National Renewable Energy Laboratory
Innovation for Our Energy Future

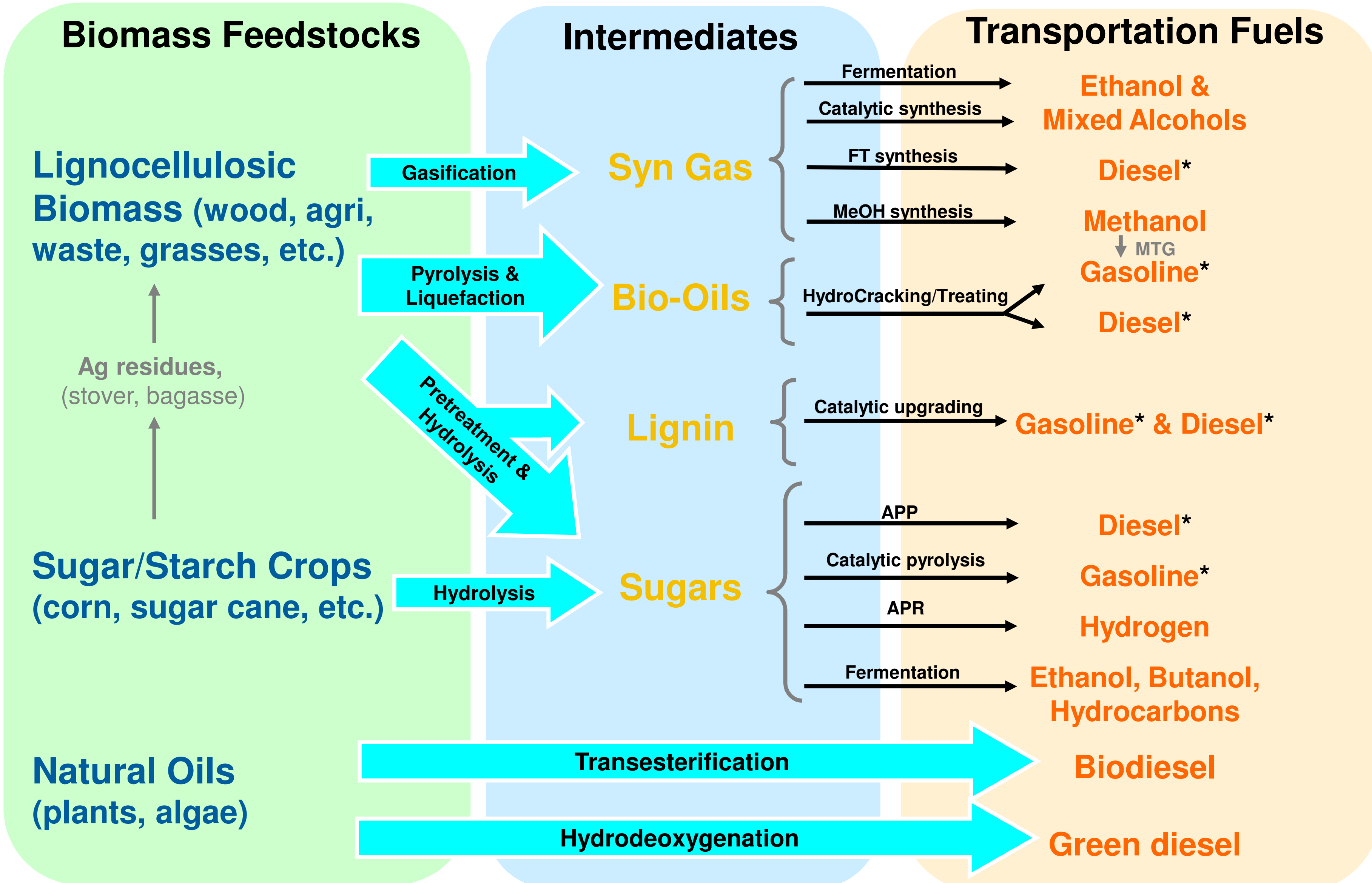
State of Technology (SOT) Assessment

Analysis Platform Peer Review

Andy Aden, PE

March 20, 2009

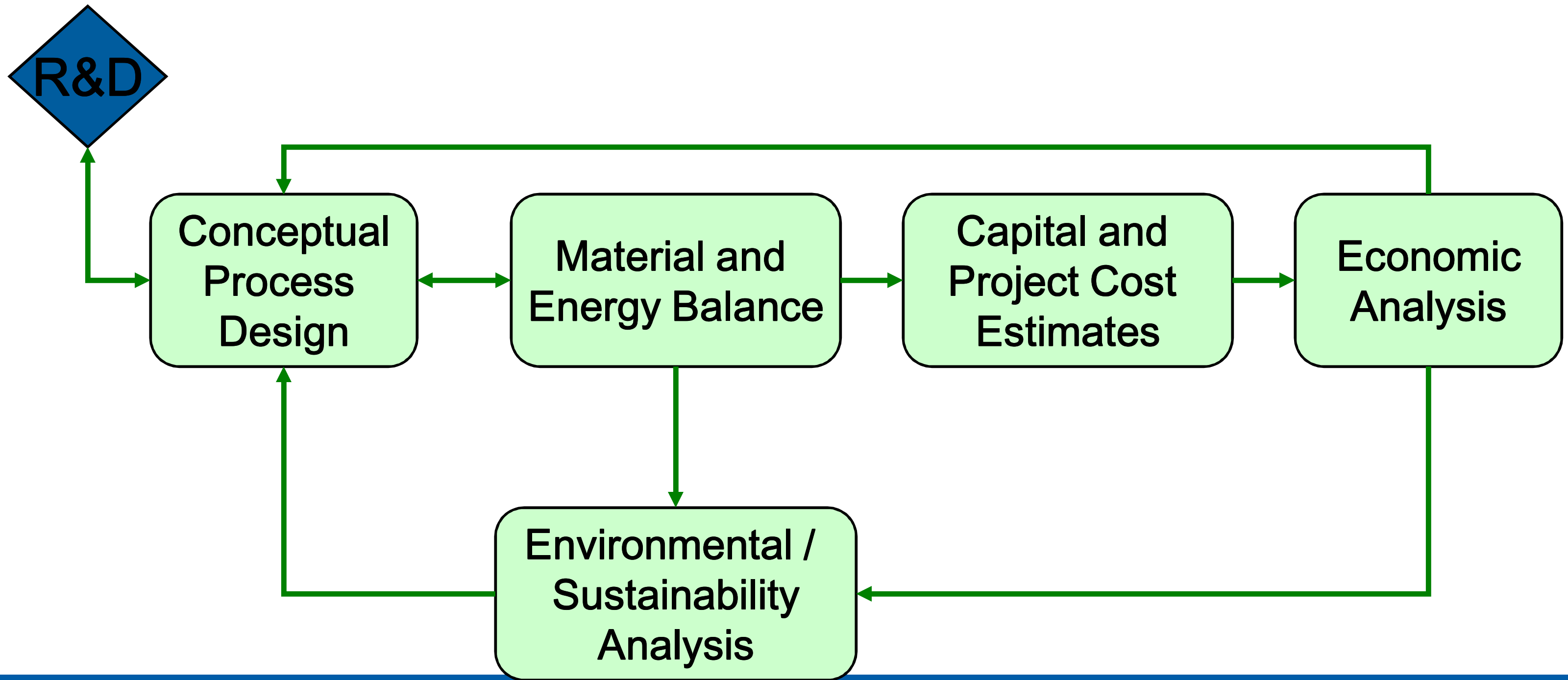
Biofuels Transportation Options



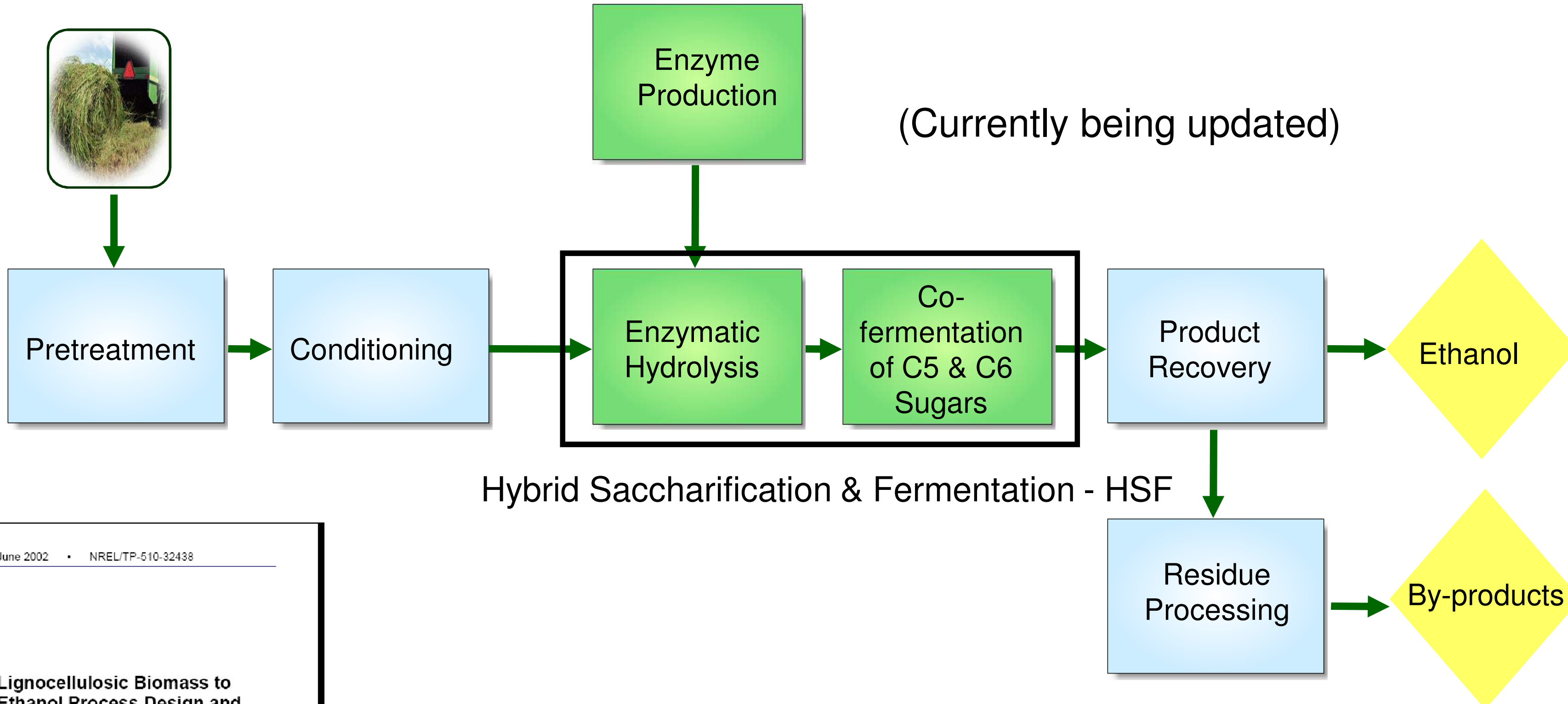
* Blending Products

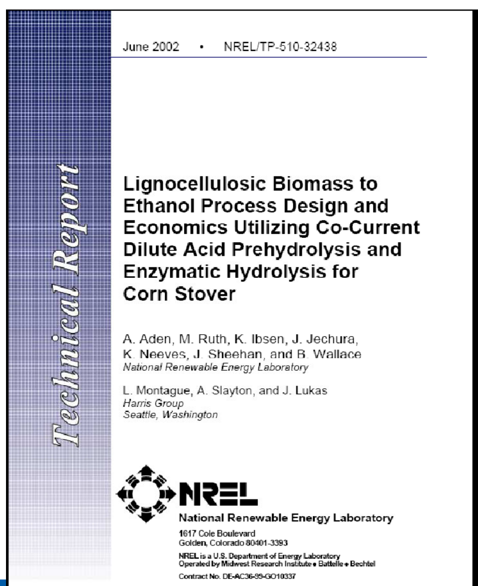
What is the State of Technology?

- Annual update of technoeconomic cost model parameters with data from actual laboratory and/or pilot scale experiments (Experimentally verified data is key!)
- Use published and peer-reviewed design reports and technoeconomic models as basis for tracking progress
- Used to demonstrate technical progress and translate into easy-to-understand economic progress towards the 2012 goal
- Used to guide both biochemical and thermochemical platforms



Biochemical Conceptual Design Report Drives R&D Direction





June 2002 • NREL/TP-510-32438

Technical Report

Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover

A. Aden, M. Ruth, K. Ibsen, J. Jechura, K. Neeves, J. Sheehan, and B. Wallace
National Renewable Energy Laboratory

L. Montague, A. Slayton, and J. Lukas
Harris Group
Seattle, Washington

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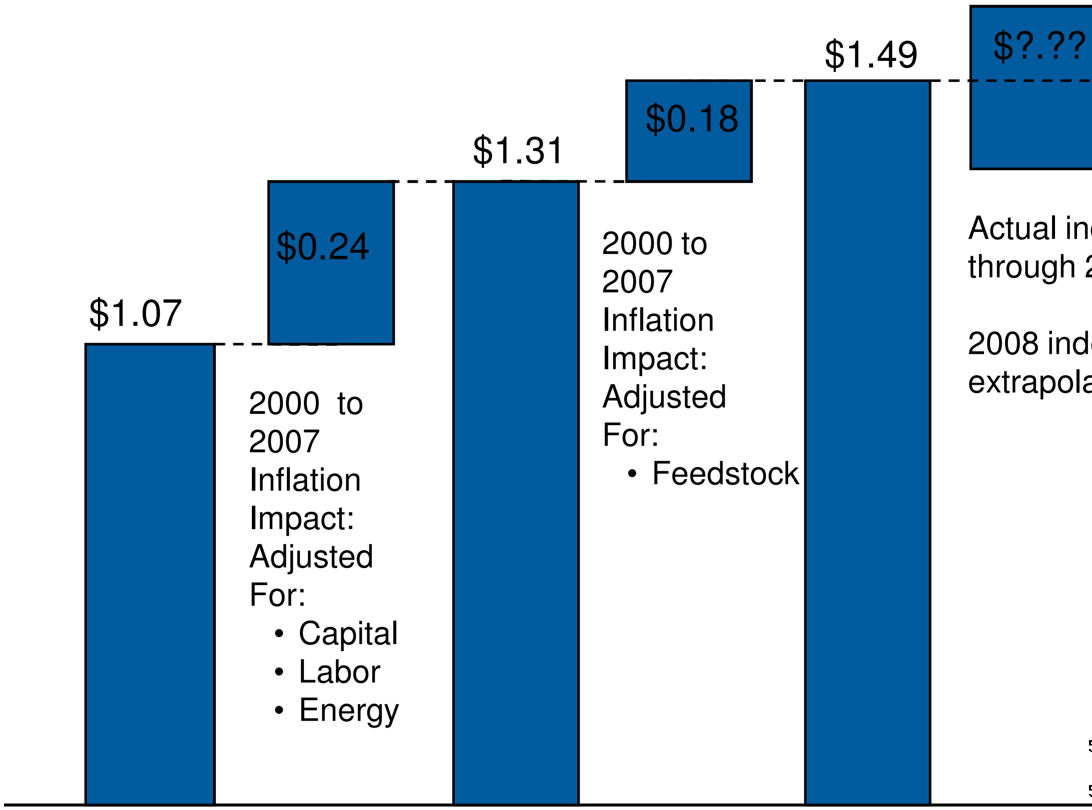
- **Conceptual design of a 2,000 tonnes/day commercial plant – one possible tech package, not optimized**
- **NREL pilot plant based on this process**
- **Basis for connecting R&D targets to cost targets**
- **Has undergone rigorous peer review**
- **Basis for comparison against other technology options**

Economic Indices are Updated



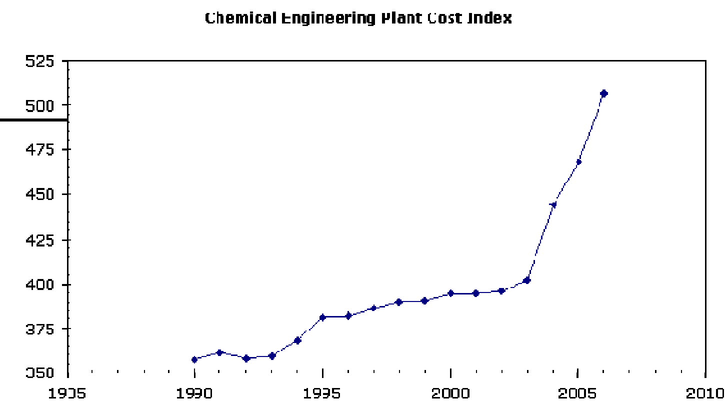
Actual indices through 2007.

2008 index is extrapolated

President's AEI Goal:
2000$ Real dollars
$35 feedstock
(Corn stover)

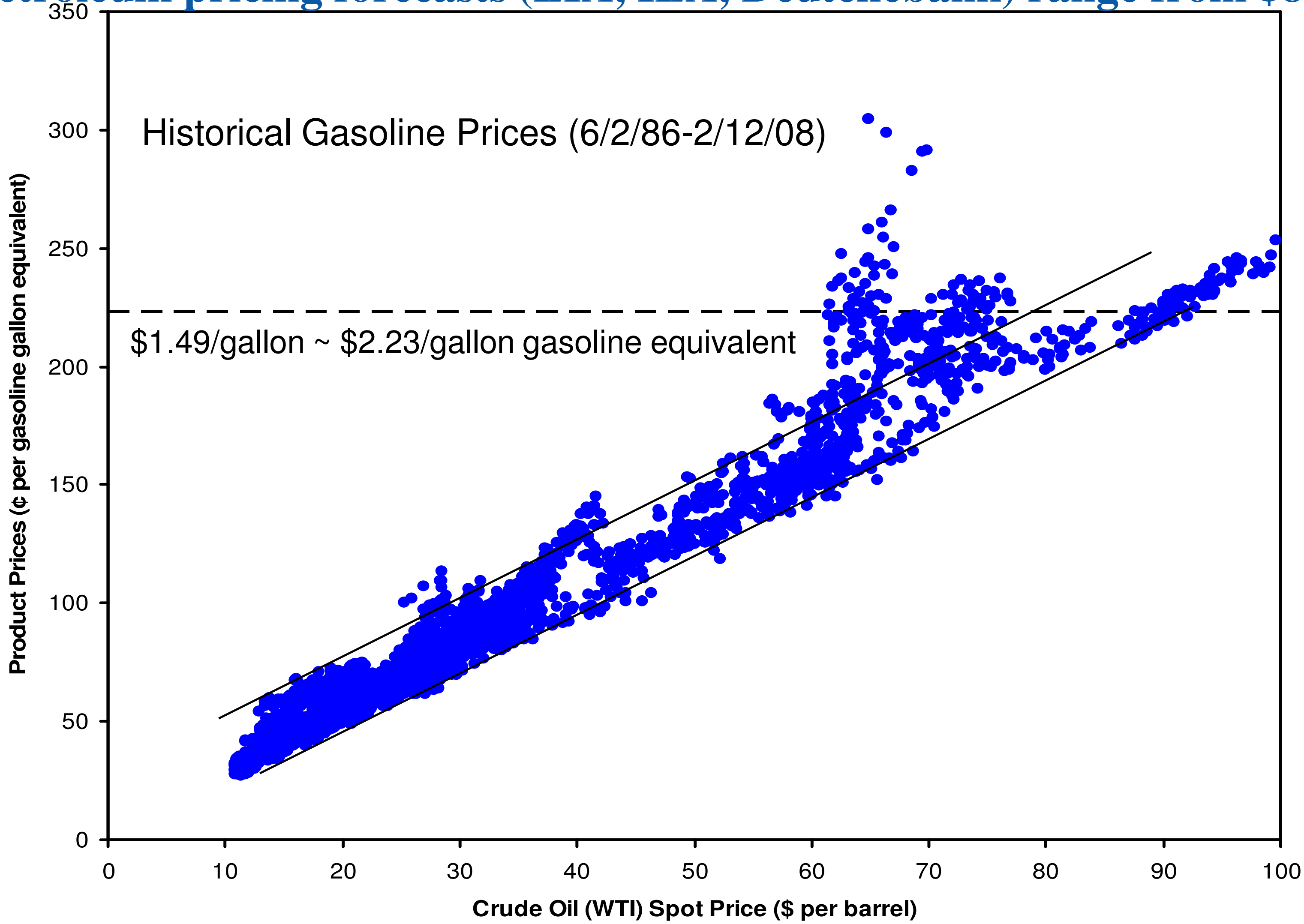
President's AEI Goal:
2007$ Real dollars
$35 feedstock
(Corn stover)

President's AEI Goal:
2007$ Real dollars
$51 feedstock
(Corn stover)

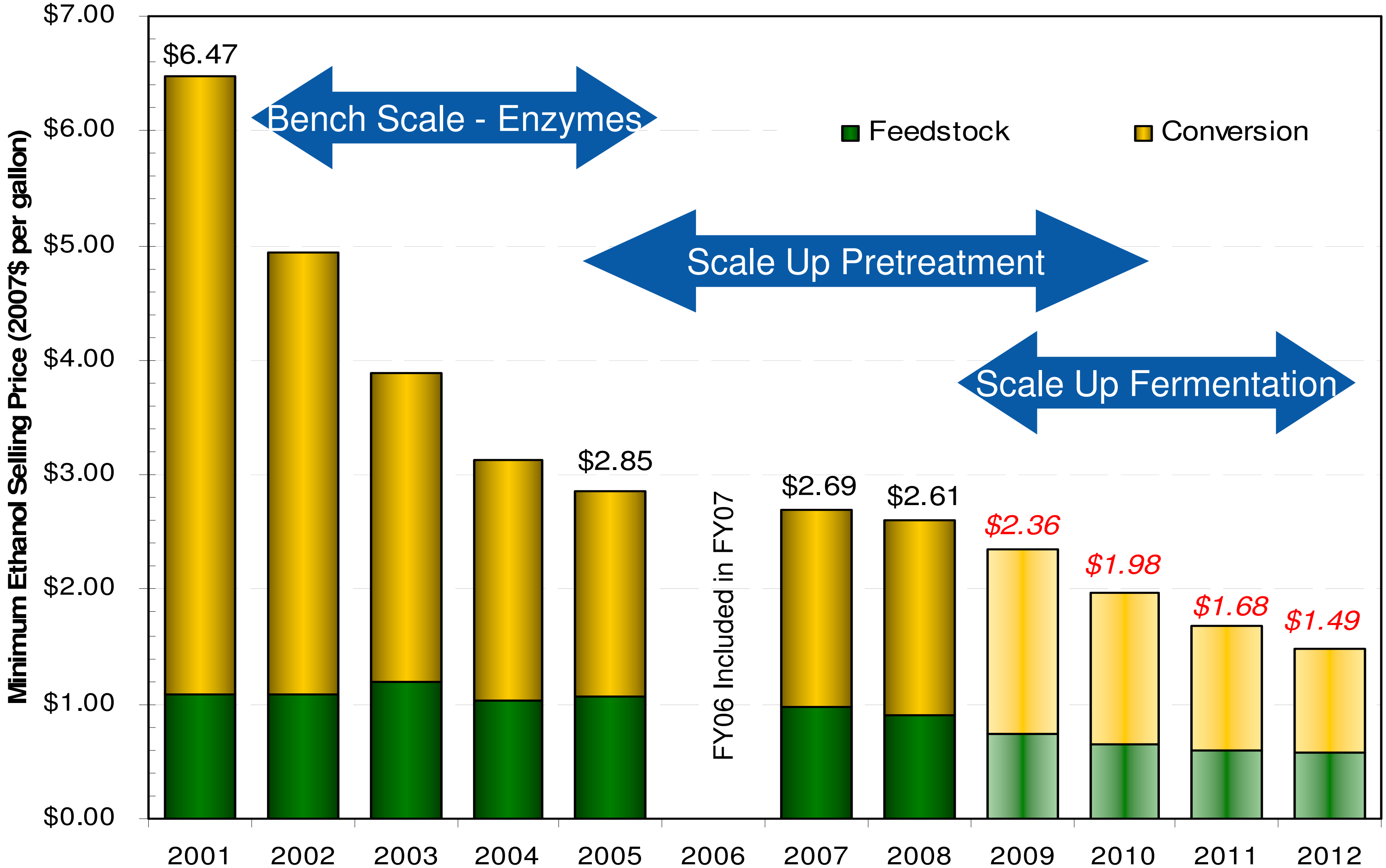


Cost Targets

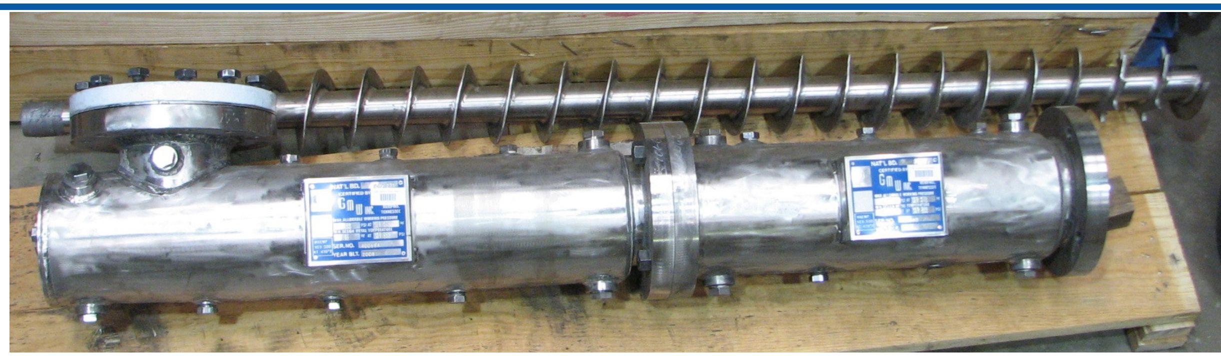
Targeting cost-competitiveness with petroleum for 2012
Petroleum pricing forecasts (EIA, IEA, Deutchebank) range from \$80-\$100/bbl



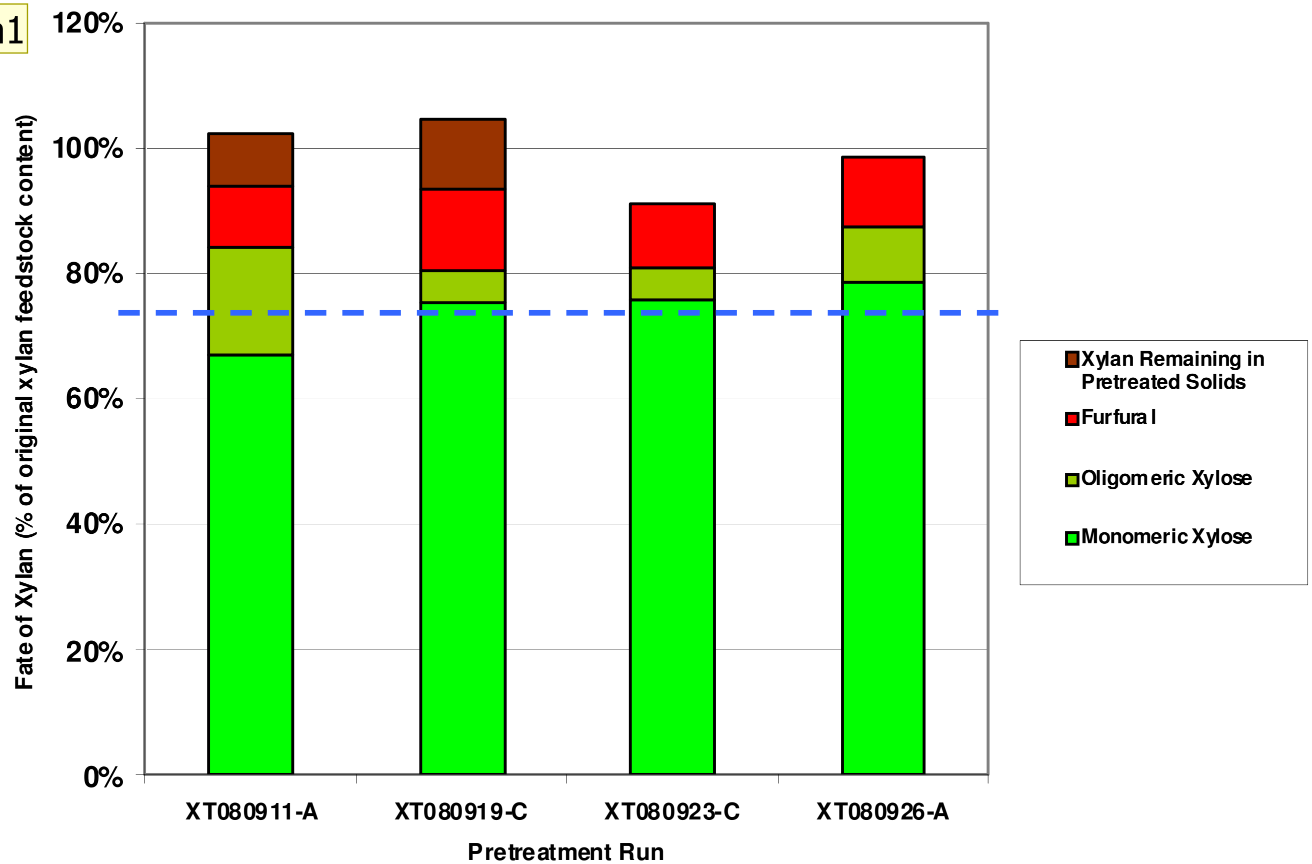
FY08 Biochemical State of Technology
(yr $2007 actual)



Biochemical Platform R&D Highlights



- Exceeded xylan conversion target of 75% in continuous reactor system at pilot scale at NREL
- Conditions
  - 20-30% total solids
  - 170-185°C
  - 2-6 minute residence time
- Additional yield possible from oligomers or unconverted xylan
- Engineering reactor system for better control of residence time distribution



Slide 8

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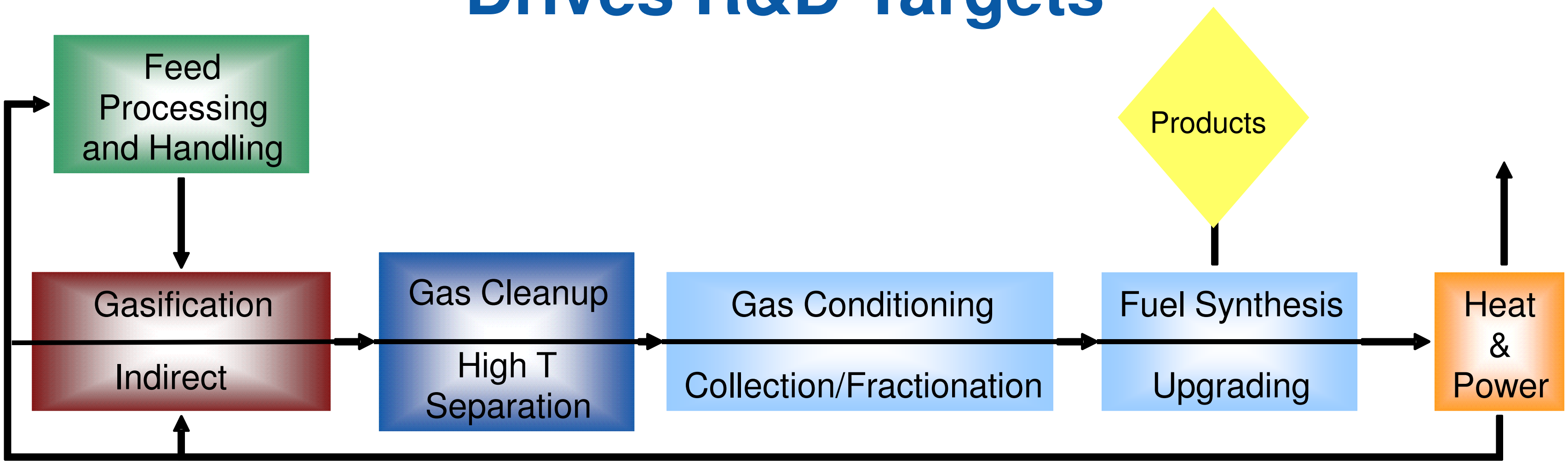
a1 aaden, 3/3/2009

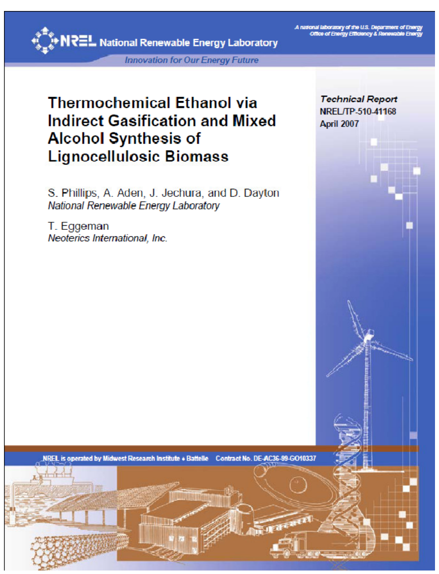
Technical Achievements Translate into Cost Savings

	2007 SOT	2008 SOT	2009	2010	2011	2012
Minimum Ethanol Selling Price	**$2.69**	**$2.61**	**$2.36**	**$1.98**	**$1.68**	**$1.49**
Feedstock Contribution ($/gal)	**$0.97**	**$0.90**	**$0.74**	**$0.65**	**$0.60**	**$0.57**
Conversion Contribution ($/gal)	**$1.72**	**$1.71**	**$1.62**	**$1.33**	**$1.08**	**$0.92**
Yield (Gallon/dry ton)	72	73	78	83	87	90
Technical Targets						
Feedstock						
Feedstock Cost ($/dry ton)	$69.60	$65.30	$57.50	$53.70	$52.00	$50.90
Pretreatment						
Solids Loading (wt%)	30%	30%	30%	30%	30%	30%
Xylan to Xylose	75%[a]	75%[b]	80%	85%	88%	90%
Xylan to Degradation Products	13%[a]	11%[b]	8%	6%	5%	5%
Conditioning						
Ammonia Loading (mL of 30wt% per L hydrolyzate)	50	50	50	50	35	25
Hydrolyzate solid-liquid separation	yes	yes	yes	yes	yes	no
Xylose Sugar Loss	2%	2%	2%	2%	1%	1%
Glucose Sugar Loss	1%	1%	1%	1%	1%	0%
Enzymes						
Enzyme Contribution ($/gal EtOH)	$0.35	$0.35	$0.35	$0.17	$0.12	$0.12
Saccharification & Fermentation						
Total Solids Loading (wt%)	20%	20%	20%	20%	20%	20%
Combined Saccharification & Fermentation Time (d)	7	7	7	5	3	3
Corn Steep Liquor Loading (wt%)	1%	1%	1%	1%	0.6%	0.25%
Overall Cellulose to Ethanol	85%	85%	85%	85%	85%	85%
Xylose to Ethanol	76%	80%	80%	80%	85%	85%
Minor Sugars to Ethanol	0%	0%	40%	80%	85%	85%

Thermochem Conceptual Design Report Drives R&D Targets



Indirect Gasification and Mixed Alcohol Synthesis


NREL National Renewable Energy Laboratory
Innovation for Our Energy Future

Thermochemical Ethanol via Indirect Gasification and Mixed Alcohol Synthesis of Lignocellulosic Biomass

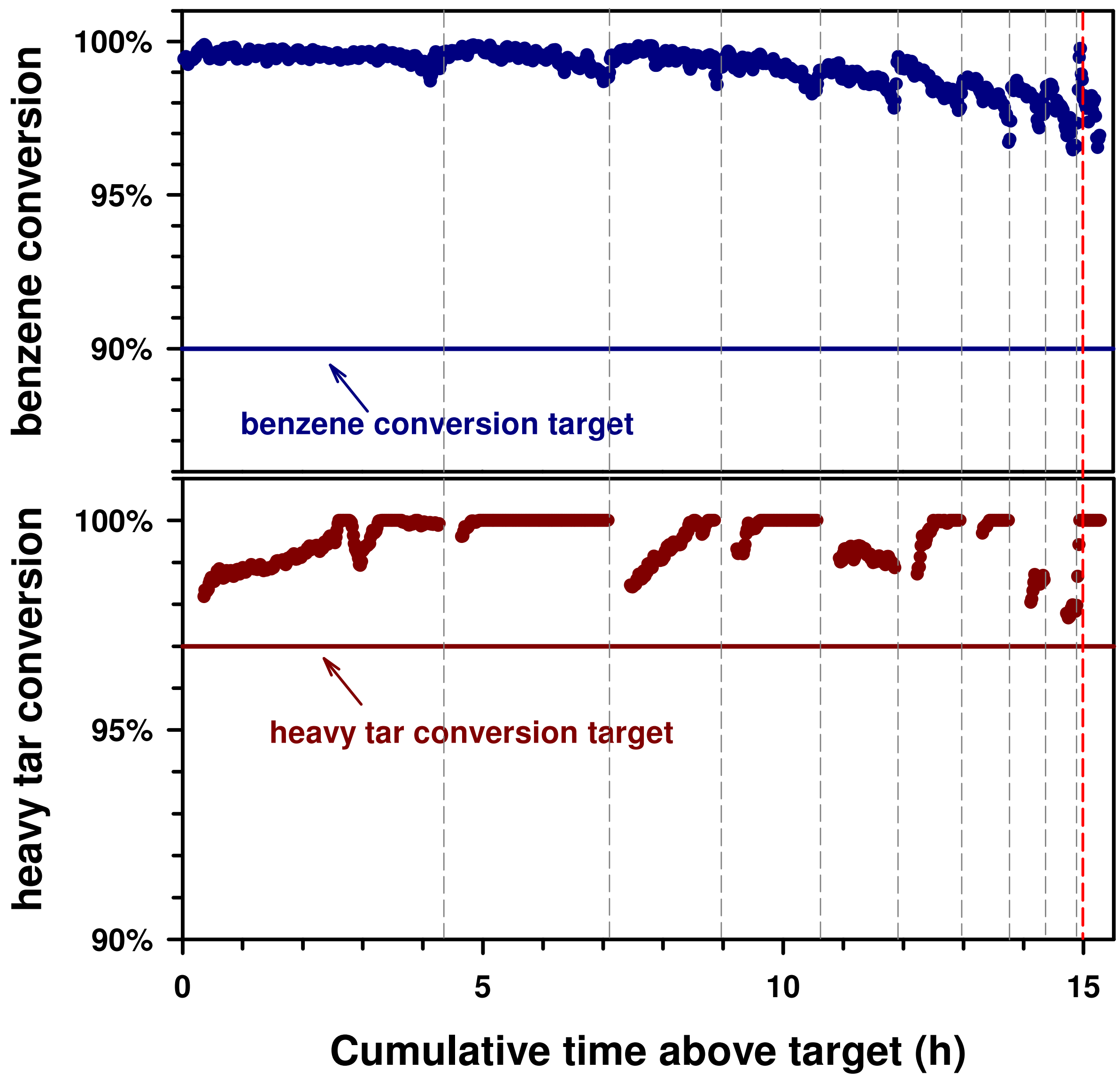
S. Phillips, A. Aden, J. Jechura, and D. Dayton
National Renewable Energy Laboratory

T. Eggeman
Neoterics International, Inc.

Technical Report
NREL/TP-510-41168
April 2007

- **Conceptual design of a 2000 tonnes/day commercial plant**
- **NREL pilot plant based on this process**
- **Basis for connecting R&D targets to cost targets**
- **Has undergone rigorous peer review**

Thermochemical Platform R&D Highlights



Tar Reforming:

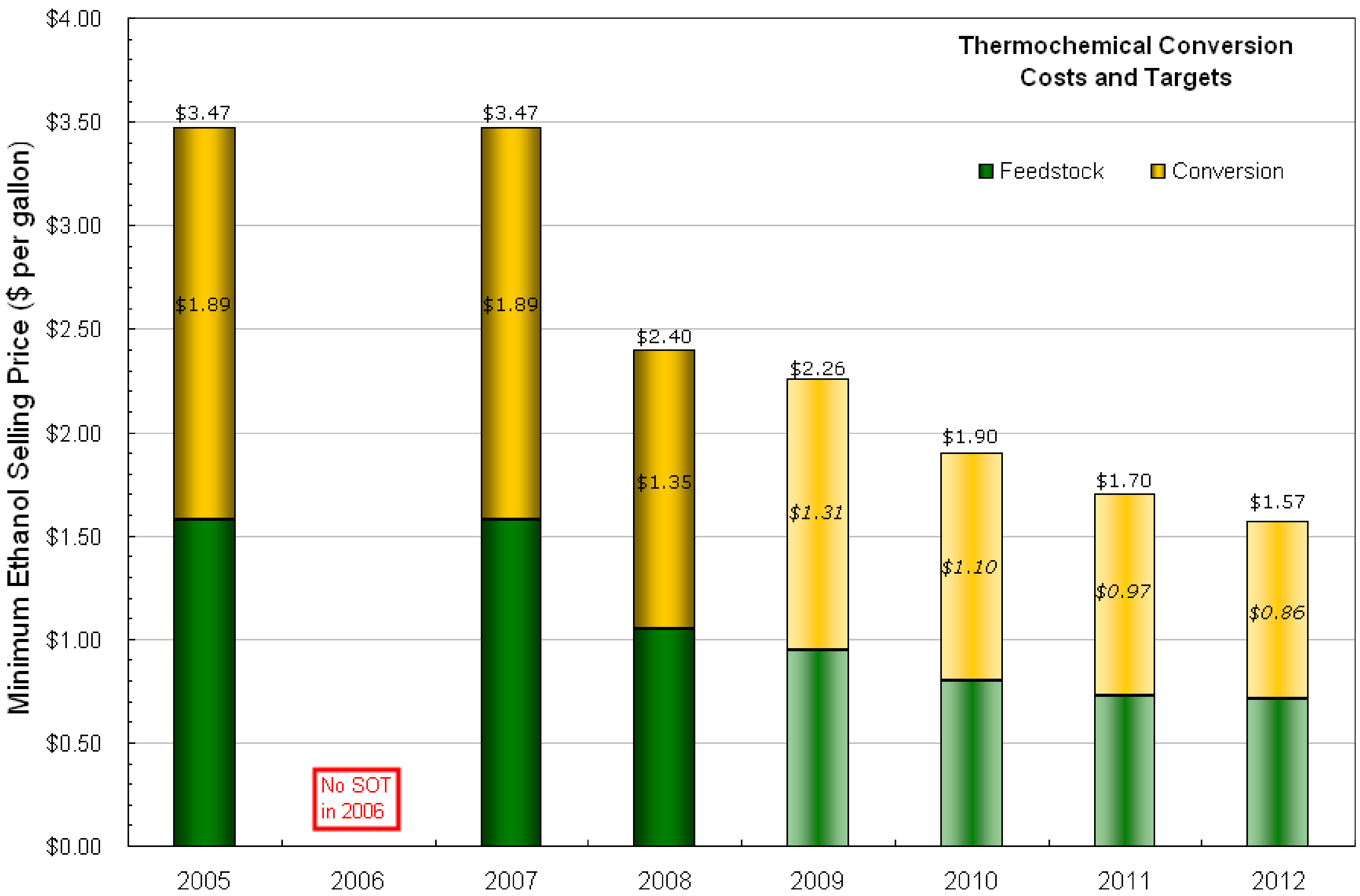
-15 hours cumulative time online at pilot scale

- 50% Methane conv.

- > 90% benzene conv.

- 97% tar conv.

FY08 Thermochemical State of Technology
(year-2007$ actual)



Thermochemical Path to 2012

Access to mixed alcohol catalysts are key for demonstration!

	2005	2006	2007	2008	2009	2010	2011	2012
Minimum Ethanol Selling Price ($/gal)	$3.47	no SOT Model	$3.47	$2.40	$2.26	$1.90	$1.70	$1.57
Conversion Cost ($/gallon ethanol)	$1.89	-	$1.89	$1.35	$1.31	$1.10	$0.97	$0.86
Installed capital cost ($/annual gal MA)	$4.91	-	$4.91	$3.42	$3.36	$2.95	$2.64	$2.64
Mixed Alcohol Yield (gal/dry ton)	50.3	-	50.3	71.3	72.5	79.6	83.7	83.7
Feedstock								
Feedstock cost ($/dry ton)	$67.55	-	$67.55	$63.50	$58.20	$54.20	$51.80	$50.70
Cleanup and Conditioning								
Tar reformer light HC reforming - % CH_4 conversion	20%	-	20%	50%	50%	80%	80%	80%
Tar reformer heavy HC reforming - %tar conversion	95%	-	97%	97%	97%	99%	99%	99%
Catalytic Fuel Synthesis								
Compression for fuel synthesis (psia)	2,000	-	2,000	2,000	1,500	1,500	1,500	1,500
Overall CO conversion	40%	-	40%	40%	40%	40%	50%	50%
CO selectivity to alcohols (CO_2- free basis)	80	-	80	80	80	80	80	80

Advanced Biofuels Matrix

Advanced fuels – beyond ethanol

- Other alcohols – butanol, isobutanol, mixed alcohols
- Other non-alcohol oxygenates – DME, DMF
- Hydrocarbon fuels – Fischer-Tropsch, hydrocarbons from fermentation (infrastructure-compatible), Methanol-To-Gasoline
- Plant and animal oils – algae

Hybrid Processes (not clearly biochemical or thermochemical)

- Syngas fermentation
- Aqueous phase reforming
- Ethanol via acid intermediates

Evaluation including

- State of technological maturity
- Technical challenges
- Companies pursuing
- Economics, source, level of detail/rigor

Detailed technoeconomic models don't exist for all advanced biofuels

NREL is evaluating what data does exist to assess what modeling needs are

Sustainability Challenges

Biomass to Biofuels System

Greenhouse Gas Emissions

Economic Prosperity
- Rural and urban communities
- Industry

Social Well-being

Biofuels and Biomass
- Supply infrastructure
- *Fuel production*
- Distribution and use

Land
- Use and change
- Competition with food
- Soil

Biodiversity

Water
- *Use*
- Quality
- *Efficiency of use*

Environmental Impacts

Increase Food and Energy Security

Summary

Platform analysis and the State of Technology assessments have demonstrated significant research progress in both platforms

Analysis will continue to quantify progress while working closely with researchers

Analysis plays a crucial role in guiding the platform R&D and clearly translating research results into cost reductions

Established SOT methodology is based in engineering and scientific rigor

Thank you to team members:

- NREL: Abhijit Dutta, David Hsu, David Humbird, Ling Tao
- INL: Richard Hess, Chris Wright, Jake Jacobson, Gary Gresham
- ORNL: Bob Perlack
- PNNL: Don Stevens, Sue Jones, Rick Orth
- DOE: Valerie Sarisky-Reed, Zia Haq, Paul Grabowski, Leslie Pezzullo

Publications and Presentations

Aden, A. (2007) "Biochemical Production of Ethanol from Corn Stover: 2007 State of Technology Model", NREL Technical Report NREL/TP-510-43205, May 2008. http://www.nrel.gov/docs/fy08osti/43205.pdf

Biochem design report: Aden, A, et.al. (2002) "Lignocellulosic Biomass to Ethanol Process Design and Economics Utilizing Co-Current Dilute Acid Prehydrolysis and Enzymatic Hydrolysis for Corn Stover", NREL Technical Report NREL/TP-510-32438, June 2002. http://www.nrel.gov/docs/fy02osti/32438.pdf

Thermochem design report: Phillips, S., et.al. (2007) "Thermochemical Ethanol via Indirect Gasification and Mixed Alcohol Synthesis of Lignocellulosic Biomass", NREL Technical Report NREL/TP-510-41168, April 2007. http://www.nrel.gov/docs/fy07osti/41168.pdf

Future Work

For the near term 2012 goal:

- In FY09, incorporate R&D achievements from the broader R&D community (industry, academia)
- SOT process being applied to pyrolysis
- Make FY08 SOT data publicly available and peer reviewed,

  FY07 biochem is publicly available at http://www.nrel.gov/docs/fy08osti/43205.pdf
- Validate 2012 performance target using pilot plant data, baseline process design, and mature technology cost estimate

Transitioning from basis of old biochemical design report (2002) to new design report (2009) to incorporate updated environmental considerations (e.g. water use) and process knowledge