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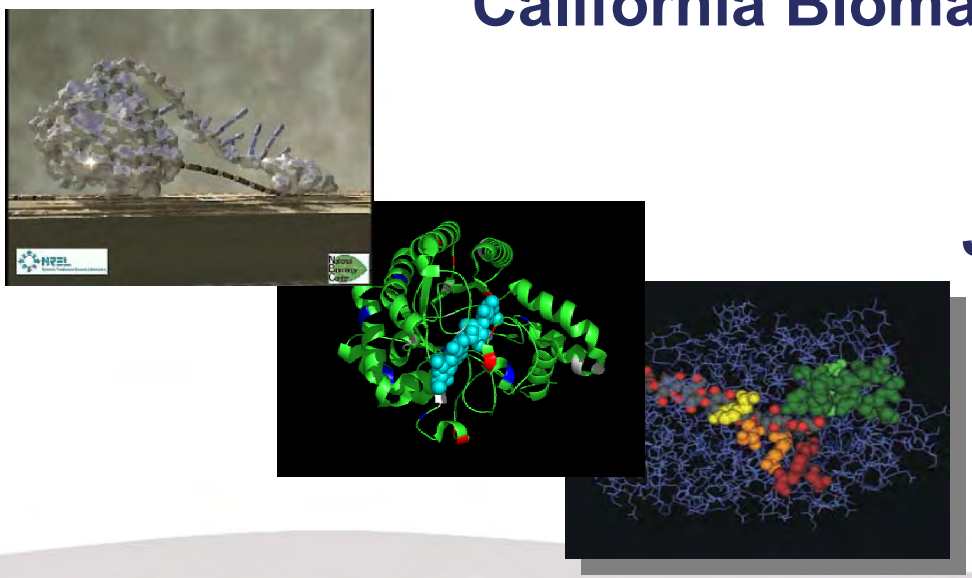
Enzymes for ethanol from lignocellulosic feedstocks

California Biomass Collaborative Forum
Fresno, CA
January 26, 2006



Colin Mitchinson

Genencor Intl.

Cellulosic Biomass Conversion

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- The Role of Cellulosics in the Ethanol Marketplace
- Cellulase Efforts at Genencor Intl.
- Status
- The Challenges Moving Forward

Bioethanol Growth Trend

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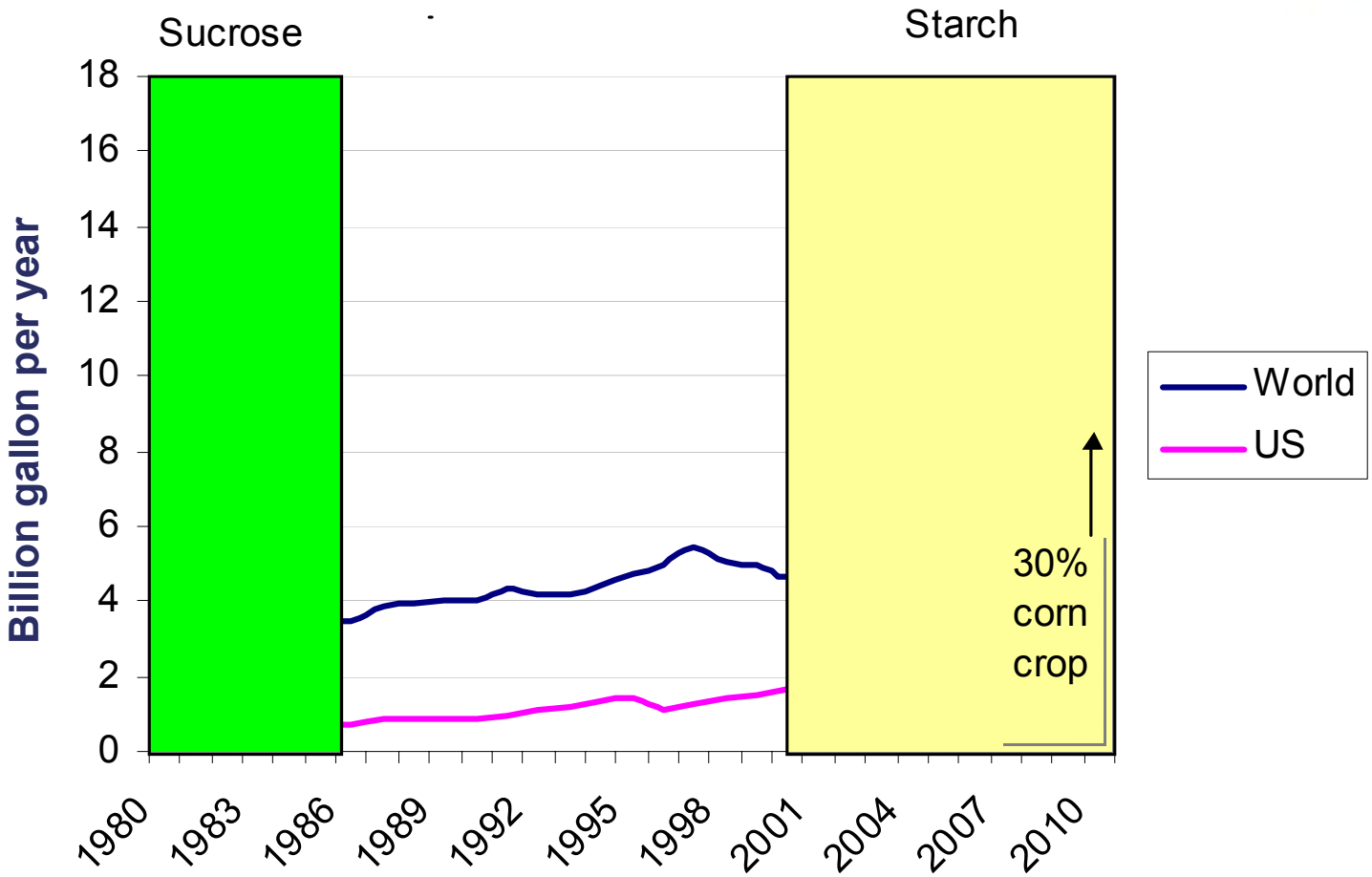

Source: Renewable Fuels Assn. 2005

The Cellulosic Biomass Opportunity

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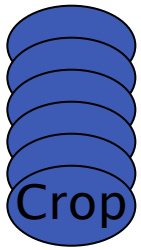

Grain

Plant residue (LC)

Pre-Treatment

Saccharification

EtOH Fermentation

Distillation → **EtOH**

- **Why Cellulosic Biomass**:
  - Plentiful, and Potentially Low Cost
  - Could be Financially Competitive
  - Potential Synergies with Conventional Processing Technologies

Every 1 billion bushel/yr Corn production yields 25 million dry tons of Corn stover which could potentially produce >2.5 billion gal EtOH per year

The BioRefinery

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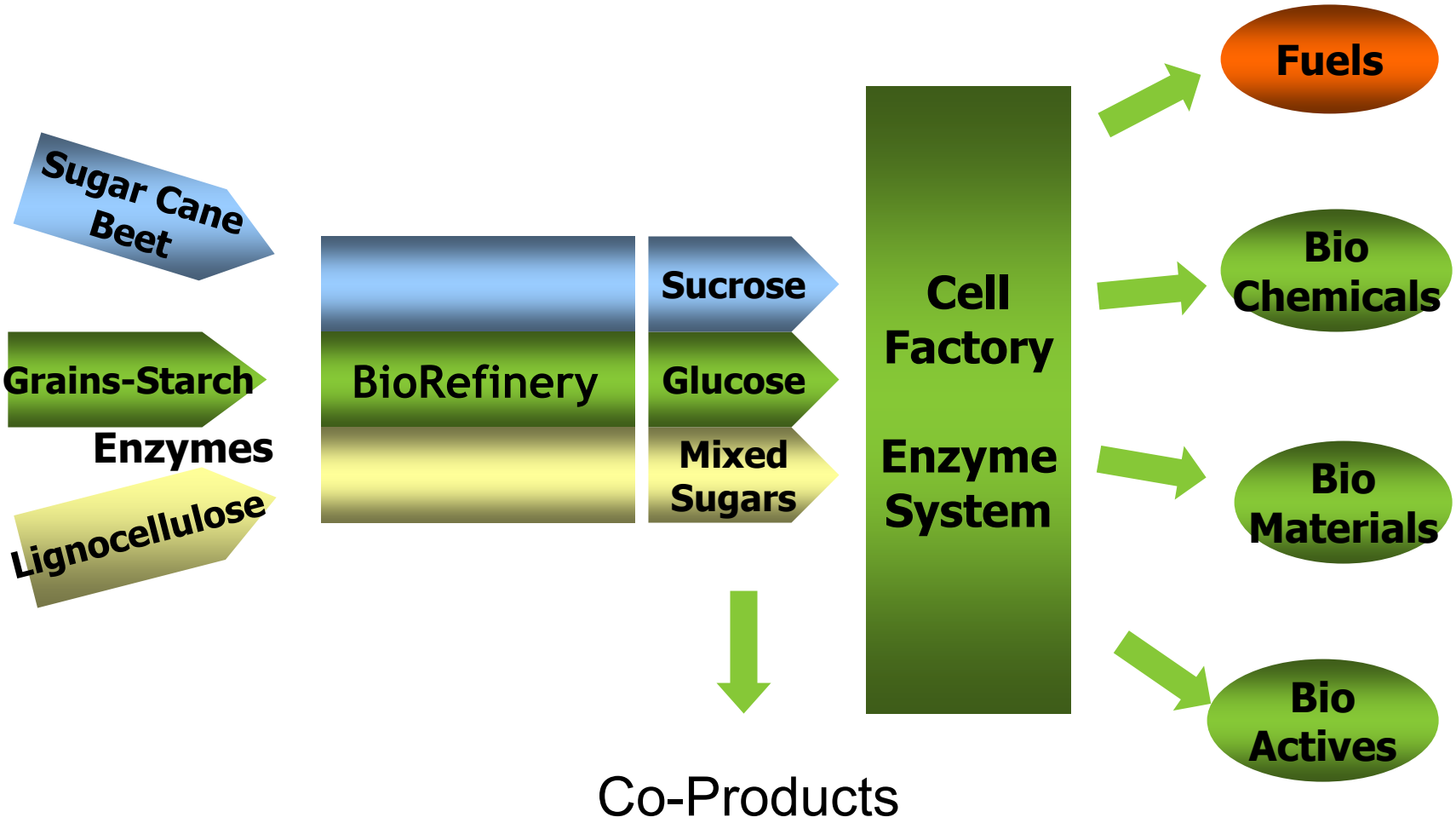

Why Biofuel from Cellulosics?

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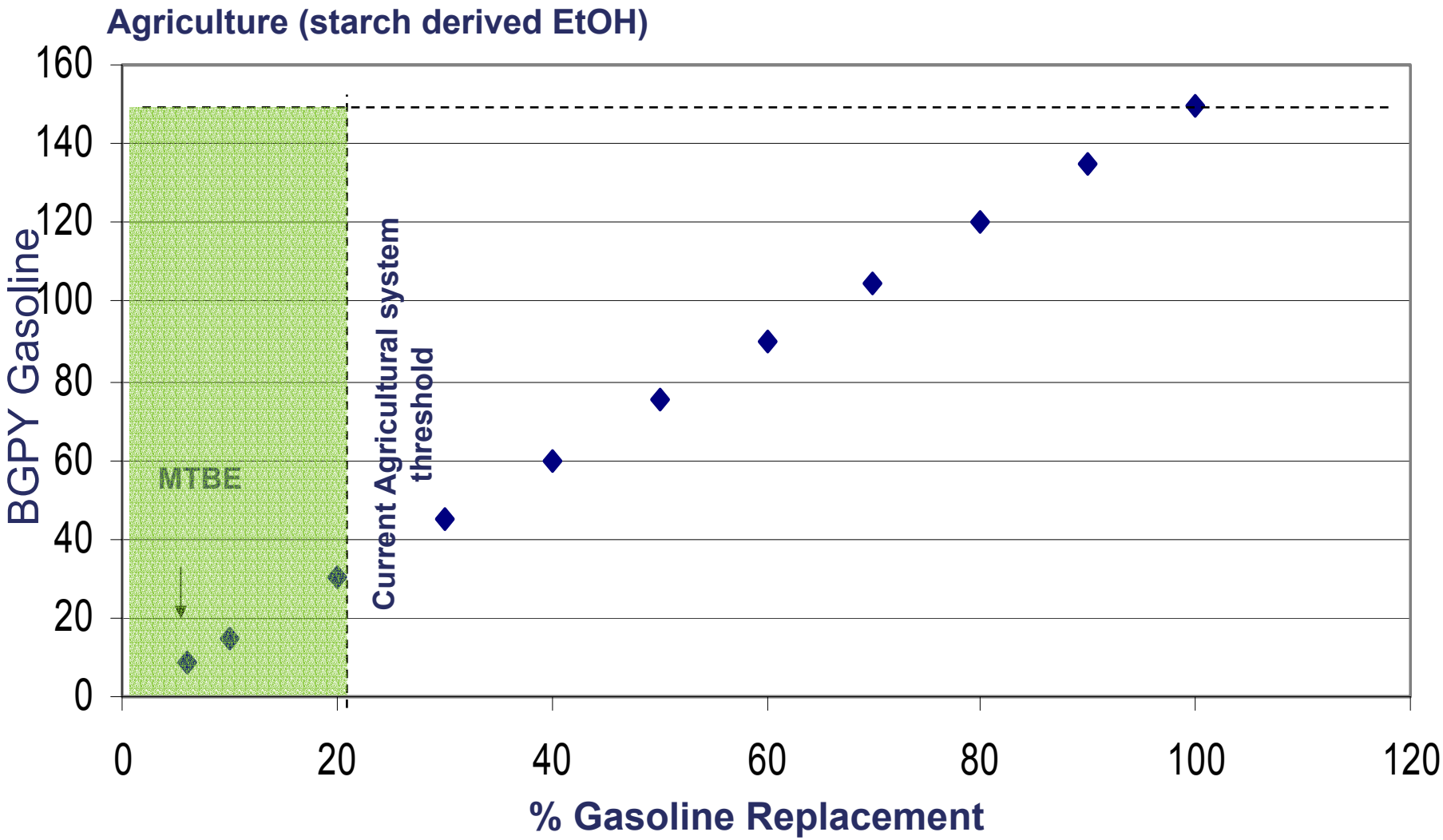

Source: Renewable Fuels Assn. 2005

The Cellulosic Biomass Challenge

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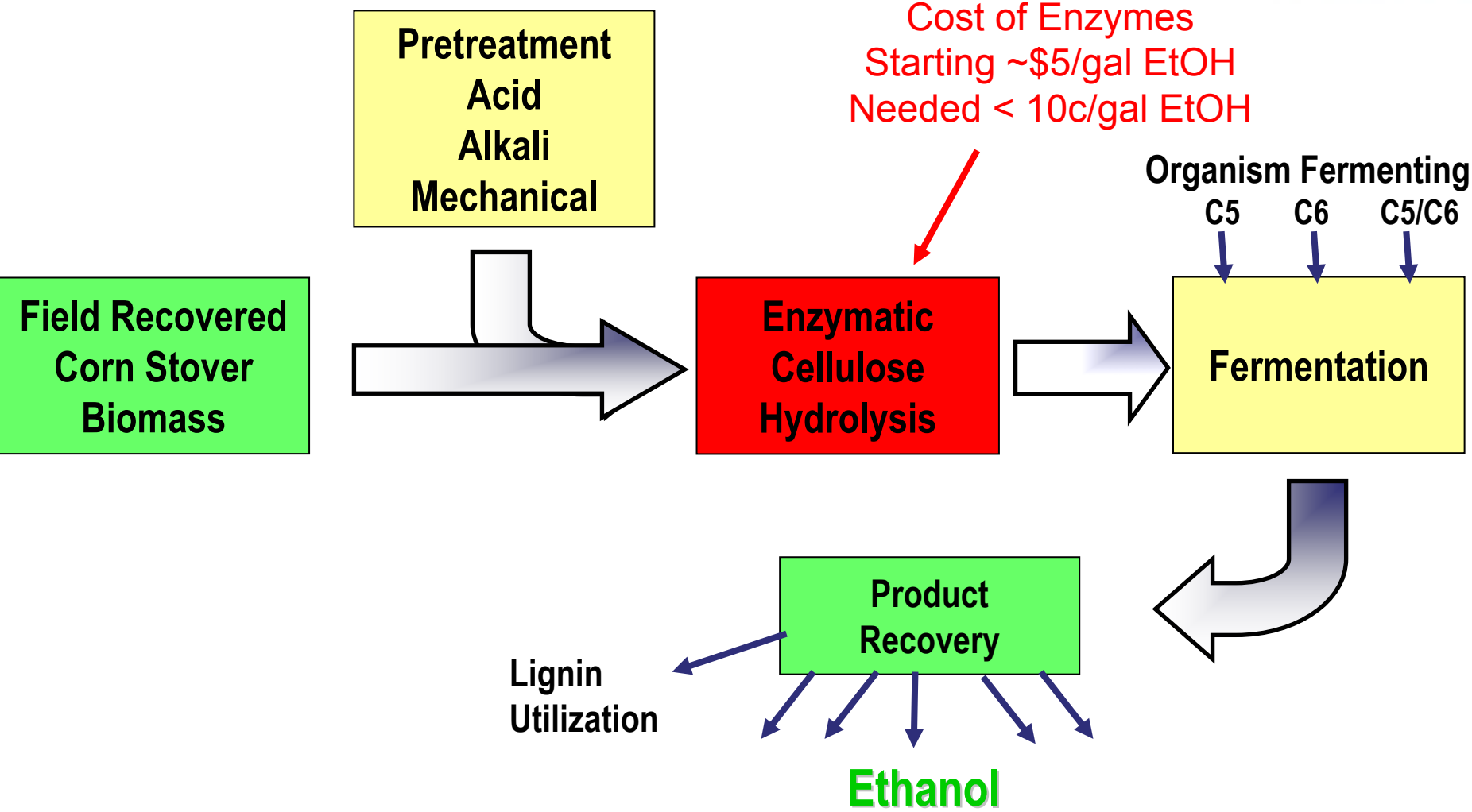

DOE / NREL Cellulase Cost Reduction Subcontract (2000-2004): STRATEGY

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- Cellulase cost reduction goal was achieved by BOTH
  - Improving production economics

    reduced $/gm enzyme
  - Improving cellulase performance

    reduced gm enzyme/gal EtOH

$$\text{Effective cellulase cost}\left(\frac{\$}{\text{gal EtOH}}\right) = \left(\frac{\$}{\text{gm enzyme}}\right)\left(\frac{\text{gm enzyme}}{\text{gal EtOH}}\right)$$

Cellulase Production cost reduction

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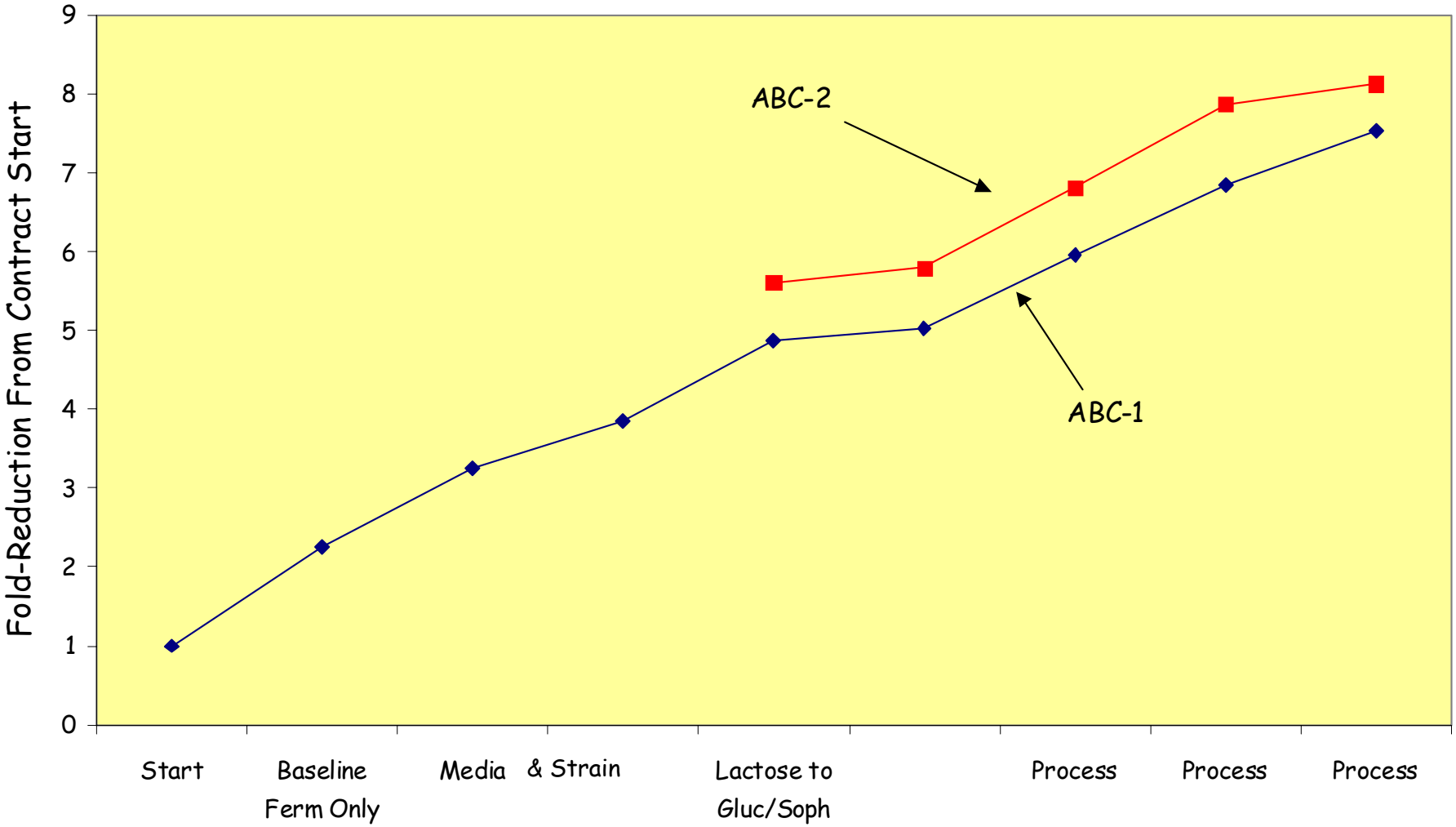

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Cellulases:
Multiple synergistic components

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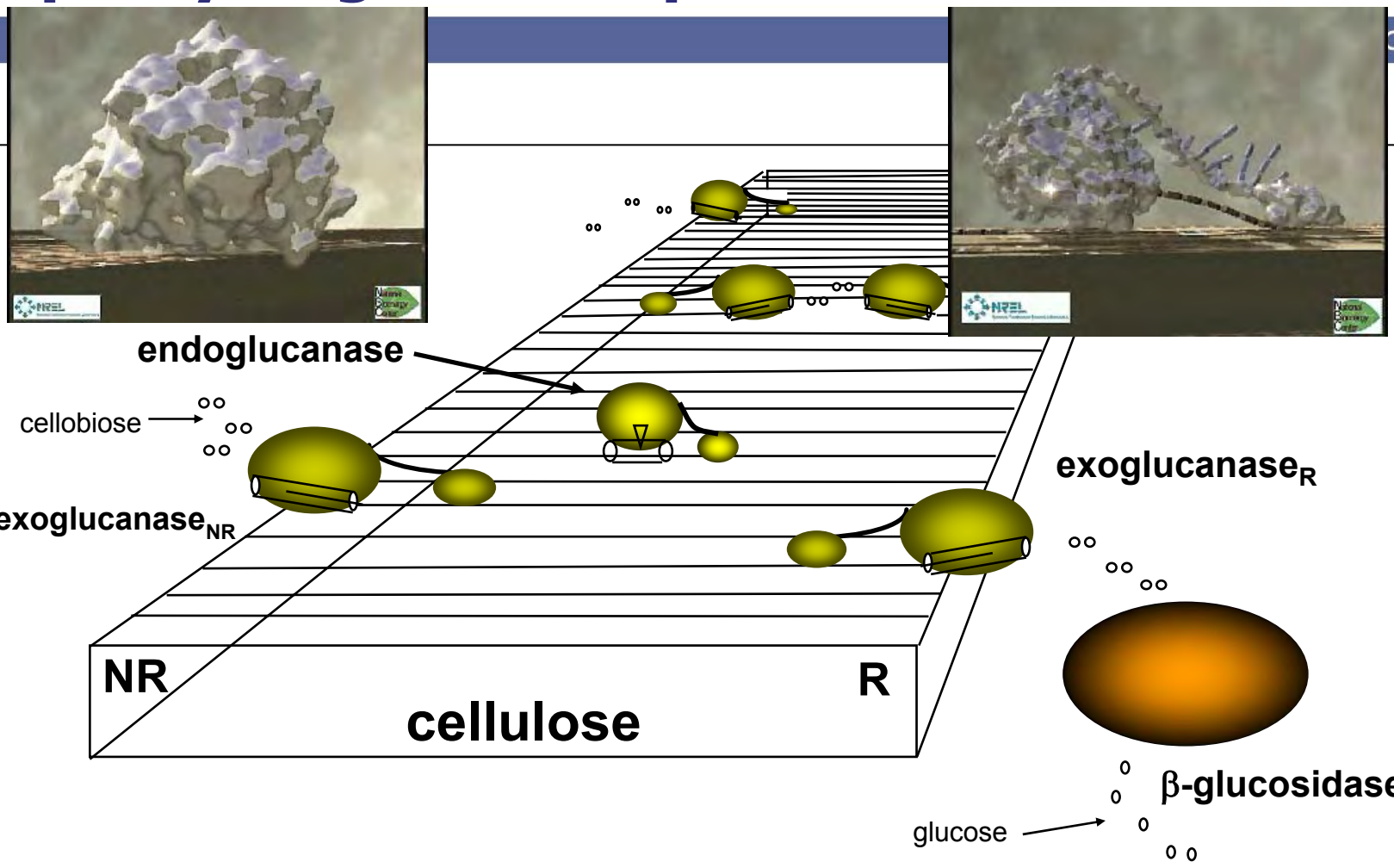

By kind permission of Dr. Mike Himmel, NREL

Improved cellulase performance

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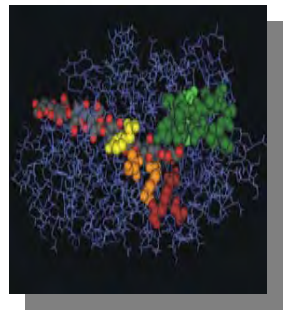

- KNOWN Cellulases, in *T. reesei* & "foreign"
  e.g. Endoglucanase E1 from *A. cellulolyticus, H. grisea CBH1, etc.*

- NEW Cellulolytic components in *T. reesei*
  Genomics and Functional Genomics
  e.g. total of >10 "EG"s, >10 "β-glucosidases"

- IMPROVED Cellulases:
  T. reesei CBH1 Protein Engineering
  e.g. Increased stability Tm +10.9°C

Improved cellulase performance

ABC *vs* Control; 3 days

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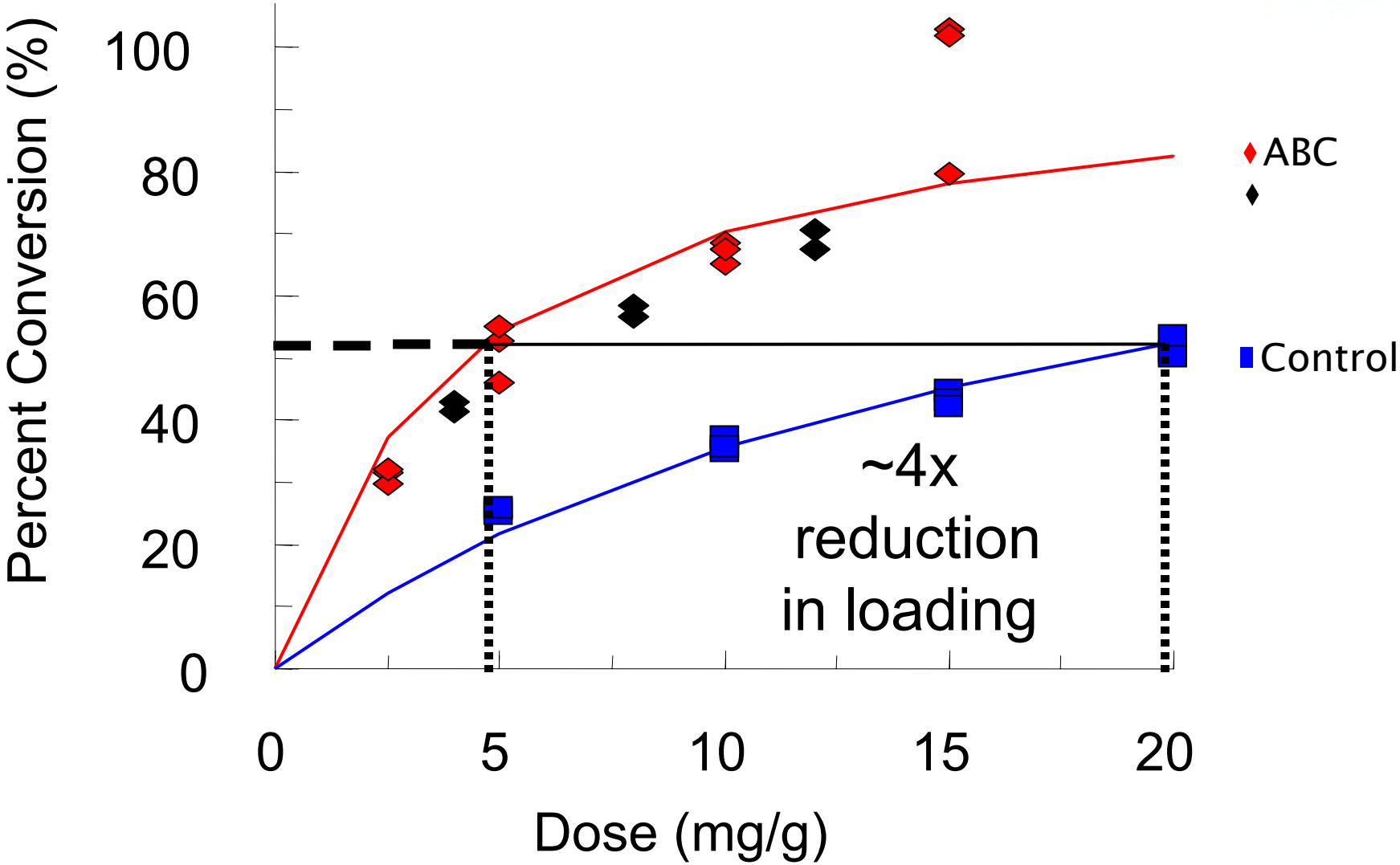

Overall Cellulase Cost Reduction

Improved cellulases produced in improved strain and process.

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Improvement	Factor
Improved cellulase production costs - Elimination of post fermentation - Media improvements - Carbon source - Other process improvements - Strain Improvements	ca. 8 X
Improved cellulase performance - Improved native enzyme mix - Improved "foreign" cellulases - Protein engineered cellulases - Recruited improved heterologous cellulases into T. reesei	> 2.5 X
Total	> 20 X

Audited by NREL

Validated by NREL

Overall Cellulase Cost Reduction

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- Starting Cost of Cellulases (existing commercial products):

  ca. $5 / g EtOH

- Final Cost of Cellulases (Advanced Biomass Cellulases) reduced ca. 30X (August 2004):

  10 – 18 c / g EtOH.

  - Includes changes & improvements to substrate (NREL / DOE)
  - SSF cost model well defined (NREL)
  - ABCs perform better in HHF or SHF processes, overall costs less well modeled.

- All technologies needed for commercial ABC production ready (enzymes, strains, production processes).

Remaining Challenges

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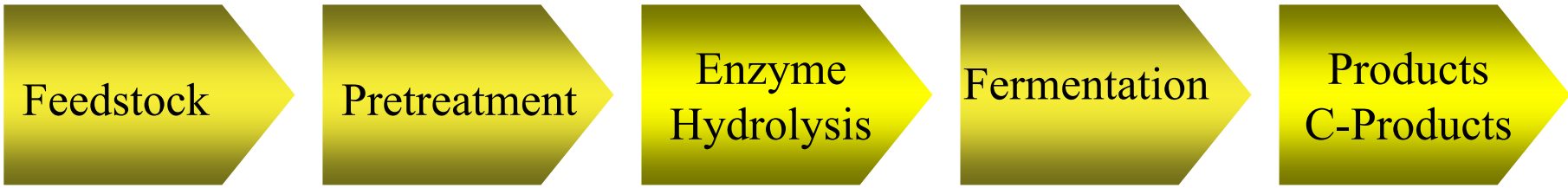

- Broad Spectrum of Viable Options
- Infrastructure required
- Cost
- Composition & Ease of pretreatment

- Many candidates
- No clear winner
- Potentially High capital cost
- By Product Interference downstream

- ~0.10-.18/Gal (NREL process economic model / Metric)
- Major Capital will be required
- Whole Cell Process
- Co-Location Requirement
- Potential Hybrid Process Requirement
- Substrate Concentration & down stream Impact

- Need a Bug with C5 Capability
- Bug needs to prosper in the potentially hostile environment of hydrolysate
- Yields must be competitive

- Co-product are important

Remaining Challenges
Process Integration

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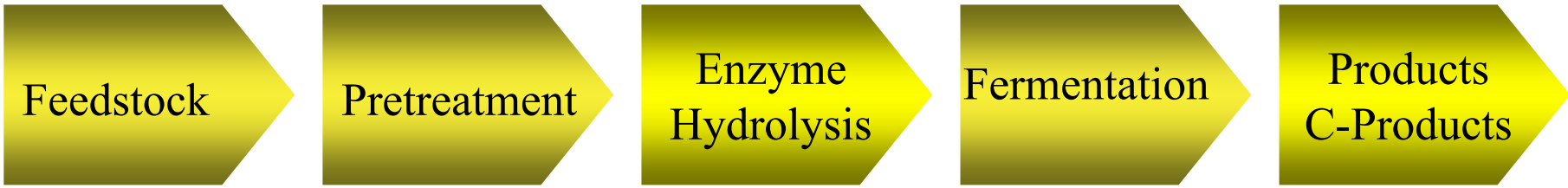

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Normal enzyme product development

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Work with commercial customers to

- Integrate ABC into their saccn. processes:
  SSF, HHF, SHF etc
- Customize ABC for their pre-treatments and fermentations.
- Reduce overall LC conversion process costs:
  Explore use of enzymes in pre-treatments and fermentations to reduce those unit costs.

In parallel, further reduce ABC costs:

- Known opportunities
- New research

BUT

Normal enzyme product development

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  Explore use of enzymes in pre-treatments and fermentations to reduce those unit costs.

In parallel, further reduce ABC costs:

- Known opportunities
- New research

BUT there are no large-scale commercial LC conversion customers.

ABC enzyme product development

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- Work with LC conversion process developers:
  - Industrial e.g. Cargill-Dow / NatureWorks
  - Academic e.g. CAFI II
- Leverage ABC use into existing biomass conversion processes e.g.
  - Starch ethanol
  - Cane sugar
  - Beet sugar……
- Explore other conversion opportunities e.g.
  - Waste paper recycling
  - Pulp & paper processing
  - Municipal waste…….
- Continued Genencor LC-Biomass conversion R&D.

Improved Production Economics Operating System Approach

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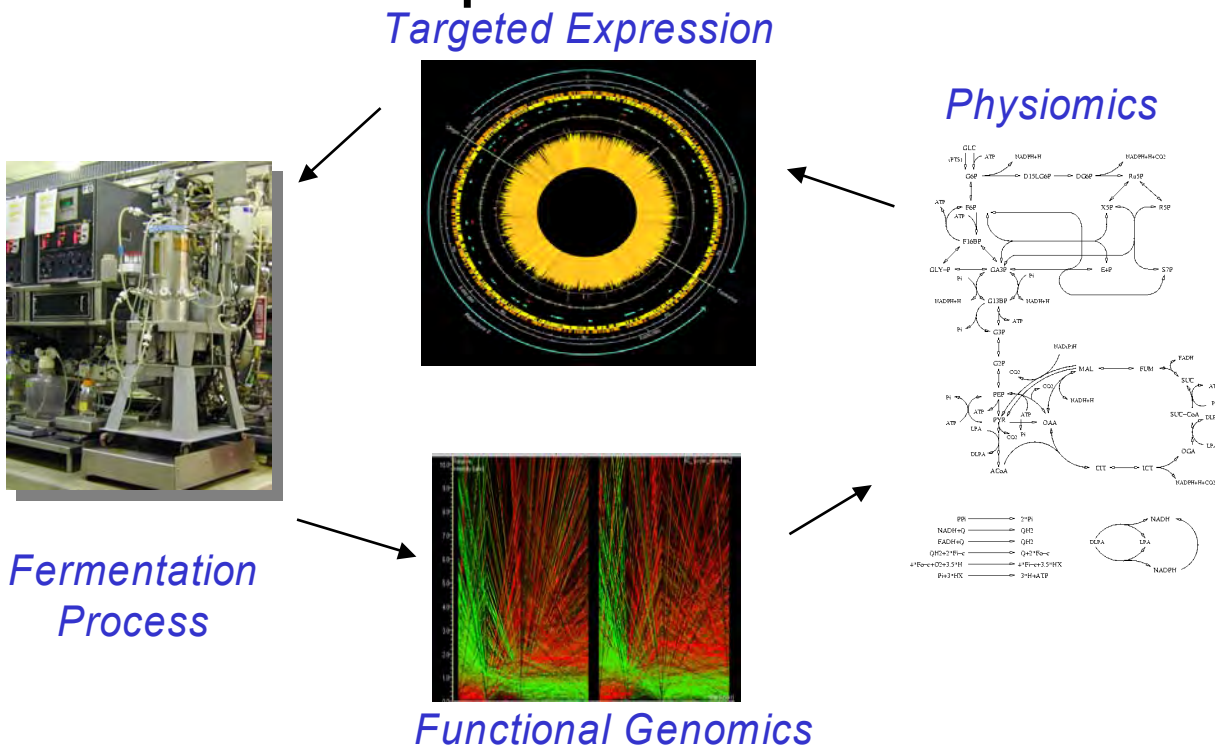
- Production Strain Development
- Production Process Improvement



Process & Strain Improvements

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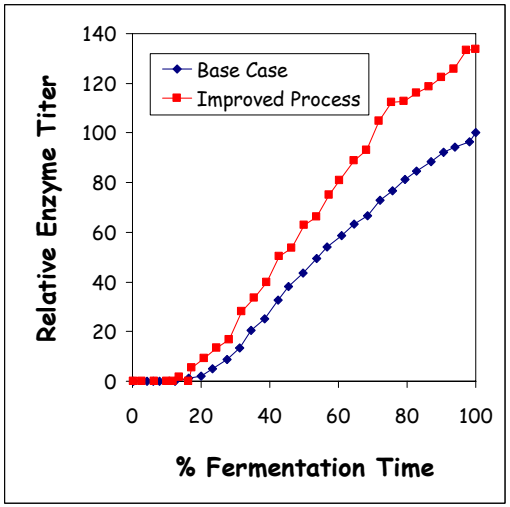
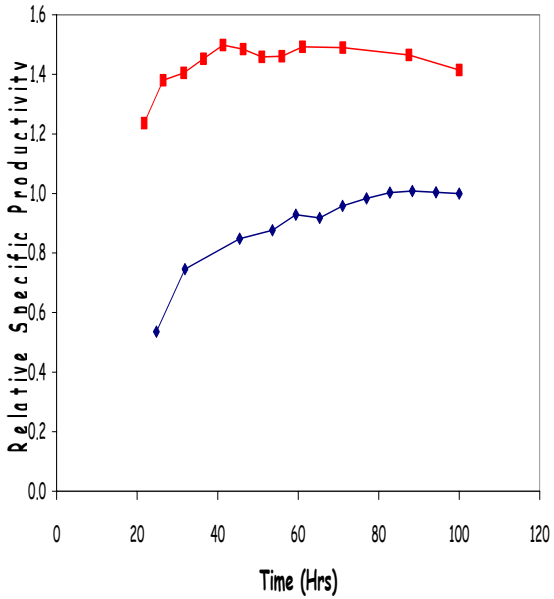
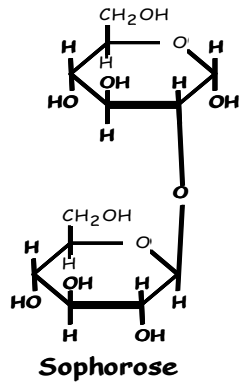


Process Improvements, Protocols, Media, etc



Classical Mutagenesis Yields: Major enhancement to specific productivity



Metric	% of Lactose Control
Volumetric productivity	117
Yield (cellulase on sugar)	112

In Situ Sophorose Production

Technical Strategy

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Engineer & recruit limiting cellulase components that have enhanced thermostability / specific activity

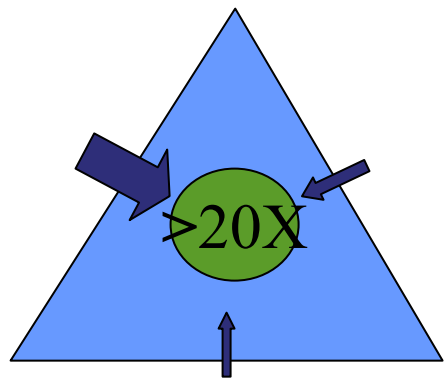
Protein Engineering, Novel Cellulolytic Activities, Assays and Screens

Develop an enhanced *T. reesei* production organism (Platform organism) to produce all the key activities in one host

Regulation, induction, derepression, genomics

Improve the manufacturing Process to minimize production cost

Breakthrough economics required



What Goes Around Comes Around

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- Wood was originally the major energy source for the US until approximately 1890.
- EtOH Commonly Used as a transportation Fuel in the 1920's
- Coal then provided more than 50 % of the nation's energy until around 1940.
- Now, Oil and Gas are the major source of energy and materials used in the US.
- However, increasing demands have started again the use of Carbohydrate as energy source, first as MBTE replacement.

Starch vs. Biomass comparison

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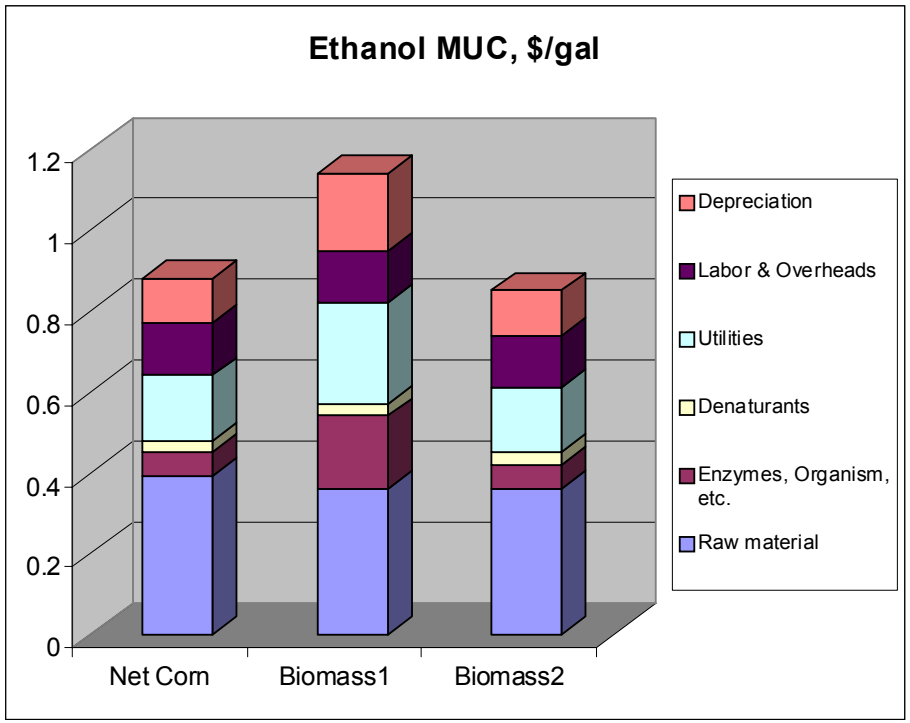

- With DDG Credit, Net Corn Raw Material Cost Is Very Similar To That Of Biomass Process
- Cost Components Of Biomass Process Other Than Raw Material, Can At Best Match Those Of Corn Process (Scenario Biomass2),
- Market Dynamics (High Demand, Lower Supply Of Corn) Could Change, Making Corn Based MUC Higher Than That Of Biomass Process
- Incentives (CO_2 Credit, Subsidies, Higher Petroleum Prices) Could Make Net Biomass MUC Lower Than That Of Corn Process

NREL/TP-580-28893. Oct 2000.

Energy cost comparison
(@$50/bbl crude)

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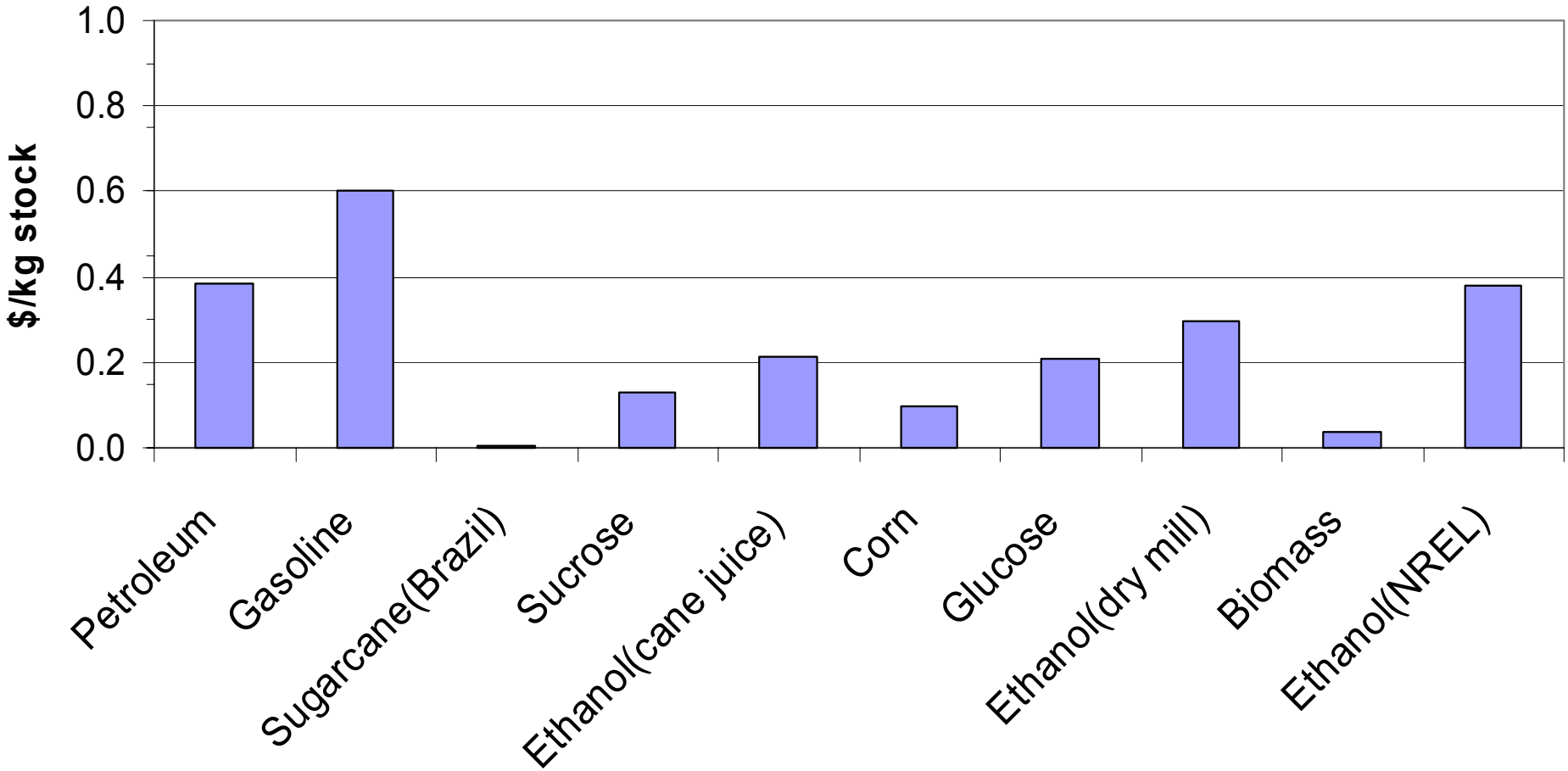

NREL/TP-580-28893. Oct 2000.

Substrate/Process Evolution

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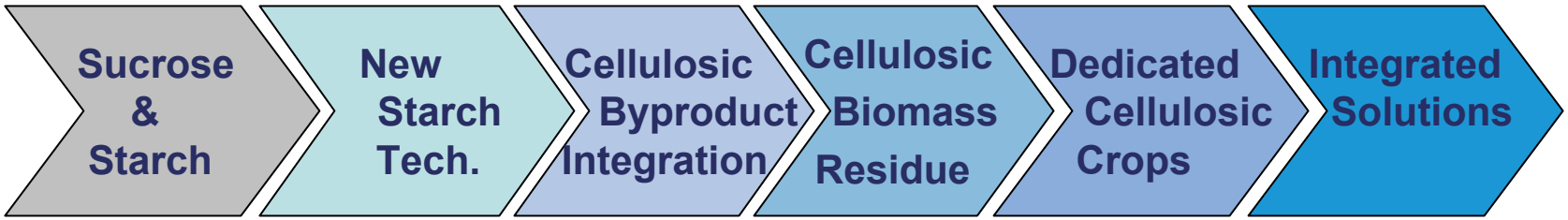

>250M Gal EtoH/yr by2013

Fermentable Sugars

Ethanol

Public Policy Role.
Policy Initiatives are Critical

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Three Policy Steps Needed to Make Biomass Sugars & Ethanol Affordable & Sustainable

- Invest in continued R&D with special focus on integration & commercialization challenges
- "The first billion gallons": Incentives to "de-risk" investment in pioneer plants to overcome advantages of incumbent technology
- Adopt a renewable fuel standard and flex-fuel vehicle requirement