Pretreatment: The Key to Unlocking Low Cost Cellulosic Ethanol

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Cellulosic Ethanol Forum and Technology Roundtable
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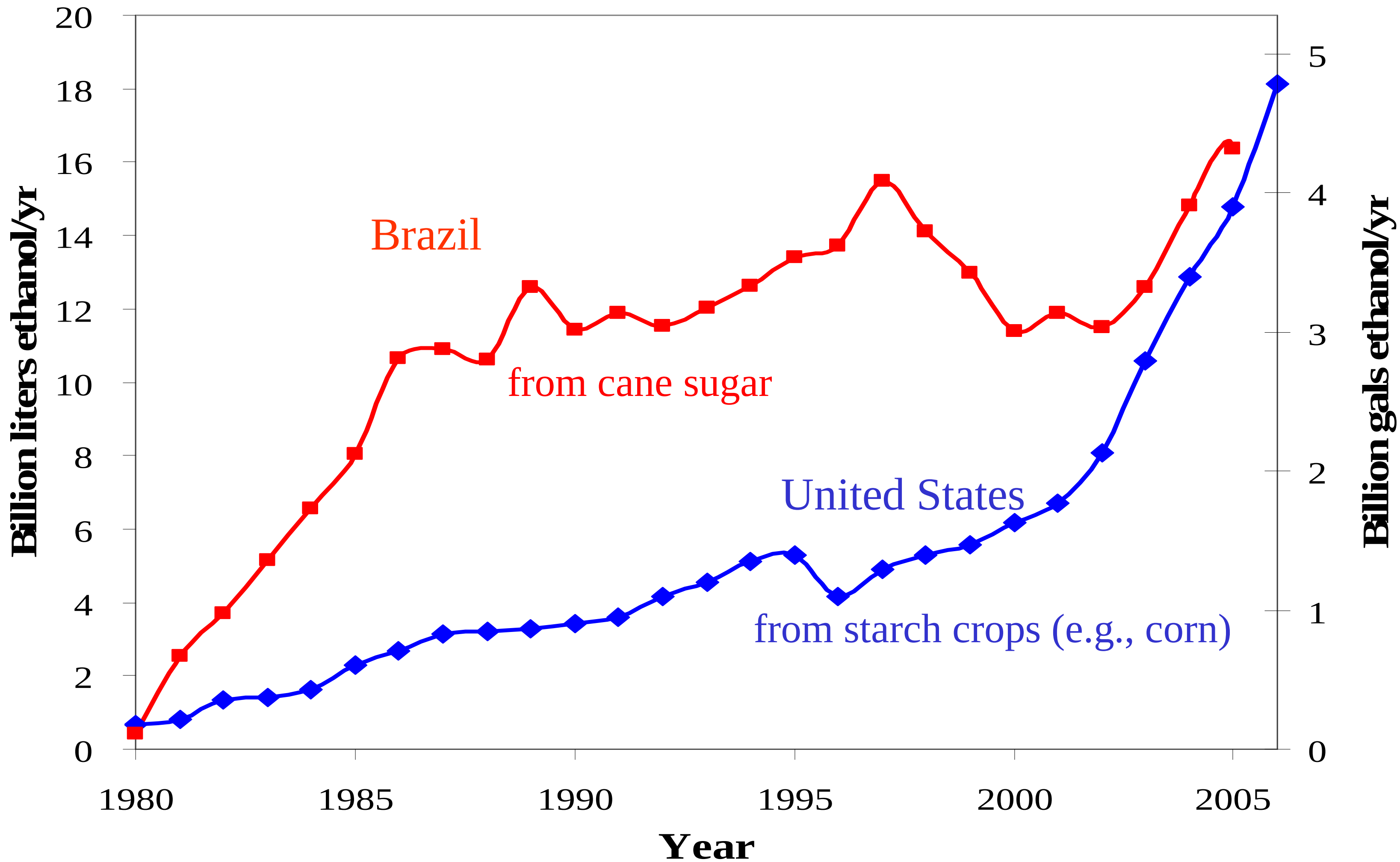
Ethanol Production in Brazil and the United States

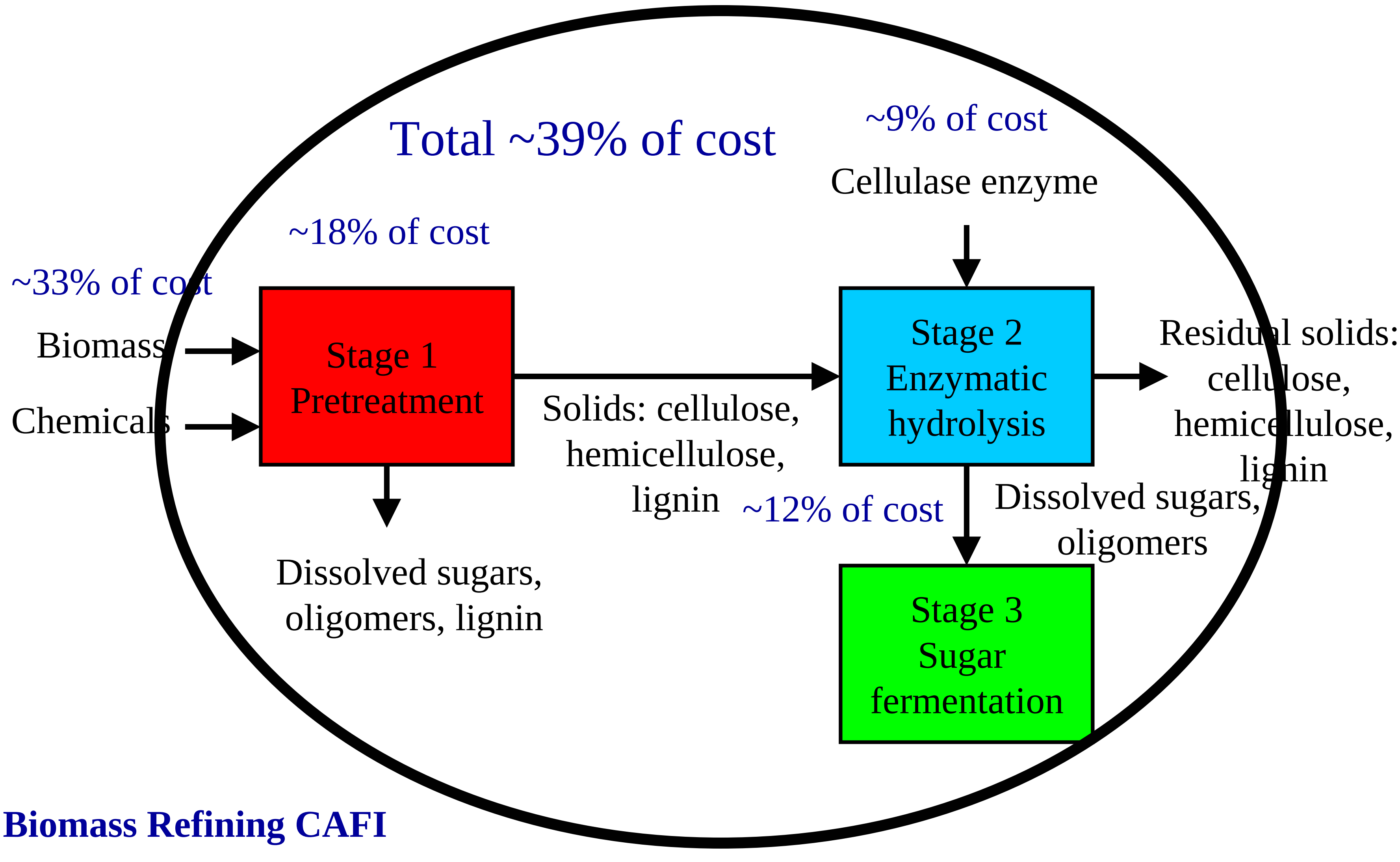



V-Power
Álcool Comum
Gilbarco
TOTAL A PAGAR
LITROS
PREÇO POR LITRO
1,59
2,69
CONOCO
ConocoPhillips
Silco
Regular
279 9
Diesel
309 9
E-85
Motor Fuel
1.99 9/10
Car Wash
For higher octane!

Biological Processing of Cellulosic Biomass

- Biological processing of cellulosic biomass to ethanol and other products offers the potential of high yields vital to economic success
- Biological processing can take advantage of the continuing advances in biotechnology to dramatically improve technology and reduce costs
- In response to recent petroleum price hikes, new initiatives seek to support major research efforts to reengineer plants and biological processes for more efficient conversion of plants into fuels, e.g.
  - $500 million over 10 years for BP Energy Biosciences Institute
  - $250 million over 5 years for 2 DOE Bioenergy Research Centers

Major Process Steps



Importance of Pretreatment

- Although significant, feedstock costs are low relative to petroleum
- In addition, feedstock costs are a very low fraction of final costs compared to other commodity products
- Pretreatment is the most costly process step: the only process step more expensive than pretreatment is no pretreatment
  - Low yields without pretreatment drive up all other costs more than amount saved
  - Conversely enhancing yields via improved pretreatment would reduce all other unit costs
- Need to reduce pretreatment costs to be competitive

CAFI Background

- Biomass Refining Consortium for Applied Fundamentals and Innovation (CAFI) organized in late 1999, early 2000
- Included top researchers in biomass hydrolysis from Auburn, Dartmouth, Michigan State, Purdue, NREL, Texas A&M, U. British Columbia, U. Sherbrooke
- Mission:
    - Develop information and a fundamental understanding of biomass hydrolysis that will facilitate commercialization,
    - Accelerate the development of next generation technologies that dramatically reduce the cost of sugars from cellulosic biomass
    - Train future engineers, scientists, and managers.

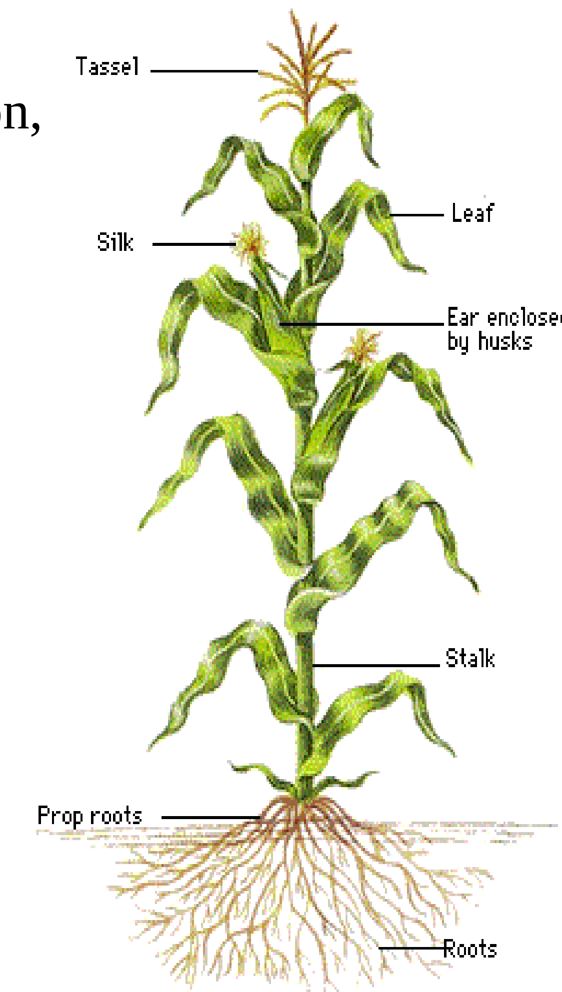
USDA IFAFS Project Overview: CAFI 1

- Multi-institutional effort funded by USDA Initiative for Future Agriculture and Food Systems Program for $1.2 million to develop comparative information on cellulosic biomass pretreatment by leading pretreatment options with common source of cellulosic biomass (corn stover) and identical analytical methods
  - **Aqueous ammonia recycle pretreatment** - YY Lee, Auburn University
  - **Water only and dilute acid hydrolysis by co-current and flowthrough systems** - Charles Wyman, Dartmouth College
  - **Ammonia fiber explosion (AFEX)** - Bruce Dale, Michigan State University
  - **Controlled pH pretreatment** - Mike Ladisch, Purdue University
  - **Lime pretreatment** - Mark Holtzapple, Texas A&M University
  - **Logistical support and economic analysis** - Rick Elander/Tim Eggeman, NREL through DOE Biomass Program funding
- Completed in 2004

CAFI 1 Feedstock: Corn Stover

- NREL supplied corn stover to all project participants (source: BioMass AgriProducts, Harlan IA)
- Stover washed and dried in small commercial operation, knife milled to pass ¼ inch round screen

Glucan	**36.1 %**
Xylan	**21.4 %**
Arabinan	**3.5 %**
Mannan	**1.8 %**
Galactan	**2.5 %**
Lignin	**17.2 %**
Protein	**4.0 %**
Acetyl	**3.2 %**
Ash	**7.1 %**
Uronic Acid	**3.6 %**
Non-structural Sugars	**1.2 %**



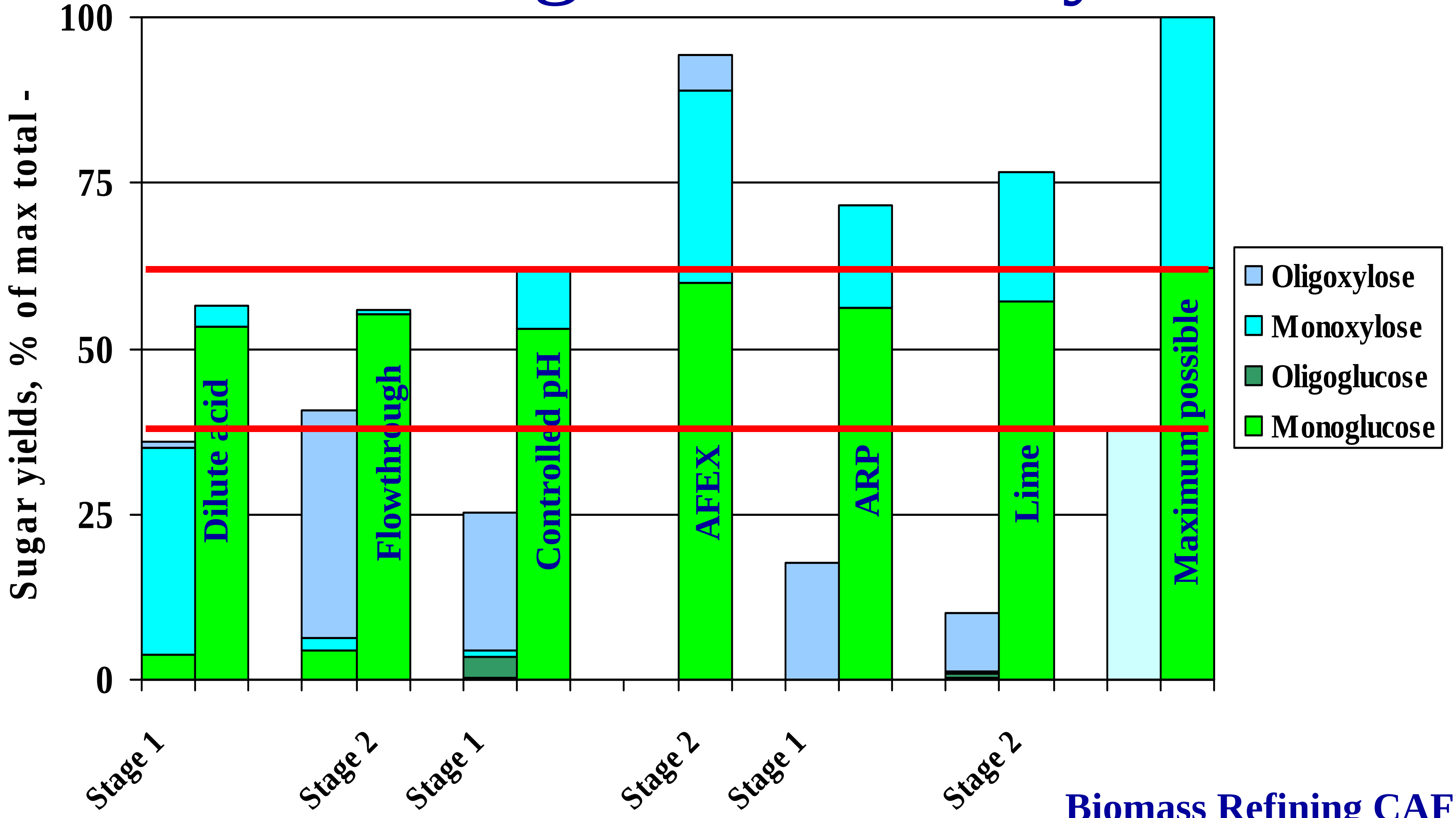
Overall Yields for Corn Stover at 15 FPU/g Glucan

Increasing pH

Pretreatment system	Xylose yields*			Glucose yields*			Total sugars*		
	Stage 1	Stage 2	Total xylose	Stage 1	Stage 2	Total glucose	Stage 1	Stage 2	Combined total
Maximum possible	37.7	37.7	37.7	62.3	62.3	62.3	100.0	100.0	100.0
Dilute acid	32.1/31.2	3.2	35.3/34.4	3.9	53.2	57.1	36.0/35.1	56.4	92.4/91.5
SO_2 Steam explosion	14.7/1.0	20.0	34.7/21.0	2.5/0.8	56.7	59.2/57.5	17.2/1.8	76.7	93.9/78.5
Flowthrough	36.3/1.7	0.6/0.5	36.9/2.2	4.5/4.4	55.2	59.7/59.6	40.8/6.1	55.8/55.7	96.6/61.8
Controlled pH	21.8/0.9	9.0	30.8/9.9	3.5/0.2	52.9	56.4/53.1	25.3/1.1	61.9	87.2/63.0
AFEX		34.6/29.3	34.6/29.3		59.8	59.8		94.4/89.1	94.4/89.1
ARP	17.8/0	15.5	33.3/15.5		56.1	56.1	17.8/0	71.6	89.4/71.6
Lime	9.2/0.3	19.6	28.8/19.9	1.0/0.3	57.0	58.0/57.3	10.2/0.6	76.6	86.8/77.2

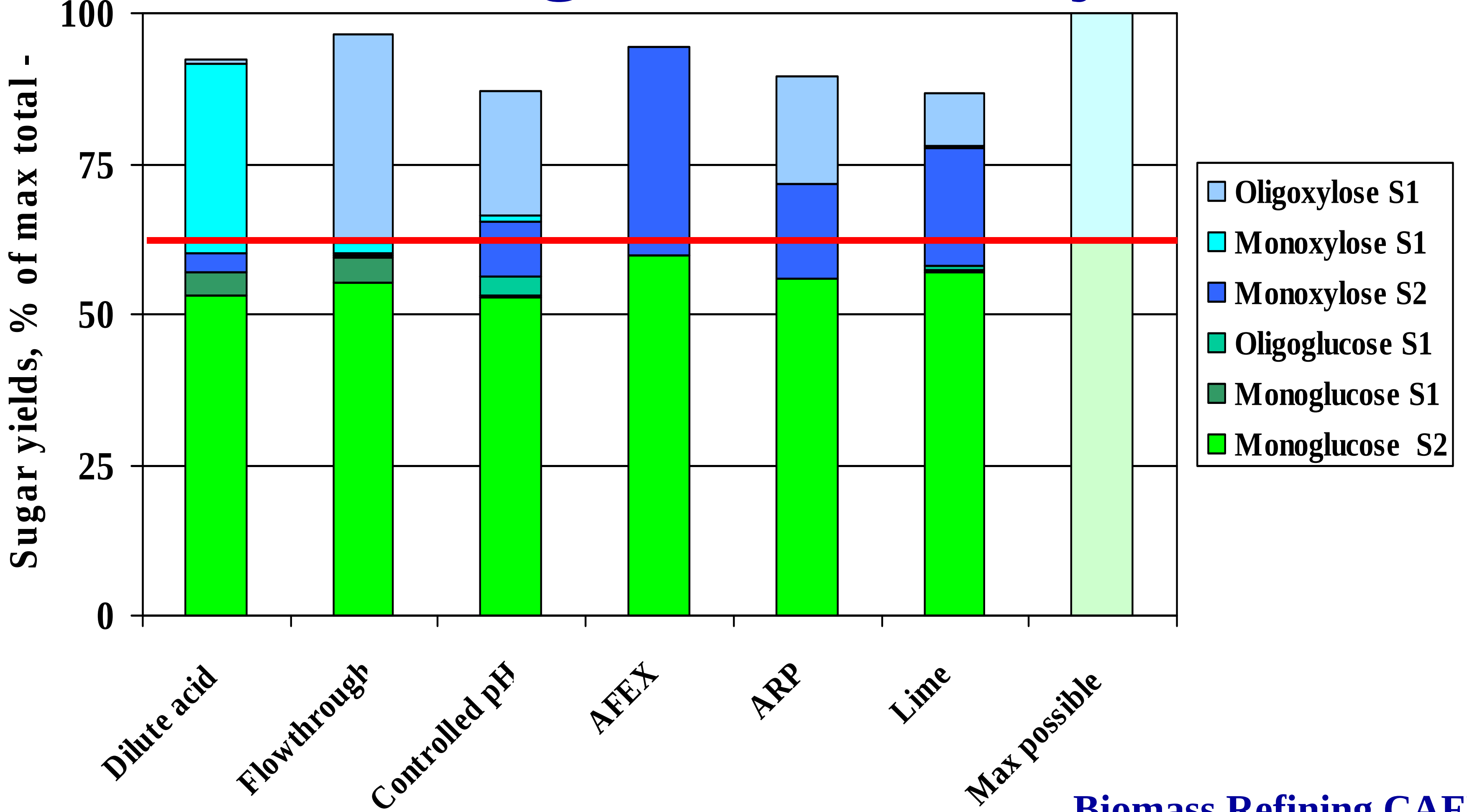
*Cumulative soluble sugars as total/monomers. Single number = just monomers.

Sugar Yields from Corn Stover at 15 FPU/g Glucan Enzyme



Biomass Refining CAFI

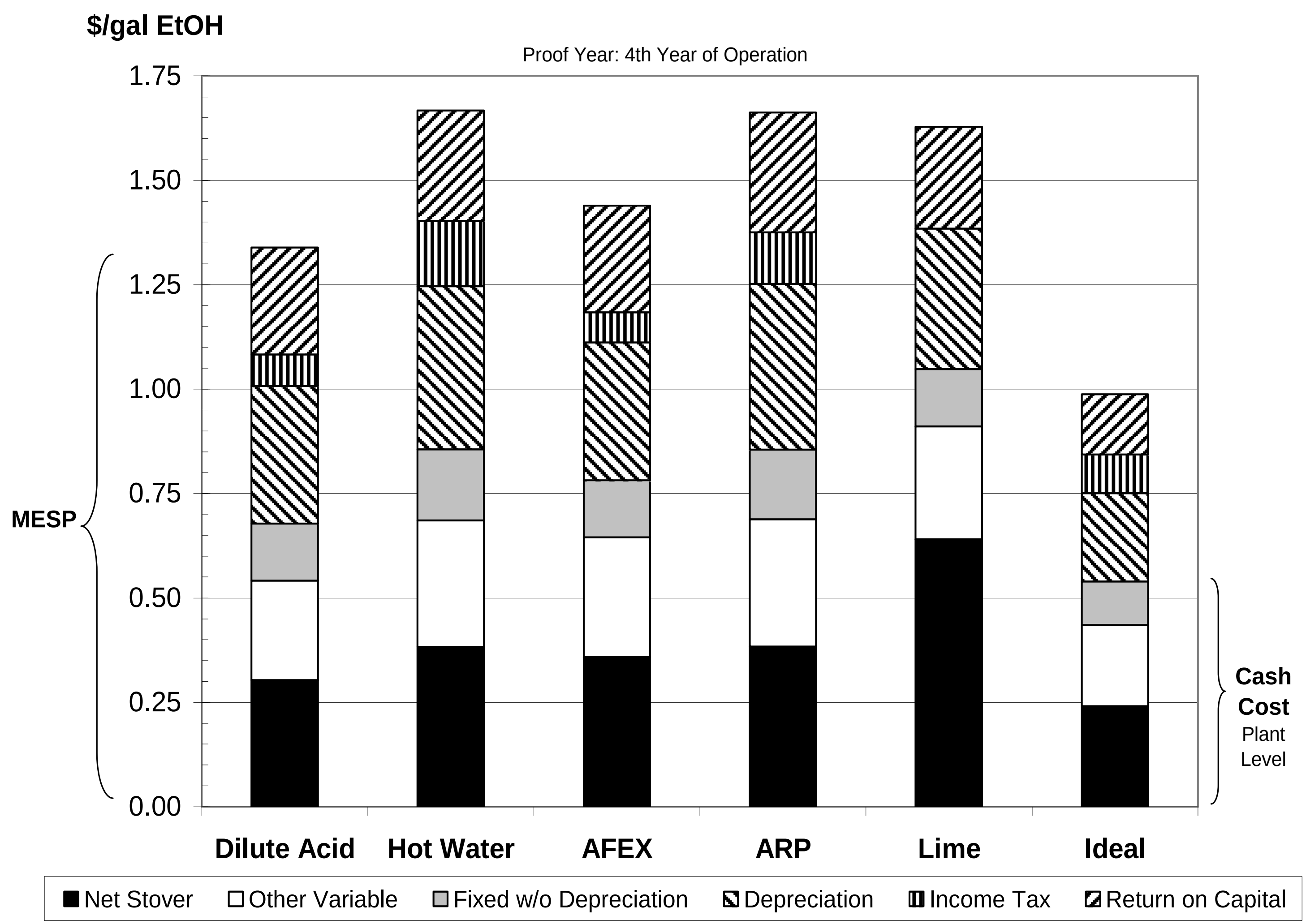
Sugar Yields from Corn Stover at 15 FPU/g Glucan Enzyme



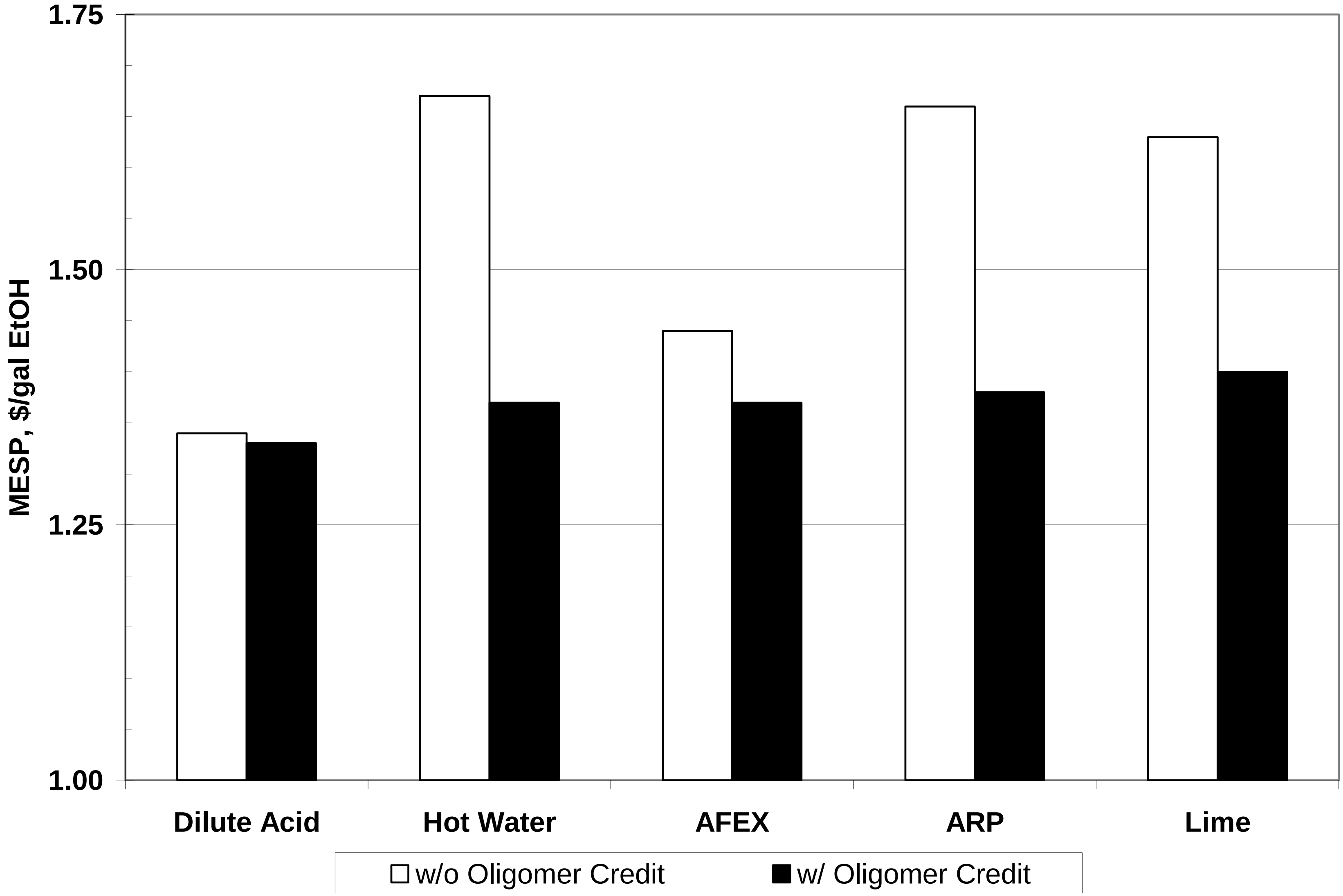
Biomass Refining CAFI

Minimum Ethanol Selling Price (MESP)

Assumptions: 2.5 years construction, 0.5 years start up, 20 year plant life, zero net present value when cash flows are discounted at 10% real after tax rate



Effect of Oligomer Conversion



Biomass Refining CAFI

DOE OBP Project: CAFI II

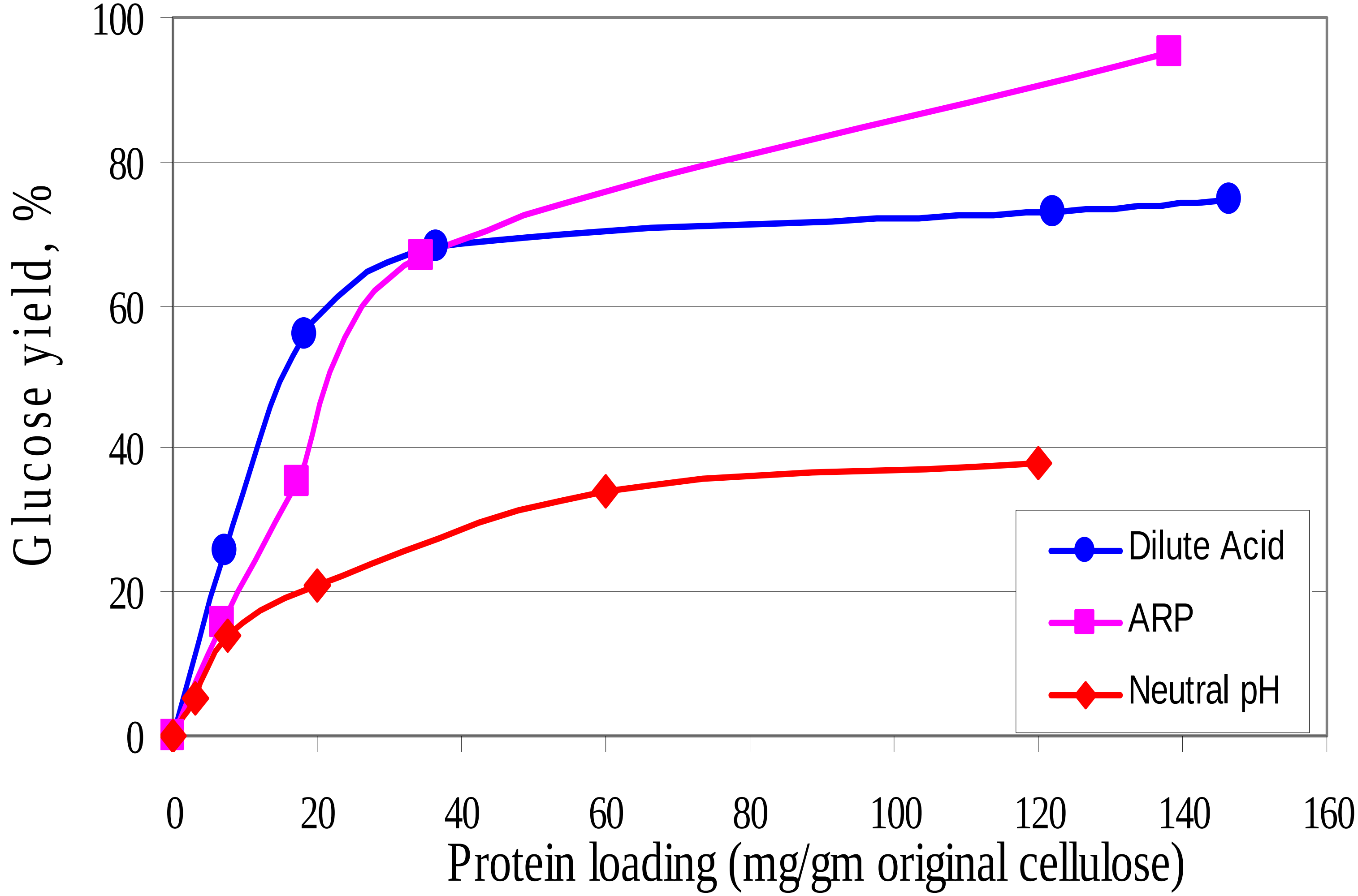
- Started in April 2004 after completion of USDA IFAFS funded CAFI I on corn stover
- Funded by DOE Office of the Biomass Program for $1.88 million through a joint competitive solicitation with USDA
- Using identical analytical methods and feedstock sources to develop comparative data for corn stover and poplar
- Determining in depth information on
  - Enzymatic hydrolysis of cellulose and hemicellulose in solids
  - Conditioning and fermentation of pretreatment hydrolyzate liquids
  - Predictive models
- Evaluating AFEX, ARP, controlled pH, dilute acid, lime, sulfur dioxide pretreatments
- Genencor supplies commercial and advanced enzymes

CAFI II Standard Poplar

Component	Composition (wt %)
Glucan	43.8
Xylan	14.9
Arabinan	0.6
Mannan	3.9
Galactan	1.0
Lignin	29.1
Protein	nd
Acetyl	3.6
Ash	1.1
Uronic Acids	nd
Extractives	3.6

1/4 inch Milled Poplar

Effect of Protein Loadings on Cellulose Hydrolysis of Poplar Solids



Biomass Refining CAFI

Digestion time =72hr

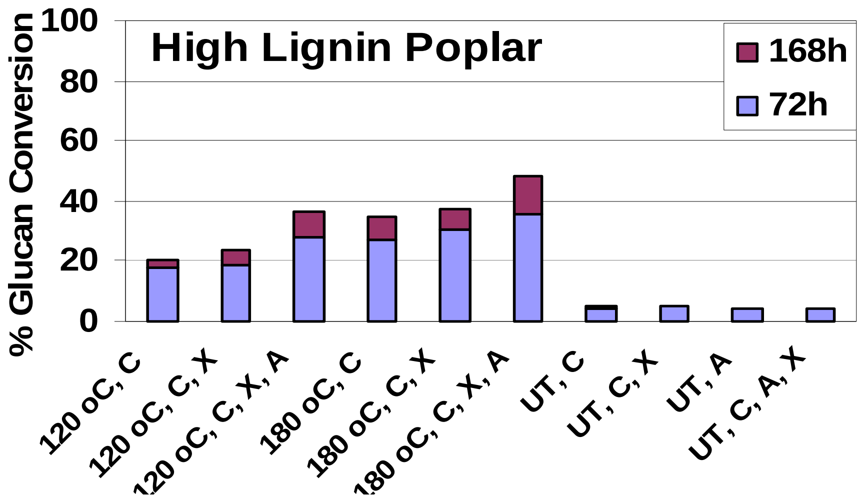
CAFI II Initial Poplar

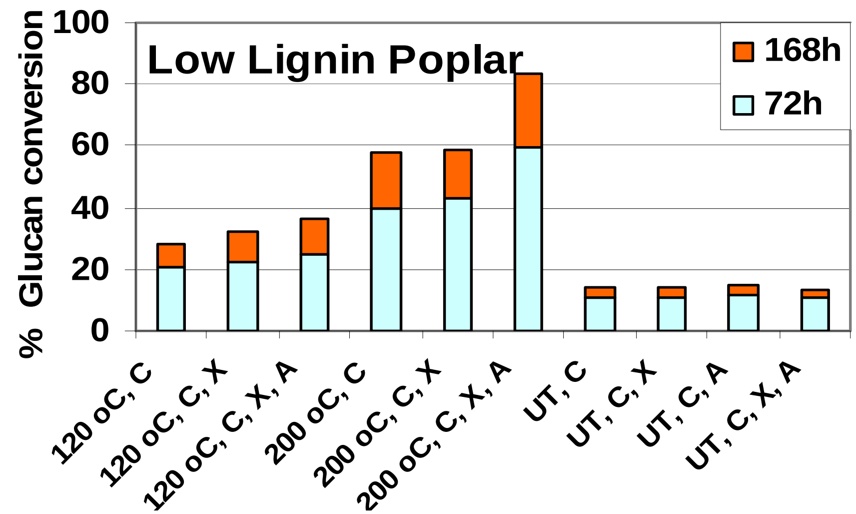
- Feedstock: USDA-supplied hybrid poplar (Arlington, WI)
  - Debarked, chipped, and milled to pass ¼ inch round screen
  - Not enough to meet needs

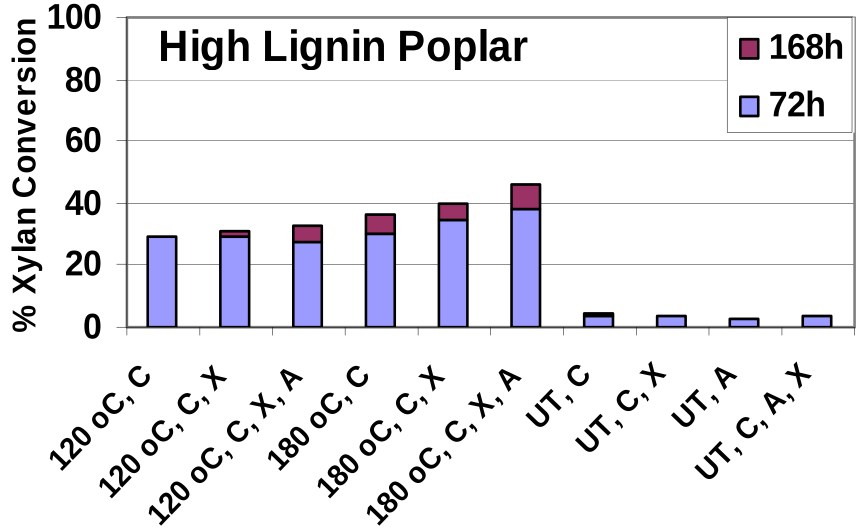
Component	Wt %
Glucan	45.1
Xylan	17.8
Arabinan	0.5
Mannan	1.7
Galactan	1.5
Lignin	21.4
Protein	nd
Acetyl	5.7
Ash	0.8
Uronic Acids	nd
Extractives	3.4

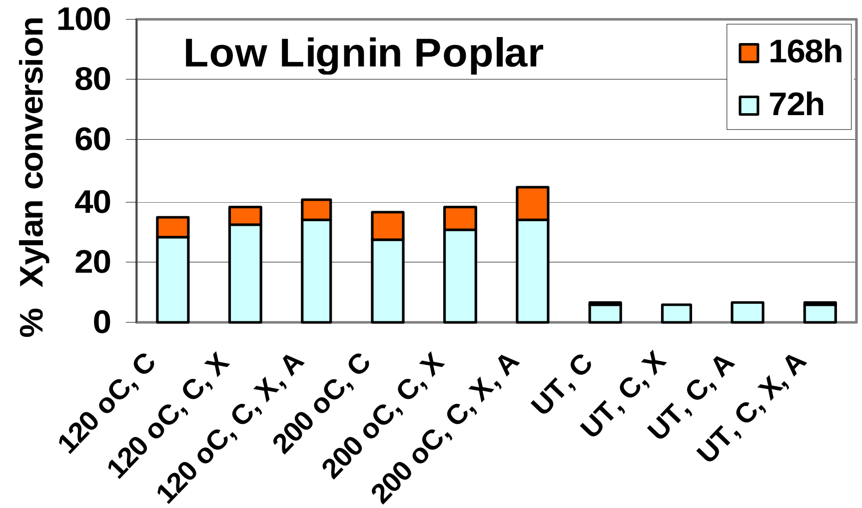
AFEX Optimization for High/Low Lignin Poplar

C - Cellulase	**UT - Untreated**
(31.3 mg/g glucan)	**<u>AFEX condition</u>**
X - Xylanase	**24 h water soaked**
(3.1 mg/g glucan)	**1:1 (Poplar:NH3)**
A - Additive	**10 min. res. time**
(0.35g/g glucan)	









SO_2 Overall Yields at 15 FPU/g of Glucan (148 hours hydrolysis)

Pretreatment conditions	Xylose yields*			Glucose yields*			Total sugars*		
	Stage 1	Stage 2	Total xylose	Stage 1	Stage 2	Total glucose	Stage 1	Stage 2	Combined total
Maximum possible	**25.8**	**25.8**	**25.8**	**74.2**	**74.2**	**74.2**	**100**	**100**	**100**
190°C,5min,3% SO_2 (High lignin poplar)	**20.3/13.7**	**2.7**	**23/16.4**	**1.5**	**69.9**	**71.4**	**21.8/15.2**	**72.6**	**94.4/87.8**
200°C,5min,3% SO_2 (High lignin poplar)	**19.3/14.0**	**2.4**	**21.7/16.4**	**2.3**	**71.9**	**74.2**	**21.6/16.3**	**74.3**	**95.9/90.6**
190°C,5min,3% SO_2 (Low lignin poplar)	**18.4/12.9**	**3.5**	**21.9/16.4**	**1.0**	**73.2**	**74.2**	**19.4/13.9**	**76.7**	**96.1/90.6**

Why Is Variability Important?

- Impacts yields for all but SO_2 pretreatment
- Assumption is that all hardwoods of same type behave similarly
- Woody crops proponents plan to use standing forest to “store” wood, but harvest season may affect yields
- Important to understand what causes this and whether it impacts other feedstocks such as herbaceous crops or agricultural residues

Differences Among Poplar Species*

Original Poplar - Low Lignin	Poplar Standard - High Lignin
•Arlington, WI near Madison •Very rich, loamy soil •Demonstrated some of best growth rates •Harvested and shipped in February 17, 2004 •Planted in 1995, probably in spring but possibly in fall	•Alexandria, Minnesota •Lower growth rate than Arlington •Slightly shorter growing season •Harvested and shipped in August 2004 •Planted in spring 1994

* Based on information provided by Adam Wiese, USDA Rheinlander, WI

Closing Thoughts

- Biology provides a powerful platform for low cost fuels and chemicals from biomass
  - Can benefit both crop production and conversion systems
- The resistance of one biological system (cellulosic biomass) to the other (biological conversion) requires a pretreatment interface
- Advanced pretreatment systems are critical to enhancing yields and lowering costs
- Not all pretreatments are equally effective on all feedstocks
- Focus on 2 biologies - plants and biological conversion - without integrating their interface – pretreatment – will not significantly lower costs

Acknowledgments

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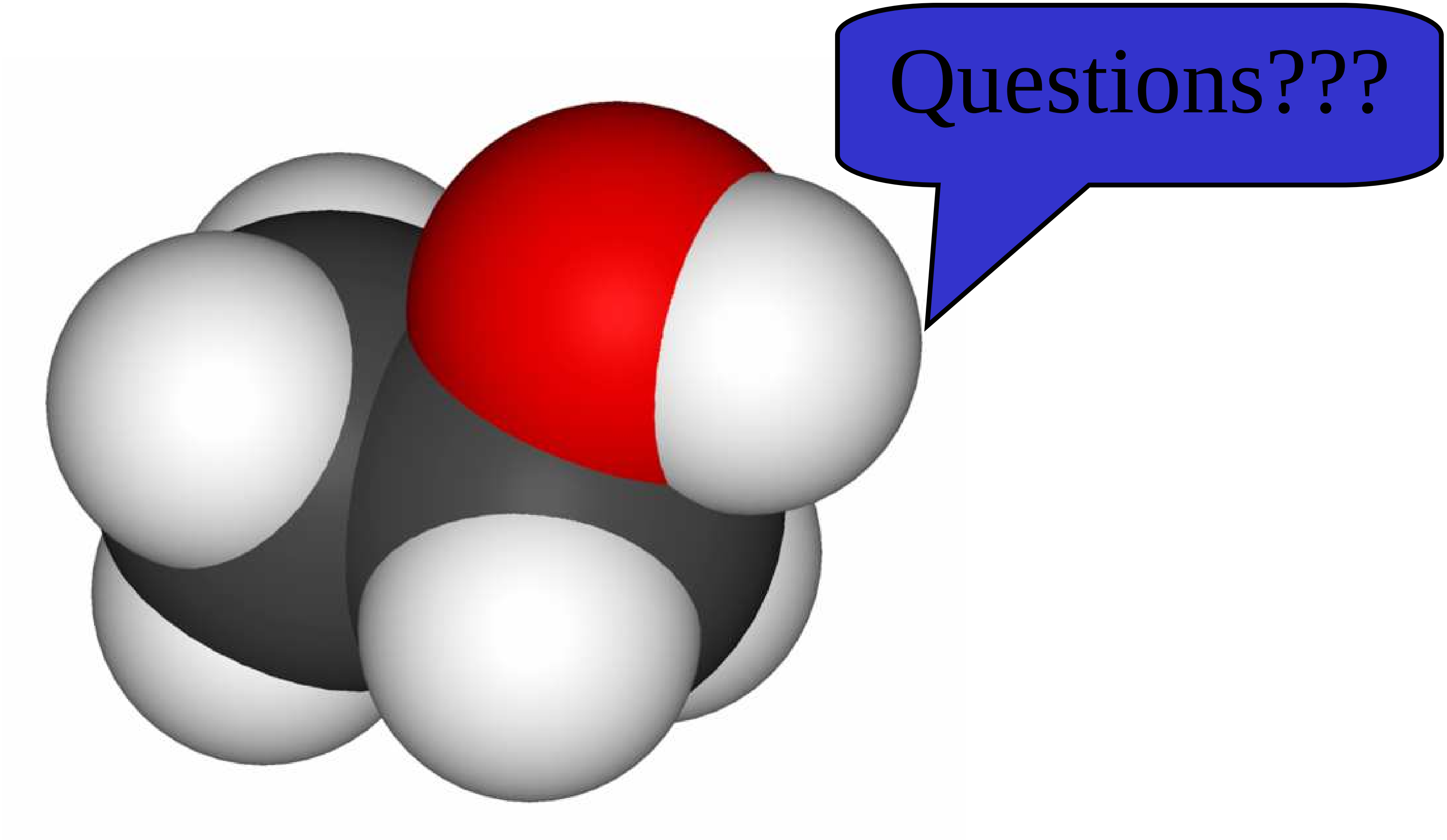
- Natural Resources Canada
- All of the CAFI Team members, students, and others who have been so cooperative
- Ford Motor Company and University of California at Riverside

Today’s Speakers and Topics

- Thomas Foust, National Renewable Energy Laboratory: "DOE and NREL Perspectives on Cellulosic Ethanol - Budget, Research Objectives, Research Achievements"
- Val Tiangco, California Energy Commission: “Potential of Cellulosic Ethanol in California including Feedstock Availability, Research Objectives, Promising Approaches”
- Larry Gross, Altra: “The Current Ethanol Industry: Growth and Challenges”
- Douglas Cameron, Khosla Ventures: “Growth of Ethanol in the USA including Regional Feedstock Availability”
- Michael Ladisch, Purdue University: “Current and Emerging Technologies for Production of Cellulosic Ethanol”
- Bruce Dale, Michigan State University: “Energy Balance and Greenhouse Gas Emission Implications for Large Scale Production of Cellulosic Ethanol”


Questions???