An Integrated Approach to the Recovery of Fiber, Chemicals and Energy from Fibrous Textile and Carpet Waste

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Polymers as a Resource for Industry

What is Needed?
- Completing the Life Cycle of Polymers Back to Chemicals by Linking:
  - Chemical Industry
  - Material Manufacturers
  - Municipalities
  - Consumers
- Benefits:
  - Increase the Sustainability of the Chemical Industry
  - Provide Additional Source of Chemicals
  - Provide Information for Design of Products for Recycling

Plastics in the Environment

Recycling

Monomer building blocks
Resins
Products
Consumers
Disposal
Energy recovery

Chemical Recycling

- Mixed Polymers are Costly to Separate and Lose Performance Properties When Blended
- Recycling Back to Chemicals has the Potential to be Economical and Allow Plastics to be Truly Recyclable
- Measure the Efficiency by How Much of the Embodied Energy is Saved
- Transporting Materials for recycling adds Costs, Which suggests Smaller Plants Near Waste Source

The purer the recycle stream - the higher the value (and cost)
Flexible Chemical Processing

- Processing Facilities Convert Several Mixed Polymer Materials
  - Target Feedstocks are Sorted and Stockpiled
  - Each Type is Processed in Long Duration Runs
- Target Materials:
  - Carpets: Nylon 6, Nylon 66, PET, and Polypropylene
  - PET/Cotton Textiles
  - Polyurethanes
  - Engineering Polymer Blends
- Selective Pyrolysis is used to Recover Valuable Monomers
- Gasification is Used to Convert Organic Residue to Synthesis Gas
  - Syn Gas used on Site to make Chemicals

Thermocatalytic Recovery of High-Value Chemicals from Waste Plastics (Flexible Chemical Processing)

Sustainability in the Chemical Industry

- from the U. S. Chemical Industry Technology Vision 2020:
  - "The U. S. chemical industry ... promotes sustainable development by investing in technology that protects the environment and stimulates industrial growth while balancing economic needs with financial constraints."
- Sustainability:
  - "...technological development that meets the economic and environmental needs of the present while enhancing the ability of future generations to meet their own needs."

Selective Pyrolysis

- Selective Pyrolysis: Pyrolyze One Component of a Mixture to Give one Major Product While Other Components Remain Unreacted
- Selectivity is Achieved by
  - Exploiting Differential Kinetics
  - Selective Catalytic Pyrolysis
  - Selective Reactive Pyrolysis
- NREL has Patented 8 Applications of Selective Pyrolysis
- Different Than Conventional View of Pyrolysis, Seen as Process for Converting Materials to Fuels with Low Selectivity and Value
Advantages of Selective Pyrolysis Over Other Chemical Processes

- Ability to handle a variety of waste streams with the same reactor system.
- Relatively insensitive to feedstock contamination.
- Potential to recover value from 100% of the plastics in mixtures by incorporation of gasification.
- Smaller-scale operations possible and/or desirable.

Flexible Chemical Processing

What's New?

- Integration of Caprolactam and Fiber Recovery
- Alternative Reactor Design to be Tested
- Simple Purification Process Developed
- Use of Calcium Carbonate as Catalyst
- New Emphasis on Gasification
- Recover Chemicals From PET (carpet +)

Pyrolysis of Mixed Plastics
PVC, PS, PE and PET

Nylon-6 to Caprolactam
Temperature-Programmed Pyrolysis
Nylon-6 and Polypropylene
with Catalyst

Intensity, Arbitrary Units
Temperature, C

Temperature

Caprolactam from Nylon-6
Hydrocarbons from Polypropylene

Time, min

Recycling Nylon 6 from Waste Carpet

Waste carpet
Pyrolysis
Crude caprolactam (from Nylon 6, 85%)
Residue
Pyrolysis
Oil from carpet backing
New carpet
Manufacturing
Polymerization
Nylon 6

Flexible Chemical Processing
Reactor Comparison

Fluid Bed Reactor
- Advantages
  - Temperature Control
  - Disadvantages
  - Residence Time Distribution
  - Catalyst/CaCO3 Separation
  - Gasification in Second Reactor

Auger/Screw Reactor
- Advantages
  - Plug Flow
  - Mechanical Mixing
  - Gasification in Same Reactor

Nylon - 6 Waste Streams
Fluidized Bed Pyrolysis Research

- Four Inch Fluidized Bed Reactor Operating at Hazen Research
- 0.5 kg/hr Experiments with Post Consumer Carpet
- Continuous Feeding and Product Collection System
- Good Yields of Caprolactam and Mass Balance Achieved
- Parameter Optimization Performed

- Condensed Products are Analyzed by GC/MS
  - Confirm Previous Results (90% in purity, 85% Yield)

- Estimated Production Costs are $0.50/lb for Caprolactam Using a 100 million lb/yr Plant as a Basis
Process Development Model

Business Ventures and Market Partnerships

Industrial Development

Flexible Chemical Processing
Industrial Collaboration

- United Recycling Inc evaluating process for integration with National Carpet Collection Program:
- Kemestrie Inc to demonstrate in fluid bed facility:
  - Caprolactam Recovery
  - Residue Gasification
  - Product Purification
- Product evaluation by industry

Flexible Chemical Processing Joint Development Project

- Complete Technology Development
- Demonstrate Performance
- Catalyze Partnership Formation

NREL - Technology Development

financial resources

Kemestrie, Inc - conversion system suppliers

Remanufacturers
Integrated Carpet Recycling
Distribution of Feed by Weight

- PET: 4.0%
- PP: 6.0%
- Other: 1.0%
- Backing-PP: 10.0%
- Backing-EVA: 10.0%
- nylon 6: 20.0%
- nylon 6.6: 16.0%
- CaCO3: 30.0%

Integrated Carpet Recycling
Distribution of Revenues

- Energy: 8.0%
- Chemicals: 15.0%
- CaCO3: 30.0%

Energy Recovery:
- Combustion and Steam Cycle - 20-25% Efficiency
- Gasification and Gas Engine - 25-30%
- Integrated Gasification, Combined Cycle 35-45%
- gasification and Fuel Cell 45-50%

Environmental Benefits:
- Less Gas Emissions
- Lower Temperature and More Control
Flexible Chemical Processing
Current Lab Focus

- Expand Nylon-6 Work to Other Face Fiber Types
  - Co-processing
  - Block Operation
- Refine Gasification Technology for Relevant Feedstocks
- In-line Product Purification Process Development
- New Reactor Systems
- Cheaper Catalysts

PET/Cotton Textiles

- MBMS Studies Performed to Identify Conditions to Recover the Monomer from PET in Presence of Cellulose
  - Minimal Formation of Cellulose Volatile Products
- Catalyst for PET Conversion also Catalyzes the Conversion of Cellulose to Char
- Char can be Gasified in Subsequent Step
- Issues:
  - Low Value of Chemical Product
  - Size of Plant that Results from Economics

Textiles in MSW, 1992

<table>
<thead>
<tr>
<th>Product Category</th>
<th>Generation Thou tons</th>
<th>Recovery Thou tons</th>
<th>% of Generation</th>
<th>Discards Thou tons</th>
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<tbody>
<tr>
<td>Clothing/Footwear</td>
<td>3,514</td>
<td>176</td>
<td>5.0</td>
<td>3,338</td>
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<tr>
<td>Household Linens</td>
<td>1,137</td>
<td>57</td>
<td>5.0</td>
<td>1,080</td>
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<td>Carpets</td>
<td>885</td>
<td>9</td>
<td>1.0</td>
<td>876</td>
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<tr>
<td>Tires</td>
<td>260</td>
<td>34</td>
<td>13.1</td>
<td>226</td>
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<tr>
<td>Furniture/Furnishings</td>
<td>740</td>
<td>neg.</td>
<td>neg.</td>
<td>740</td>
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<tr>
<td>Miscellaneous</td>
<td>208</td>
<td>neg.</td>
<td>neg.</td>
<td>208</td>
</tr>
<tr>
<td>Total Textiles</td>
<td>6,744</td>
<td>276</td>
<td>4.1</td>
<td>6,468</td>
</tr>
</tbody>
</table>

Neg. = Negligible
Source: Franklin Associates, Ltd.
Polyester Cloth
Isothermal/Methanol

Recycling Polyester from Polyester/Cotton Fabrics

Polyester Recycling by Selective Pyrolysis
Barriers to Success

Flexible Chemical Processing
Summary

- Integration of Caprolactam and Fiber Recovery
  - Smaller-Scale, Regional Operation
  - Energy Recovery From Residues by Gasification.

- Process Developments:
  - Alternative Reactor Design to be Tested
  - Simple Purification Process Developed
  - Use of Calcium Carbonate as Catalyst

- Recover Chemicals From PET in Textiles, etc:
  - Recovery of the PET monomer, DMT
  - Gasification of the cotton residue
  - Bench-Scale Work at NREL Continues