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

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Peter Malati, Rahul Ganguli and Vivek Mehrotra
Teledyne Scientific Company

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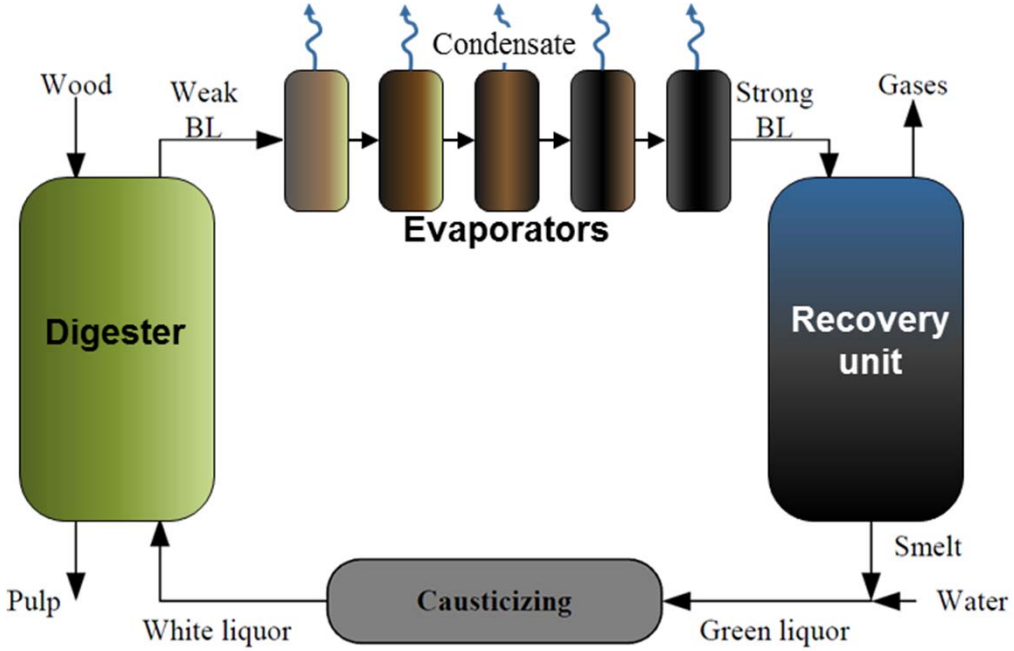
Project Objective



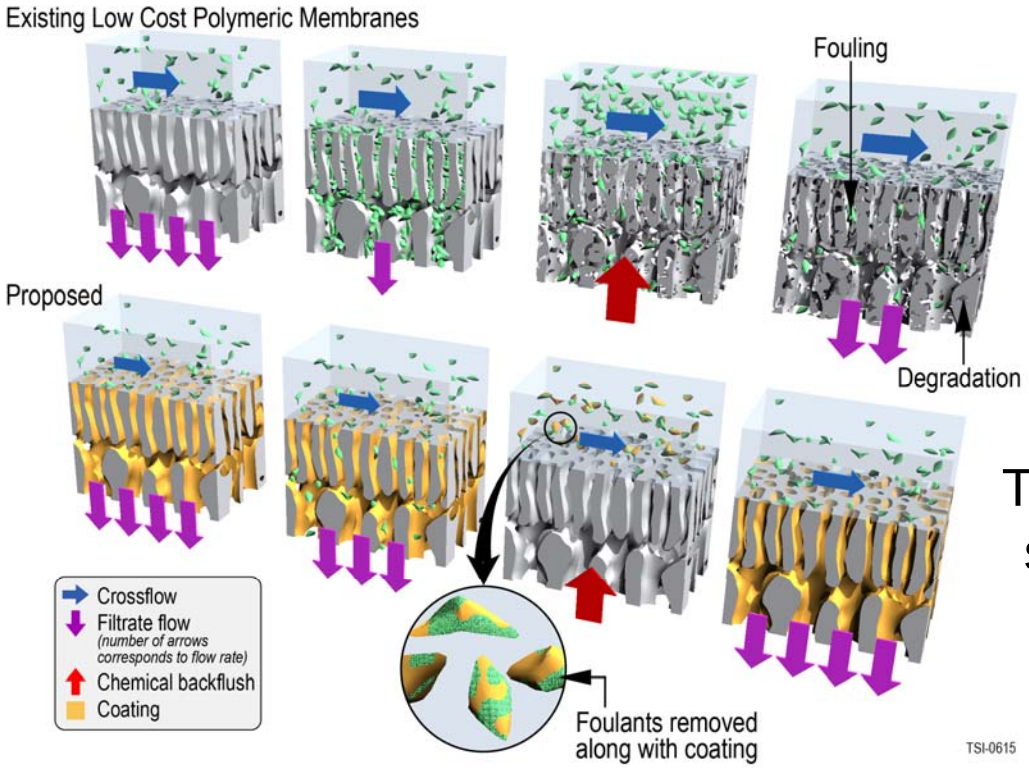
Pulp and Paper Mill

Currently, energy-intensive evaporators

- Separate water from Weak Black Liquor (WBL) for reuse
- Resulting strong black liquor 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

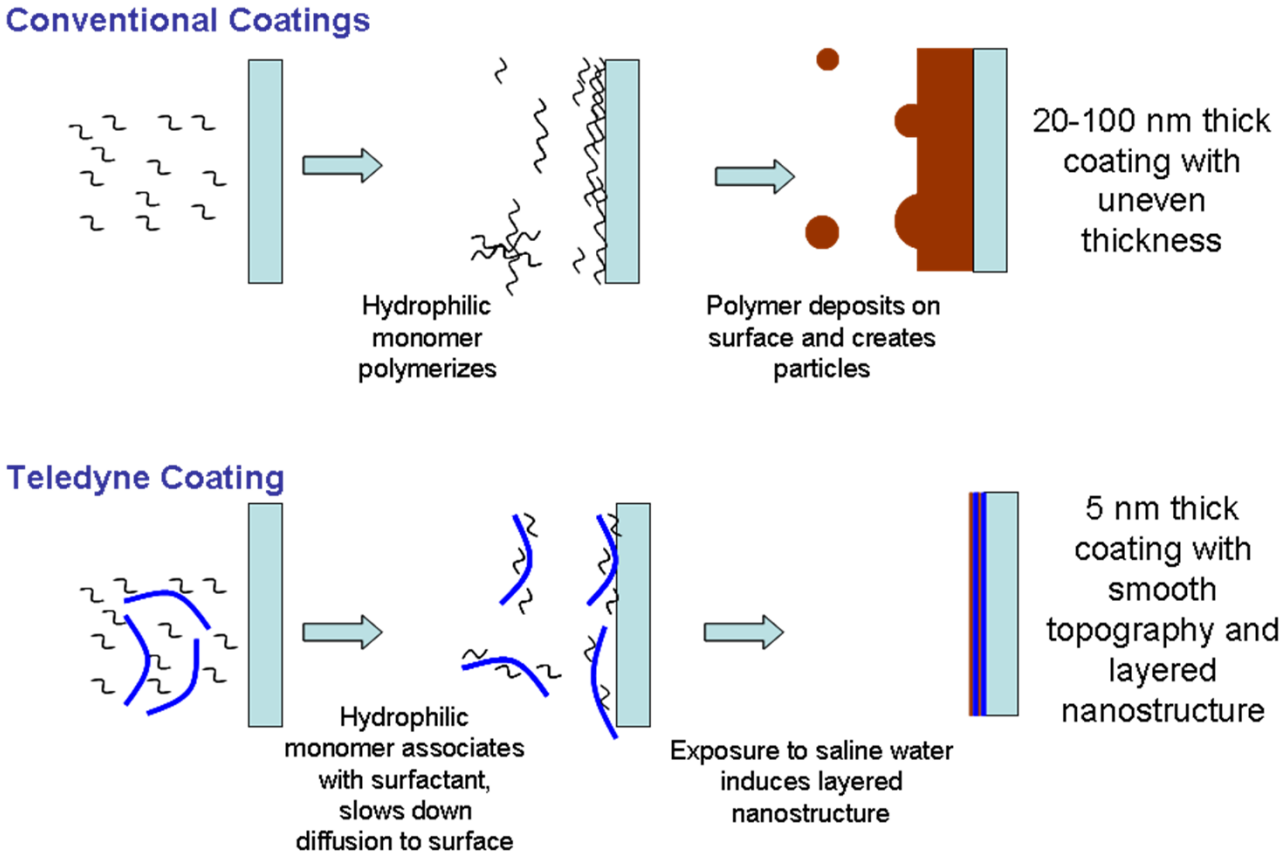
Technical Approach



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

- Although widespread adoption of membranes has lowered cost, no known methods to alleviate fouling
- Our 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.

Technical Approach (continued)



- Coating is reapplied in a single flush-through operation on membrane modules: automated reformation synchronized with existing Clean-in-Place operation
- Working with Agenda 2020 (paper industry consortium) and MeadWestVaco (major paper manufacturer)

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
  - 37% reduction in energy or ~110 TBtu/yr
- Estimated payback period for coated membranes for WBL concentration: 2-3 years, calculated at energy savings of $ 0.07/kWh

Transition and Deployment (continued)

- Membrane-based separation may also
  - Reduce water demand
  - Enable fractionation of lignin and hemicelluloses for other value-added products such as lignin-derived polyphenols
- 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
  - Establish supply chain: membranes and coating solution
  - Teledyne will supply coating solution and assist with design
  - Teledyne pursuing other adjacent areas, e.g. filtration of frac water in Oil and Gas: assists in adoption of membranes

Measure of Success

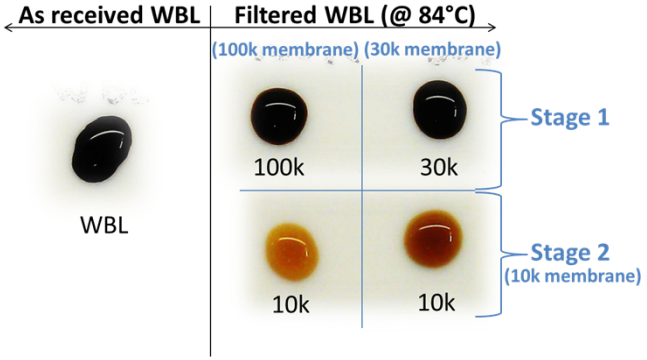
- Near term
  - Continued engagement and buy-in from paper industry
  - Achievement of technical objectives and milestones
  - TRL 5 demo at pulp and paper mill site
  - Confirmation of quantified energy savings to end-user
- Medium term: joint development of higher TRL prototypes between Teledyne and 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 <2.2 MMBtu/adt: 37% energy savings or ~110 TBtu/yr

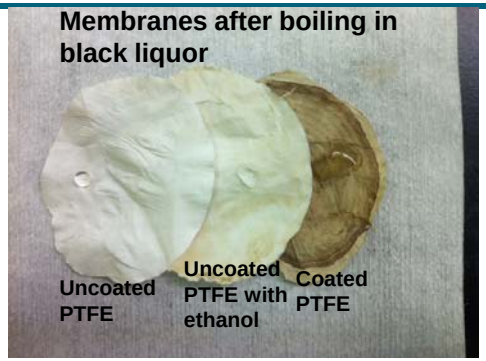
Project Management & Budget

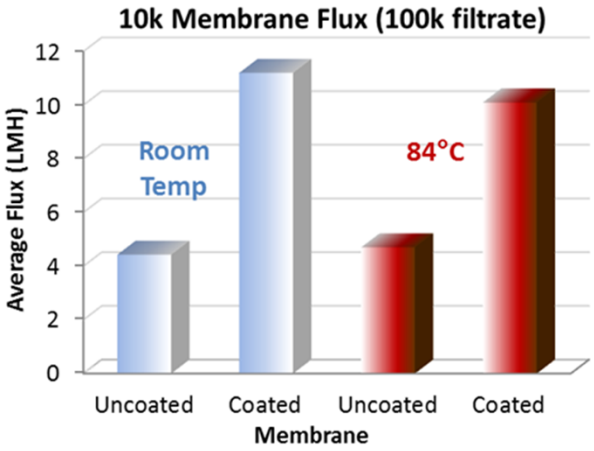
- Project duration: 36 months (Year 2 just starting)
- Progress measured by quantitative milestones
  - Jan 2014: Demo coating materials on chosen membranes with environmental stability (pH 13-14, Temperature >80°C), achieved
  - April 30, 2015: Demonstrate black liquor treatment process for >3 days with <20% drop in total flux
  - April 30, 2016: Demonstrate black liquor treatment process for >7 days with <20% drop in total flux with semi-automated backflush, chemical clean & coating reformation

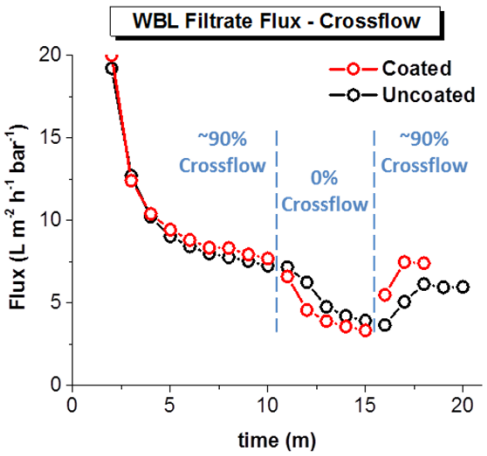
Total Project Budget	
DOE Investment	2,109,397
Cost Share	527,349 (20%)
Project Total	2,636,746

Results and Accomplishments









- Established process to concentrate black liquor with acceptable filtrate quality
  - Two stage filtration
  - Use membranes of two different pore sizes
- Demonstrated that our coatings survive process temperature and chemistry (met milestone)
  - >2X increase in flux
  - Complete flux recovery from dead end to cross flow mode
- Developed economic model for proposed process
  - Payback period: ~ 2 yrs

Work to be completed

- Demonstrate coating removal and recoating (Year 2)
- Build pilot scale concentrator with automated membrane cleaning and recoating operations (Year 2)
- Demonstrate black liquor concentration at paper and pulp manufacturer (Year 3)