

# The dos and don'ts of distillation column control

Will mainly consider (indirect) composition control

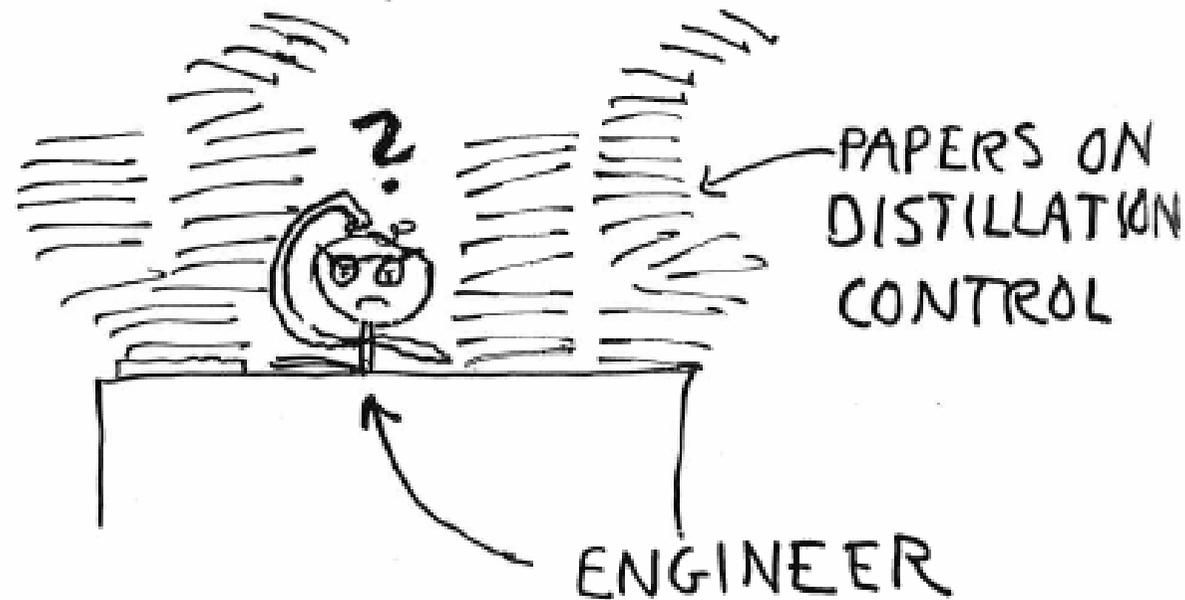
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Plenary lecture Distillation'06, London, 05 Sep 2006

# DISTILLATION CONTROL

- Studied in hundreds of research and industrial papers over the last 60 years



# Objectives of this work

- Apply general plantwide control procedure (Skogestad, 2004) to distillation
- From this derive (if possible) simple recommendations for distillation control
- Is the latter possible? Luyben (2006) has his doubts:
  - *“There are many different types of distillation columns and many different types of control structures. The selection of the “best” control structure is not as simple as **some papers**\* claim. Factors that influence the selection include volatilities, product purities, reflux ratio, column pressure, cost of energy, column size and composition of the feed” + **prices products***

\* He may be referring to my work...

# Outline

1. Introduction
2. General procedure plantwide control
3. Primary controlled variables distillation
  - Usually compositions
4. Stabilizing control distillation
  - Secondary controlled variables (levels, pressure)
5. Control “configurations” (level control)
6. Myth of slow composition control
7. Temperature control
8. Indirect composition control
9. Other: Logarithmic compositions
10. Conclusions

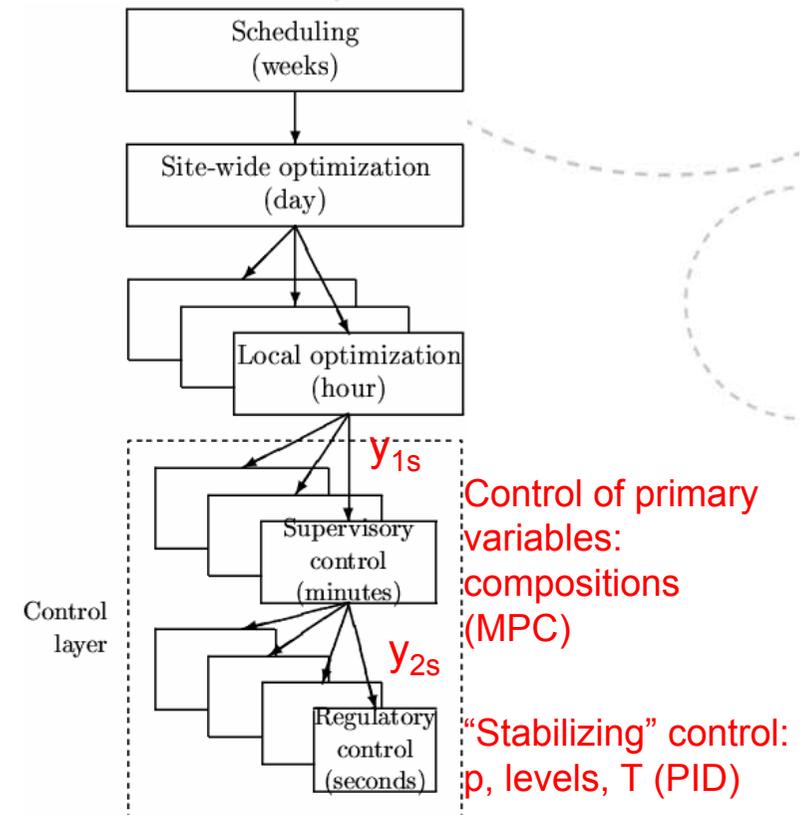
## 2. General procedure plantwide control

Step I. “Top-down” steady-state approach to identify active constraints and primary controlled variables ( $y_1$ )

- Self-optimizing control

Step II. Bottom-up identification of regulatory (“stabilizing”) control layer.

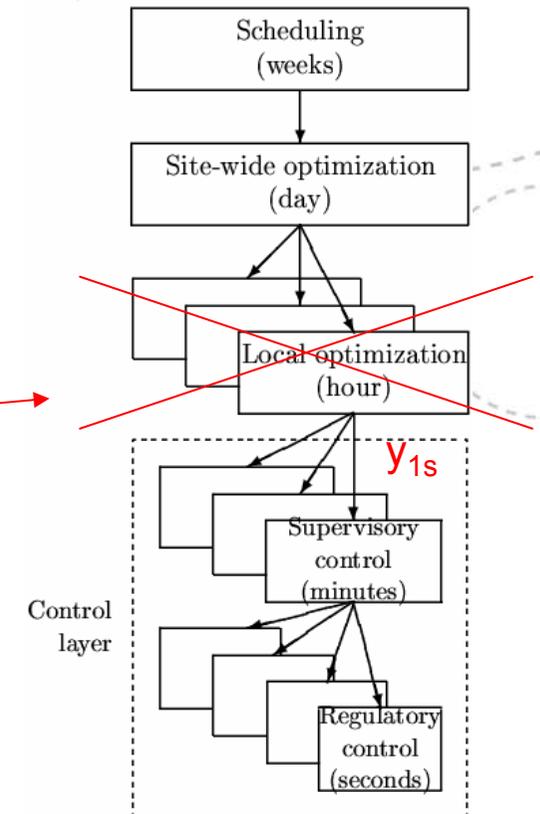
- Identify secondary controlled variables ( $y_2$ )



# Step I. Top-down steady-state approach

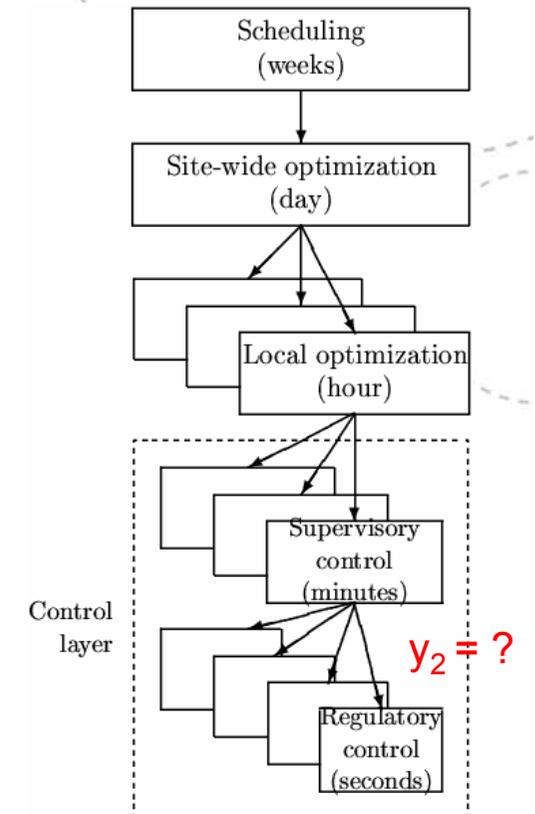
- Optimal operation: Minimize cost  $J$   

$$J = \text{cost feeds} - \text{value products} - \text{cost energy}$$
 subject to satisfying constraints
- What should we control ( $y_1$ )?
  1. Active constraints
  2. “Self-optimizing” variables  
 These are “magic” variables which when kept at constant setpoints give indirect optimal operation by controlling some “magic” variables at
    - Maximum gain rule: Look for “sensitive” variables with a large scaled steady-state gain



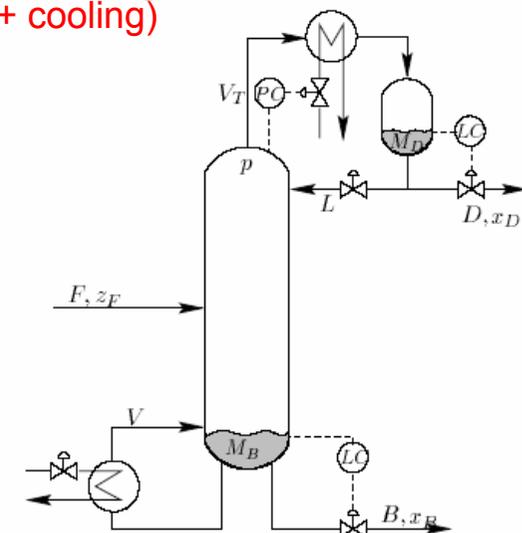
# Step II. Regulatory control layer

- Main objectives
  - “Stabilize” = Avoid “drift”
  - Control on fast time scale
  - Simple (PI)
- Identify secondary controlled variables ( $y_2$ )
  - pressures, levels, selected temperatures
 and pair with inputs ( $u_2$ )



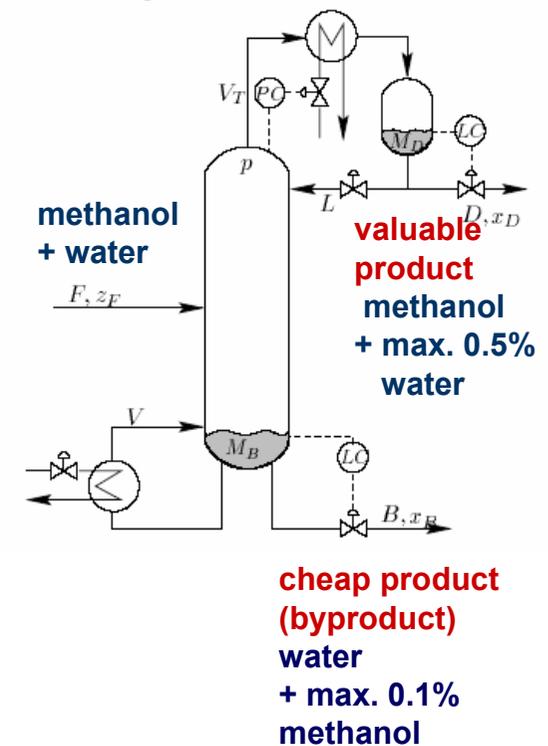
### 3. Primary controlled variables distillation

- Cost to be minimized (economics)
  - $J = -P$  where  $P = \underbrace{p_D D + p_B B}_{\text{value products}} - \underbrace{p_F F}_{\text{cost feed}} - \underbrace{p_V V}_{\text{cost energy (heating+ cooling)}}$
- Constraints
  - Purity D: For example  $x_{D, \text{impurity}} \leq \max$
  - Purity B: For example,  $x_{B, \text{impurity}} \leq \max$
  - Flow constraints:  $0 \leq D, B, L \text{ etc.} \leq \max$
  - Column capacity (flooding):  $V \leq V_{\max}$ , etc.



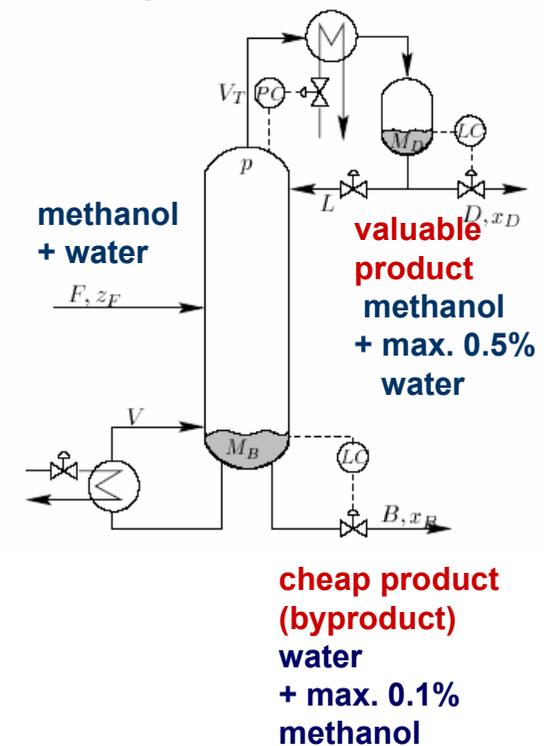
# Expected active constraints distillation

- **Valuable product: Purity spec. always active**
  - Reason: Amount of valuable product (D or B) should always be maximized
    - Avoid product “give-away” (“Sell water as methanol”)
    - Also saves energy
- **Control implications valuable product:**  
**Control purity at spec.**



# Cheap product

- **Over-fractionate cheap product?** Trade-off:
  - Yes, increased recovery of valuable product (less loss)
  - No, costs energy
- **Control implications cheap product:**
  1. **Energy expensive: Purity spec. active**  
→ **Control purity at spec.**
  2. **Energy “cheap”: Overpurify**
    - (a) Unconstrained optimum given by trade-off between energy and recovery.  
In this case it is likely that composition is self-optimizing variable  
→ **Possibly control purity at optimum value (overpurify)**
    - (b) Constrained optimum given by column reaching capacity constraint  
→ **Control active capacity constraint (e.g.  $V=V_{\max}$ )**
  - Methanol + water example: Since methanol loss anyhow is low (0.1% of water), there is not much to gain by overpurifying. Nevertheless, with energy very cheap, it is probably optimal to operate at  $V=V_{\max}$ .



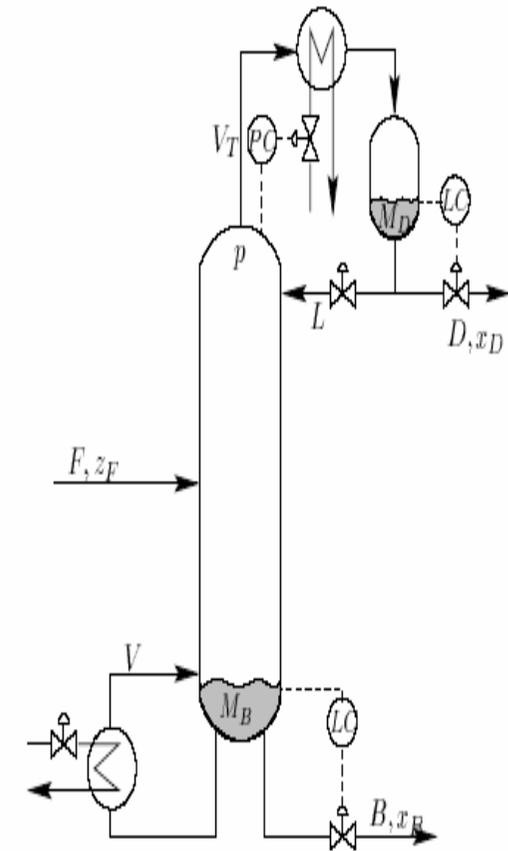
# Conclusion primary controlled variables

- Product purities are very often the primary controlled variables ( $y_1$ ) for distillation columns
- Assume in the following “two-point” composition control:  
 $y_1 = x_D, x_B$  (impurity key component)

## 4. Stabilizing control distillation

Secondary controlled variables ( $y_2$ )

- 5 dynamic degrees of freedom with given feed:
  - $u = L, V, D, B, V_T$
- To “stabilize”: Control levels and pressure:
  - $y_2 = M_D, M_B, p$
- Choice of input  $u_2$  (to be paired with  $y_2$ ):
  - $V_T$  is usually used to control  $p$
  - See part 5 (control configuration) for input for  $M_D$  and  $M_B$
- Additional  $y_2$ : Temperature is usually controlled to “stabilize” composition profile: See part 7



## 5. Control “configurations” (level control)

- **XY-configuration**

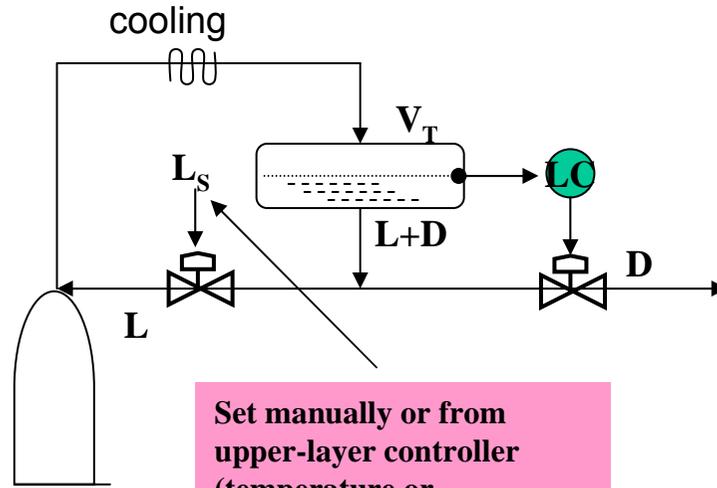
X: remaining input in top after controlling top level ( $M_D$ ):

$$X = L \text{ (reflux), } D, L/D, \dots$$

Y: remaining input in bottom after controlling  $M_B$ :

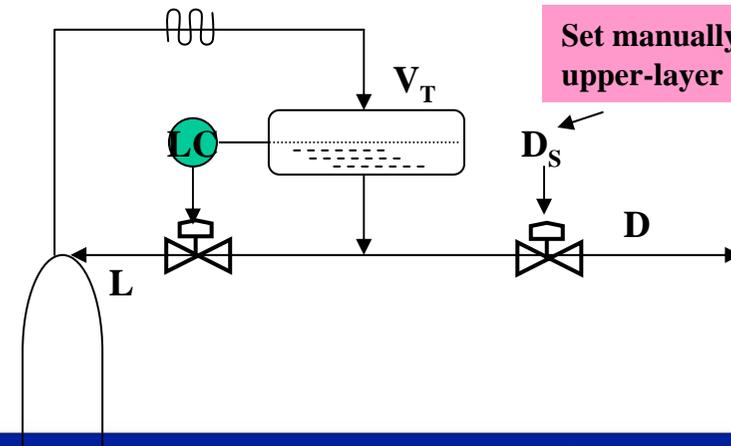
$$Y = V \text{ (boilup, energy input), } B, V/B, \dots$$

# Top of Column



“Standard” :  
LY-configuration  
 (“energy balance”)

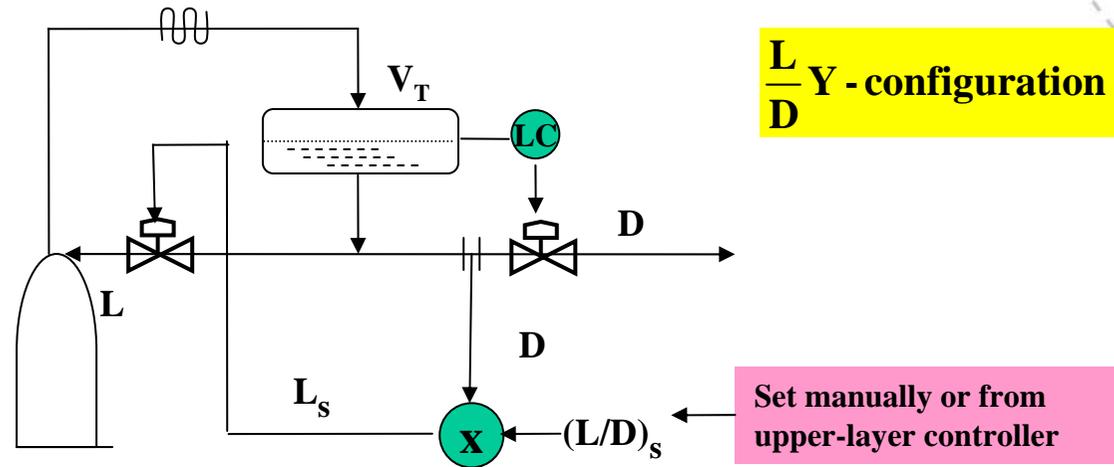
Set manually or from  
upper-layer controller  
(temperature or  
composition)



“Reversed”:  
DY-configuration  
 (“material balance”)

Set manually or from  
upper-layer controller

# Top of Column



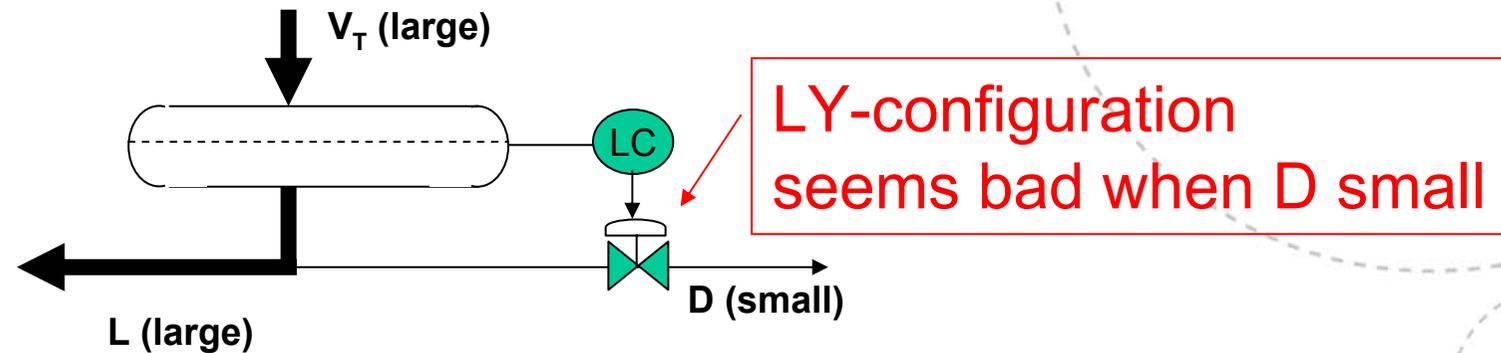
Similar in bottom...  
XV, XB, X V/B

# How do the configurations differ?

- Has been a lot of discussion in the literature (Shinskey, Buckley, Skogestad, Luyben, etc.).
- Probably over-emphasized, but let us look at it

1. Level control by itself  
(emphasized by Buckley et al., 1985)
2. Interaction of level control with composition control
3. “Self-regulation” in terms of disturbance rejection  
(emphasized by Skogestad and Morari, 1987)
4. Remaining two-point composition control problem  
(steady-state RGA - emphasized by Shinskey, 1984)

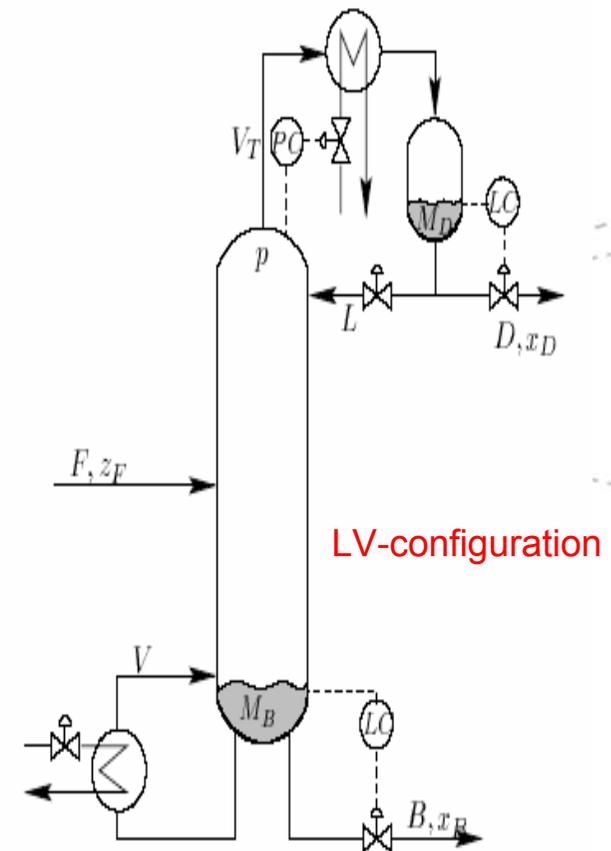
# 1. Level control by itself



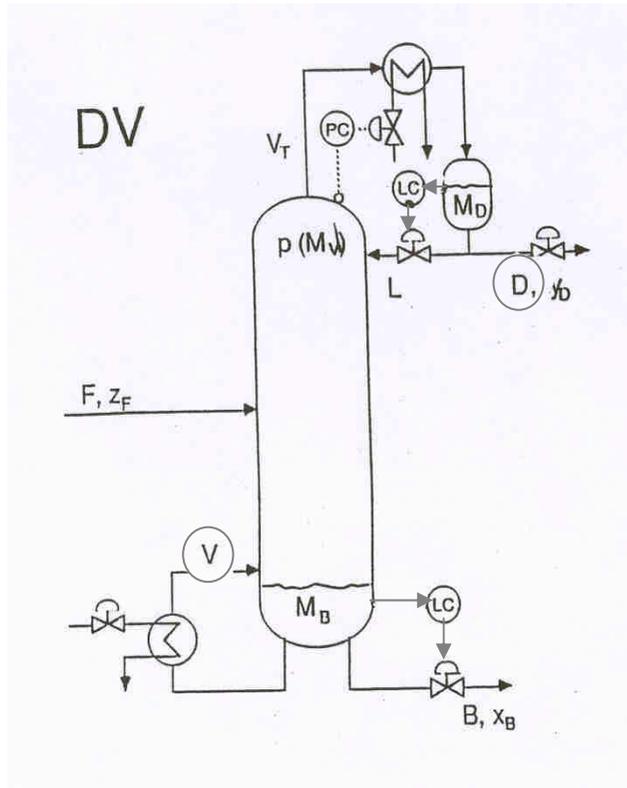
- General rule level control: Use largest flow to avoid saturation  
→ Prefer D to control top level (“standard”) if  $L/D < 1$
- Liptak (Instrument Engineers’ Handbook 2006):
  - Use D to control top level (“standard”) if  $L/D < 0.5$
  - Use L to control top level (“reversed”) if  $L/D > 6$
  - May use L or D for  $0.5 < L/D < 6$

## 2. Interaction of level control with remaining composition control

- Desired: Tuning of level controllers does not affect the remaining control system (composition control)
  - May want slow (“averaging”) level control
- Clearly favors the “standard” LV-configuration
- Other configurations (DV, LB, L/D V/B etc.) depend on tight level control



## Example DV-configuration:



Response to step change in  $V$  (bottom) depends on level tuning in top

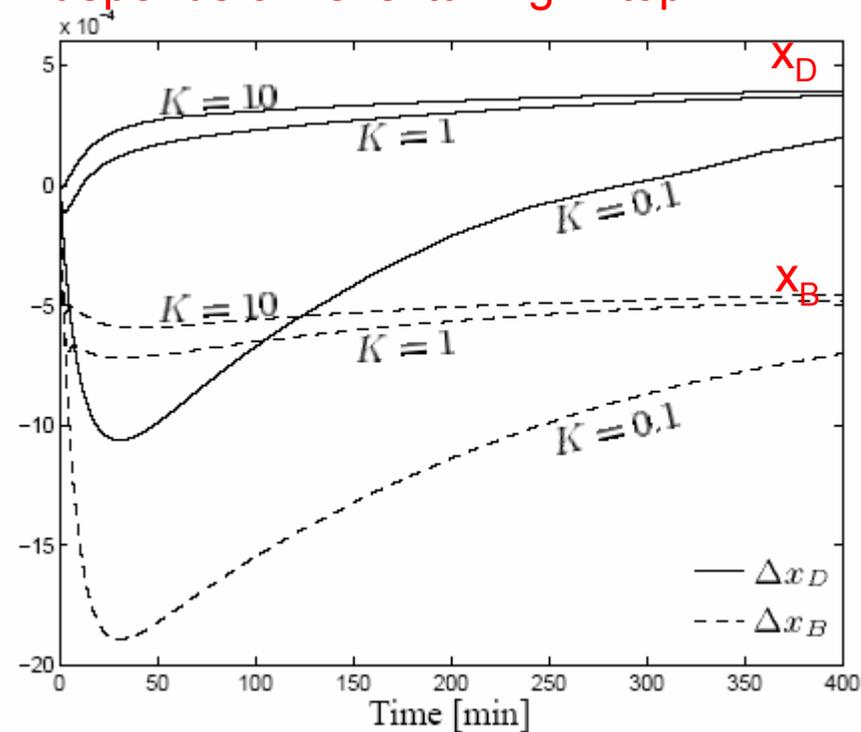


Figure 10: Tuning of the condenser level controller has a strong effect on the “open-loop” response for the DV-configuration. (Responses are for a 1% increase in  $V$  with condenser level controller  $\Delta L = K \Delta M_D$ )

INNOVATION AND CREATIVITY

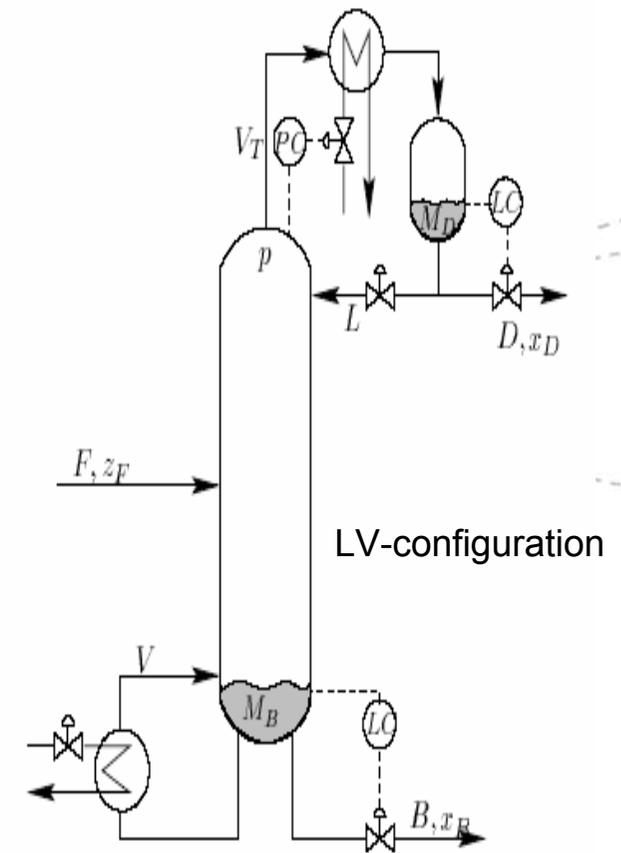
### 3. “Self-regulation” for disturbances

Disturbances in  $F$ ,  $L$ ,  $V$  and feed enthalpy:

- LV is usually worst
- DV and LB are better
- L/D V/B usually best (especially for high reflux)

Fixed flows (configuration)	Composition deviation $\Delta X$
L/D - V/B	15.8
L/F - V/B	18.6
L - B	21.1
D - V	21.2
L/D - V	23.1
L - V	63.4

Data for column A



## 4. Remaining “two-point” composition control problem

- Distillation is generally interactive: Increasing both L and V (internal flows) at the same time counteract each other
- Interactions in terms of steady-state RGA (want  $\approx 1$ ):

$$\lambda_{11}(G^{LV}) \approx \frac{(2/N)L(L+1)}{Bx_B + D(1-x_D)} \quad \leftarrow \begin{array}{l} \text{large for column with high reflux} \\ \text{and / or both products pure} \end{array}$$

$$\lambda_{11}(G^{DV}) \approx 1 / \left( 1 + \frac{D(1-x_D)}{Bx_B} \right) \quad \leftarrow \begin{array}{l} \text{always between 0 and 1} \\ \text{close to 1 for pure btm} \end{array} \quad (\text{Shinskey, 1967})$$

$$\lambda_{11}(G^{(L/D)(V/B)}) \approx \lambda_{11}(G^{LV}) / \left( 1 + \frac{L}{D} + \frac{V}{B} \right) \quad \leftarrow \begin{array}{l} \text{Generally good!} \\ \text{Especially high reflux} \end{array}$$

$$\lambda_{11}(G^{DB}) = \infty \quad \leftarrow \dots\text{oopss.. (seems hopeless)}$$

$$\lambda_{11}(G^{LB}) = \lambda_{11}(G^{LD}) = 1 - \lambda_{11}(G^{DV}) \quad \leftarrow \text{close to 1 for pure top}$$

column A

=50.2

= 0.5

= 3.91

=  $\infty$ 

=0.5

## Summary: How do configurations differ?

1. Level control by itself
2. Interaction of level with composition control
3. “Self-regulation” for disturbances
4. Remaining composition control problem

LV not for  $L/D > 6$

LV best!

LV not good

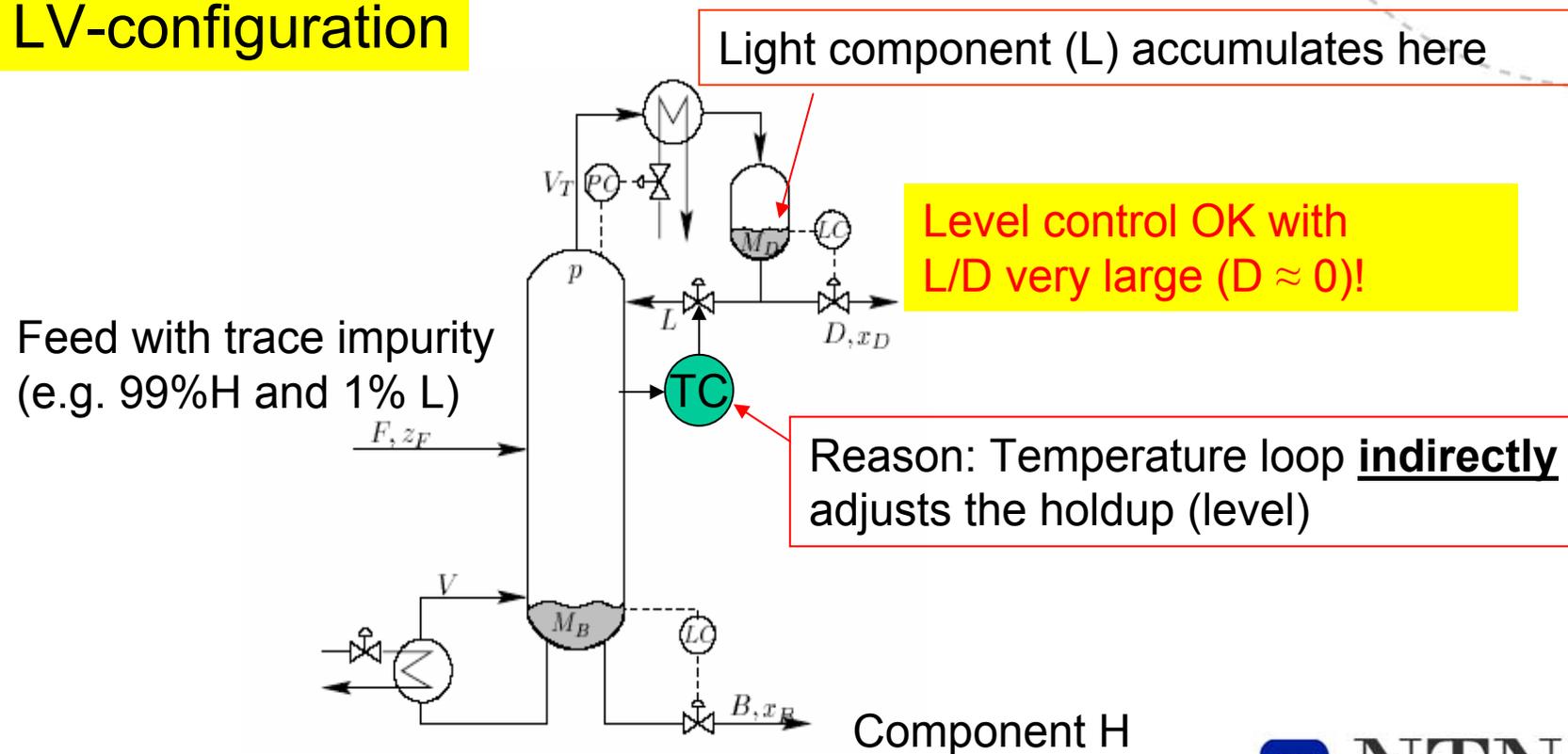
LV not good

Conclusion: LV promising only for no. 2  
BUT: This is without temperature loop

# BUT....

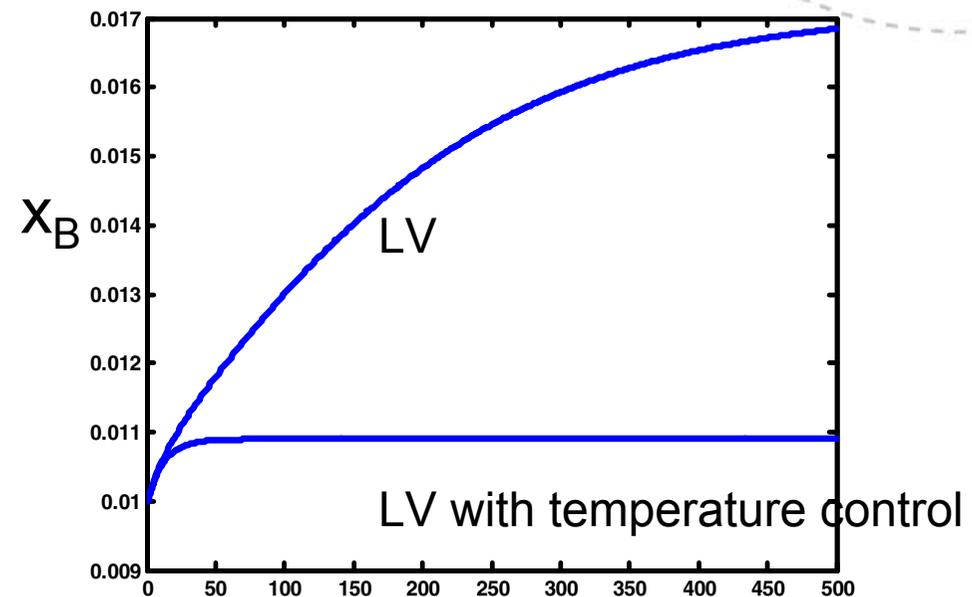
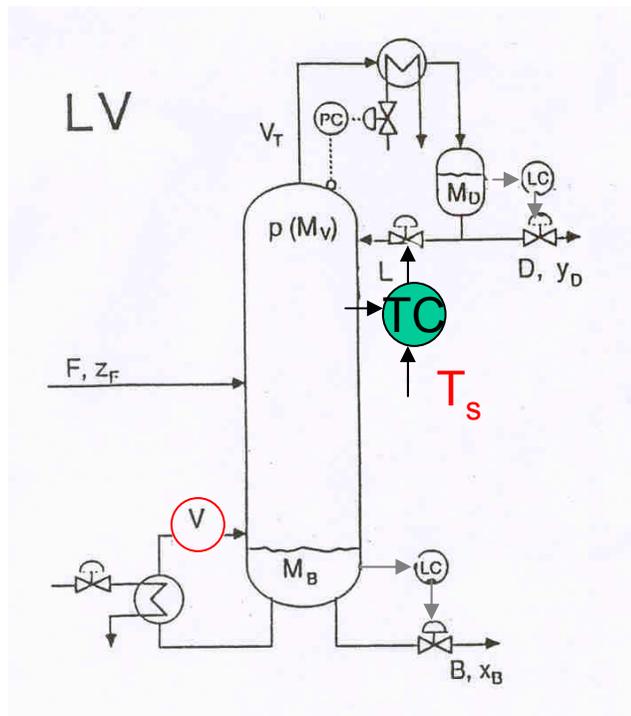
## 1. Level control with LV much better with T-control:

### LV-configuration



# Another BUT:

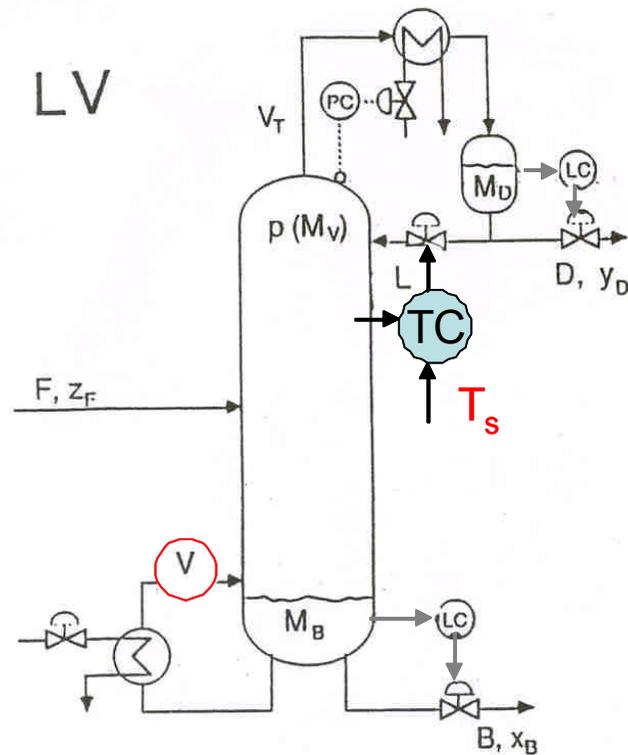
## 3. “Self-regulation” with LV much better with T-control:



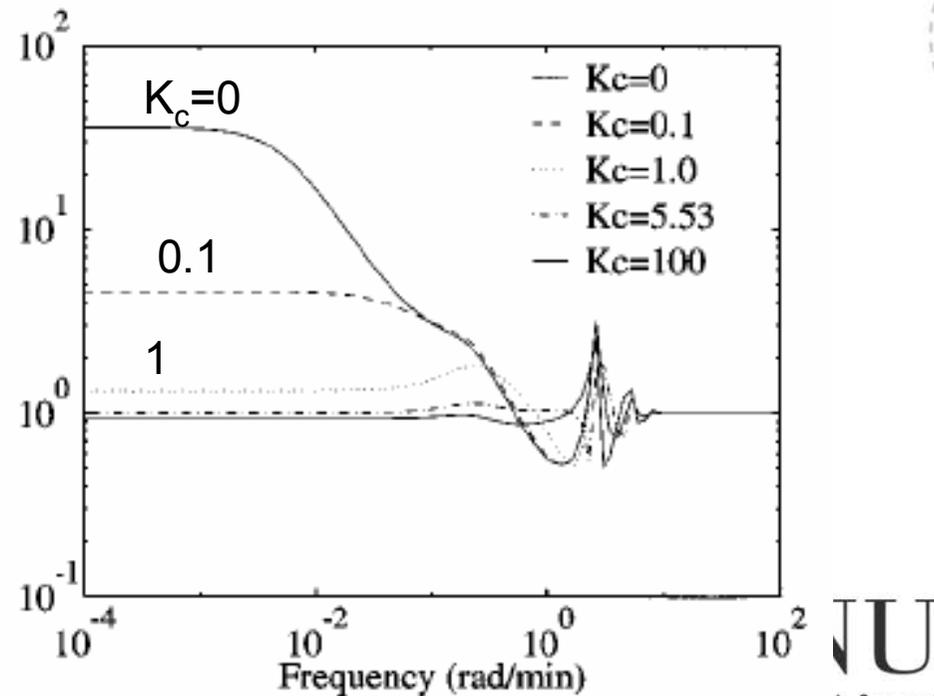
LV-configuration: Response to 1% increase in  $F$

# Yet another BUT:

4. Remaining two-point composition control:  
**RGA with LV much better with T-control**

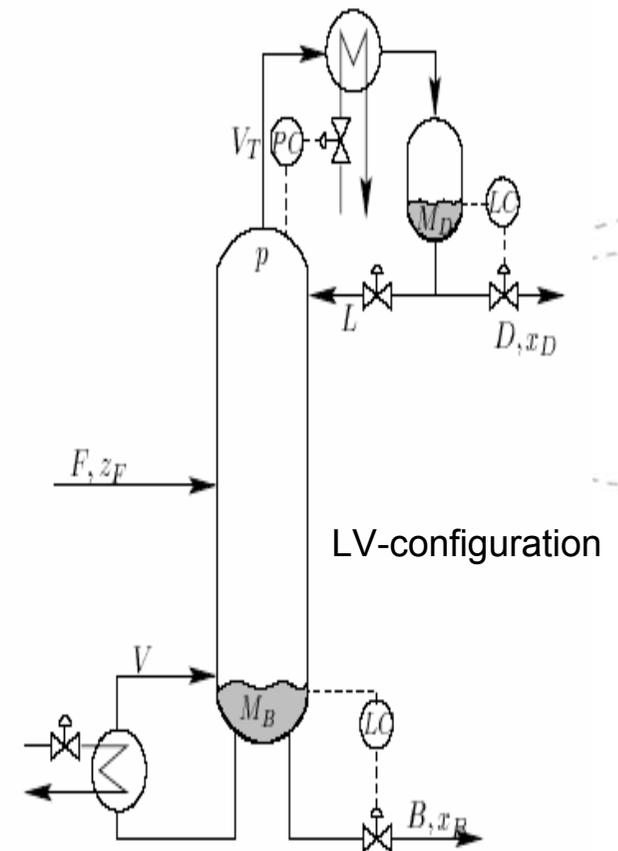


Resulting RGA with temperature control:



# Conclusion configurations

- **Normally use LV-configuration,** because it is
  - simplest
  - level tunings do not matter for column behavior
  - can get smooth variations in product rates  $D$  and  $B$

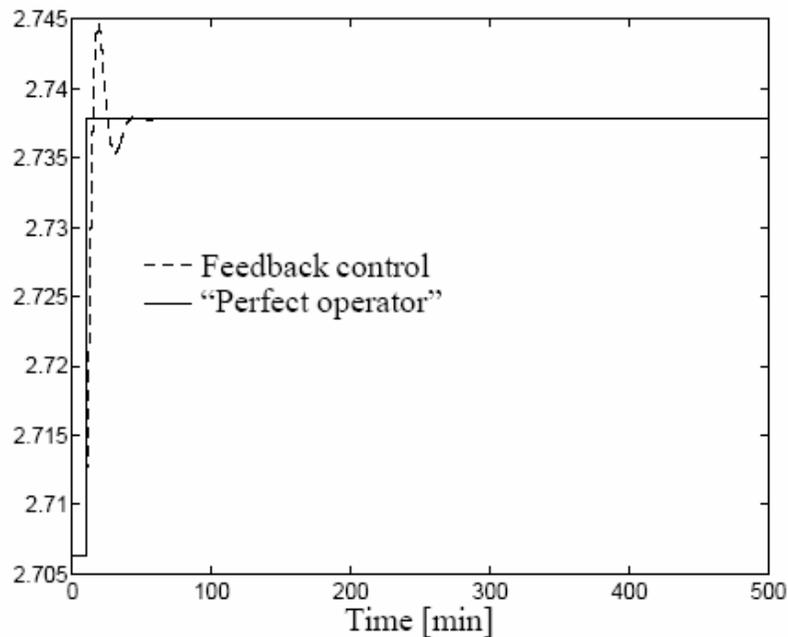


# 6. Myth of slow distillation control

- **Let's get rid of it!!!**
- Compare manual (“perfect operator”) and automatic control for “column A”:
  - 40 stages,
  - Binary mixture with 99% purity both ends,
  - relative volatility = 1.5
- First “one-point” control: Control of top composition only
- Then “two-point” control: Control of both compositions

# Myth about slow control

## One-point control



(a) Reflux  $L$

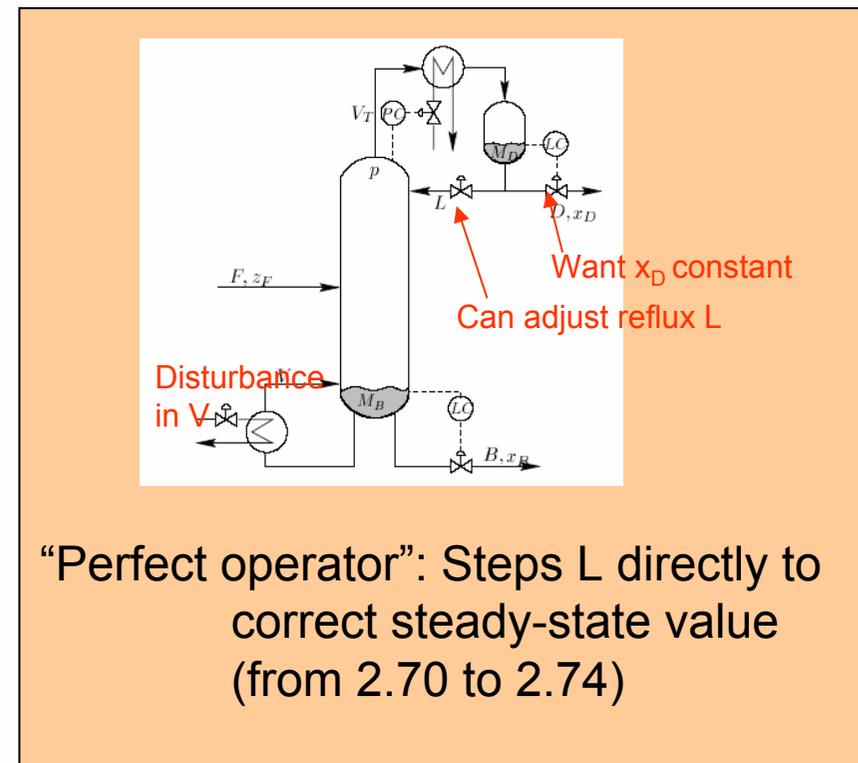
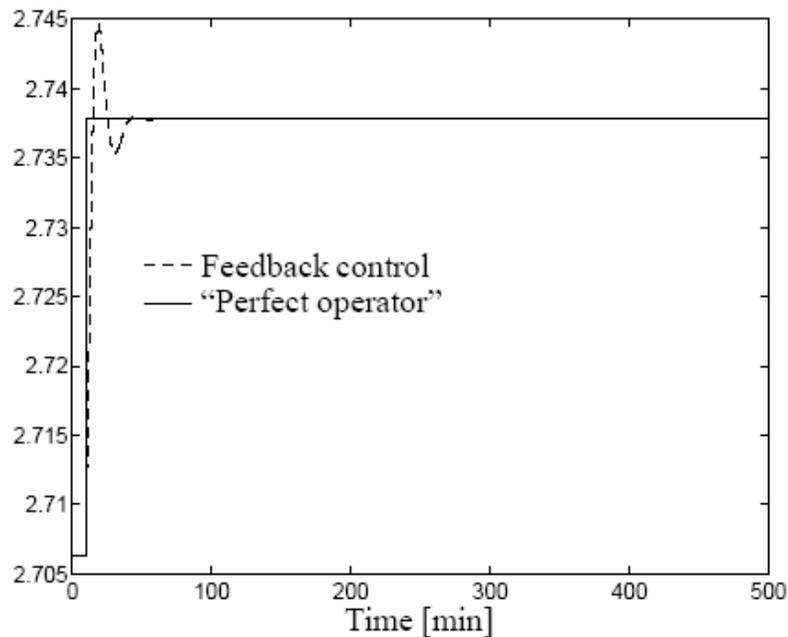


Figure 12: One-point control of  $x_D$ : Response to a 1% step increase (disturbance) in  $V$ . Solid line: Simultaneous step increase in  $L$  (“perfect operator”). Dashed line: Feedback where  $L$  is used to control  $x_D$  (PI-settings:  $k = 60$ ,  $\tau_I = 3.6$  min)

# Myth about slow control

## One-point control



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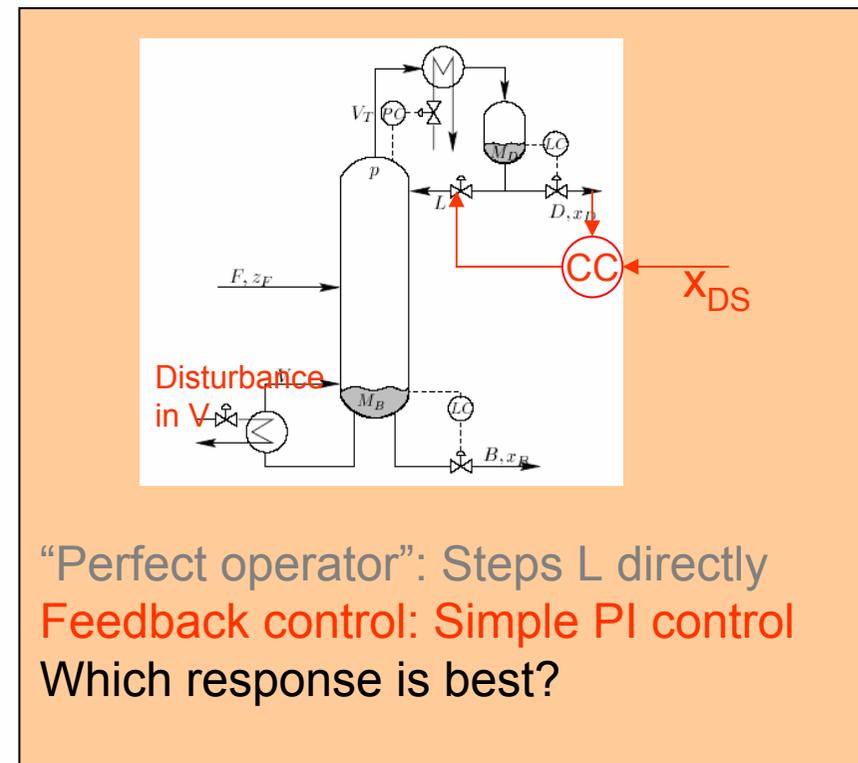


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# Myth about slow control

## One-point control

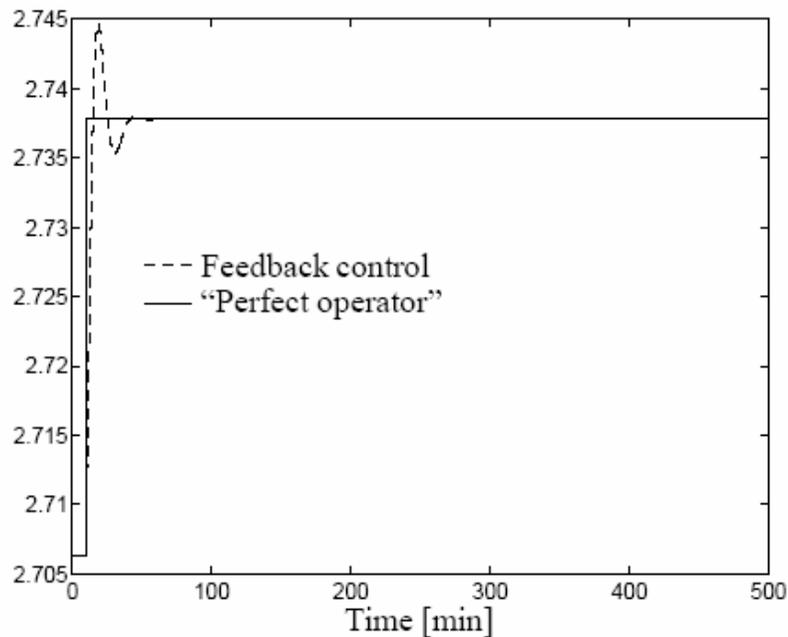
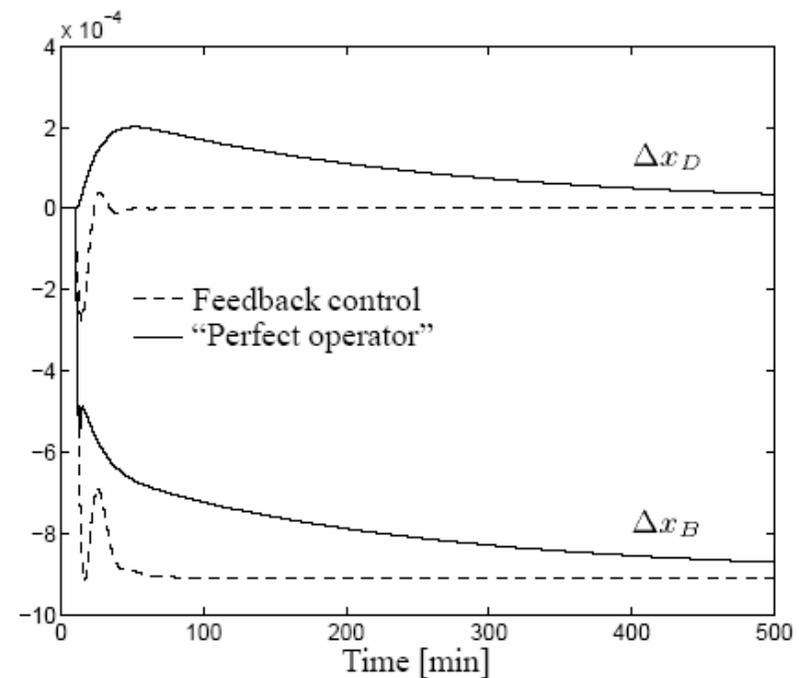
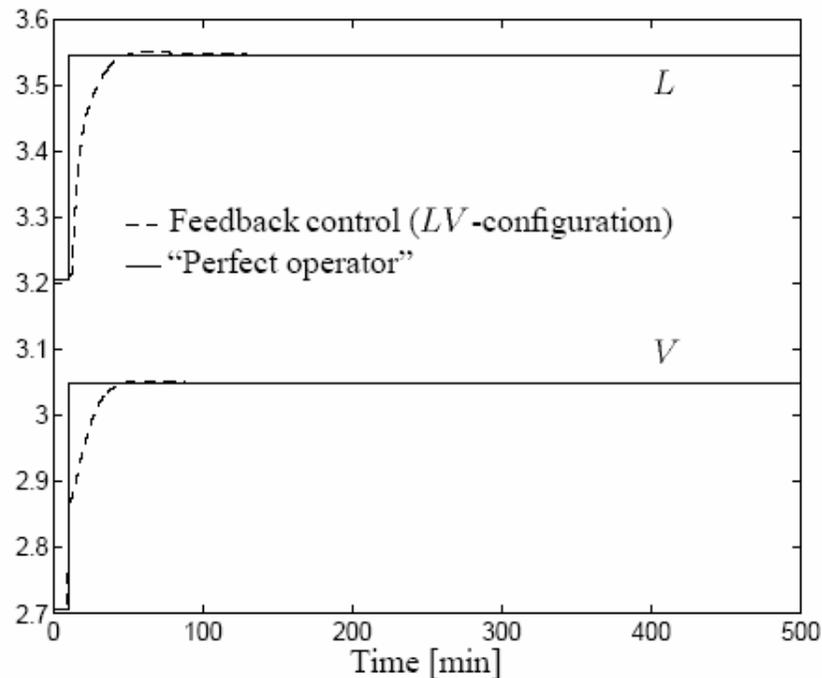
(a) Reflux  $L$ (b) Compositions,  $\Delta x_D(t)$  and  $\Delta x_B(t)$ 

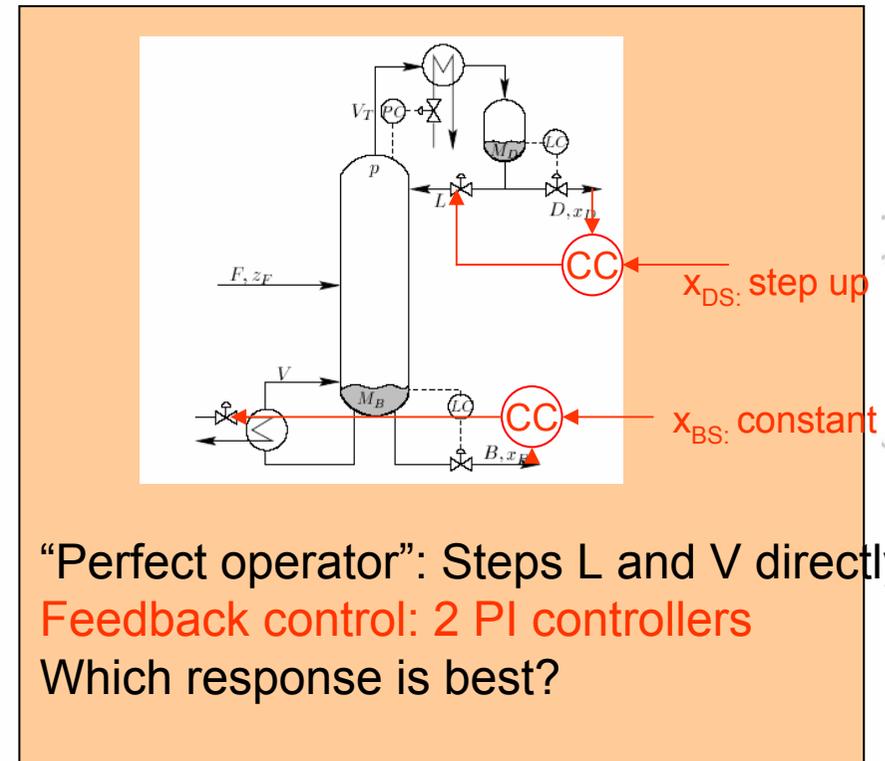
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# Myth about slow control

## Two-point control



(a) Reflux  $L$  and boilup  $V$

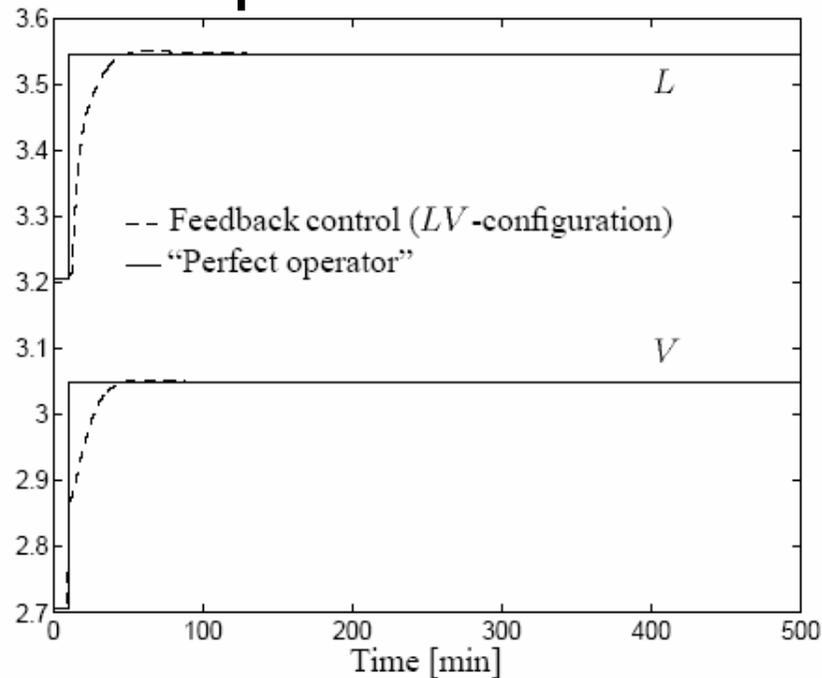


“Perfect operator”: Steps  $L$  and  $V$  directly  
**Feedback control: 2 PI controllers**  
 Which response is best?

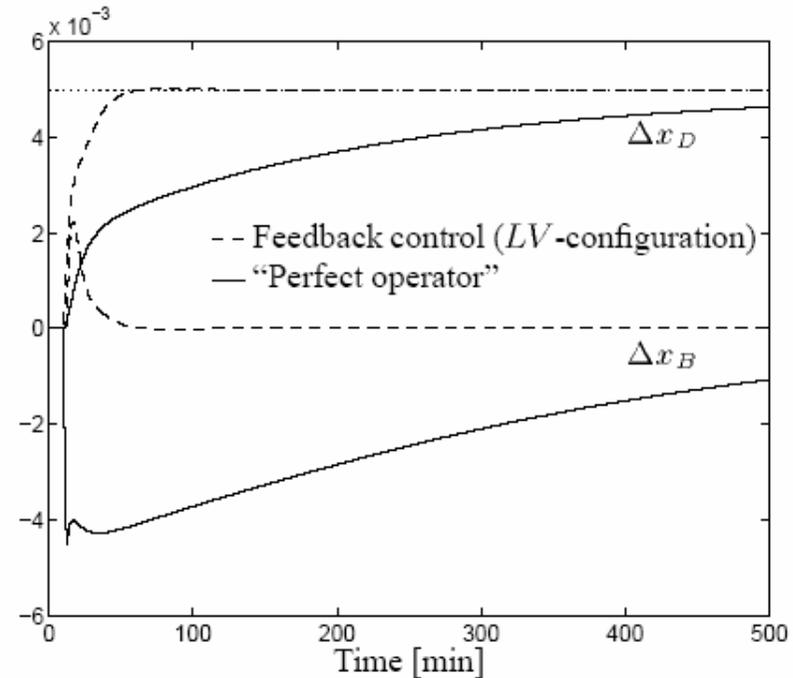
Figure 13: Two-point control: Setpoint change in  $x_D$  from 0.99 to 0.995 with  $x_B$  constant. Solid line: Simultaneous step increase in  $L$  and  $V$  to their new steady-state values (“perfect operator”). Dashed line: Feedback control using the  $LV$ -configuration with PI-settings in (82).

# Myth about slow control

## Two-point control



(a) Reflux  $L$  and boilup  $V$



(b) Compositions,  $\Delta x_D(t)$  and  $\Delta x_B(t)$

Figure 13: Two-point control: Setpoint change in  $x_D$  from 0.99 to 0.995 with  $x_B$  constant. Solid line: Simultaneous step increase in  $L$  and  $V$  to their new steady-state values (“perfect operator”). Dashed line: Feedback control using the  $LV$ -configuration with PI-settings in (82).

# Myth about slow control

## Conclusion:

- Experience operator: Fast control impossible
  - “takes hours or days before the columns settles”
- BUT, with feedback control the response can be fast!
  - Feedback changes the dynamics (eigenvalues)
  - Requires continuous “active” control
- Most columns have a single slow mode (without control)
  - Sufficient to close a single loop (typical on temperature) to change the dynamics for the entire column

# 7. Temperature control

Benefits of closing a temperature loop:

1. Stabilizes the column profile (and thus keeps disturbances within the column)
2. Indirect level control: Reduces the need for level control (as a result of benefit 1)
3. **Indirect composition control:** Strongly reduces disturbance sensitivity
4. Makes the remaining composition problem less interactive (e.g. in terms of the RGA) and thus makes it possible to have good two-point composition control

# 8. Indirect composition control

## Which temperature to control?

- Evaluate relative steady-state composition deviation:

$$\Delta X \stackrel{\text{def}}{=} \sqrt{L_{\max}} = \max_{\|e'_c\|_2 \leq 1} \sqrt{\left( \frac{x_{\text{top}}^H - x_{\text{top},s}^H}{x_{\text{top},s}^H} \right)^2 + \left( \frac{x_{\text{btm}}^L - x_{\text{btm},s}^L}{x_{\text{btm},s}^L} \right)^2}$$

- $e_c$  includes:
  - disturbances ( $F$ ,  $z_F$ ,  $q_F$ )
  - implementation measurement error (0.5 for T)

- Have looked at 15 binary columns and 5 multicomponent (Hori, Skogestad and Al-Arfaj, D&A 2006)
- Main focus on “column A”
  - 40 theoretical stages
  - Feed in middle
  - 1% impurity in each product
  - Relative volatility: 1.5
  - Boiling point difference: 10K

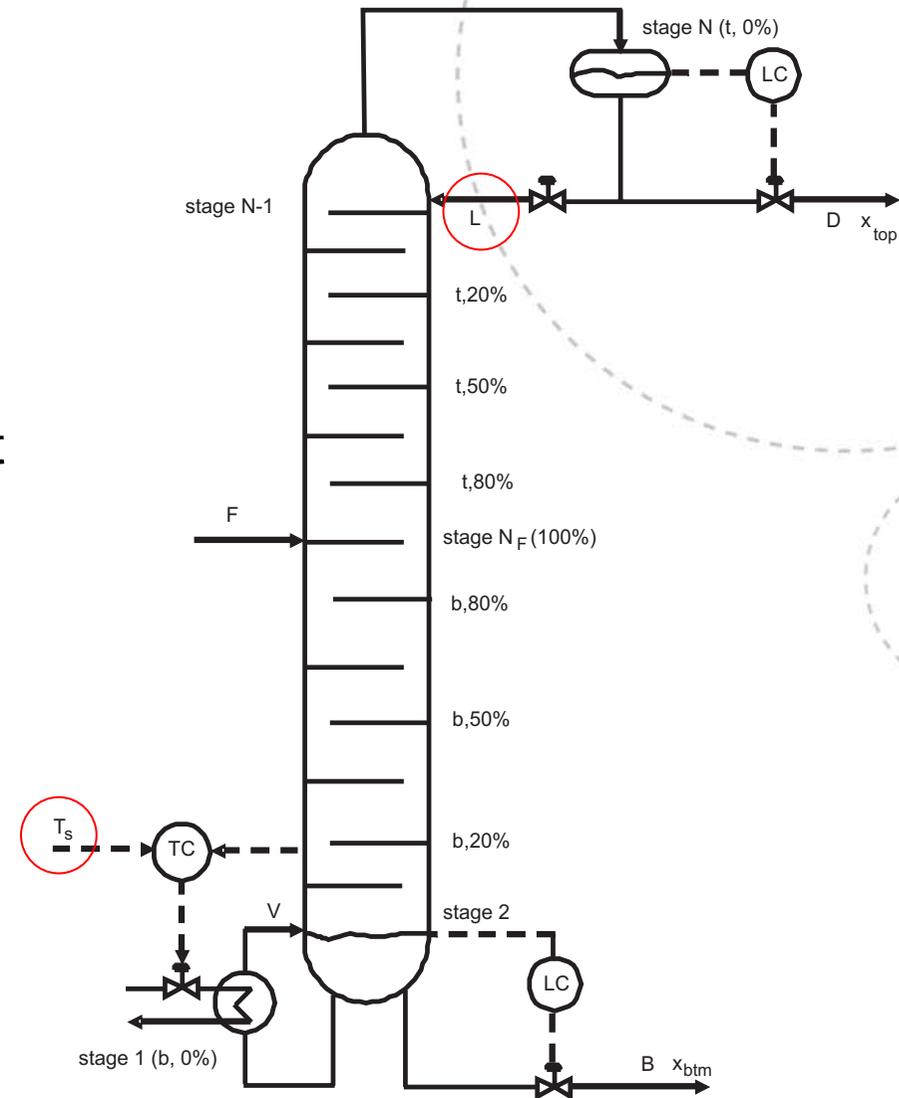


Table: Binary mixture - Steady-state relative composition deviations ( $\Delta X$ ) for binary **column A**

Fixed variables	X
$T_{b,55\%} - T_{t,55\%}^*$	<b>0.530</b>
$T_{b,70\%} - L/F^*$	<b>0.916</b>
$T_{b,50\%} - L/F$	0.975
$T_{b,75\%} - V/F^*$	1.148
$T_{b,90\%} - L^*$	<b>1.223</b>
$T_{b,70\%} - L/D^*$	1.321
$T_{b,50\%} - L$	<b>1.386</b>
$T_{t,95\%} - V^*$	1.470
$L/D - V/B$	15.84
$L/F - V/B$	18.59
$L - B$	21.06
$D - V$	21.22
$L - V$	<b>63.42</b>
$D - B$	infeasible

\* Temperature optimally located  
\*\* Optimal temperature in opposite section.

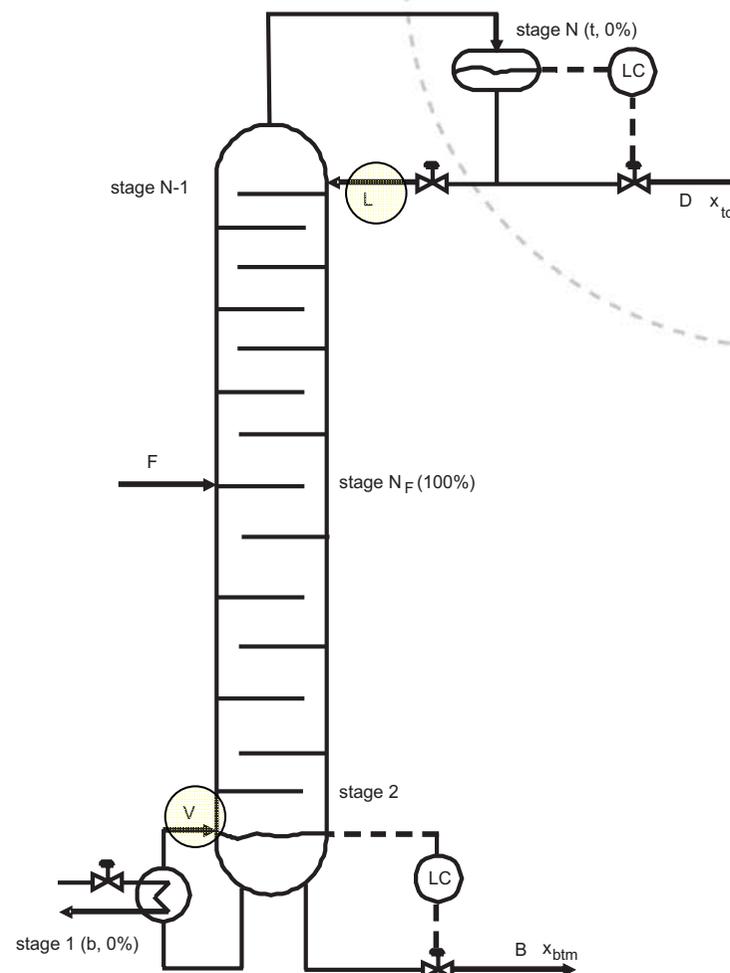


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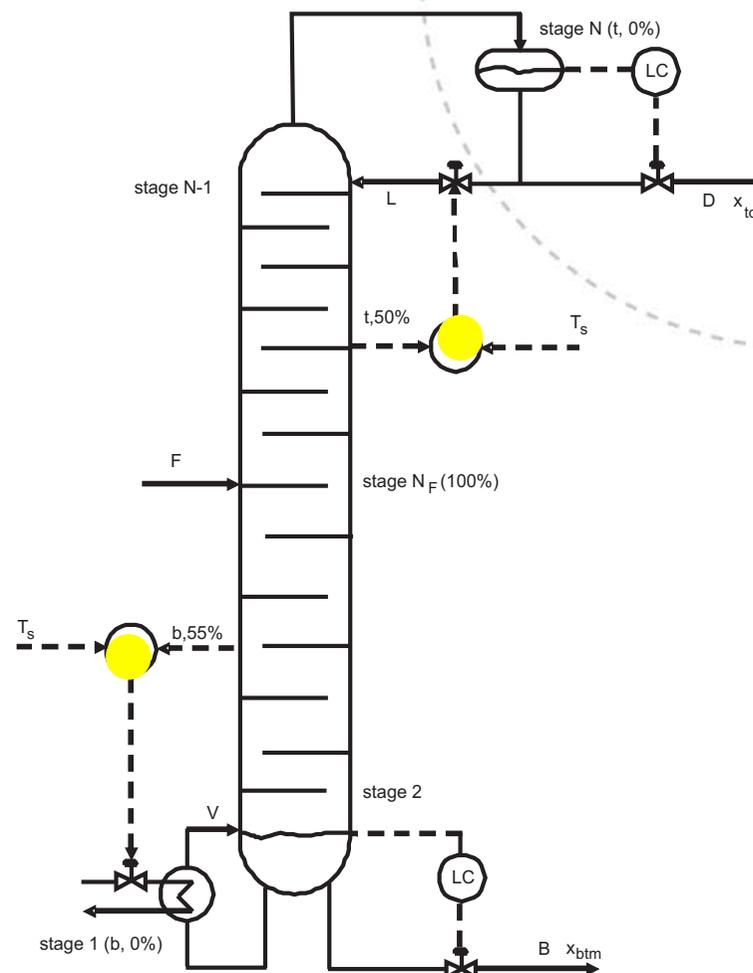




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\* Temperature optimally located  
\*\* Optimal temperature in opposite section.

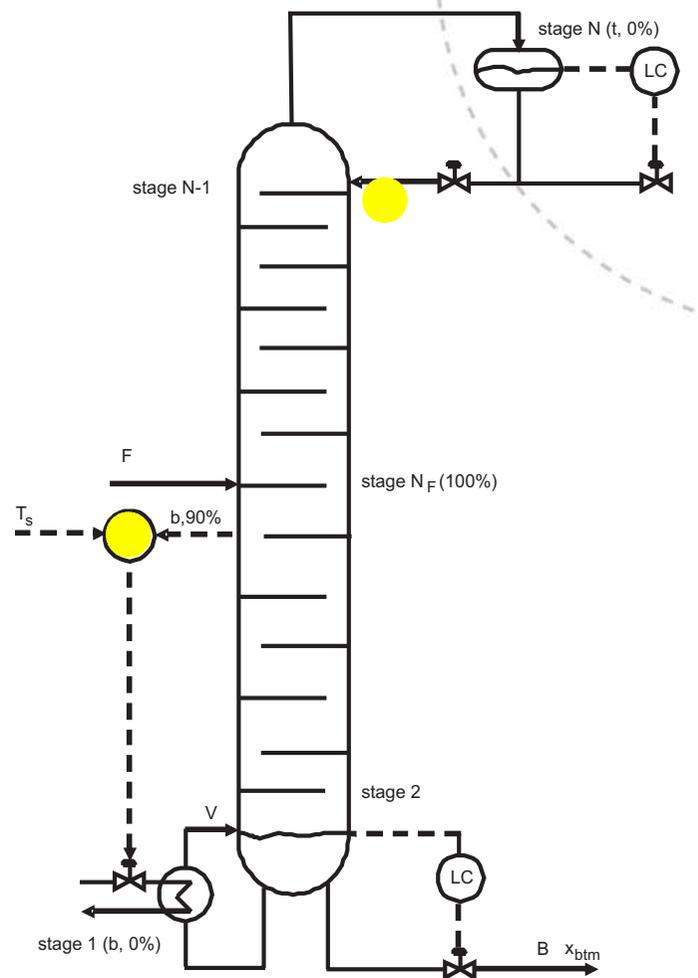


Table: Binary mixture - Steady-state relative composition deviations ( $\Delta X$ ) for binary **column A**

Fixed variables	X
$T_{b,55\%} - T_{t,55\%}^*$	<b>0.530</b>
$T_{b,70\%} - L/F^*$	<b>0.916</b>
$T_{b,50\%} - L/F$	0.975
$T_{b,75\%} - V/F^*$	1.148
$T_{b,90\%} - L^*$	<b>1.223</b>
$T_{b,70\%} - L/D^*$	1.321
$T_{b,50\%} - L$	<b>1.386</b>
$T_{t,95\%} - V^*$	<b>1.470</b>
$L/D - V/B$	15.84
$L/F - V/B$	18.59
$L - B$	21.06
$D - V$	21.22
$L - V$	63.42
$D - B$	infeasible

\* Temperature optimally located  
\*\* Optimal temperature in opposite section.

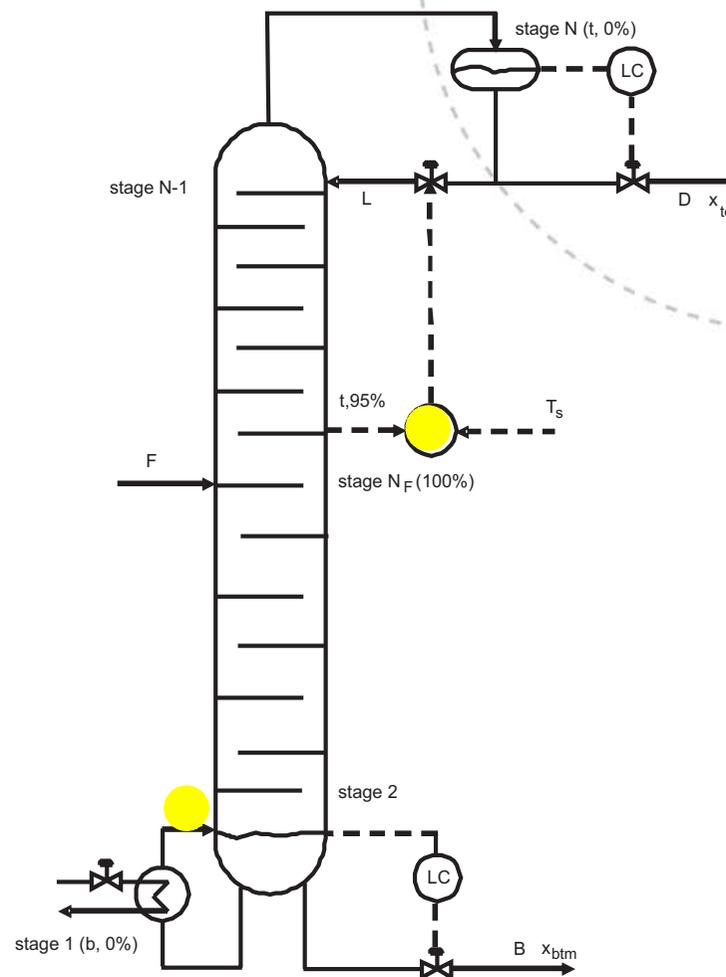
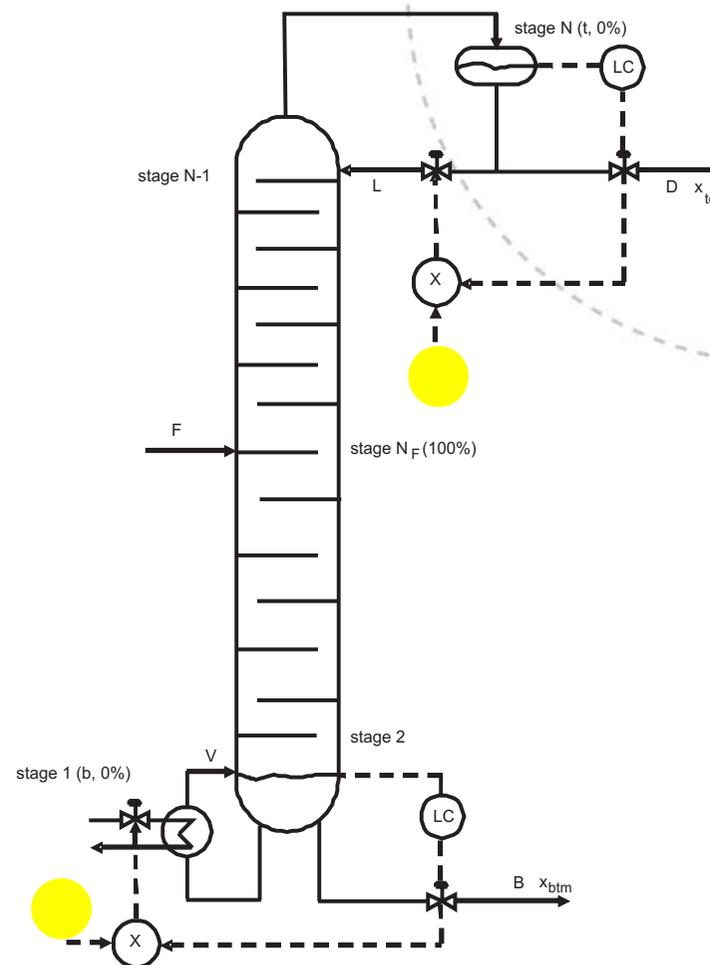


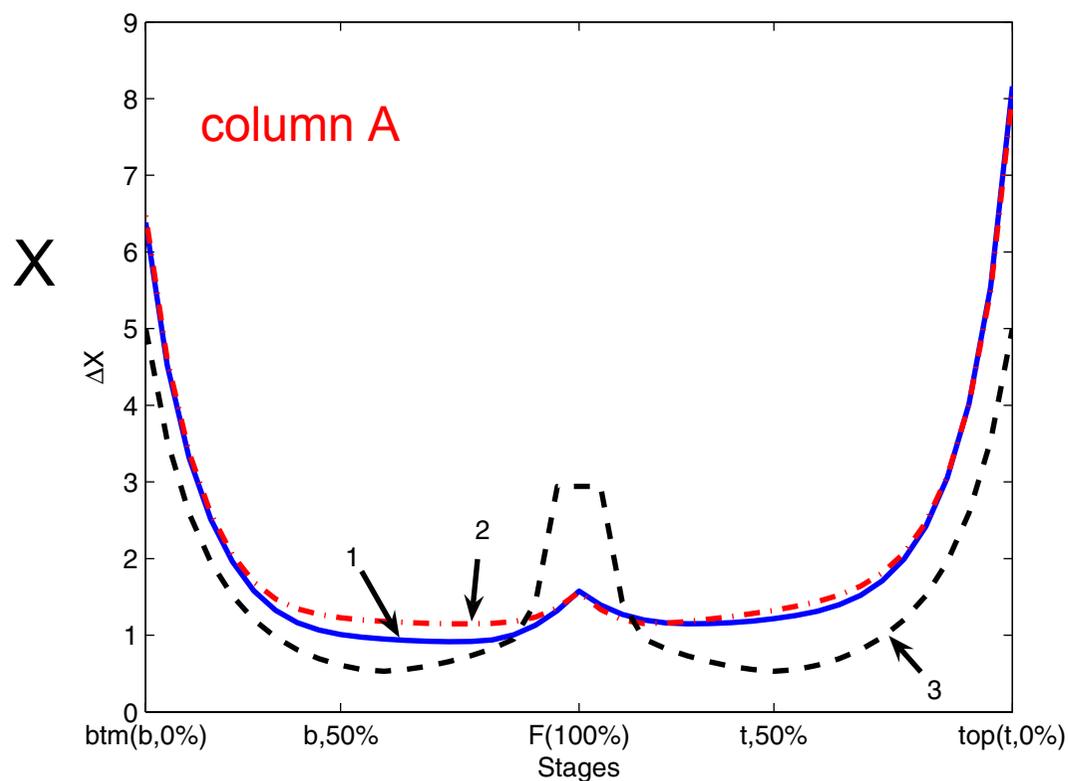
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$D - B$	infeasible

\* Temperature optimally located  
\*\* Optimal temperature in opposite section.



## Avoid controlling temperature at column ends



- Composition deviation:
  - 1- L/F and one temperature
  - 2- V/F and one temperature
  - 3- Two temperatures symmetrically located

# Conclusion temperature control

- **Rule 1.** Avoid temperatures close to column ends (especially at end where impurity is small)
- **Rule 2.** Control temperature at important end
- **Rule 3.** To achieve indirect composition control: Control temperature where the steady-state sensitivity is large (“maximum scaled gain rule”).
- **Rule 4.** For dynamic reasons, control temperature where the temperature change is large (avoid “flat” temperature profile). (Binary column: same as Rule 3)
- **Rule 5.** Use an input (flow) in the same end as the temperature sensor.
- **Rule 6.** Avoid using an input (flow) that may saturate.

# 9. Logarithmic compositions

- $X^{\log} = \ln (x_L/x_H)$
- $T^{\log} = \ln (T_{H,ref} - T)/(T - T_{L,ref})$

# The response is nonlinear....

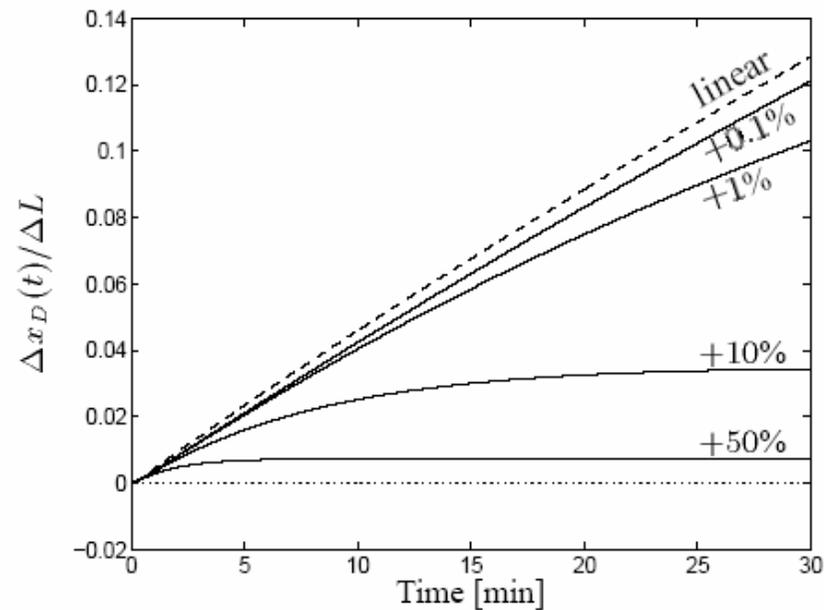


Figure 7: Nonlinear response in distillate composition for changes in  $L$  of 0.1%, 1%, 10% and 50%.

The response is nonlinear....  
but this can be corrected by taking log –  
especially dynamically

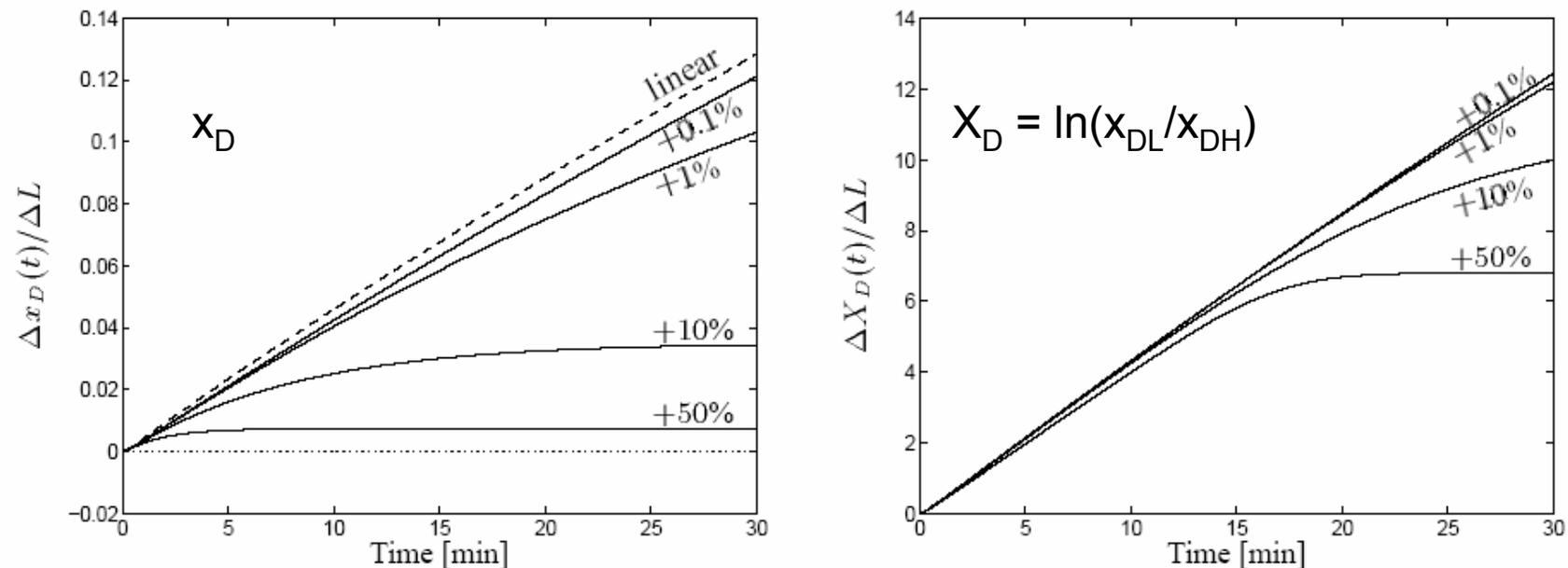
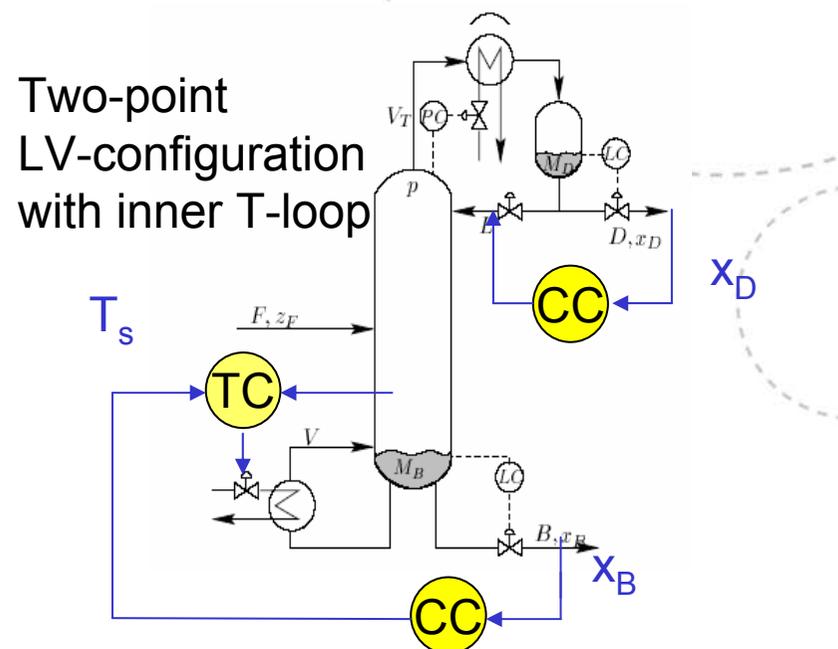


Figure 7: Nonlinear response in distillate composition for changes in  $L$  of 0.1%, 1%, 10% and 50%. Right plot: Logarithmic composition

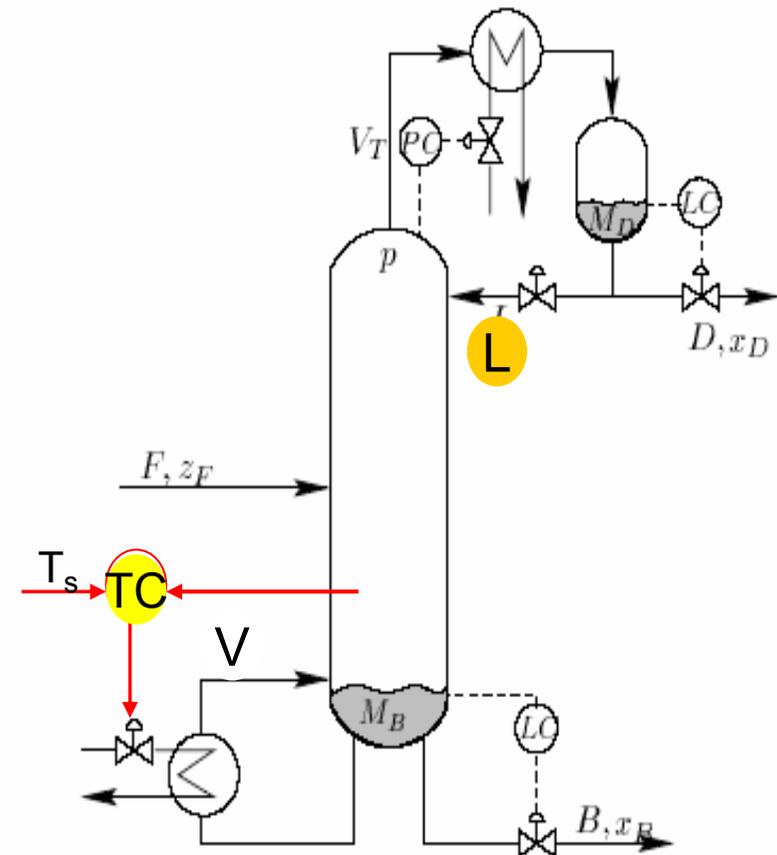
## 10. Conclusions composition control

- Not as difficult as often claimed
- First rule: Close a tight temperature loop (P-control OK)
- LV-scheme recommended for most columns
- Use log transformations to reduce nonlinearity
- Use estimators based on temperature



# Issues distillation control

- The “configuration” problem (level and pressure control)
  - Which are the two remaining degrees of freedom?
    - e.g. LV-, DV-, DB- and L/D V/B- configurations
- The temperature control problem
  - Which temperature (if any) should be controlled?
- Composition control problem
  - Control two, one or no compositions?



- Thanks to Eduardo Hori  
(more on temperature control: see his talk Wednesday at 09.20)

# Self-optimizing control

1. Control active constraints
2. Remaining unconstrained degrees of freedom: Use maximum gain rule for finding the “magic” controlled variables:

Look for variables that maximize the minimum singular value of the scaled steady-state gain matrix  $G'$ ,

$$\begin{aligned} &\text{maximize } \underline{\sigma}(G'), \quad G' = S_1 G S_2 \\ &S_1 = \text{diag}\left\{\frac{1}{\text{span}(c_i)}\right\} \\ &\text{span}(c_i) = |\text{opt. range } c_i| + |\text{noise } c_i| \\ &S_2 = J_{uu}^{-1/2} \end{aligned}$$

# Some guidelines for selecting $y_2$ and $u_2$ in the stabilizing (regulatory) control layer

## Selection of measurement $y_2$ :

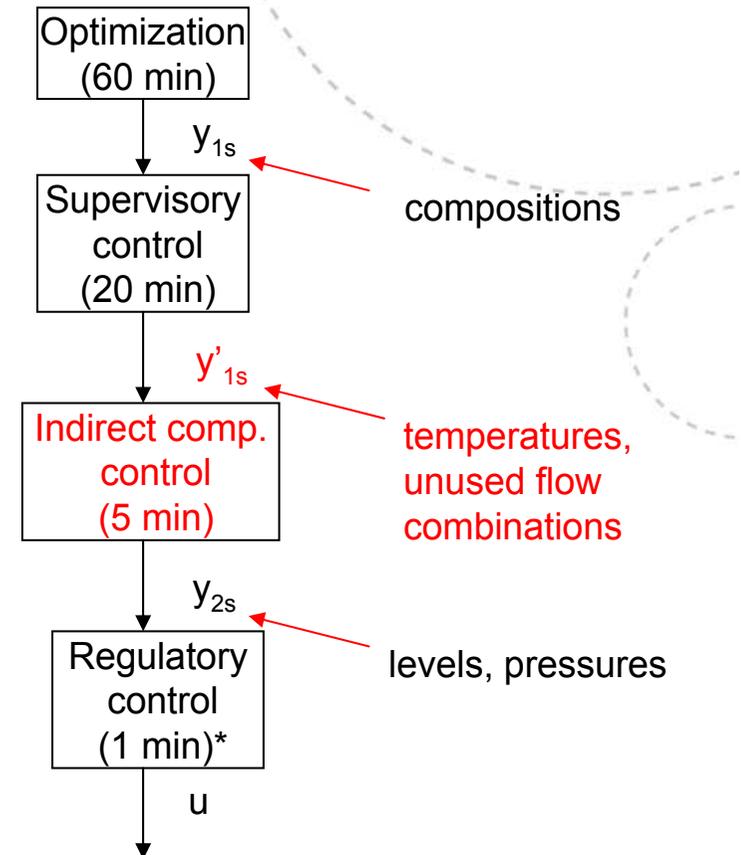
1. “Maximum gain rule” is useful also for selecting  $y_2$ :  
*Control variables that “drift”*
2. Avoid “unreliable” measurements (because regulatory layer should not fail)
3. For dynamic reasons: Avoid variables  $y_2$  with a large (effective) time delay.  
*Items 2 and 3 normally exclude compositions as secondary controlled variables  $y_2$ .*

## Selection of input $u_2$ (to be paired with $y_2$ ):

1. Avoid variables  $u_2$  that may saturate
2. Avoid variables  $u_2$  where (frequent) changes are undesirable, for example, because they disturb other parts of the process.
3. Prefer pairing on variables “close” to each other such that the effective time delay is small.

# May need additional layer for “Indirect composition control”

- Observation: The “magic” self-optimizing variables ( $y_1$ ) are often compositions
- But compositions measurements are often unreliable and delayed
- May need additional layer for “indirect composition control” ( $y'_1$ )
- Can use maximum gain rule to obtain  $y'_1$  (steady-state)



\* Time scales may vary: Temperature control may be faster than level control

Perry, 5th. Edition, 1973:

DISTILLATION-COLUMN CONTROL 22-123

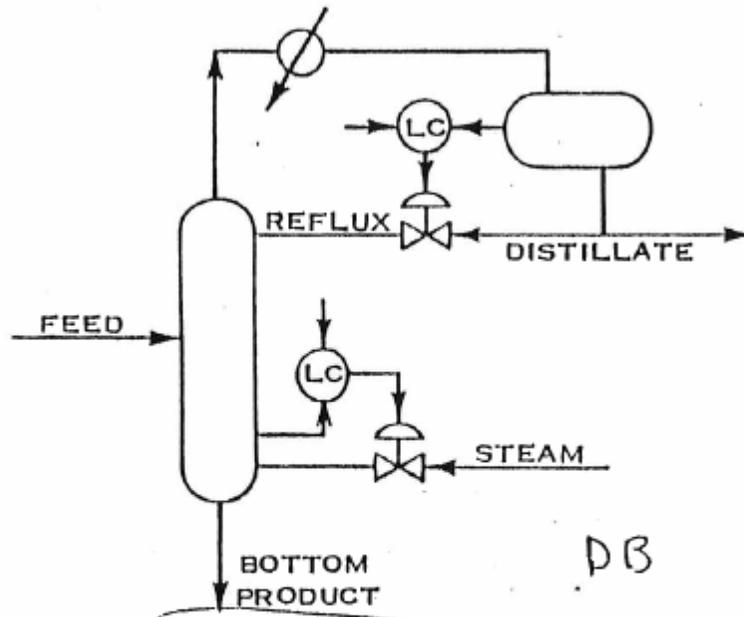


Fig. 22-184. Non-regulatory level-controller arrangement with distillate and bottom-product rates as the manipulated variable for separation control.

Two of the arrangements may be eliminated from consideration immediately since they will not maintain internal column inventory. An example of such a non-regulatory arrangement is shown in Fig. 22-184. Here variations in feed rate result in variations in inventory of liquid on the column trays unless the product rates are correspondingly adjusted to satisfy the column material balance. This type of inventory control also leaves one without a source of manipulatable energy for control of the separation.

- Be careful about steady-state analysis:
- DB-configuration is “impossible” at steady-state, but works dynamically (provided both composition loops are closed)
  - It is used in practice for columns with very high L/D (Luyben)

# Conclusion configurations

- **Normally use LV-configuration**, because it is
  - simplest
  - level tunings do not matter for column behavior
  - can get smooth variations in product rates D and BDisadvantages:
  - interactive (but less so at high frequencies important for control)
  - sensitive to flow disturbances

Note: Disadvantages less important if we close a “fast” temperature loop  
.... even less important if we use composition control on top

- Use other configuration in top (e.g. D-, L/D-) if L/D large and small condenser holdup
- Use other configuration in bottom (e.g. -B, -V/B) if V/B large and small reboiler holdup

# Which temperature should we control?

1. **Heuristic 1: Steep temperature profile**

Makes sense from a dynamic point of view:

Initial slope of response is proportional to temperature difference

2. **Heuristic 2: Small optimal variation for disturbances** (Luyben, 1975)

3. **Heuristic 3: Large sensitivity, or more generally, large gain in terms of the minimum singular value** (Moore, 1992)

4. **Self-optimizing control** (Skogestad et al.)

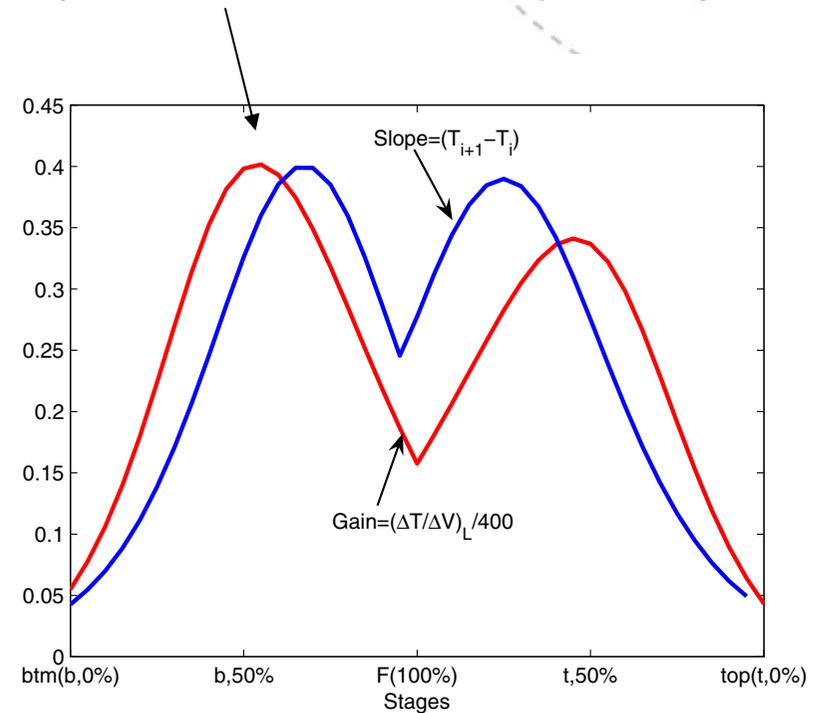
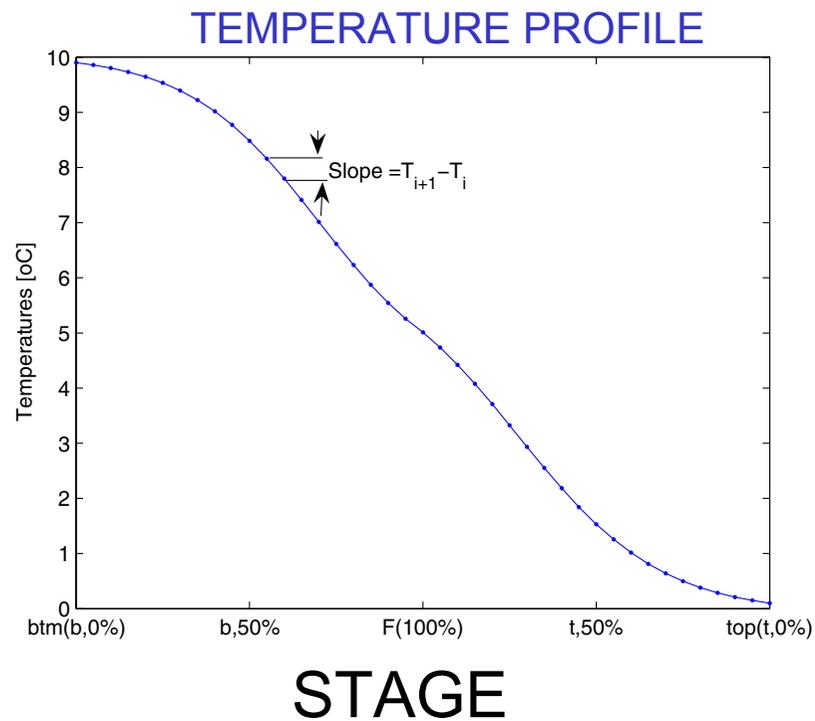
a. “Maximum scaled steady-state gain rule”: Combines heuristic 2 and 3

b. “Exact” local method (evaluate steady-state composition deviation  $\Delta X$ )

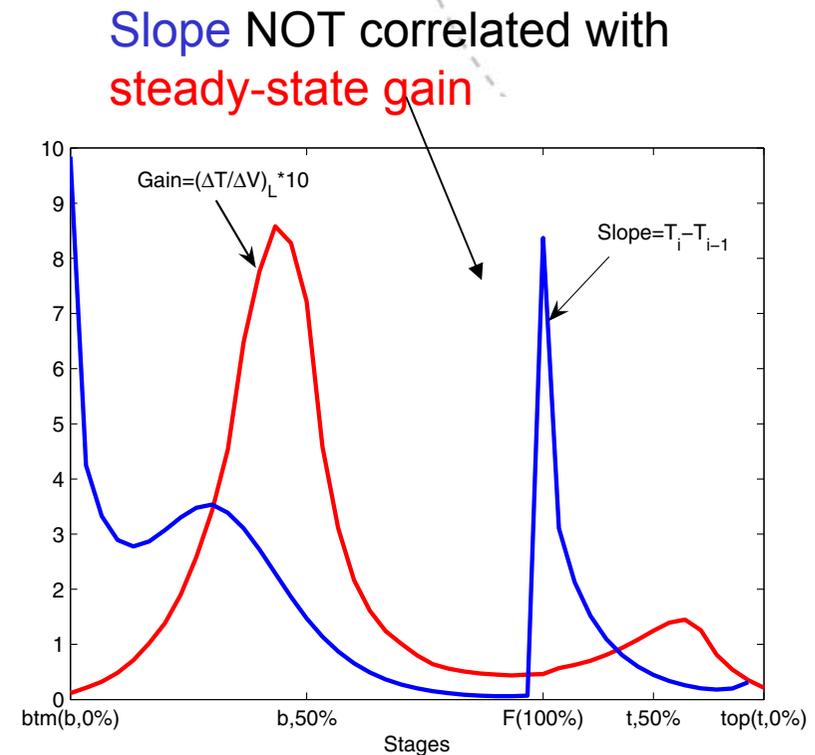
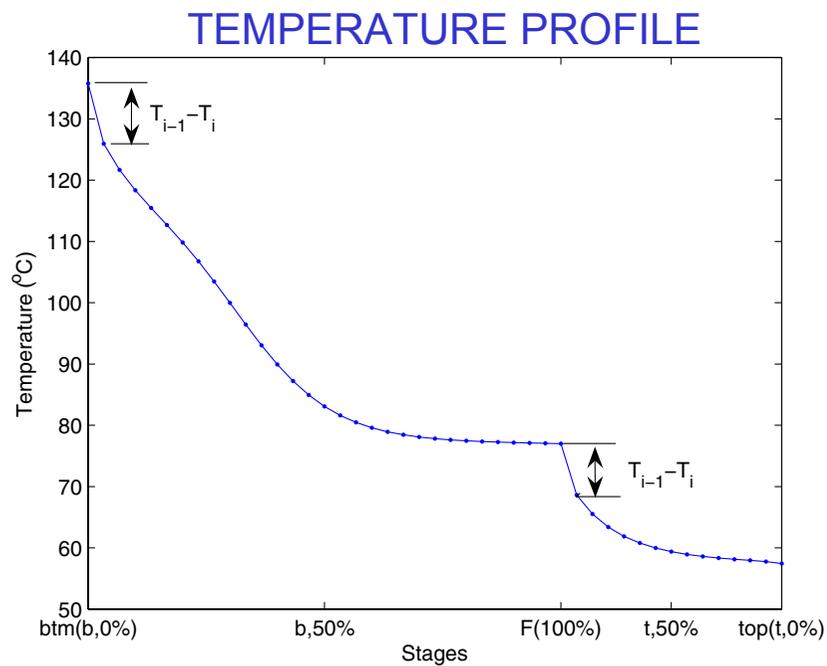
c. Brute-force steady-state evaluation of loss

# Binary column

slope closely correlated with **steady state gain**



# Multicomponent column



Conclusion: Temperature slope alone OK only for binary columns

Table: Multicomponent Columns: steady-state composition deviations.

A/B	X	B/C	X	C/D	X	“Real” B/C nC <sub>5</sub> /nC <sub>6</sub>	X
T <sub>t,95%</sub> - V/B	0.96	T <sub>b,70%</sub> - T <sub>t,75%</sub>	1.71	T <sub>b,85%</sub> - L/D	1.38	T <sub>b,30%</sub> - T <sub>t,33%</sub>	1.07
T <sub>b,80%</sub> - V/F	1.03	T <sub>b,90%</sub> - L/F	1.77	T <sub>b,40%</sub> - L/F	1.63	T <sub>t,33%</sub> - V	1.74
T <sub>b,80%</sub> - L/F	1.05	T <sub>b,95%</sub> - L	1.88	T <sub>b,50%</sub> - L/F	1.64	T <sub>t,33%</sub> - L	1.78
T <sub>b,80%</sub> - V	1.07	T <sub>b,75%</sub> - L/D	1.91	T <sub>b,45%</sub> - L	1.88	T <sub>t,33%</sub> - L/F	1.85
T <sub>b,75%</sub> - L	1.08	T <sub>b,95%</sub> - V/F	2.03	T <sub>b,40%</sub> - V/F	2.07	T <sub>t,33%</sub> - V/B	2.17
T <sub>b,80%</sub> - T <sub>t,100%</sub>	1.86	T <sub>b,50%</sub> - L/F	2.11	T <sub>b,95%</sub> - T <sub>t,75%</sub>	2.26	T <sub>t,33%</sub> - V/F	2.19
T <sub>b,50%</sub> - L/F	1.98	T <sub>100%</sub> - V	2.22	T <sub>t,90%</sub> - V	2.28	T <sub>b,50%</sub> - L	2.94
T <sub>b,65%</sub> - L/D	2.00	T <sub>b,50%</sub> - L	2.29	T <sub>t,80%</sub> - V/B	4.45	T <sub>t,33%</sub> - L/D	2.95
T <sub>b,50%</sub> - L	2.00	T <sub>t,90%</sub> - V/B	2.60	L/D - V/B	31.8	T <sub>b,50%</sub> - L/F	3.08
L/F - V/B	44.7	L/D - V/B	32.0				

## Conclusion: Fix L and a temperature