg/Nm3-wet) reformer in reformer out (initial) reformer in reformer or Components benzene 7785 280 6874 during reforming toluene 393 0 326 during reforming phenol 46 29 39 during reforming cresols 0 0 0 network phenanthrene 792 0 535 network "other tar" (as 128) 2157 0 1691 0 "heavy tar" (as 178) 1417 0 824 0 "total tar" (minus 78) 7188 72 5250 52 total tar" (minus 78) 7188 72 5250 52 total tar" (minus 78) 7188 97.8% 9 9 11/07-12/07 2 56.0% 97.3% 9 S:B=2 R500=700 I I I I I I I I I I I I I I <td></td>												
benzene 7785 280 6874 toluene 393 0 326 phenol 46 29 39 cresols 0 0 0 naphthalene 2383 42 1834 phenanthrene 792 0 535 "other tar" (as 128) 2157 0 1691 0 "theavy tar" (as 178) 1417 0 824 0 "total tar" (minus 78) 7188 72 5250 52 Methane benzene naphthalene methane benzene methane methane NDE# 50.3% 95.6% 97.8% 9 9 11/07-12/07 2 56.0% 95.6% 97.3% 8 S:B=2 SE Keine Reservalue Reser	tar (mg/Nm3-wet)	refo	ormer in	refo	ormer out (i	nitial)	refo	ormer in	r	eformer d		components
toluene 393 0 326 phenol 46 29 39 cresols 0 0 0 naphthalene 2383 42 1834 phenanthrene 792 0 535 "other tar" (as 128) 2157 0 1691 0 "theavy tar" (as 178) 1417 0 824 0 "total tar" (minus 78) 7188 72 5250 52 methane benzene naphthalene methane 0K_NREL32b 1 50.3% 95.4% 97.8% 9 11/07-12/07 2 56.0% 95.6% 97.3% 8 S:B=2 R500=700 I	benzene		7785			280		6874			C	lurina reformina
phenol 46 29 39 cresols 0 0 0 naphthalene 2383 42 1834 phenanthrene 792 0 535 "other tar" (as 128) 2157 0 1691 0 "heavy tar" (as 178) 1417 0 824 0 "total tar" (minus 78) 7188 72 5250 52 initial conv.* sample time (min) 52 InDe# methane benzene naphthalene methane OK_NREL32b 1 50.3% 95.4% 97.8% 9 11/07-12/07 2 56.0% 97.3% 8 53 S:B=2 85.00=700 8 9 1 1 1 R500=700 700 70 1 7 1 7 1	toluene		393			0		326			-	
Cresols 0 0 0 naphthalene 2383 42 1834 phenanthrene 792 0 535 "other tar" (as 128) 2157 0 1691 0 "heavy tar" (as 178) 1417 0 824 0 "total tar" (minus 78) 7188 72 5250 52 Methane benzene naphthalene methane methane OK_NREL32b 1 50.3% 95.4% 97.8% 9 11/07-12/07 2 56.0% 97.3% 8 8 S:B=2 R500=700 1 1 1 1 7C=950 1 1 1 1 1 1	phenol		46			29		39				
naphthalene 2383 42 1834 phenanthrene 792 0 535 "other tar" (as 128) 2157 0 1691 0 "heavy tar" (as 178) 1417 0 824 0 "total tar" (minus 78) 7188 72 5250 52 "total tar" (minus 78) 7188 72 5250 52 Methane benzene naphthalene methane 52 Methane benzene naphthalene methane 9 0K_NREL32b 1 50.3% 95.4% 97.8% 9 11/07-12/07 2 56.0% 95.6% 97.3% 8 S:B=2 F500=700 F500 F500 F500 F500 F500 TC=950 F500 F500 F500 F500 F500 F500 F500 F500 F500	cresols		0			0		0				
phenanthrene 792 0 535 "other tar" (as 128) 2157 0 1691 0 "heavy tar" (as 178) 1417 0 824 0 "total tar" (minus 78) 7188 72 5250 52 InDe# methane benzene naphthalene methane OK_NREL32b 1 50.3% 95.4% 97.8% 9 11/07-12/07 2 56.0% 95.6% 97.3% 8 S:B=2 R500=700	naphthalene		2383			42		1834				
"other tar" (as 128) 2157 0 1691 0 "heavy tar" (as 178) 1417 0 824 0 "total tar" (minus 78) 7188 72 5250 52 InDe# methane benzene naphthalene methane OK_NREL32b 1 50.3% 95.4% 97.8% 9 11/07-12/07 2 56.0% 95.6% 97.3% 8 S:B=2 850=700 56.0% 95.6% 97.3% 8 R500=700 6 6 6 6 6 TC=950 6 6 6 6 6	phenanthrene		792			0		535		L		
"heavy tar" (as 178) 1417 0 824 0 "total tar" (minus 78) 7188 72 5250 52 InDe# initial conv.* sample time (min) methane benzene naphthalene methane OK_NREL32b 1 50.3% 95.4% 97.8% 9 11/07-12/07 2 56.0% 95.6% 97.3% 8 S:B=2 8500=700 95.6% 97.3% 8 8 R500=700 95.6% 97.3% 8 8 9 DCC=950 95.6% 97.3% 9 9 Data 9 9 9 9 9 Data 9 9 9 9 9 1000000000000000000000000000000000000	"other tar" (as 128)		2157			0		1691			0	
"total tar" (minus 78) 7188 72 5250 52 InDe# initial conv.* sample time (min) methane benzene naphthalene methane OK_NREL32b 1 50.3% 95.4% 97.8% 9 11/07-12/07 2 56.0% 95.6% 97.3% 8 S:B=2 55.0% 95.6% 97.3% 8 8 R500=700 7C=950 1000000000000000000000000000000000000	"heavy tar" (as 178)		1417			0		824			0	
initial conv.* sample time (min) InDe# methane benzene naphthalene OK_NREL32b 1 50.3% 95.4% 97.8% 9 11/07-12/07 2 56.0% 95.6% 97.3% 8 S:B=2 8500=700 7C=950 1000000000000000000000000000000000000	"total tar" (minus 78)		7188			72		5250			52	
InDe# methane benzene naphthalene methane OK_NREL32b 1 50.3% 95.4% 97.8% 9 11/07-12/07 2 56.0% 95.6% 97.3% 8 S:B=2 8 56.0% 95.6% 97.3% 8 R500=700 7C=950 9 9 9 9					initial conv	V.*		sam	ple 1	time (min))	•
OK_NREL32b 1 50.3% 95.4% 97.8% 9 11/07-12/07 2 56.0% 95.6% 97.3% 8 S:B=2 8 9		InDe#	metha	ine	benzene	na	phthalene	•	met	hane		
11/07-12/07 2 56.0% 95.6% 97.3% 8 S:B=2 R500=700 TC=950 Notional Resource to be reproved a beratery	OK_NREL32b	1	50	.3%	95.4%	6	97.8	%		Q	9	
S:B=2 R500=700 TC=950	11/07-12/07	2	56	.0%	95.6%	6	97.3	%		8	8	
R500=700 TC=950	S:B=2	_			, ,							
	R500=700											
	TC=950											
	Benn-000										L Nation	al Renewable Energy Laboratory

Updated Gasifier Correlations

- Current correlation based on 1980s data with yield only a function of temperature
 - Bain, R.L. (1992). "Material and energy balances for methanol from biomass using biomass gasifiers," 136 pp, NREL Report No. TP-510-17098.
- Updated correlation to predict more components and tars in the product gas.
- Updated correlation to consider the feed composition and additional process variables.
- Updated correlation to use original data and recent data from the NREL TCPDU for corn stover, switchgrass, wheat straw, Vermont wood, and oak (H₂).
- Data are analyzed and regression analysis conducted using Unscrambler software.



New Correlation: Significant Variables

- Ultimate Analysis
 - Moisture
- Ash
 - Carbon
 - Hydrogen
 - Oxygen
 - Nitrogen
 - Sulfur
 - Chlorine
- Process Variables
 - Thermal Cracker Temperature (TC)
 - Steam to Biomass Ratio (SB)
 - Thermal Cracker Residence Time (RT)

 $Y = B_{int} + X_{c}^{*}B_{c} + X_{H}^{*}B_{H} + X_{o}^{*}B_{o} + X_{N}^{*}B_{N} + X_{s}^{*}B_{s} + X_{Tc}^{*}B_{Tc} + X_{sB}^{*}B_{sB} + X_{RT}^{*}B_{RT} + S_{Tc}^{2*}B_{Tc}^{2} + S_{sB}^{2*}B_{sB}^{2} + S_{RT}^{2*}B_{RT}^{2} + I_{TC:SB}^{*}B_{TC:SB} + I_{TC:RT}^{*}B_{TC:RT} + I_{SB:RT}^{*}B_{SB:RT}$

– SB² – RT²

Squared Effects

– TC²

- Interaction Effects
 - TC*SB
 - TC*RT
 - SB*RT



Comparison of Current and New Correlations

Component	New R ²	Current R ²
1-Butene	0.88	
2-c-Butene	0.71	
2-t-Butene	0.71	
Carbon Dioxide	0.81	0.42
Carbon Monoxide	0.73	0.40
Ethane	0.72	0.85
Ethylene	0.96	0.88
Acetylene	0.96	0.72
Hydrogen	0.81	0.92
Methane	0.84	0.70
Propane	0.90	
Propene	0.95	
Hydrogen Sulfide	0.85	

Component	New R ²	Current R ²
Benzene	0.97	
Toluene	0.83	
Phenol	0.93	
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
NF Dry Gas Flowrate	0.98	0.94



Update of ASPEN and Economic Models



Objective: Update existing ASPEN model using updated gas yield composition correlations



Link to Model and Report:

http://devafdc.nrel.gov/biogeneral/Aspen_Models/



FY08 Future Work

- Data Generation
 - Parametric gasification testing with pine
 - Tar reformer testing (one condition, new catalyst)
 - Slip-stream syngas testing
 - H₂S removal (Sud Chemie proprietary sulfur getter)
 - High temperature shift (Sud Chemie proprietary shift catalyst)
 - Membrane separation (option)
- Process Modeling
 - Multivariate analysis incorporate pine data
 - ASPEN analysis
 - http://devafdc.nrel.gov/biogeneral/Aspen_Models
 - EXCEL process summaries
 - Comparison with 2005 ASPEN model
 - Spath, P.; Aden, A.; Eggeman, T.; Ringer, M.; Wallace, B.; Jechura, J. (2005). Biomass to Hydrogen Production Detailed Design and Economics Utilizing the Battelle Columbus Laboratory Indirectly-Heated Gasifier. 161 pp.; NREL Report No. TP-510-37408.
- Import Updated Model into H2A Model
- Go / No-Go Decision



Project Summary

Relevance:	Answer questions about 2012 (\$1.60 /gge) and 2017 (\$1.10 / gge) MYPP objectives for hydrogen produced from biomass gasification.
	Address efficency, capital intensity, and reforming barriers.
Approach:	A three phase approach is being used: 1) gasification, reforming, and shift reaction testing to produce a clean hydrogen-rich syngas, 2) material and energy balance modeling using updated gasifier correlation and ASPEN, and 3) updated H2A economic estimates
Technical Progress:	One gasifer / reformer campaign completed; initial update of gasifier correlation complete
Future Work:	Complete gasifier / reformer / shift reactor testing
	Complete technical modeling
	Complete H2A economics

