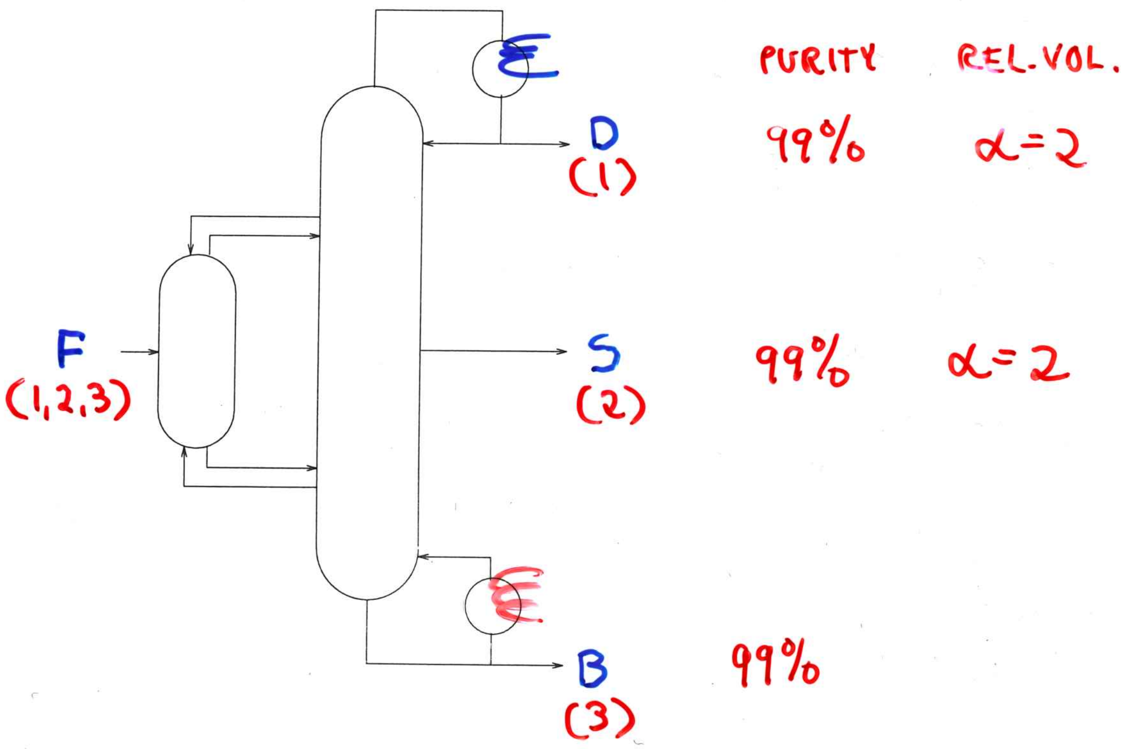
DYNAMICS AND CONTROL OF INTERGRATED THREE PRODUCT (PETLYUK) DISTILLATION COLUMNS

Erik A. Wolff, Sigurd Skogestad and Kjetil Havre

Chemical Engineering
University of Trondheim - NTH
N-7034 Trondheim, Norway

+ STEADY-STATE BEHAVIOR



ST. LOUIS, USA, NOV. 93
AIChE Annual Meeting

OUTLINE

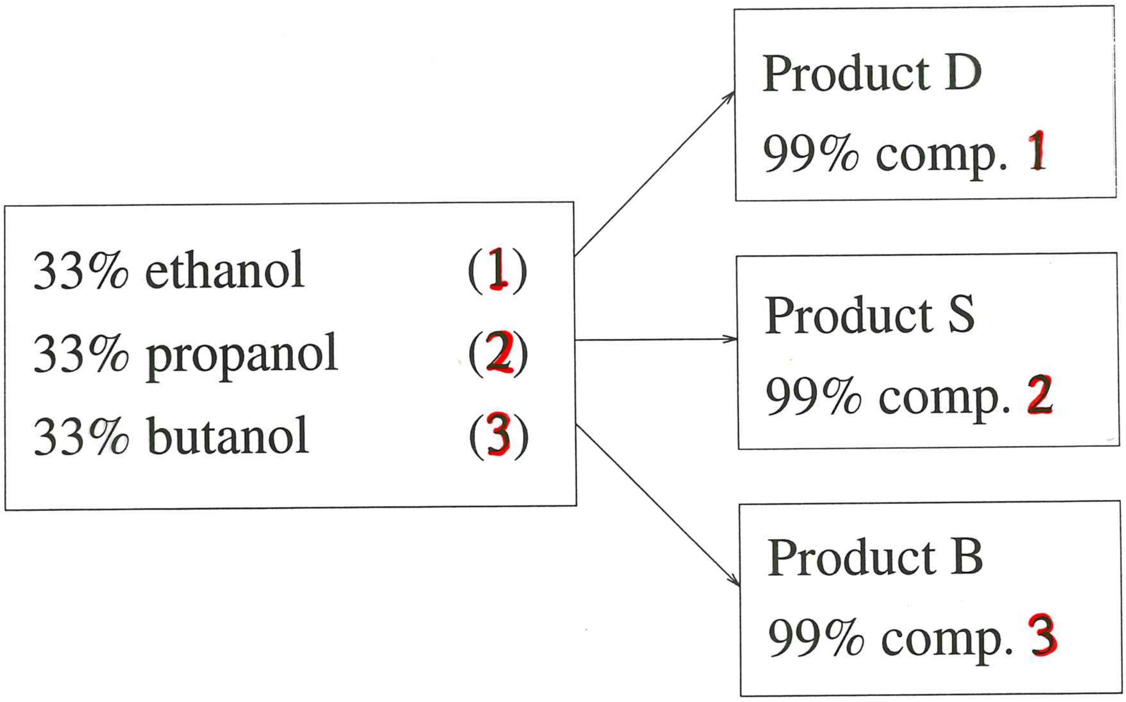
- PREVIOUS WORK
- EXAMPLE. ALTERNATIVE SEQUENCES
- PETLYUK COLUMN
- DEGREES OF FREEDOM =5
  - 3 or 4 specs ⇒ 1 extra DOF to minimize energy
- NON-FEASIBLE OPERATING REGIONS
- CONTROL, 3×3, 4×4
  - Linear
  - Instability
- CONCLUSION

Previous work

- First described by Cahn and Di Micelli (Patent, 1962).
- Petlyuk et al. (1965) presents alternative schemes for minimizing thermodynamic loss.
- Glinos and Malone (1988) look at optimal regions for ternary separation, recommending Petlyuk when x_{F2} is small.
- Fidowski and Krolikowski (1986) optimized the energy use w.r.t. one internal stream distribution.
- Chavez et al. (1986) discussed multiple steady states in complex columns.
- Lately: University-industry project at UMIST (Triantafyllou and Smith, 1992).

Example System

Equimolar feed composition is separated to three 99% pure streams.

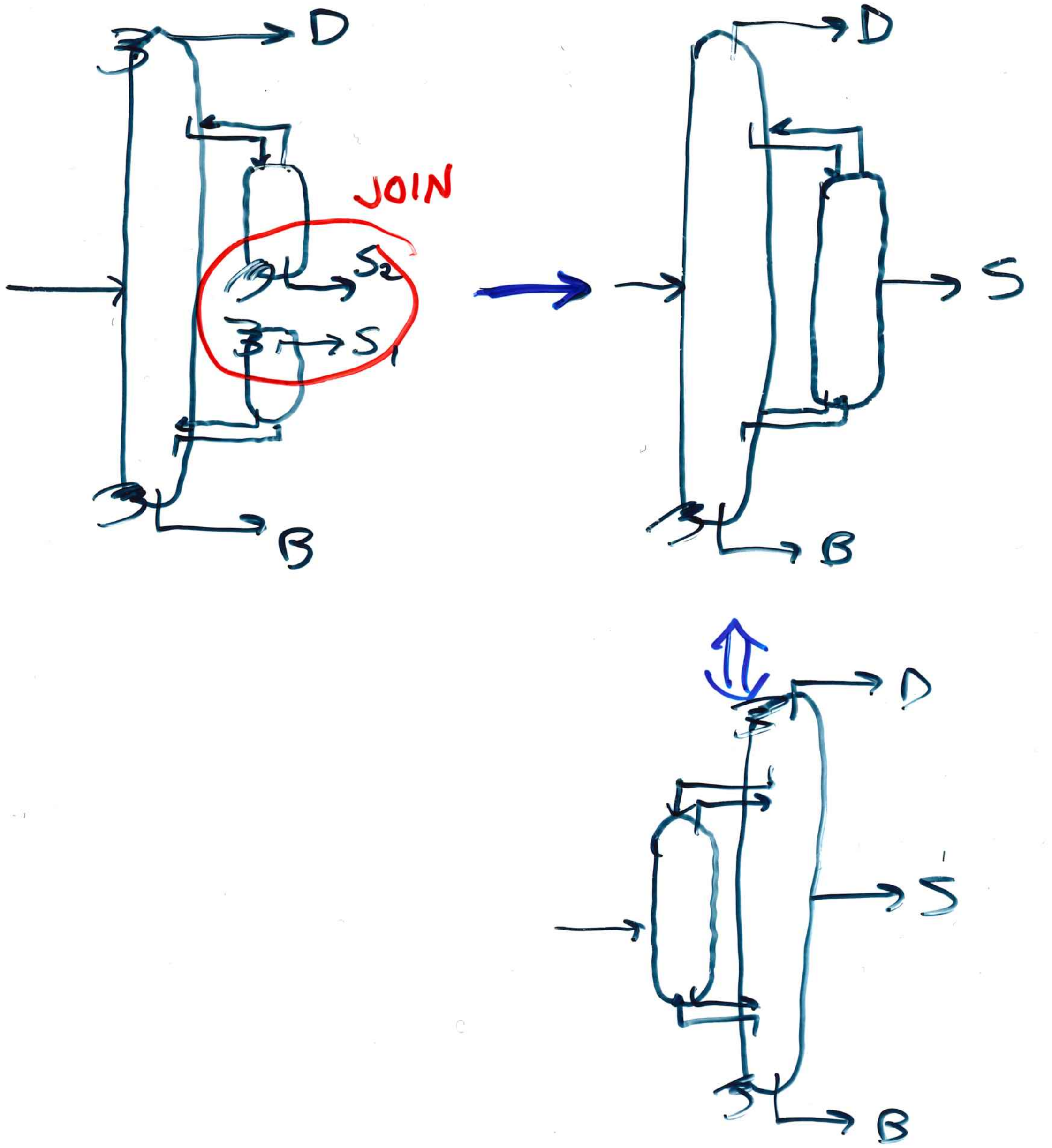


Relative volatility:

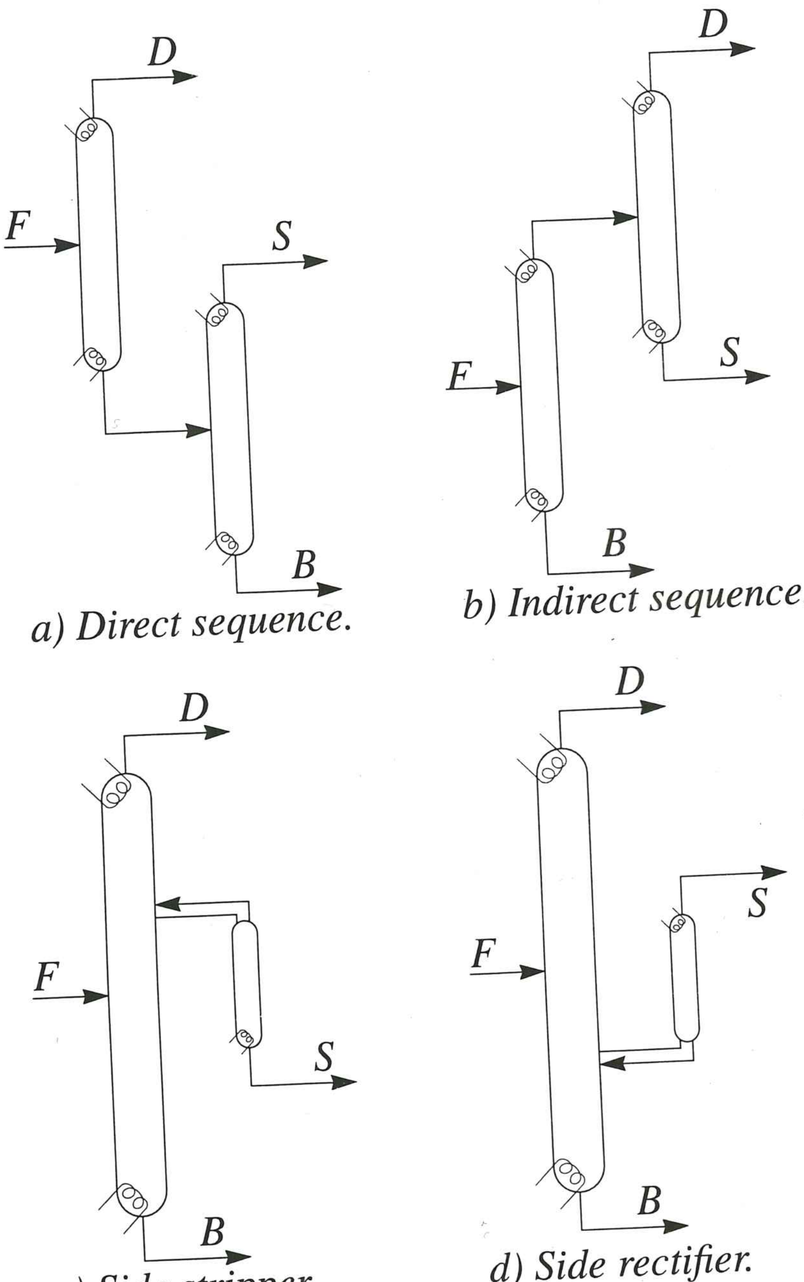
$$\alpha_{13} \approx 4$$

$$\alpha_{23} \approx 2$$

WHY DOES IT WORK ?



Alternative sequences



a) Direct sequence. b) Indirect sequence.

c) Side stripper. d) Side rectifier.

100%

108%

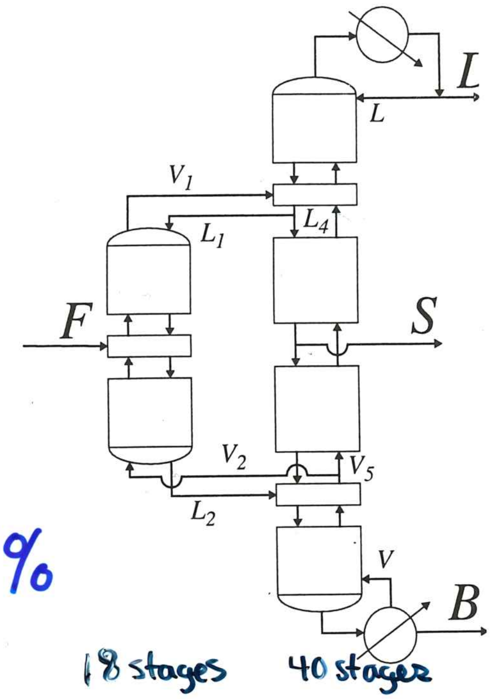
89%

88%

Figure 1: Standard configurations for ternary separation

≈ 60 stages

Petlyuk column



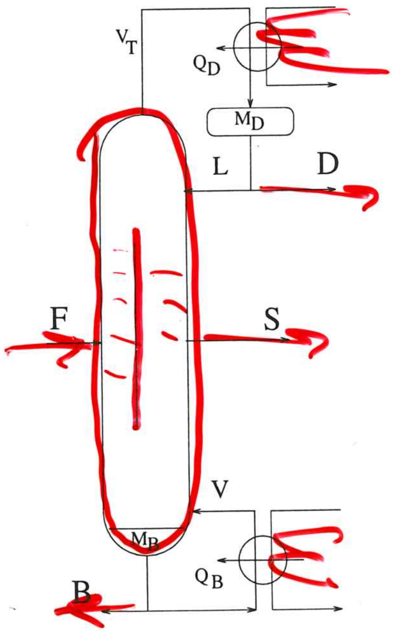


Figure 2: Double-wall implementation

Use of Petlyuk

- Large savings in Capital and Energy costs possible.
- Average possible savings 30%.
- Maximum savings compared to direct sequence; 50 %.

Industry: Only one report from BASF in 1988.

$\Rightarrow$ Why not used more?

Here: investigate controllability, limitations.

Degrees of freedom. Regular column.

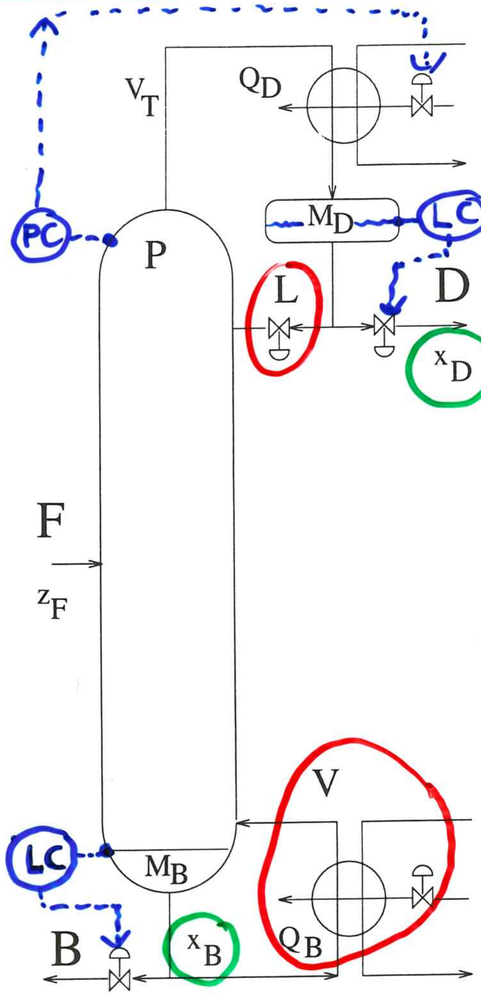


Figure 3: Regular two-product column.

- Control: 5 DOF (L, V, Q_D, D, B)
- Steady-state with const. pressure and levels: 2
  2 DOF (e.g., L, V). "ONE FOR EACH HEATER/COOLER AND SIDESTREAM"
  0
- Want to control 2 compositions (x_D, x_B) $\Rightarrow$ System specified.

Degrees of freedom. Petlyuk

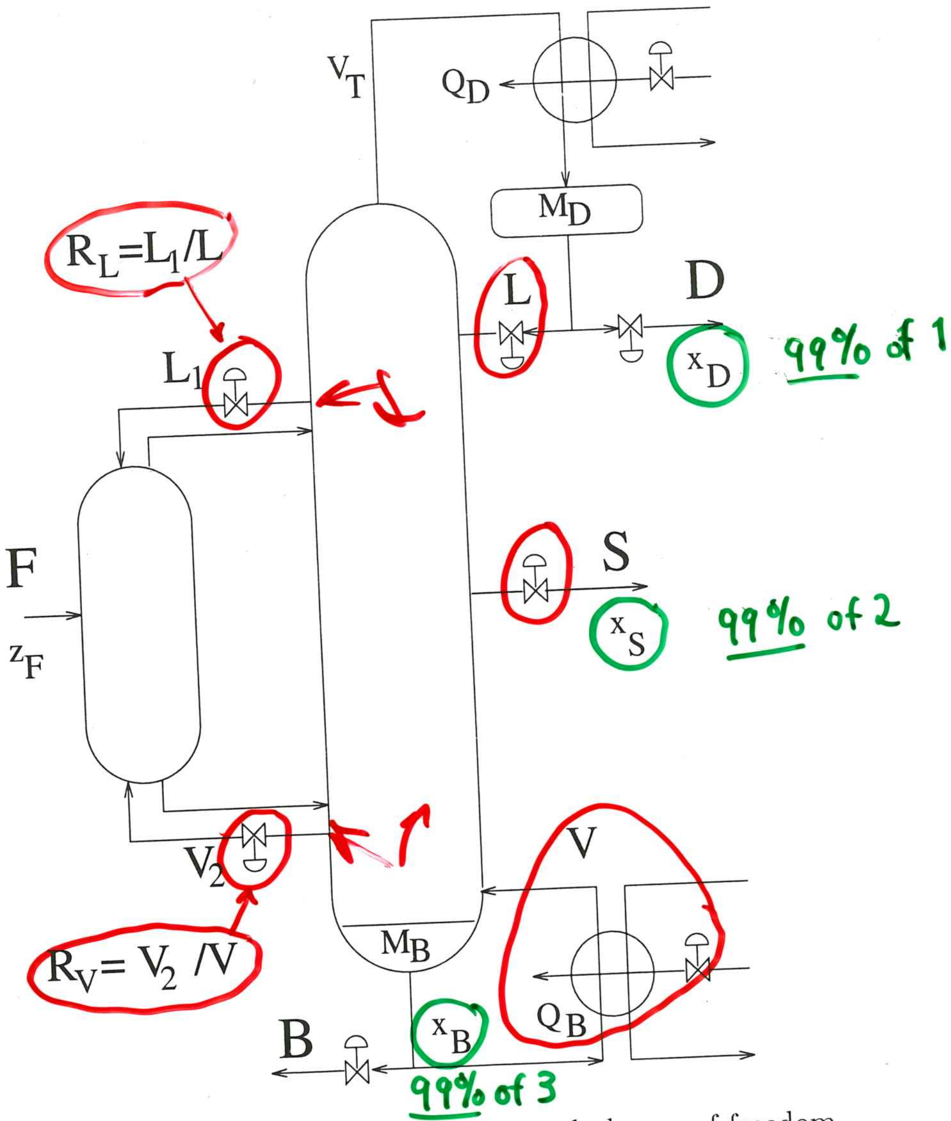


Figure 4: Petlyuk column with valves for each degree of freedom.

- Steady-state: 3 additional DOF's (S, R_L, R_V) $\Rightarrow$ DOF = 5 (S, R_L, R_V, L, V).
- Want to control 3 compositions (x_D, x_S, x_B) $\Rightarrow$ 2 extra DOF's (R_L, R_V).
- Use to minimize energy consumption (Q_B).

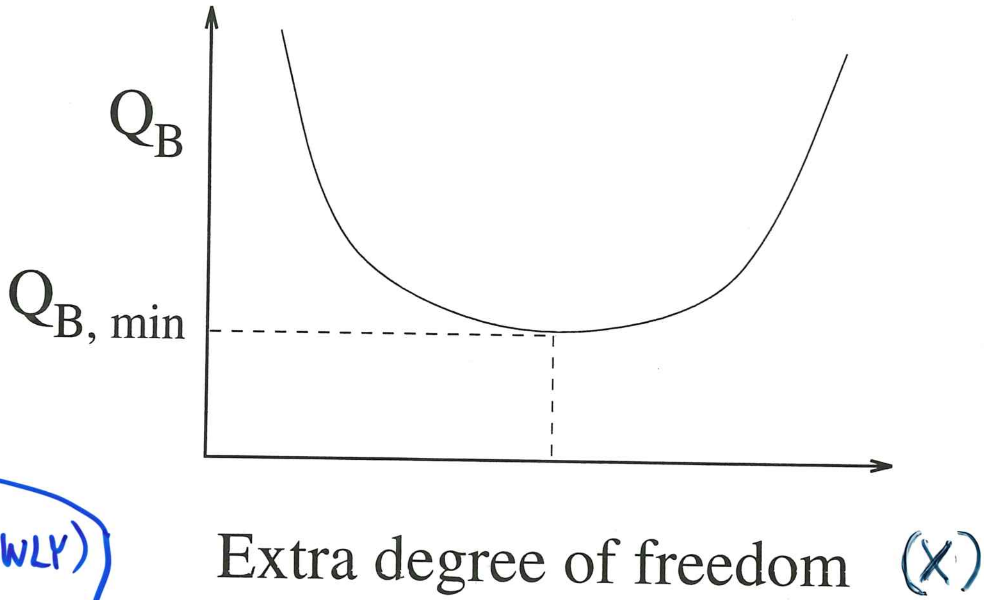
Degrees of freedom, alternative.

0.5% of 1

- Want to control 4 compositions (x_D, x_{S1}, x_{S3}, x_B) $\Rightarrow$ Only one extra DOF

0.5% of 3

- Use to minimize energy consumption. Expect:

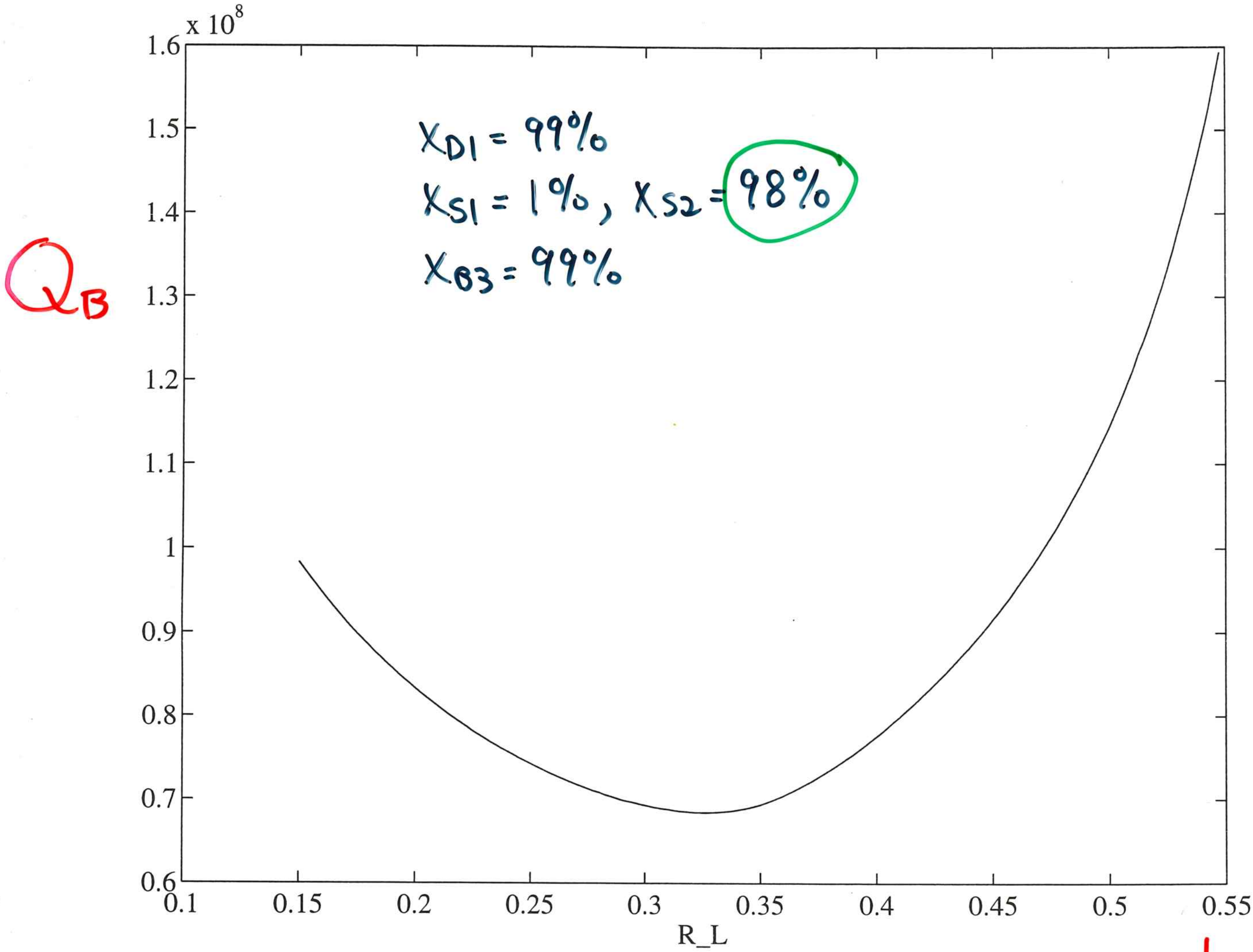


ADJUST (SLOWLY) DURING OPERATION

Figure 5: Using one DOF for optimization

$X = \underbrace{R_L, R_V}, L/D, S,$ compositions (inside)....

SPEC. 4 COMPOSITIONS



$\rightarrow R_L = \frac{L_1}{L}$

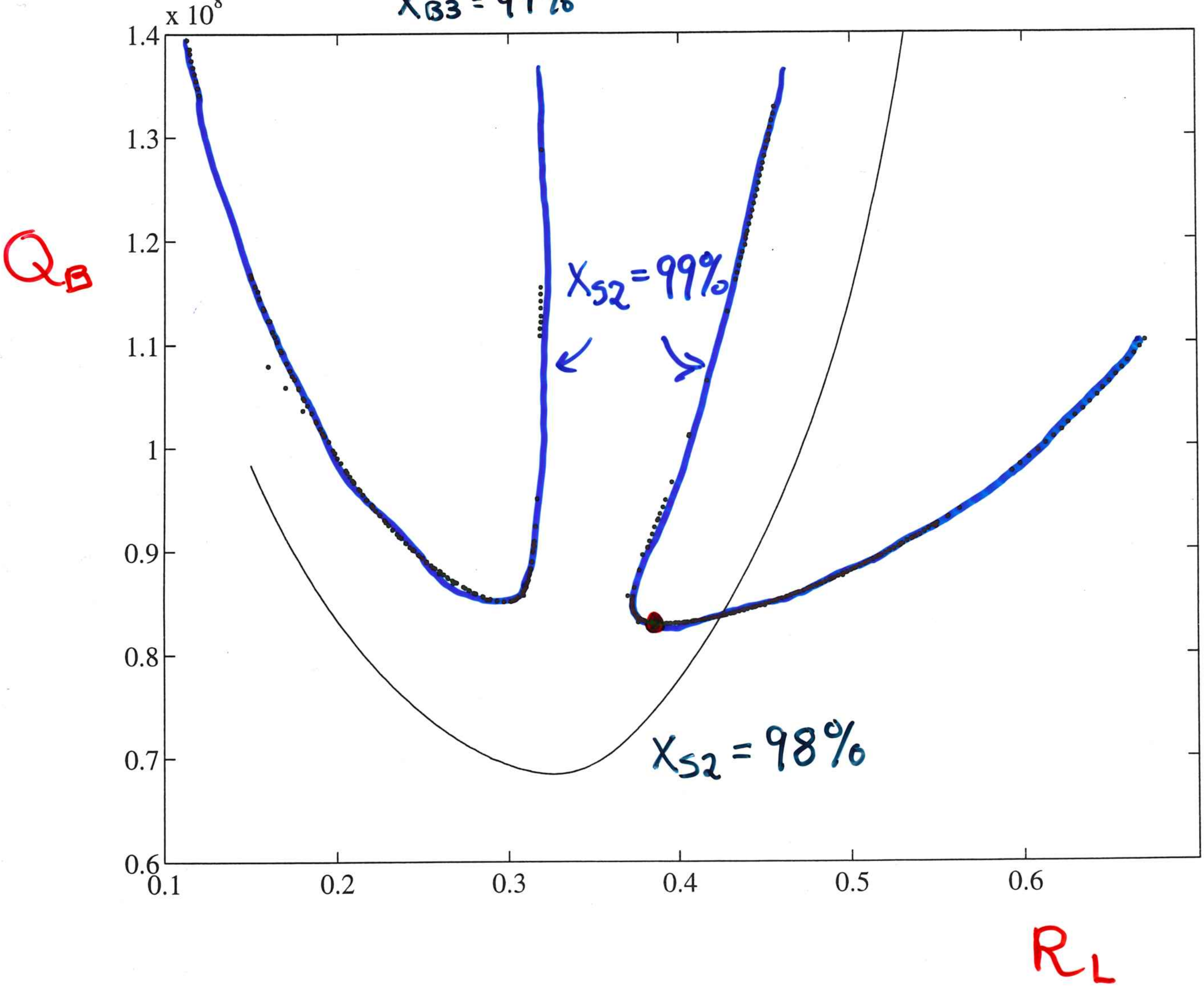
(reflux to prefractionator)

SPEC 4 COMPOSITIONS

$X_{D1} = 99\%$

$X_{S1} = X_{S3}$

$X_{B3} = 99\%$



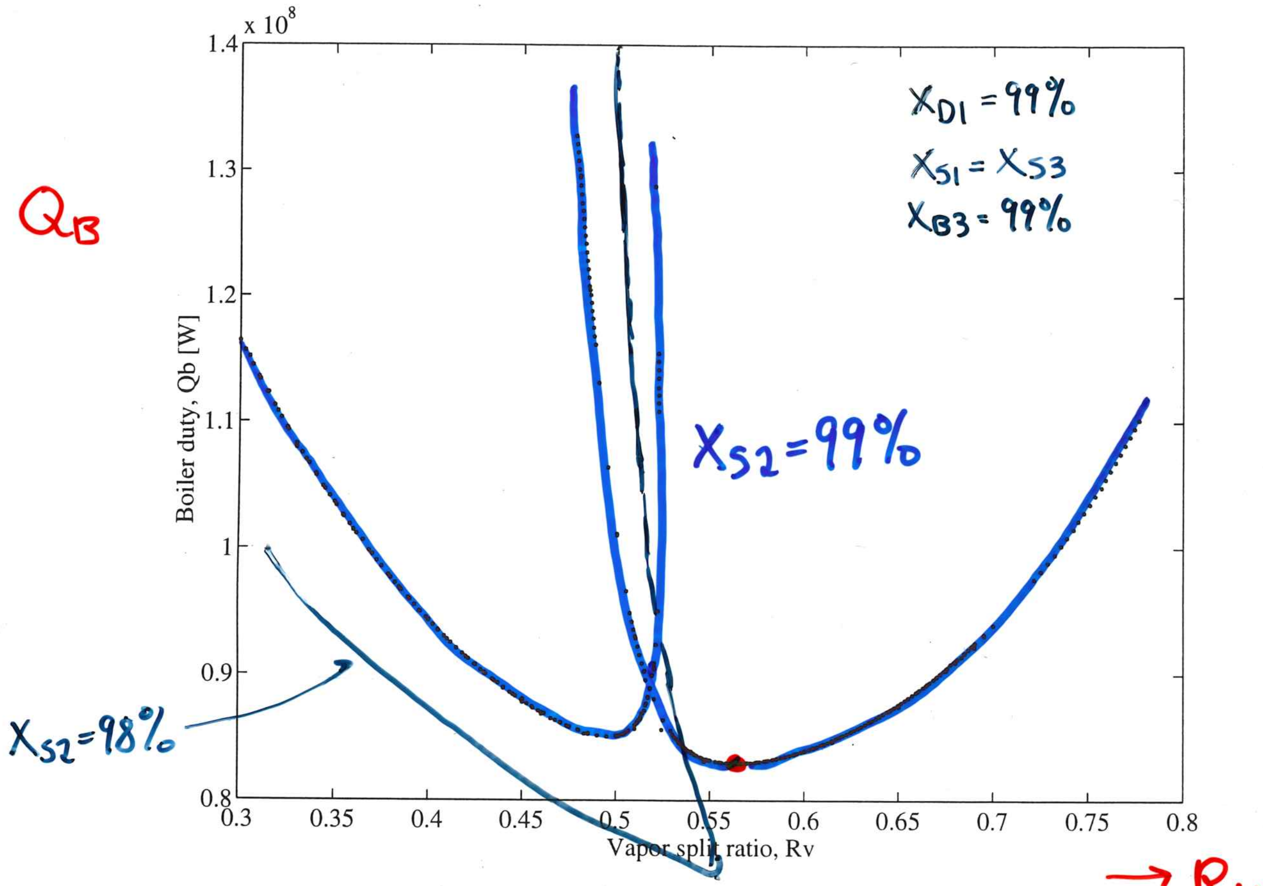
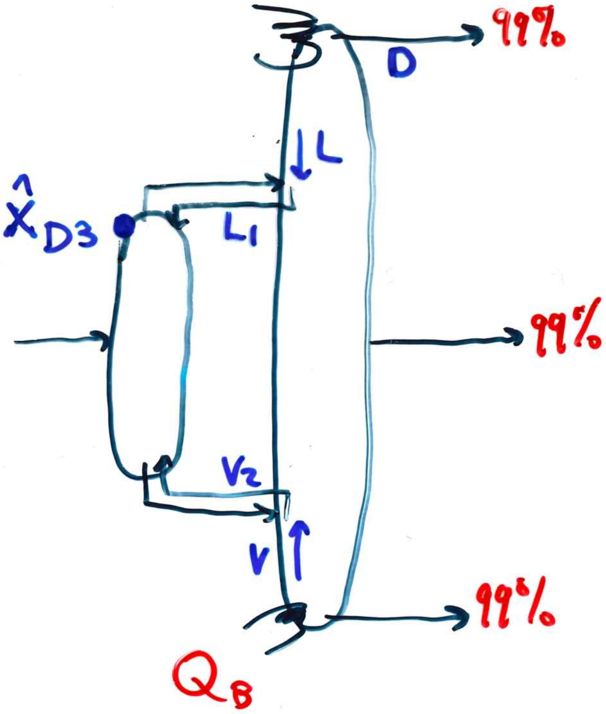
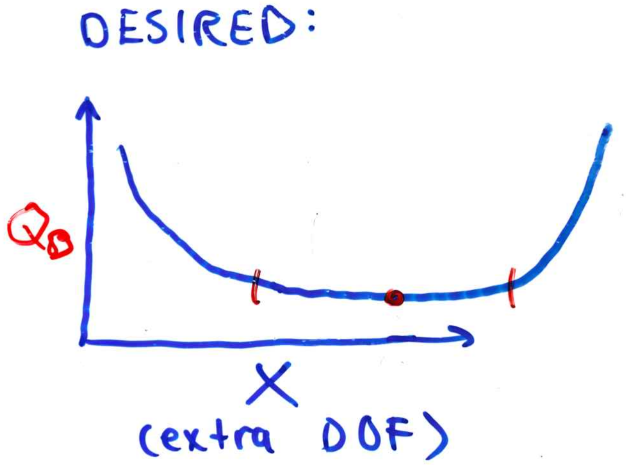
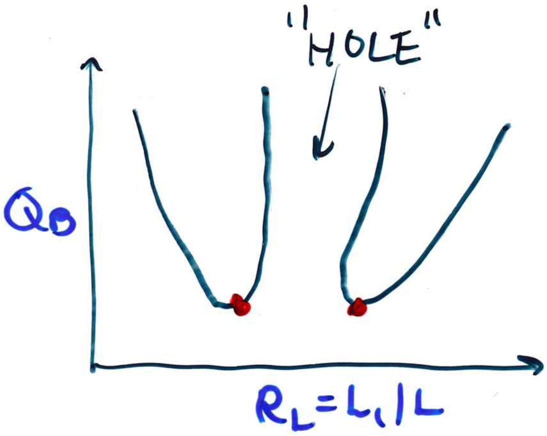
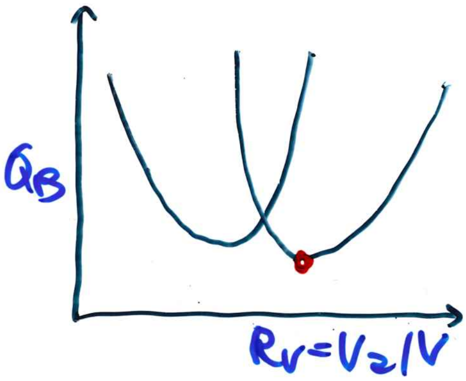


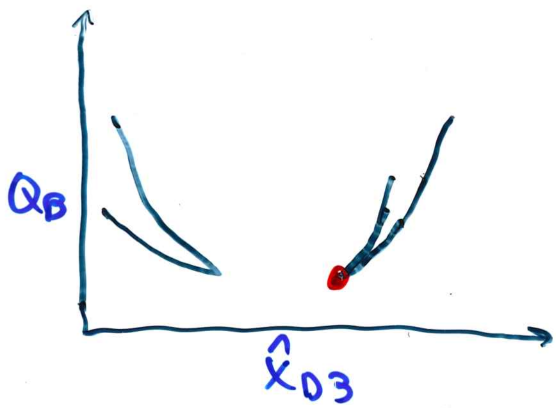
Figure 6: Multiple solutions to $Q_B = f(R_V)$, $x_{S2} = 0.99$

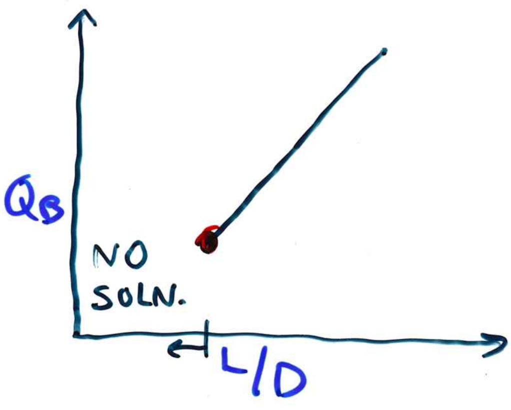












- NO GOOD "X" FOUND
- DESIGN AND OPERATION DIFFICULT

Controllability analysis

Variable scalings:

- y: $\Delta x_{ij} = 0.01$
- u: $\Delta L = \Delta V = 30\%$
- d: $\Delta F = 10$, $\Delta x_{Fi} = 20\%$

Plant representation:

$$y(s) = G(s)u(s) + G_d(s)d(s)$$

Analysis tools:

- Relative gain array,

$$\Lambda = G \times G^{-T}$$

- Closed loop disturbance gain:

$$\Delta = \tilde{G}G^{-1}G_d$$

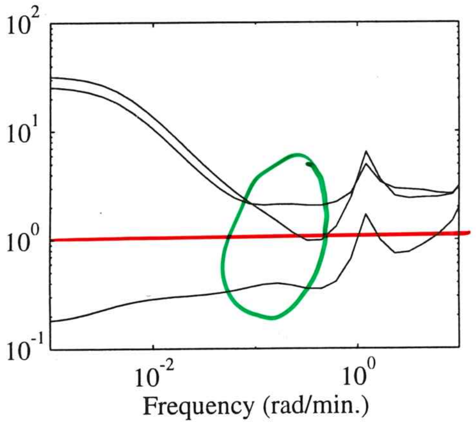
3x3 Controllability

$$y = \begin{pmatrix} x_{D1} \\ x_{B3} \\ x_{S2} \end{pmatrix} \quad u = \begin{pmatrix} L \\ V \\ S \end{pmatrix} \quad d = \begin{pmatrix} R_L \\ R_V \\ \text{Feed} \end{pmatrix}$$

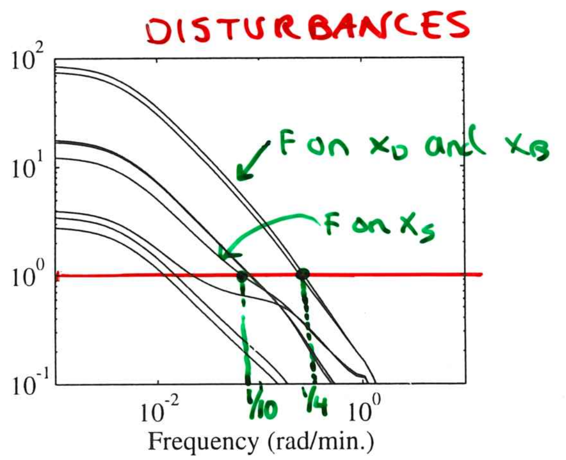
$$G(0) = \begin{pmatrix} 124.67 & -124.48 & 0.11 \\ -118.86 & 119.31 & 20.02 \\ 5.82 & -5.16 & -4.30 \end{pmatrix}$$

$$\Lambda(0) = \begin{pmatrix} 26.19 & -25.19 & 0.00 \\ -32.65 & 32.83 & 0.82 \\ 7.47 & -6.64 & 0.17 \end{pmatrix}$$

RGA (Λ)



(a) Relative gain array, λ_{ii}.



(b) Closed loop disturbance gain, δ_{ij}.

Figure 8: Analysis results for three point control

Dynamic simulations (3x3)

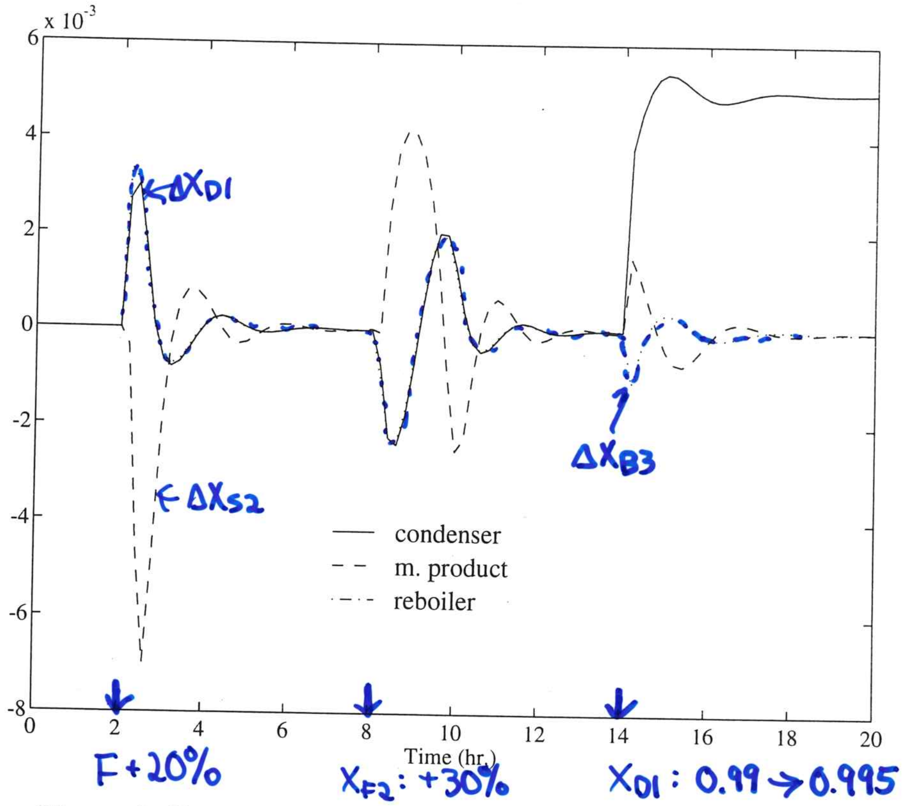


Figure 9: Response to perturbation set, ΔF, Δx_F and $\Delta x_{D1,s}$.

$L \leftrightarrow x_{D1} = 99\%$

$S \Leftrightarrow x_{S2} = 99\%$

$V \Leftrightarrow x_{B3} = 99\%$

Fixed:

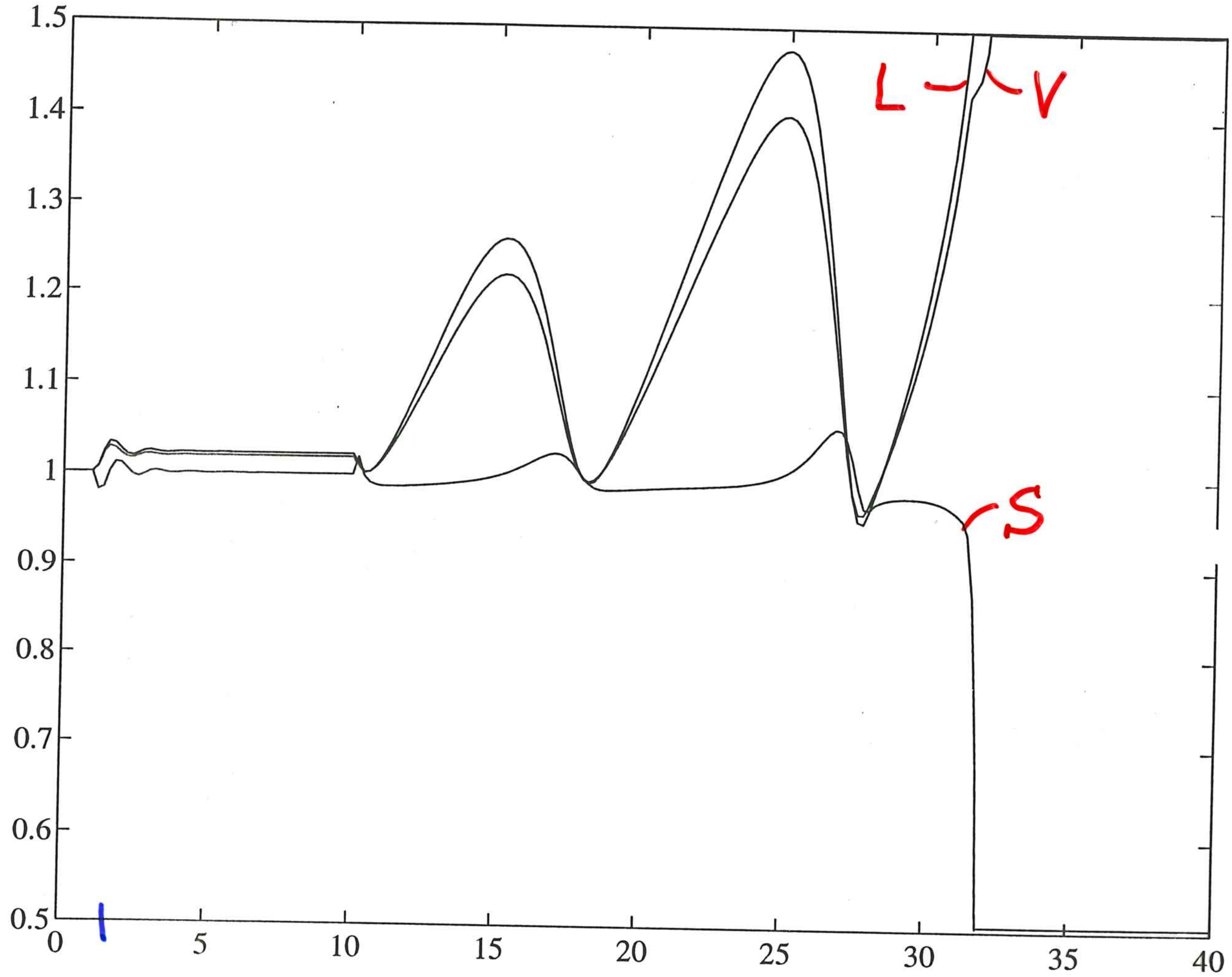
R_L, R_V

WORKS OK!

4x4 CONTROL

$L \leftrightarrow X_D$ $S \leftrightarrow X_{S2}$ $V \leftrightarrow X_B$ R_V FIXED

$R_L \leftrightarrow X_{S1}$



99% 98% 99.5%

SETPOINT X_{S2}

- R_V IN REGION WHERE $Q_B \rightarrow \infty$.

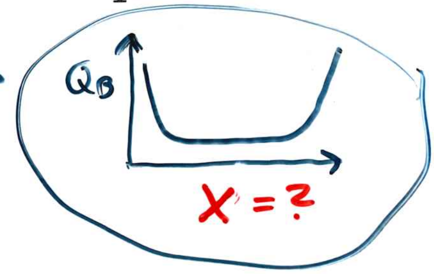
$\Rightarrow$ INSTABILITY

Conclusion

- Complicated design and dynamics.
- "Hole" in operating range for $R_L \Rightarrow$ Very difficult to specify the extra degree of freedom.
- 3x3 gives ok control for limited perturbation set.
- 4x4 small improvement over 3x3.

General problem:

- Want to find variable x which gives near optimal Q_B over large range $x_{low} - x_{high}$.
- Want good control for remaining 4x4.



- Explain "hole"