Continuous Membrane Assisted IBE Fermentation from AVAP® Cellulosic Sugars

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Bioenergy Technologies Office
2017 Project Peer Review- Biochemical Conversion

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Thomaston Biorefinery

Sugar is the Crude®

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

- Project start date
  - BP-1: Jul. 22, 2015
  - BP-2: Mar. 1, 2017
  - End: Nov. 30, 2017
- Pilot Startup: Nov. 1, 2016
- Percent complete: 70%

Barriers Addressed

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

Budget

- Total project funding
  - DOE share: $3.089 million
  - Cost share: $1.949 million
- Funding received
  - 2015: $210,902.98
  - 2016: $2,003,767.02

Project Participants

- Project Management
  - American Process Inc.
- L/L extraction
  - University of Maine
- Genetic Engineering: (T.B.A.)
- Sugars: AVAPCo (affiliate of API)

Project Summary Description

- This project utilizes lignocellulosic 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 of 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 has been achieved for 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

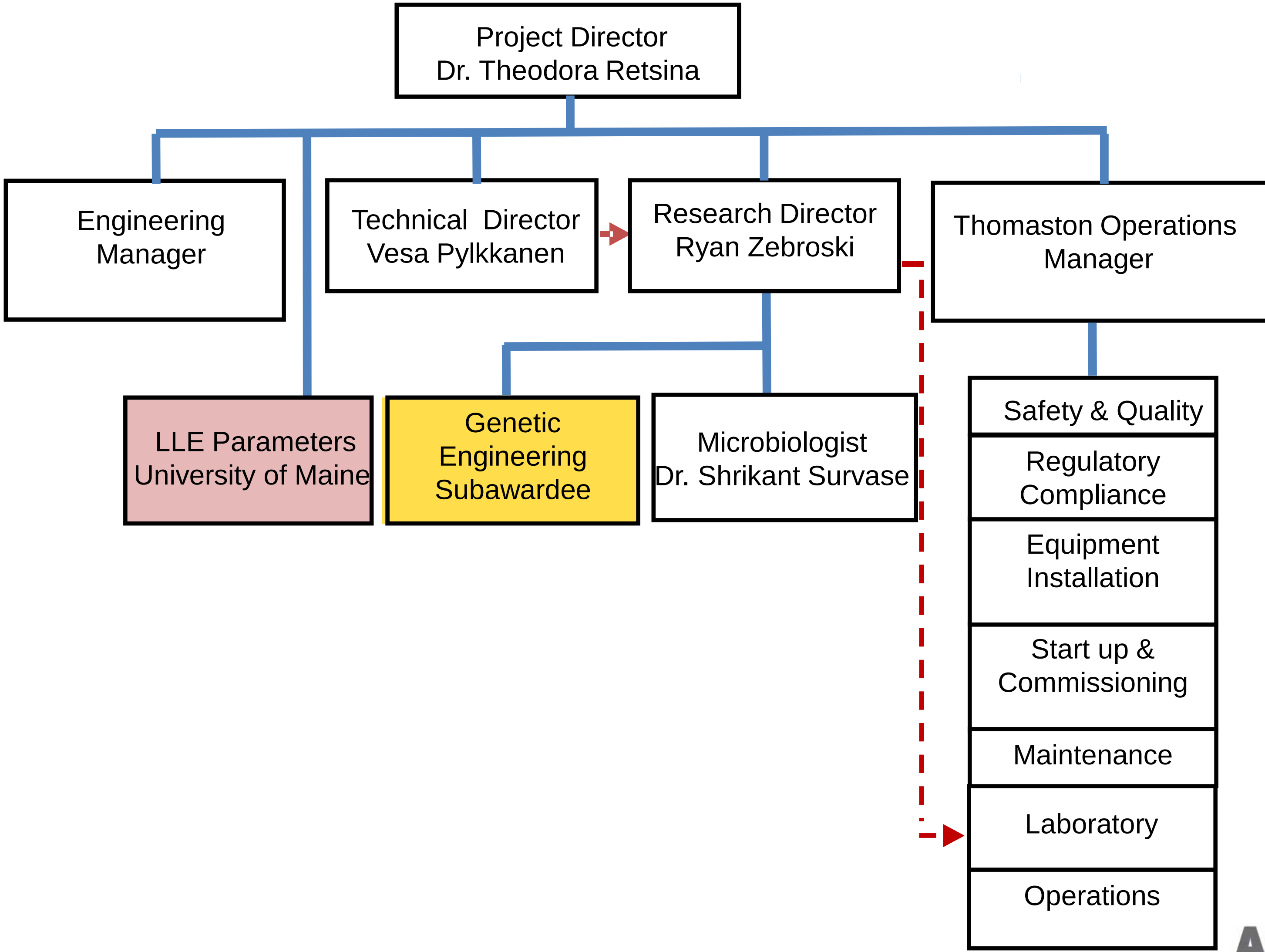
Challenges to overcome (background):	Proposed Solutions
Current *Clostridia* strains produce low value acetone product (30%)	Use modified *Clostridium* to induce isopropanol instead of acetone
Butanol inhibits cell growth and production at very low concentration of ~2%	Recycle cells in continuous fermentation to accelerate solvent production
Pentoses are not readily co-consumed in the mixed cellulosic sugars	Filed patent disclosure for novel concurrent continuous fermentation scheme with raffinate recycle
Low product titer lead to high energy demand and a large waste water volume	Use novel liquid/liquid extraction to recover alcohols from broth and reuse water

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

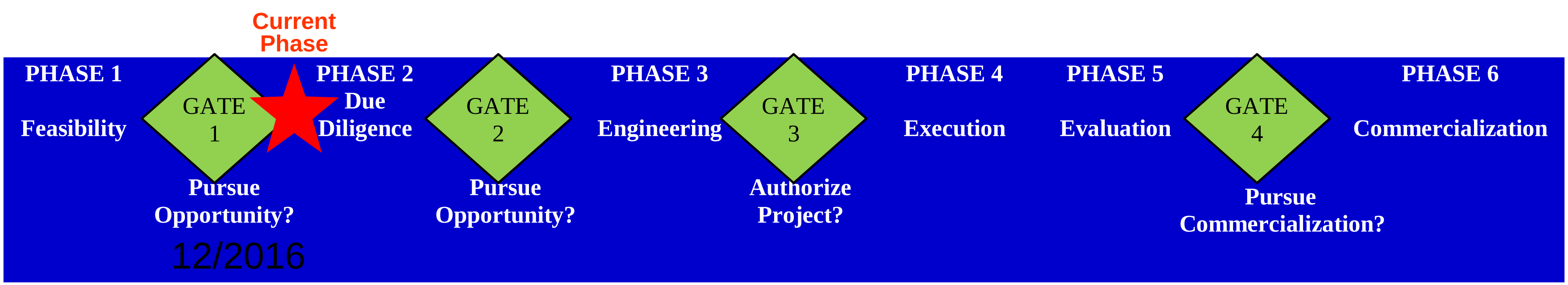
Project Organizational Chart w/ Key Personnel



Management Approach

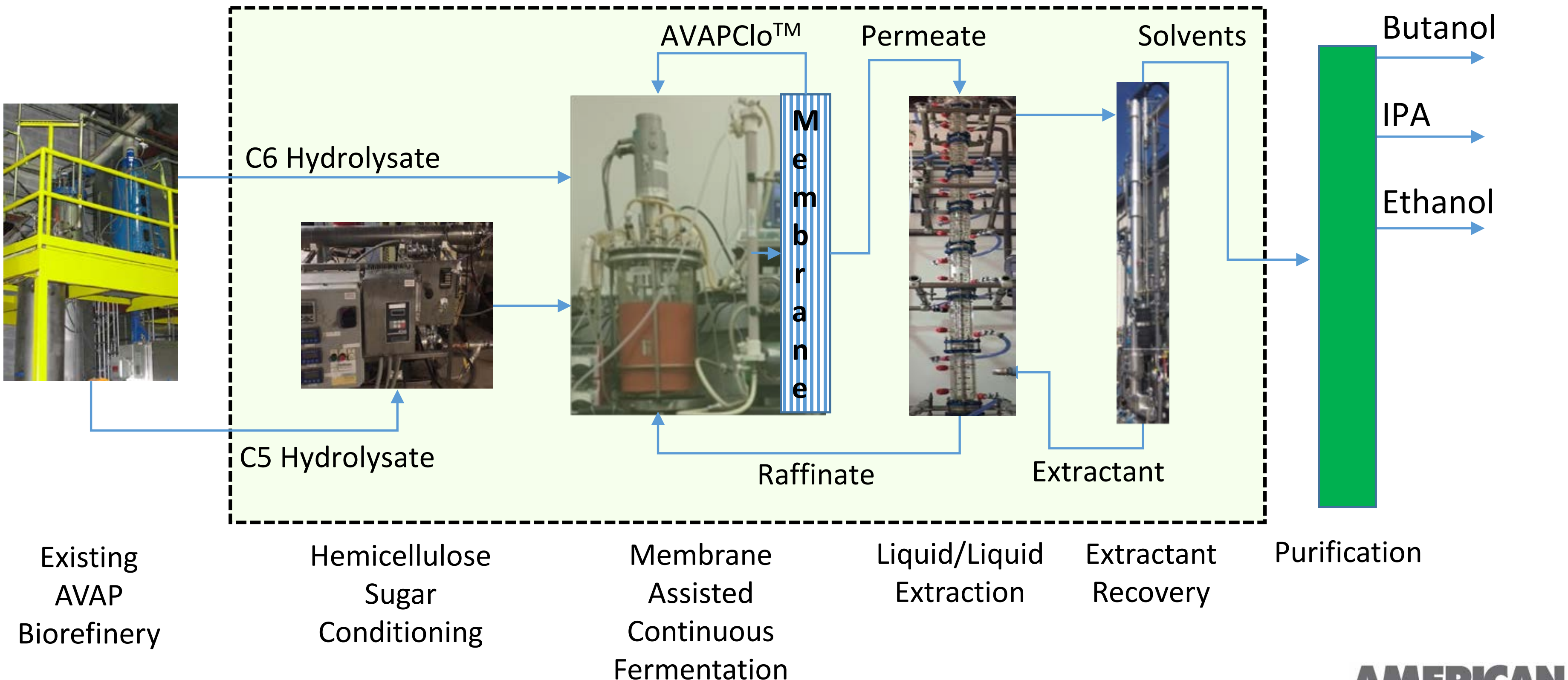
- API's project management plan incorporates:

- 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



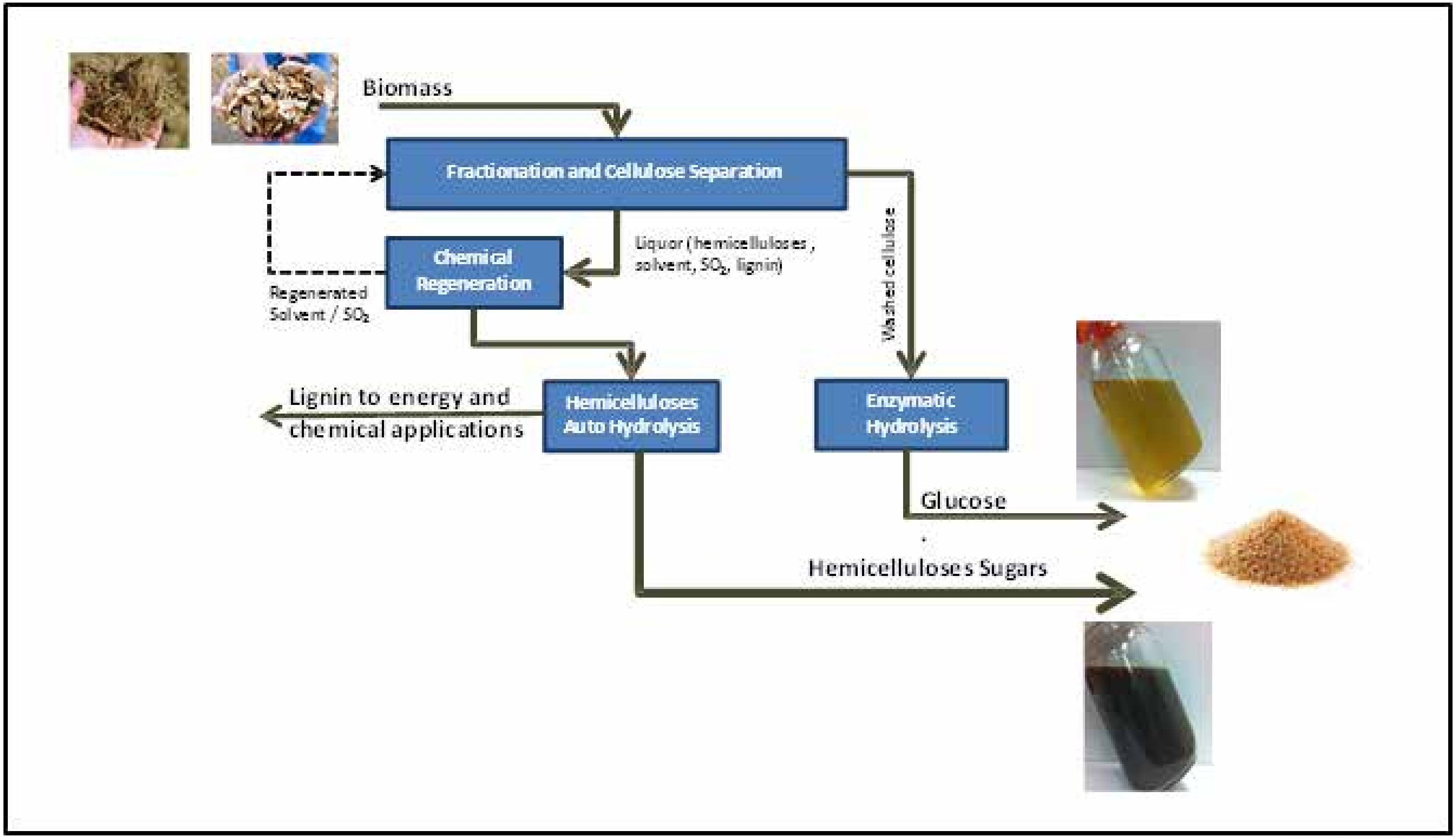
Project Scope

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 0.3 g/g from original biomass sugars
  - Reach average productivity of 12 g/l/h (industrial batch < 0.5 g/l/h)
  - Operate integrated pilot plant 500 hours continuously
  - Recover at least 90% of butanol and 99% of the extractant in one pass

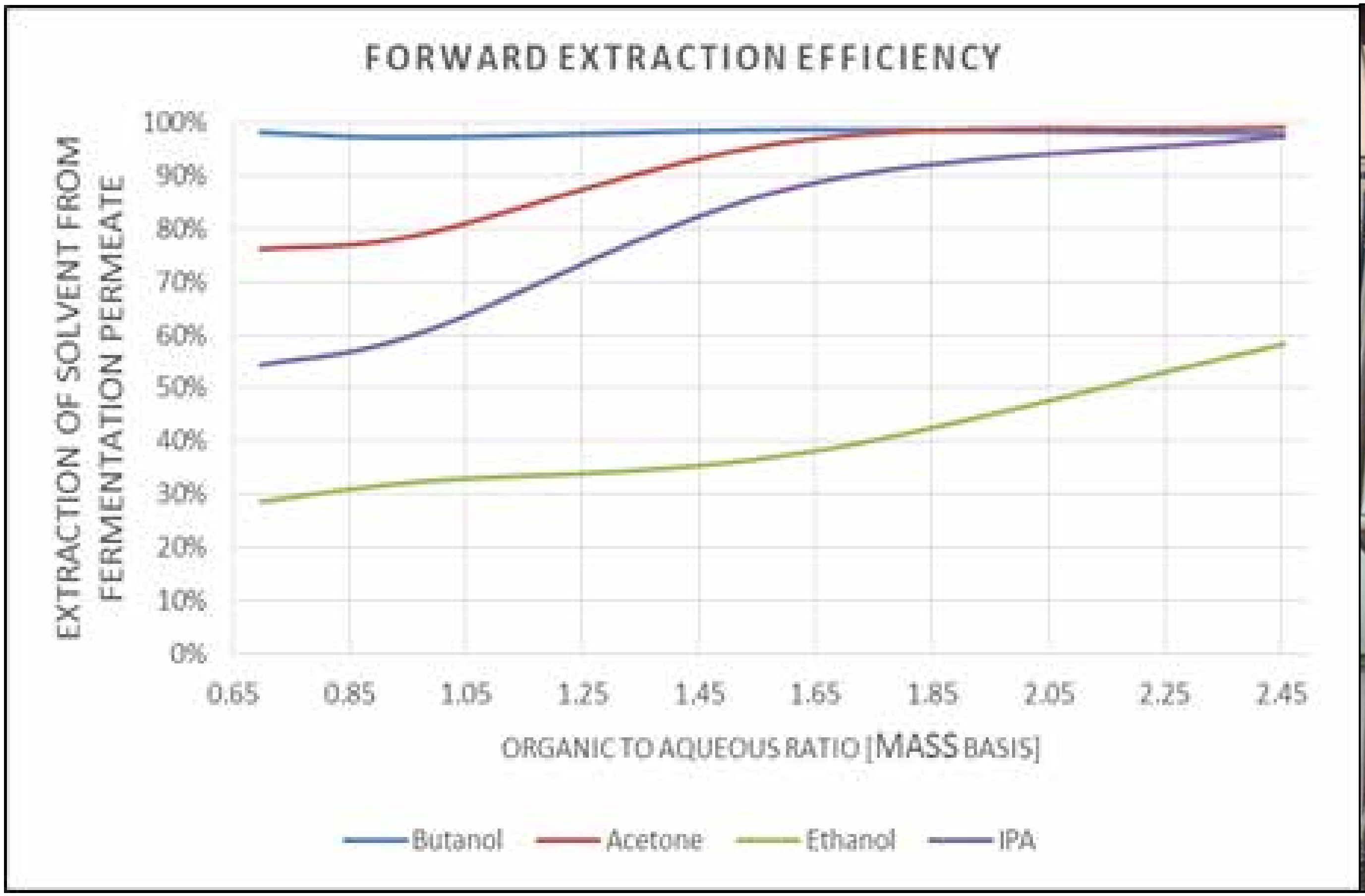
- Financial Targets
  - Reduce IBE production cost to target $2.05/gallon
  - Maintain facility capital cost at below $10/annual gallon

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 to that of pure xylose in the same system
  - Reached pine C5&C6 average productivity of 10 g/l/h at 0.33 g/g yield in pilot
- Designed and operated liquid-liquid extraction column
  - **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 solubility in water
  - Recycled half of the raffinate back to fermenter dilution with no negative impact on fermentation

Concurrent Membrane Assisted Fermenters

Liquid/Liquid Extraction

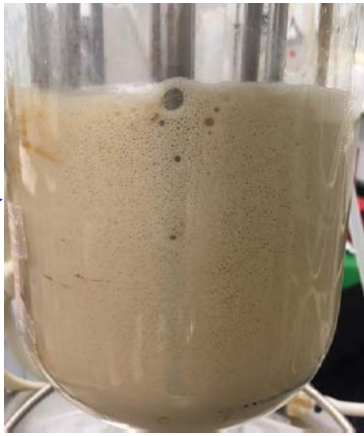


Progress Toward Technical Targets

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

Major Challenges

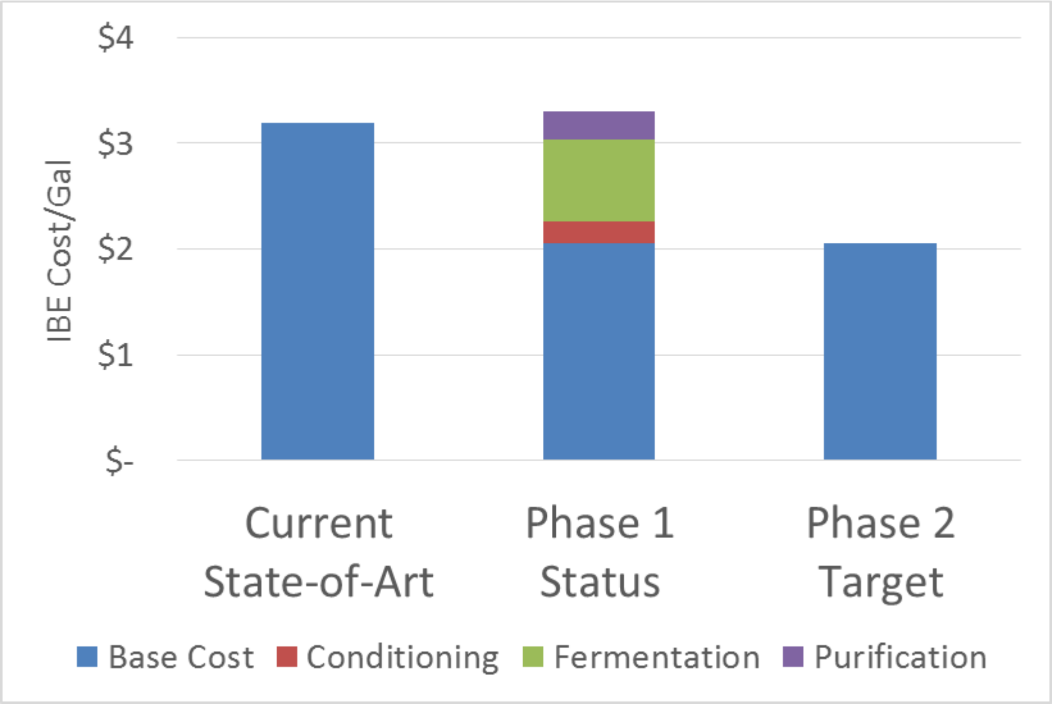
- Conversion of C5 sugars in the presence of Glucose
  - Separate hemicellulose sugar to concurrent fermentation - successful
  - Grow cells in C6 fermentor and purge into C5 fermentor - successful
- Conversion of Acetone to Isopropanol reduced over time
  - Use modern gene alteration to induce more isopropanol – plan in place in BP2
- Pine wood hemicellulosic hydrolyzate proved more inhibitive
  - Add conditioning steps to remove lignin compounds - successful
  - Optimization of the scheme under investigation – ongoing in BP2
- Foaming and two phase flow through membranes



  - Scale down industrial foam control methods – in progress for BP2
- **Liquid/Liquid Extraction and recycling of streams performed better that expected (beneficial effect!)**

Capturing the Economic Opportunity

- Remaining IBE project gaps to target of $2.05/gal
  - Reduce conditioning sugar loss ($0.21/gal opportunity)
  - Convert more acetone to isopropanol ($0.78/gal)
  - Increase product recovery rate ($0.26/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 low 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
- Intensifying of an integrated cellulosic biofuel process

Future Work – R&D

Conditioning sizing and optimization

- Screen four conditioning steps in different configuration for the C5 sugars and ferment in continuous mode to determine most cost effective treatment
- Develop sizing criteria for the conditioning equipment

Genetic Engineering

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

Milestone 9. Five-hundred hour integrated pilot run - May 2017

- Test system performance in the final configuration
- Obtain operability and fouling information over long run

Expected outcomes

- Successful demonstration of the pilot plant confirming the targets
- Data collected for the engineering phase

Future Work – Engineering and TEA

Milestone 10. Engineering -Update Basis of Design Document - 8/2017

- Value engineering and major equipment data sheets
  - Capital Cost Estimation
- Process Integration
- Integrated Process Simulation (Heat and Material Balance)
  - Operating Cost Estimation

Milestone 11. Life Cycle Analysis - 11/2017

Milestone 12. Techno-Economic Analysis - 11/2017

- Sensitivity
- Market Study

Expected Outcomes

- Mixed alcohol yield of 69 gal/dry ton from softwood feedstock
- IBE production cost for commercial $2.05/gal
- Profitable at 1200 dry tons per day biomass feedstock at $65/ton

Summary

- **Relevance:**
  - The AVAP-IBE intensified process is suitable for higher alcohol production
  - Replication potential for 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 0.3 g/g of yield lignocellulosic sugars
  - Continuous fermentation productivity of 12 g/l/h to halve Capital Expense
  - Low energy LLX with >90% butanol removal at <1% extractant loss
  - Commercial target OPEX: $2.05/gal, CAPEX: <$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 97.5% of butanol removed
- **Commercialization challenges:**
  - Profitability at low oil price without a co-product
  - Competition of sugars for cellulosic ethanol