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Golisano Institute for Sustainability
ROCHESTER INSTITUTE OF TECHNOLOGY

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Assessing End-of-Life Environmental Impacts of Nanomaterials

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NSF Grantees Conference
December 4-6, 2013

Need: bridge fate with end-of-life paths of products

- Recyclability
- Ingestion
- Inhalation

- Absorption by skin/Dermal
- Public sewer

- Burning
- Landfill
- Air release

Common fates from toxicology and ecology

-Asmatulu et al., 2012, Life-cycle and nanoproducts: end-of-life assessment, J Nanoparticle Research

Life-cycle approach for products containing nanomaterials

Raw Material Extraction → Manufacture → Usage

end-of-life

- Recycling
- Re-synthesis
- Re-manufacture
- Testing & Reuse
- Disposal: Landfill +/- Energy

LCAs of nanomaterials
Reproduced from Gavankar , et al. 2012, Int. J. of LCA

Reference	ENPs	E	M	U	EOL
Lloyd and Lave 2013	Nano-clay reinforced composites	O	O	X	X
Steinfeldt et al 2004	Nano containing electronics	O	O	X	X
Lloyd et al 2005	Platinum group metal NPs	O	O	X	X
Osterwalder et al 2006	Various oxide NPs	X	O	X	X
Ross et al 2007	Polypropylene nanocomposite	O	O	X	X
Kushnir and Sanden 2008	Fullerenese and CNTs	O	O	X	X
Healy et al 2008	SWCNTs	O	O	X	X
Khanna et al 2008	CNTs	O	O	X	X
Kohler et al 2009	CNTs	X	O	O	O
Bauer et al 2008	TiN, TiAlN	O	O	O	O
Khanna and Bakshi 2009	Carbon polymer nanocomposites	O	O	X	X
Meyer et al 2010	Silver nano	O	O	X	X
Sengil and Theis 2011	Quantum dot photovoltaics	O	O	X	X
Grubb and Bakshi 2011	Titanium dioxide	O	O	X	X

End-of-Life is an important consideration for ENPs….

- Advocate for including EOL for exposure

  -Abbott & Maynard, 2010, Exposure Assessment Approaches for Engineered NM, Risk Analysis

- Argue for full risk assessment of post-use

  -Ostertag and Husing, 2008, Identification of starting points for exposure assessment in the post-use phase of nanomaterial-containing products, J Clean. Prod.

… but End-of-Life is difficult to characterized

- Lack of detection tech in waste industry

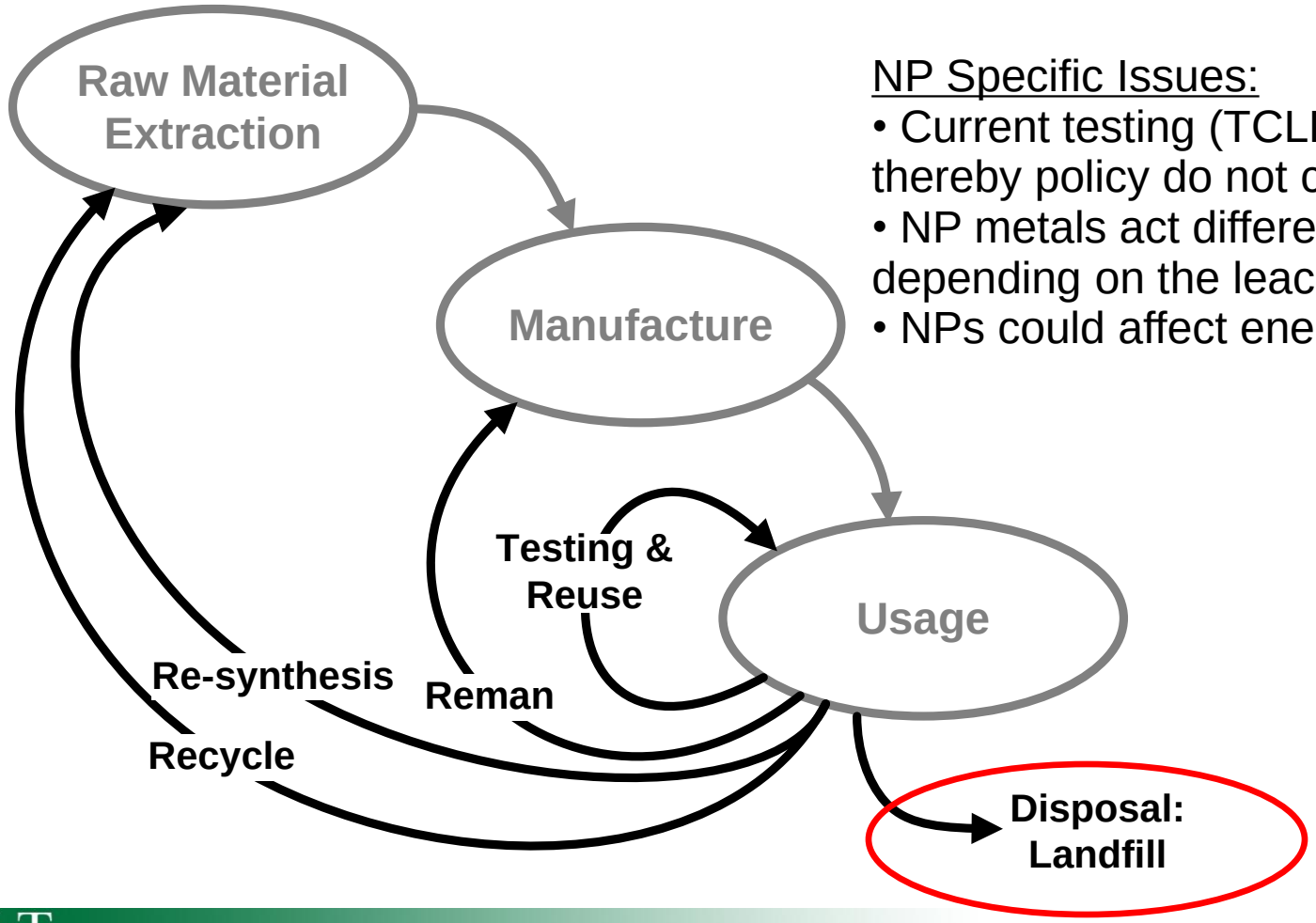
  -Abbott & Maynard, 2010, Exposure Assessment Approaches for Engineered NM, Risk Analysis

- High uncertainty of impacts at EOL

  -Breggin & Pendergrass, 2007, Addressing Nanotechnology Waste and Product Disposal: Can the Superfund Safety Net Catch Tiny Particles?, J of Env Law

  -Gao, et al., 2008, Env. Tox. And Chem.

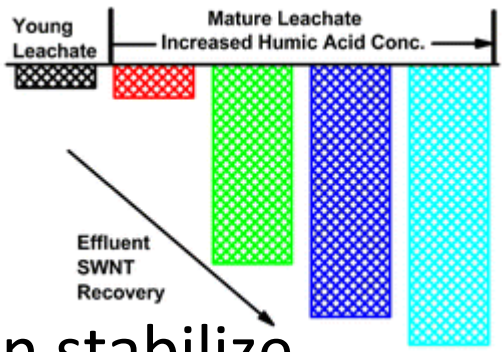
End-of-Life
for products containing nanomaterials



NP Specific Issues:

- Current testing (TCLP/WET) and thereby policy do not cover NPs
- NP metals act differently depending on the leachate
- NPs could affect energy recovery

Landfill Impacts



- Estimate 50%-95% will reside in landfills
- Humic acid present in mature leachate can stabilize SWCNTs

  -Lozano, et.al. Waste Manage. 2012

- SWCNTs transport is waste dependent; greatest in glass, least in paper, low transport in “new” waste due to acetic acid, high transport in “mature” leachate due to humic acid

  -Khan, et. al, 2013, Env. Sci. & Tech.

- Zn, Ti, and Ag NPs will migrate to leachate

  -Bolyard, et. al, 2013, Env. Sci. & Tech.

Landfill Impacts with energy recovery

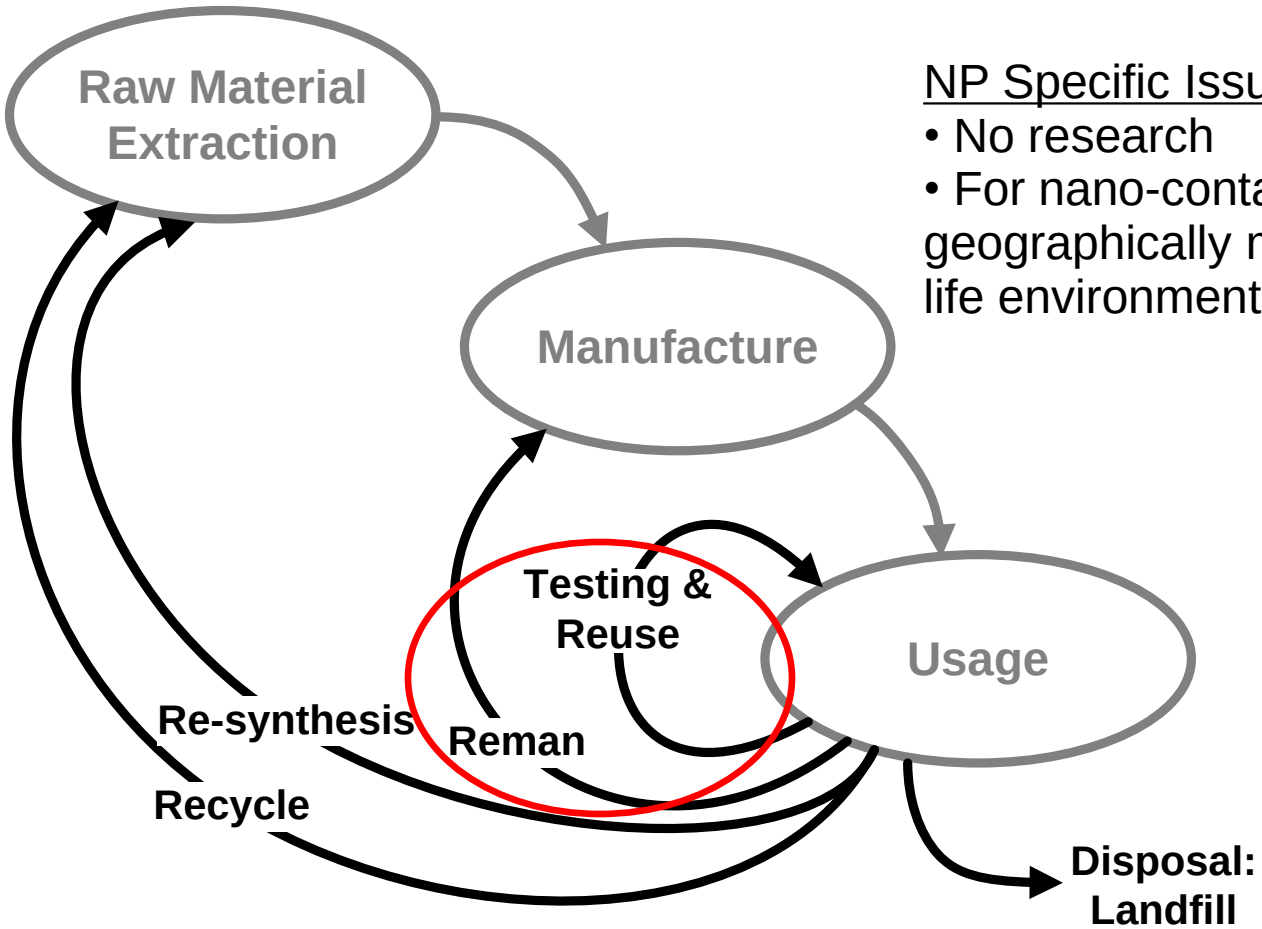
- Nano-silver can inhibit methanogenesis and biogas production from MSW at concentrations higher than 10 mg/kg

  -Yang, et al., 2012 Waste Manage.

- Zn, Ti, and Ag NPs will migrate to leachate but did not affect biochemical oxygen demand or methane potential

  -Bolyard, et. al, 2013, Env. Sci. Tech.

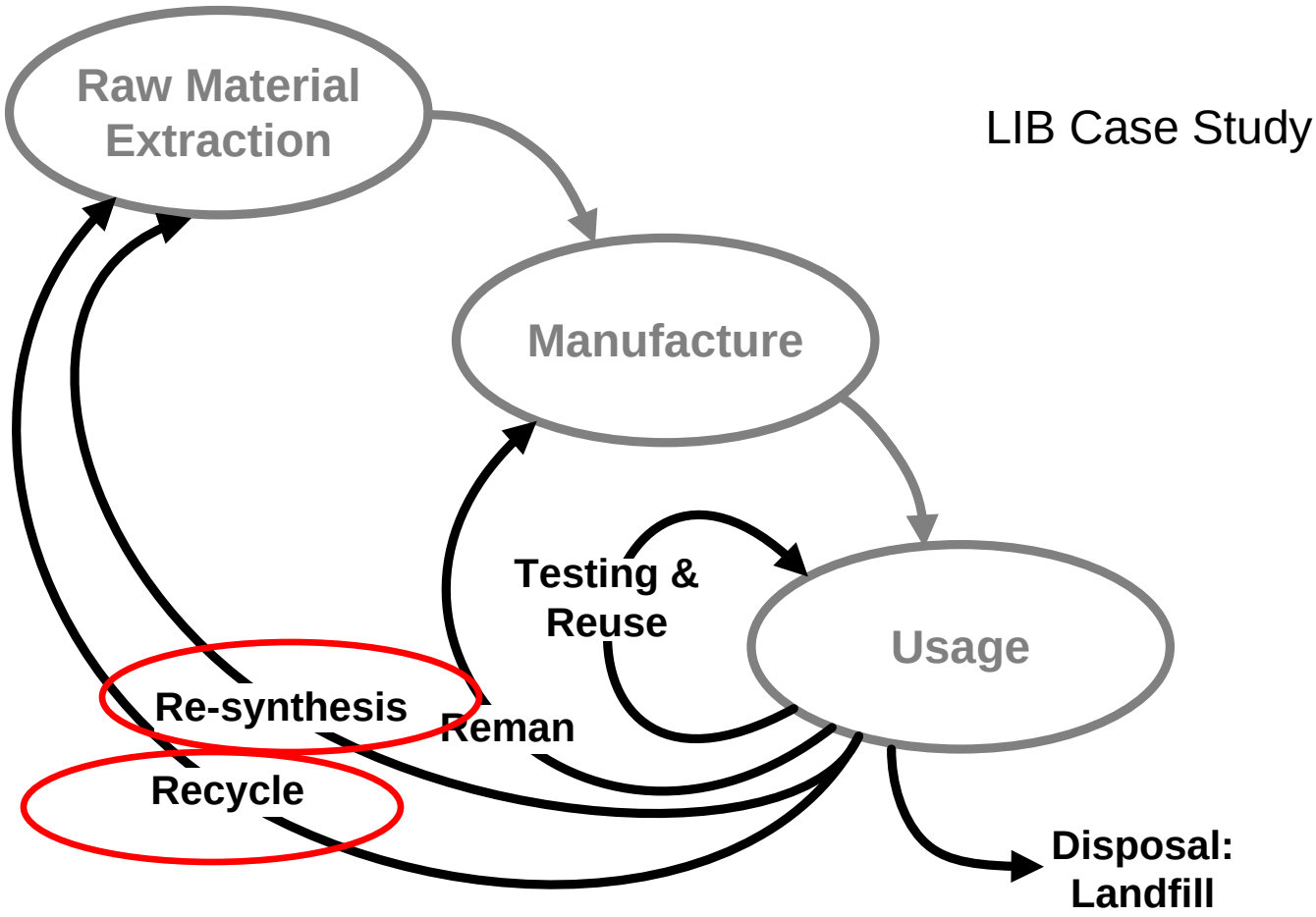
End-of-Life
for products containing nanomaterials



NP Specific Issues:

- No research
- For nano-containing electronics, geographically moving the end-of-life environmental burden

End-of-Life
for products containing nanomaterials



LIB Case Study

Options and Questions

Landfill

- Leaching potential of hazardous metals (uncertain)
- Ban in many places
  - In the EU
  - In the US
    - No federal level regulation yet
    - The New York State Rechargeable Battery Law
    - California Law (AB1125)

Recycling/Reuse

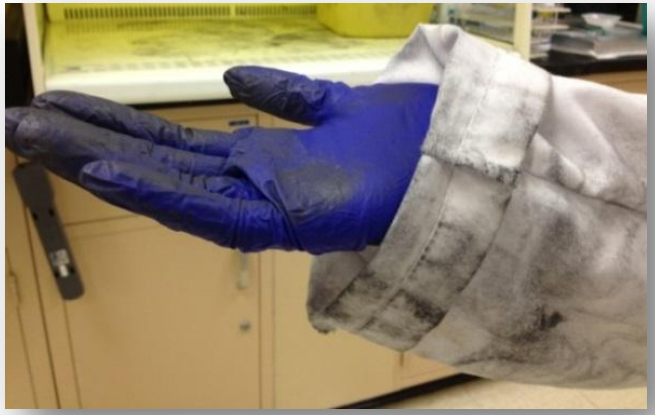
- Environmental savings (Dewulf et al., 2010)
- Economic values of materials in spent LIBs
  - Lowering the cost of recycling will make recycling LIBs popular

- Recoverable value?
- Environmental impacts?

Ref: Dewulf, J., Van der Vorst, G., Denturck, K., Van Langenhove, H., Ghyoot, W., Tytgat, J. and Vandeputte, K. (2010) 'Recycling rechargeable lithium ion batteries: Critical analysis of natural resource savings', *Resources, Conservation and Recycling,* 54(4), 229-234.

Potential Issues

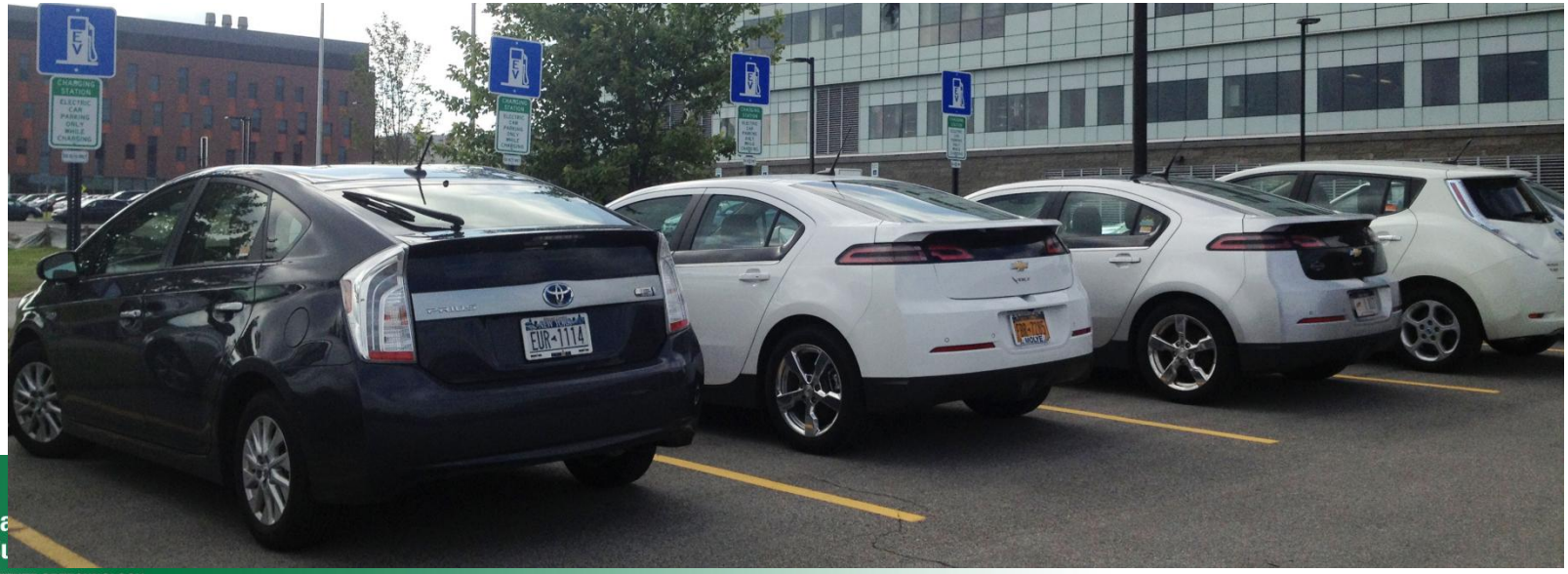
Recycling	Energy Consumption	GHG Emission	Hazardous Wastes	NP Exposure
Pre-recycling				
Pyrometallurgical				
Hydrometallurgical				



- Exposure to dust: carbon black? Other materials?
- Potential for exposure to nanoparticles

NPs in Electric Vehicles

Cathode	Vehicles	NPs?	Refs
$LiCoO_2$	Tesla Roadster, Model S	✓	Schneider 2007
$LiFePO_4$	Coda Sedan, Tata Nano	✓	Hernandez 2011, Lucas 2012
$LiMnO_2$-MMC	Chevy Volt	✓	Fletcher 2011
$LiMn_2O_4$	Nissan Leaf	✓	Hernandez 2011



Exposure assessment of EOL techs

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<u>Goal</u>
Fill research gaps in the LCI for LIBs, with a focus on end-of-life

Research questions:

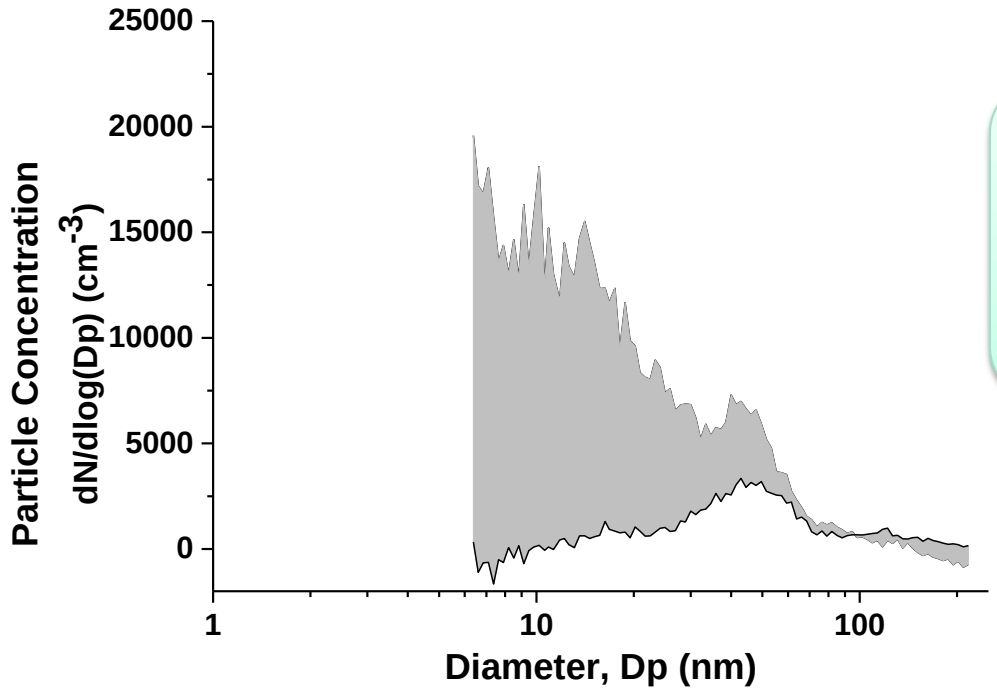
Understand how particle size distribution and particle concentration

- Change over time
- Vary by location

Equipment:
TSI's Scanning Mobility Particle Sizer (SMPS) Spectrometer

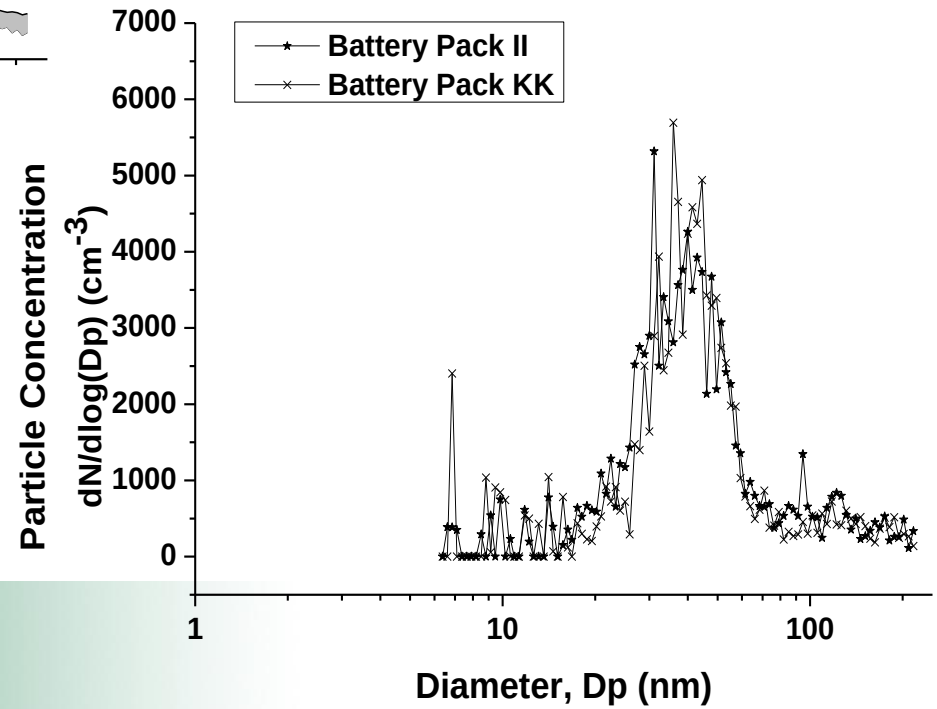
- Size range: 2.5 – 1,000 nm
- Particle concentration: 0-10^7 particles/cm^3

Preliminary work



- Particle concentration changed substantially over time for ultrafine particles (<100 nm)

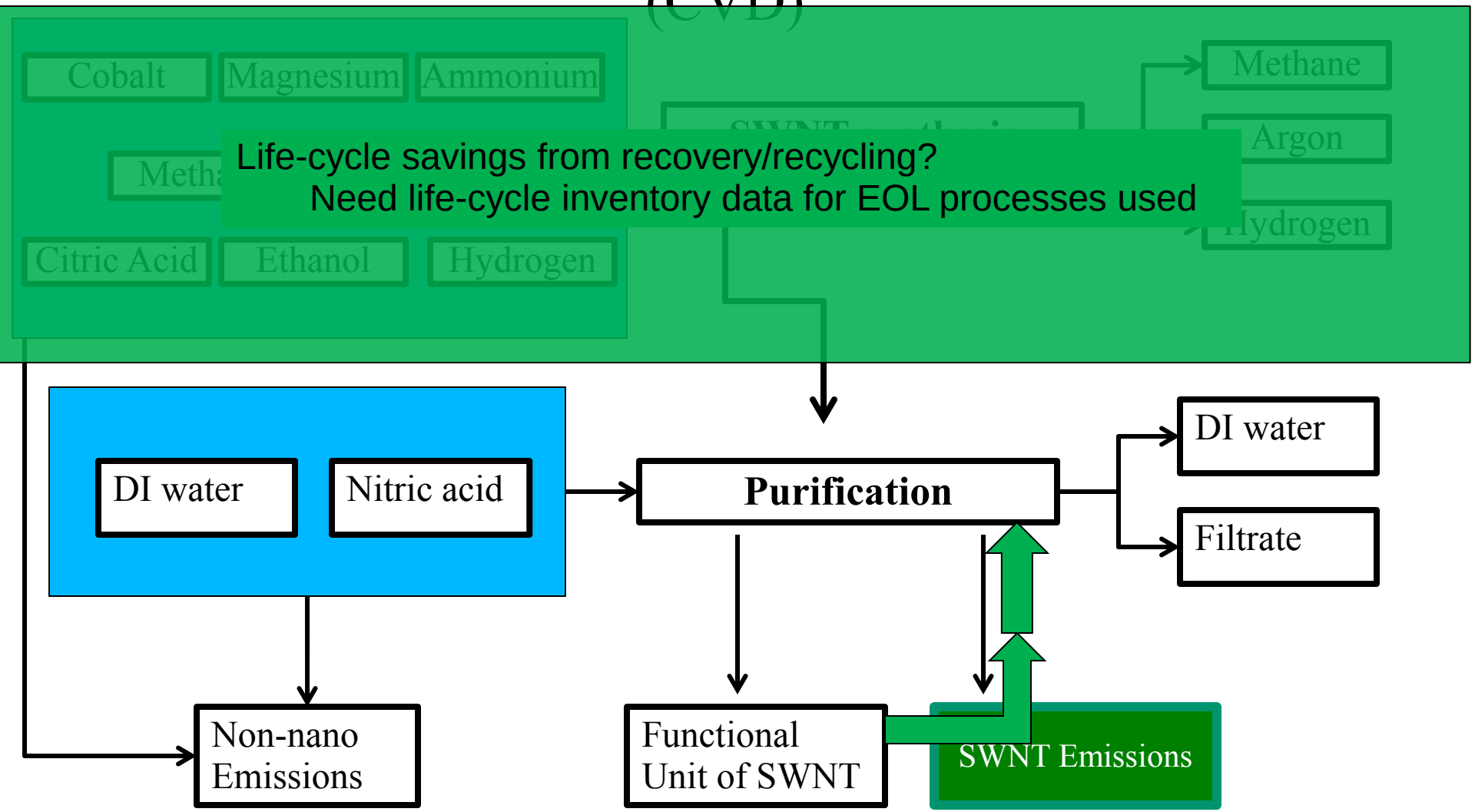
Scan up time = 45 secs; retrace time = 10 sec



- The fume hood can protect workers
- Risk still remains

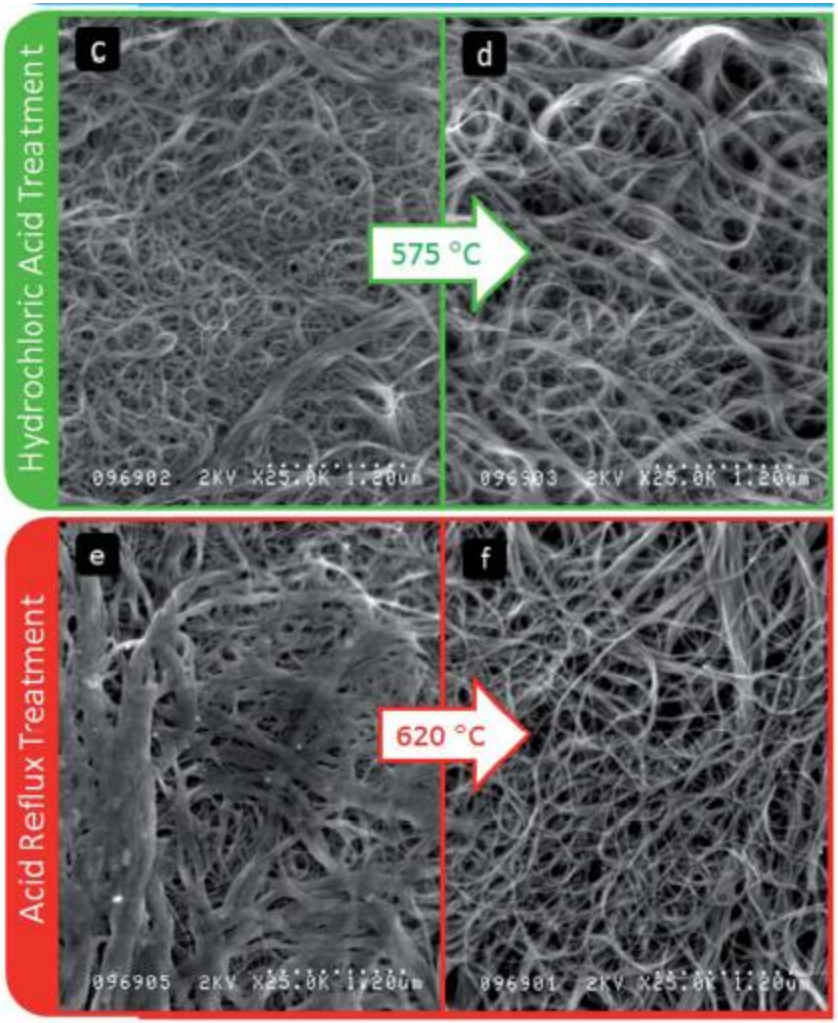
Single Wall Carbon Nanotubes

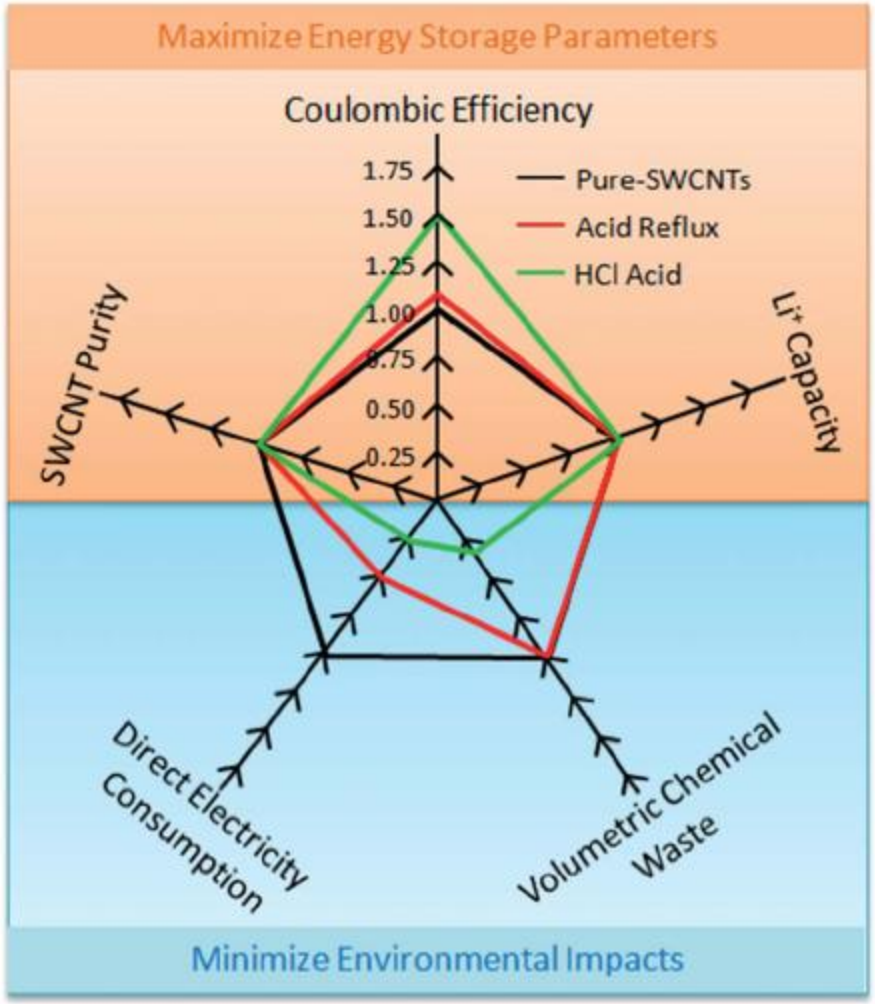
(CVD)



Healy et al. 2008

Life cycle implications of SWCNT re-synthesis





Recycling Single-Wall Carbon Nanotubes from Lithium Ion Batteries. Schauerman et al., *J. Mat. Chem*. 2012, 22, 12008-12015

Recycling at EOL for CNT-Polymers

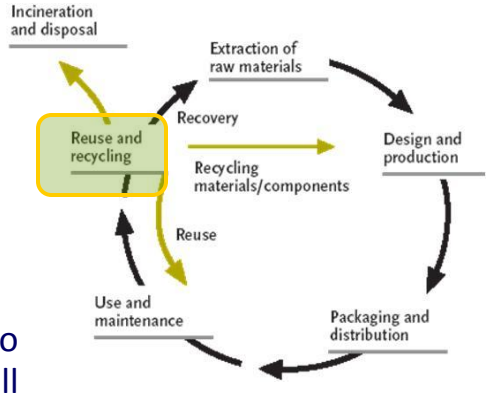
Sustainability infers need for recycling strategies for both manufacturing scrap and post-consumer waste

Determine effect of molding cycles on recyclate properties

- thermal and/or mechanical degradation?
- chemical and physical changes?
- decrease in final properties?

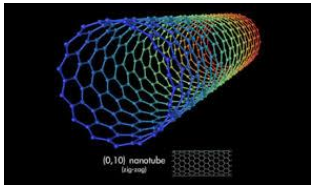
Determine maximum number of cycles to maintain the level of quality for secondary materials

Assess potential for worker exposure during recycling processes, such as machining and grinding



Zhang, Mead and Bello
University of Massachusetts Lowell

Other life-cycle recycling work



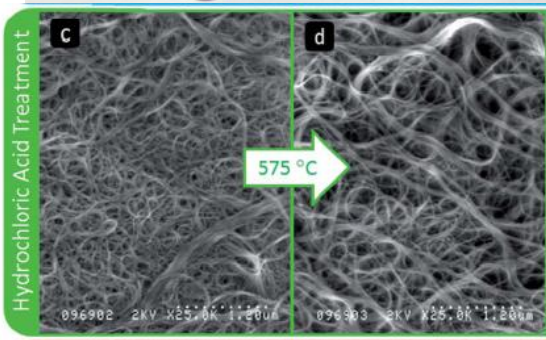
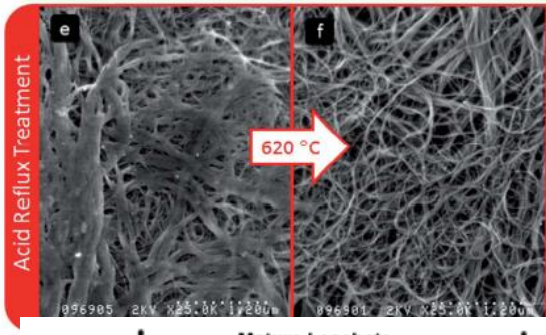
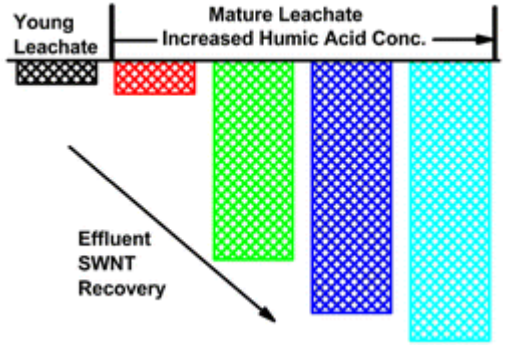
- Pyrometallurgical recovery might require more energy with NPs (Olapiriyakul & Caudill, 2009)
- CNT potential release high during recycling phase (Kohler et al, 2008)
- For some recycling processes, end result is still release to landfill or wastewater treatment facility (Bystrzejewska-Piotrowska et al, 2009)

Discussion

Needs:

- Quantify EOL routes for NPs in products
- Develop NP specific inventories and impact factors (Data & Metrics)

Questions:

How to design NP containing products with the end in mind? Design for X

How to create better metrics to inform either NP related or waste management policy?