Conversion of Waste CO_2 & Shale Gas to High Value Chemicals

DE-EE0005766
Novomer, Inc. (Praxair Sub-Contractor)
Project Period: 8/1/2013-3/31/2016

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Project Objective

- Overall Objective – To develop, build, and validate a semi-integrated laboratory scaled continuous process with capacity of 5kg/day to make CO_2-based drop-in chemicals.

- Achieve industry leading cost for Acrylic Acid, Succinic Anhydride, and Propiolactone based polymers
  - Novomer process can leverage lower cost ethylene feedstocks from shale and other sources
  - Lowest capital cost due to simple unit operations

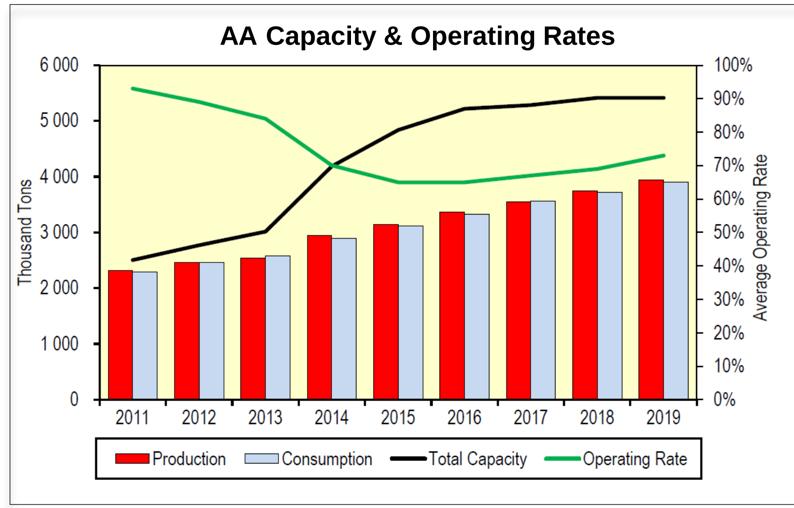
- Low Carbon & Energy Footprint
  - >99% catalyst selectivity results in high atom efficiency and almost zero wasted feedstock.

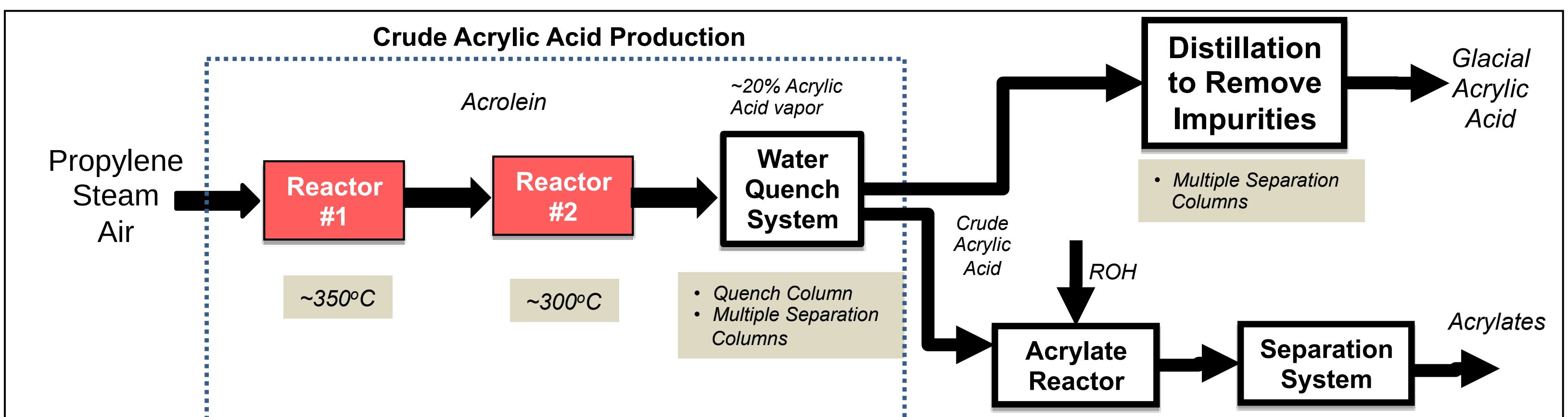
Technical Approach

- The current propylene oxidation process to make **Acrylic Acid** (AA) is energy intensive and has operating challenges.

<u>Characteristics of Existing Propylene Process</u>

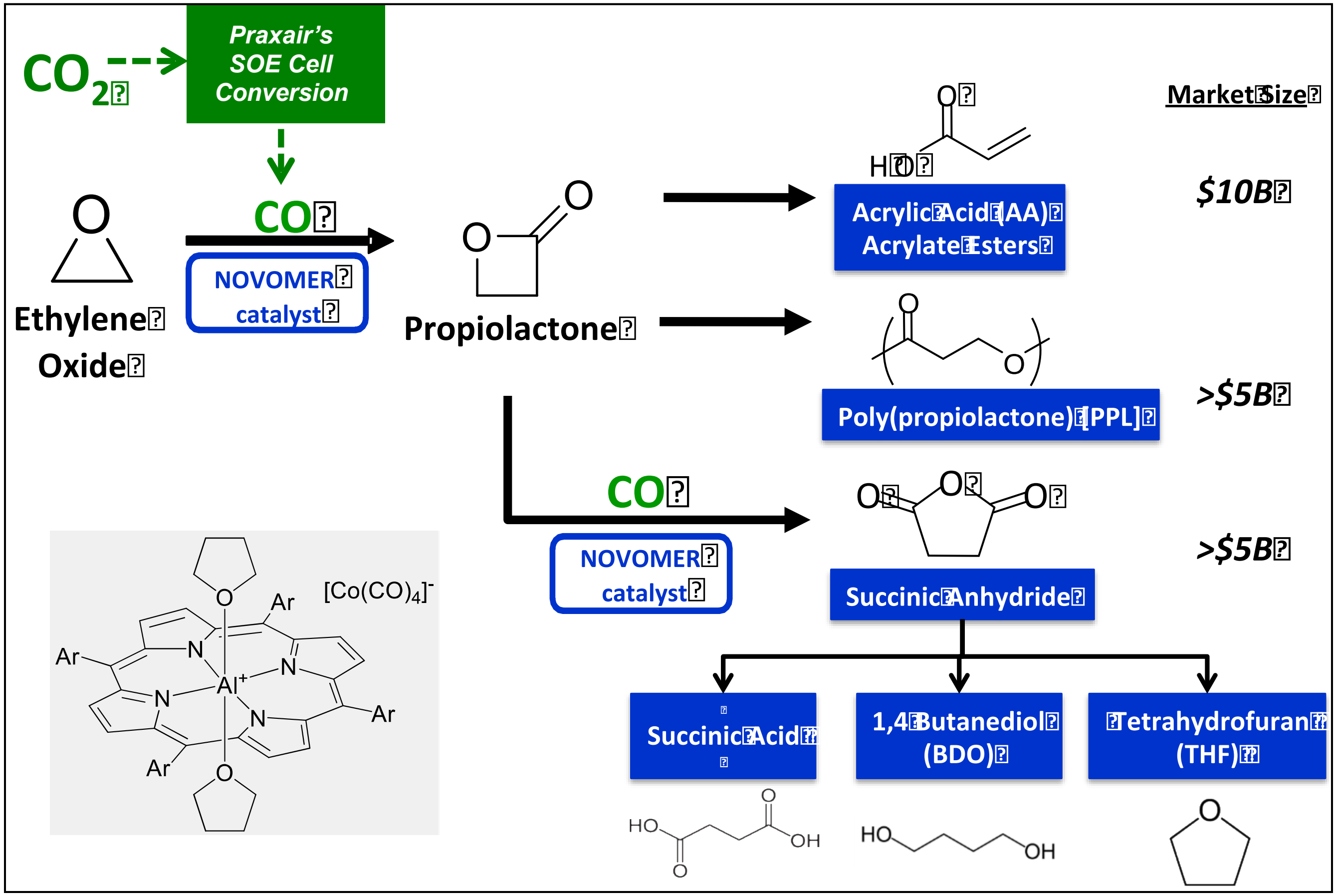
- Complex, expensive reactors
  - Molten salt cooling system
- Sensitive catalytic systems
- Difficult downstream separation
- Energy intensive process
- Global operating rates (60-70%) significantly below industry average (graph inset)





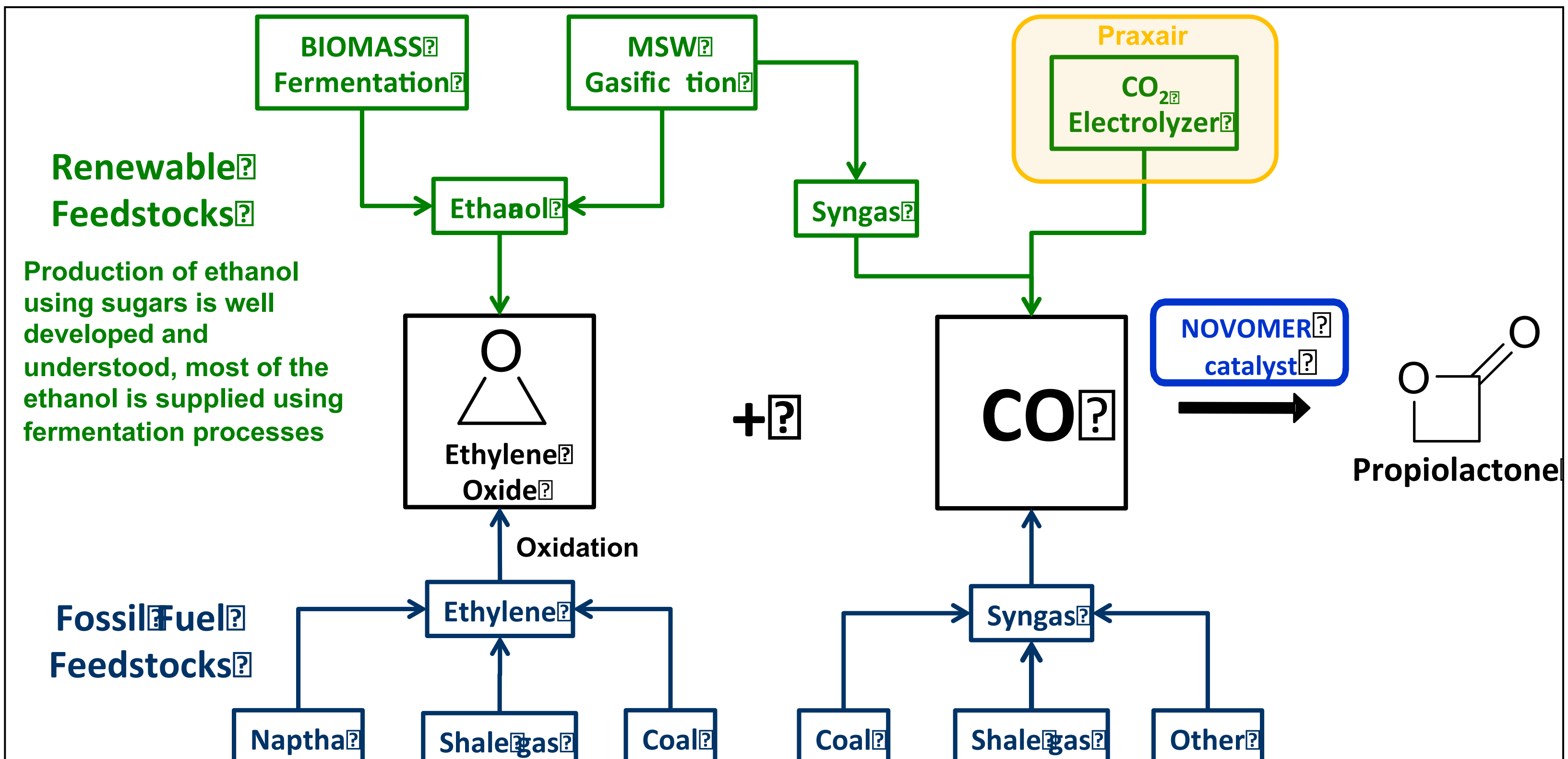
Technical Approach

- Advantages of Novomer Process:
  - High Selectivity Catalyst (>99%)
  - Leverages low cost shale gas & ethylene derivatives
  - Lower energy & carbon footprint
  - Novomer process changes the paradigm with respect to transporting Glacial AA



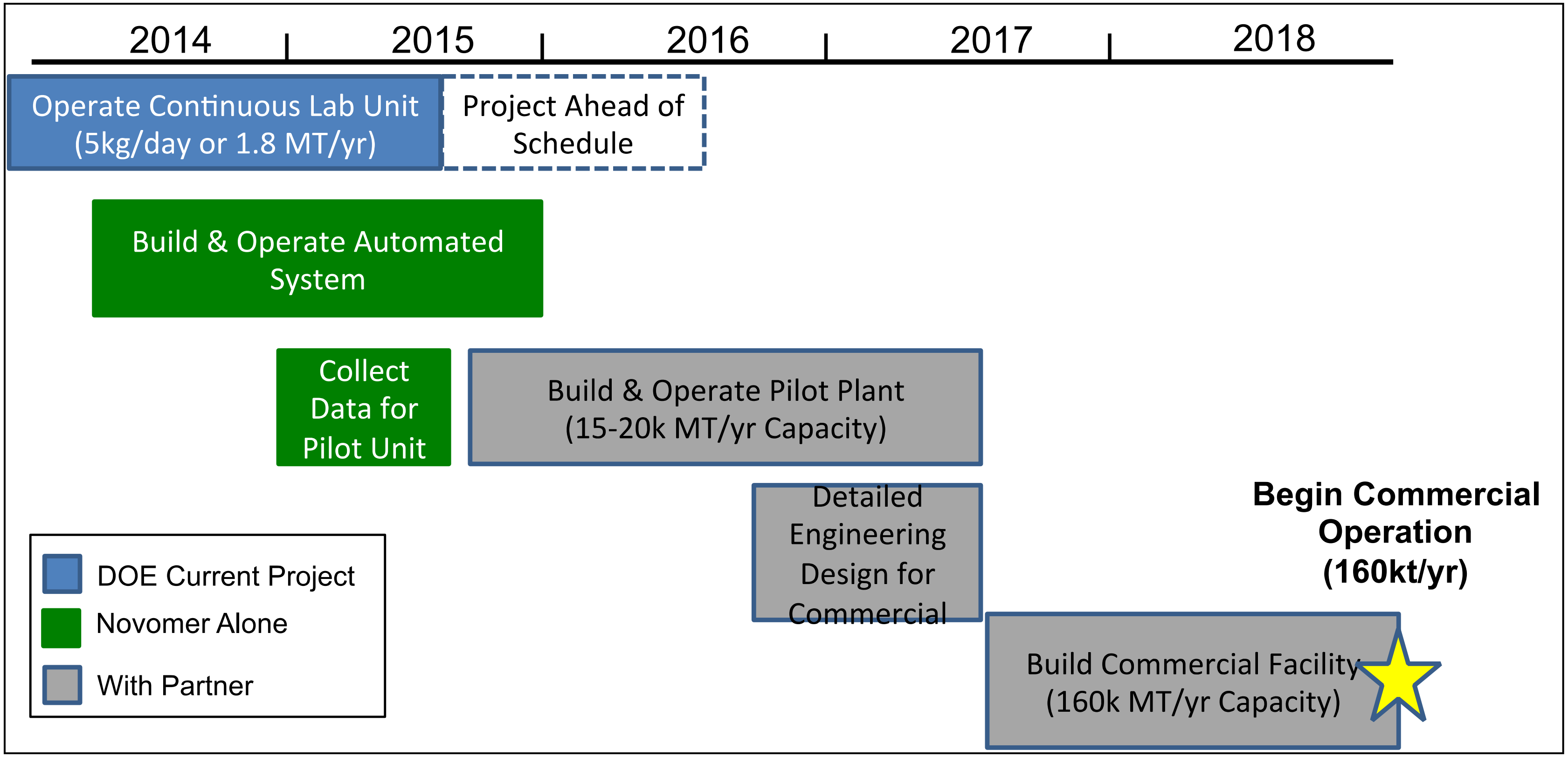
Transition and Deployment

- Novomer process is feedstock agnostic & appeals to a wide range of chemical & brand companies for deployment
  - Brand owners interested in carbon negative AA from bio-based sources
  - Chemical manufacturer with low cost ethylene feedstock interested in higher value derivatives and diversification.



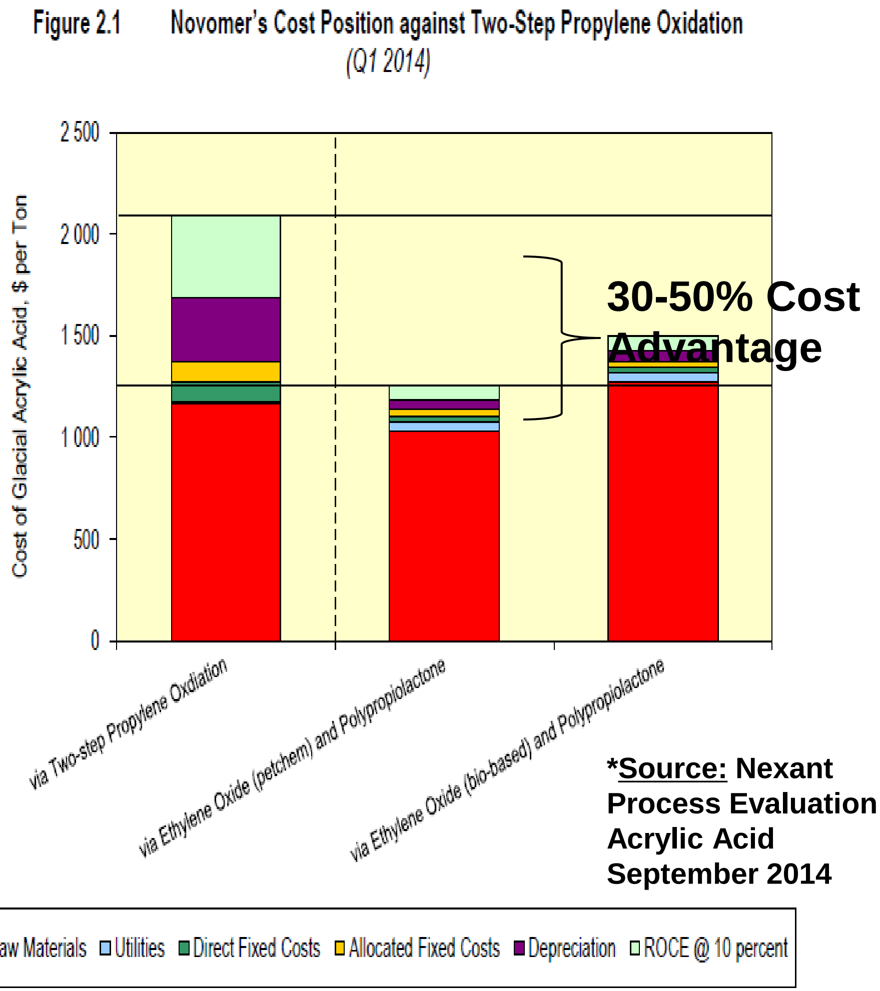
Transition and Deployment

- Novomer is collecting data to build & operate a 15-20KT/yr pilot plant facility.
- First commercial plant will be ready for production at end of 2018.

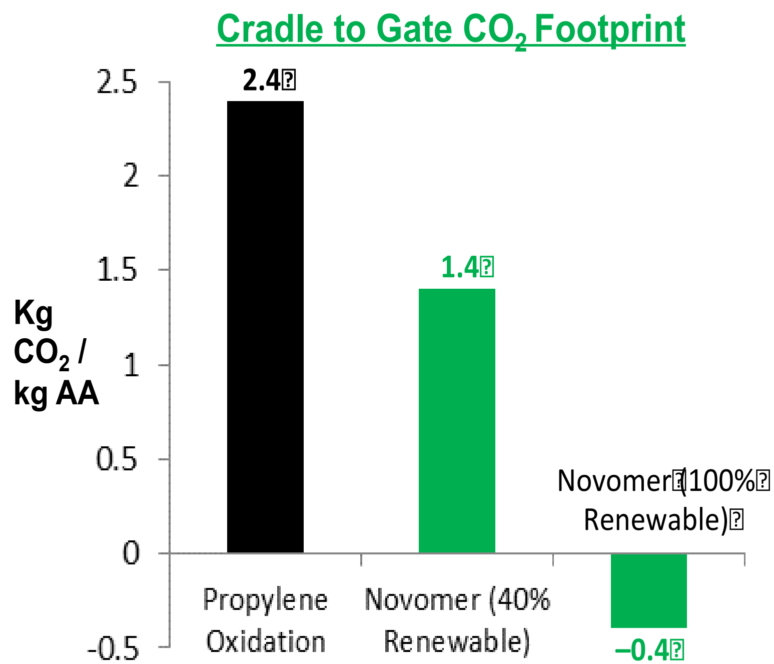


Measure of Success

- Novomer's process will be 30-50% lower cost and have a significantly lower carbon & energy footprint.



*Source: Nexant Process Evaluation Acrylic Acid September 2014



Project Management & Budget

- Project Duration – Aug 1 2013 to Mar 31 2016
  - BP1 – All Tasks & Go/No-Go Decision Points Complete
  - BP2 – Novomer Tasks Complete. Praxair Tasks on Schedule.
  - BP3 – Long term catalyst testing already started

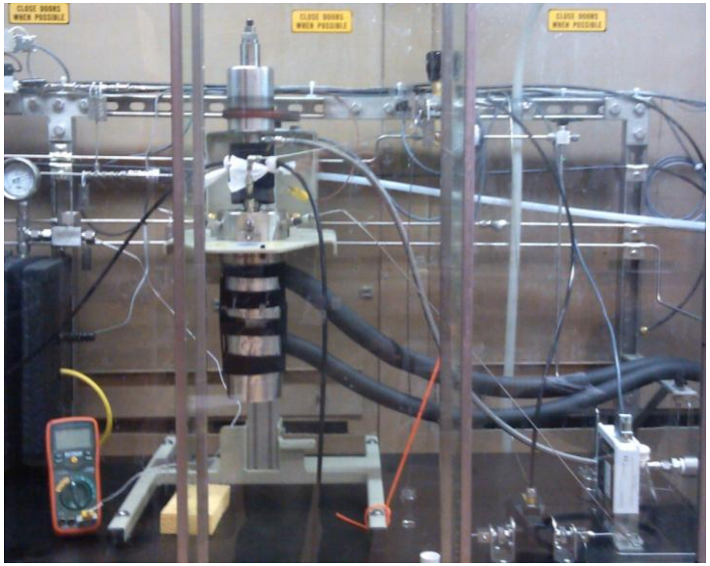
Total Project Budget	
DOE Investment	$5.0M
Cost Share	$1.8M
Project Total	$6.8M

	SOPO Task	Complete	Status / Comments
Budget Period (BP) 1	Task 1 – Evaluate, Build, & Test Major Carbonylation Unit Operations	✓	
	Task 2 – Preliminary Economics & LCA	✓	
	Task 3 – SOE Cell Test Infrastructure & Materials Development	✓	
	Task 4 – Project Management & Reporting	✓	
BP 2	Task 5 – Integrate Lab Scale Continuous Process	✓	
	Task 6 – Combustion Assisted CO_2/CO Electrolysis Cell Testing	In Progress	Praxair Leading this Effort
	Task 7 – Develop Robust Catalyst Synthesis	✓	
BP 3	Task 10 – Finalize & Validate Carbonylation Process	In Progress	Requires 1 month of operation. Have been running system for several weeks.
	Task 11 – Integrate Carbonylation & SOE Process		System will be operated with CO from Praxair's SOE cell.

Results and Accomplishments

Major Accomplishments

- Determined optimal reactor configuration
  - Built & Tested 3 Different reactor configurations (Single phase CSTR, two phase CSTR, and Loop Reactor)
- Identified separation scheme for Catalyst
  - Evaluated membrane, liquid/liquid extraction, and distillation
- Dramatic Improvement in Catalyst Performance
  - Improved catalyst activity by 3X, Reduced solvent cost by 1/2, and improved solubility by 5X
- Validated Economics, Energy, and CO_2 Footprint
  - Third parties (CCTI & Nexant) provided external validation
- Operated Continuous System with recycle for weeks at a time (BP3 Project Goal is 1 month)



Reactor System (Rochester, NY)

Exceeded BP1 Go/No-Go Metrics

	BP1 Goal	Achieved
Impurity Concentration	<5%	<0.1%
Residence Time	<600 min	60 min
Lactone Concentration	>15wt%	30wt%
Catalyst Rejection	>80%	99.2%
EO Conversion	>60%	>90%