NREL
National Renewable Energy Laboratory

Successful Solid-Liquid Separations Within a Biomass-to-Ethanol Process

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NREL at a Glance

- Only national laboratory ***dedicated*** to renewable energy and energy efficiency R&D
- Research spans fundamental ***science*** to ***technology*** solutions
- ***Collaboration*** with industry and university partners is a hallmark
- Research programs ***linked*** to market opportunities

Biomass Opportunities

- Energy Security
  - Dramatically reduce or even end dependence on foreign oil
    - Biomass is the only renewable that directly reduces or dependency on liquid transportation fuels
- Economics
  - Spur the creation of a domestic bioindustry
    - The new industrial biorefinery model, with its production of products including fuels and chemicals from biomass, will help enable this domestic industry
- Environment
  - Carbon Neutral Processes
  - Lower GHG emissions
- Part of the answer in other EERE Programs/Interest
  - Biomass to Hydrogen and Distributed Energy

The New Industrial Biorefinery

Biomass Feedstock

– Trees
–Grasses
– Agricultural Crops
– Agricultural Residues
– Animal Wastes
– Municipal Solid Waste

Conversion Processes

- Enzymatic Fermentation
- Gas/liquid Fermentation
- Acid Hydrolysis/Fermentation
- Gasification
- Combustion
- Co-firing

USES

Fuels:
– Ethanol
– Renewable Diesel

Power:
– Electricity
– Heat

Chemicals
– Plastics
– Solvents
– Chemical Intermediates
– Phenolics
– Adhesives
– Furfural
– Fatty acids
– Acetic Acid
– Carbon black
– Paints
– Dyes, Pigments, and Ink
– Detergents
– Etc.

Food and Feed

Biomass' Major Molecules

Lignin: 15-25%

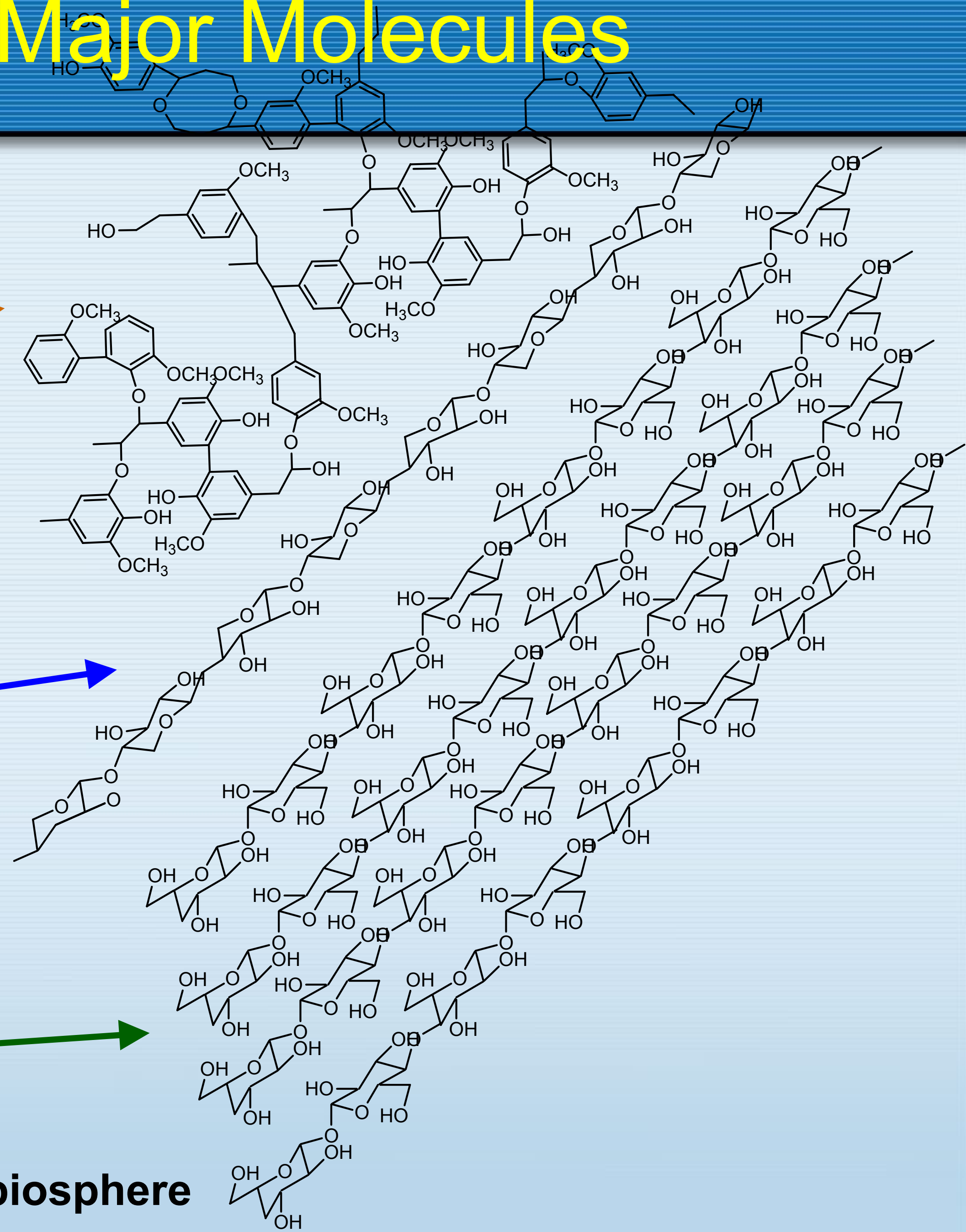
- Complex network of aromatic compounds
- High energy content
- Treasure trove of novel chemistry

Hemicellulose: 23-32%

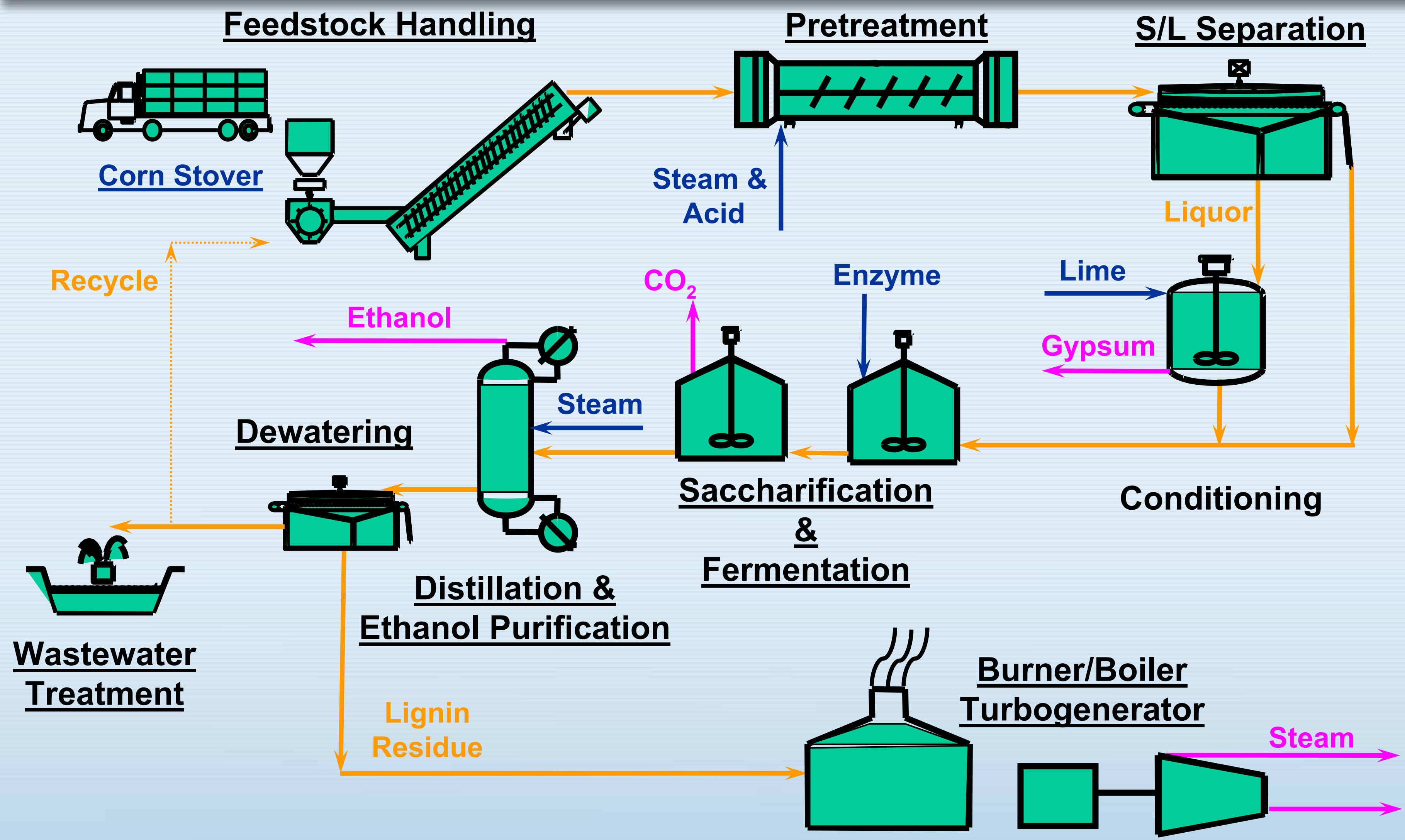
- A collection of unusual 5- and 6-carbon sugars linked together in long, substituted chains
- Xylose is the 2nd most abundant sugar in biosphere

Cellulose: 38-50%

- Long chains of glucose
- Most abundant form of carbon in biosphere



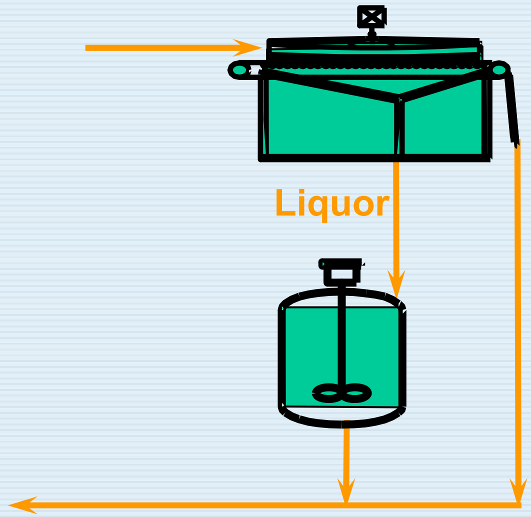
Conceptual Process Design



Lignocellulosic Biomass to Ethanol Process Design and Economics NREL/TP-510-32438 June, 2002
http://www.nrel.gov/docs/fy02osti/32438.pdf

Solid-liquid Separations

S/L Separation

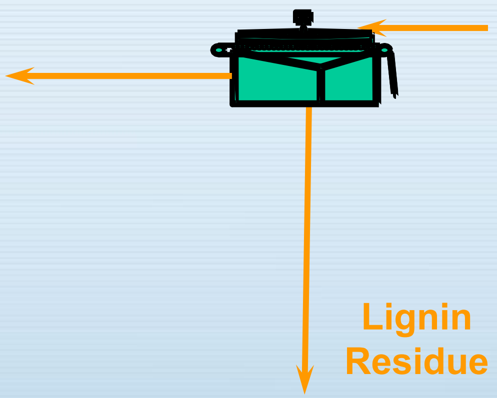


Conditioning

Conditioning:

- 1) Acid Recovery (washing)
- 2) Detoxification / gypsum recovery

Dewatering



Dewatering:

- drying lignin residue for combustion
- liquor sent to evaporation to recover dissolved solids, recycled

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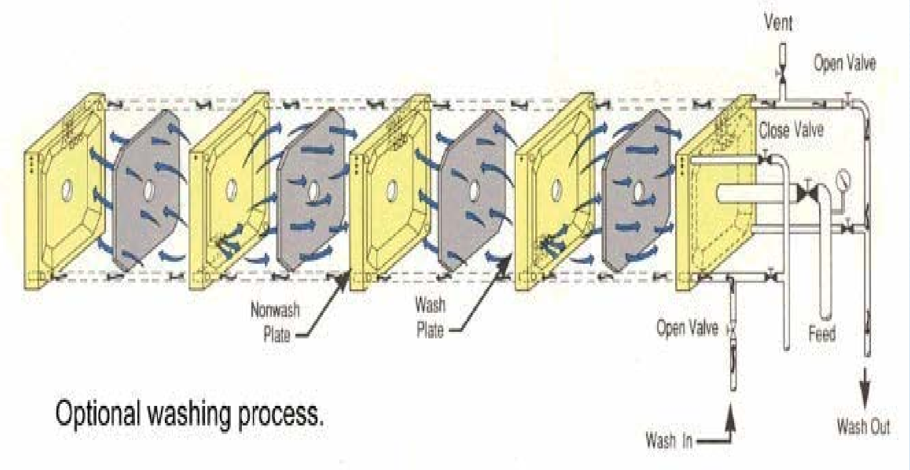
Biomass Separation Challenges

- Porosity / Structural stability
  - Structure behaves “sponge-like” taking up water, but not readily releasing it
- High temperature environment
  - Corrosive
  - Potentially reactive
- Other materials present
  - Oils
  - Fines
  - Proteins
- Lack of system characterization
  - Particle size distribution

Critical Equipment Subcontract

- NREL engaged the Harris Group (HGI) to perform vendor testing, process design, and costing for S/L sep
  - NREL Subcontract ACO-9-29067-01 http://www.afdc.doe.gov/pdfs/5455.pdf
- Several equipment types explored
  - Hydrolysate wash: horizontal belt filter, pressure filter
  - Dewatering: centrifuge, filter press, belt filter press, pressure filter
- Results incorporated into process design and techno-economic analysis for 2000 dry metric tonnes per day



Optional washing process.

Subcontract Results

Hydrolysis

Equipment	Manufacturer	Wash Water *(lb/lb feed)*	Acetic Acid Residual *(mg/mL)*	Estimated Capital Cost
Horizontal belt filter	"B"	1.1 – 1.2	No data	$6,300,000
Horizontal belt filter	"D"	1.1	1.7	$27,000,000
Pressure filter	"C"	0.58	0.9	$8,500,000

Post-Distillate

Equipment	Manufacturer	Cake Solids	Estimated Capital Cost
Centrifuge	"A"	19.9%	$8,800,000
Centrifuge	"B"	22.9%	no data
Filter press, Opt 1	"B"	34.9% - 39.7%	$17,300,000
Filter press, Opt 2	"B"	39.7% - 44.4%	$24,500,000
Pressure filter	"C"	88.0%*	$8,100,000
Belt filter press	"B"	no data	no data

*This seemed abnormally high. After re-analyzing the data, 56% solids used in design.

Do These Results Make Sense?

- From AIChE Solid/Liquid Separation: Course #289

	Solid Dryness	Liquid Clarity	Thickening	Washing	Classifi-cation	Particle Breakage
CAKE FILTERS						
Gravity filters	F	G	P	G	-	E
Batch, semi-batch vacuum filters	G	G	P	E	-	E
Continuous vacuum filters	G	G	P	F	-	E
Batch,semi-batch pressure filters	E	E	P	E	-	G
Continuous pressure filters	E	E	P	F	-	G
Compression filters	E	F	-	F	-	P
Filtering centrifuges	G	E	P	E	-	F-P
Precoat filters	-	E	-	-	-	-
SETTLERS						
Gravity - clarifier	P	E	G	-	-	E
Gravity - thickener	P	G	E	P	-	E
Tubular centrifuge	P	E	-	-	-	F
Disc centrifuge - solid bowl	P	E	-	-	-	G
Disc centrifuge - desludger	P	E	E	P	-	F
Disc centrifuge - nozzle	P	G	G	F	P	F
Solid bowl centrifuge	F-G	E-G	P	P	P	P
Hydrocyclones	P	P	G	F	E	P

E - excellent, G - good, F - fair, P - poor, "-" - should not be considered

NREL's Process Development Unit

A fully integrated biomass to ethanol plant

- Processes one ton per day of biomass
- Produces 100 proof ethanol
- Flexible integration and set-up
- Capable of round the clock operations
- Collects data from over 900 process points
- Batch and continuous operations

PDU S/L Separation Equipment

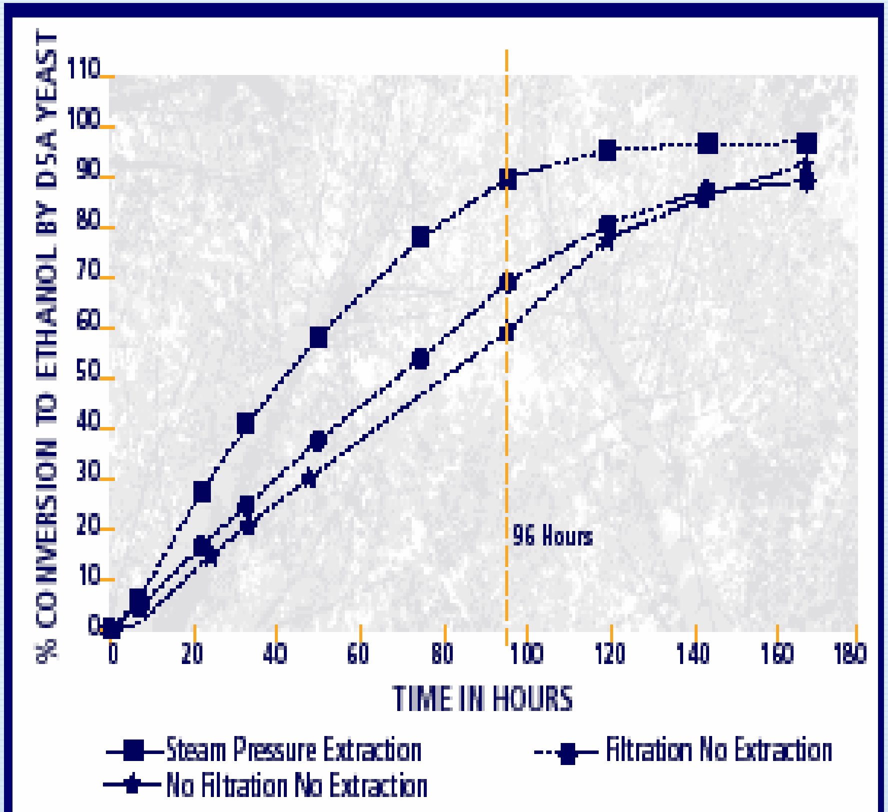
- Pilot-scale equipment:
  - Bock lined centrifuge
  - Sharples solid bowl decanter centrifuge
  - Pneumapress pressure filter
  - Bench-scale testing also
- Current uses:
  - In-house program research
  - WFO/CRADA with industrial partners
  - Hydrolysate / Fermentation residue production for testing

Pressure Filter Data

Number of Washes		Wash Ratio (kg water/kg slurry)	Wash Ratio (kg water/kg BD solids)	Xylose Recovered in Filtrate (% initial)
Lab Scale Test—Sunds Pretreated ¾" Hardwood Chips (TVA)—Harris Subcontract Data				
0		0	0	45
1		0.67	2.67	57
1		0.73	2.91	71
1		0.91	3.62	65
2		1.09	4.34	98
2		1.09	4.34	97
2		0.87	3.46	96
2		**0.58**	**2.31**	**96**
Pilot Scale Test—Sunds Pretreated Corn Stover (NREL)				
0		0	0	71
1		0.43	4.97	86
1		0.66	7.70	90
1		1.56	18.12	92

"Hot Wash" Process Variation

- Adding a pressurized "hot wash" step immediately following pretreatment (while still at T&P) improves enzymatic digestibility
- Theorize that lignin re-precipitates back onto cellulose, interfering w/ enzyme hydrolysis
- Pneumapress was only vendor in subcontract with suitable equipment for elevated temperature (135°C) operation
- Soluble lignins with potentially valuable unique properties are separated out



Improved digestibility of yellow poplar with Pressurized Hot Wash.

NREL Patents #6,022,419 & #6,228,177

What's Next?

- Working with industrial partners.
- Working with different feedstock with different S/L characteristics.
- Different co-product opportunities.
- Looking to improve economics for downstream processing.

Acknowledgement

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Harris Group Inc.

PNEUMAPRESS
FILTER CORPORATION