A Process Control Odyssey: (In and Out of Control)

Dale E. Seborg

University of California, Santa Barbara

Nordic Process Control Workshop Åbo, Finland January 18, 2018

Nordic Process Control Pioneers

Denmark

Sten Bay Jørgensen
Mögens Kümmel

Finland

Kurt-Erik Haggblöm
Kurt Waller

Norway

Jens Balchen
Magne Fjeld
Sigurd Skögestad

Sweden

Karl Johan Åström
Lennart Ljung
Bjorn Wittenmark

And A Fashion Leader …

The Early Days: Wisconsin

- Hometown: Madison, Wisconsin

- **B.S. degree: Univ. of Wisconsin**

Graduate Studies at Princeton

Lessons Learned:

- + Excellent academic environment
- + Modern control theory is elegant
  ($u(t) = Kx(t)$) will solve all of your control problem
- - No female students at Princeton (then)
- - Ivy League football is not very exciting

Siren Call 1: University of Alberta

Six months before finishing my Ph.D program at Princeton:

- I wasn't interested in an academic position
- I had agreed to ~ 15 industrial interviews
- Then a brochure from the U. of Alberta arrived. They had:
  - Two process control faculty and were looking for a third
  - Computer-controlled pilot plants

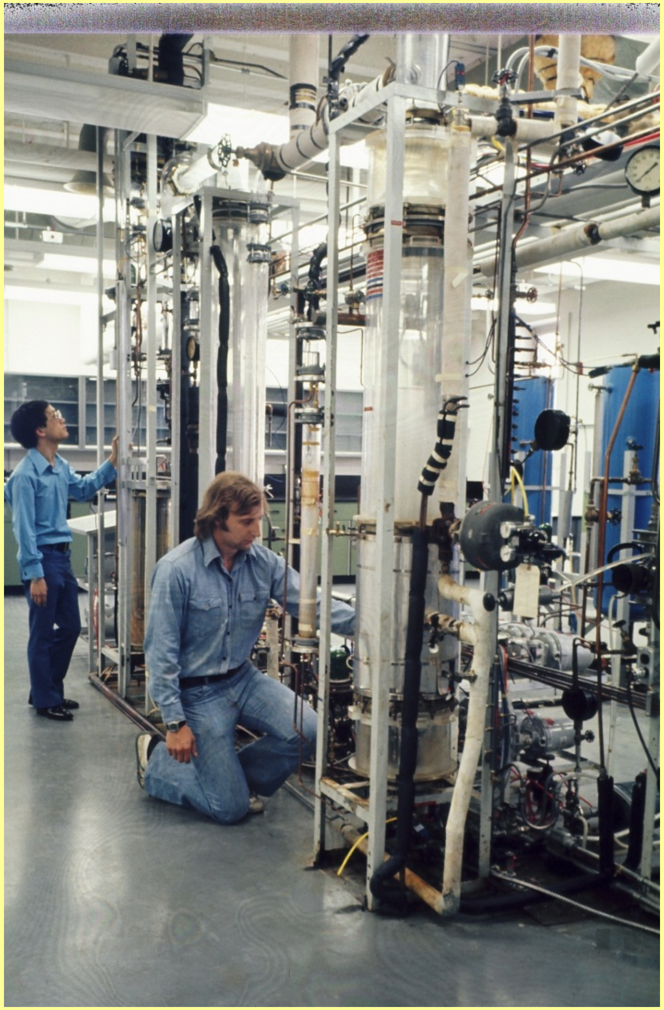
I decided to apply ….

Advanced Process Control at the University of Alberta

- In 1968, the field of computer process control, was in its infancy
- The first commercial computer control systems (e.g., IBM 1800) were introduced in the mid-1960s
- Professor Grant Fisher (U of A) was a visionary leader in this field
- The U of A research group performed pioneering experimental applications of advanced process control techniques to pilot plant processes

Computer-Controlled Pilot Plants

Grant Fisher

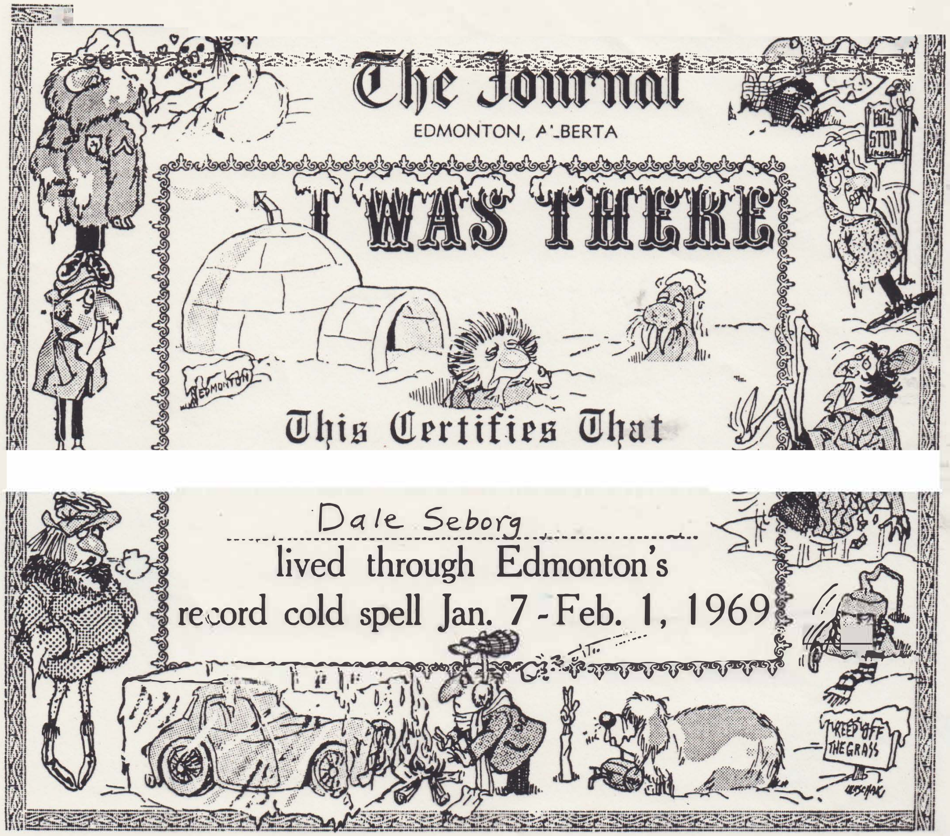


Double-Effect Evaporator

IBM 1800 Real-time Computer (~1965)

- Computer Memory: 32 KB
- Hard drive: 1 MB capacity and a random access time of 1 s

Winters in Edmonton



Daily High and Low Temperatures Recorded at Edmonton Industrial Airport (°F)

	H	L		H	L		H	L		H	L		H	L
Jan. 7	-6	-14	Jan. 12	18	-26	Jan. 17	-10	-16	Jan. 22	-16	-35	Jan. 27	-22	-27
Jan. 8	-11	-21	Jan. 13	-10	-24	Jan. 18	-13	-22	Jan. 23	-13	-30	Jan. 28	-20	-31
Jan. 9	-18	-25	Jan. 14	-11	-18	Jan. 19	-16	-22	Jan. 24	-6	-31	Jan. 29	-23	-31
Jan. 10	-16	-23	Jan. 15	-13	-20	Jan. 20	-16	-31	Jan. 25	-9	-18	Jan. 30	-22	-39
Jan. 11	-14	-24	Jan. 16	-12	-25	Jan. 21	-15	-31	Jan. 26	-15	-25	Jan. 31	-11	-30
												Feb. 1	-10	-20

Edmonton Winter: 1968-69 (my first year there)

Jan. 17	-10	-16	Jan. 22	-16	-35	Jan. 27	-22	-27
Jan. 18	-13	-22	Jan. 23	-13	-30	Jan. 28	-20	-31
Jan. 19	-16	-22	Jan. 24	-6	-31	Jan. 29	-23	-31
Jan. 20	-16	-31	Jan. 25	-9	-18	Jan. 30	-22	-39
Jan. 21	-15	-31	Jan. 26	-15	-25	Jan. 31	-11	-30
						Feb. 1	-10	-20

Where was global warming when I *really* needed it !!

Comparison of C2 Responses

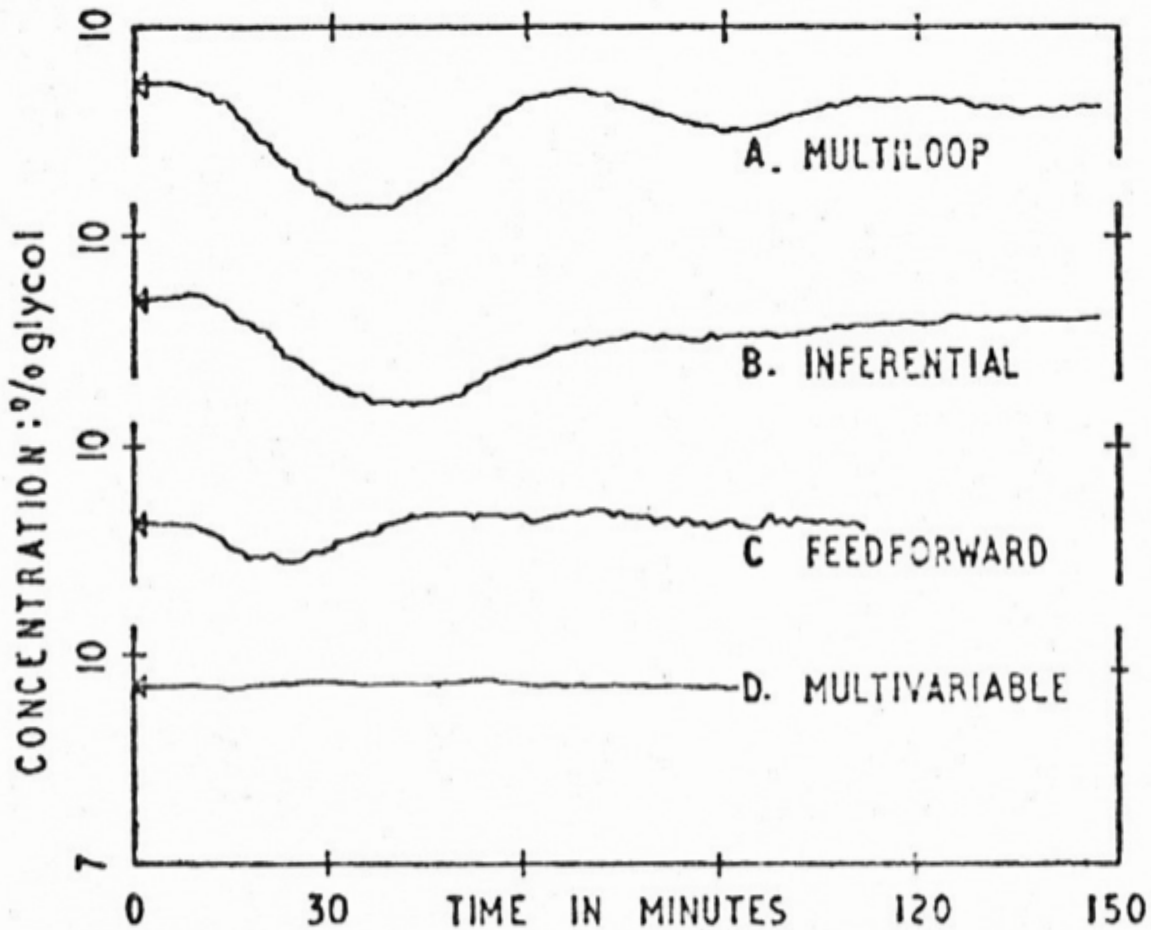
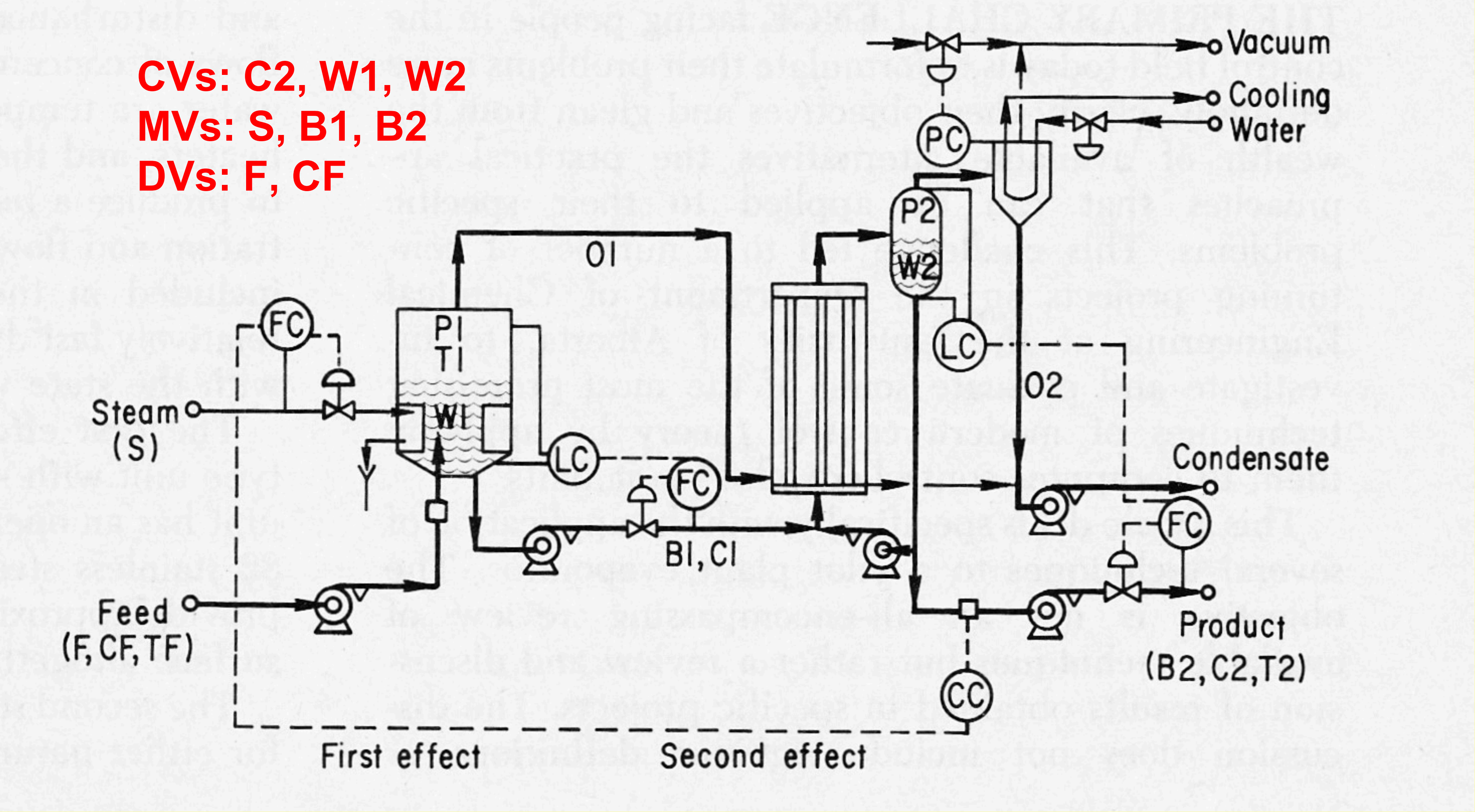


Fig. 3 Comparison of experimental responses of the product concentration to 20 percent increases in feed flow rate

Pilot-Scale Double Effect Evaporator

CVs: C2, W1, W2
MVs: S, B1, B2
DVs: F, CF

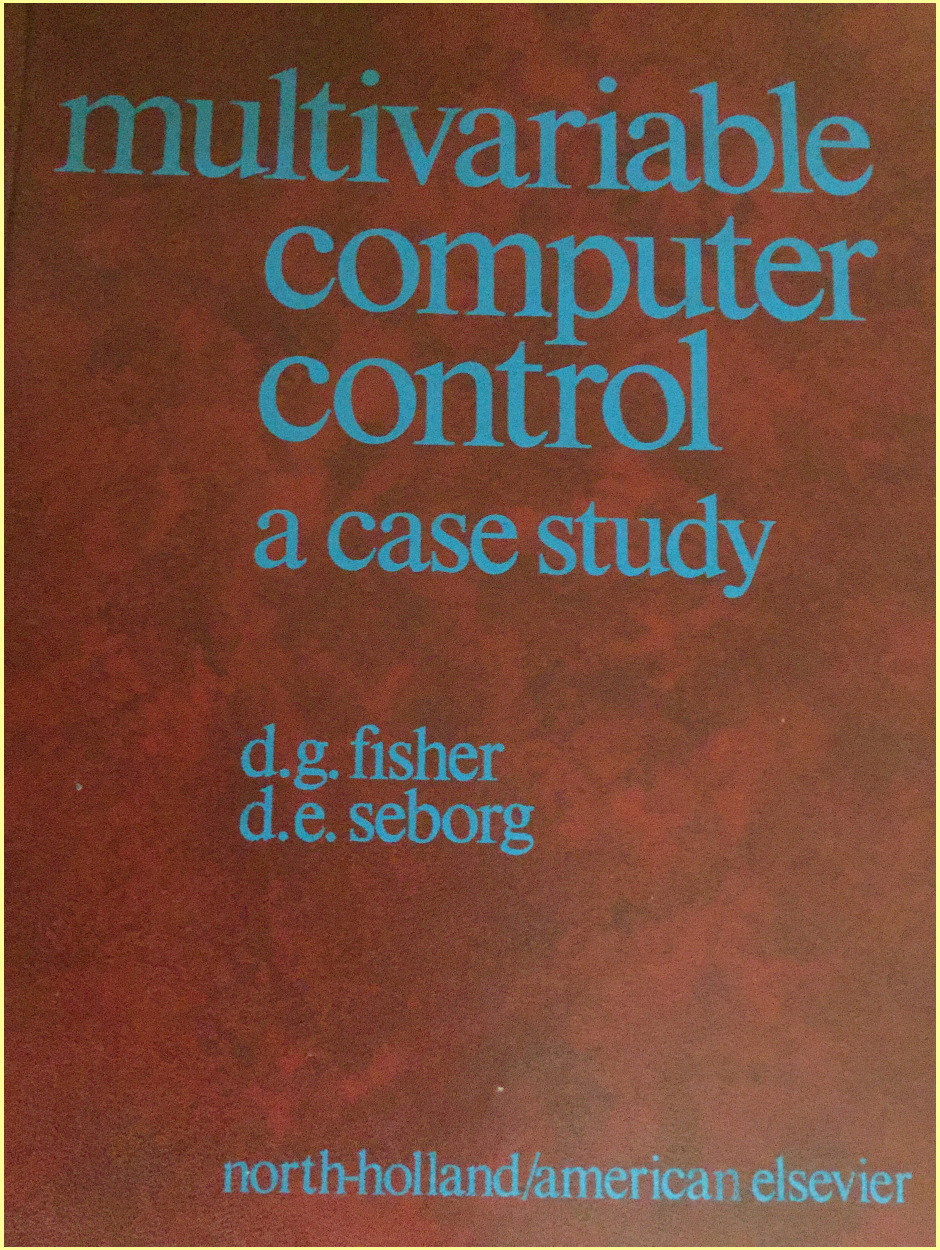


Evaporator Model

$$
\begin{bmatrix} \dot{W}1 \\ \dot{C}1 \\ \dot{H}1 \\ \dot{W}2 \\ \dot{C}2 \end{bmatrix} = \begin{bmatrix} 0 & -.00156 & -.1711 & 0 & 0 \\ 0 & -.1419 & .1711 & 0 & 0 \\ 0 & -.00875 & -1.102 & 0 & 0 \\ 0 & -.00128 & -.1489 & 0 & .00013 \\ 0 & .0605 & .1489 & 0 & -.0591 \end{bmatrix} \begin{bmatrix} W1 \\ C1 \\ H1 \\ W2 \\ C2 \end{bmatrix}
$$

$$
+ \begin{bmatrix} 0 & -.143 & 0 \\ 0 & 0 & 0 \\ .392 & 0 & 0 \\ 0 & .108 & -.0592 \\ 0 & -.0486 & 0 \end{bmatrix} \begin{bmatrix} S \\ B1 \\ B2 \end{bmatrix}
$$

$$
+ \begin{bmatrix} .2174 & 0 & 0 \\ -.074 & .1434 & 0 \\ -.036 & 0 & .1814 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} F \\ CF \\ HF \end{bmatrix} \qquad (26)
$$


multivariable
computer
control
a case study
d.g. fisher
d.e. seborg
north-holland/american elsevier

Example 1
An Experimental Application of Self-Regulator (STR)

- The STR is an innovative adaptive control technique developed by Åström and Wittenmark in a famous 1973 paper in *Automatica*.
- **Basic idea**:
  - Apply minimum variance (MV) control in a recursive manner
  - On-line estimation of model parameters in a linear discrete-time model
  - At each sampling instant, update the MV control law based on the new parameter estimates
- **Equipment:** Pilot- Scale Double Effect Evaporator at the University of Alberta

STR Model

The STR is based on a linear, discrete-time model:

$$A(q^{-1})\,y(t) = B(q^{-1})u(t-k) + C(q^{-1})\xi(t) + d(t) \qquad (2)$$

where q^{-1} is the backward shift operator, $q^{-1}y(t) = y(t-1)$, and the A, B, and C polynomials are defined by

$$A(q^{-1}) = 1 + \sum_{i=1}^{n} a_i q^{-i}$$

$$B(q^{-1}) = \sum_{i=0}^{m} b_i q^{-i}$$

$$C(q^{-1}) = \sum_{i=0}^{n} c_i q^{-i}$$

Assume that $C(q^{-1})=0$ and $B(q^{-1})$ are non-minimum phase; that is, they have no roots outside the unit circle.

Experimental STR Application

- **Multi-loop Control Configuration**:

  *C*2-*S*: STR
  *W*1-*B*1: PI
  *W*2-*B*2: PI

- **Unmeasured Disturbances**

  +/- 20% step changes in *F*
  - 30% step change in *CF*

- **Comparisons with Conventional Multi-loop PI Control**

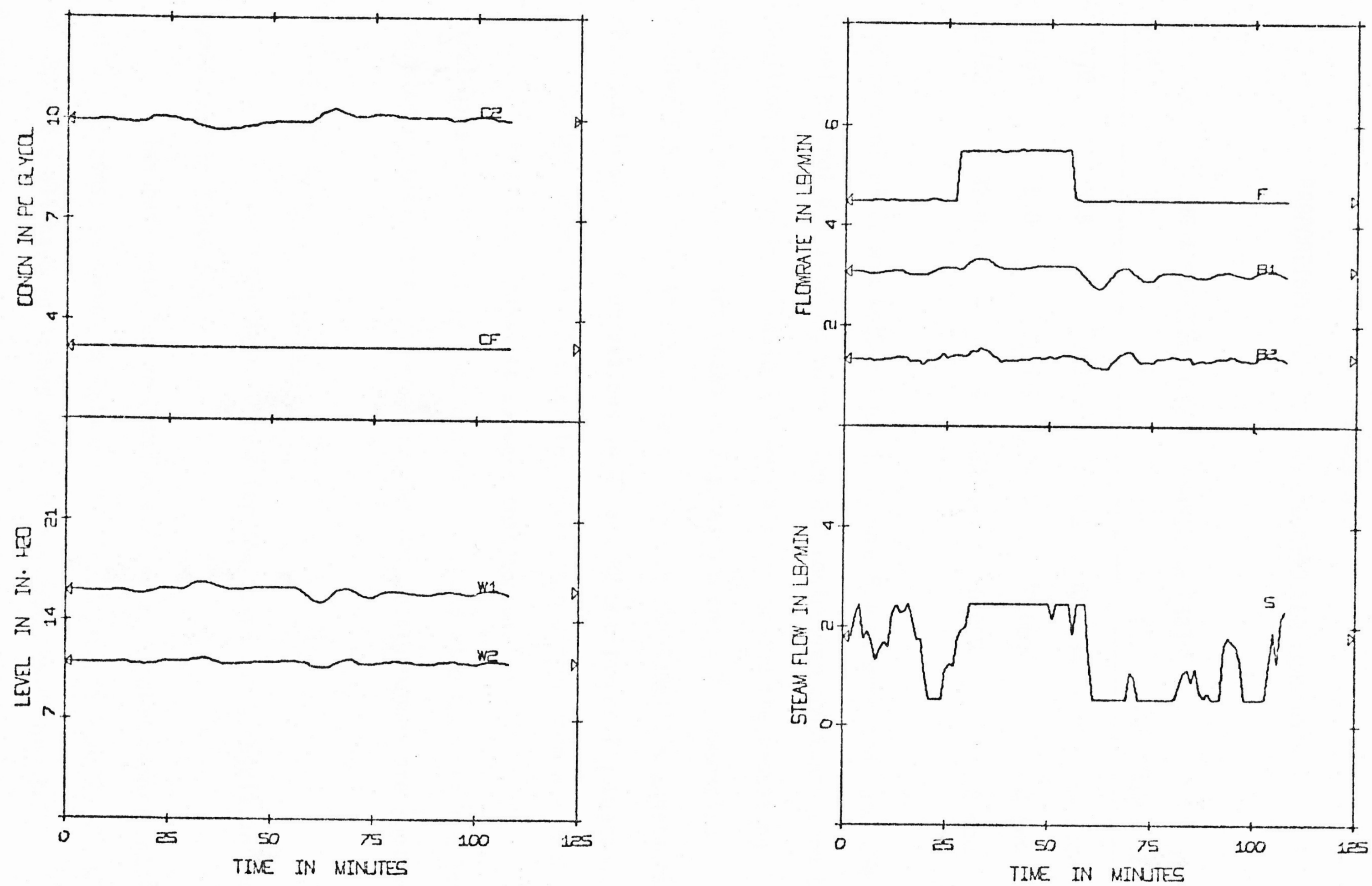


Figure 5.5 Evaporator response (EXP/+20% F, -20% F/ML PI control)

Figure 1: Multi-loop PI control for +/- 20% step changes in F.

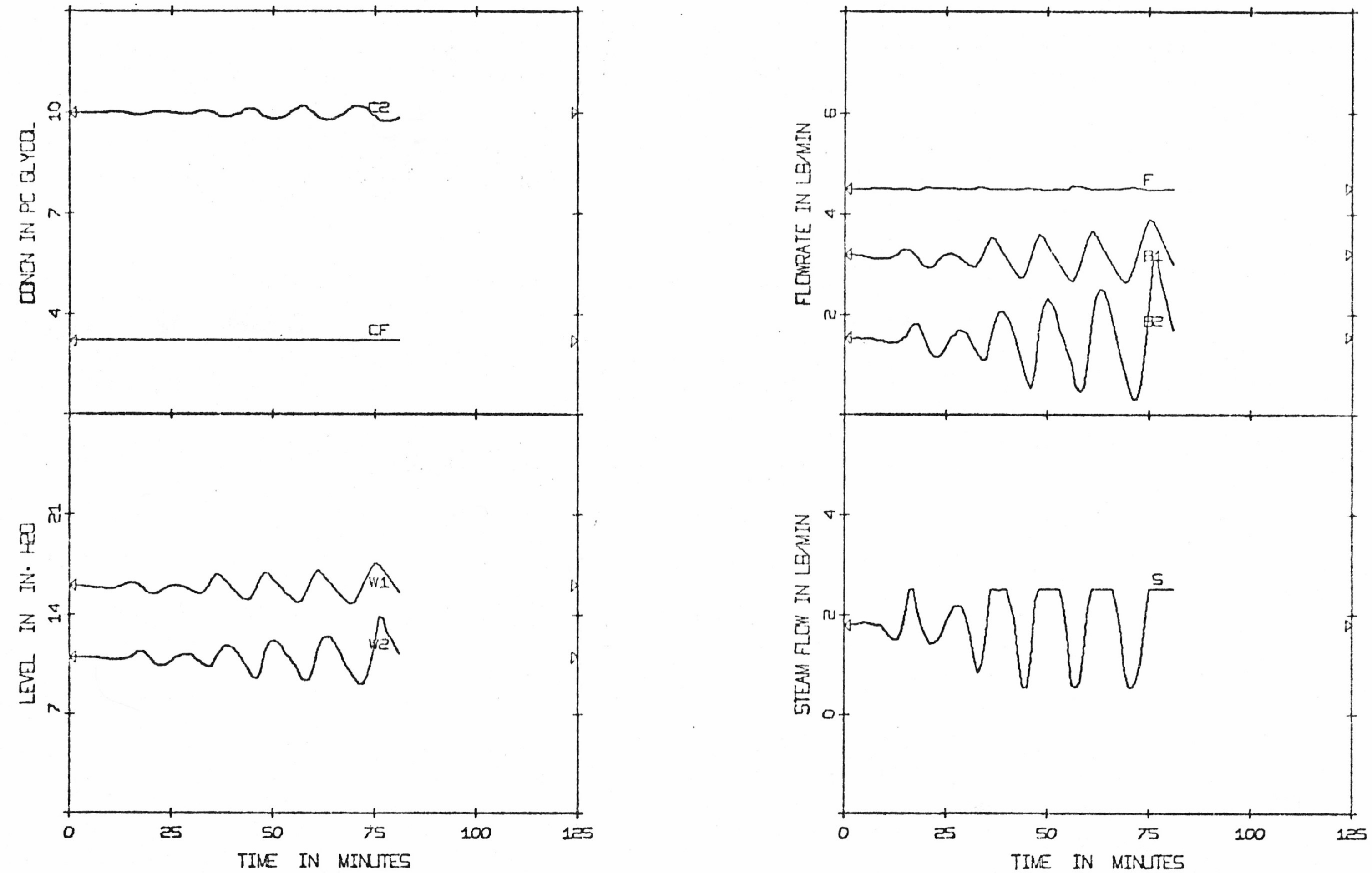


Figure 5.20 Evaporator response (EXP/STR), $\beta_0 = 0.1$

Figure 3: STR control; no disturbance $\beta_0 = 0.1$.

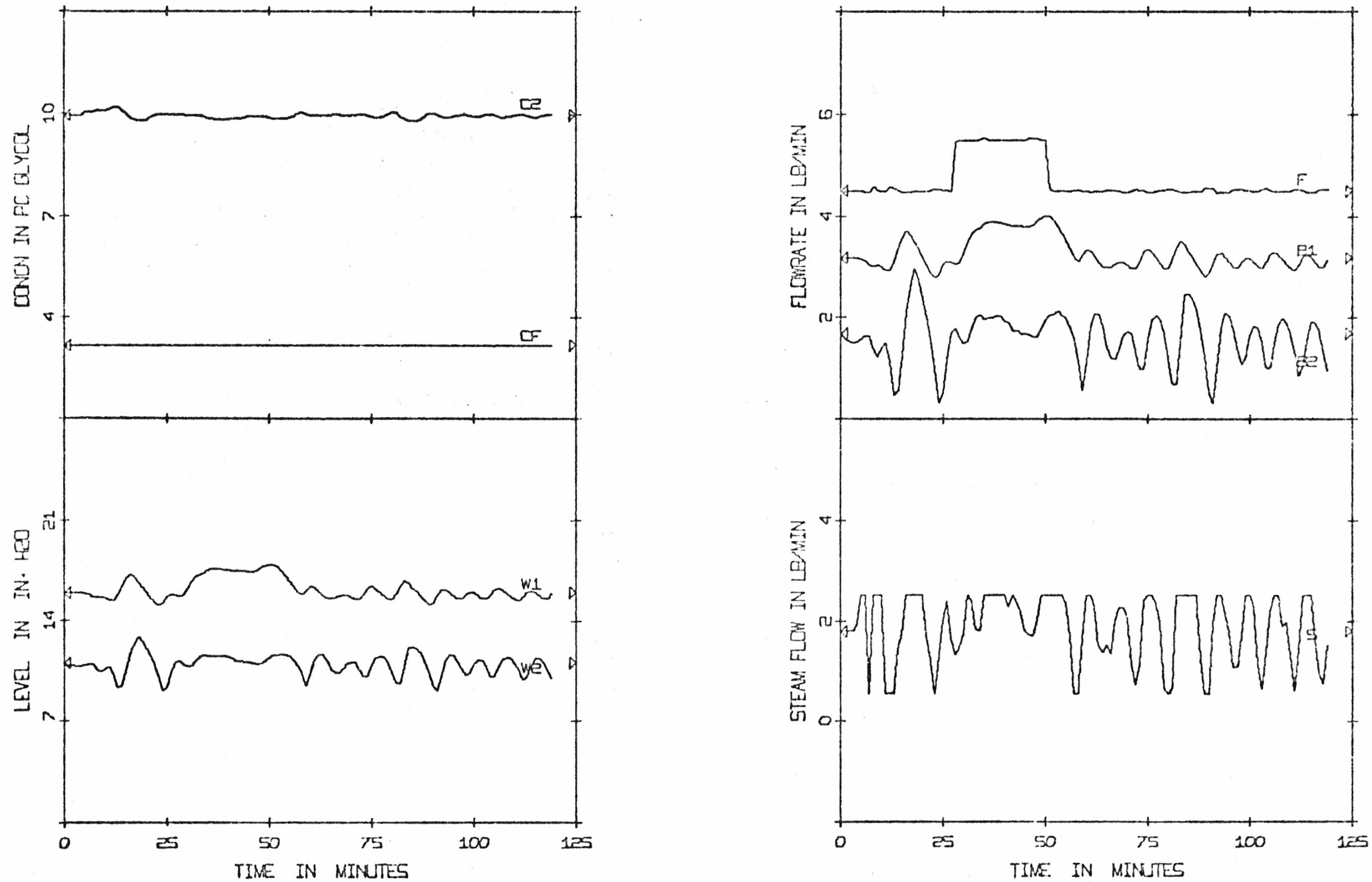


Figure 5.25 Evaporator response (EXP/+20% F, -20% F/STR), 4th order model

Figure 4: STR control; +/- 20% disturbances and the 4th-order model.

Summary: STR Application

1. The STR provided erratic, often unstable responses in both simulation and experimental studies
2. A well-tuned STR was comparable and perhaps slightly superior to multi-loop PI control only
3. And worst of all (for a relatively junior faculty member) …

The results were judged to be unsuitable for journal publication by evil, misguided reviewers.

- **Question: Why was this STR application a failure when more complicated “advanced control” methods were successful?**

- **Answer: A Revelation came …**

- Nine years later, the Lund research group published a paper:

  Åström, K. J., P. Hagander, and J. Sternby, “Zeros of Sampled Systems,” *Automatica* **2**0, 31 (1984).

- They showed that a discrete-time version of a continuous-time model can exhibit non-minimum phase behavior *even though the contnuous-time model does not.*

- Evaporator Models: NMP Behavior?

  Continous-time: **N**o

  Discrete-time**:** **Yes**

- **Mystery Solved!**

STR Application: Lessons Learned

- 1. “Early adopters” can have unfortunate surprises.
- 2. Hundreds of hours performing simulations and experiment can save you 30 minutes in the library.

Example 2
An Experimental Application of Time-Delay Compensation Techniques

- **Objective**: Compare two time-delay compensation methods, Smith and Analytical Predictors with PI Control
- Both simulation and experimental studies for a pilot-scale distillation column at the University of Alberta (the "Wood-Berry" column

U of A Pilot-Scale Distillation Column

- **Feed:** MeOH and water
- Eight bubble cap trays; 22.5 cm diameter column
- **CVs**: methanol compositions in top & bottoms streams
- **MVs**: reflux flow rate (R) and steam flow rate (S)
- **DVs**: feed flow rate & composition

Wood-Berry Column Model

$$\begin{bmatrix} y_1(s) \\ y_2(s) \end{bmatrix} = \begin{bmatrix} \dfrac{12.8e^{-s}}{16.7s+1} & \dfrac{-18.9e^{-3s}}{21s+1} \\ \dfrac{6.6e^{-7s}}{10.9s+1} & \dfrac{-19.4e^{-3s}}{14.4s+1} \end{bmatrix} \begin{bmatrix} u_1(s) \\ u_2(s) \end{bmatrix} \qquad (18-12)$$

where:

$y_1 = x_D =$ distillate composition, %MeOH

$y_2 = x_B =$ bottoms composition, %MeOH

$u_1 = R =$ reflux flow rate, lb/min

$u_1 = S =$ reflux flow rate, lb/min

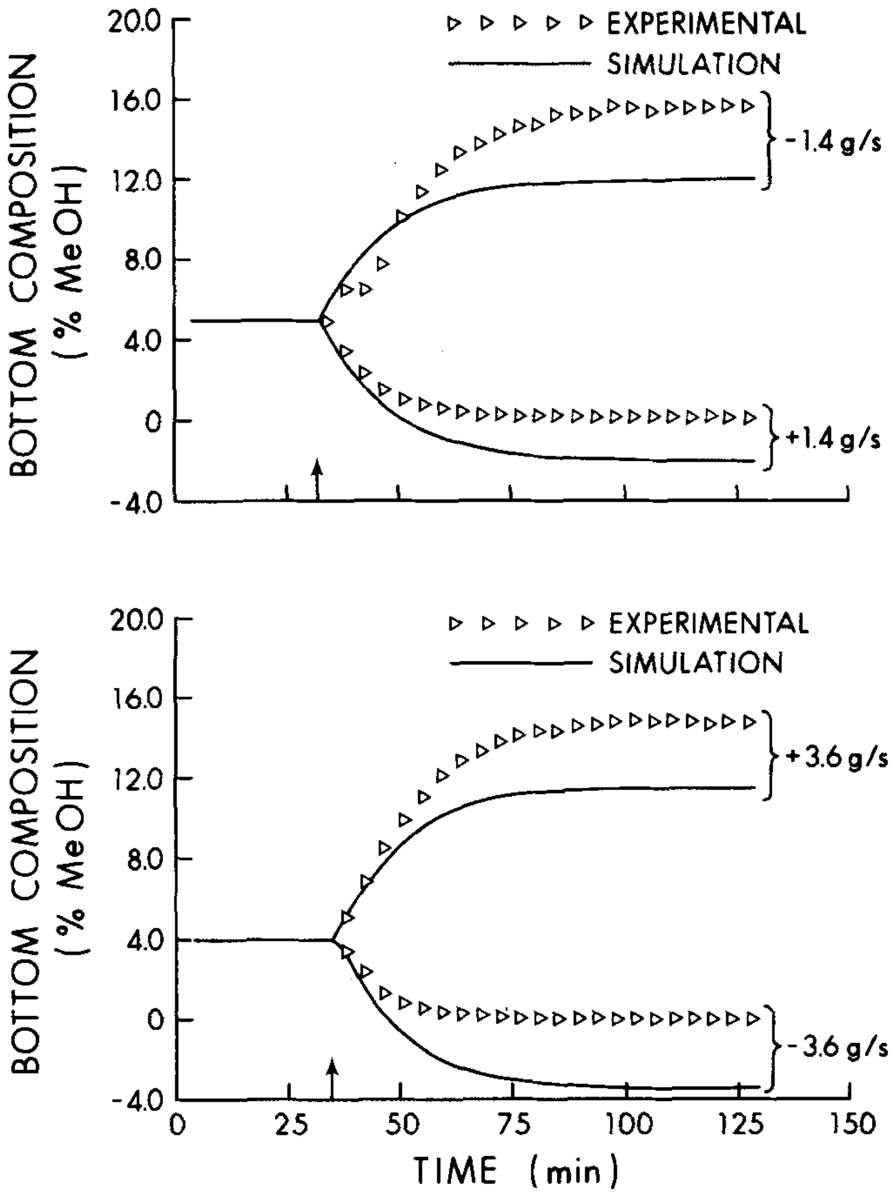
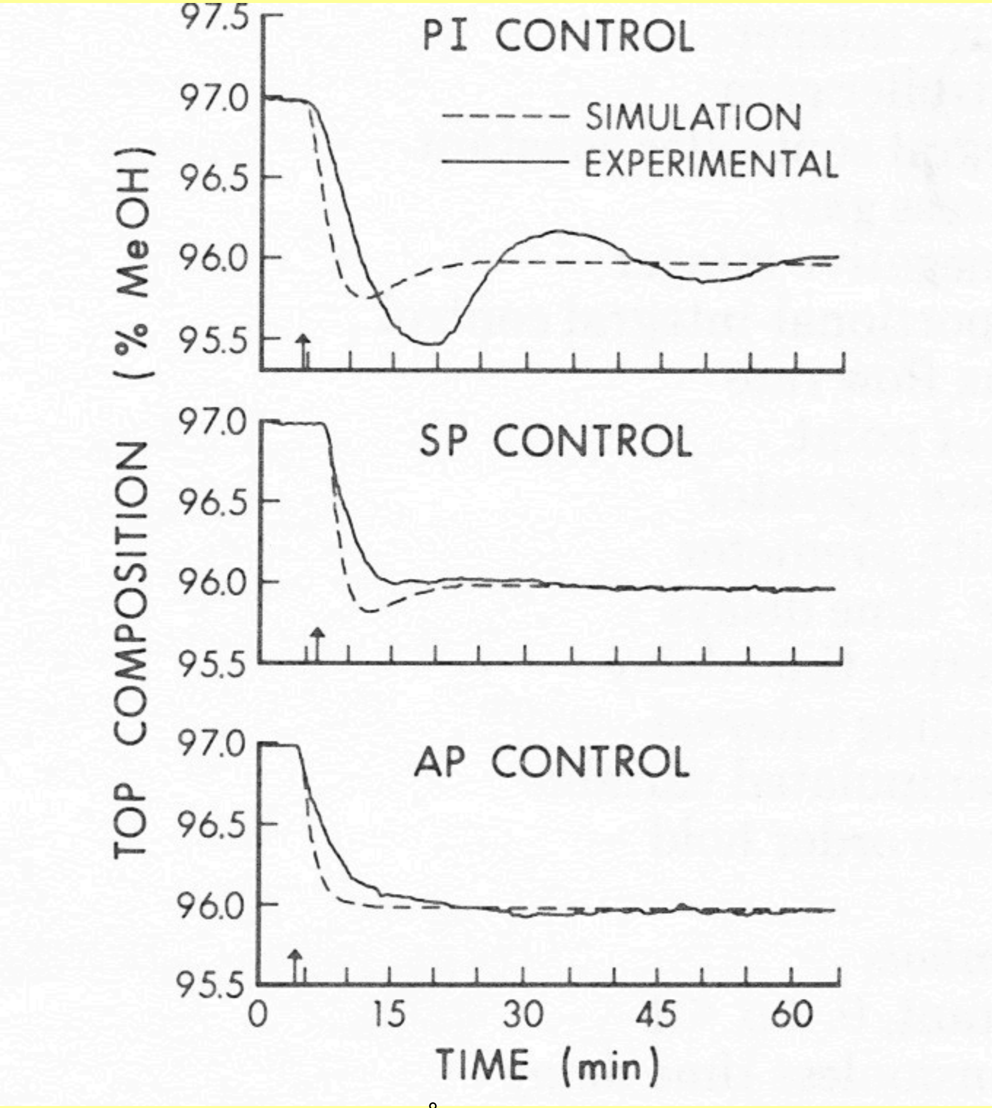
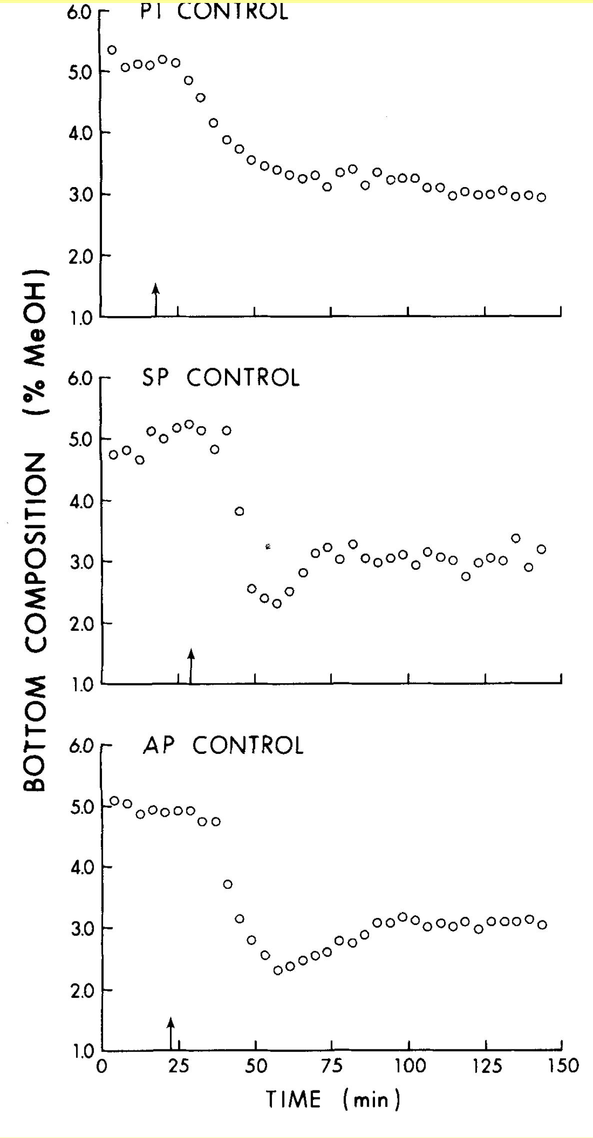


Fig. 5. Open-loop responses for step changes in steam (top) and feed flow (bottom).

Top Composition Control: Comparison of set-point changes



Bottoms Composition Control: Comparison of set-point changes



Question: Why Was Bottom Composition Control So Poor?

Answer:

- A filter in the sample line to the GC had been mistakenly replaced with a filter with a smaller pore size.
- This increased the time delay associated with the GC measurement and produced a larger “plant-model mismatch”.
- Thus the control was relatively poor.

Lesson Learned:

- A good control strategy is no match for a sub-par sensor

Publications

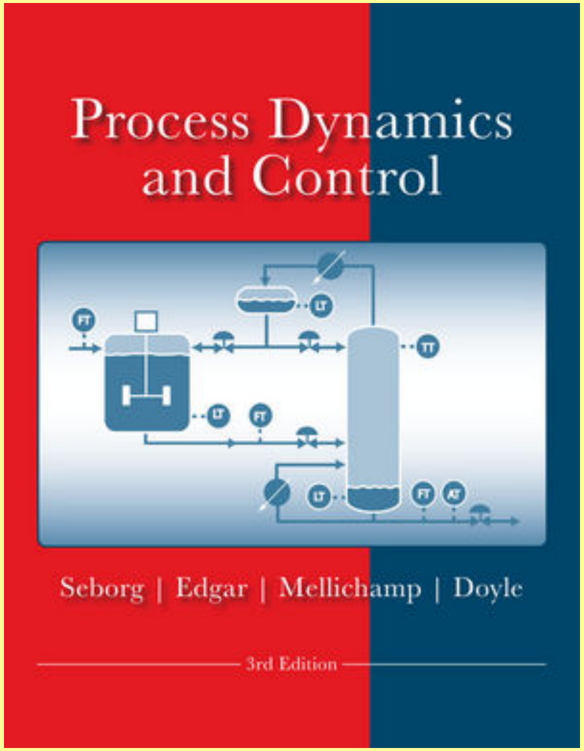
- Meyer, C., D.E. Seborg and R.K. Wood, “An Experimental Application of Time Delay Compensation Techniques to Distillation Column Control,” I*EC Process Design and Develop.*, **17**, 62-67 (1978).

- Meyer, C.B.G., R.K. Wood and D.E. Seborg, “Experimental Evaluation of Analytical and Smith Predictors for Distillation Column Control,” *AIChE J.*, **25**, 24-32 (1979).

Thank you kind, intelligent reviewers.

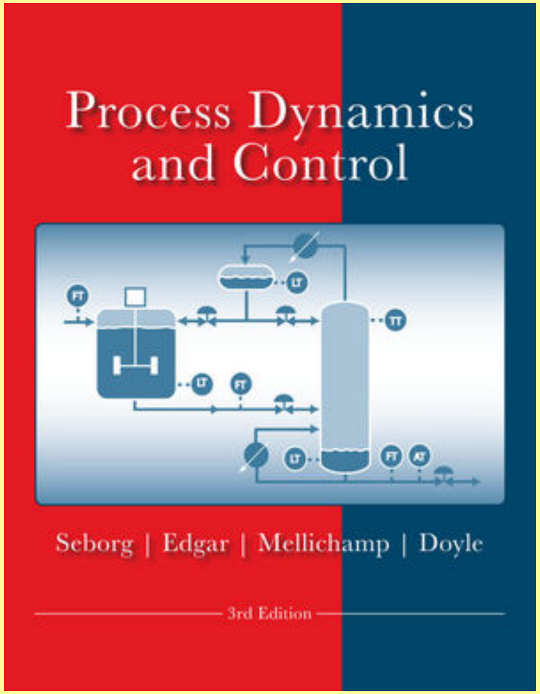
And Then Came the Siren Call From UCSB…

The Book


Process Dynamics
and Control
Seborg | Edgar | Mellichamp | Doyle
3rd Edition

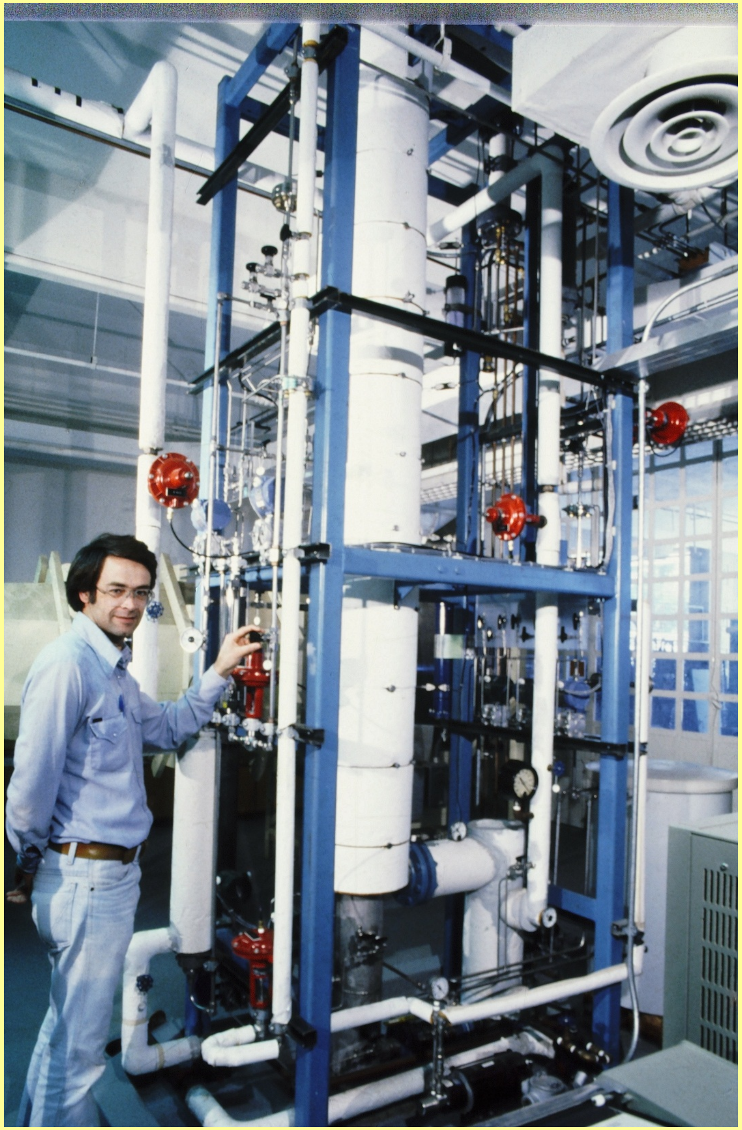
The Book

- **Seborg, Edgar, Mellichamp and Doyle, *Process Dynamics and Control, 4th ed.,* Wiley (2016).**
- **The book has been translated into Japanese, Korean, Chinese and Turkish.**
- **Book abbreviation: SEMD**
- **However, I prefer to think of it as**
  “Seborg and Helpers”



Multicomponent Distillation Column at UC-Santa Barbara

- Ternary mixture of butanols (n-, s, & t-)
- Six inch **diameter**, 12 sieve trays,
- Fully instrumented
- On-line GC measurements of x_B and x_D (every 5 min)
- Steam-heated reboiler
- Cooling water condenser
- Relatively fast dynamics



Jacinto Marchetti and the UCSB distillation column

MPC Project:
Two Point Composition Control

- CVs: n-butanol components in B and D
  MVs: R and B
- Identify MIMO model using PRBS excitation in R & S
- Design MPC system
  ⇒
- Compare MPC with mult--loop PI controllers tuned manually and a one-way decoupler

- **Results:** MPC was only *marginally* better.
- **Analysis:** During the PRBS identification, the steam supply was drifting.

  Consequently, the Identified model was inaccurate.

- **Lesson (re-learned):** Model identification and validation are critical steps in model-based control applications.

Some Final Thoughts

- Control methods developed by other disciplines usually need some "house breaking" for process control applications
- Experimental applications of promising new control methods are essential:
  - They illustrate real-world situations that are not anticipated.
  - They help researchers avoid the "Narcissus Phenomena"
  - They help students find industrial (and academic) jobs
- Interactions and involvement with industry are essential for process control faculty

• Process control has been, and still is, a wonderful field!

What Are You Doing, Now That You Are Retired?

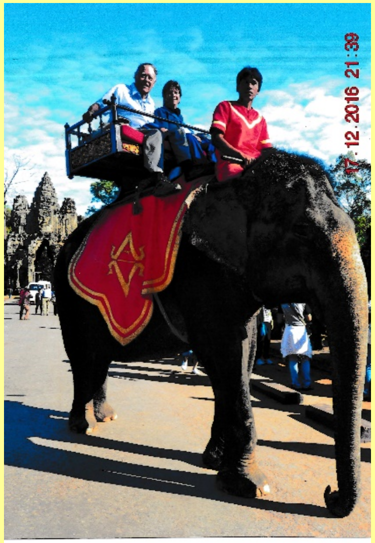
My answer:

As little as possible;

I'm retired!

But I have been …

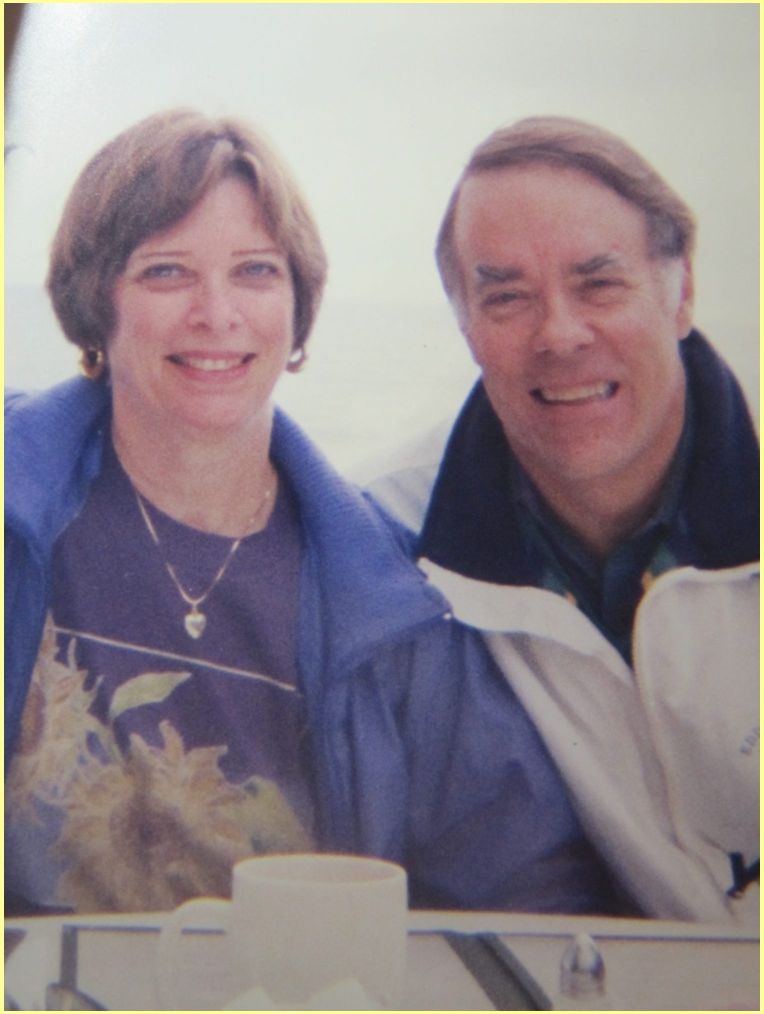
Traveling




CAPE OF GOOD HOPE
THE MOST SOUTH—WESTERN POINT
OF THE AFRICAN CONTINENT

And Visiting Family

With the Perfect Travel Companion!




Thank you!
Tak!
Kiitos!