Challenges and Research needs for Modular Design and Process Intensification for Fractionation of Liquids

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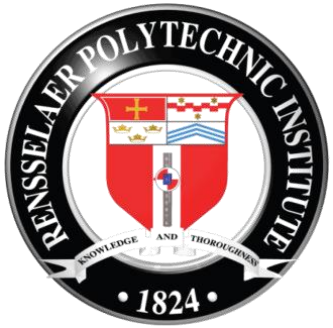

NSF/DOE Modular Manufacturing Workshop
January 17-18, 2017

SEPARATIONS
Challenges and Research Needs

1. Replacing energy intensive distillation
   (chemical and petroleum industries)

2. Replacing batch with continuous processing for recovery of biological molecules
   (biotechnology and pharmaceutical industry)

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1. Replacing energy intensive distillation (reduce CO_2 emissions)

$$E_{INDUSTRIAL} = \sim 0.33 \times E_{GLOBAL}$$

1-3

$$E_{SEPARATIONS} = \sim 0.50 \times E_{INDUSTRIAL} = 0.10\text{-}0.15 \times E_{GLOBAL}$$

4

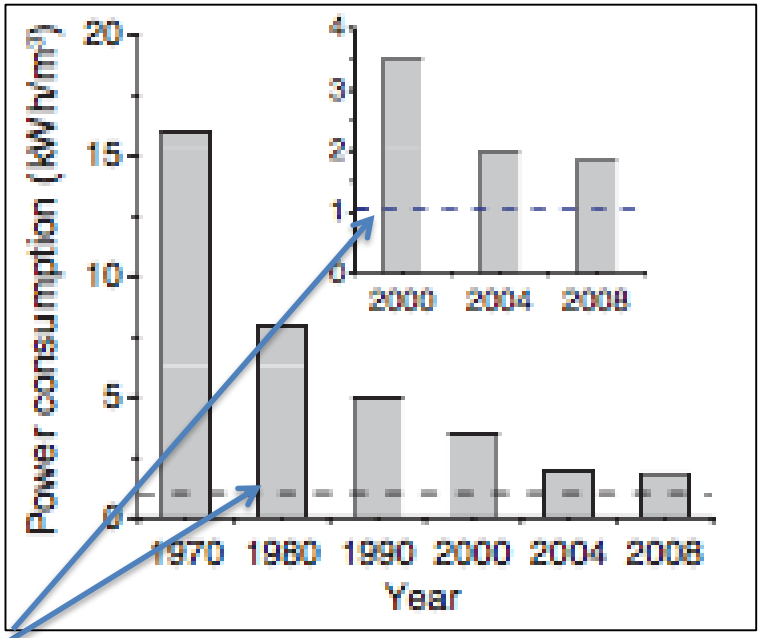
~80% OF INSTALLED SEPARATIONS SYSTEMS = THERMALLY-DRIVEN
(Majority is distillation) (latent heats of vaporization)

Opportunity: Replace distillation

DOE/EIA-038ER 2012 Report; 2. Humphrey and Keller, Sep Process Techn., McGraw-Hill, NY 1997; 3. Sholl and Lively, *Nature* 2016; 4. Robinson et al. ONRL/BCS Materials for Separation Technologies: Energy and Emission Reduction Opportunities, 2005

Reverse osmosis membranes already displaced distillation

Energy Reduction[1]



Theoretical minimum: 1.06 kWh/m³

Massive SW Desal Plant[2] (624,000 m³/d) Sorek, Israel

Membrane close to theoretical minimum BUT pre-& post-treatment needs process intensification.
300 m people drink desalinated water
RO cost for water is at least 50% of distillation
Price in Israel for water is ~55% of cost of water in LA

(1) Elimelech & Phillip (2011) Science; (2),http://www.water-technology.net/projects/sorek-desalination-plant/>;

Challenges and Research Needs for Membranes

Need:

- Solvent stable economical membranes and modules[1]
- Environmentally friendly solvents to produce the membranes[1]
- Extensive pre- and post-treatment for desalination (increase energy needs by factor of 2 or more)[2]
- Mathematical predictive formalism for membrane filtration[3]
- INTEGRATED MODULAR DESIGN (with solar and wind)

Europe ahead[1,4]
Will reduce energy use and CO_2 footprint substantially

(1) Marchetti et al *Chem. Reviews* 2014; (3) Baruah et al., *Biotech Progress* 2005; (2) Imbrogno, Kilduff and Belfort (2016) Desalination; (4) Evonik Commercial pamphlet 2016.

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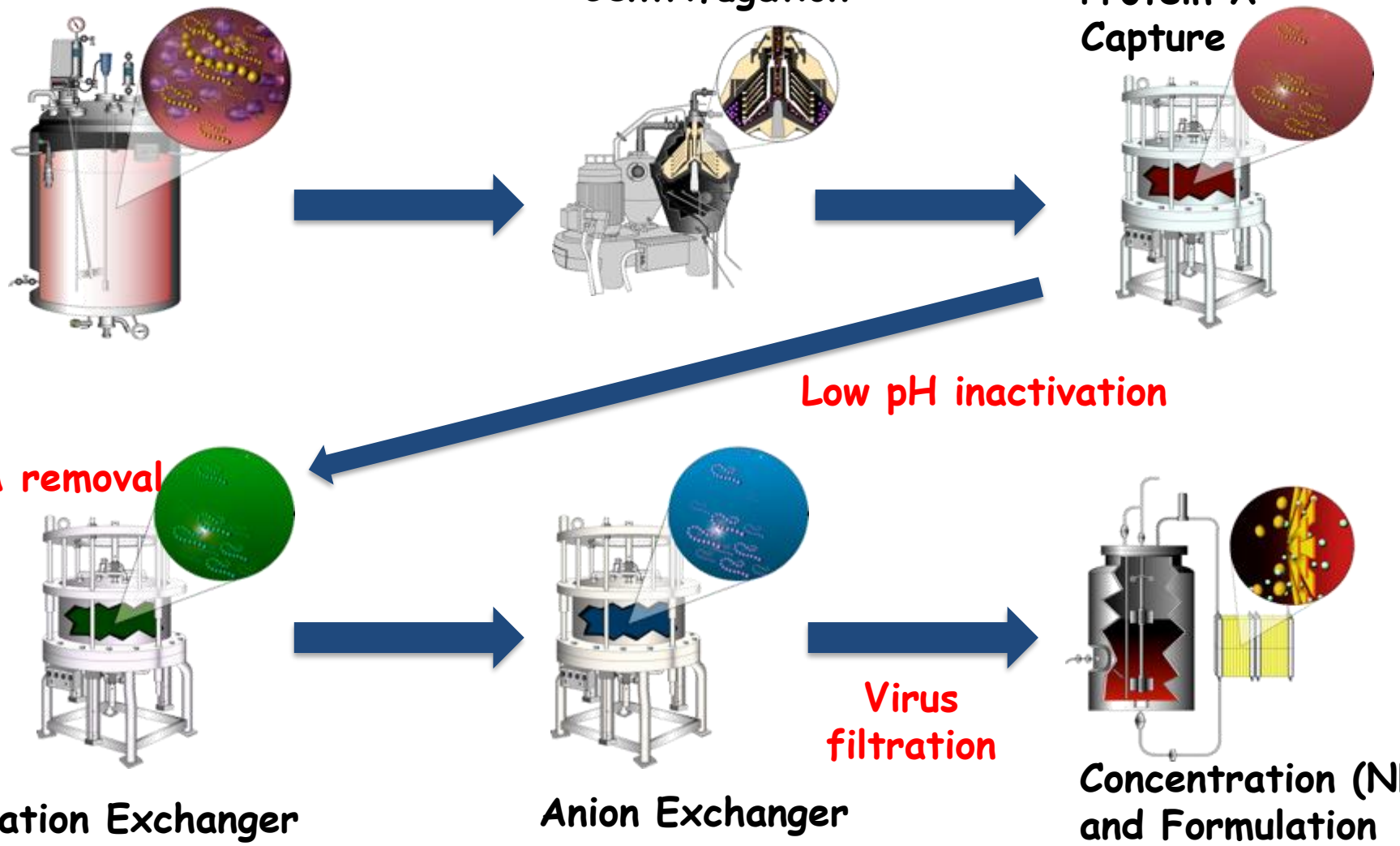
Manufacturing process for monoclonal antibodies
(from Ann Lee, Genentech, Roche)



2. Current Status of Bioprocessing

Facts:

- Bioprocessing still dominated by BATCH PROCESSES
- TITERS INCREASING from 1-10 mg/ml of biologically derived therapeutic protein[1]
- COMPLEX PROCESSING : Enormous space-time demand for production of final product[2]
  (assemble molecular fragments from different sources, large hold-up volumes, excipient additives; long periods and drug shortages)

Opportunity: Process intensification and modular design by integrating reactor with separators[1]

(1) Gallucci et al. *Processes* 2016; (2) Adamo et al. *Science* 2016

Replacing batch with continuous processing

Why continuous? More efficient use of facility with modular design and process intensification

Benefits include:

- Reduction in capital equipment costs and facility size
- Increase in productivity (largely because all equipment is in use at all times)
- Greater flexibility
- Improved product quality (because of greater uniformity in process time)

Most US and European Biotech producers are evaluating continuous bioprocessing

(1) Zydney *Biotech and Bioengr* 2016

SEPARATIONS
Conclusions

1. Replacing energy intensive distillation with non-thermal separation processes such as **synthetic membranes, adsorption, solvent extraction and crystallization** technologies
   (chemical and petroleum industries)

2. Replacing batch with **continuous processing** for recover of biological molecules
   (biotechnology and pharmaceutical industry)