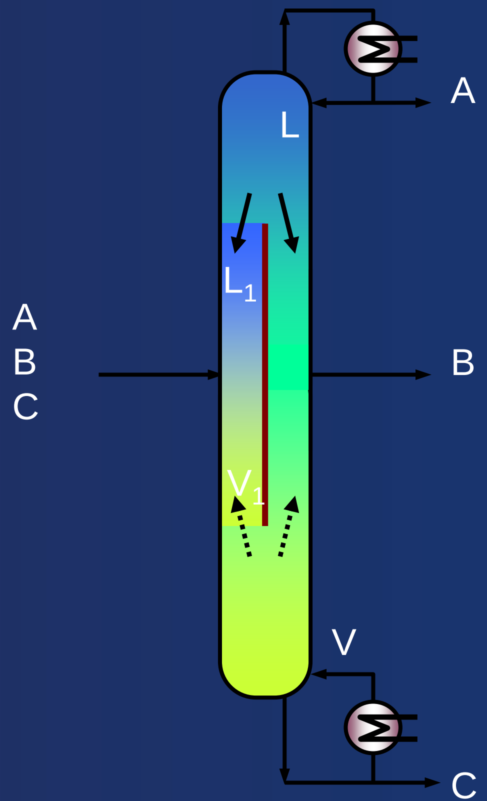
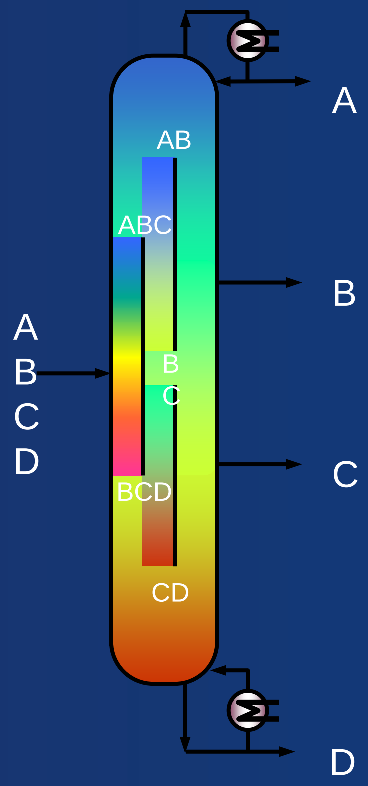
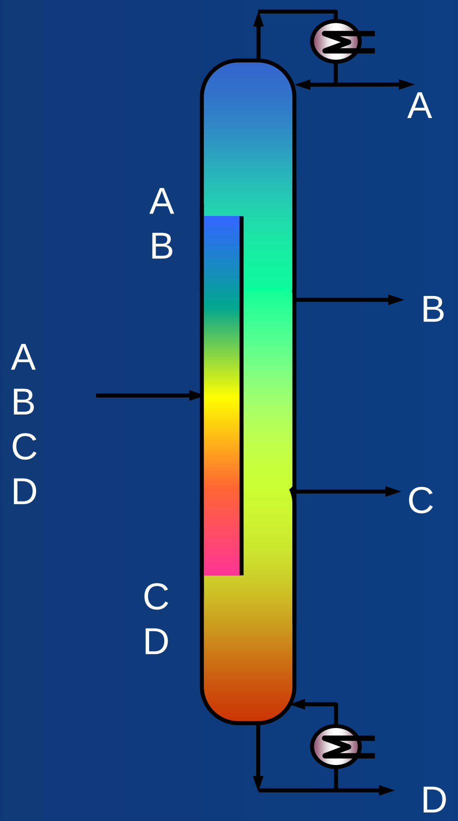
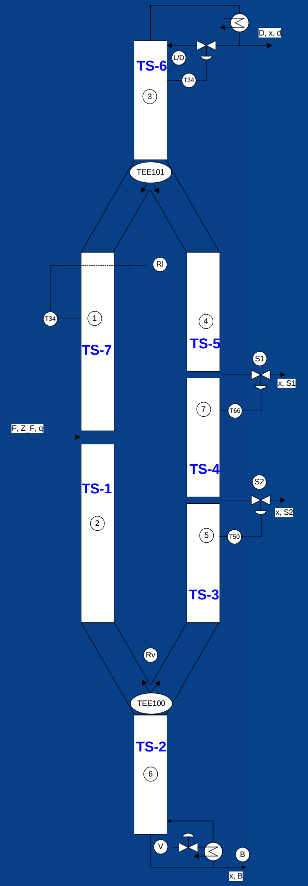






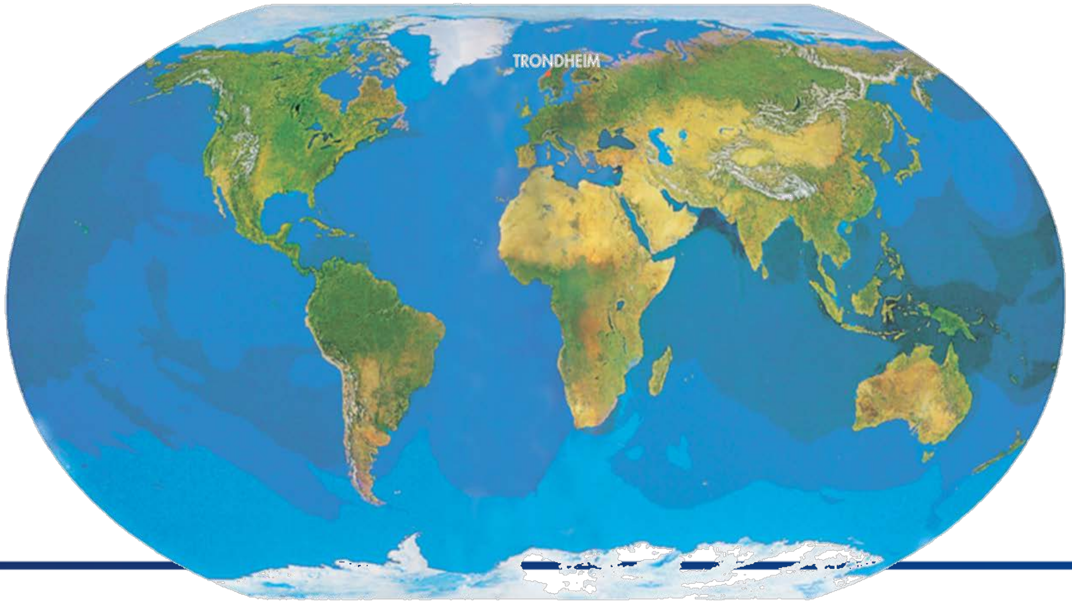


DWC Workshop – NTNU Trondheim – 5-6. October 2023

SINTEF NTNU

The Vmin-method and the need for vapor split control

Ivar J. Halvorsen



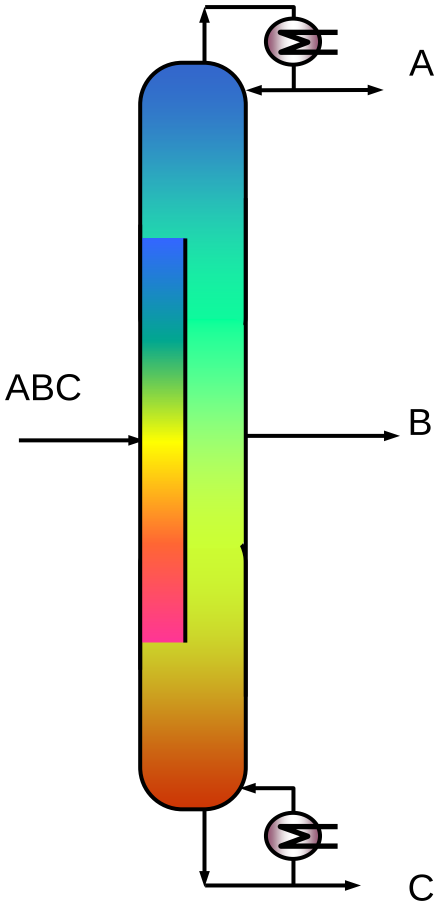
Distillation consumes energy

- 2-5% of the world industry heat consumption
- There is a potential for more energy efficient solutions
- Picture: Fractionation columns at the Snøhvit LNG-plant in Hammerfest

Foto: I.Halvorsen 21.09.2005

The Dividing Wall Column (DWC)

- Here: 3-product arrangement
- Remarkable properties:
  - 3-product DWC **saves 10-30% in BOTH energy AND capital cost**
  - **4-product DWC has potential for more**
- **But, still:**
  - **Challenges in design and operation?**



Content

- Introduction - minimum energy - operation
- Vmin-diagram basics
- Connecting column sections to make a DWC
- DWC operation and flexibility by the Vmin-diagram
- Importance of correct prefractionator operation
- Impact from feed property variations
- 4-product colums – Kaibel column
- When is active vapor split beneficial

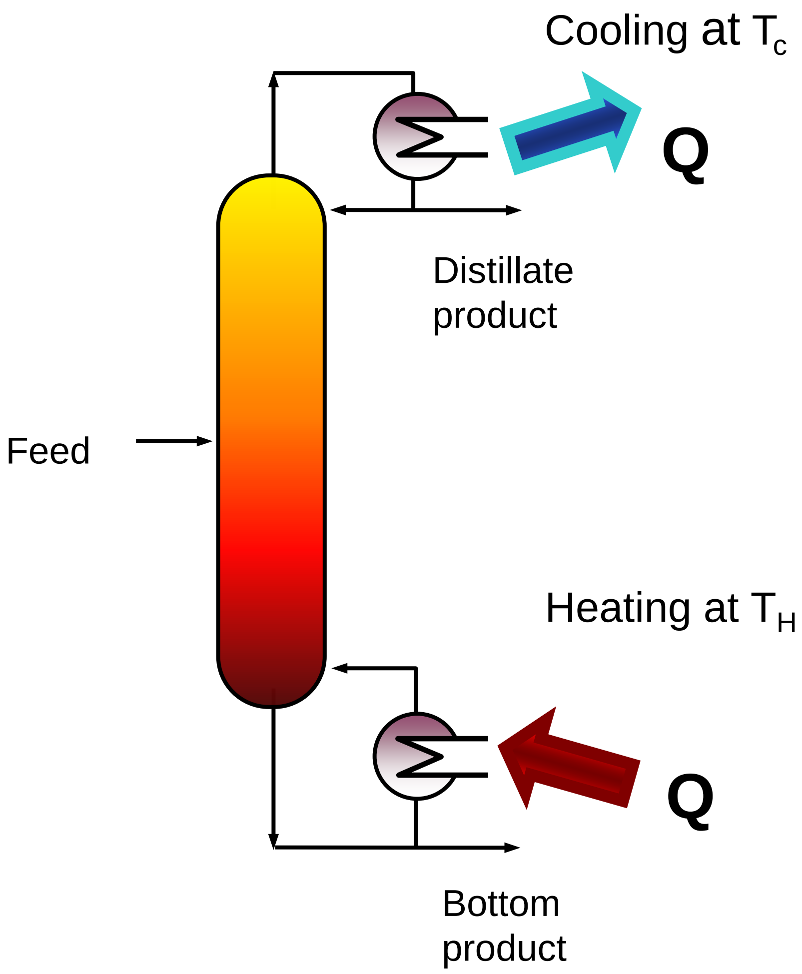
Teoretical minimum energy

An ideal reversible process requires:

$$Q_{\min} = \frac{\Delta S T_C}{1 - \frac{T_C}{T_H}}$$

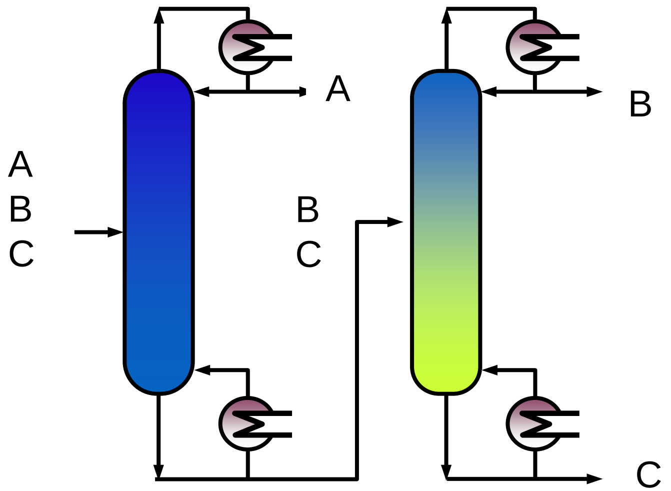
Where entropy of mixing is

$$\Delta S = -\sum_i R x_i ln(x_i)$$

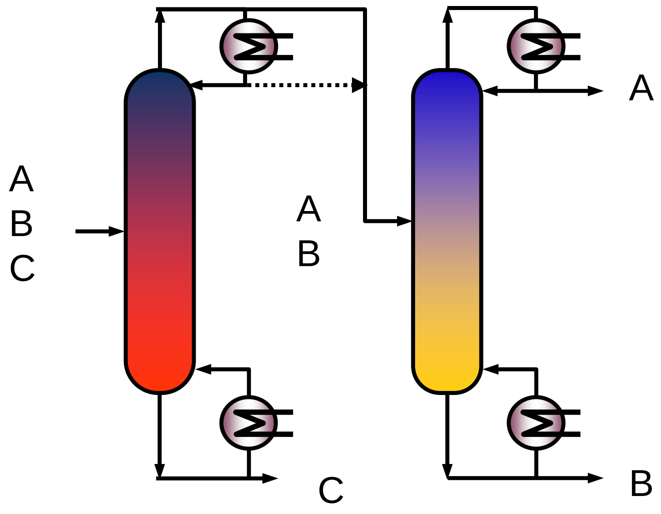


Conventional alternatives for 3-product separation: Sequence of binary columns

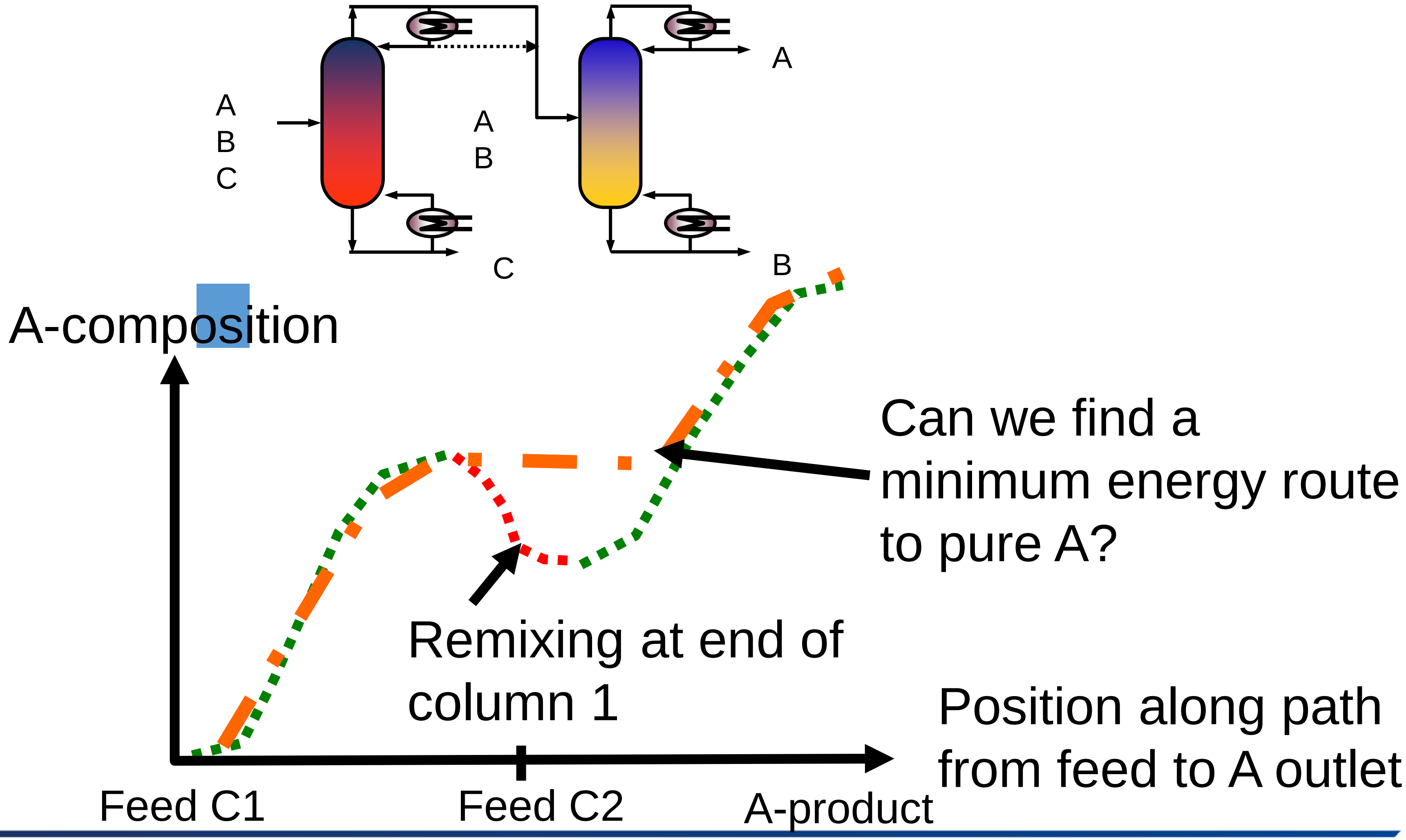
Direct Split: DS



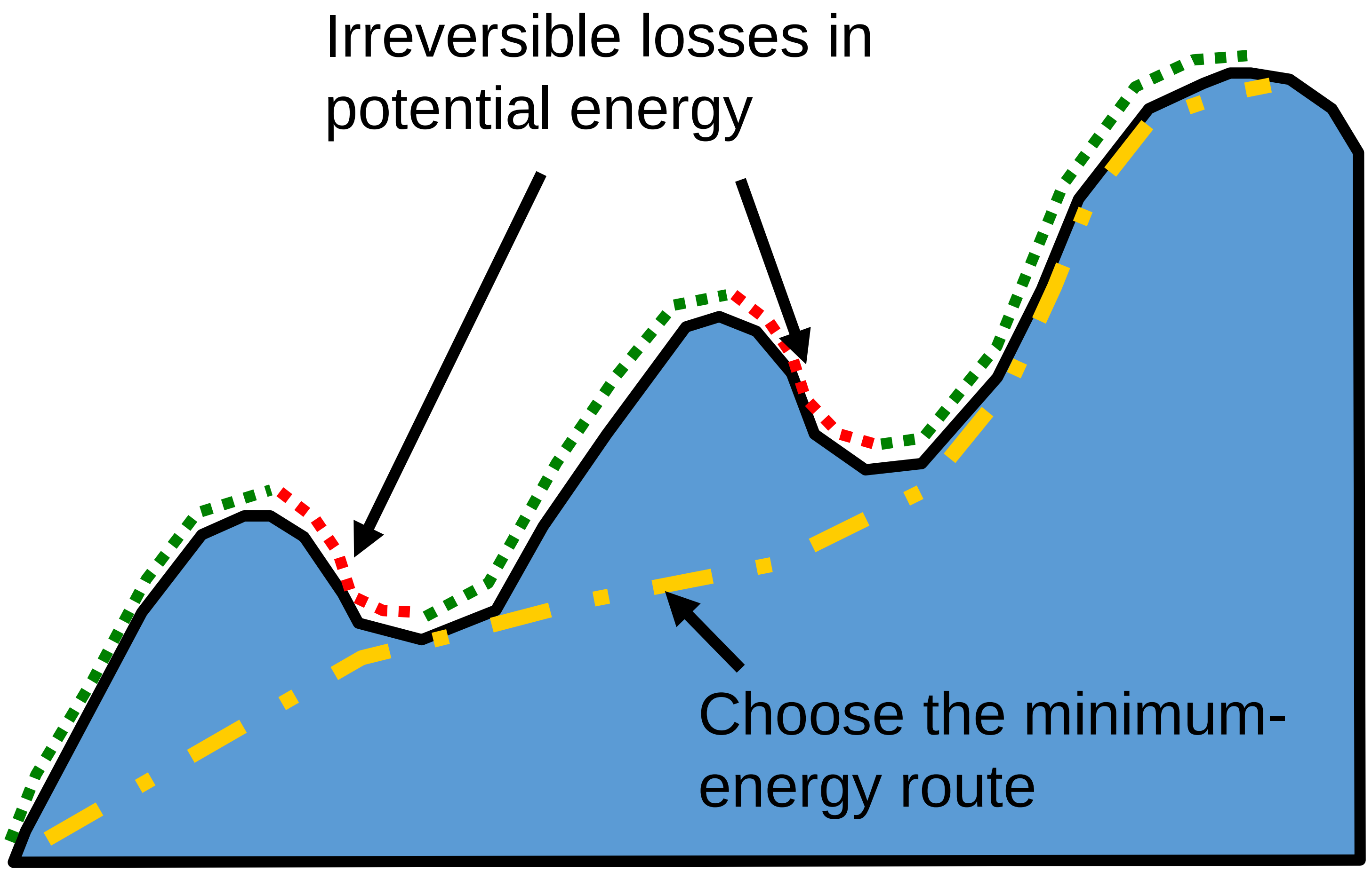
Indirect split: IS



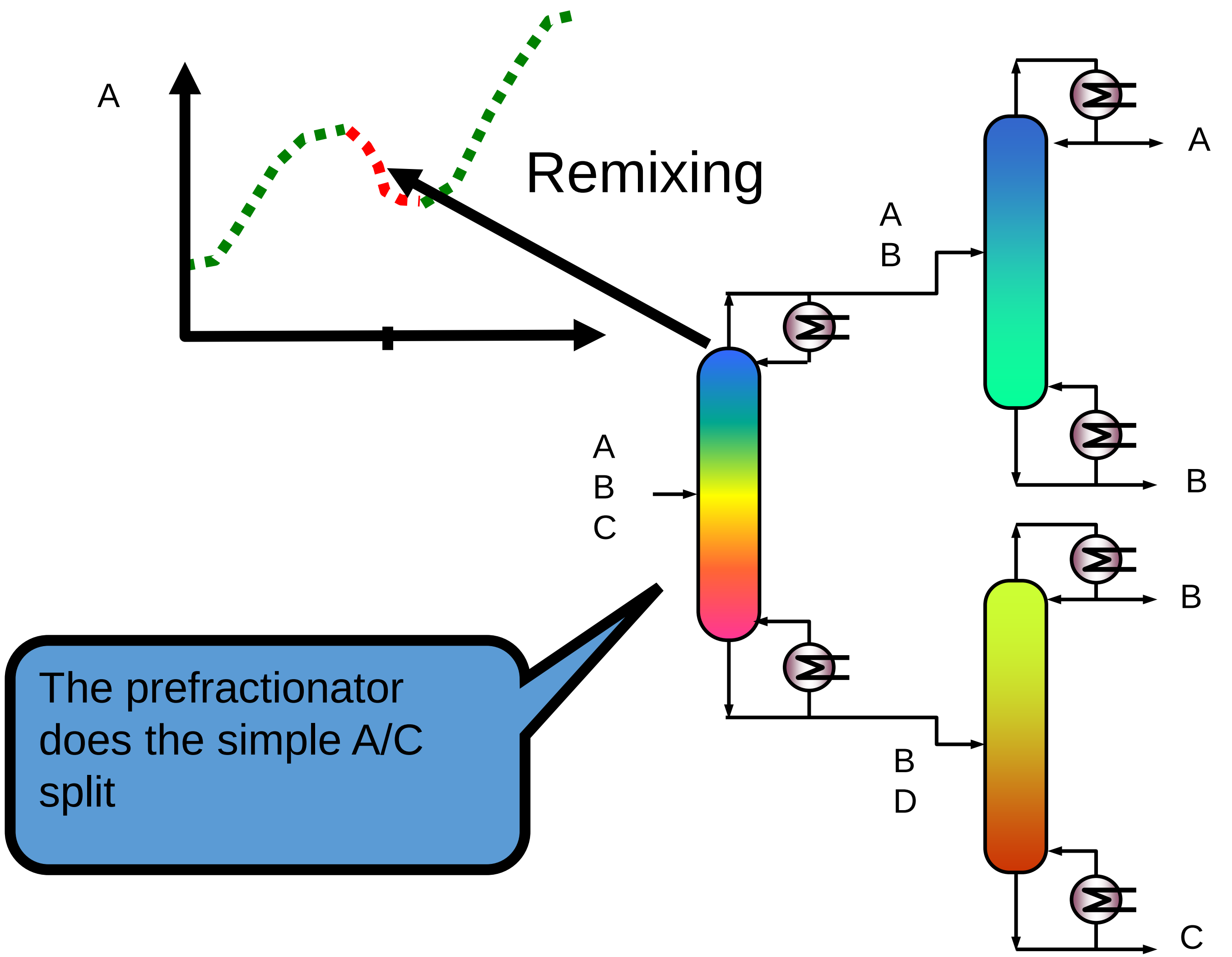
Increasing purity require energy- Mixing gives irreversible loss



Minimum energy path to the mountain top



Prefractionator arrangement

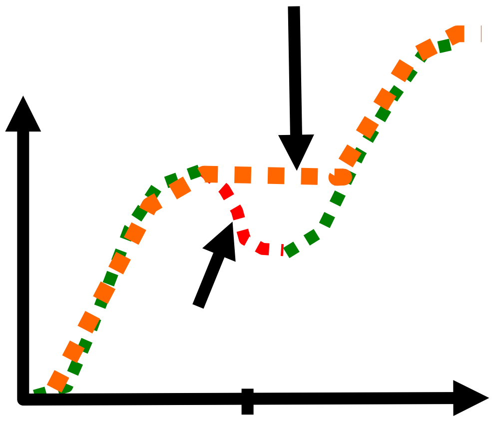


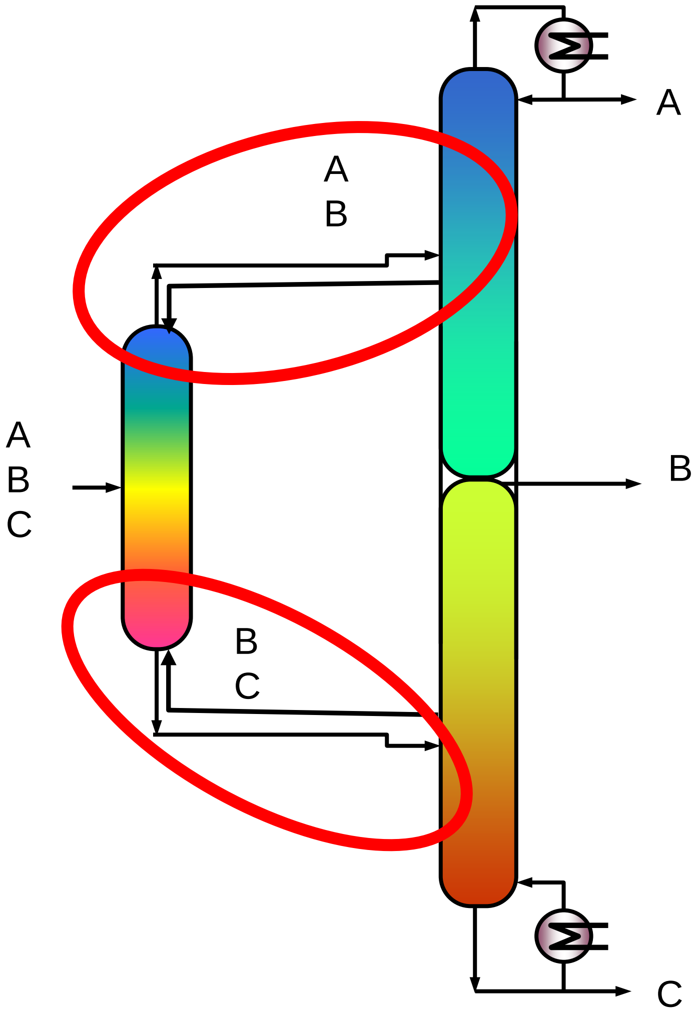
Implementation: DWC

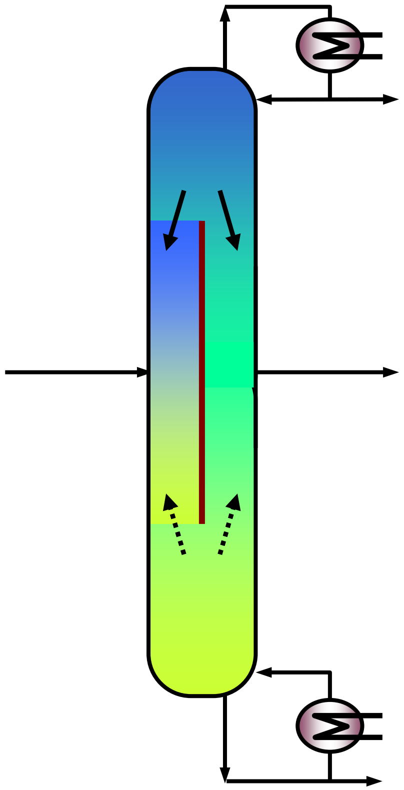
The Dividing wall column

Apply full thermal coupling

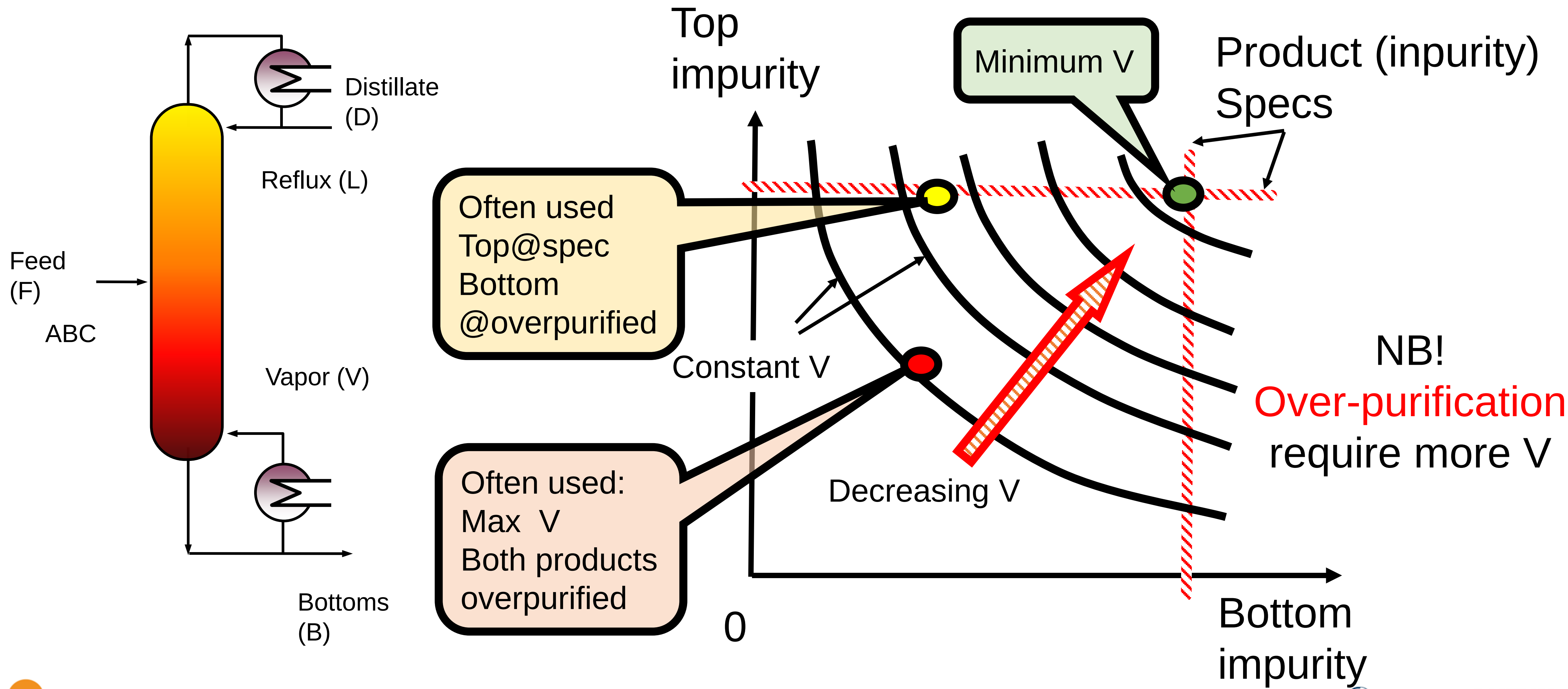
The Petlyuk column eliminates mixing loss at the interconnections.





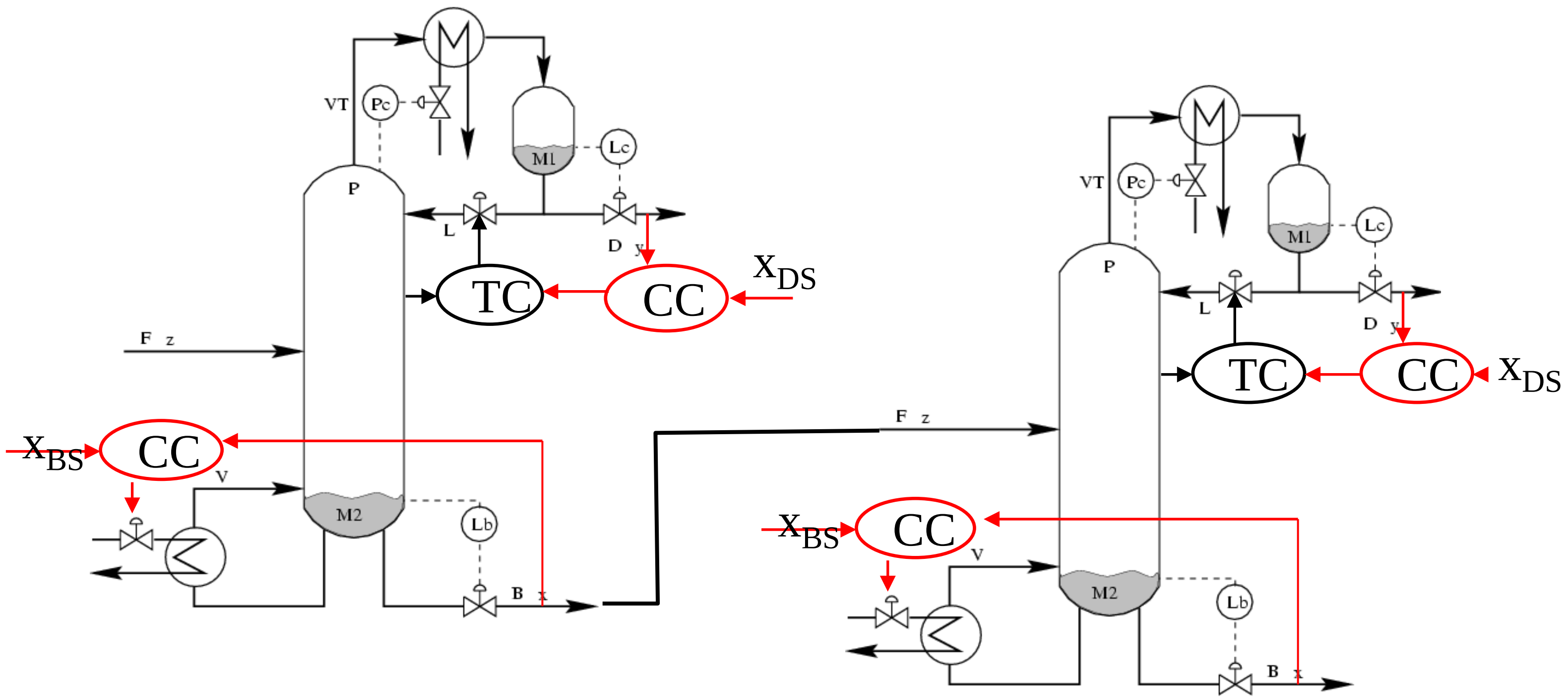


Trivial mimimum energy for binary column



Minimising energy in conventional binary sequence:

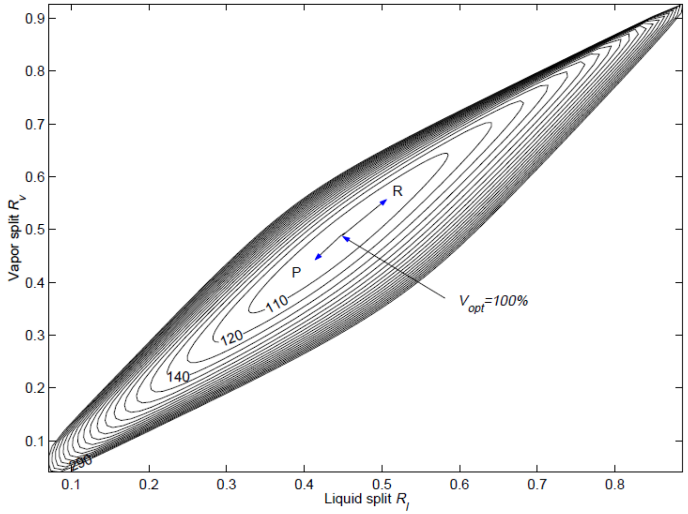
- Two-point composition control for each column =>Minimum energy!



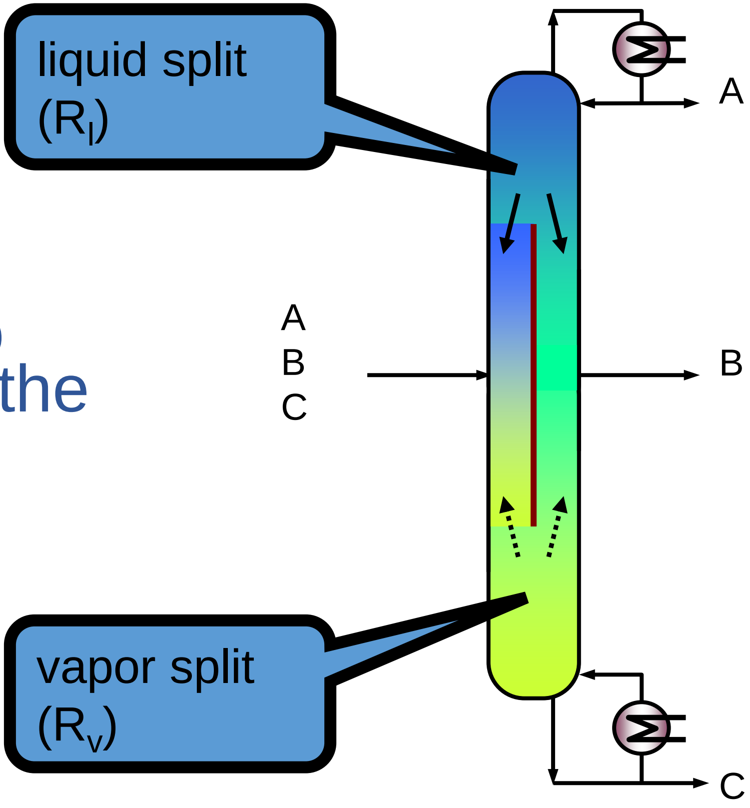
- No need for RTO (Real Time Optimisation)

Why is it not sufficicient just to control products to spec in a DWC?

Energy, V=f(splits)

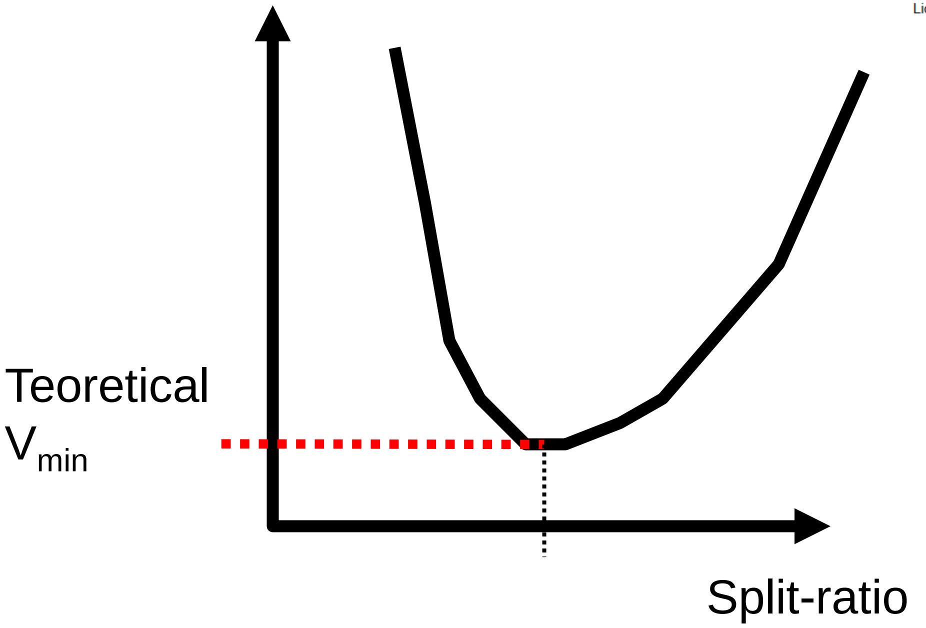


Reboiler vapor requirement depends strongly on the flow splits!



Need a strategy to set/adjust the splits!

Energy, V=f(splits)



Key: Focus on prefractionator operation

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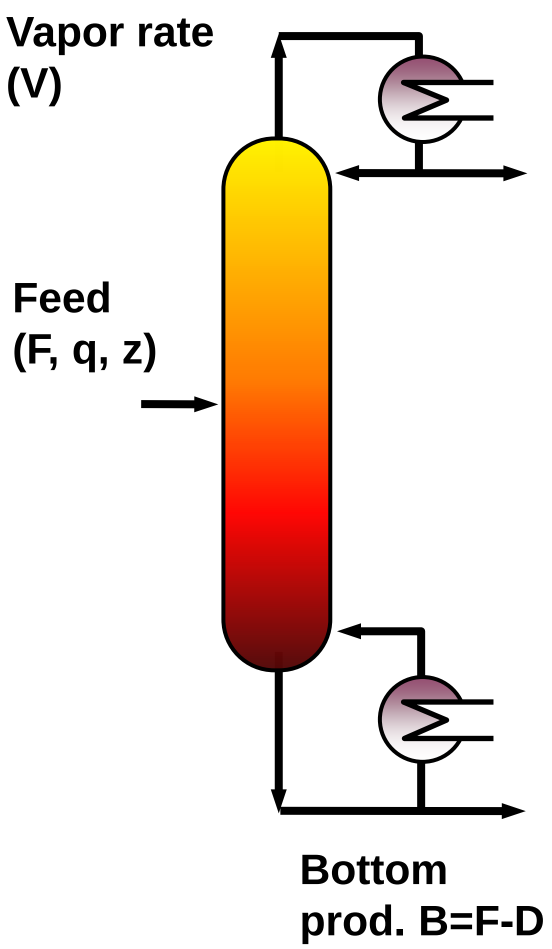
Tool for assessing Multicomponent separation – The Vmin diagram

- Start with assessment for a single binary column
- Extend to 3 products
- Extend to 4 products

How will all components become distributed to products in a single binary column?



Problem:

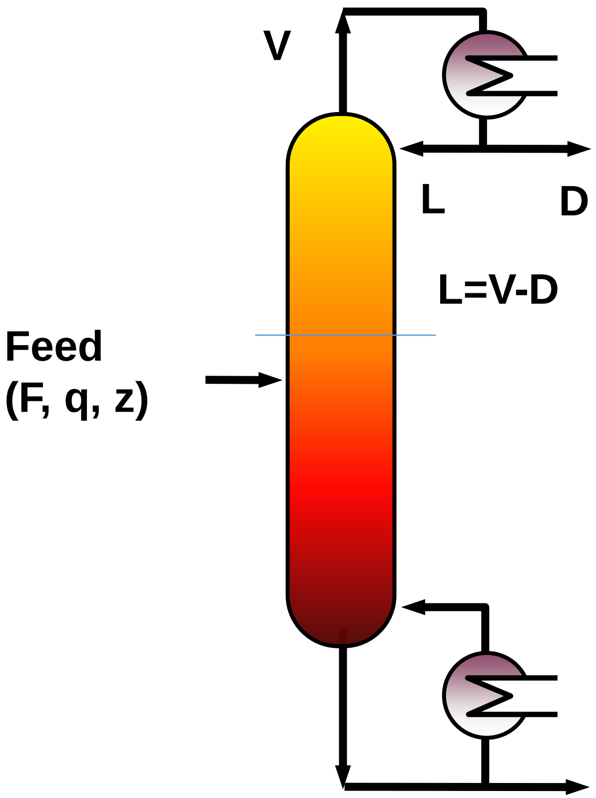
How to set boilup (V) and product flow (D) to obtain wanted recovery?

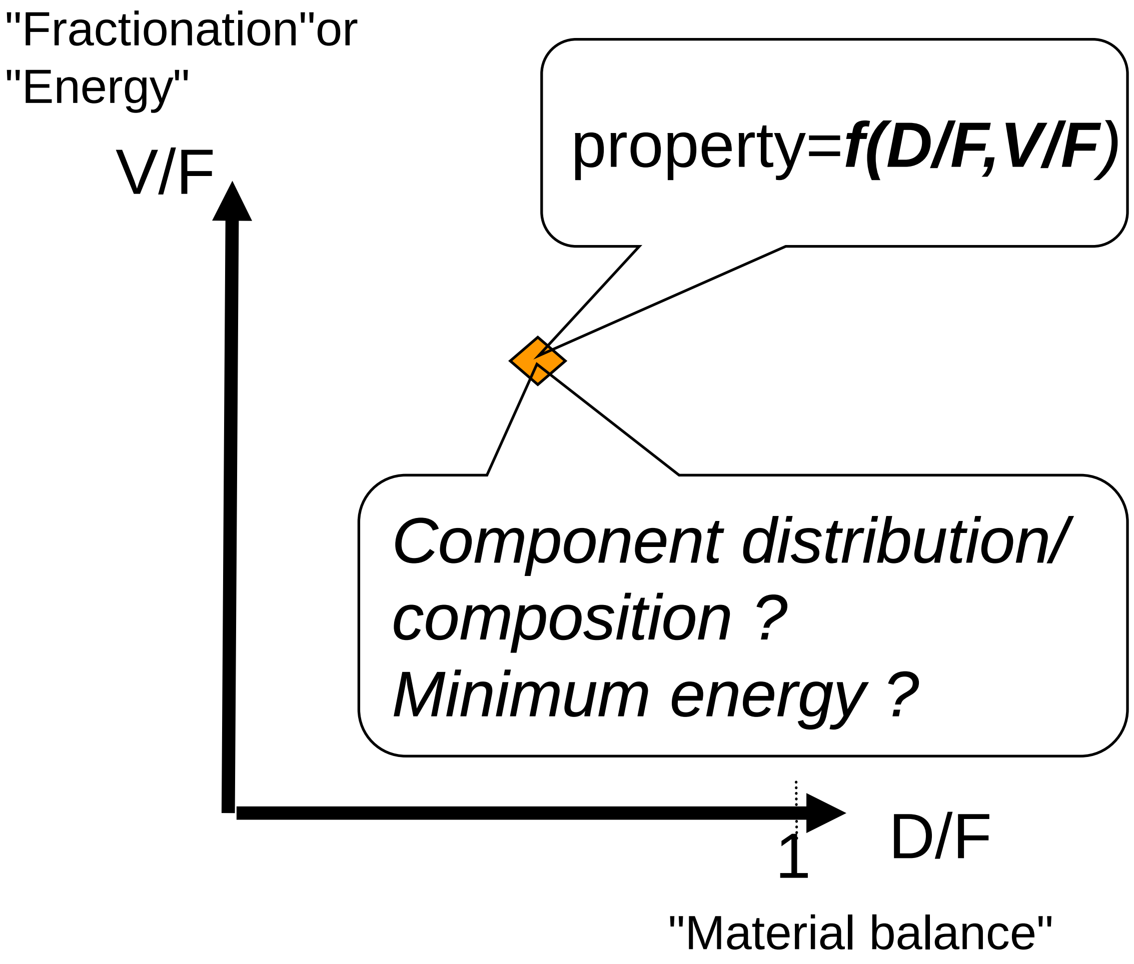
What is Vmin?

Simple for binary feed, but what about general multicomponent feed?

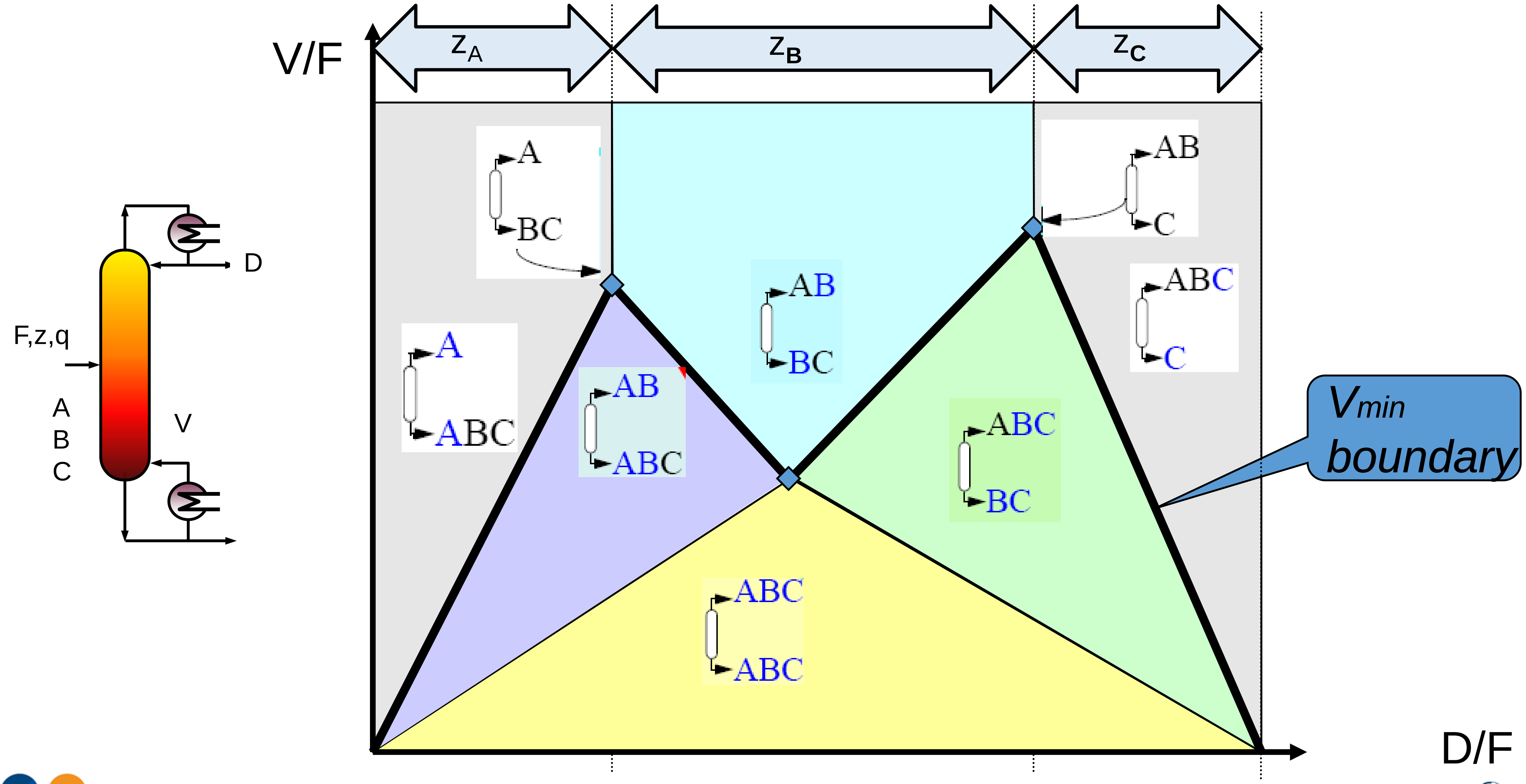
The V_{min}-diagram

Two degrees of freedom only.
Here, choose: D/F,V/F

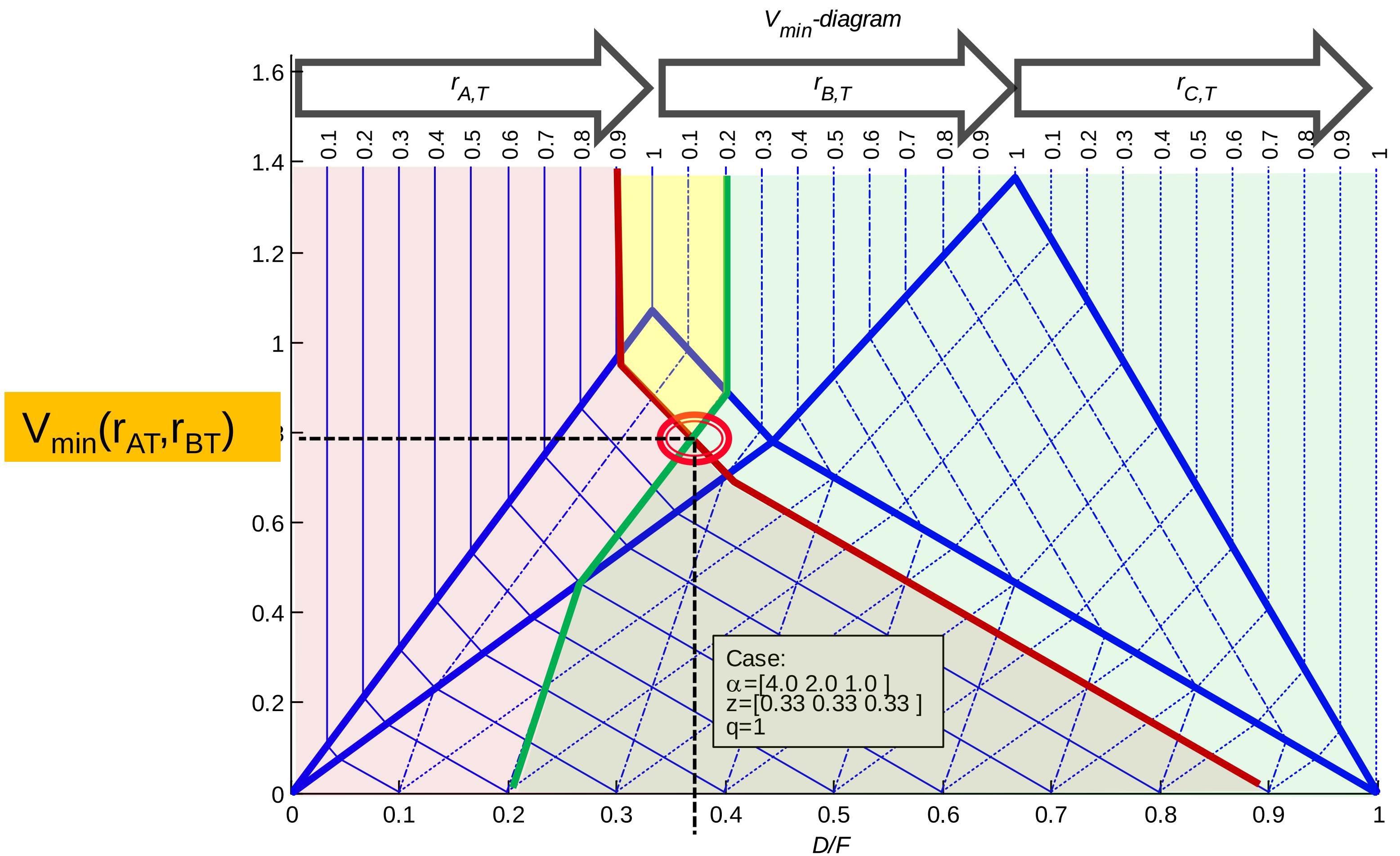




The V_{min}-diagram – 3 component example



The V_{min}-diagram – split specification

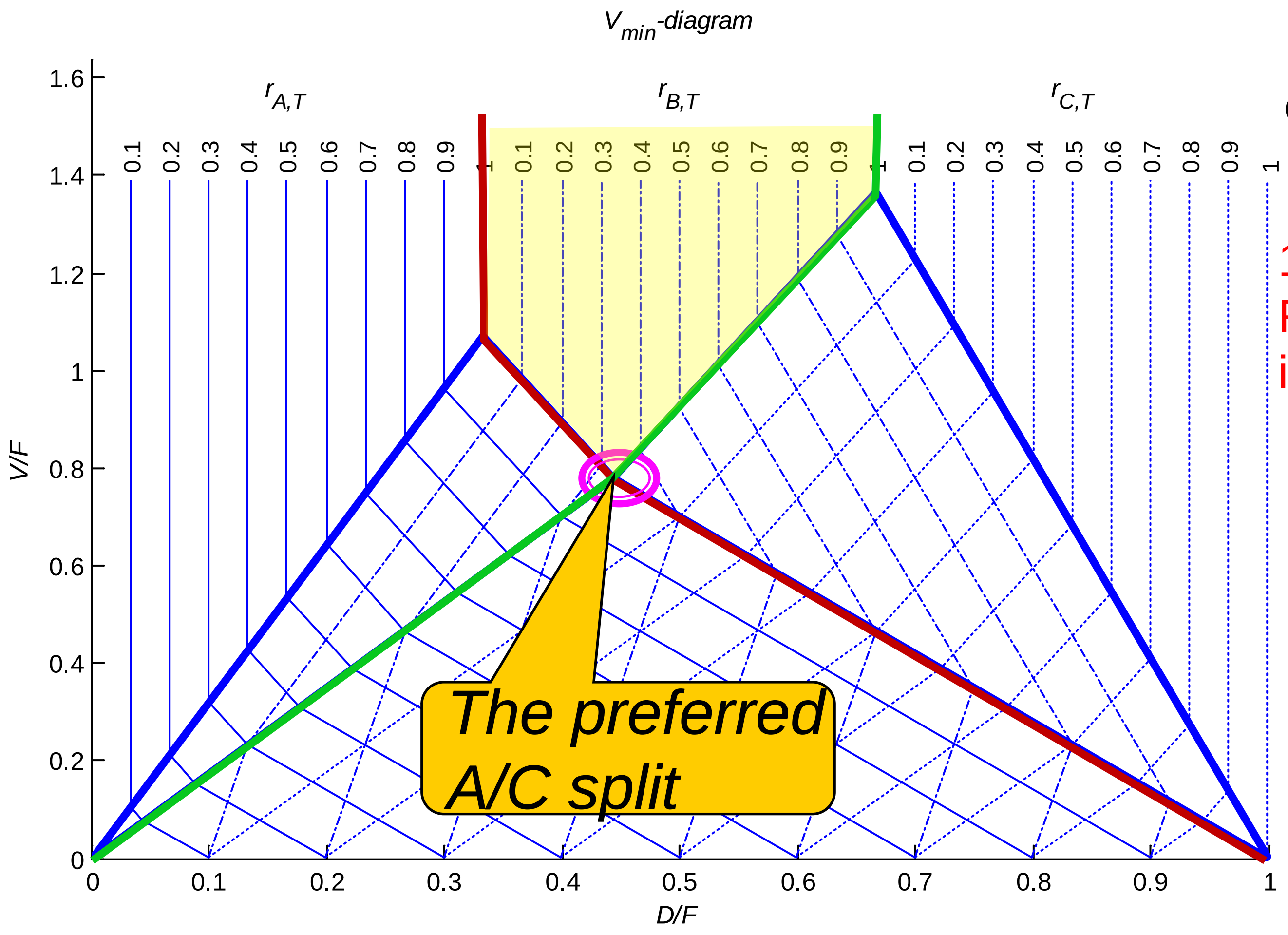


Spec example:

1: Recovery of A in top > 0.9

2: Recovery of B in bottom >0.8 ⇔ Recovery of B in in top <0.2

The V_{min}-diagram – The preferred A/C split



Product Spec example:

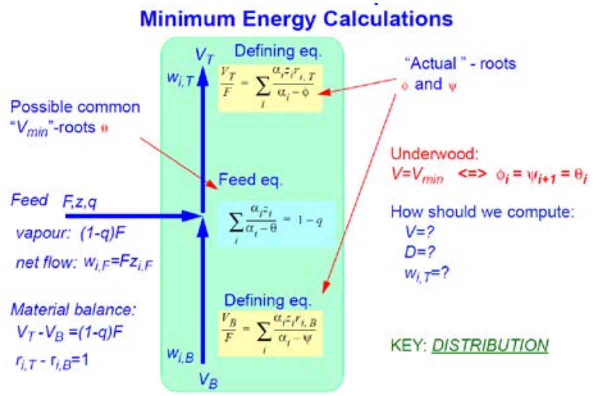
1: Recovery of A in top > 0.99

2: Recovery of C in top <0.01

How to obtain the Vmin-diagram

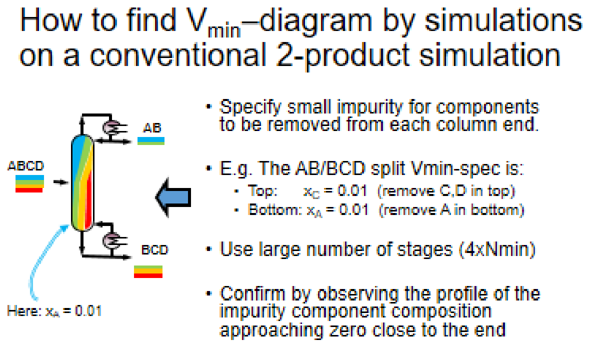
A: Ideal assumptions:

- Use analytic functions based on Underwood equations (See Halvorsen and Skogestad 2003) (Solved in milliseconds)
- Based on the following feed data only:
  - Molar fractions
  - Relative volatility (or K-values),
  - liquid fraction



B: Real mixtures:

- Do one simulation for each point (A/BC, AB/C, AB/BC)
- Or – setup a simple sequence with special heat connection (will show later)
- Use N~4Nmin (Asses each section individually)
- Use sensible impurity specifications to define distribution boundaries. (Same spec. as used for calculating Nmin)

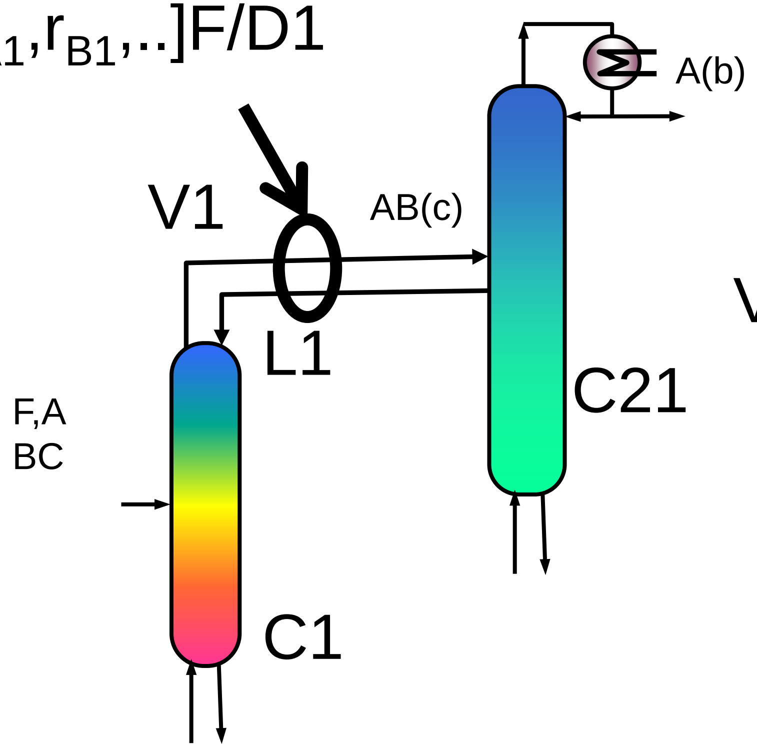


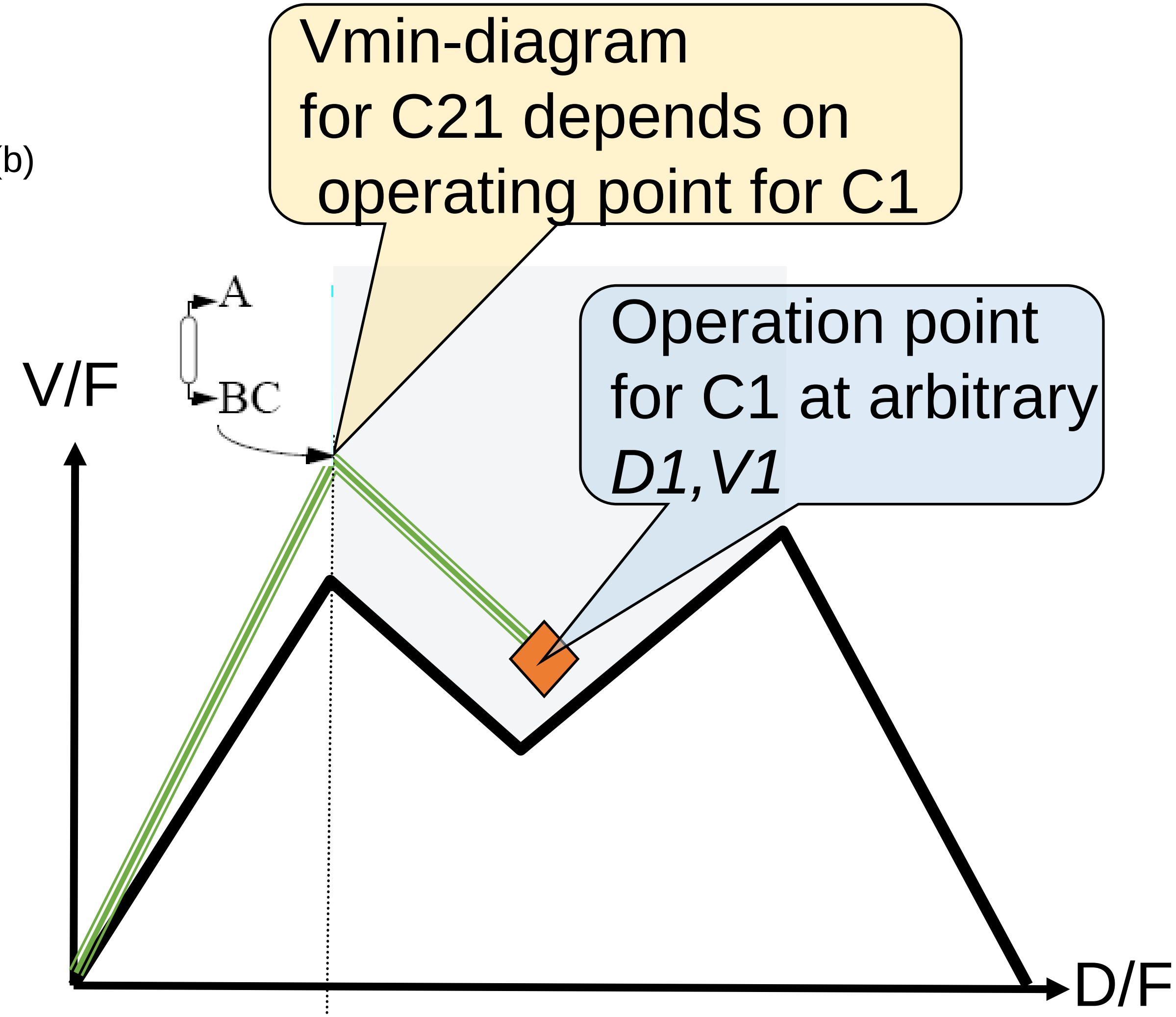
The V_{min}-diagram – for thermally coupled columns

$F21 = D1 = V1 - L1$

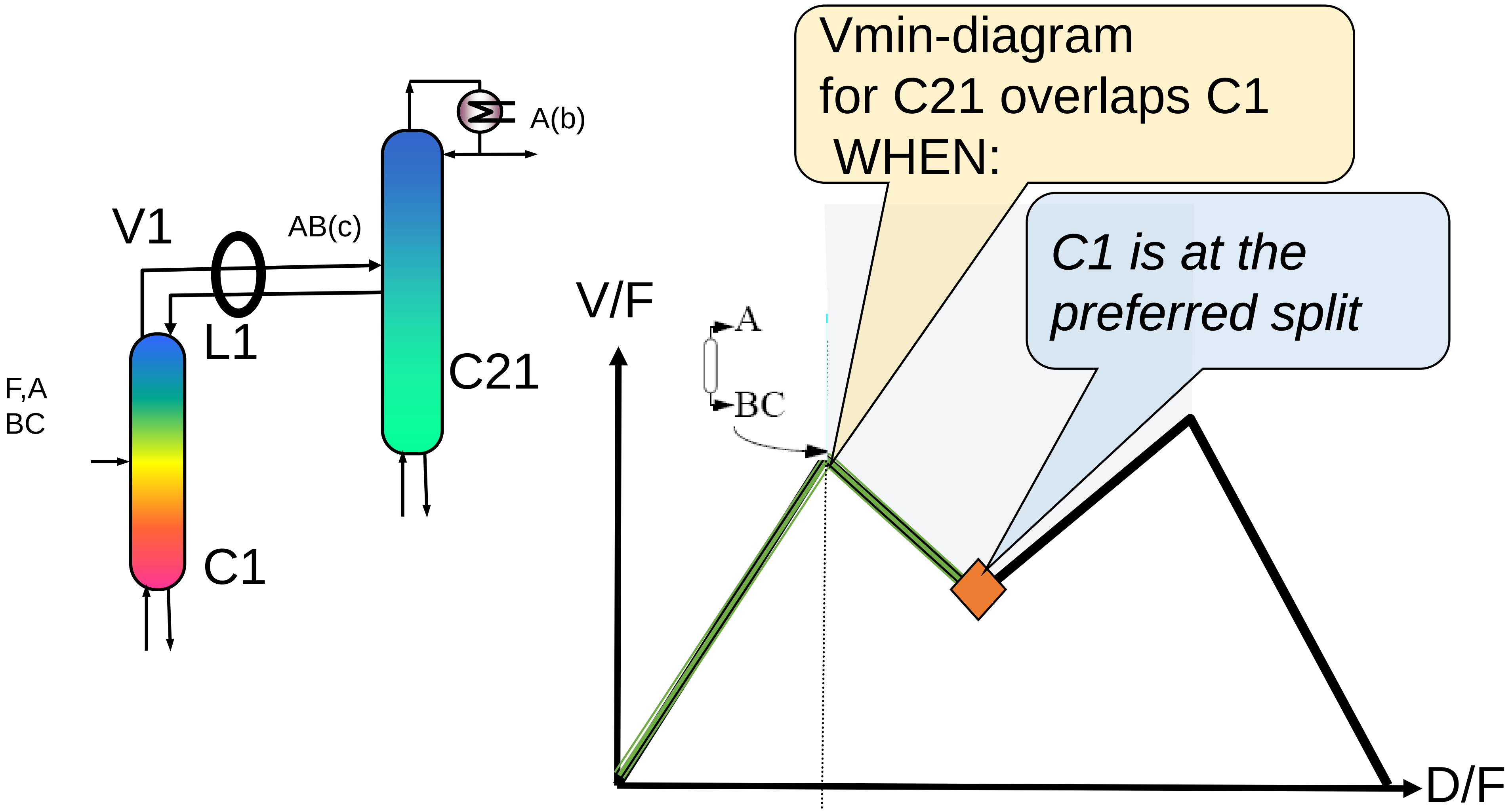
$q21 = -L1/D1$

$z21 = [r_{A1}, r_{B1}, ..]F/D1$

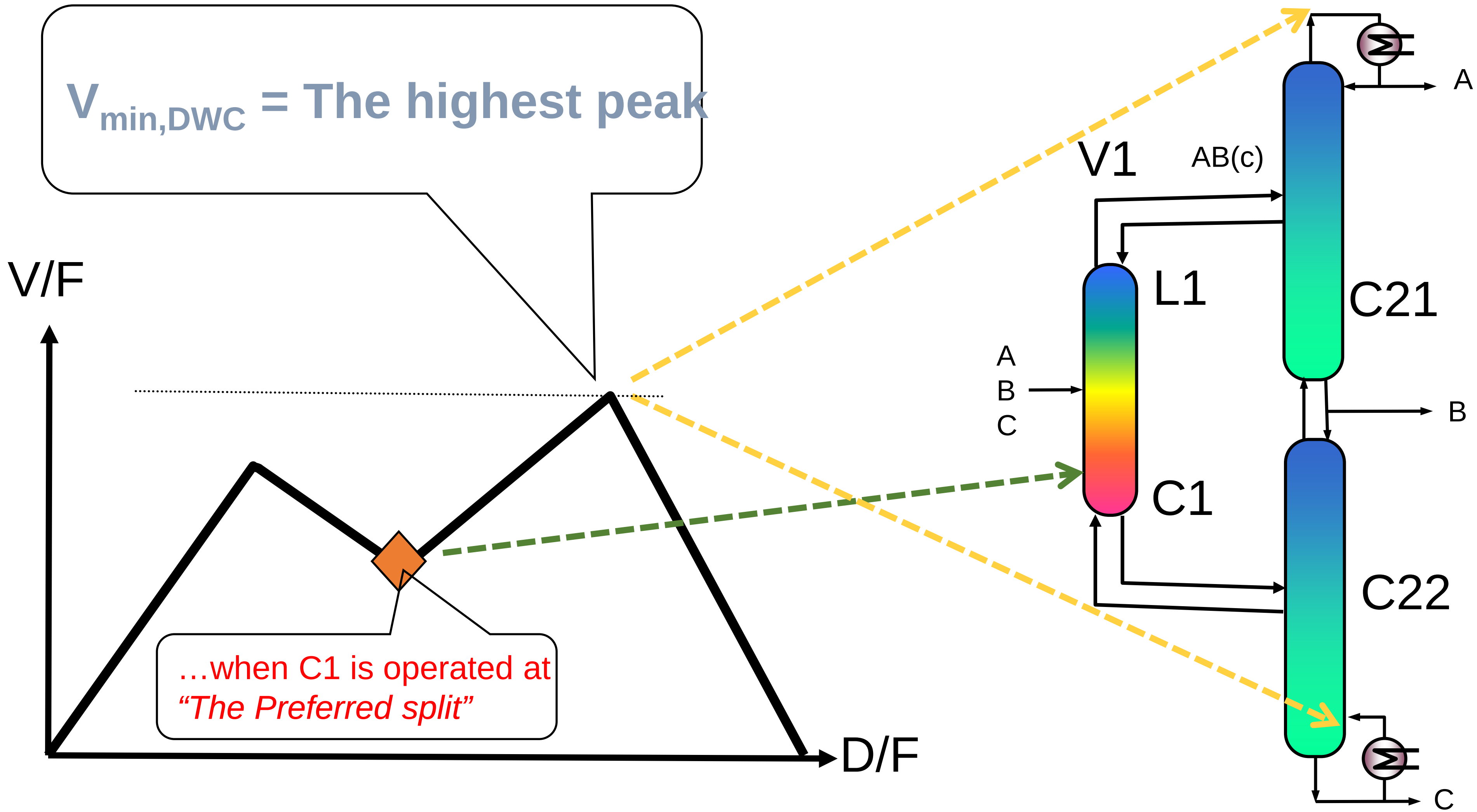




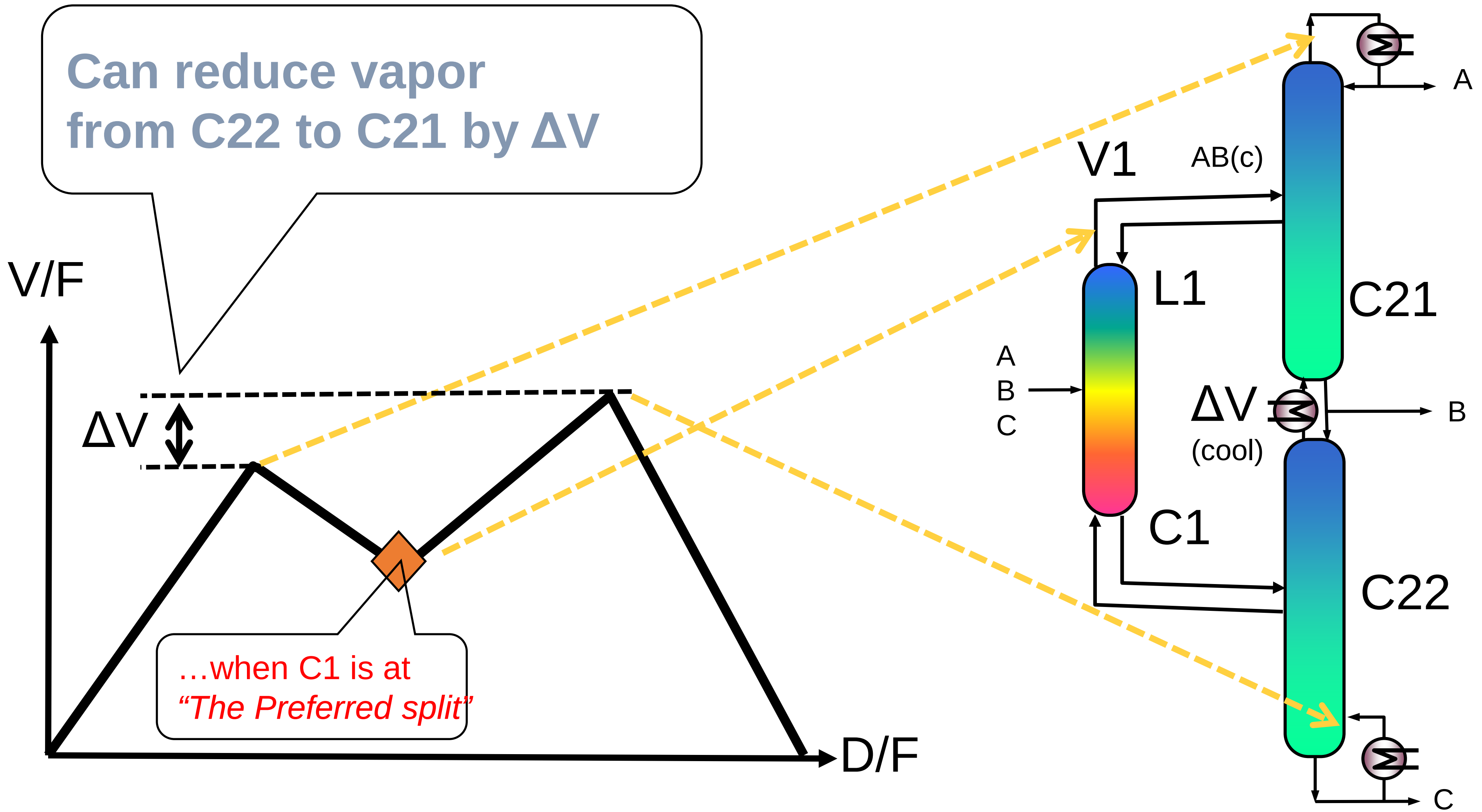
The V_{min}-diagram – for thermally coupled columns



The V_{min}-diagram contains – optimal DWC flow rates

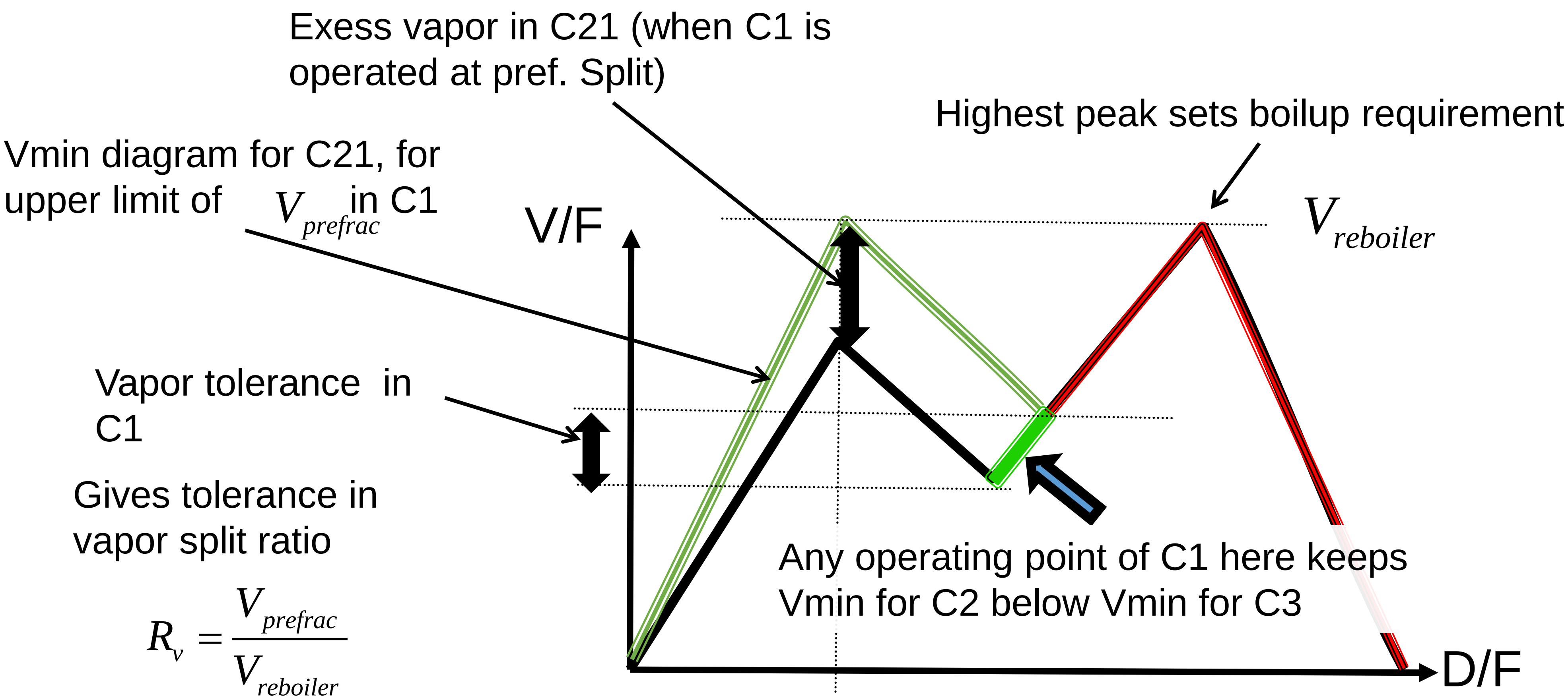


The V_{min}-diagram – Heatex at Sidestream location



The V_{min}-diagram – shows clearly DWC flexibility

Key: Different height of the peaks gives tolerances in operation and design



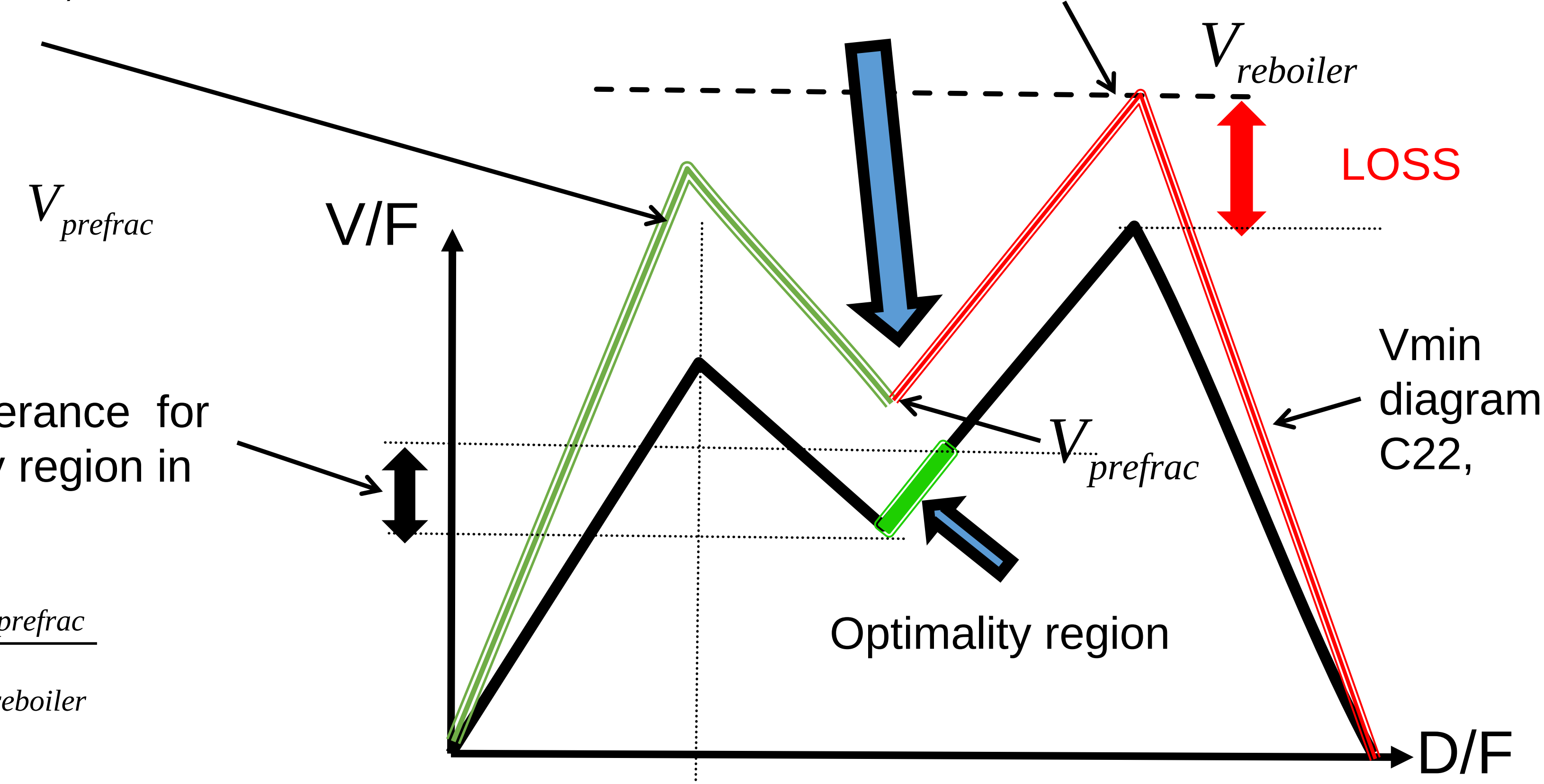
$$R_v = \frac{V_{prefrac}}{V_{reboiler}}$$

The V_{min}-diagram – How to operate prefractionator

Key: Very important to operate prefractionator in optimality region

Vmin diagram for C21,

Suboptimal operation of PF increases required boilup in main column!



Vapor tolerance for optimality region in PV (C1)

$$R_v = \frac{V_{prefrac}}{V_{reboiler}}$$

The V_{min}-diagram – How do the splits move the operating point in the prefractionator

Liquid split $R_L = \frac{L_{prefrac}}{L_{condenser}}$

Vapor split $R_v = \frac{V_{prefrac}}{V_{reboiler}}$

Prefractionator flowrates

$$D_{prefrac} = R_v V_{reboiler} - R_l L_{condenser}$$

$$V_{prefrac} = R_v V_{reboiler}$$

$$L_{condenser} \approx V_{reboiler} - D_{condenser}$$
$$D_{prefrac} = V_{prefrac} - L_{prefrac}$$

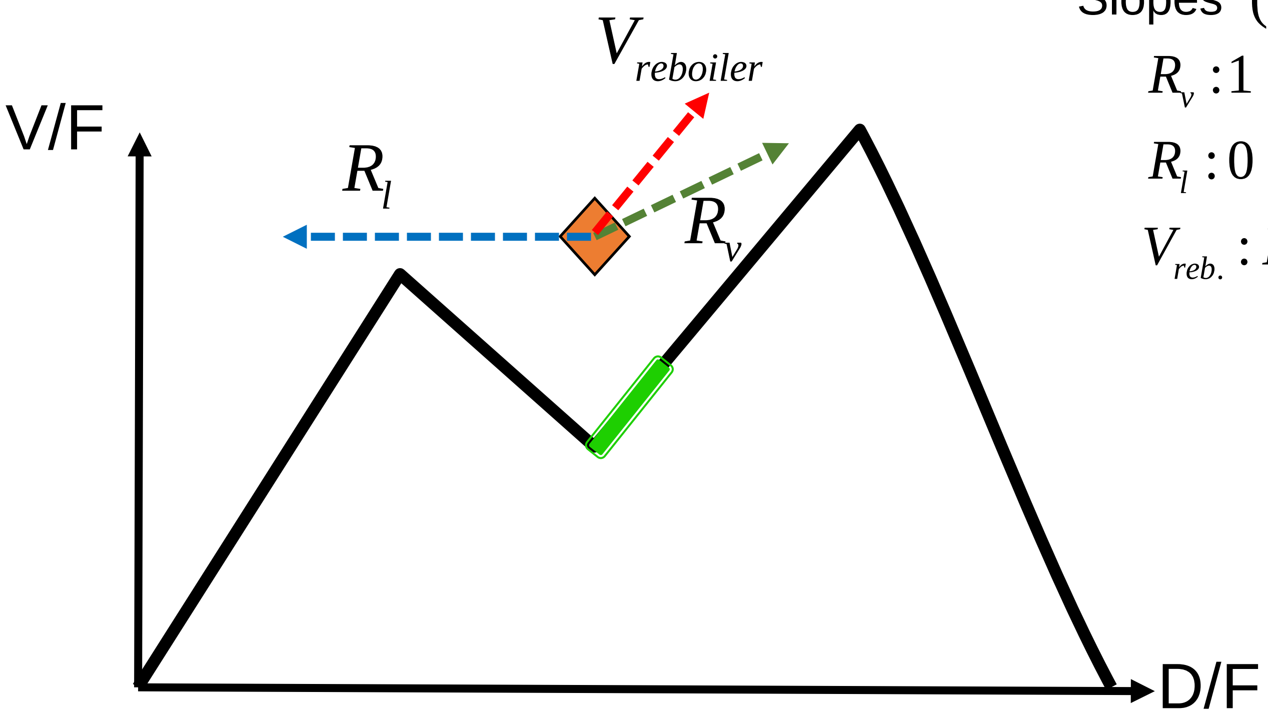
How operating point is moved by increase in $R_v, R_l, V_{reboiler}$

Slopes $(\Delta V / \Delta D)$

$R_v : 1$

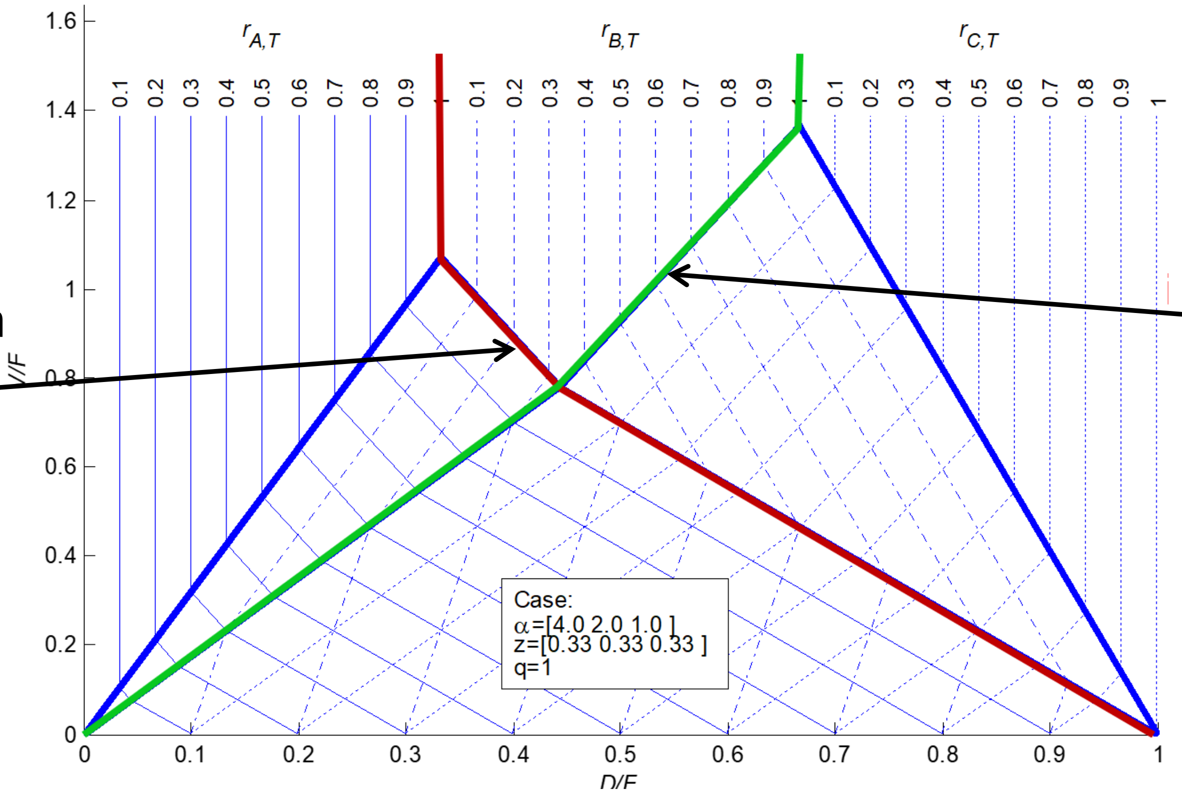
$R_l : 0$

$V_{reb.} : R_v / (R_v - R_l)$



How to recognize that operation is close to a distribution boundary

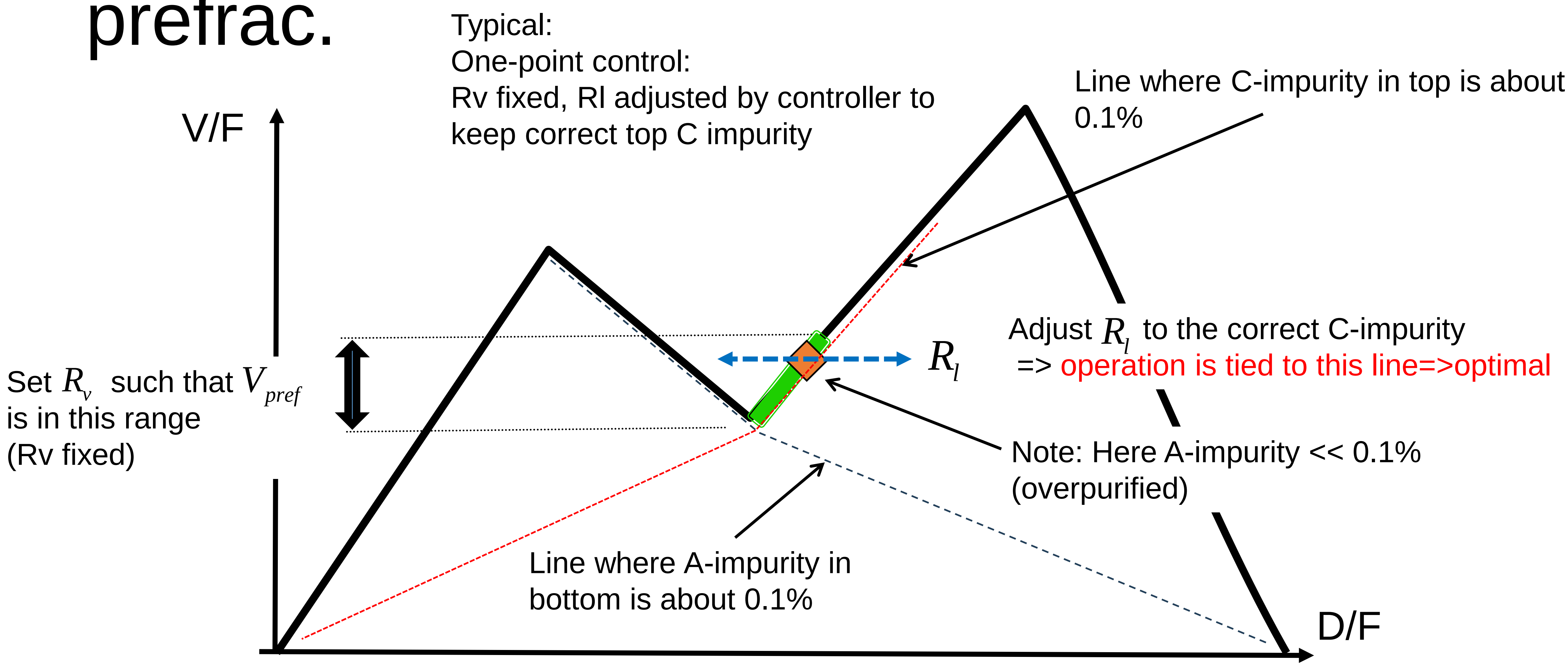
Line where A-impurity in bottom is small (e.g. about 0.1%)



Line where C-impurity in top is small (e.g. about 0.1%

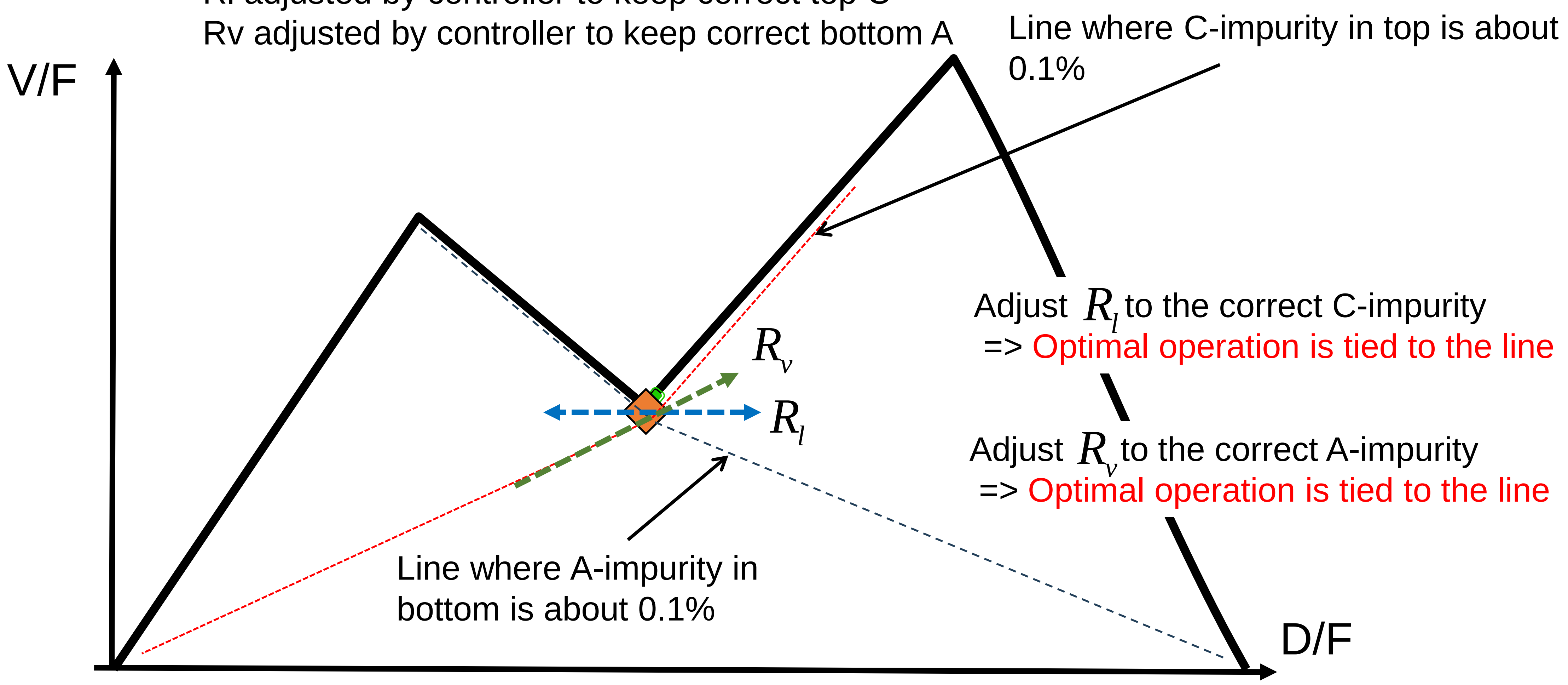
Distribution boundary: A component is at the limit of disappering in one end – this is characterised by a small impurity – but not overpurification!

How to select controlled variables in prefrac.



How to select controlled variables in prefrac.

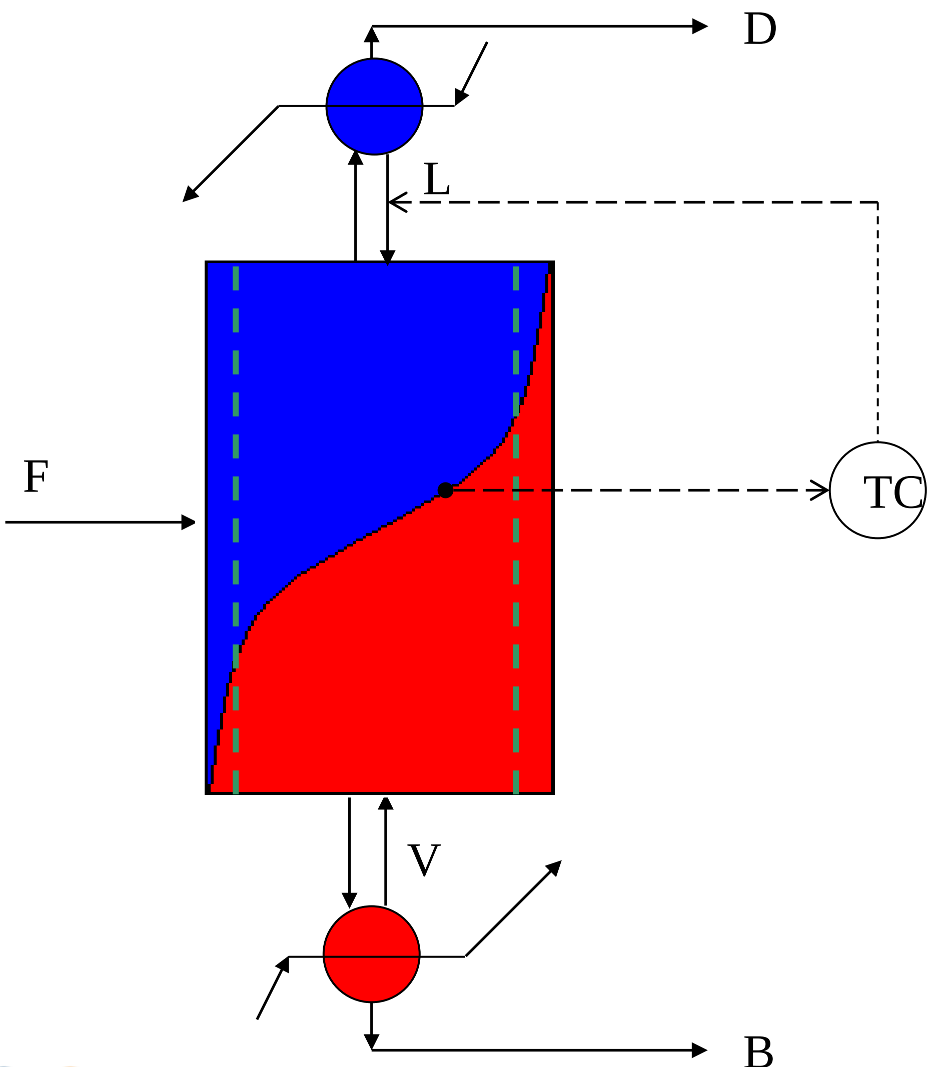
Want preferred split => RequireTwo-point control:
Rl adjusted by controller to keep correct top C
Rv adjusted by controller to keep correct bottom A



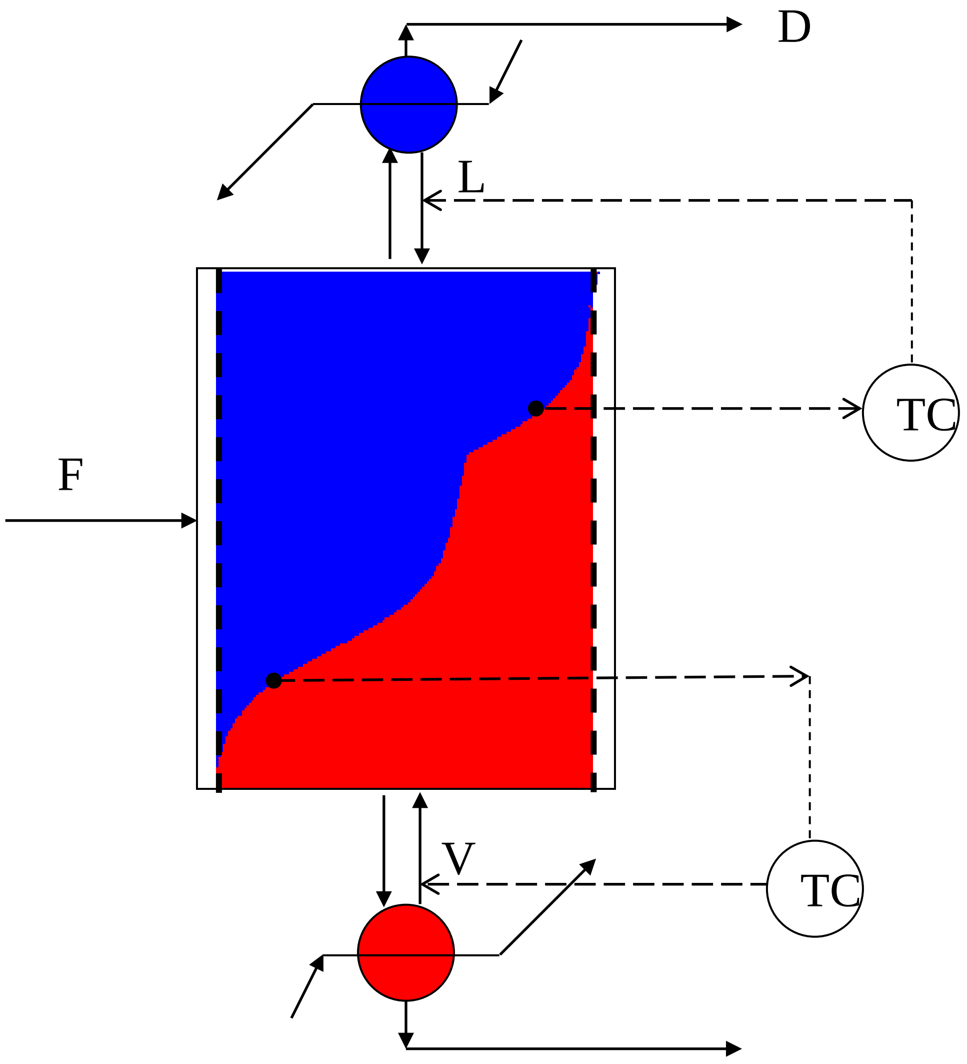
Practical control: Use temperatures

- Direct composition control is not common
- Use temperature profile to infer composition estimate
- May also use combination of temperature points

One-point control



Two-point control

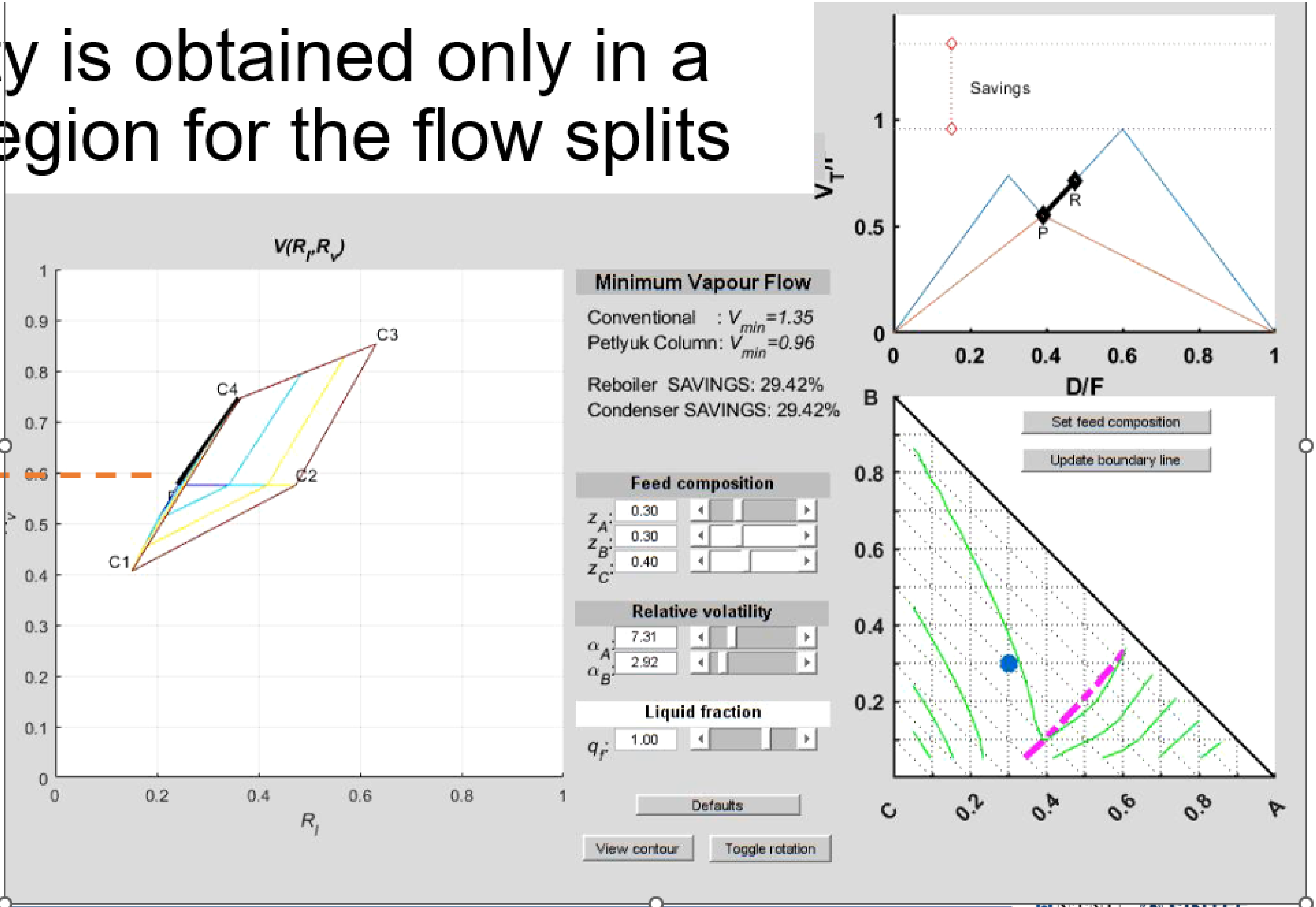


When is active vapor split beneficial ?

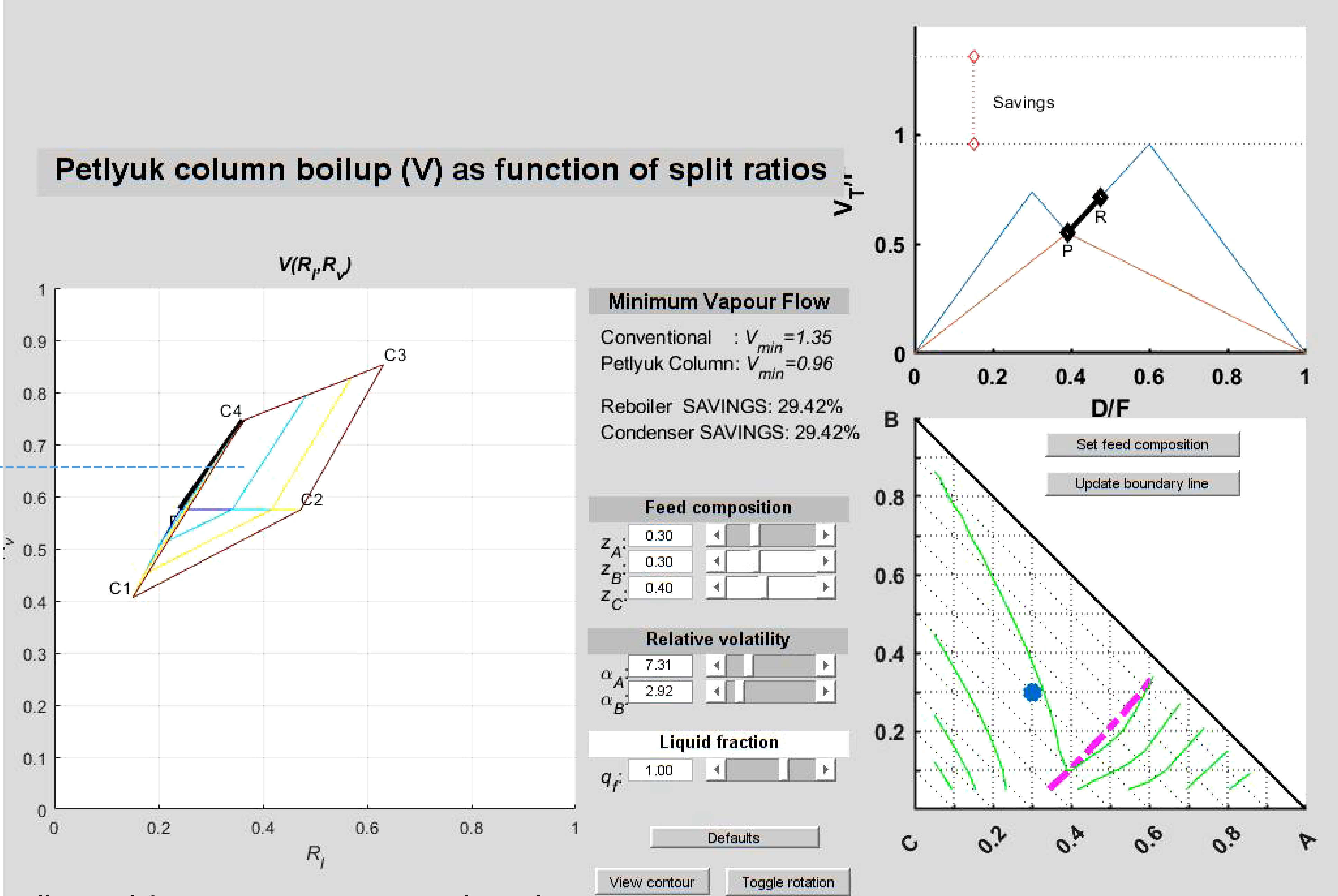
Optimality is obtained only in a narrow region for the flow splits

How manipulation of feed liquid fraction can move the optimal vapor- and liquid-splits

Ex: Fix Rv=0.6



Avoid uncontrolled vasriations in feed liquid fraction



May fix Rv

Adjust Rl from 0.25-0.38 to track optimum

About the need for on-line adjustment of Vapor split

- Most (all) industrial 3-product DWCs in the world use fixed Rv
- This is OK for the majority of cases.
- E.g.: Vmin-diagram peaks are of different height.
- And when changes in feed properties (composition and liquid fraction) are limited

- And, if some reduced energy saving is accepted
- Or if the some sidestream impurity is accepted

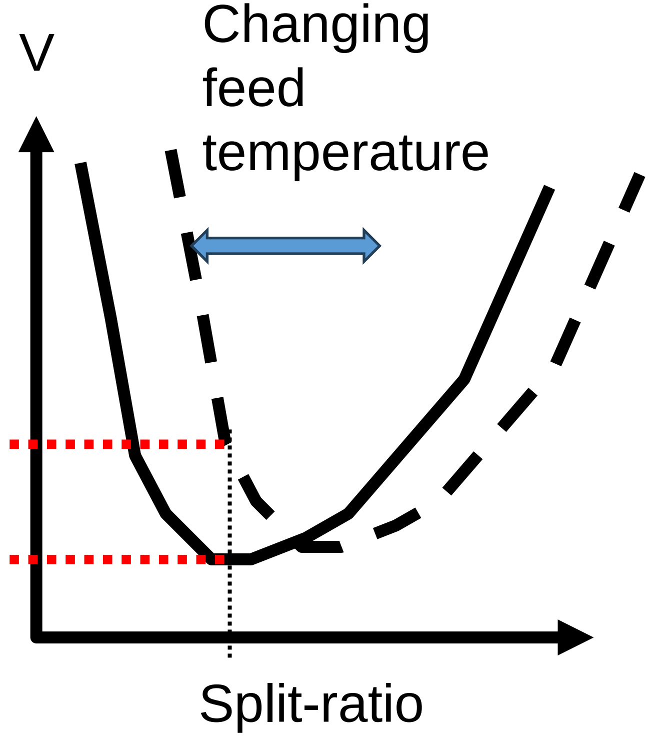
Use active vapor split when:

- The peaks in the Vmin diagram are of similar height, and/or:
  - When significant changes in feed composition is expected
  - When full energy saving is required
  - When sidestream impurity is undesirable

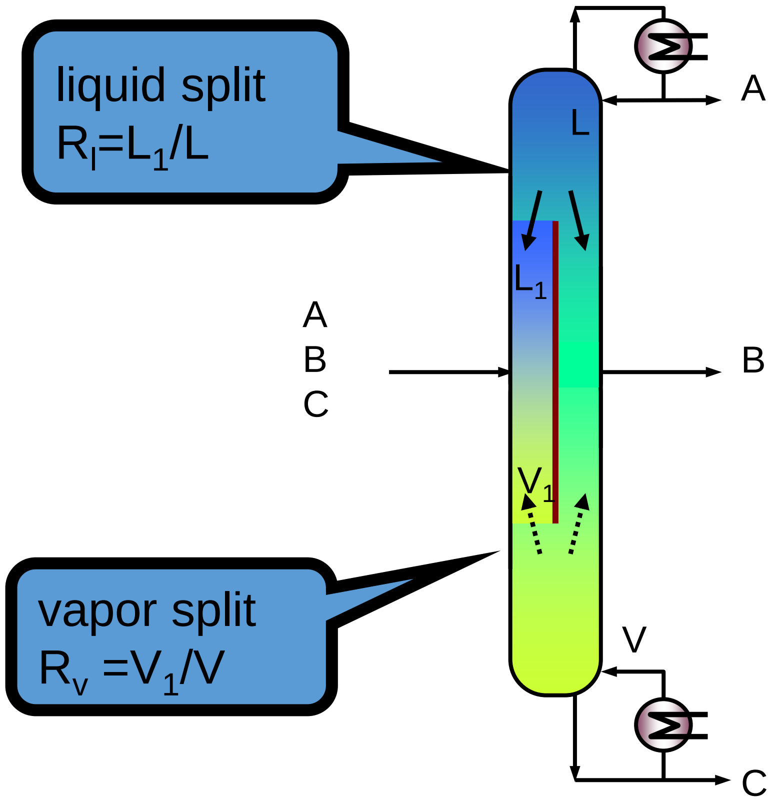
(Assume that number of stages is selected to enable the desired purity.)

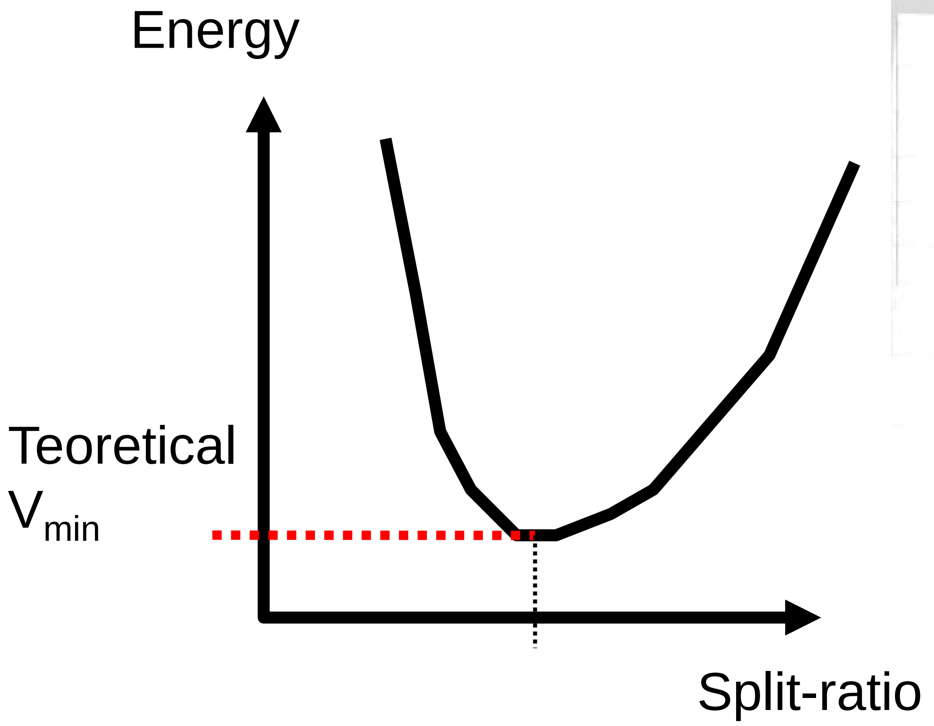
Adjust the feed temperature:
The hidden "vapor split adjustment"

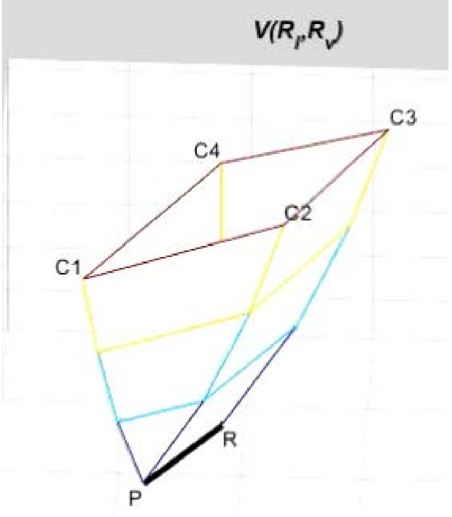
- The optimality region is strongly affected by Feed liquid fraction
- Uncontrolled Feed temperature variations are severe disturbances
- Thus: It is strongly recommended to control feed temperature to a setpoint
- The feed temperature controller setpoint becomes an additional degree of freedom!
- The impact is not by affecting the internal split, but to MOVE the whole OPTIMALITY region such that the actual column split becomes INSIDE the optimality region!



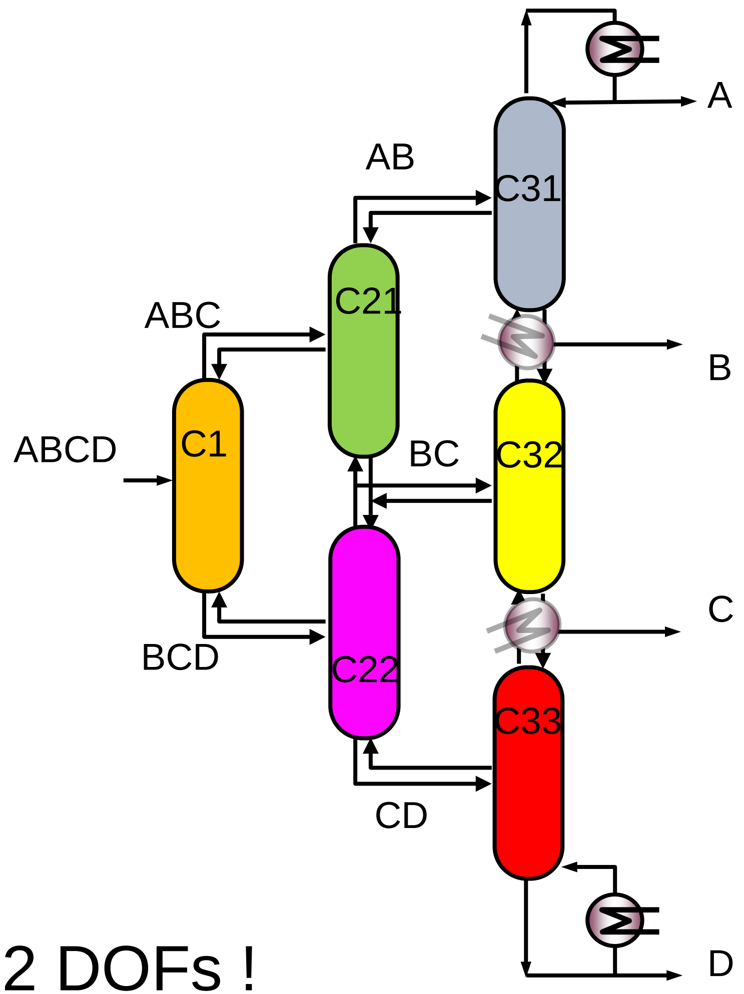
Important for obtaining savings in practice:
Adjust/Control the splits. At least one!



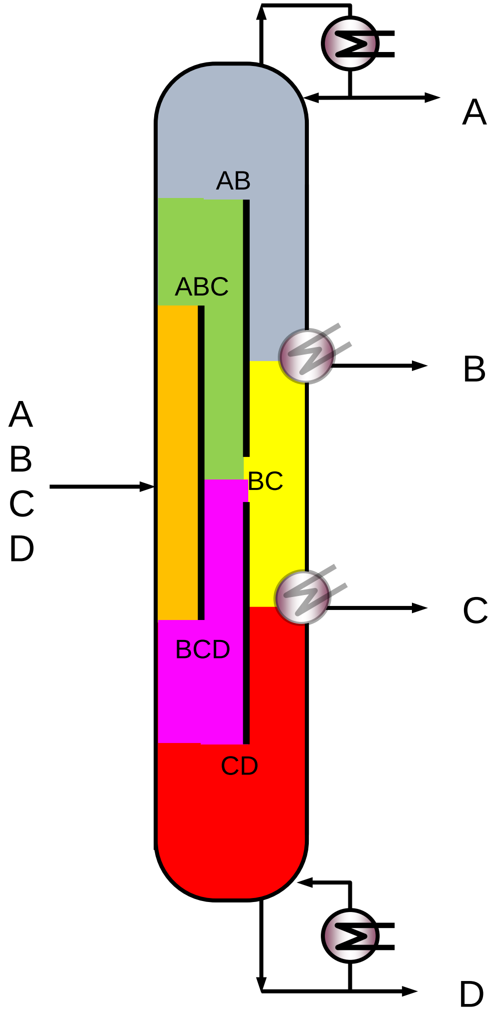




Generalized 4-product DWC

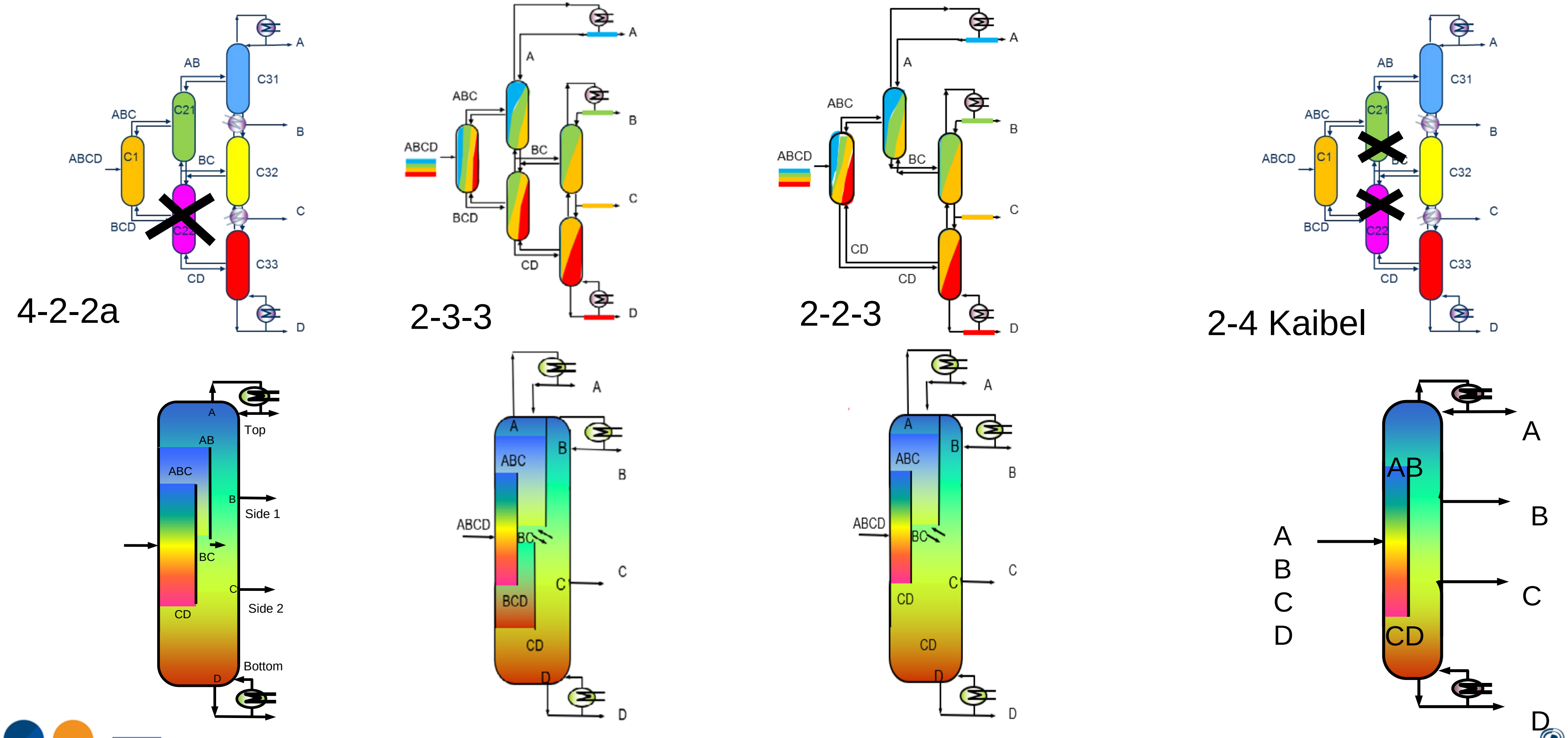


The Vmin-diagram can be used to identify possible simplifications for specific classes of feeds



12 DOFs !

Several different 4-component arrangements can be obtained by simplifying the general arr.



Can reach same savings as full 4p structure (for some feeds)

Less savings

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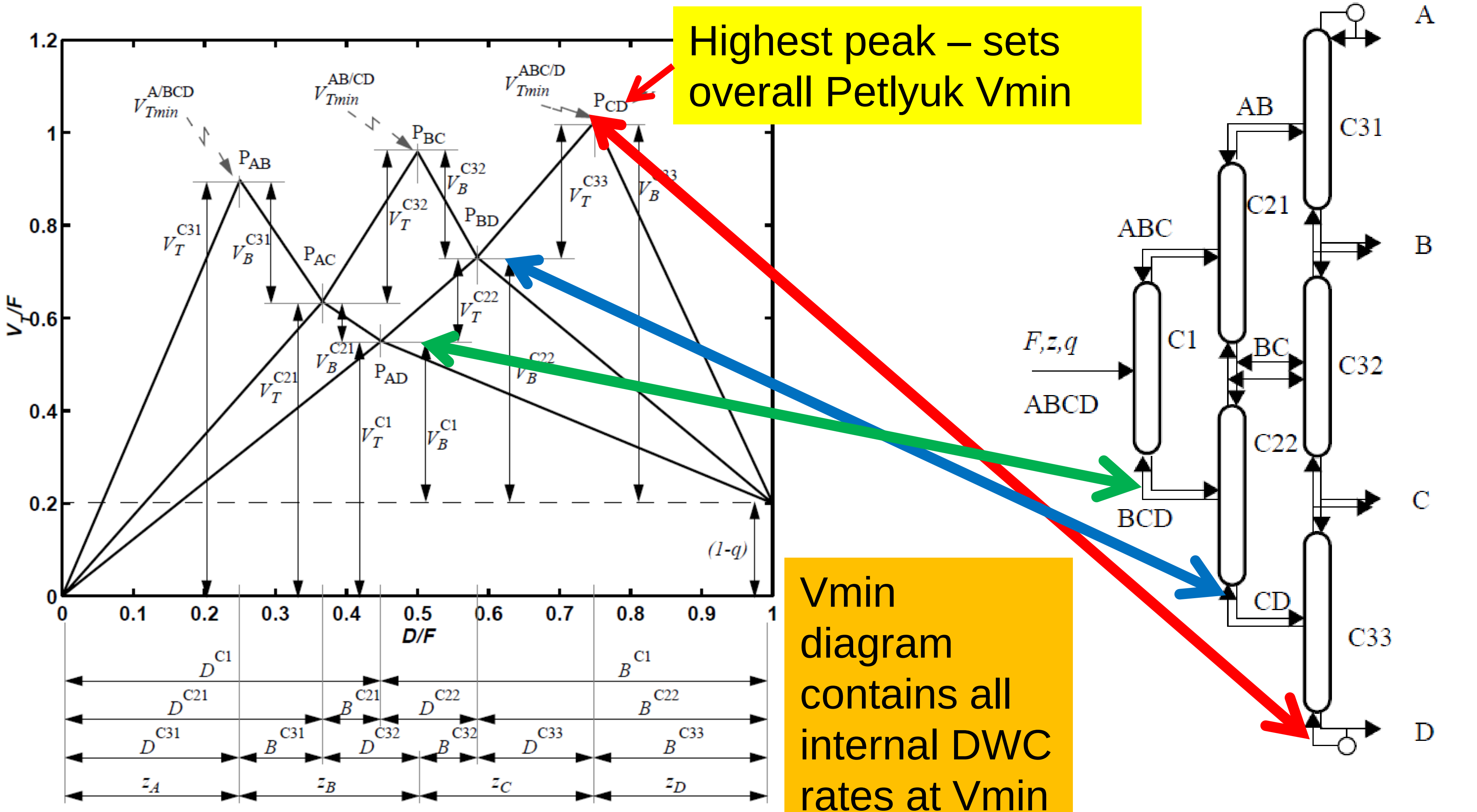
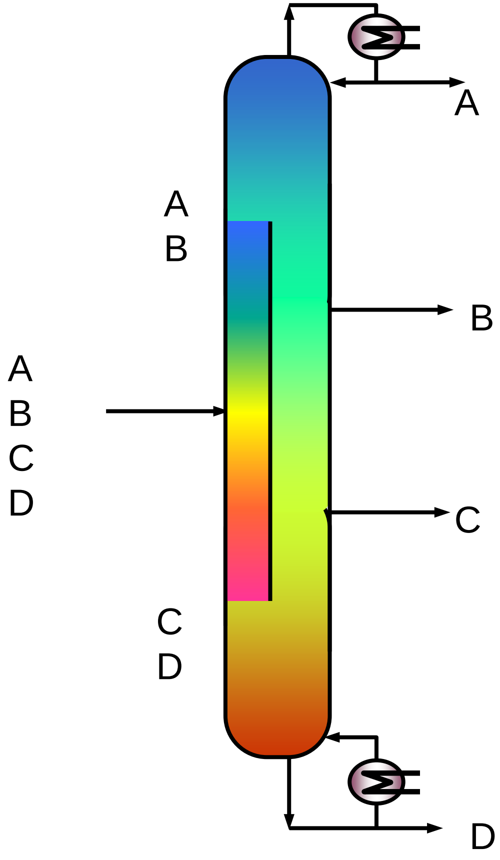
Vmin diagram for 4-product DWC/Petlyuk

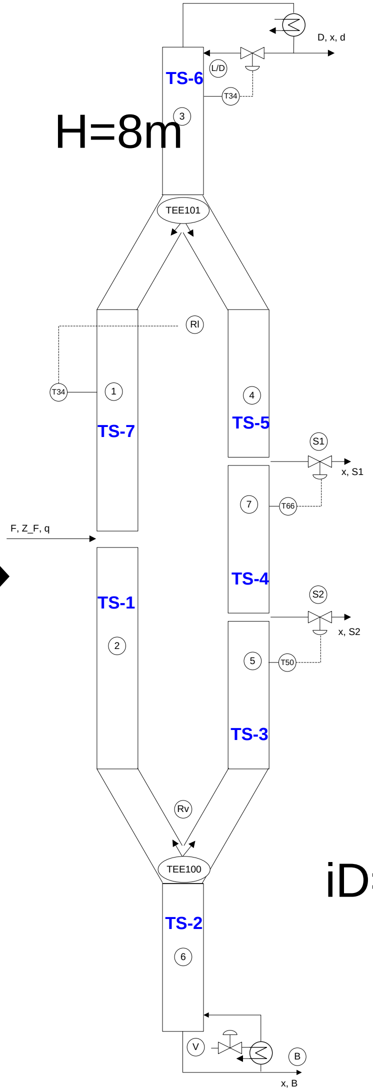


Highest peak – sets overall Petlyuk Vmin

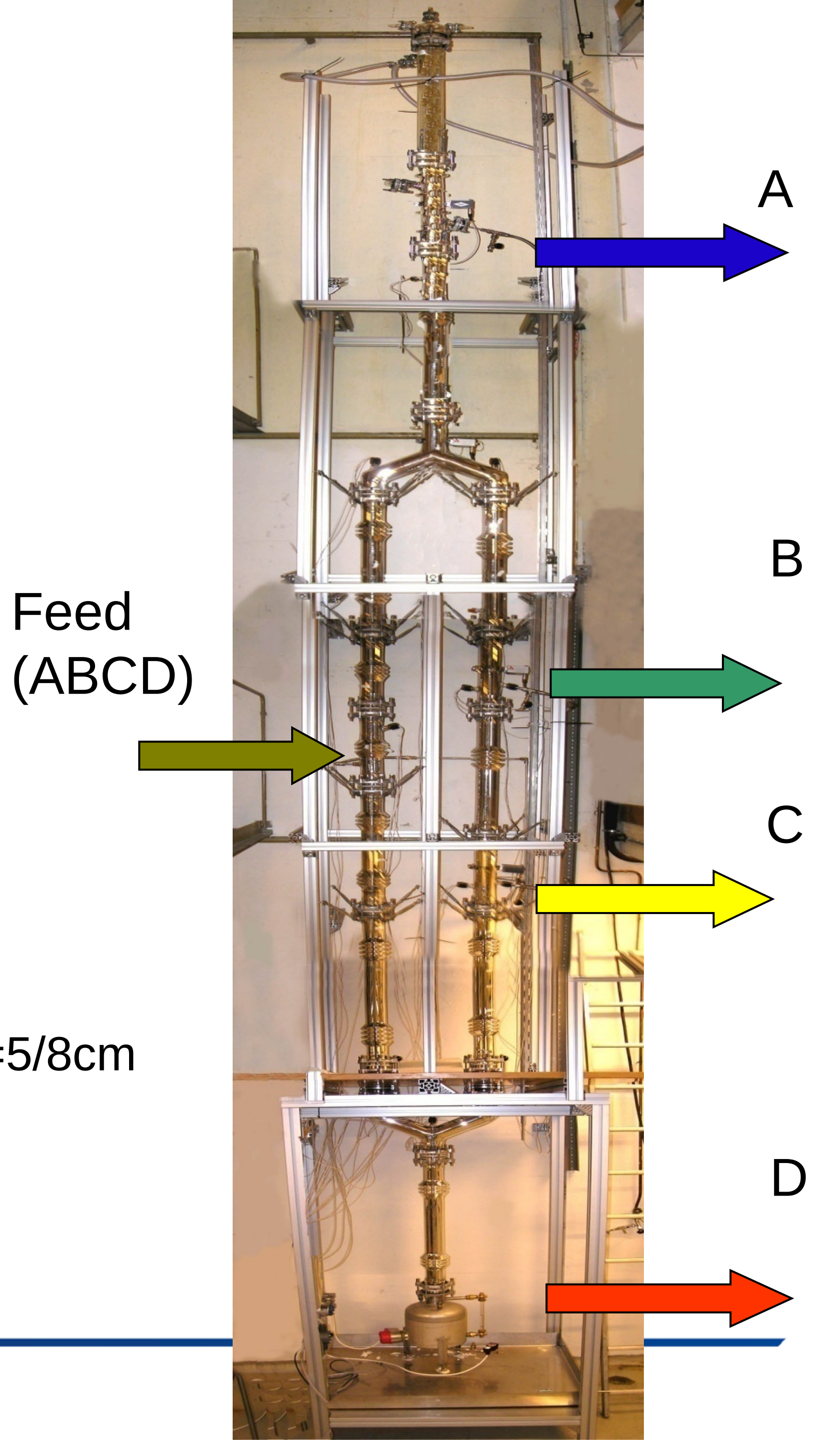
Vmin diagram contains all internal DWC rates at Vmin

The Kaibel column at NTNU/SINTEF





iD=5/8cm



Vmin diagram – Kaibel column

Kaibel Column:

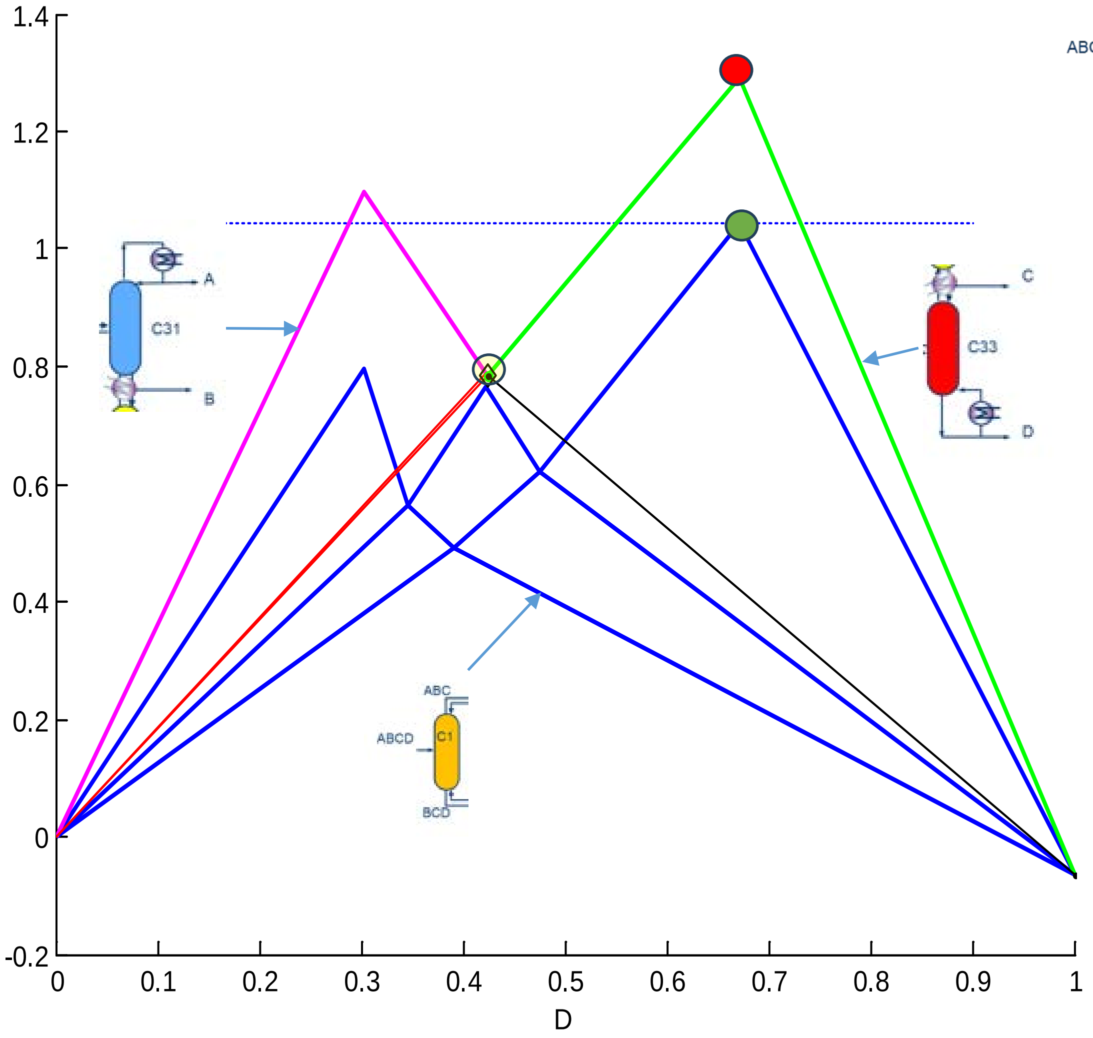
Do sharp AB/BC split in C1

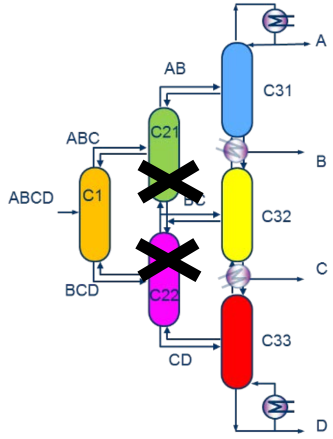
=>

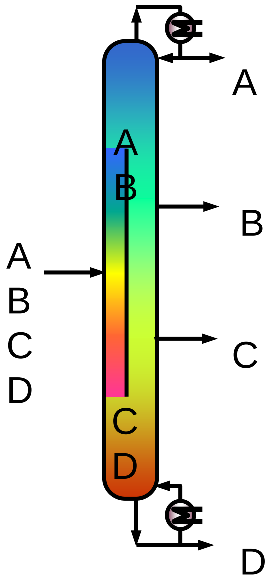
Lifted peaks and minimum boilup

=>

But can remove a partition wall! (C21+ C22)



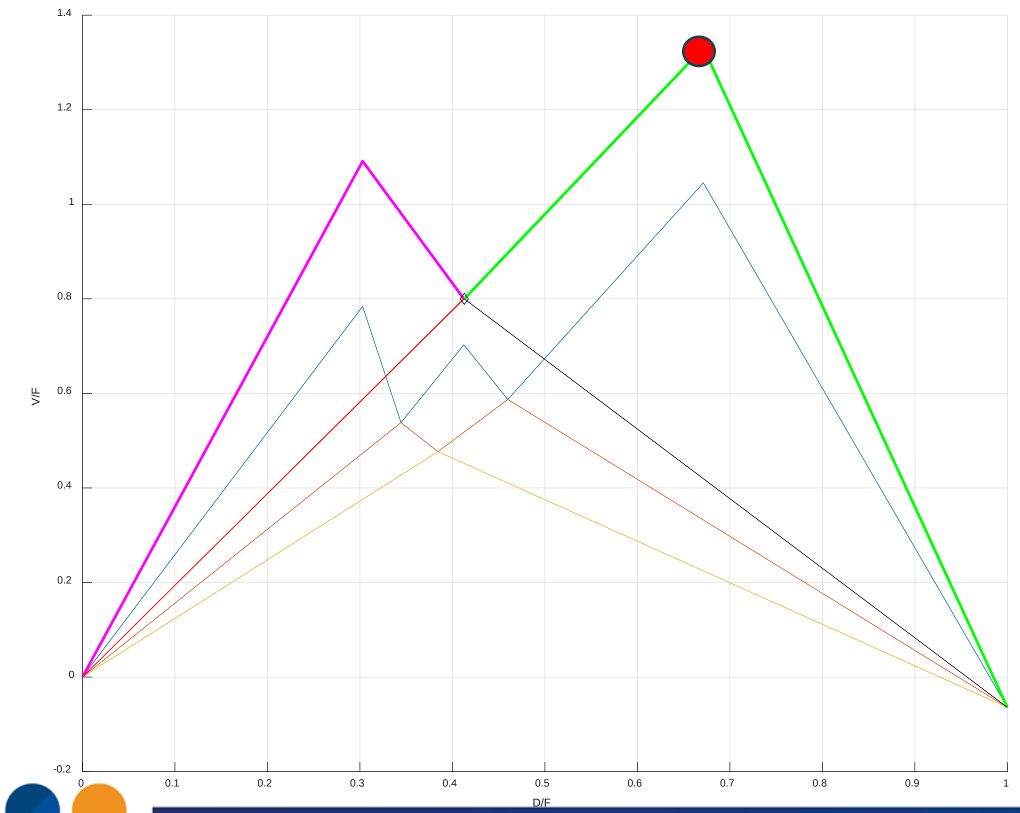




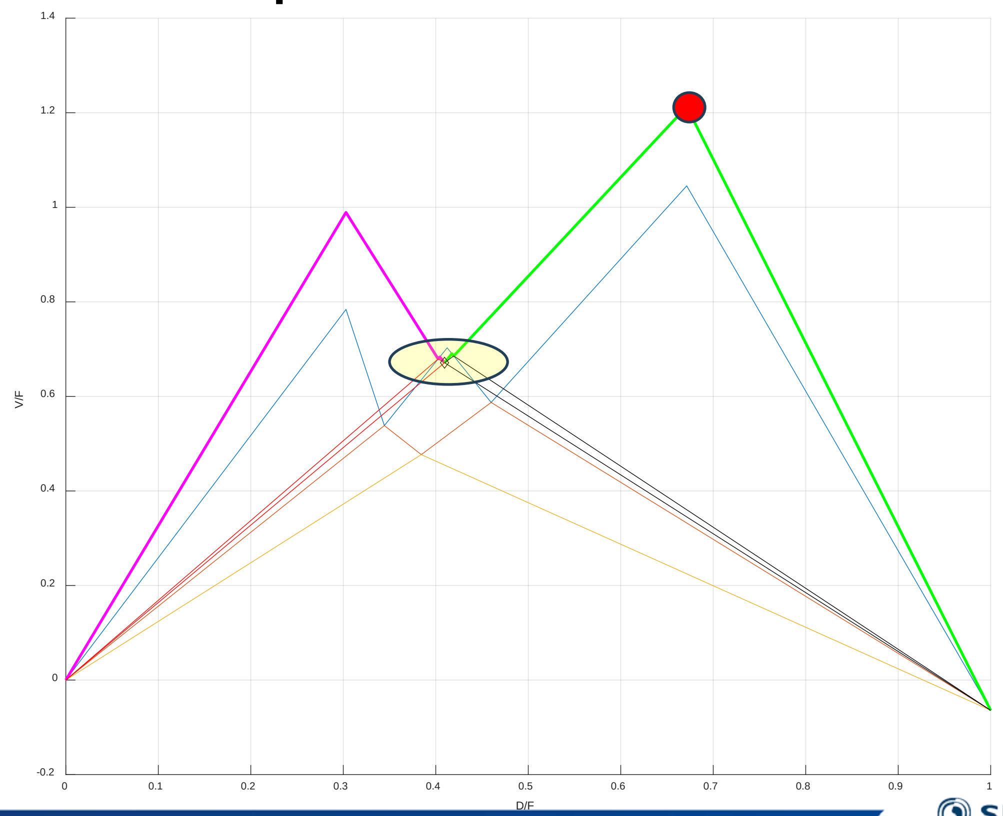
Kaibel 2-4

Options with one-point control

- Higher energy in prefrac=>
  Higher reboiler duty



- Impure AB/CD split =>
- Lower reboiler duty,
  but impure side streams



Kaibel column needs active use of both splits to achieve potential energy savings

- There is not a "wide optimality region" for the Kaibel-column
- Optimal operation of the pefractionator is exactly at the B/C split.
- Require two-point control for achievement of full savings

- One-point control can be used if increase in total reboiler duty can be accepted. (Reduced effective savings)
- Or, if significant impurities can be accepted in the side-streams

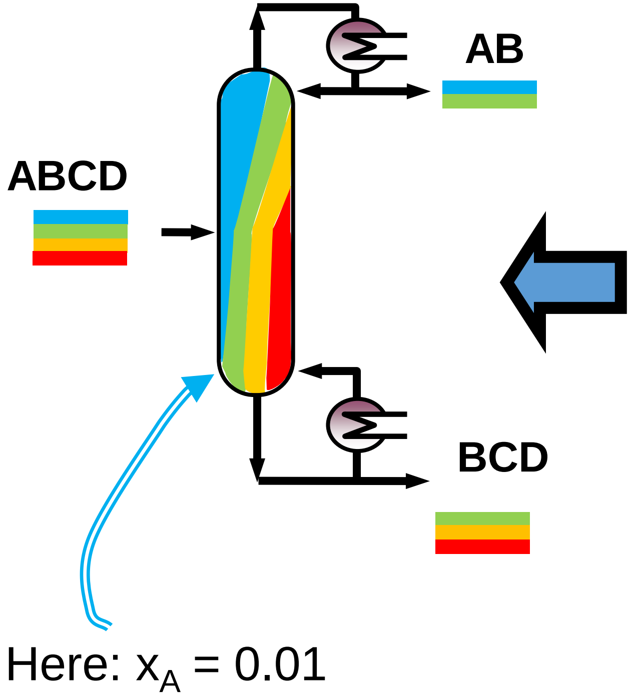
Conclusion

- DWC columns are attractive for savings in both energy & capital
- Some separations are particularly well suited and easy to control
- Some separations require more precise control of the prefractionator, including on-line adjustment of vapor split
- As we will show in the following: Feedback control by manipulating vapor split is very important

Extras

How to find V_{min}–diagram by simulations on a conventional 2-product simulation

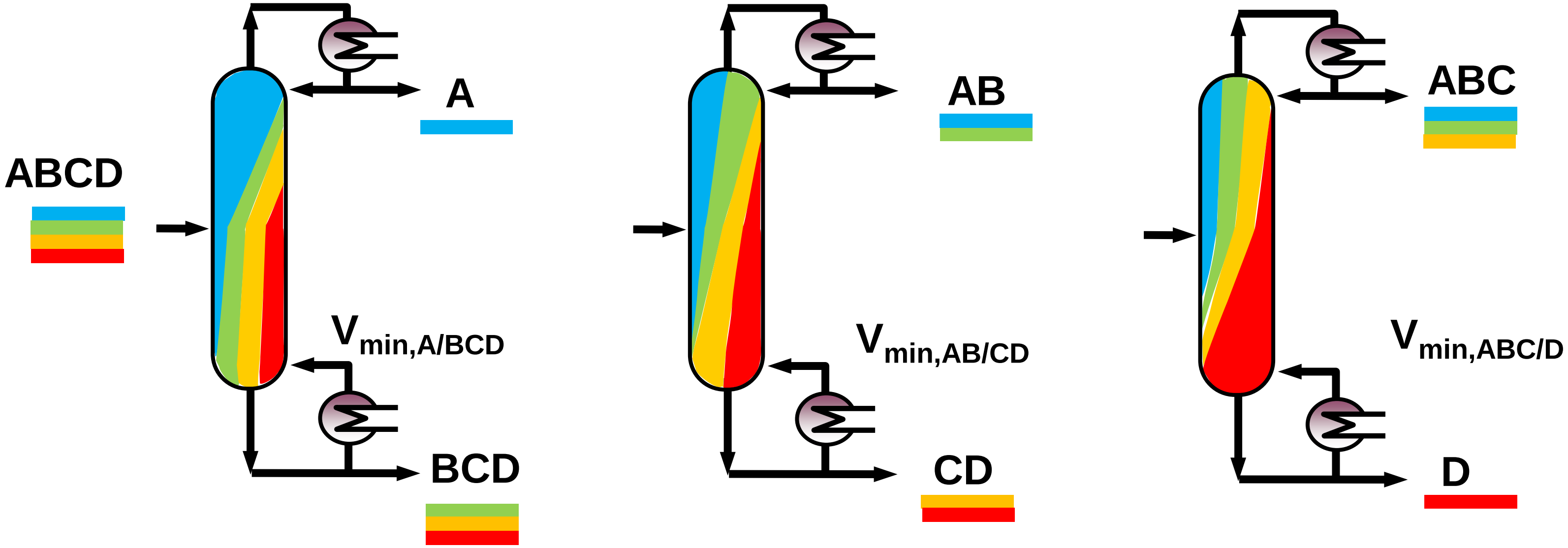
Method no 1



- Specify small impurity for components to be removed from each column end.
- E.g. The AB/BCD split Vmin-spec is:
  - Top: x_C = 0.01 (remove C,D in top)
  - Bottom: x_A = 0.01 (remove A in bottom)
- Use large number of stages (4xNmin)
- Confirm by observing the profile of the impurity component composition approaching zero close to the end

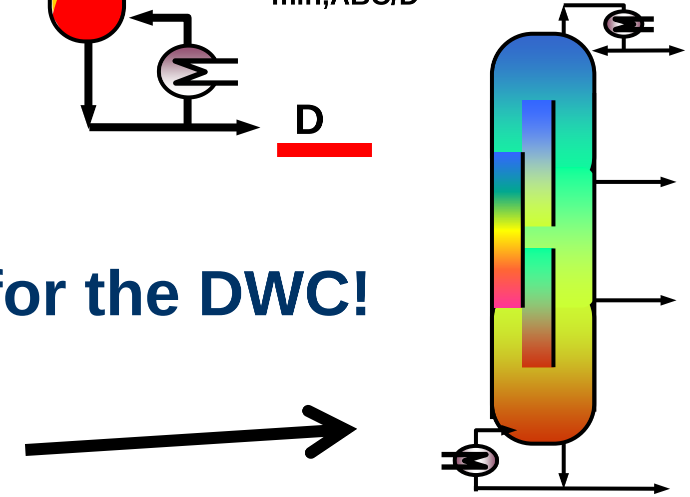
Amazingly simple to find V_{min} for DWC

4-product example, just consider 3 separate sharp split cases:



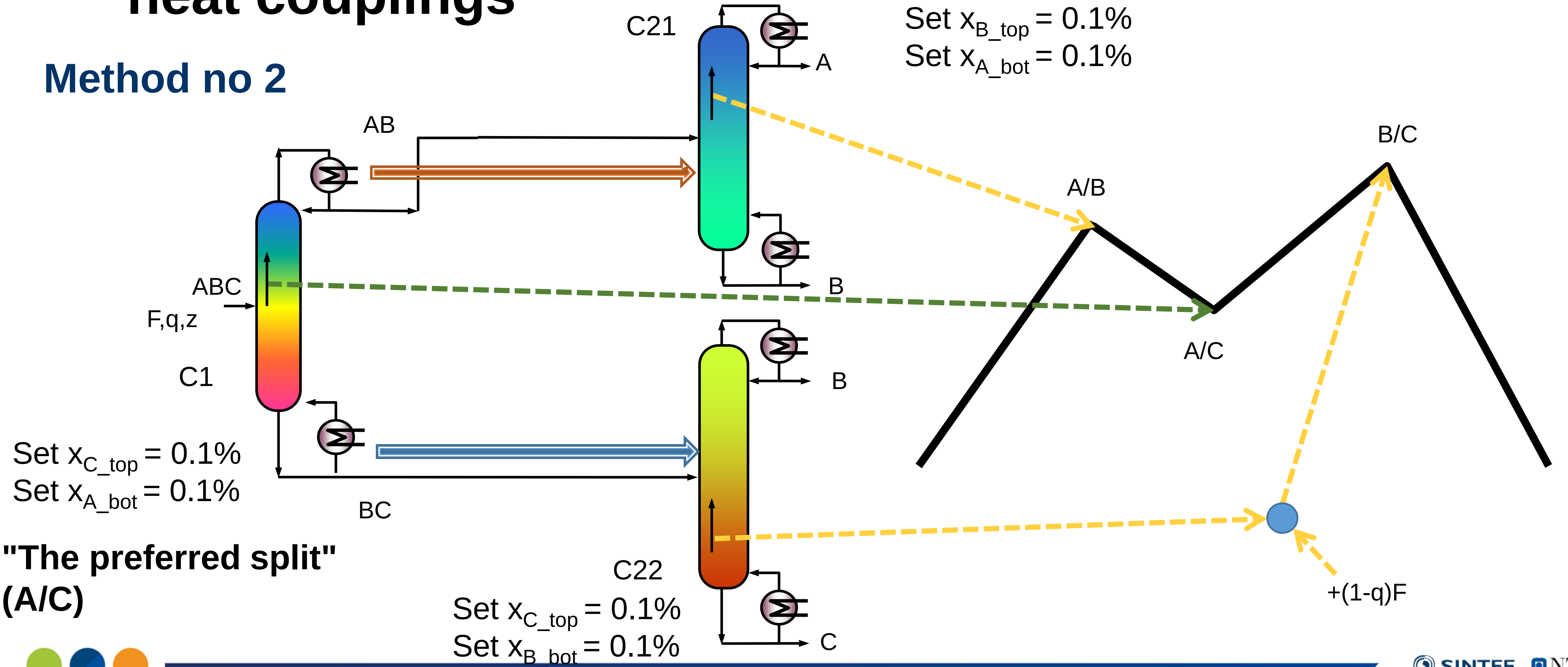
Use the most difficult product split V for the DWC!

$V_{min,DWC} = \max(V_{min,A/BCD}, V_{min,AB/CD}, V_{min,ABC/D})$



The Vmin-diagram can be found directly from internal flows of the "equivalent conventional columns with heat couplings"

Method no 2



"The preferred split" (A/C)

How to get around complex simulation initialisation and simulator recycle blocks

- Simulate for the Vmin-diagram with real mixtures by using equivalet sequences of heat integrated conventional columns
- Initial specifications: Every column should run at its "local" prefeferred spec.
- This will reveal which internal separation that is most demanding
- Operation of the other columns in the arrangement can then be altered until their operation "moves" and increases the most demanding
- Main advantages
  - Simple one-pass conventiopnal column simulations without need for "simulation recycle blocks"
  - Obtain flow rates for direct initialisation of thermally coupled sections (use two model twins, one with conventional equivalents and one with the physical correct setup.

Based on proposal from Halvorsen (2001):

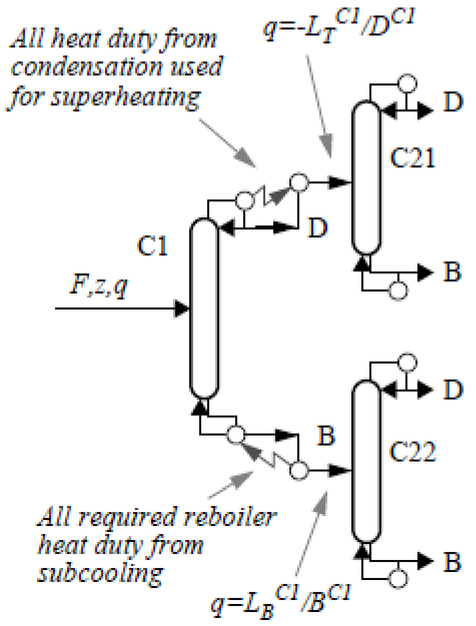


Figure D.1:
Computational equivalent to
the Petlyuk arrangement

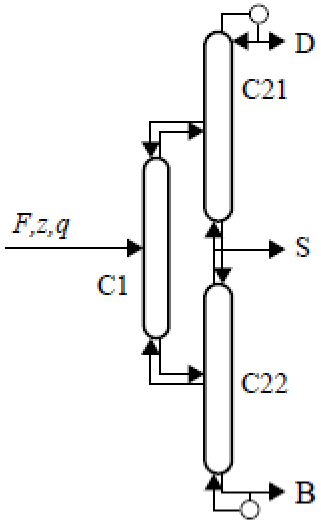
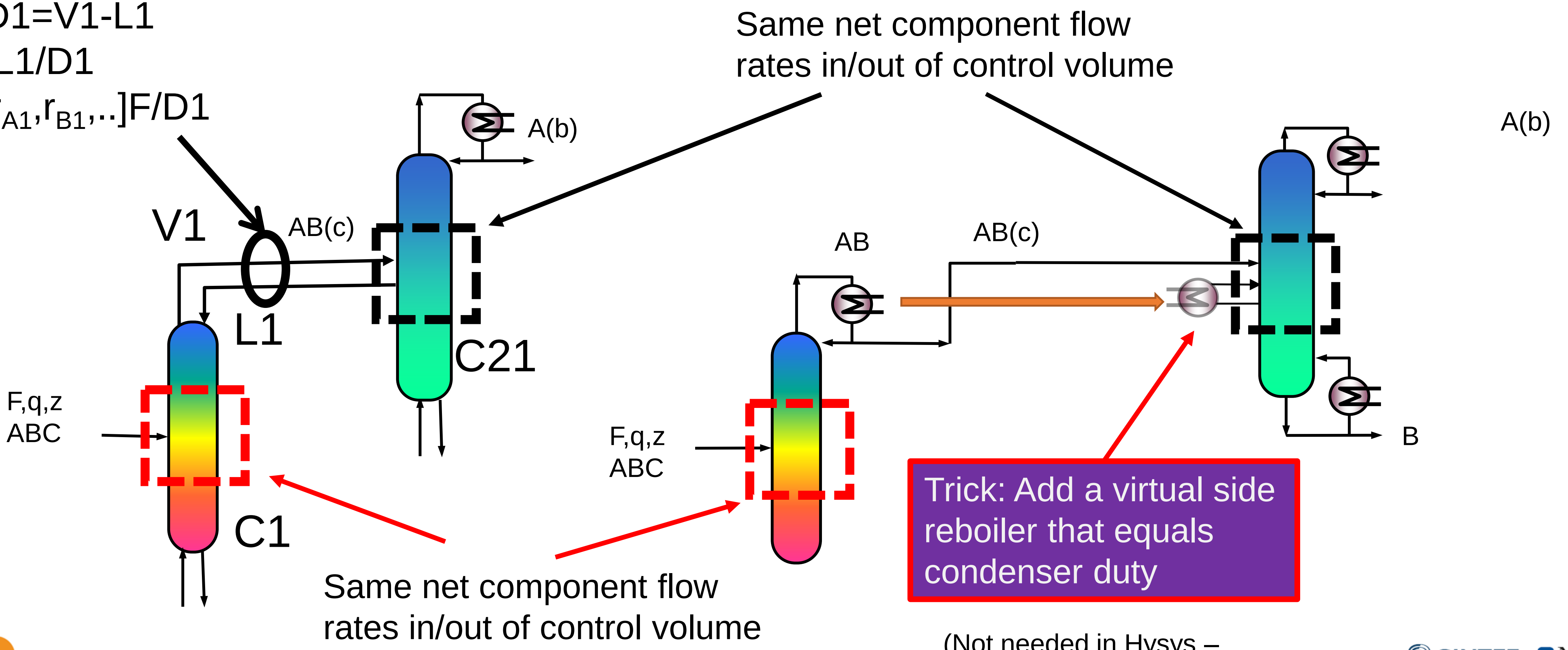


Figure D.2:
Petlyuk arrangement

- Use the same internal flow rates in both configurations
- The two-way full thermal coupling is equivalent to direct coupling + virtual heat coupling (some restrictions apply)
- E.g.: Hysys allows direct heat coupling (no need for extra side condenser/reboiler devices)

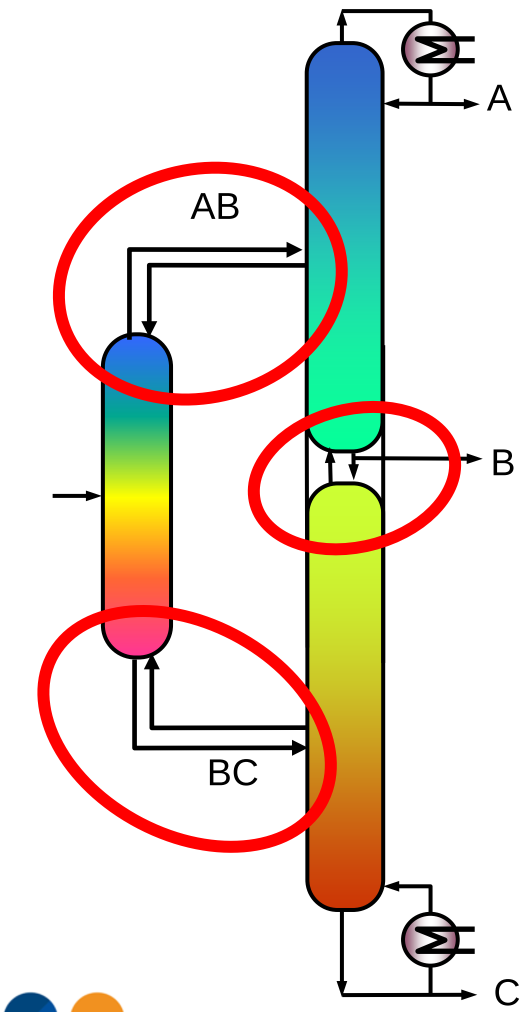
The termal coupling can be "replaced" with a "virtual" direct heat coupling

$F21=D1=V1-L1$
$q21=-L1/D1$
$z21=[r_{A1},r_{B1},..]F/D1$



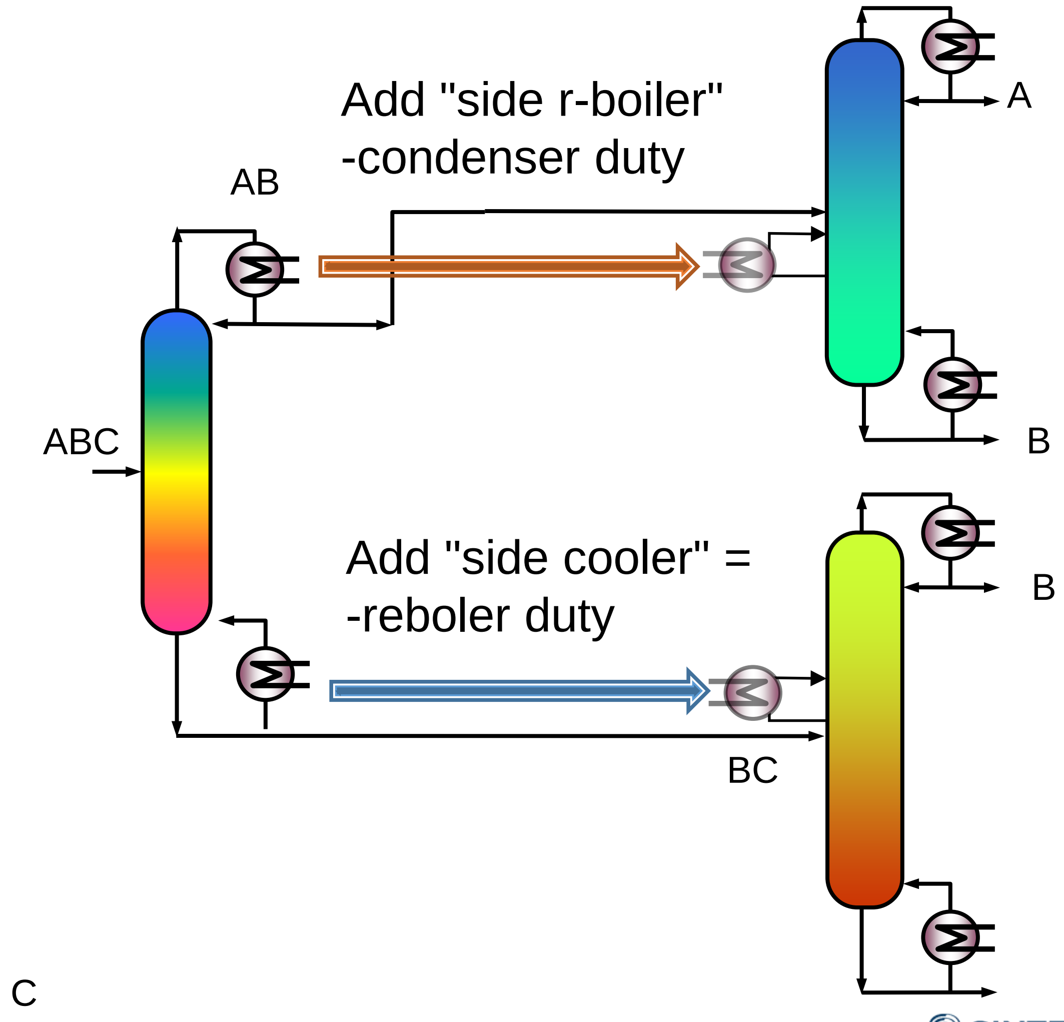
(Not needed in Hysys –
Direct heat coupling is allowed.)

A DWC can be simulated by a conventional sequence with virtual heat connections

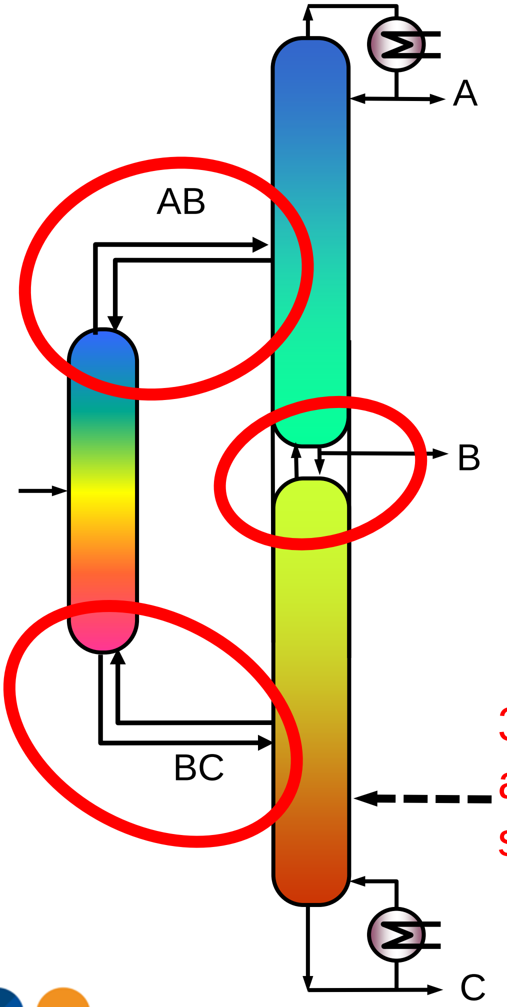


Thermal coupling implies no net heat in connections

The virtual heat coupling "zero out" the net heat in the conventional equivalent



What will be different?

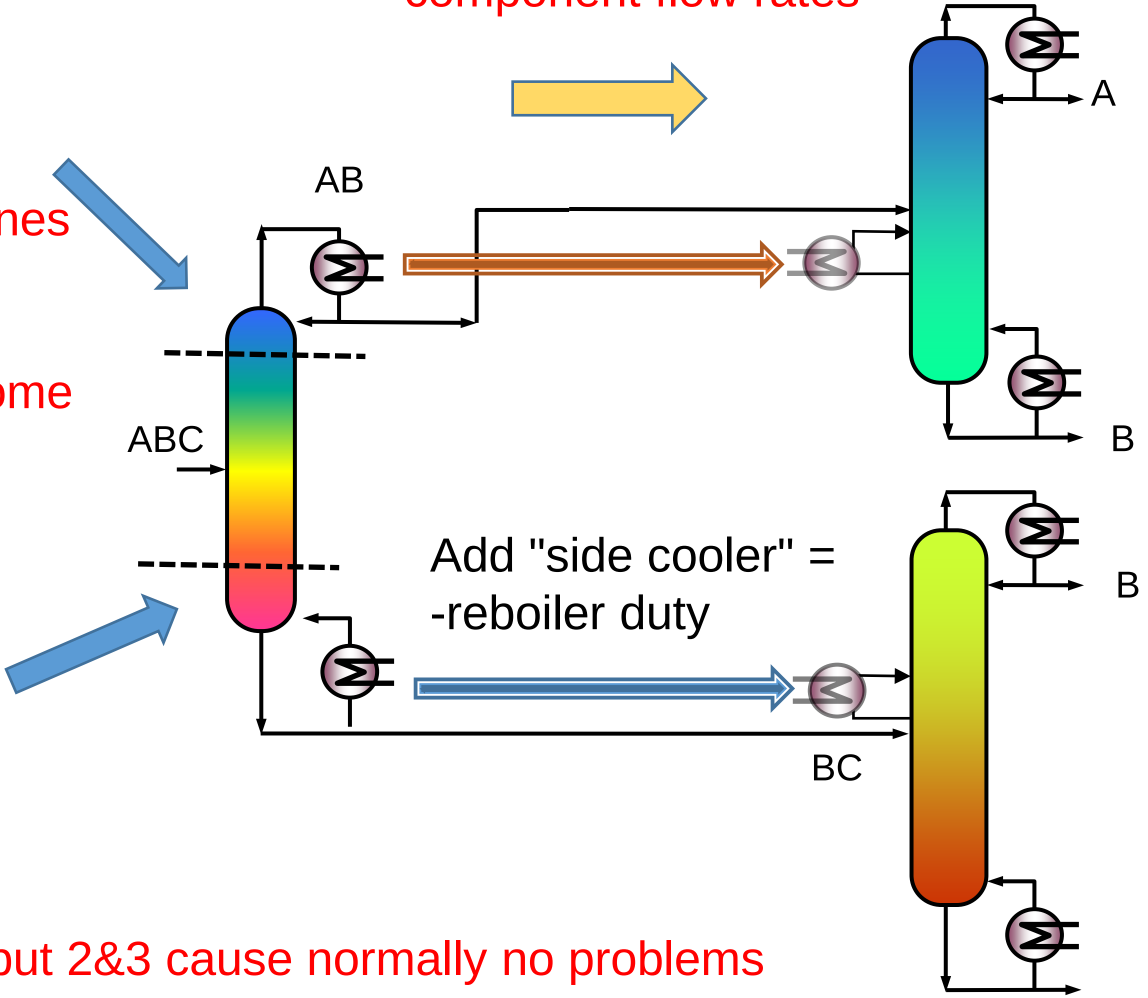


1) Remixing zones in top/bottom

(may require some extra stages in conventional equivalent)

2) Only positive net component flow rates

3) Cannot handle additional feeds into succeding columns



Must handle 1) but 2&3 cause normally no problems