Separation Systems Design Under Uncertainty

Final Presentation for REU program

August 3, 2006

Jamie Polan

Advisors: Professor Linninger

Andrés Malcolm

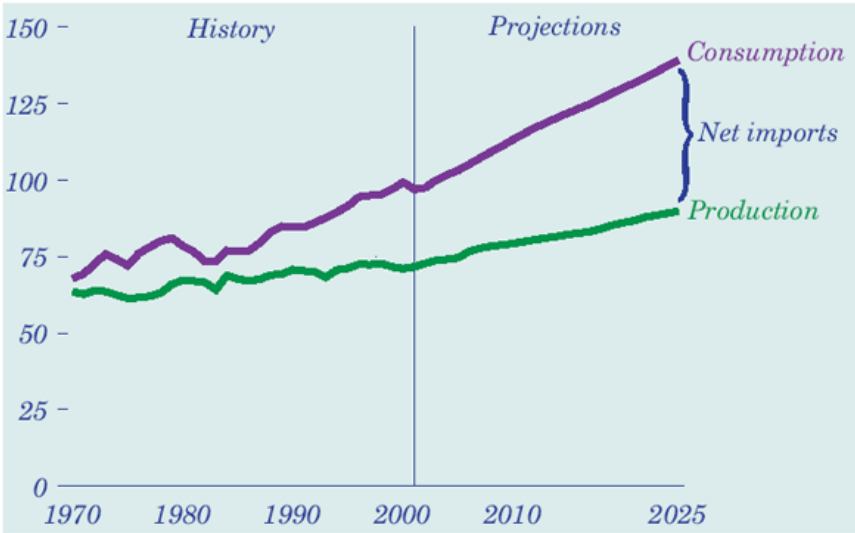
Laboratory for Product and Process Design

University of Illinois- Chicago

Department of Chemical Engineering

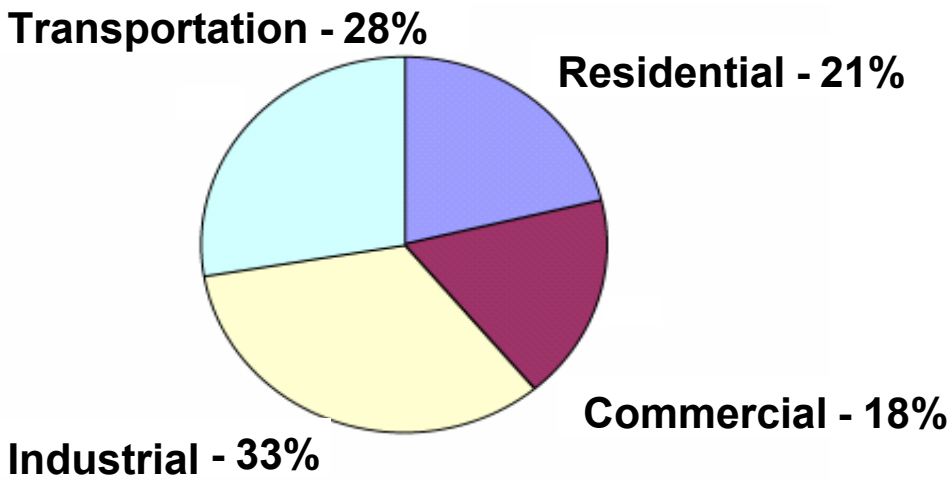
Motivation

Total energy production and consumption 1970 – 2025 (quadrillion Btu)



http://www.eia.doe.gov/oiaf/aeo/production.html

U.S. Energy Consumption by Sector (2004)

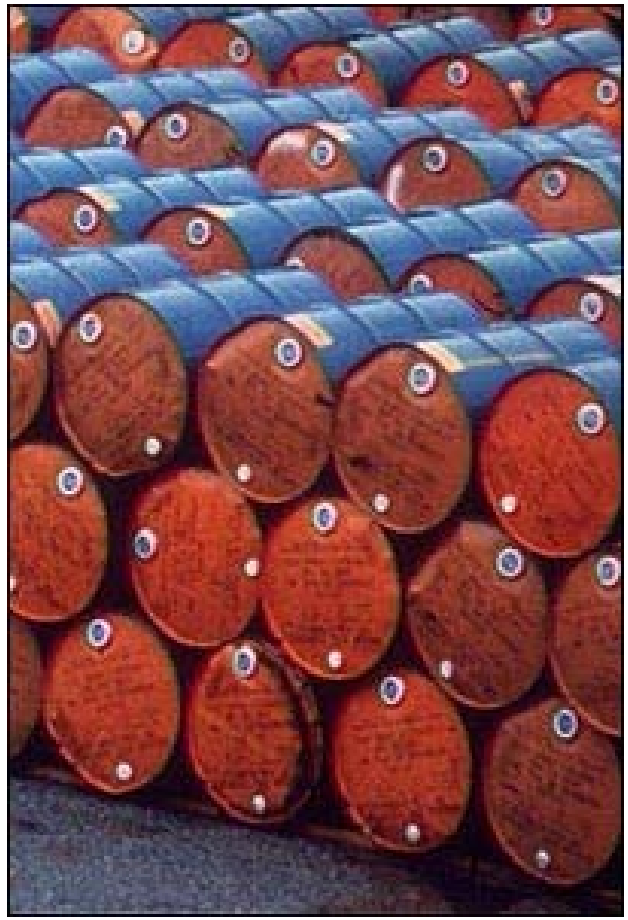


http://www.eia.doe.gov/emeu/aer/consump.html

- **Must consume less energy to reduce dependence on foreign sources**
- **Could start by decreasing amount of energy in industry (33%)**
  - **chemical industry (24%)**
  - **petroleum refining industry (10%)**
- **Separations is a large part of the energy expense of these industries (60%)**

Why Distillation?

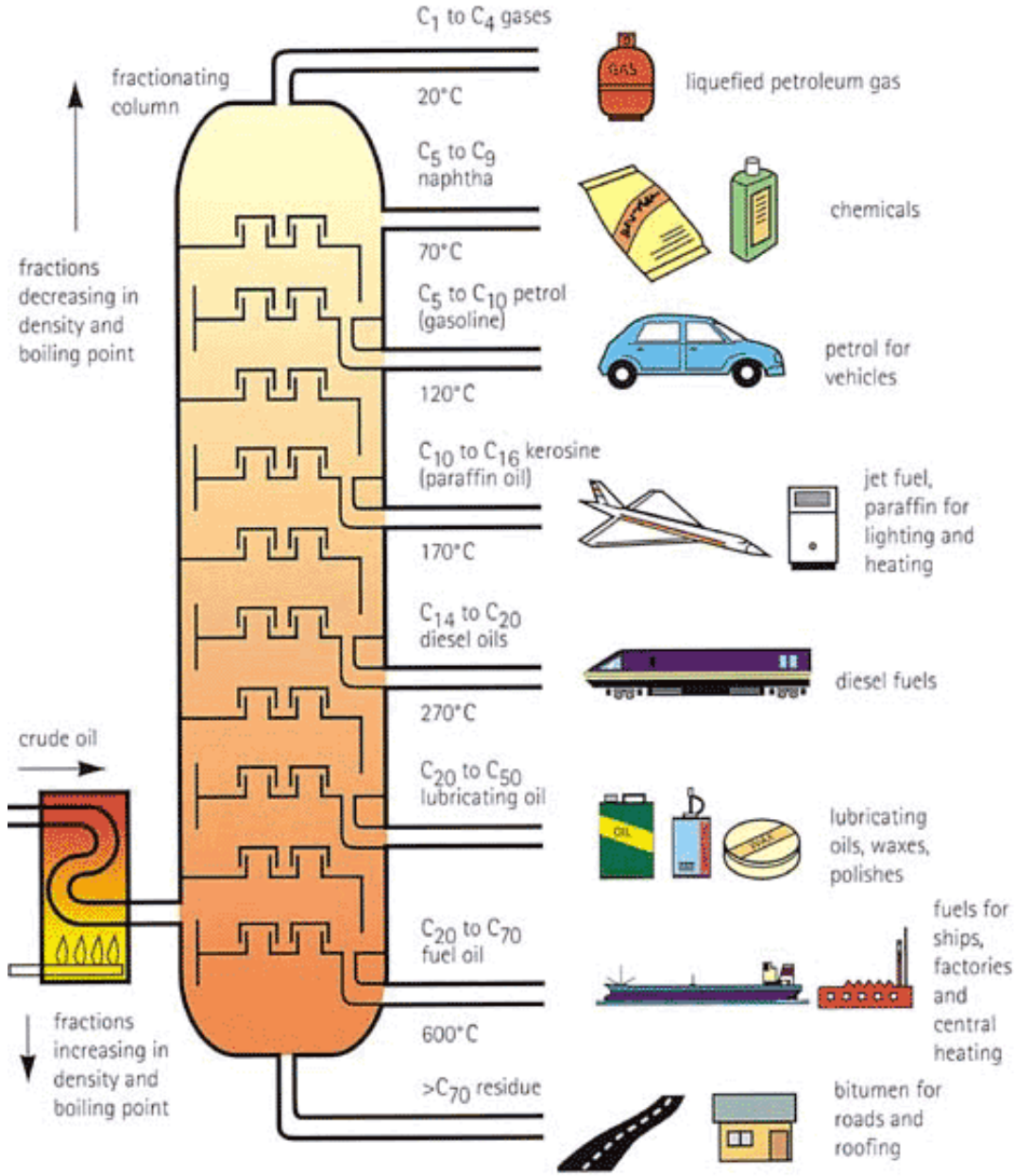
- **95% of separations energy used for distillation**
- **More than 6% of total U.S. energy consumption used for distillation**
- **Total consumption by U.S.**
  94.27 quadrillion Btu
- **Consumption by distillation**
  6.03 quadrillion Btu
- **If process improved 0.1%, we could save**
  - 6.03×10^{12} Btu
  - Over 1 million barrels of crude oil
  - **$70 million/year**



http://news.bbc.co.uk/1/hi/sci/tech/4669260.stm

Distillation

- **Common method of separation in chemical and petroleum refining industries**
- **Uses concept of relative volatility**
  - tendency to vaporize
  - more volatile = higher vapor pressure at operating temperature
- **Very energy intensive**
  - 40,000 distillation columns
  - >200 different processes
- **Optimizing process will increase efficiency & minimize energy waste**



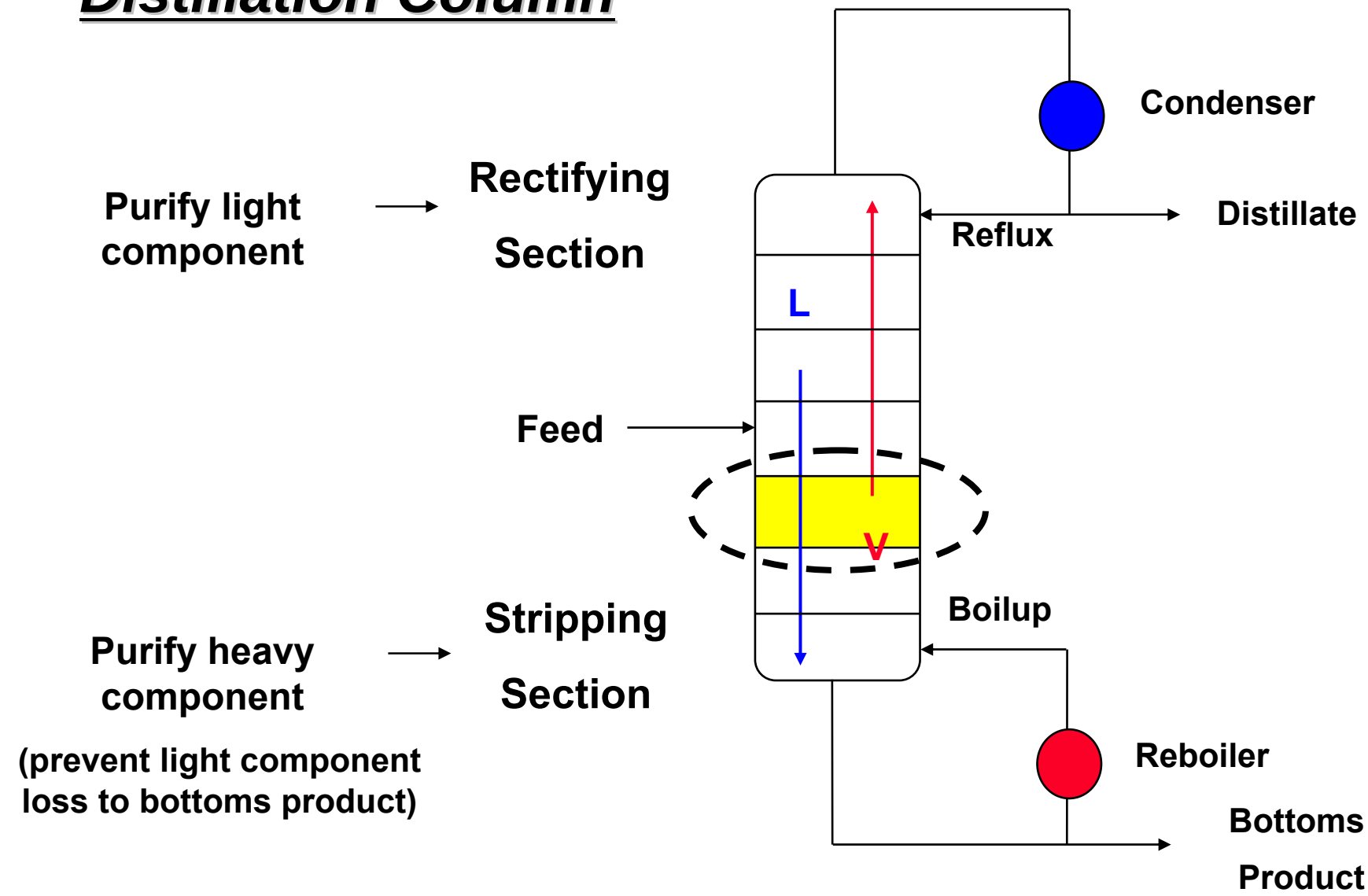
http://www.energyinst.org.uk/education/coryton/page7.htm

How to Improve the Process of Distillation

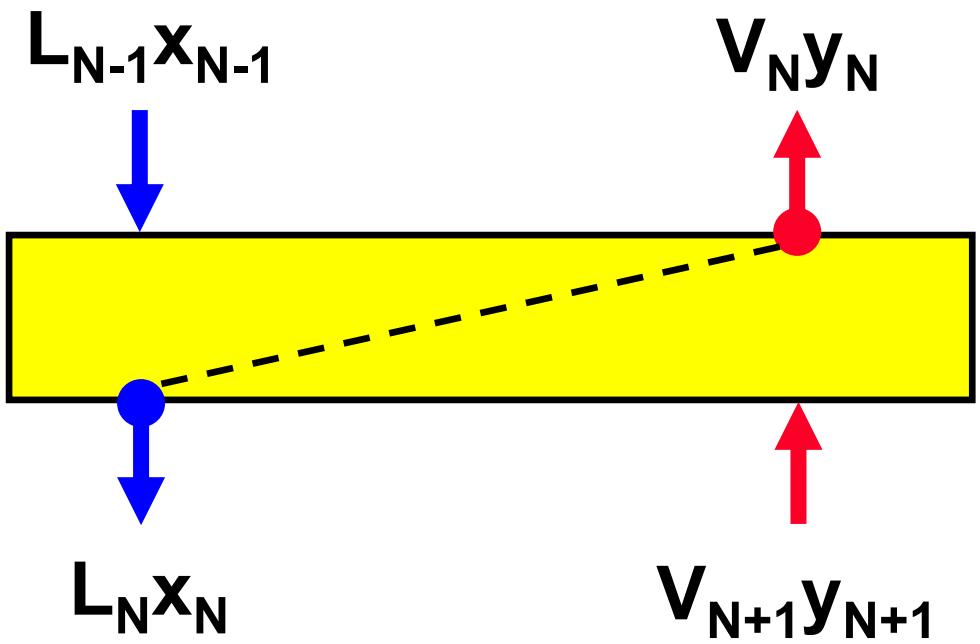
- **Steady state process behavior is well-known; less is known about performance of dynamic systems**
- **Study the dynamic process to see how uncertainty affects**
  - performance
  - cost
  - energy required
- **Show effects of uncertainty with integrated design and control**
- **Considering control is necessary to perform a realistic uncertainty analysis**

More energy efficient columns in real life situations by considering the effects of dynamics and uncertainty in the design stage

Distillation Column



Tray Balance



Vapor Liquid Equilibrium

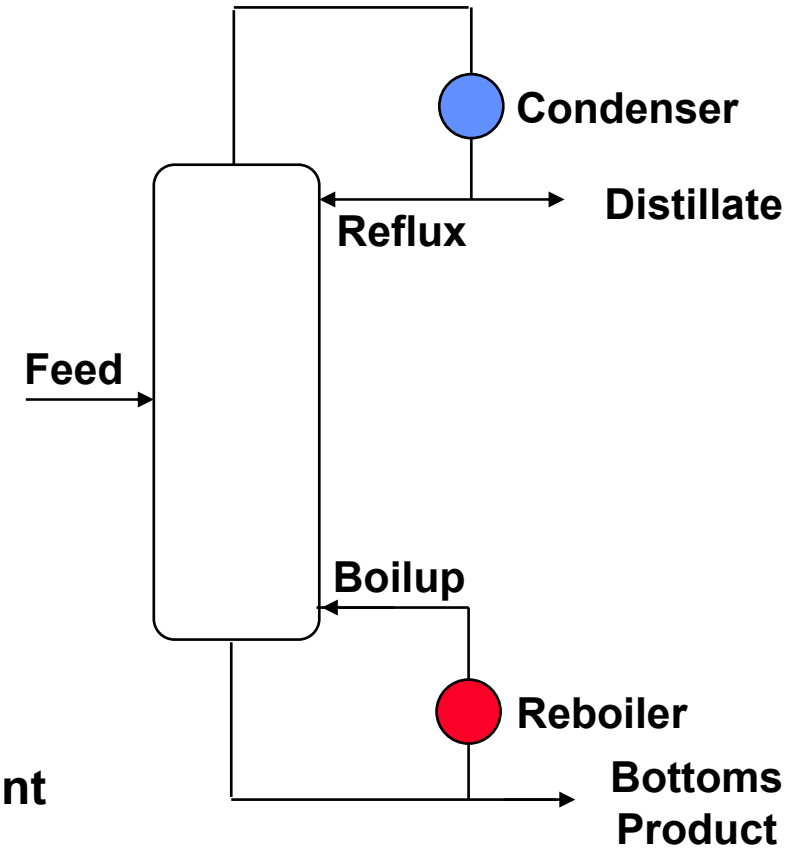
$$y_N = \frac{\alpha\, x_N}{1 + (\alpha - 1)\, x_N}$$

Case Study – Dynamic Column Model

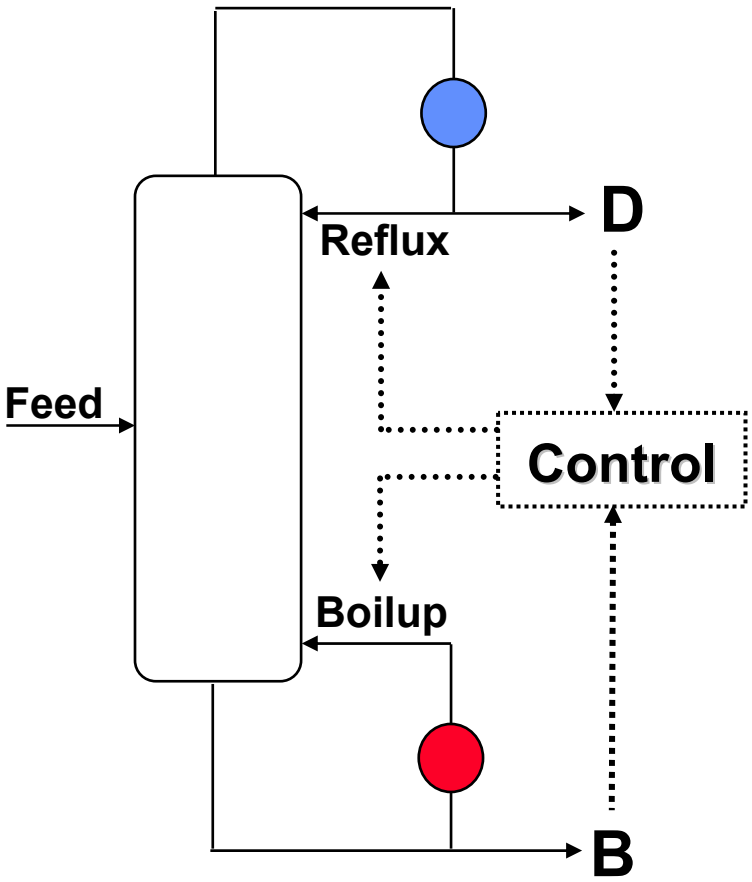
- **Components**
  - hexane
  - p-xylene

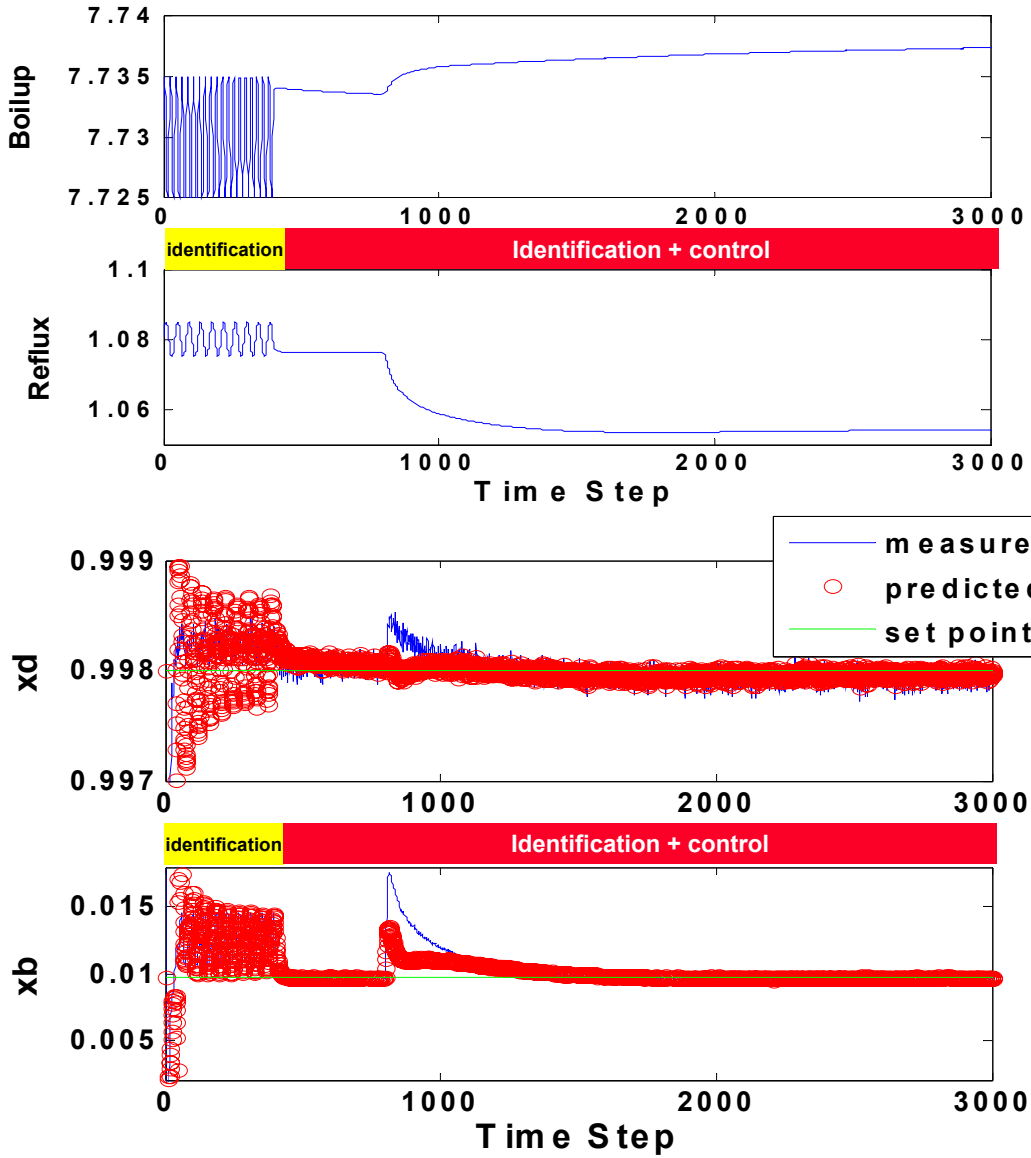
- **Inputs**
  - Temperature - 70°F
  - Pressure – 1 atm (1.01325 bar)
  - Feed rate basis – 5 kmol/hr
  - Feed compositions
    - » $z_h = 0.4$
    - » $z_x = 0.6$

- **Aim: Using Matlab, study how different sources of uncertainty affect the operation and cost of a dynamic column**



Controlled Column





Sensitivity Studies of Design and Uncertainty Effects on Cost

- **Changing design affects mainly capital cost**
  - More trays, higher capital cost

- **Uncertain process parameters affect operating cost**
  - Feed composition
    - » Lower z_F, higher operating cost
  - Relative volatility
    - » Lower α, higher operating cost

- **Uncertainty in both z_F and α leads to significantly higher costs**
  - Avg. operating cost variation - $3,700
  - 40,000 columns
  - Over $135 million total

- **This cost could be diminished if these sources of uncertainty were considered while designing columns**

Conclusions/Future Directions

- **More energy efficient columns can be obtained by considering the effects of dynamics and uncertainty in the design stage**
- **Design & uncertainty greatly affect costs**
  - More trays - higher capital cost
  - Feed less concentrated in light component - higher operating cost
  - Lower relative volatility – higher operating cost
- **Many types of uncertainty should be studied simultaneously**
  - With both lower z_F and α, millions of dollars are lost to uncertainty

- **Improve operating cost model**
  - better correlation of cost to energy requirements
- **Develop systematic design methodology**
  - predict column performance, cost, & energy requirements when many variables are uncertain
- **Study other parameter variations**
  - heat quality
  - tray efficiency

http://www.eia.doe.gov/kids/energyfacts/

References

Annual Energy Outlook 2003. Energy Information Association, DOE, 2003. http://tonto.eia.doe.gov/FTPROOT/forecasting/0383(2003).pdf

Bansal, Vikrant, John D. Perkins, and Efstratios N. Pistikopoulos, A Case Study in Simultaneous Design and Control Using Rigorous, Mixed-Integer Dynamic Optimization Models, Ind. Eng. Chem. Res. 2002, 41, 760-778.

Bequette, B. Wayne, Process Dynamics: Modeling, Analysis, and Simulation, Prentice Hall PTR, New Jersey, 1998.

Doherty, M.F. and M.F. Malone. Conceptual Design of Distillation Systems. McGraw-Hill, 2001.

Douglas, James M. Conceptual Design of Chemical Processes. McGraw Hill, 1988.

Eldridge, R. Bruce and A. Frank Seibert. Hybrid Separations/Distillation Technology: Research Opportunities for Energy and Emissions Reduction, 2005.

Energy and Environmental Profile of the U.S. Petroleum Refining Industry. U.S. DOE/OIT, December 1998. http://www.eia.doe.gov/emeu/mecs/iab98/petroleum/sector.html

Felder, Richard M. and Ronald W. Rousseau. Elementary Principles of Chemical Processes, 3rd ed. John Wiley & Sons, New York, 2000.

Malcolm, A. and A. A. Linninger, Integrating systems design and control using dynamic flexibility analysis, submitted to I&ECR, 2006.

Manufacturing Energy Consumption Survey. Energy Information Administration, DOE, 2001. http://www.eia.doe.gov/emeu/mecs/iab98/petroleum/energy_use.html

NIST – National Institute of Standards and Technology – Chemistry WebBook Database. Accessed Wed, May 31, 2006.

Perry, Robert H., Don W. Green. Perry's Chemical Engineers' Handbook. The McGraw-Hill Companies, Inc., 1999.

Seader, J.D. and Ernest J. Henley. Separation Process Principles. John Wiley & Sons, Inc., New York, 1998.

World Crude Oil Prices. Energy Information Association, DOE, 2006. http://tonto.eia.doe.gov/dnav/pet/pet_pri_wco_k_w.htm

Acknowledgements

- **Supplement from NSF DMI 0328134 "CLEAN CHEMICAL MANUFACTURING UNDER UNCERTAINTY" PI Andreas A. Linninger**
- **Professor Andreas Linninger**
- **Andrés Malcolm**
- **LPPD**

http://www.schoolscience.co.uk/petroleum/index.html