Sacrificial Protective Coating Materials that can be Regenerated In-Situ to Enable High Performance and Low Cost Membranes

DE-EE0005759

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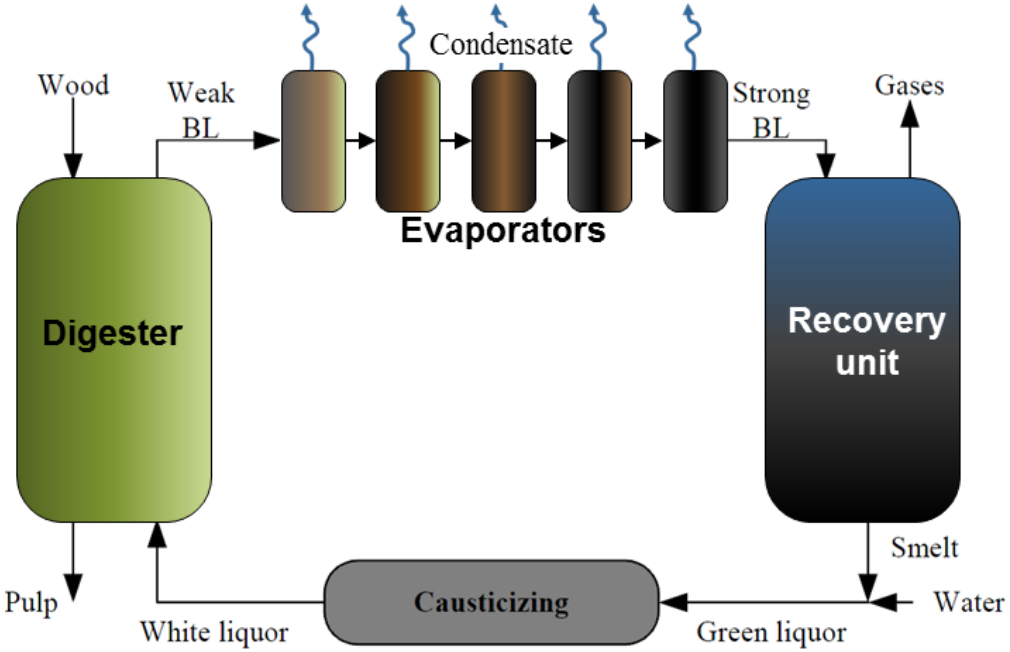
U.S. DOE Advanced Manufacturing Office Program Review Meeting
Washington, D.C.
May 28-29, 2015

Project Objective



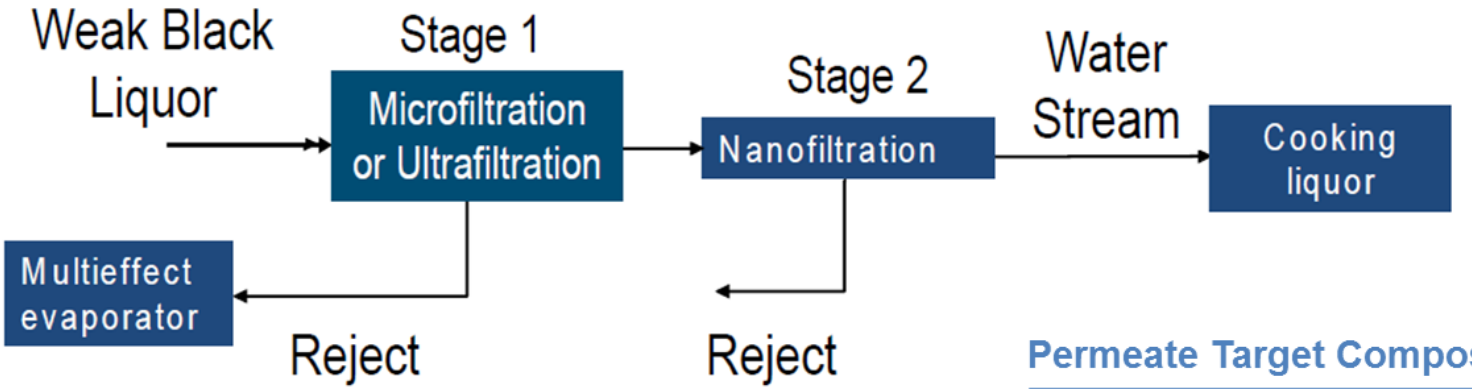
Pulp and Paper Mill

Currently, energy-intensive evaporators

- Separate water from Weak Black Liquor (WBL) at 15% solids for reuse
- Resulting strong black liquor (60-80% solids) burned in recovery unit

- Develop membrane filtration for separation of water from WBL: pressure-driven flow for separation saves energy
- However, membrane clogging and fouling is a major problem
  - Wide spectrum of foulants in WBL: organics, colloids, ions
  - Fouling increases operational maintenance costs
  - Lower flux requires larger capital investment
  - Membrane must sustain hot (>85°C) WBL at pH of 13-14

Technical Approach: Process Flow



Replace the first two evaporator stages with membrane filtration

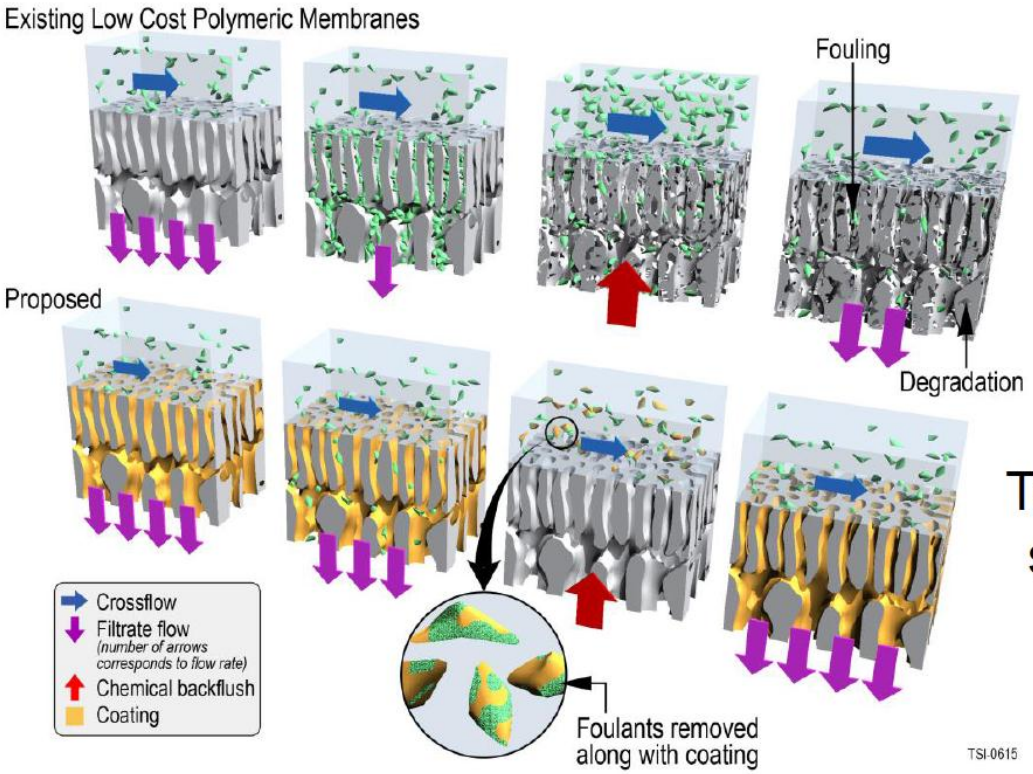
Permeate Target Composition

Condenser 2 - Concentration	
TOC	~400-600 mg L^{-1}
Sulfate	~18-30 mg L^{-1}
Methanol	~870 mg L^{-1}

Alternate processes such as coagulation, ion exchange can be added to ensure all target product quality specifications are met when preparing cooking liquor. We will not add additional salts to ensure salt concentrations do not increase over time in this closed loop system.

Single biggest problem with membranes : Fouling

Technical Approach (Continued)



Teledyne coating: both membrane surface and inner pore walls are coated without affecting flux

- Coating resists fouling under WBL conditions
  - Foulants adhere weakly to our coating. Coating is periodically re-applied in the field. Both lead to higher flux and recovery, and lower maintenance
  - Working with Agenda 2020 (paper industry consortium) and MeadWestVaco

Transition and Deployment

- Pulp and paper mills are third largest energy-using manufacturing sub-sector in US
  - Accounted for 7 percent of total U.S. industrial energy
  - Produced 78 million metric tons of paper and paperboard (19% of global production)
- WBL concentrated from ~15% solids to ~65-80% solids by multi-stage evaporators consuming ~400 TBtu/yr
- If first two stages of evaporators are replaced with membrane separation
  - 14% reduction in energy or ~55 TBtu/yr
- Estimated payback period for coated membranes for WBL concentration: 2-3 years

Transition and Deployment

- Commercialization approach
  - Technology development in close collaboration with paper industry for rapid adoption
  - TRL 5 validation at a pulp and paper facility (Year 3)
  - Demonstrate performance improvement at customer site: enables continued development beyond TRL 5
  - Teledyne pursuing other adjacent areas, e.g. filtration of frac and produced water in Oil and Gas: assists in adoption of membranes

Measure of Success

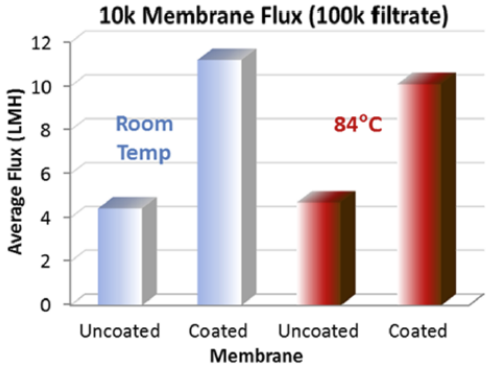
- Near term
  - Continued engagement and buy-in from paper industry
  - Achievement of technical objectives and milestones
  - TRL 5 demo at pulp and paper mill site
  - Confirmation of quantified energy savings to end-user
- Medium term: joint development of higher TRL prototypes between Teledyne and paper industry
- Longer term: adoption of membrane separation in pulp and paper manufacturing
- Energy savings estimate by paper consortium
  - Reduction in energy from 3.5 MMBtu/adt to <2.8 MMBtu/adt: 14% energy savings or ~55 TBtu/yr

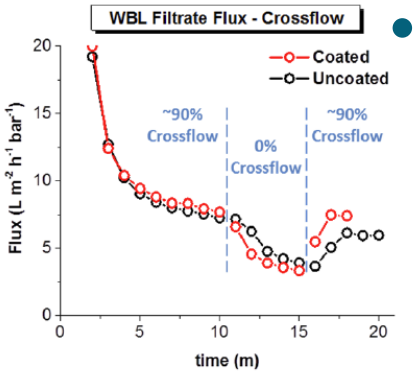
Project Management & Budget

- Project duration: 36 months (Year 2 started in March 2015)
- Progress measured by quantitative milestones
  - August 31, 2015: Demonstrate black liquor treatment process with less than 10% drop in flux after coating of membrane module
  - February 29, 2016: Demonstrate black liquor treatment process for >3 days with <20% drop in total flux

Total Project Budget	
DOE Investment	$ 2,109,297
Cost Share	$ 973,888
Project Total	$ 3,083,185

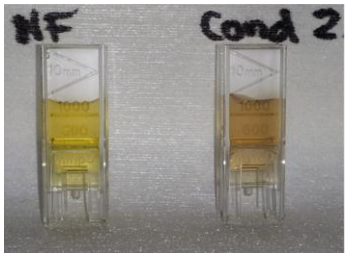
Results and Accomplishments

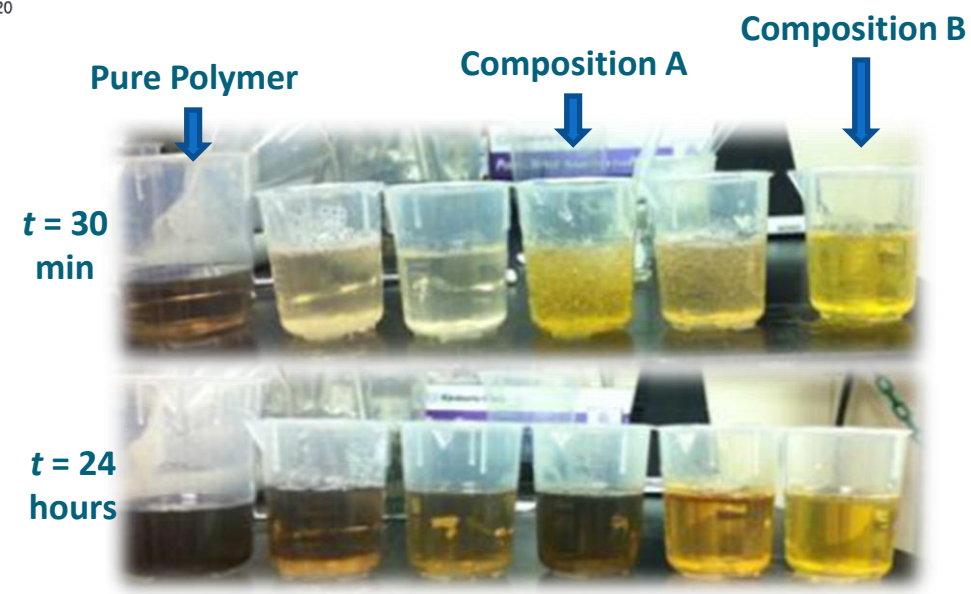




- Demonstrated that our coatings survive process temperature and chemistry
  - >2x increase in flux
  - Complete flux recovery from dead end to crossflow mode

- Developed coating process that enables preferential formation of intermediates that are polymerized later (minimizes particle formation and pore clogging)
- Reduced TOC and sulfate by 62% and 87%, respectively, via nanofiltration





Work to be completed

- Demonstrate coating removal and recoating (Year 2)
- Demonstrate black liquor concentration at pulp and paper manufacturer (Year 3)