DOE Bioenergy Technologies Office (BETO) 2019 Project Peer Review

Continuous Membrane Assisted IBE Fermentation from AVAP® Cellulosic Sugars

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Biochemical Conversion

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Thomaston Biorefinery

Project Goal Statement

Create an economically viable process for the production of butanol from the underutilized natural resources domestically available:

- economically sustainable biofuel at or below DOE target selling price
- suitable for roll-out in multiple regions containing agricultural residues and underutilized forest residuals
- able to compete in the butanol market without subsidy

Quad Chart Overview

Timeline

BP-1: Jul. 22, 2015
BP-2: Mar. 1, 2017
End: Mar 30, 2018

Barriers Addressed

Ct-G. Efficient Conditioning
Ct-J. Process Integration
Ct-L. Aqueous Phase Utilization

	Costs (kUSD)			
	Pre FY17	FY17	FY18	Total Planned Funding
DOE Funded	1,723	1,027	339	3,089
Project Cost Share	662	592	728	1,949

Objective

Produce an economically sustainable biofuel at or below DOE target selling price

End of Project Goal

Demonstrate the technical performance of the API IBE pilot plant, and model a heat integrated plant to arrive at or below the DOE target selling price for biofuel.

- IBE alcohols yield 0.30-0.33 g/g biomass
- Average productivity of 10-12 g/l/h
- Fermentation solvent titer of 15 g/l
- Continuous pilot operation for 500 hr.

Project Overview

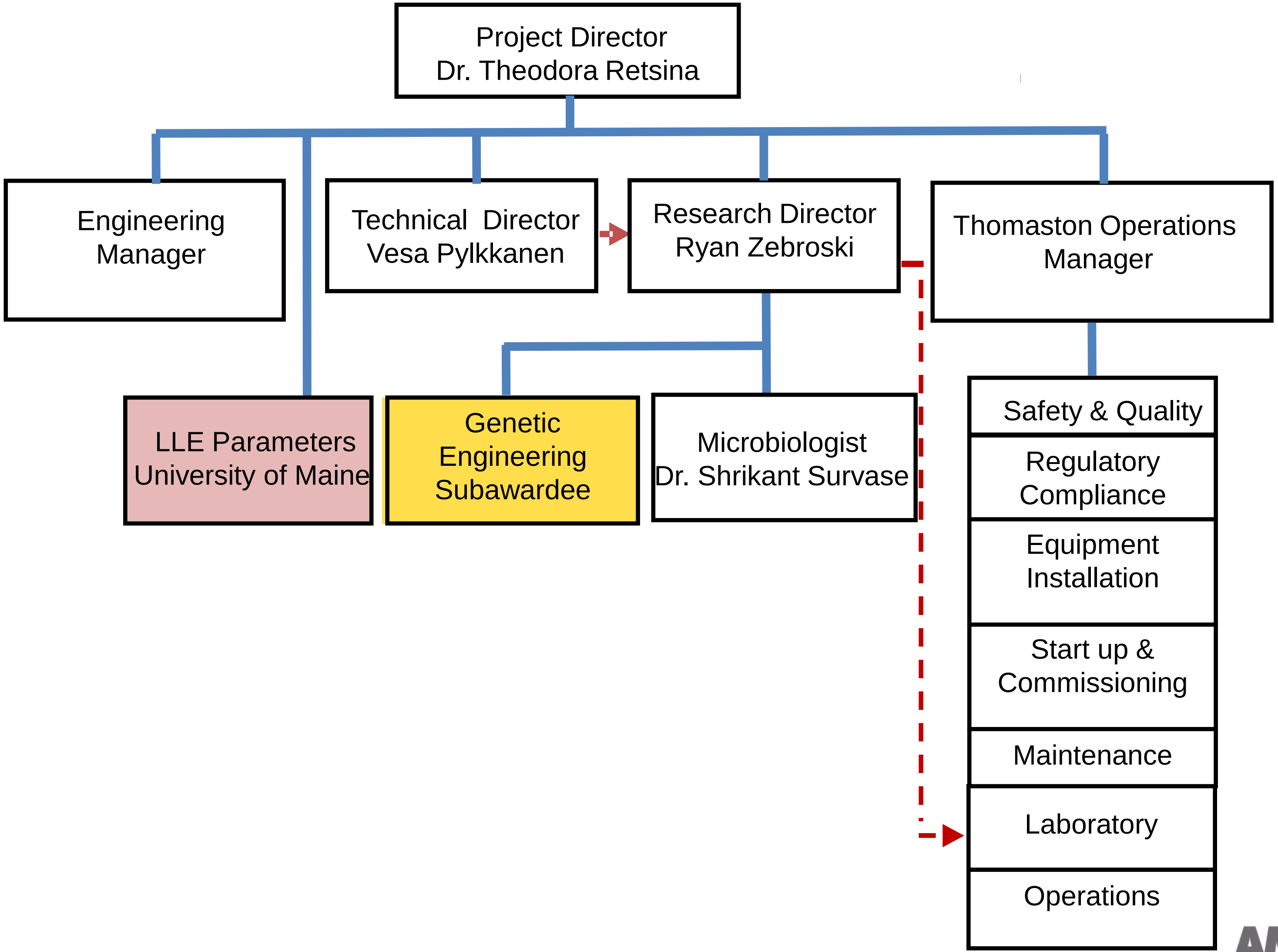
- This project utilizes pine wood, corn stover and cane straw derived sugars from the AVAP process pilot plant in Thomaston, Georgia.
- n-butanol, isopropanol and ethanol (IBE) are produced by fermentation utilizing the AVAPClo™ strain (genetically modified *Clostridia acetobutylicum*).
- IBE alcohols are approved blending components for gasoline and are upgradable to drop-in fuels.
- Fermentation productivity target increased 20-fold over traditional batch process by continuous membrane assisted fermentation to achieve a target fermentation capital cost reduction of 50%.
- Traditional steam stripping solvent recovery has been replaced with a novel non-toxic liquid/liquid extraction, targeting reduction of thermal energy use by 50%.
- Recycling water, unused sugars, nutrients and metabolic intermediates back to fermentation is demonstrated from the liquid/liquid extraction raffinate.

Project Overview

- Challenges to overcome (background):
  - Current *Clostridia* strains produce low value acetone product (30%).
  - Butanol inhibits cell~~s~~ growth and production at very low concentration of ~2%.
  - Pentoses are not readily co-consumed in the mixed cellulosic sugars.
  - Low product titers lead to a high energy demand and a large waste water volume.

- Solutions Developed
  - Use modified *Clostridium* to induce isopropanol production instead of acetone.
  - Recycle cells in continuous fermentation to accelerate solvent production.
  - Use novel liquid/liquid extraction to recover alcohols from broth and reuse water.

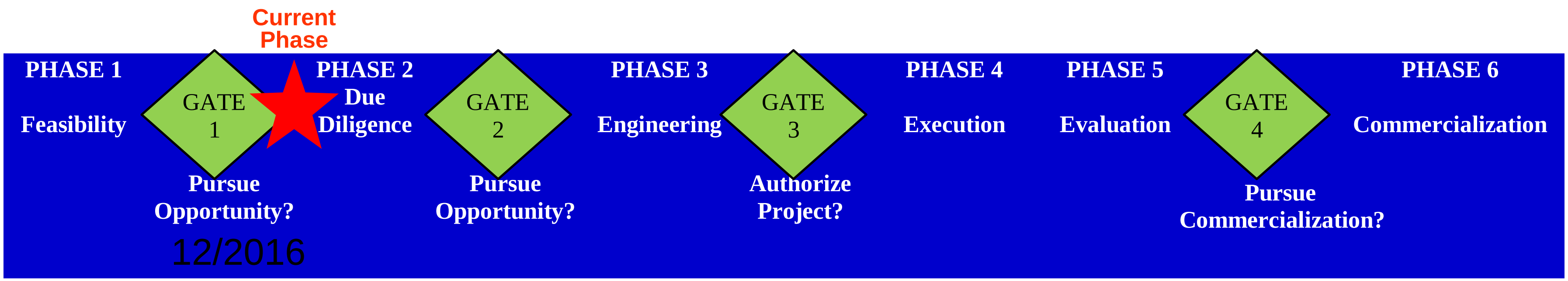
Project Organizational Chart - Key Personnel



Management Approach

- API's **project management plan incorporates:**

- **Heat and material balance** review at establishing project feasibility
- **Basis of design document** to set engineering parameters
- Process **hazard analysis** to foresee process risks
- Monthly **budget, schedule and resource** meeting
- **Stage-Gate Process** each defined by specific activities with milestones to decrease technical and economic uncertainty and risk



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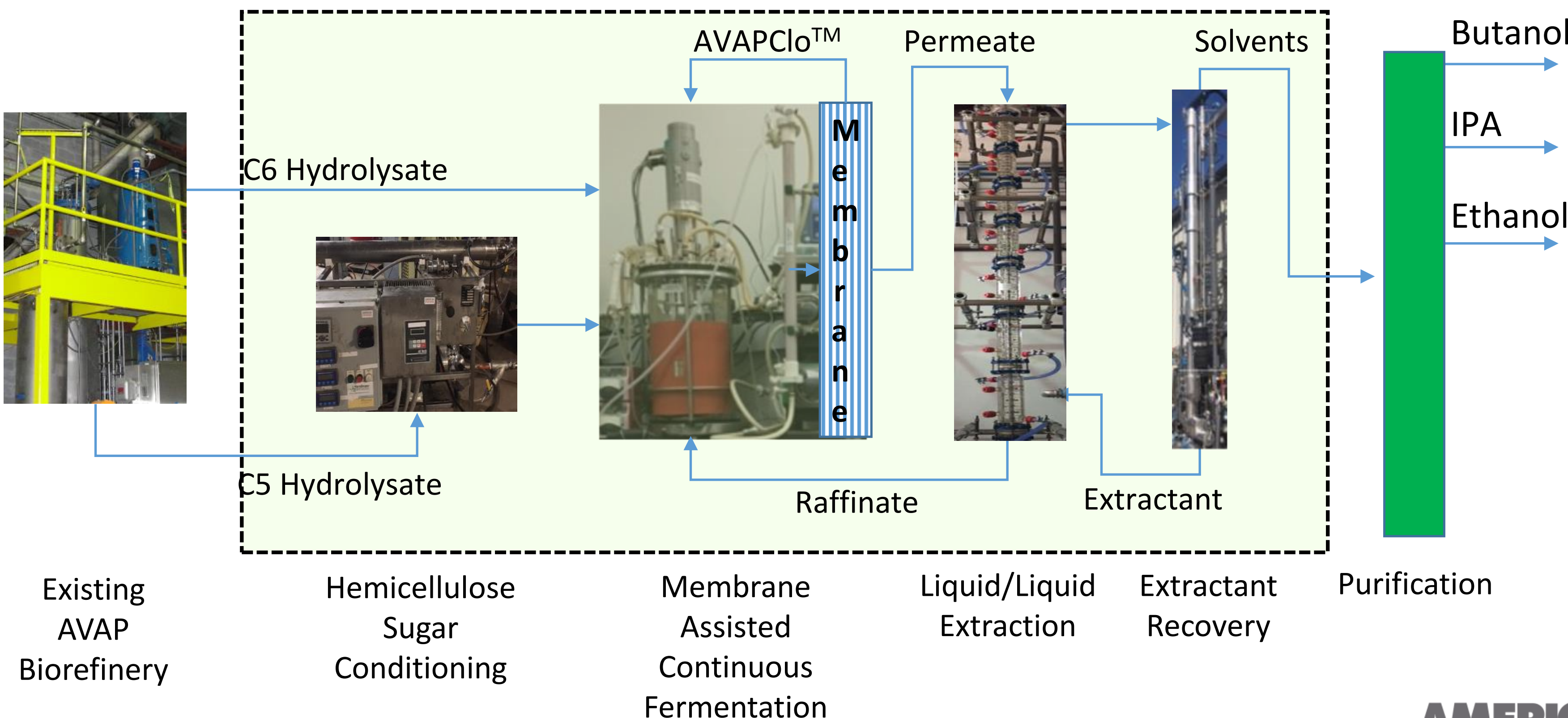
Technical Approach

- API's **technical R&D plan incorporates:**

- **Comprehensive heat and material balance** using simulation models
- **Analytical tests** to verify the data for baseline model
- Process **optimization** at smallest practical scale
- **Extended performance test** for robustness and recycle streams
- Process **Scale-up** at factor of 10 with **integrated operation**
- **Value engineering** to improve project cost against a baseline that integrates techno-economic evaluation
- Use **Process Integration** to minimize energy demand

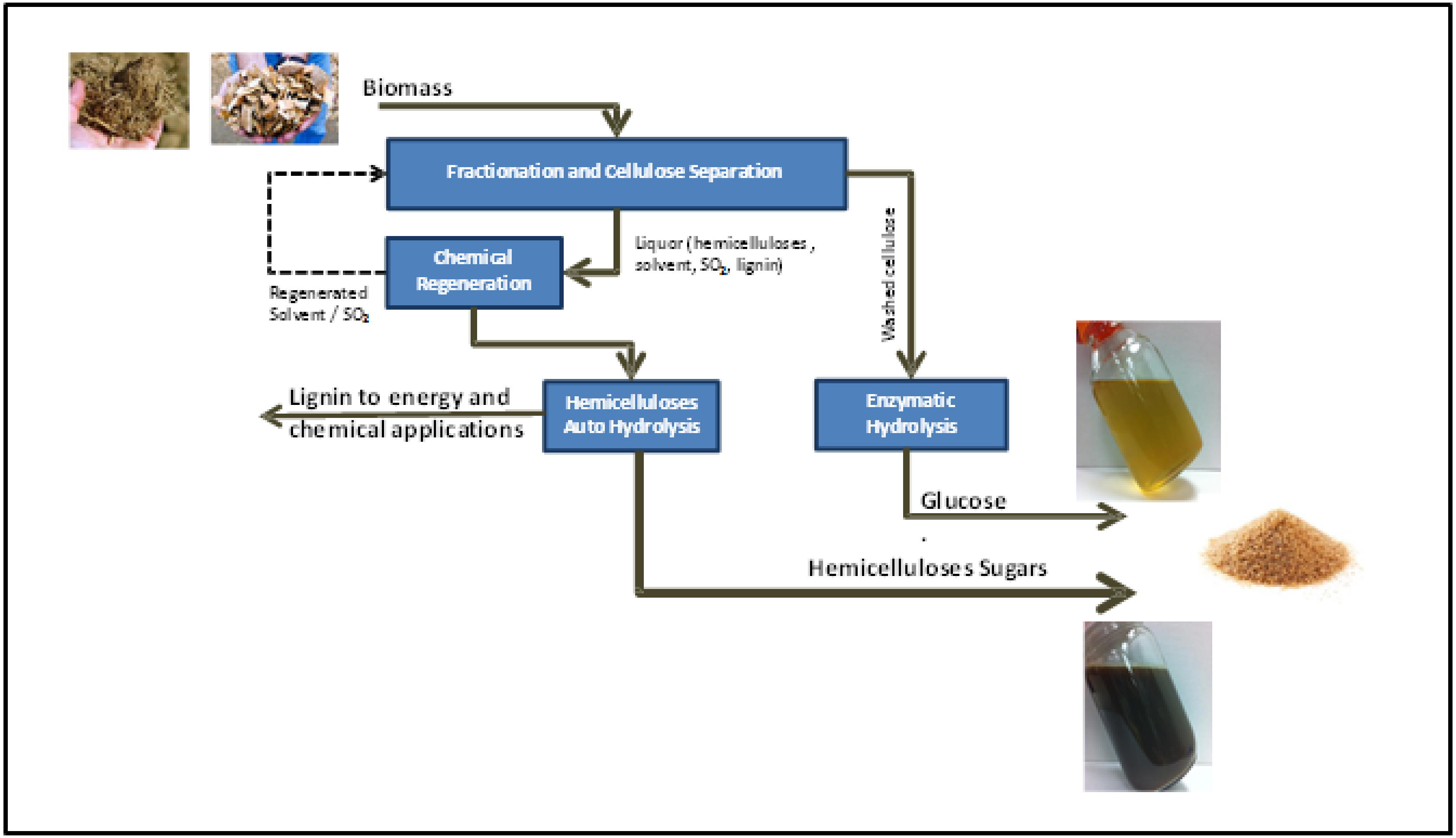
Project Scope

AVAP-IBE demonstrates integrated, pilot scale IBE production from lignocellulosic sugar using membrane assisted recycle of GMO Clostridia. The pilot plant includes product recovery from the dilute broth using novel non-toxic liquid/liquid extraction.



AVAP Biomass Fractionation

Cellulosic and hemicellulosic sugars are produced in the existing biorefinery



Critical Success Factors

- Technical Targets
  - Produce IBE alcohols at overall yield of 0.30-0.33 g/g from original biomass sugars (Benchmark 0.29 g/g from batch fermentation)
  - Reach average productivity of 10-12 g/l/h (Benchmark 0.5 g/l/h from batch ferm.)
  - Operate integrated pilot plant 500 hours continuously
  - Recover at least 90% of butanol and 99% of the extractant in one pass

- Financial Targets
  - Reduce IBE production cost to target $2/gallon
  - Maintain facility capital cost at below $10/annual gallon

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Accomplishments

- Established conditioning scheme to three biomasses
  - No conditioning was necessary for any cellulosic (C6) hydrolysate
  - Established conditioning scheme for hemicellulosic (C5) hydrolysate
- Progressively optimized fermentation parameters
  - **Milestone 3.1**: Fermented 500 hours uninterrupted using corn stover C6 hydrolysate
  - Reached C5 productivity equivalent of pure xylose in the same system
  - Reached a pine C5&C6 average productivity of 10 g/l/h at 0.33 g/g yield in pilot
  - Reached a corn stover C5&C6 average productivity of 8.85 g/l/h at 0.36 yield in pilot
- Designed and Operated LLX and Reactive Distillation Columns
  - **Milestone 8.1**: Performed 100-hour integrated run to with 97.5% butanol recovery
  - **Milestone 9.3**: Non-toxic extractant proved good selectivity and low raffinate loss
  - Recycled half of the raffinate to fermenter dilution with no negative impact
  - Achieved 90% butanol recovery with < 0.04% extractant loss at 0.4:1 O:A
  - Produced make-up extractant in reaction section of distillation column.

Technical Targets and Results Achieved

Parameter/Performance	Unit	Target	BP1 Achieved	BP2 Achieved
Feed (hydrolyzate type)		Pine	AVAP Pine C5&C6	AVAP Corn Stover C5&C6
Fermentation				
Total sugars to total solvents (ABEI)	g/g	0.33	0.33	0.36
Fermentation titer, total solvents	(g/L)	15	15.4	14.6
Average volumetric productivity	(g/L-h)	11	10.1	8.8
Acetone-to-Isopropanol conversion	%	>50%	14%	19%
Maximum volumetric productivity	(g/L-h)	12	13.1	11.9
Liquid/Liquid Extraction				
Recovery of Butanol	%	90	97.5	90
Extractant Loss	%	1	0.1	0.04

Concurrent Membrane Assisted Fermenters

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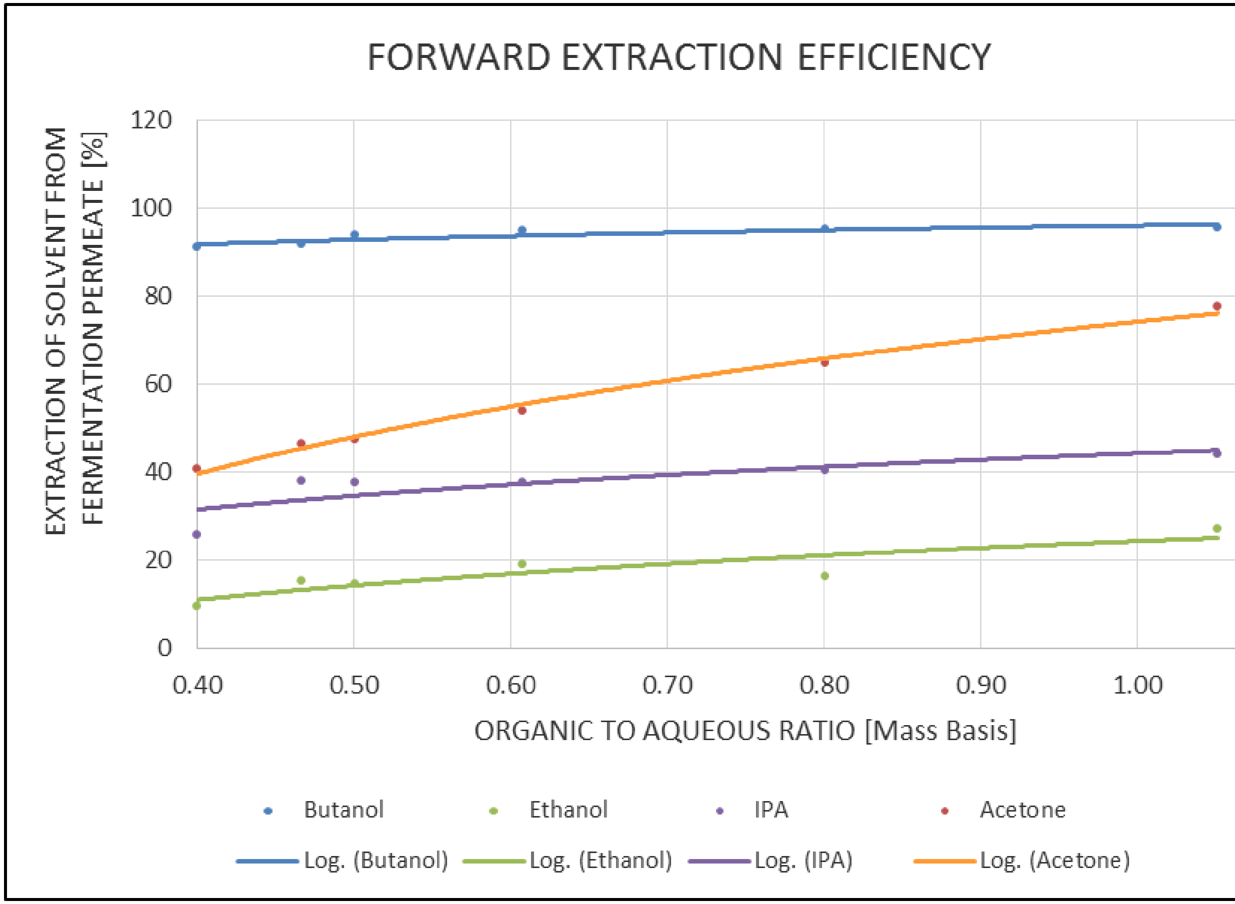
Liquid/Liquid Extraction



Major Challenges

- Conversion of C5 sugars in the presence of Glucose
  - Separate hemicellulose sugar to concurrent fermentation - successful
  - Grow cells in C6 fermentor and purge into C5 fermentor - successful
- Conversion of Acetone to Isopropanol reduced over time
  - Use gene alteration to induce more isopropanol – attempt made in BP2
- Pine wood hemicellulosic hydrolyzate proved more inhibitive
  - Add conditioning steps to remove lignin compounds - successful
  - Optimization of the scheme completed investigation in BP2
- Foaming and two phase flow through membranes
  - Scale down industrial foam control methods employed in BP2
  - Viable cell density equipment sourced for application.
- Liquid/Liquid Extraction and recycling of raffinate:
  - Source of infection due to location of sterile boundary filter – easy to remedy.
  - Beneficial effect in the recycle of nutrients and metabolic intermediates!

Economic Opportunity

- The base case analysis (1200 dry tpd at $65/ton) shows that the selling price would have to be $3.65/gallon IBE ($1242/ton) to have IRR>0% and $4.88/gallon IBE ($1490/ton) to reach positive NPV.
- Sensitivity analysis was used to determine process optimization steps that can be used to achieve profitability while using the targeted MSP of $3/gge gasoline equivalent.
  - Convert remaining acetone to isopropanol ($0.65/gal).
  - Increase xylose utilization to 75%, resulting in a 10% overall yield improvement ($0.50/gal).
  - Recovery of SO_2 & lime, on site manufacture of enzyme ($0.33/gal).
  - Reduce from start-up staffing to normal operational staffing ($0.15/gal).
  - Reduce loose ash in feedstock from 10.9% to 5.5% or less through payment based on quality. ($0.13/gal)

Relevance of AVAP-IBE Project

Supports BETO mission to create transformative technology and goal to develop commercially viable bioenergy and bioproducts by:

- Utilizing multiple feedstocks to enable nationwide implementation on existing underutilized or idle resources.
- Utilizing genetic engineering to eliminate lower value by-product
- Increasing productivity and reducing energy leading to target DOE MFSP $3/gge
  - Develop a novel fermentation scheme with productivity 20X over batch fermentation
  - Utilize a non-toxic LLX process to reduce energy use and nutrient requirements by ~50%.

The R&D on specific biomass conversion technology supports objectives by:

- Demonstrating robust fermentation technology suitable for bacteria
- Developing novel separation technology for butanol separation
- Developed optimized conditioning for bacterial fermentation of C5 hydrolysate
- Intensifying of an integrated cellulosic biofuel process

Future Work

- Fermentation System Modifications
  - Relocate sterile boundary of C5 hydrolysate.
  - Install on-line viable cell density and cell density instruments

- Genetic Engineering
  - Increase AVAPClo™ propensity to produce isopropanol instead of acetone
  - The goal is to eliminate acetone production all together

- Test C5 Finishing techniques

Expected outcome

- Licensing of technology.

Summary

- **Relevance:**
  - The AVAP-IBE intensified process is suitable for higher alcohol production
  - Replication potential in to other fermentation/purification processes
- **Approach:** API uses proper R&D scale-up followed by TEA in a Stage-Gate Process to ensure that project is aligned with the critical success factors
- **Success factors:**
  - Integrated process with overall yield 0.30-0.33 g/g of yield lignocellulosic sugars
  - Continuous fermentation productivity of 10-12 g/l/h to halve Capital Expense
  - Low energy LLX with >90% butanol removal at <1% extractant loss
  - Commercial target OPEX of $2/gal at CAPEX of <$10/annual gallon alcohols
- **Accomplishments:**
  - Continuous fermentation at 10 g/l/h productivity and 0.33 g/g solvent yield
  - Integrated extractant recovery of >99.9% with 90% of butanol removed
- **Commercialization challenges:**
  - Profitability at low oil price without a co-product