Integrated Catalytic Processes

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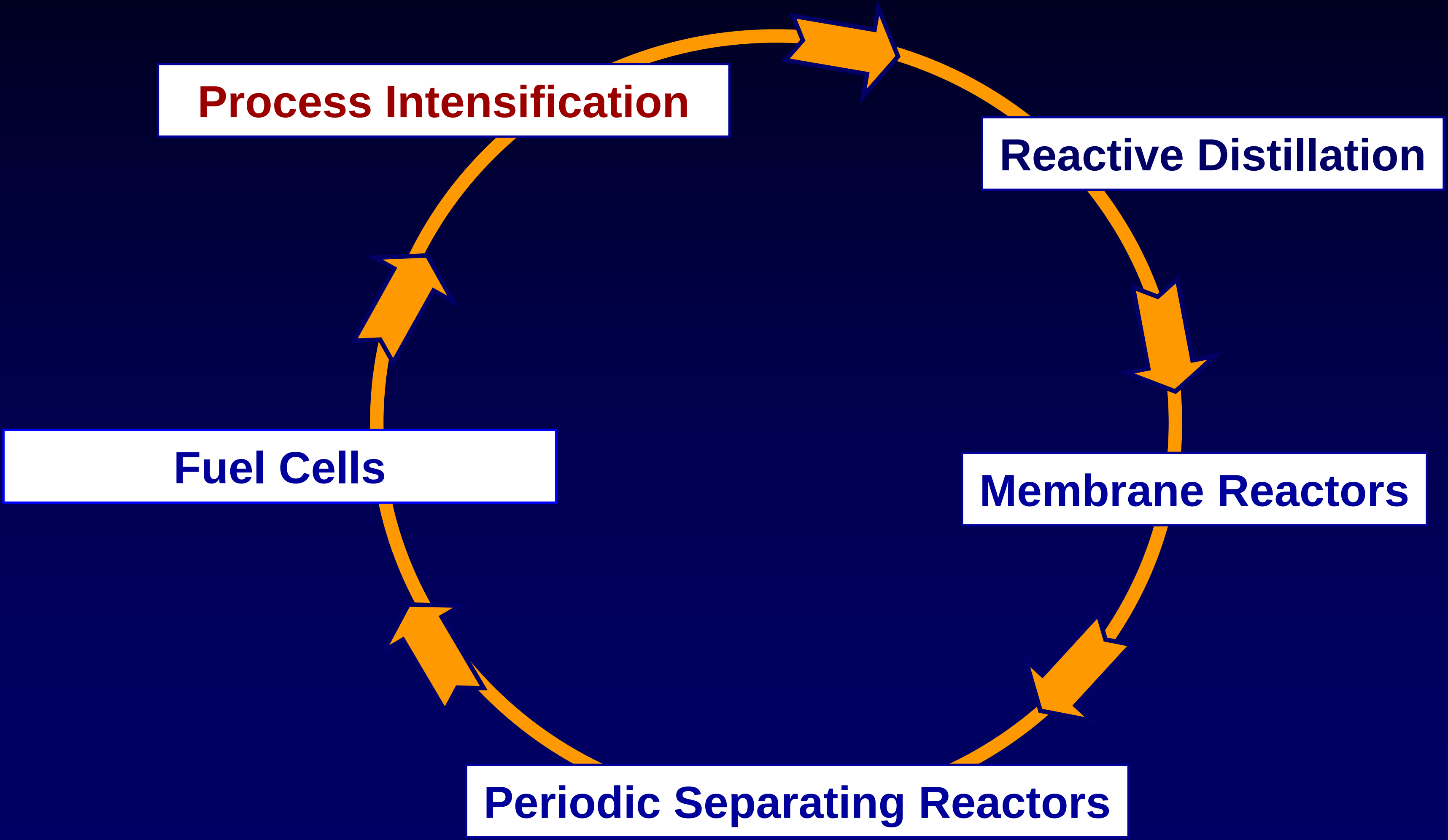
Integrated Catalytic Processes –Lecture Outline



Process Intensification

Reactive Distillation

Membrane Reactors

Periodic Separating Reactors

Fuel Cells

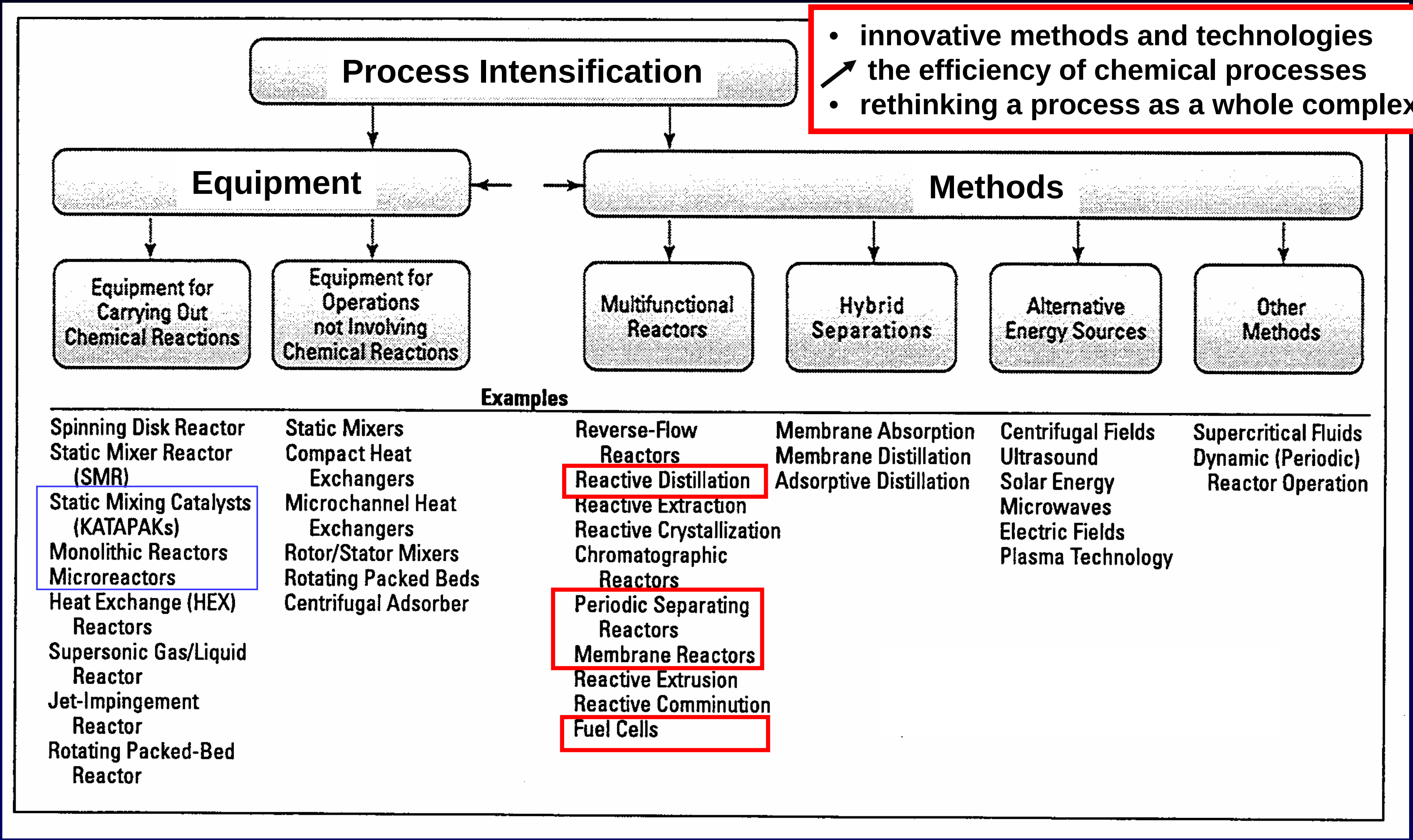
Modern Methods in Heterogeneous Catalysis Research
Fritz Haber Institute, Berlin, 24 November 2006

Process Intensification

- innovative methods and technologies

↗ the efficiency of chemical processes

- rethinking a process as a whole complex



Process Intensification

Equipment ← → **Methods**

Equipment for Carrying Out Chemical Reactions	Equipment for Operations not Involving Chemical Reactions	Multifunctional Reactors	Hybrid Separations	Alternative Energy Sources	Other Methods
Spinning Disk Reactor Static Mixer Reactor (SMR) Static Mixing Catalysts (KATAPAKs) Monolithic Reactors Microreactors Heat Exchange (HEX) Reactors Supersonic Gas/Liquid Reactor Jet-Impingement Reactor Rotating Packed-Bed Reactor	Static Mixers Compact Heat Exchangers Microchannel Heat Exchangers Rotor/Stator Mixers Rotating Packed Beds Centrifugal Adsorber	Reverse-Flow Reactors Reactive Distillation Reactive Extraction Reactive Crystallization Chromatographic Reactors Periodic Separating Reactors Membrane Reactors Reactive Extrusion Reactive Comminution Fuel Cells	Membrane Absorption Membrane Distillation Adsorptive Distillation	Centrifugal Fields Ultrasound Solar Energy Microwaves Electric Fields Plasma Technology	Supercritical Fluids Dynamic (Periodic) Reactor Operation

Examples

see: A.I. Stankiewicz, J.A. Moulijn, *Chem. Eng. Progress*, Jan. 2000, 22-34

Potential of Integrated Catalytic Processes

Synergetic interactions of chemical and physical unit operations may lead to:

↑ increase of productivity from process intensification

↑ increase of selectivity of reactions and/or separations

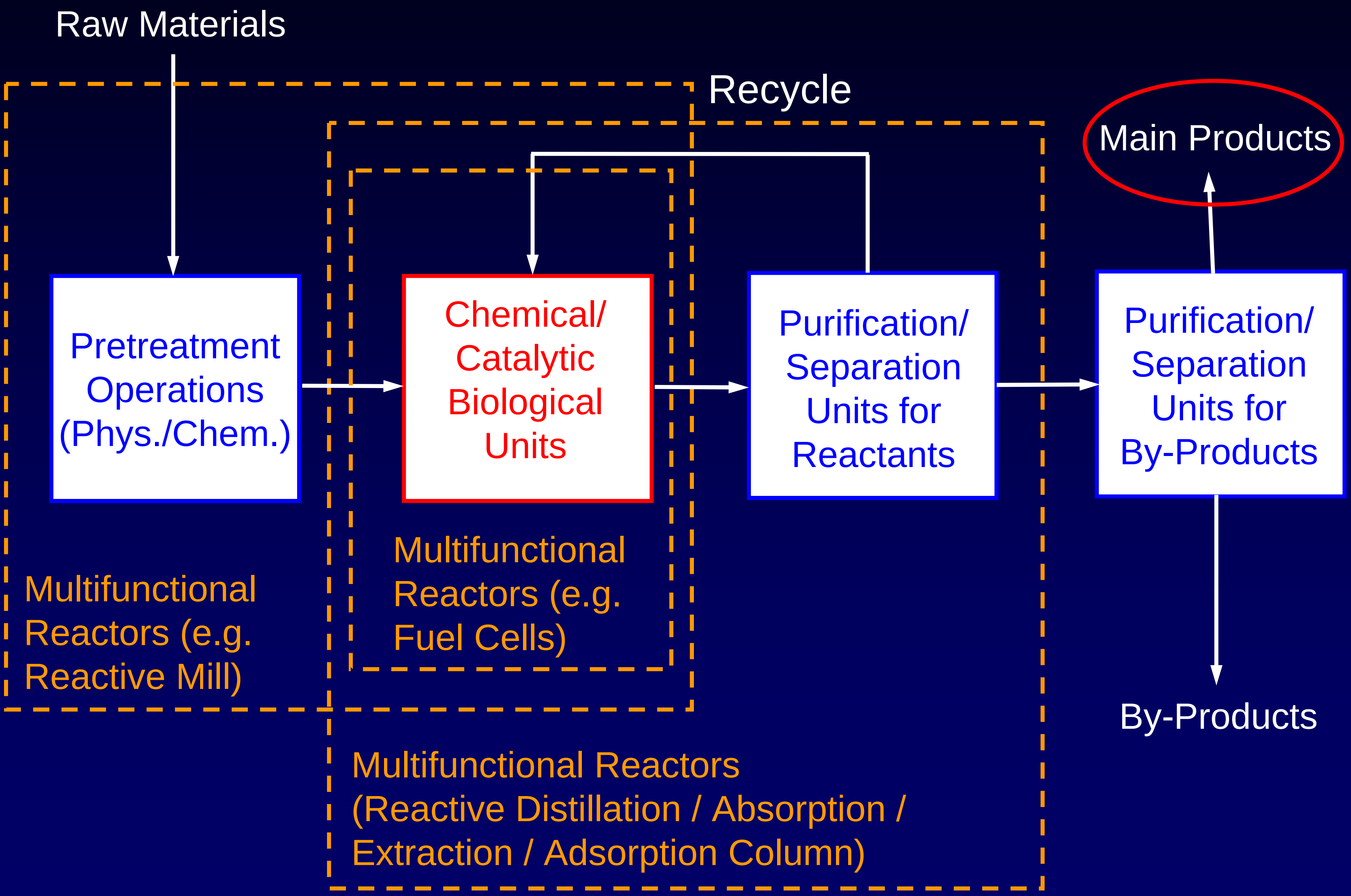
↑ improve separation by „reacting away“ azeotropic mixtures

↑ more efficient (in situ) use of energy

↑ inherent safety

↑ improved environmental compatibility
(e.g. by avoidance of by-products and hazardous solvents).

Integration of Unit Operations in Multifunctional Reactors



Raw Materials

Recycle

Main Products

Pretreatment Operations (Phys./Chem.)

Chemical/ Catalytic Biological Units

Purification/ Separation Units for Reactants

Purification/ Separation Units for By-Products

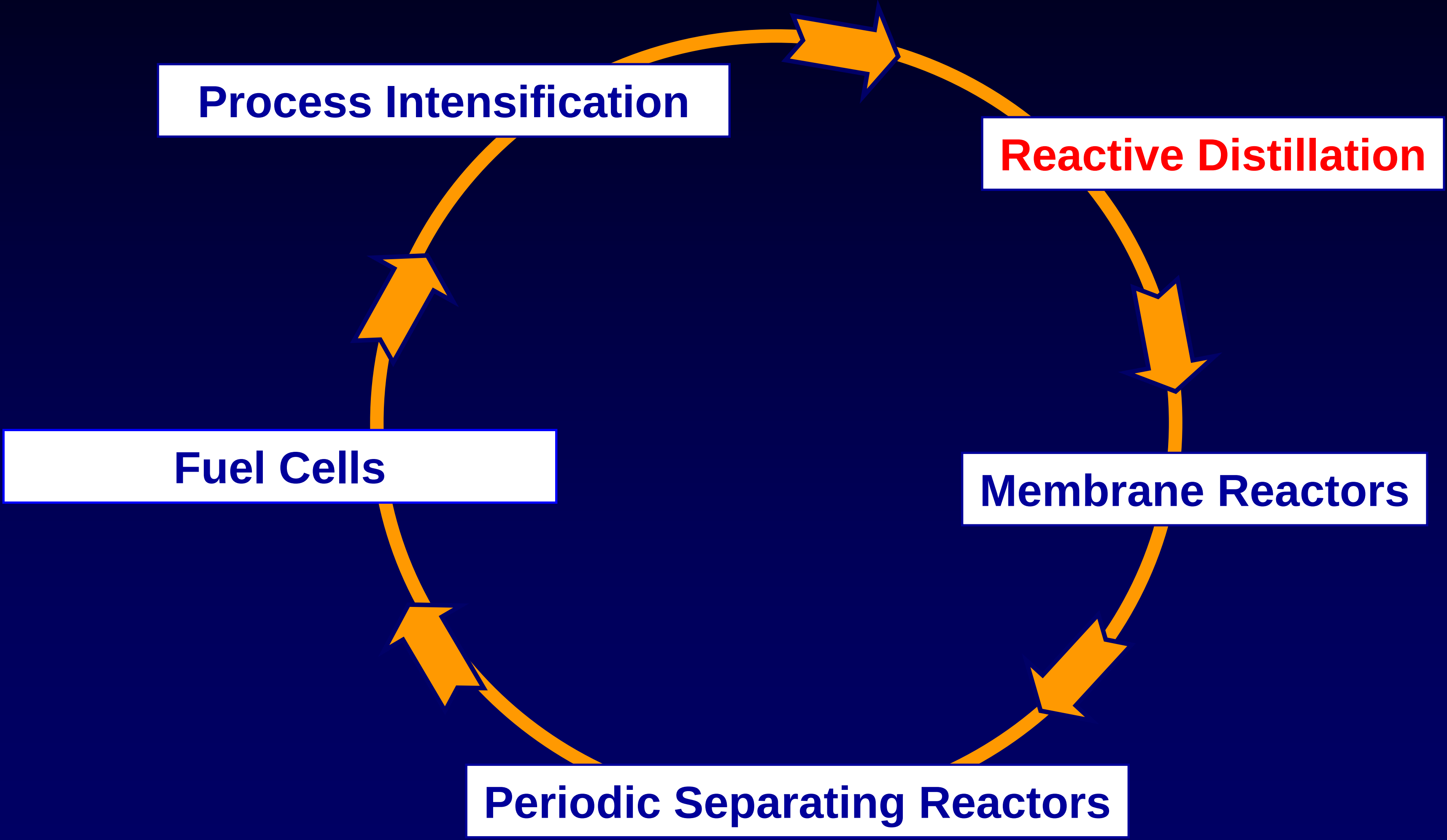
By-Products

Multifunctional Reactors (e.g. Reactive Mill)

Multifunctional Reactors (e.g. Fuel Cells)

Multifunctional Reactors (Reactive Distillation / Absorption / Extraction / Adsorption Column)

Integrated Catalytic Processes –Lecture Outline



Process Intensification

Reactive Distillation

Membrane Reactors

Periodic Separating Reactors

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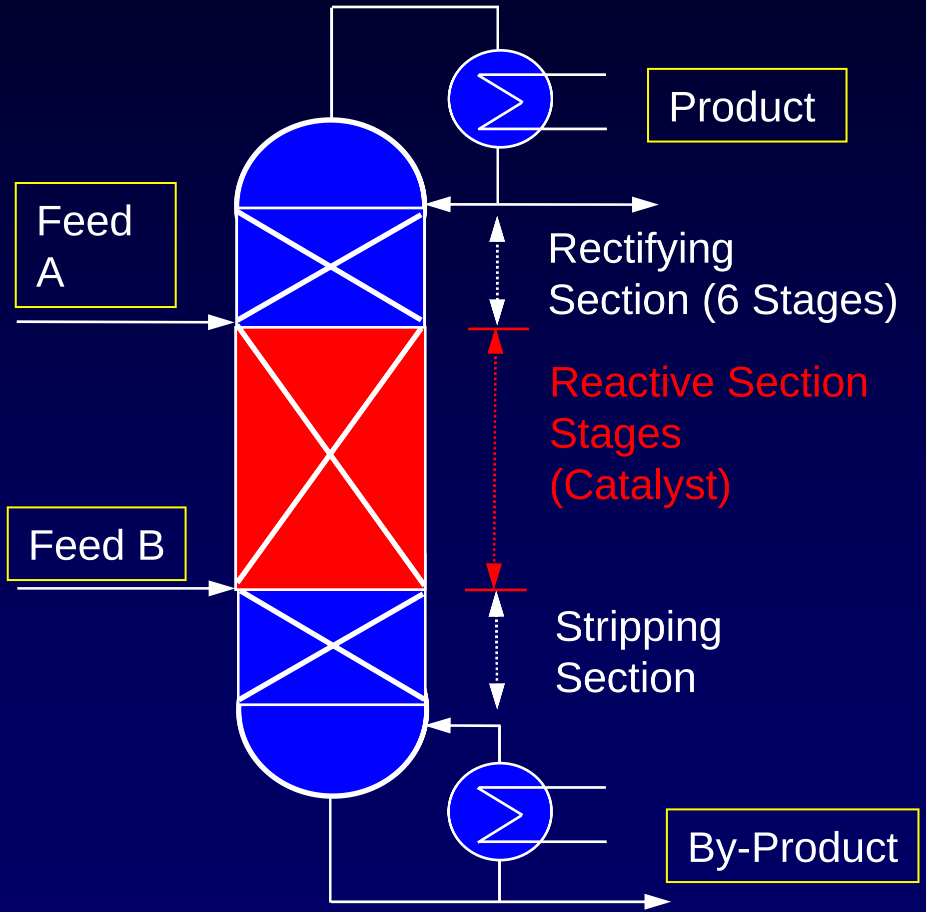
Reactive Distillation

- Combination of a Reactor and a Distillation Unit



Product

Feed A

Rectifying Section (6 Stages)

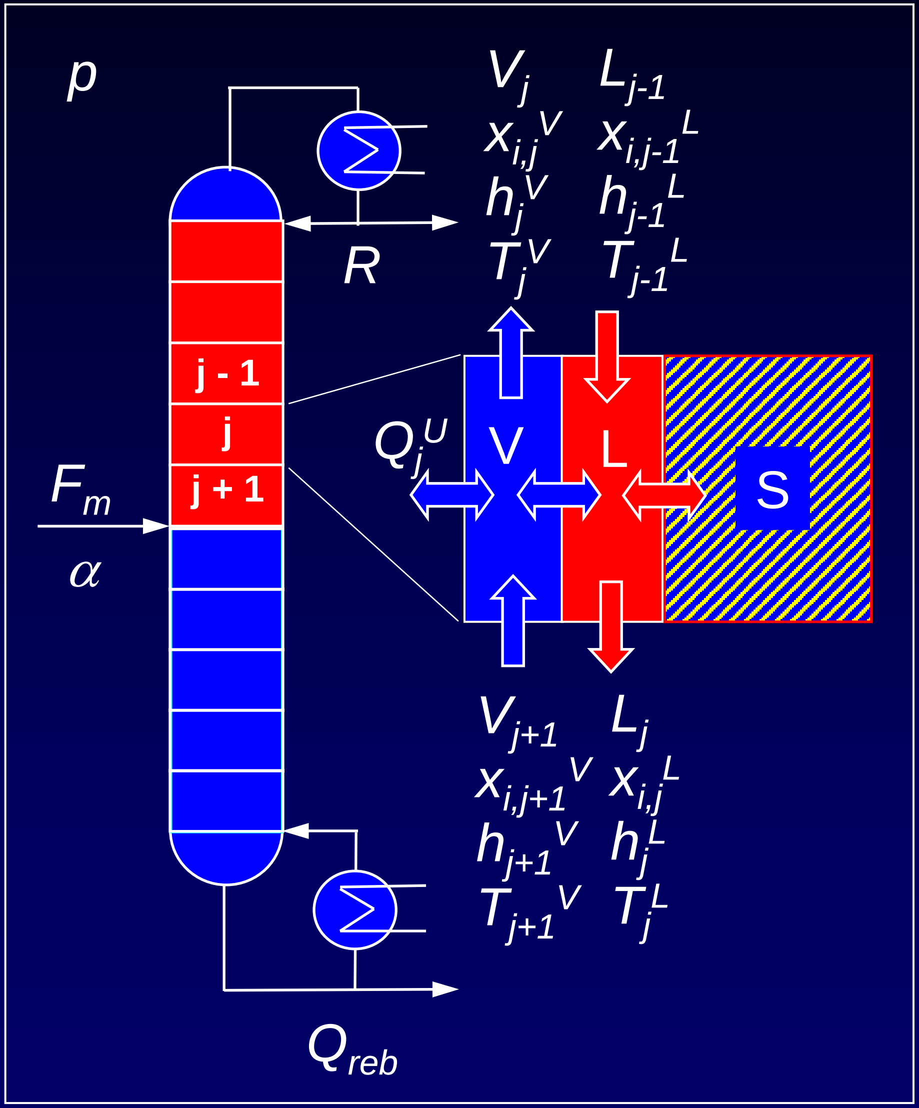
Reactive Section Stages (Catalyst)

Feed B

Stripping Section

By-Product

Modeling of Catalytic Distillation Column



PSEUDOHOMOGENEOUS MODEL
+ V/L mass transfer model
+ reaction microkinetics

HETEROGENEOUS MODEL
(„Fully rate-based“)
+ V/L mass transfer model
+ reaction microkinetics
+ intraparticle mass transfer
(Maxwell-Stefan-eqs.)

SPECIFICATIONS
+ specifications: p, F,
Relative volatility α, Q, R

Reactive Batch Distillation: Model Equations

Mass Balances

$$\frac{\mathrm{d}\,x_i}{\mathrm{d}\tau} = \underbrace{\left(x_i - y_i\left(\underline{x},T\right)\right)}_{\text{Separation by Distillation}} + Da \cdot \underbrace{\left(\nu_i - x_i\,\nu\right)}_{\text{Influence of Stoichiometry}} \cdot \underbrace{r^*\left(\underline{x},T\right)}_{\text{Reaction Kinetics}}$$

Damköhler Number

$$Da \equiv \frac{k_+(T_{ref})\cdot c_{sites}\cdot V_{cat}}{\dot{V}^o}$$

apparent
Rate constant

concentration
of active sites
on catalyst

Boiling Temperature

$$T = T\left(\underline{x},p\right)$$

+ rate control
  over pressure !
+ T is not a
  dynamic variable !

Thiel, C.; Sundmacher, K.; Hoffmann, U. (1997) *Chem. Eng. Sci.* **52**, 993-1005.

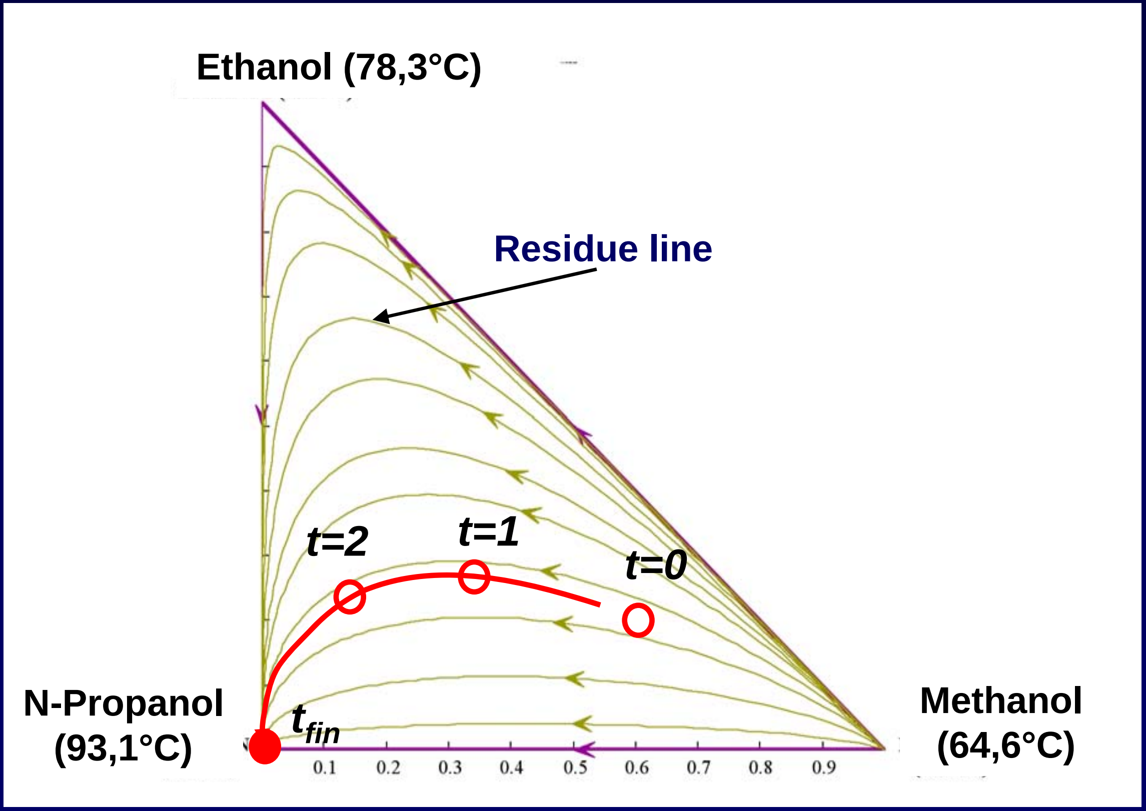
Residue Curve Maps

- Liquid residue composition with time
- 1-stage distillation (batch distillation) with no reflux

- equilibrium relationship of ternary mixures
- bottom and overhead products
- the feasibility of separation of homogeneous mixtures (stages / energy !)
- the design and operation of a distillation column (azeotropic mixtures)

Example (ideal, no azeotropes)
Starting mixture (*t=0*):

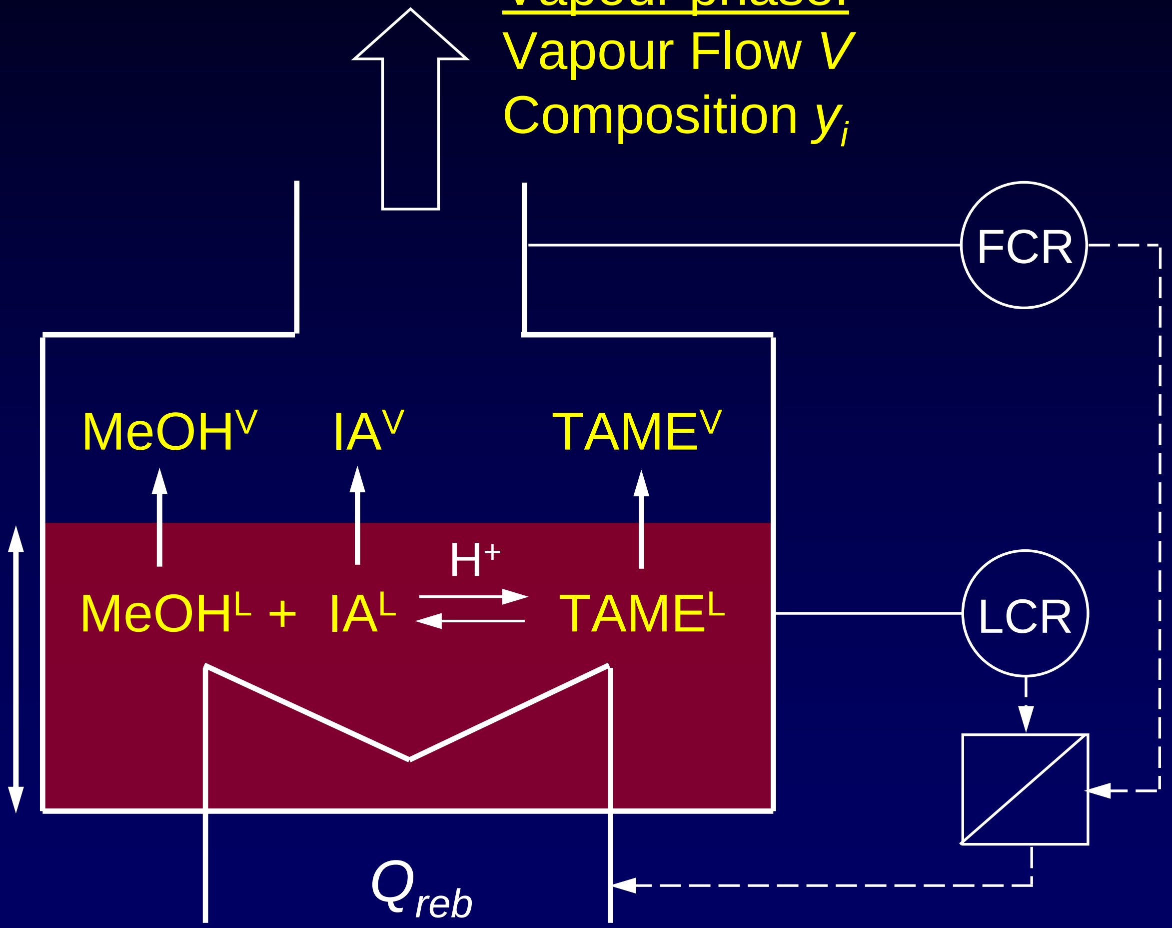
•*MeOH*	*0,6*
•*EtOH*	*0,25*
•*N-PrOH*	*0,15*



Reactive Batch Distillation: MeOH + IA ⇔ TAME

Vapour phase:
Vapour Flow *V*
Composition y_i

Heating policy:
$V / V_0 = H / H_0$

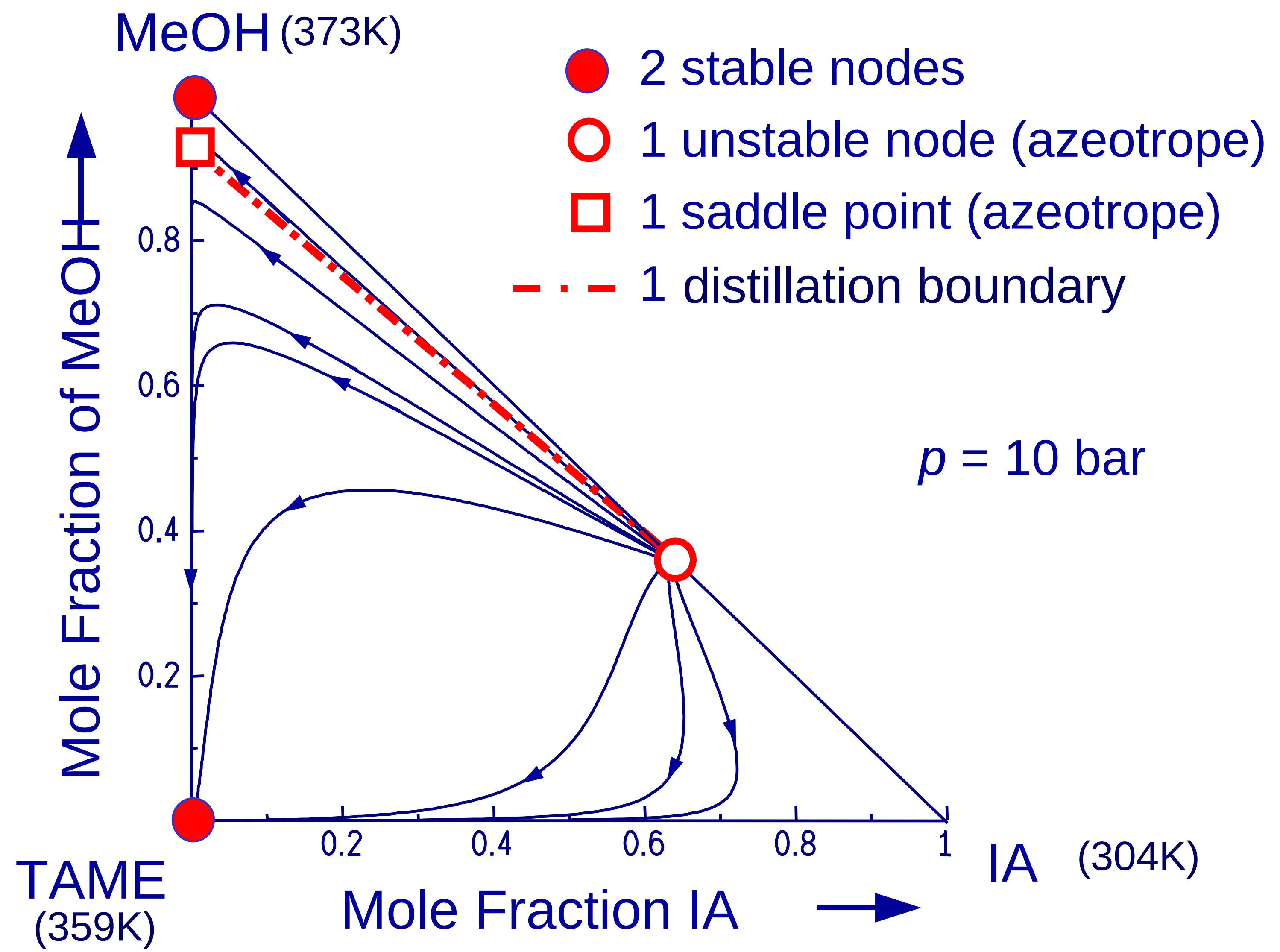


Liquid phase:
Holdup *H*
Composition x_i

Catalyst: Acidic Ion Exchange Resin (V_{cat}, c_{H+})

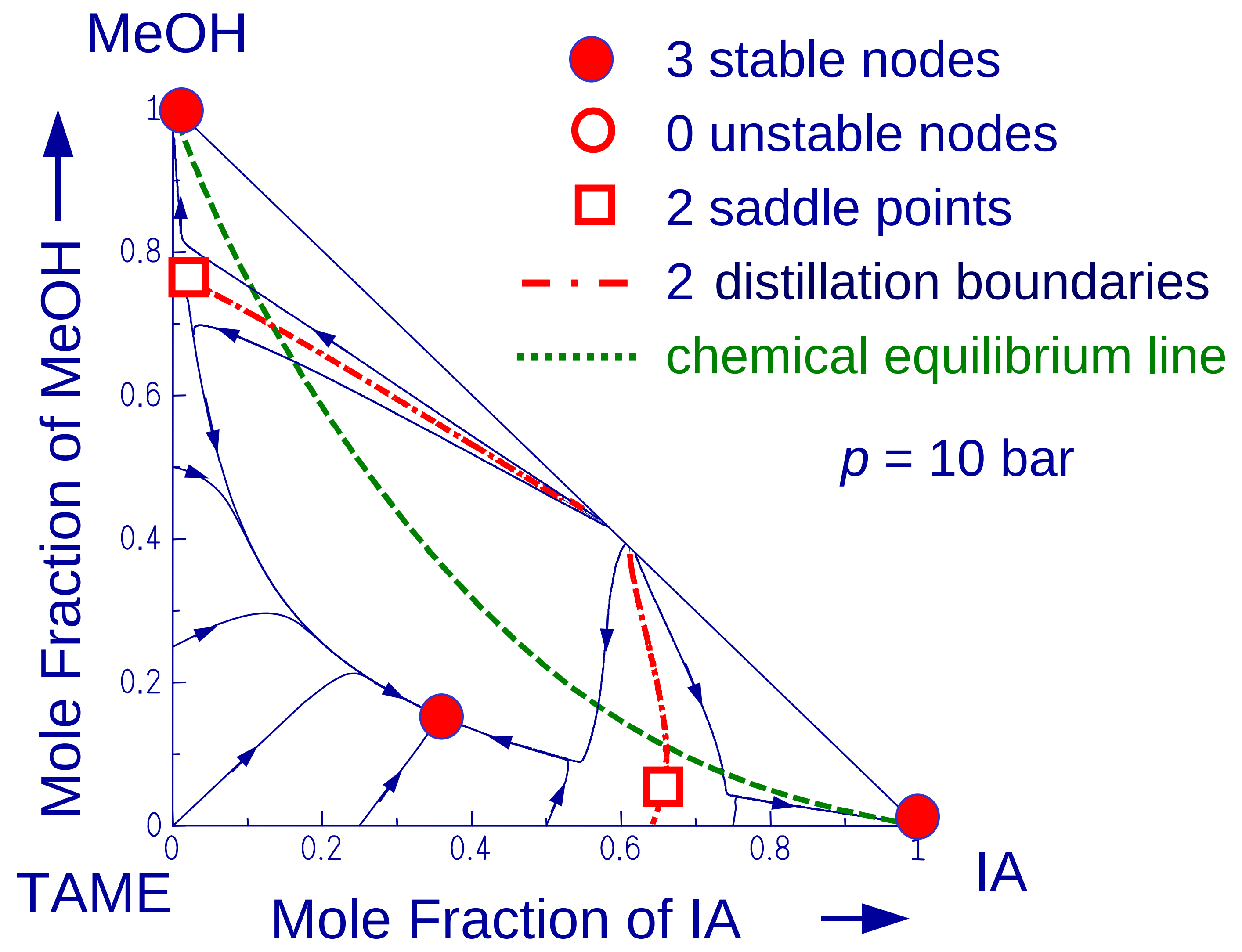
Thiel, C.; Sundmacher, K.; Hoffmann, U. (1997) *Chem. Eng. Sci.* **52**, 993-1005.

Catalytic Batch Distillation for TAME-Synthesis: No Reaction (Da = 0)



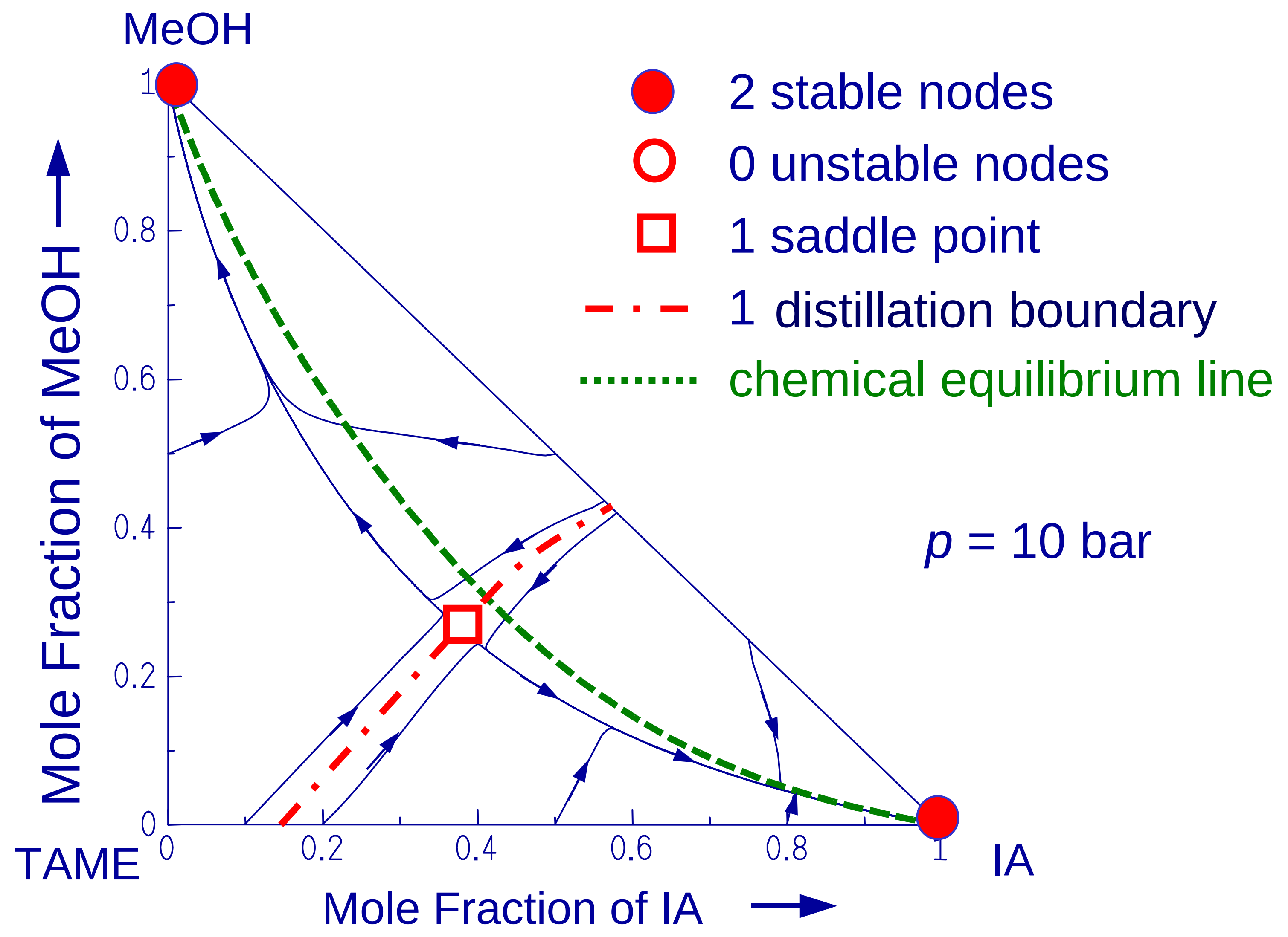
Thiel, C.; Sundmacher, K.; Hoffmann, U. (1997) *Chem. Eng. Sci.* **52**, 993-1005.

Catalytic Batch Distillation for TAME-Synthesis: Slow Reaction (Da = 10^{-4})



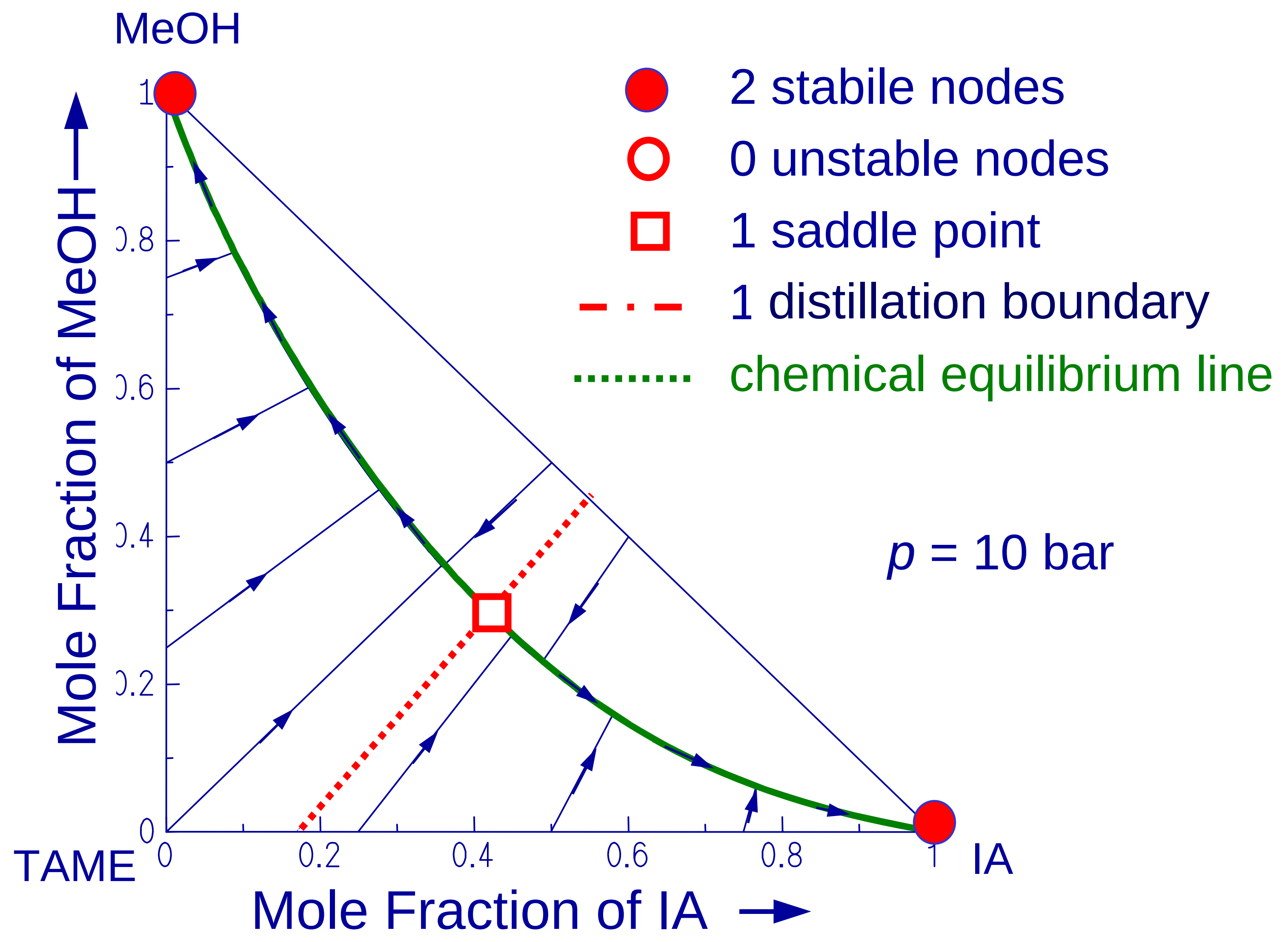
Thiel, C.; Sundmacher, K.; Hoffmann, U. (1997) *Chem. Eng. Sci.* **52**, 993-1005.

Catalytic Batch Distillation for TAME-Synthesis: Fast Reaction (Da = 10^{-3})



Thiel, C.; Sundmacher, K.; Hoffmann, U. (1997) *Chem. Eng. Sci.* **52**, 993-1005.

Catalytic Batch Distillation for TAME-Synthesis: Reaction in Equilibrium (Da > 1)



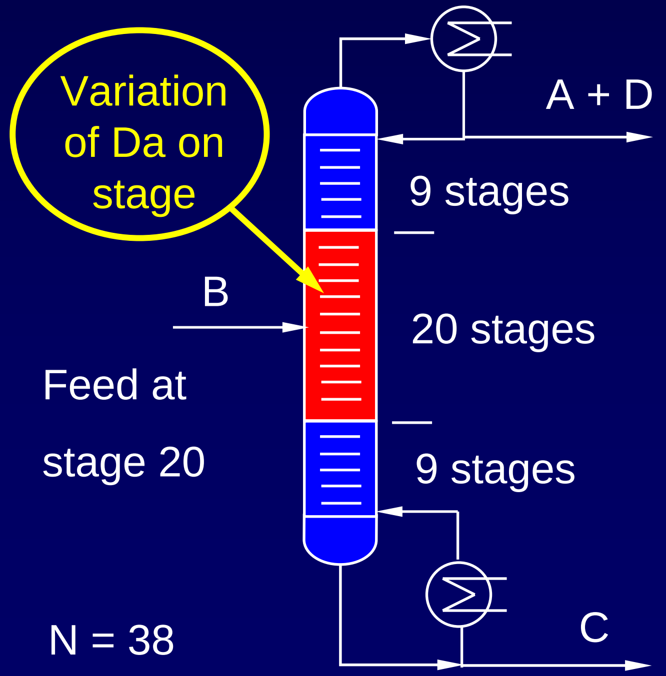
Thiel, C.; Sundmacher, K.; Hoffmann, U. (1997) *Chem. Eng. Sci.* **52**, 993-1005.

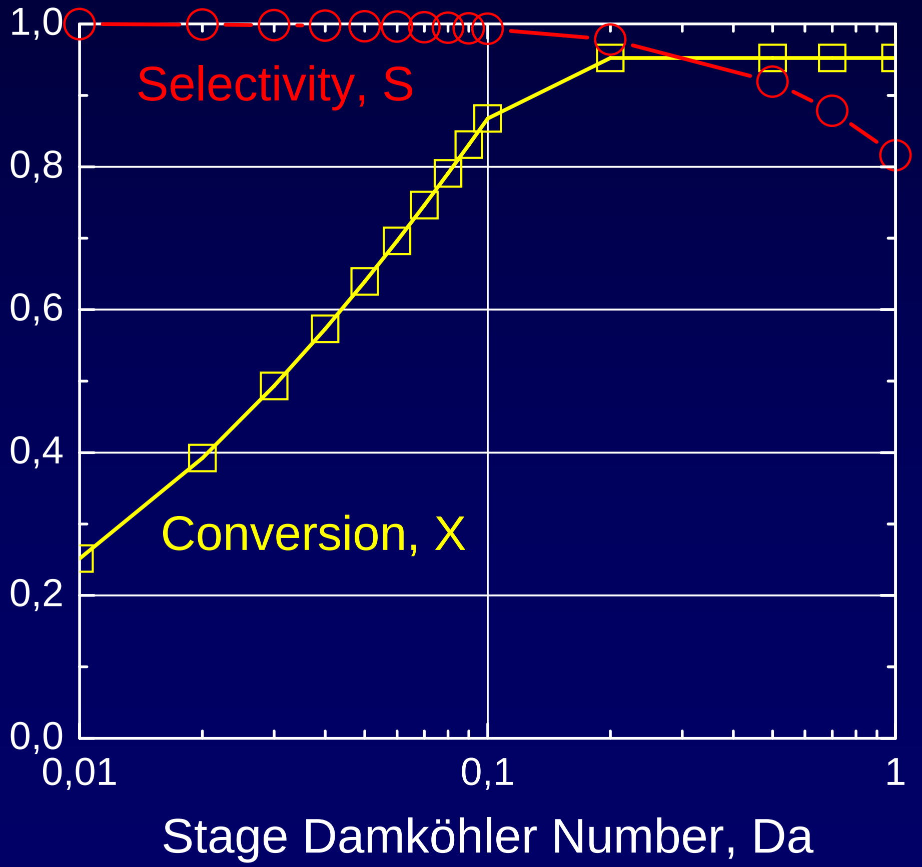
Studies of Side Reactions: Influence of Stage Damköhler Number

Main Rxn 2 B ⇔ A + C
Side Rxn 2 C → 2 D

$\alpha_{AC} = 10$ $K_{eq} = 0.25$
$\alpha_{BC} = 3$ $R = 3.8$
$\alpha_{DC} = 13$

$$r^*_{main} = \frac{x_B^2 - x_A x_C / K_{eq}}{(1 + 5\,x_C)^2} \qquad r^*_{side} = \frac{0.1\,x_C^2}{(1 + 5\,x_C)^2}$$





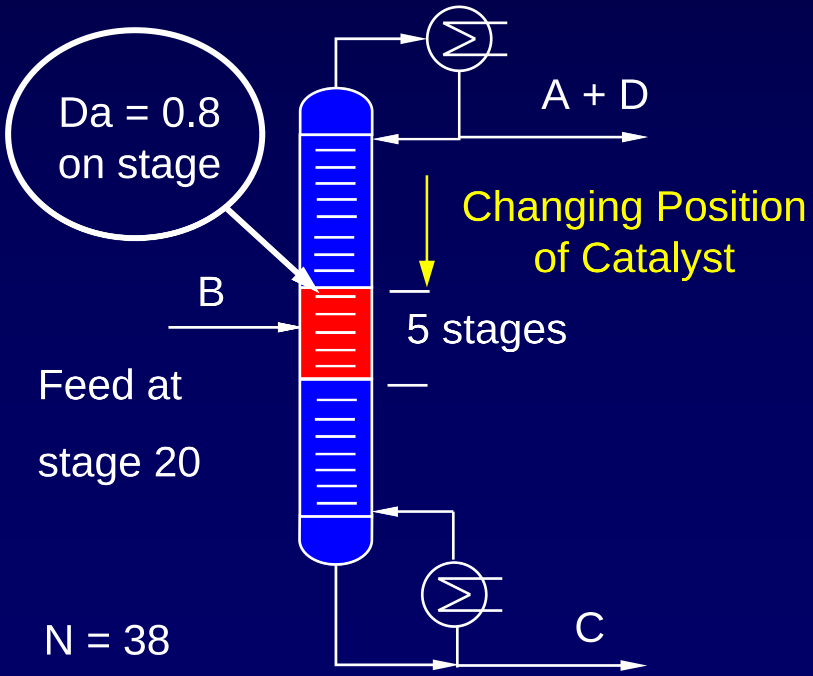
Studies of Side Reactions: Influence of Catalyst Position

Main Rxn 2 B ⇔ A + C
Side Rxn 2 C → 2 D

α_{AC} = 10
α_{BC} = 3
α_{DC} = 13

K_{eq} = 0.25
R = 3.8

$$r^*_{main} = \frac{x_B^2 - x_A x_C / K_{eq}}{\left(1 + 5\, x_C\right)^2} \qquad r^*_{side} = \frac{0.1\, x_C^2}{\left(1 + 5\, x_C\right)^2}$$



Da = 0.8 on stage

A + D

Changing Position of Catalyst

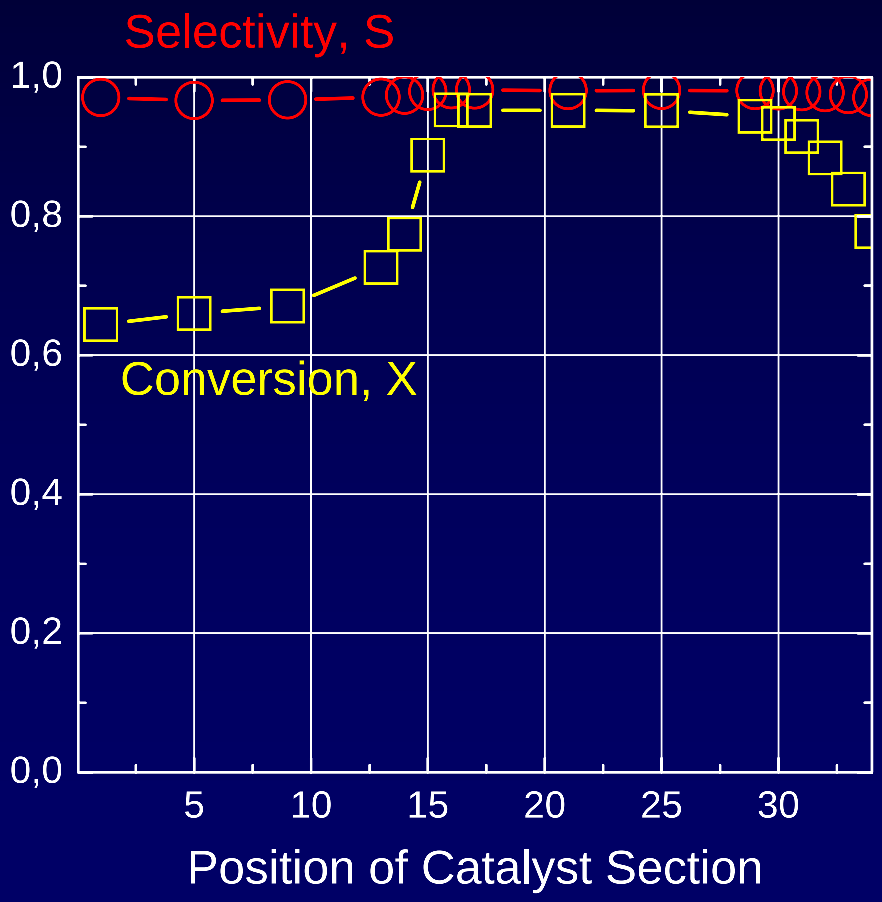
5 stages

B

Feed at stage 20

C

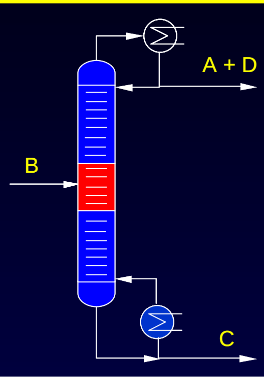
N = 38



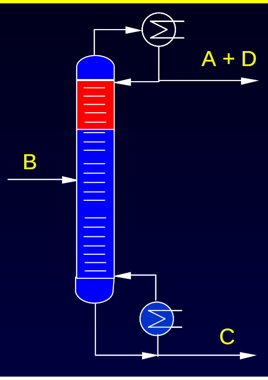
Studies of Side Reactions: Influence of Catalyst Position (Da = 0.2, Reactive Stages = 5)

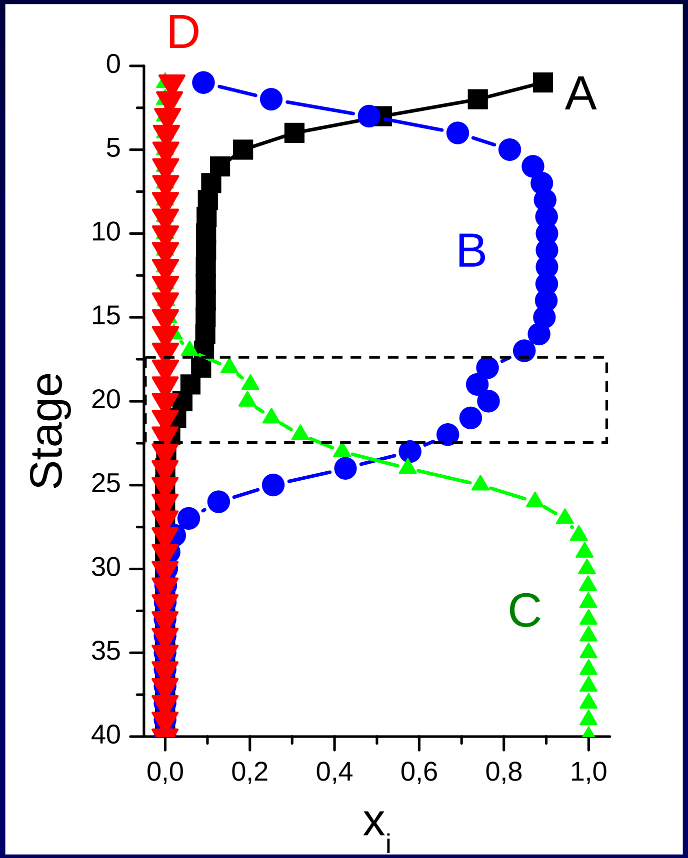
$2\,B \Leftrightarrow A + C$

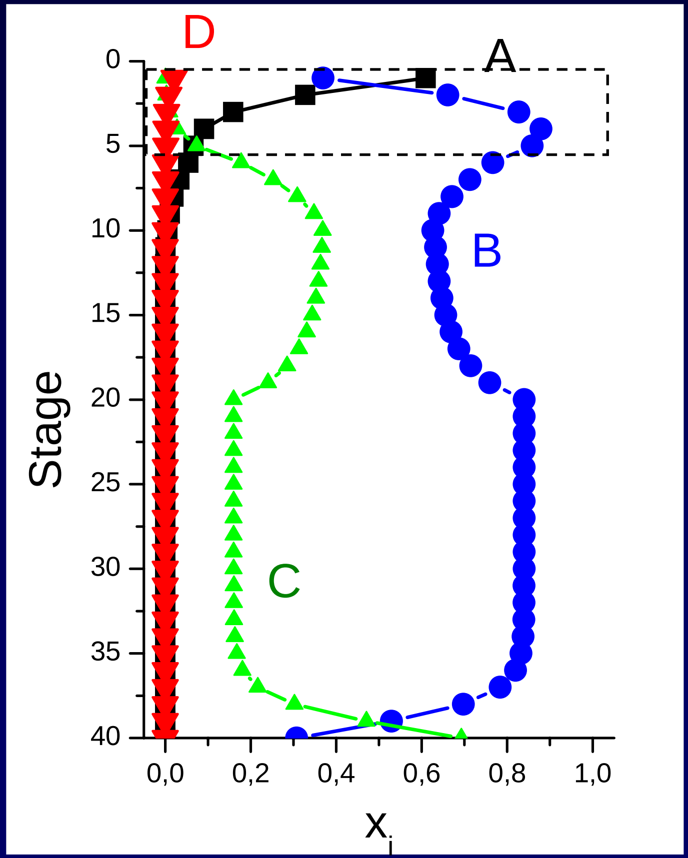
$2\,C \rightarrow 2\,D$



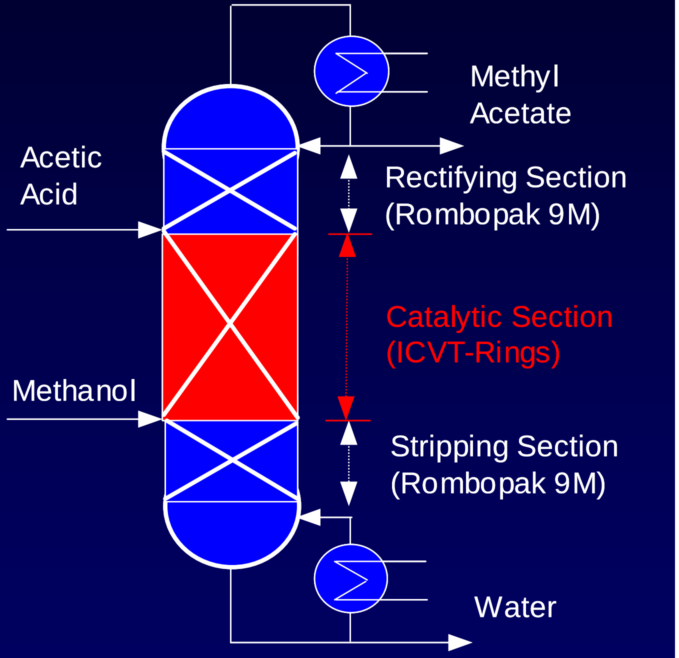
$$\frac{r^*_{main}}{r^*_{side}} \sim \frac{x_B^2 - x_A x_C / K_{eq}}{x_C^2}$$



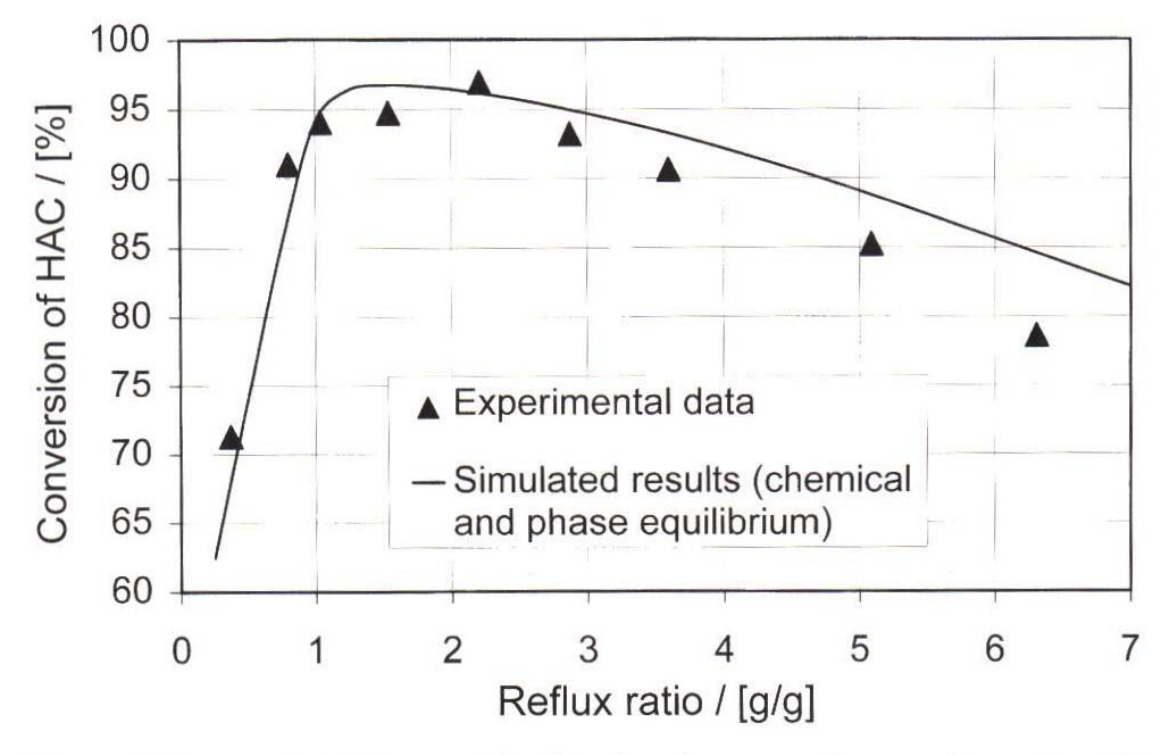




Influence of Reflux Ratio on Conversion



Conversion of Acetic Acid

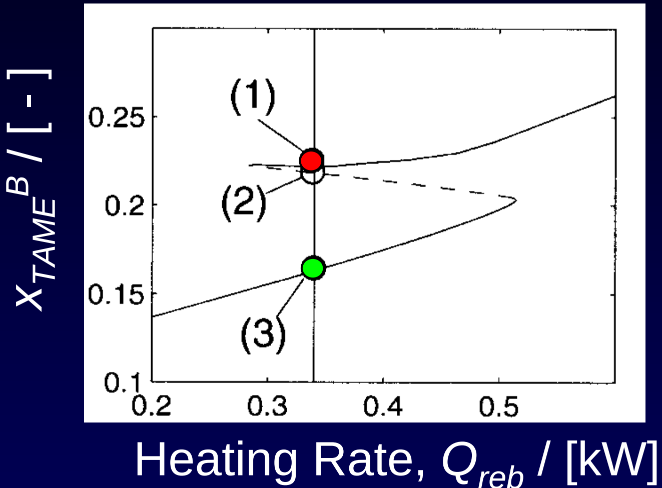


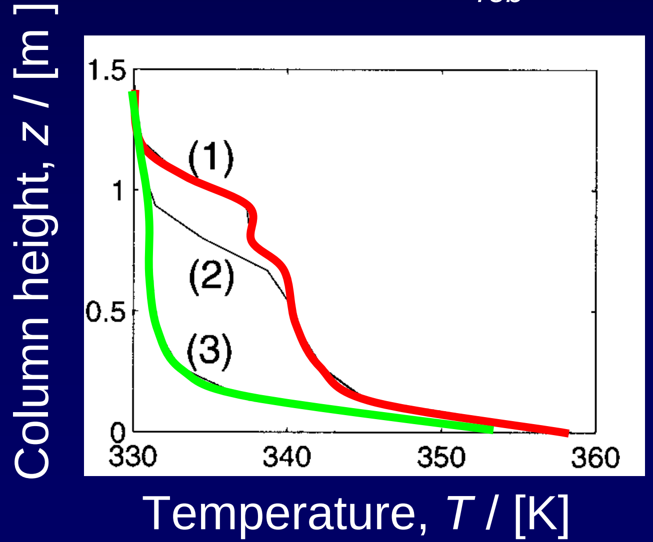
⇨ There is an optimal reflux ratio !

Bessling, B.; Löning, J.M.; Ohligschläger, A.; Schembecker, G.; Sundmacher, K., *Chem Eng. Technol.* ***21*** *(5), 393-400.*

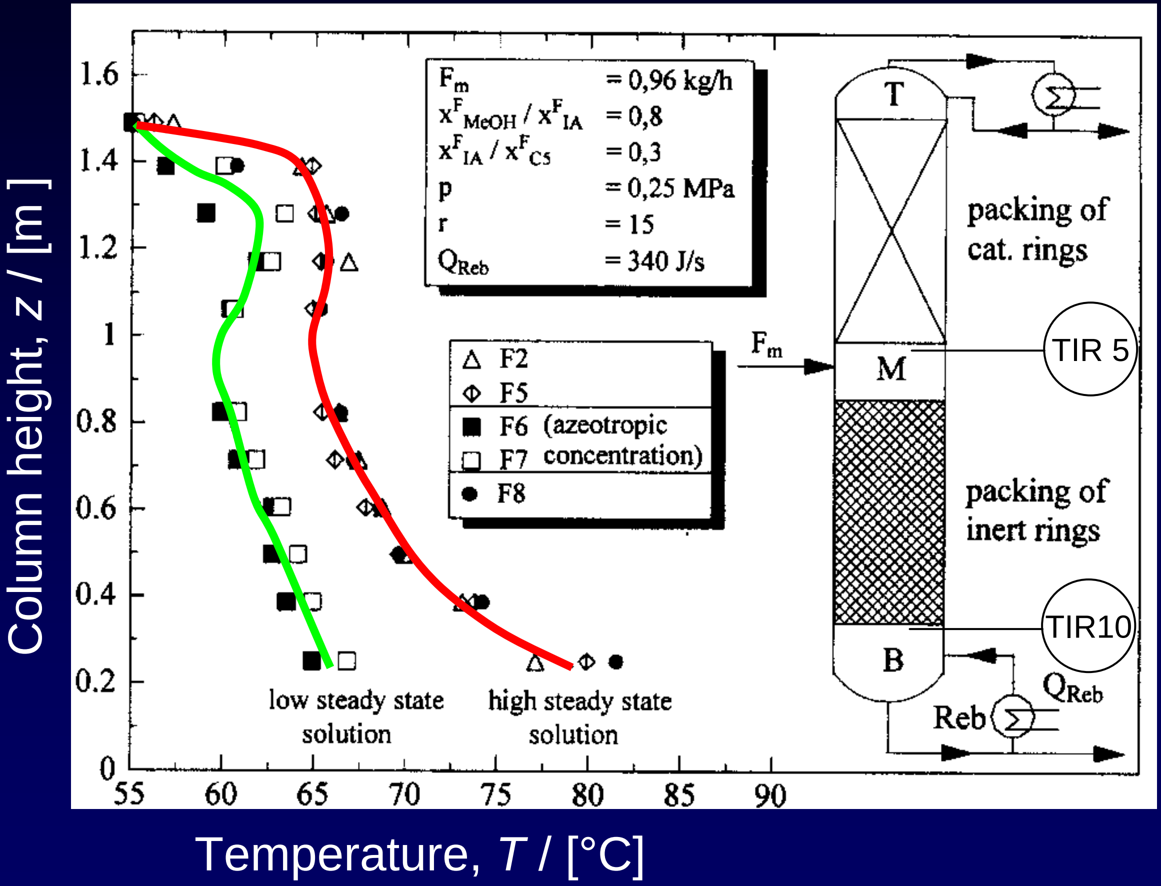
Multiple Steady States of TAME CD Column: Model Predictions and Experimental Results

Model Predictions



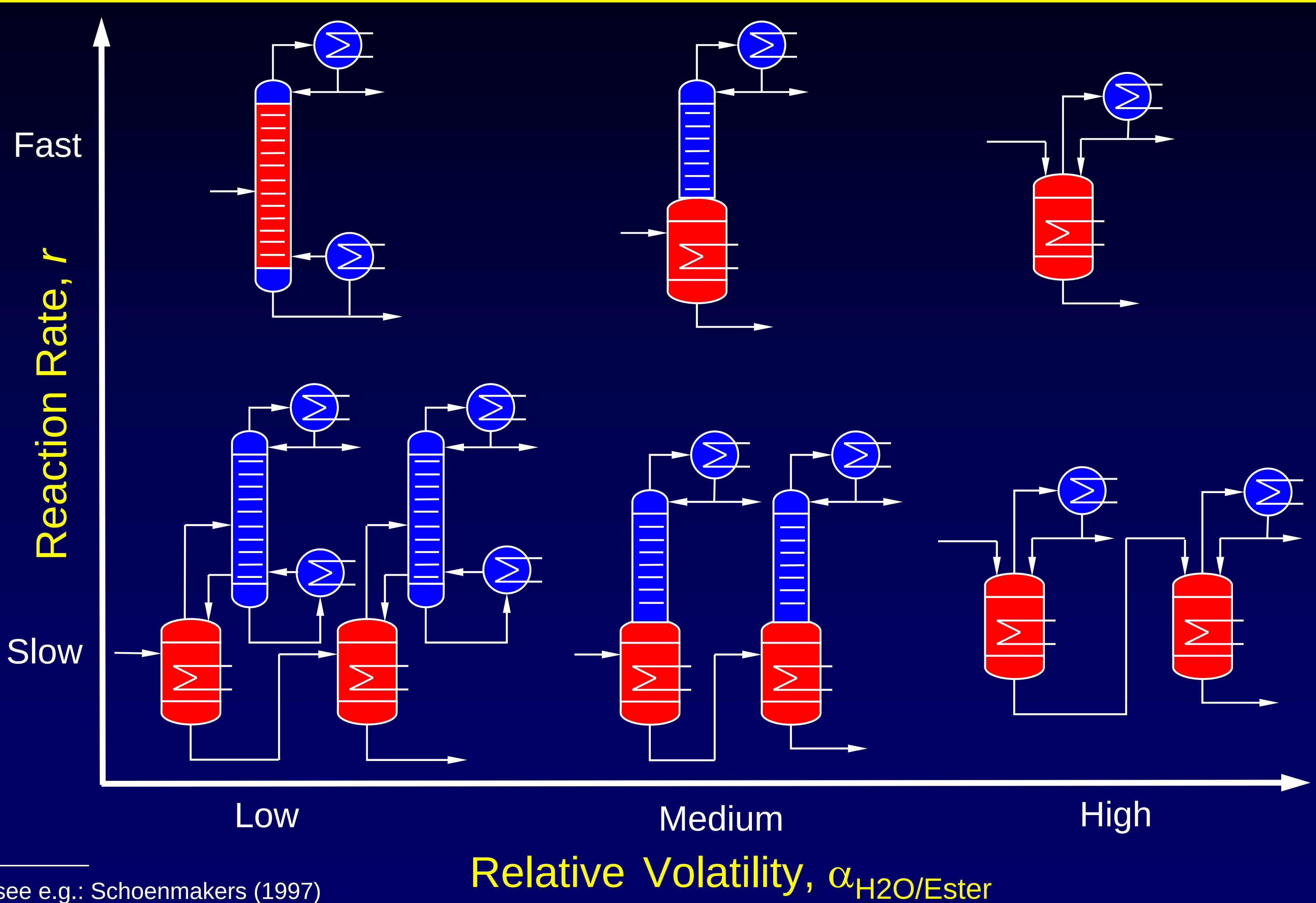


Experimental Liquid Phase Temperatures



Mohl, K.-D.; Kienle, A.; Gilles, E.-D.; Rapmund, P.; Sundmacher, K.; Hoffmann, U., *Chem. Eng. Sci.* 54 (1999) 1029-1043.

Mapping of Reactor-Separator Systems for Esterification: Alcohol + Acid ⇔ Ester + H_2O



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see e.g.: Schoenmakers (1997)

Simple Guideline for CD Reactor Selection

□ Slow reactions: Da << 1

+ reaction kinetics is limiting
+ high residence time
+ hom. catalysis: high liquid holdup
+ het. catalysis: high catalyst holdup

□ Solution

+ tray column (bubble caps)
+ packed column with random packing
+ column with external side reactors

□ Fast reactions: Da ≥ 1

+ mass transfer is limiting
+ low residence time sufficient
+ hom. catalysis: low liquid holdup
+ het. catalysis: low catalyst holdup

□ Solution

+ packed column
+ tray column with low holdup

increase p

Process Examples of Catalytic Distillation

Motives for Application of Reactive Distillation

	Motives	Examples
Reaction Problems	Overcoming Limitations of Chemical Equilibrium	Methanol + Acetic Acid ⇔ Methyl Acetate + H_2O Methanol + Isobutene ⇔ Methyl-*tert*.-butylether (MTBE) Formaldehyde + 2 Methanol ⇔ Methylal + H_2O
	Increase of Selectivity	Chlorohydrins → Propylene Oxide + H_2O → Proplene Glycol 2 Acetone → Diacetone Alcohol → Mesityl Oxide + H_2O Isobutane + 1-Butene → Isooctane + 1-Butene → $C_{12}H_{24}$
	Use of Heat of Reaction	Propene + Benzene → Cumene Ethylene Oxide + H_2O → Ethylene Glycol
Separation Problems	Separation of Closely Boiling Mixtures	m-Xylene / p-Xylene (Reactive Entrainer: Na-p-Xylene) Cyclohexene / Cyclohexane (Reactive Entrainer: Formic Acid) 1-Butene / Isobutene (Reactive Entrainer: Methanol / Water)
	Breaking of Azeotropes	Methyl Acetate / Water ; Methyl Acetate / Methanol (Entrainer: Acetic Acid)
	High Purity Separation	Hexamethylene Diamine / Water (in Nylon 6,6 process) (Reactive Entrainer: Adipic Acid)

See e.g.: Sundmacher, K., Rihko, L., Hoffmann, U., *Chem. Eng. Commun.* **127** (1994) 151-167.

Production of Methyl Acetate

Reaction:

Acetic Acid + Methanol $\overset{H^+}{\rightleftarrows}$ MeAc + Water

Catalysts: H_2SO_4 / Acidic Ion Exchange Resin

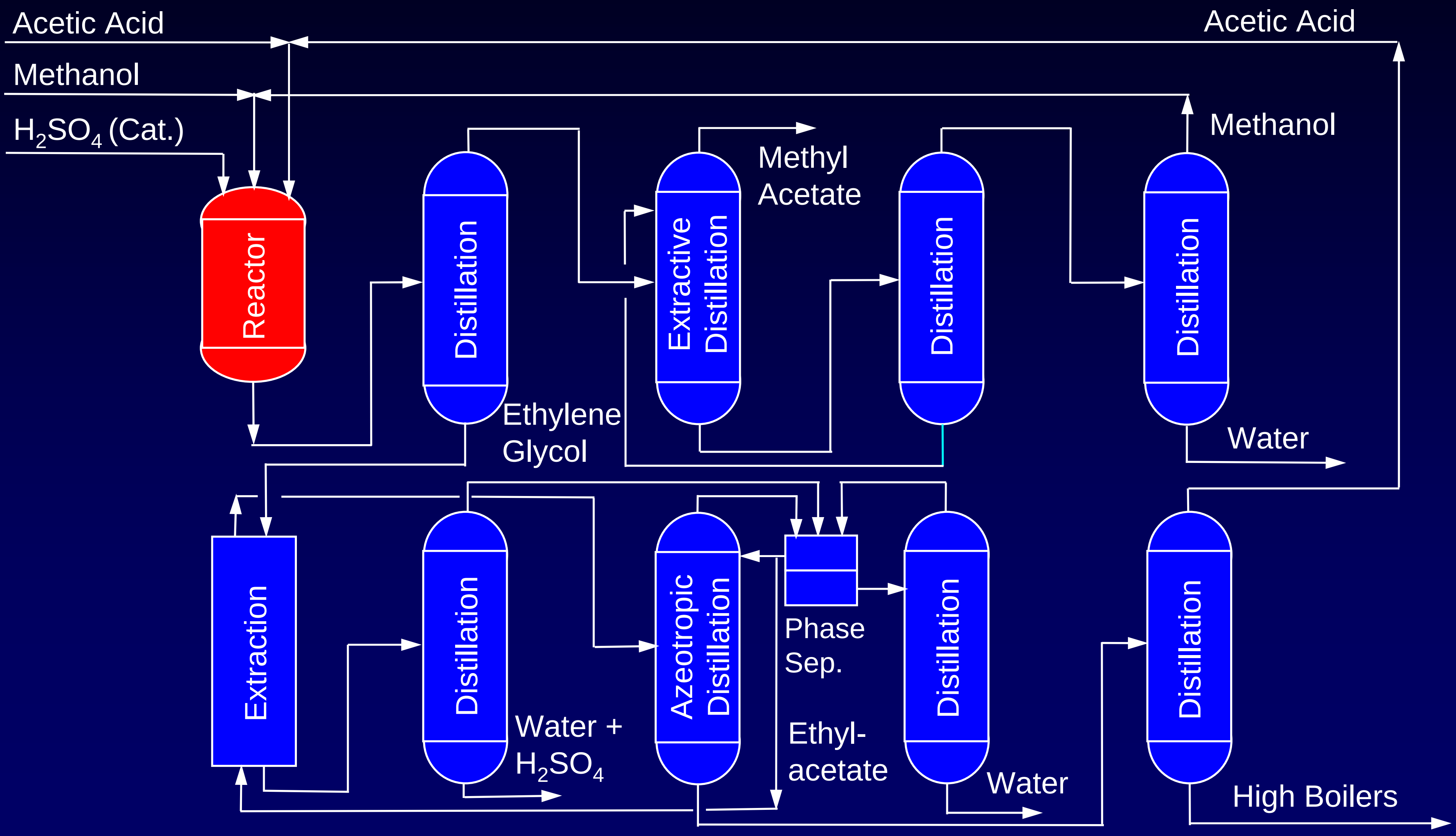
Chemical Equilibrium Constant: $K_x(25°\mathrm{C}) = 5.2$

Boiling Sequence at $p = 0.1$ MPa:

hom. azeotrope MeAc/Methanol	53.8 °C
hom. azeotrope MeAc/Water	56.7 °C
Methylacetate (MeAc)	56.9 °C
Methanol	64.6 °C
Water	100.0 °C
Acetic Acid	118.0 °C

L/L-phase splitting: in ternary system MeAc/Methanol/Water

Production of Methyl Acetate (Conventional Process)



Acetic Acid

Methanol

H_2SO_4 (Cat.)

Reactor

Distillation

Ethylene Glycol

Extractive Distillation

Methyl Acetate

Distillation

Distillation

Methanol

Acetic Acid

Water

Extraction

Distillation

Water + H_2SO_4

Azeotropic Distillation

Phase Sep.

Ethyl-acetate

Distillation

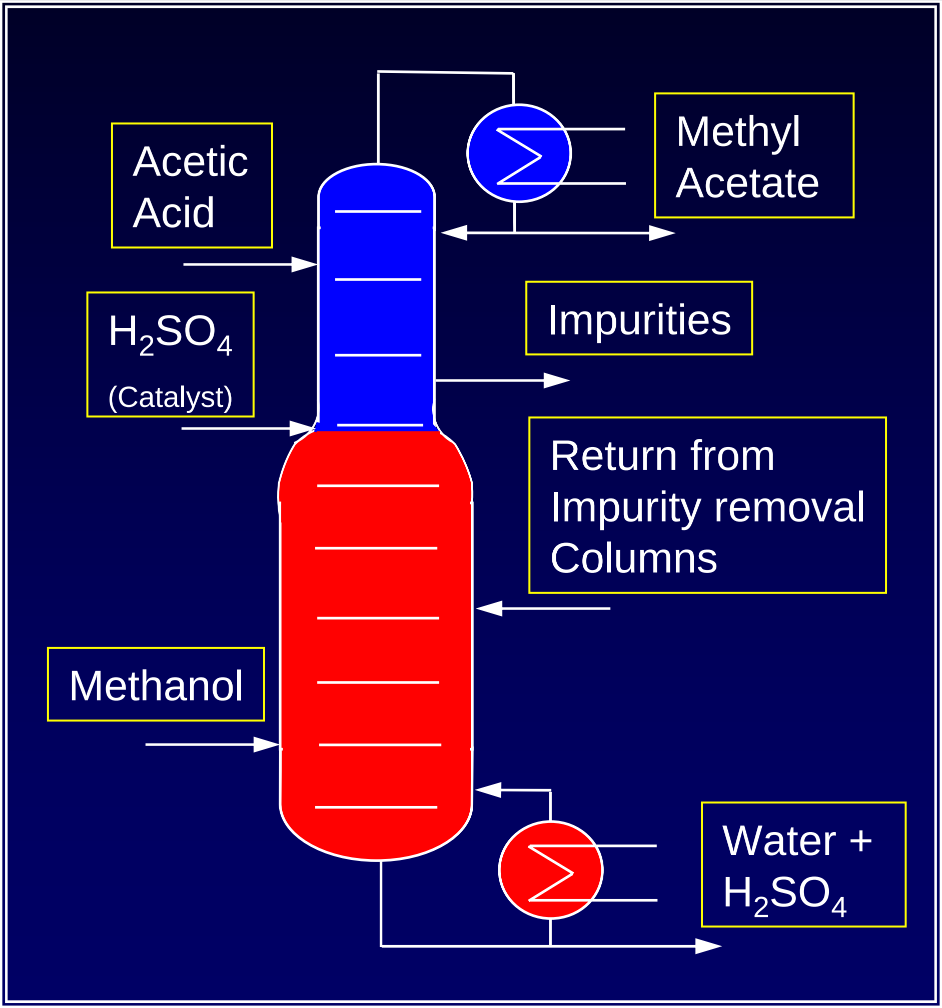
Water

Distillation

High Boilers

Production of Methyl Acetate (CD Processes)

Homogeneously Catalyzed Reaction*



Acetic Acid

H_2SO_4 (Catalyst)

Methanol

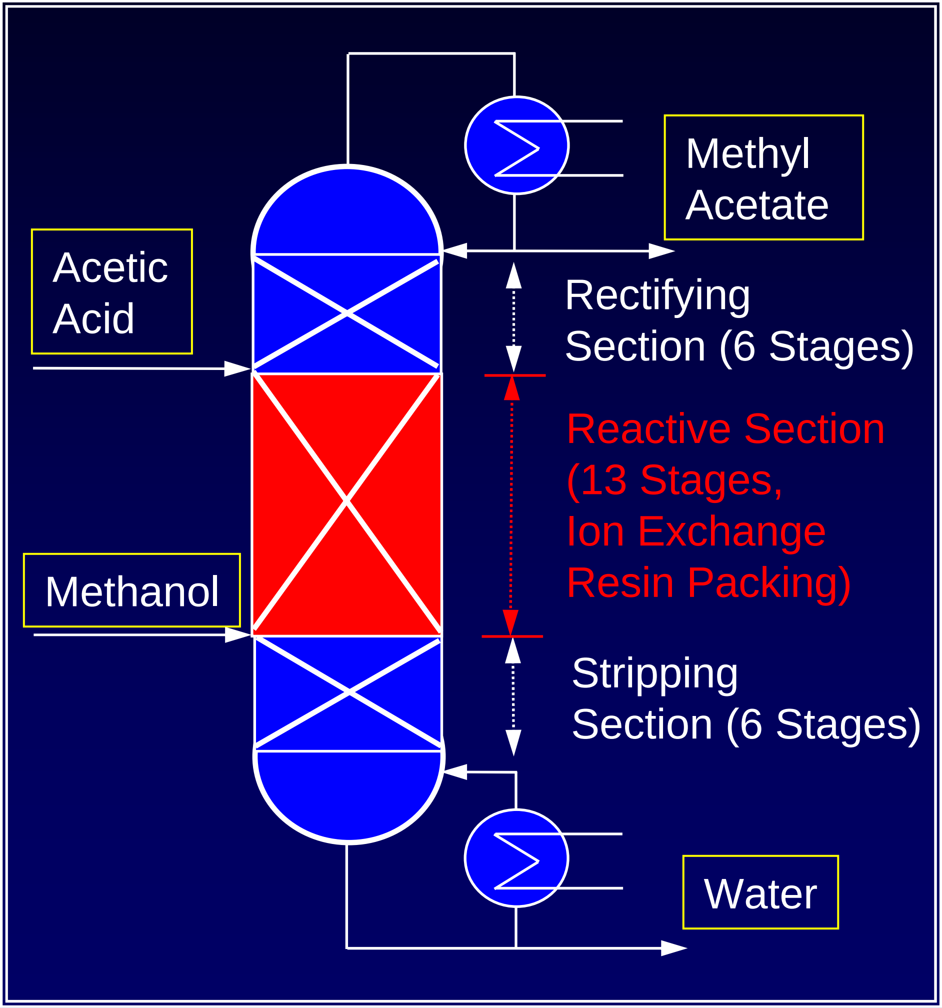
Methyl Acetate

Impurities

Return from Impurity removal Columns

Water + H_2SO_4

Heterogeneously Catalyzed Reaction**



Acetic Acid

Methanol

Methyl Acetate

Rectifying Section (6 Stages)

Reactive Section (13 Stages, Ion Exchange Resin Packing)

Stripping Section (6 Stages)

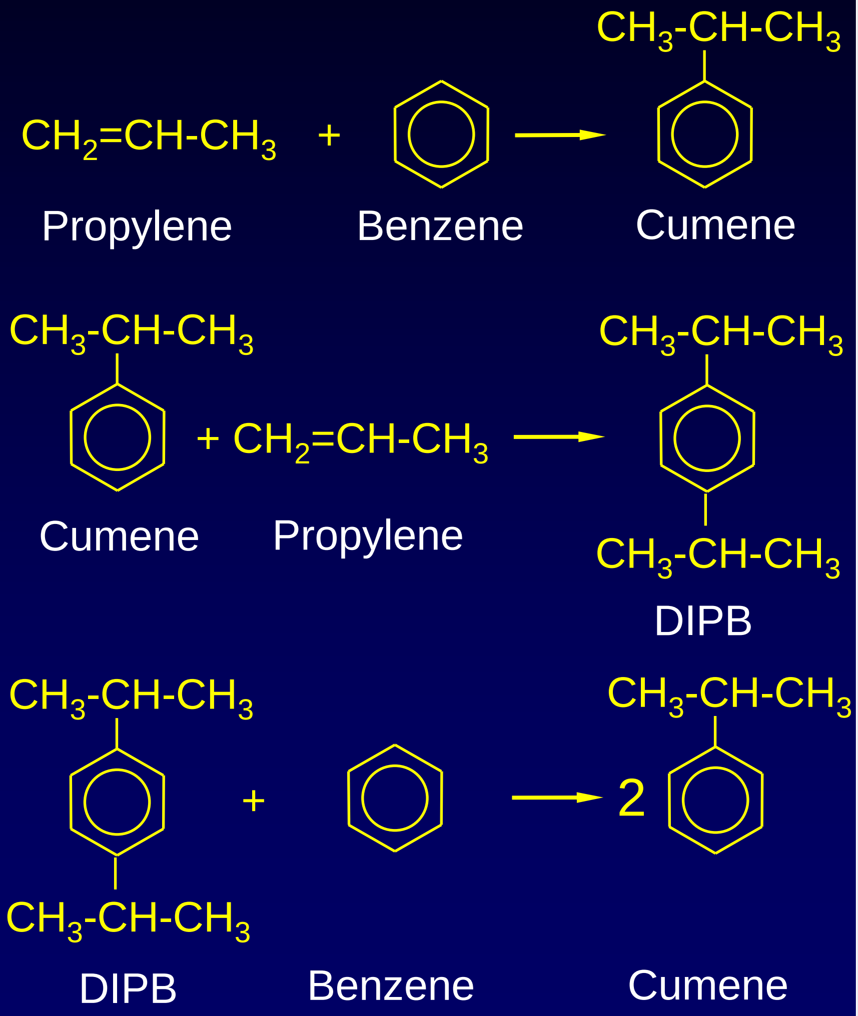
Water

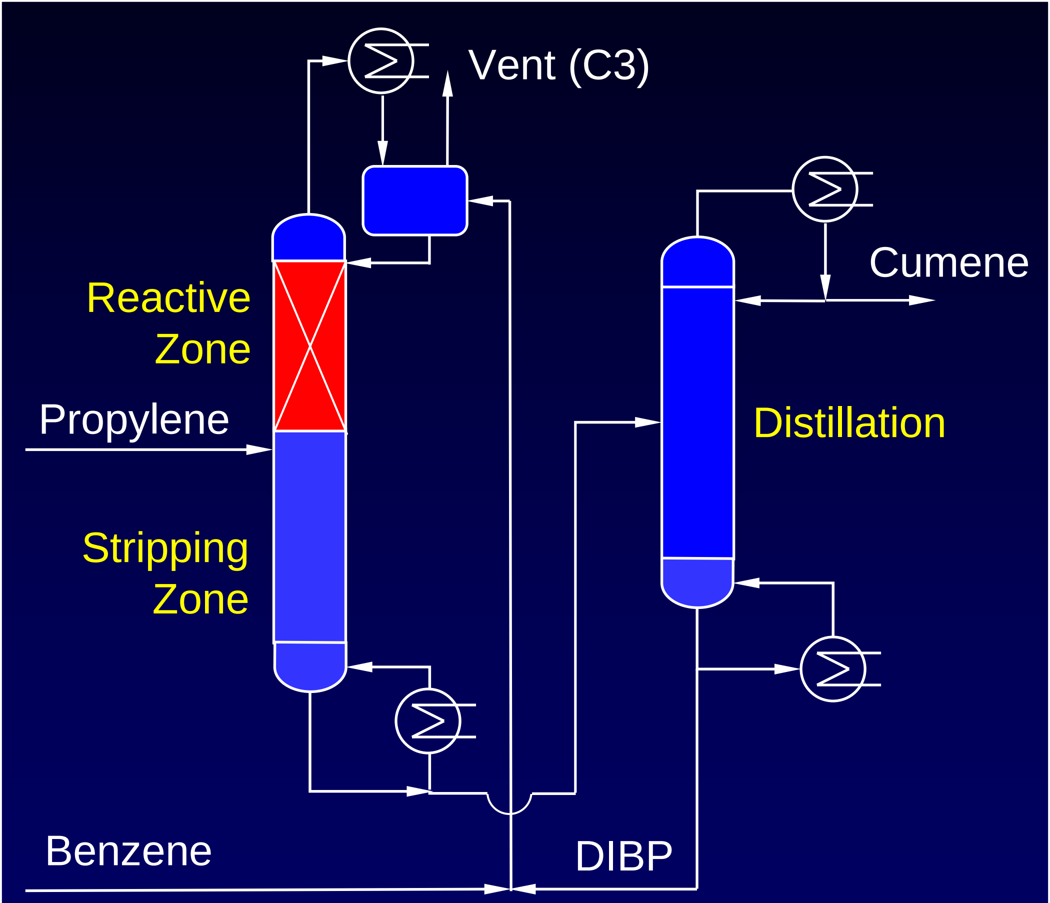
* Agreda, V.H.; Partin, L.R., US Patent No. 4,435,595 (1984, Eastman-Kodak-Process)

Bessling, B.; Löning, J.-M.; Ohligschläger, A.; Schembecker, G.; Sundmacher, K., *Chem. Eng. Technol.* **21 (1998) 393-400.

CD Application for Highly Exothermic Reactions
Example: Cumene Production

Reaction Scheme





- p = 3 - 10 bar, $T_{max} \approx 250$ °C
- Solid acid catalyst
- Reaction heat: $(-\Delta_R H) \approx 113$ kJ/mol
- By-product formation favored at higher T

Shoemaker, J.D., Jones, E.M., *Hydrocarbon Processing* (1987) 57-58.

RD Application for High Purity Separation, Example: C4-Separation (Hüls-UOP*)

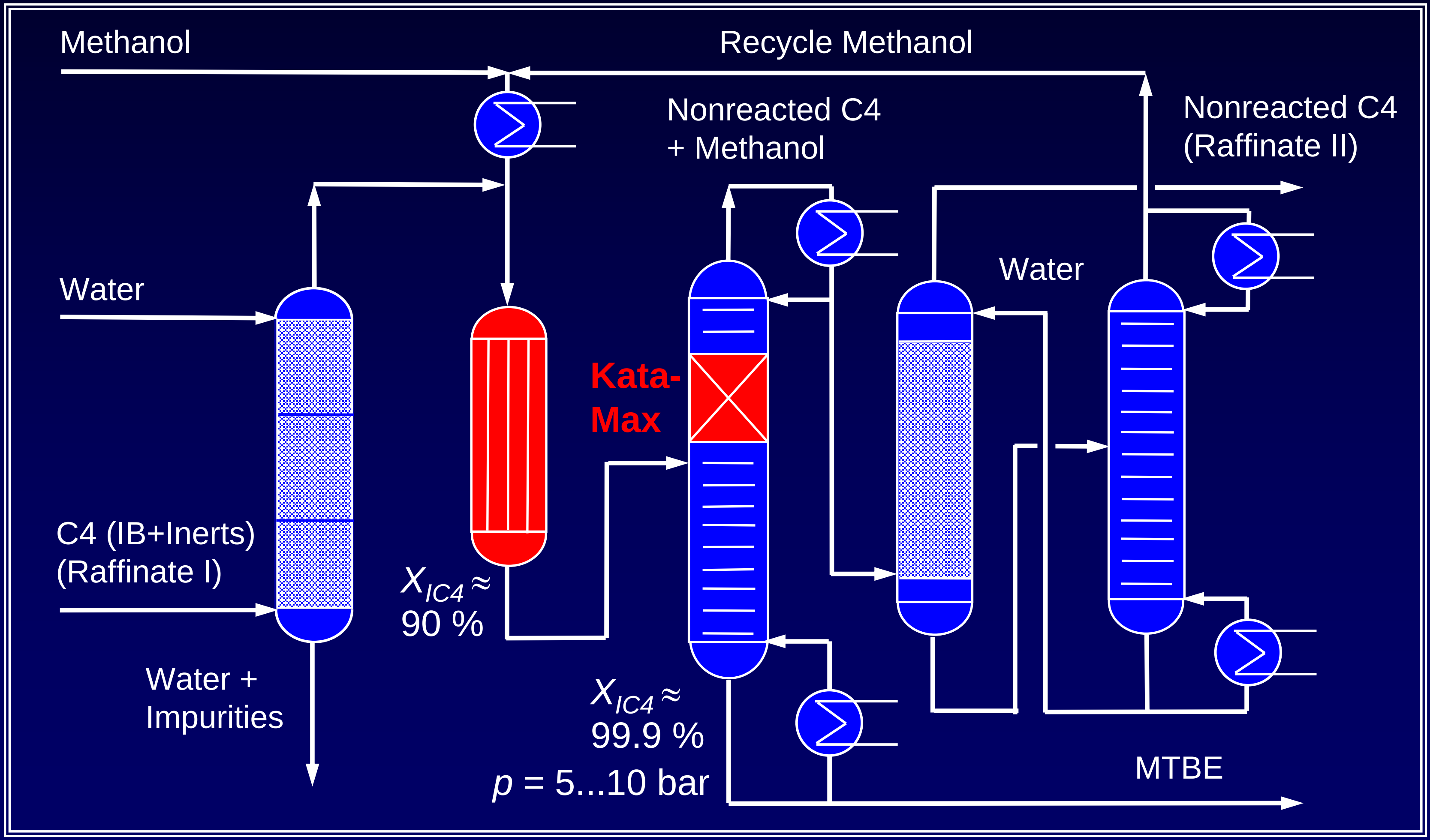
Feed Wash

Fixed Bed Tubular Reactor

Reactive Distillation Column

Methanol Extraction

Methanol/ Water Distillation



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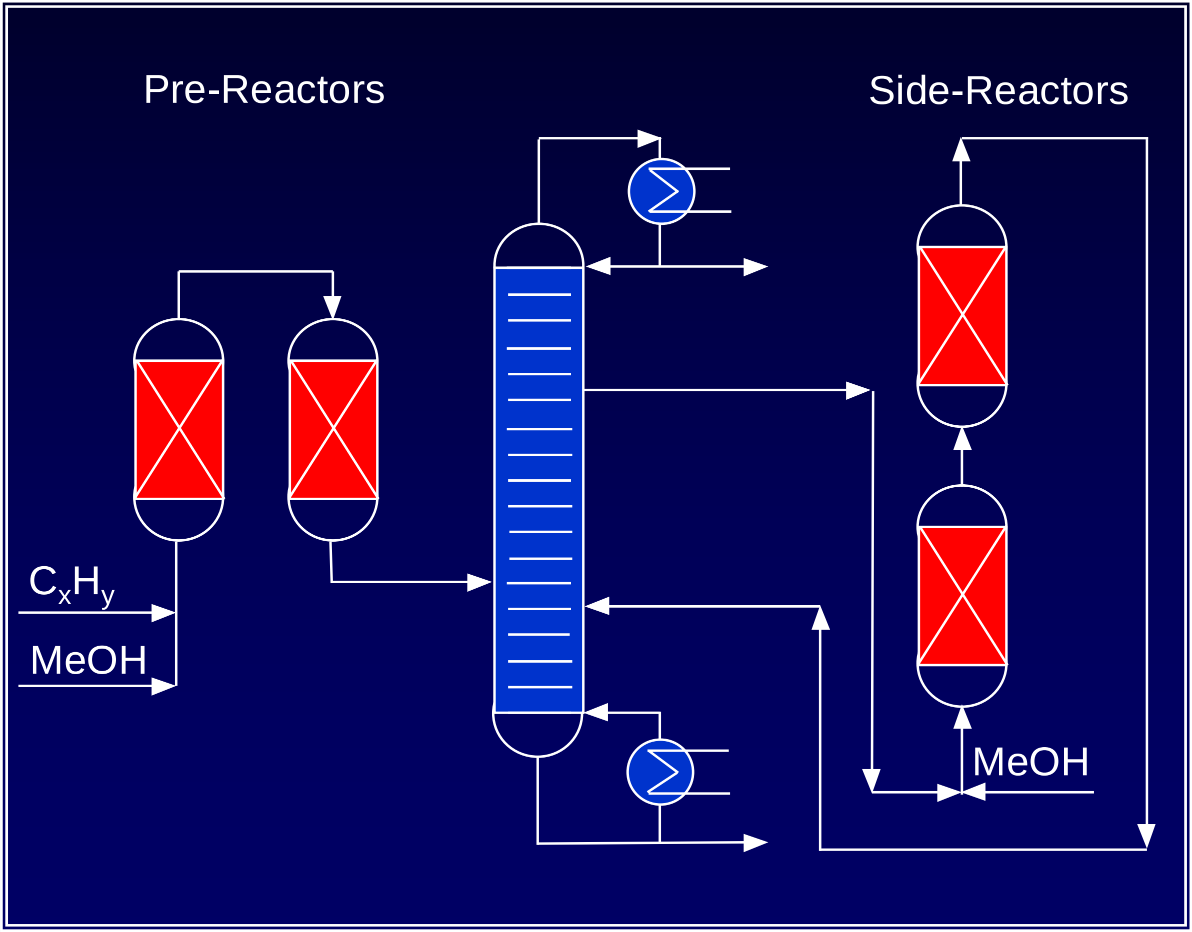
see e.g.: anonymus, *Hydrocarbon Processing* **73** (1992) 104-110.

* approx. 32 % market share

RD System based on Pre- and Side Reactors

Ether Production Flow Scheme (Neste Oil)



<u>Advantages</u>

- easy catalyst replacement
- easy control of reactant-ratio
- independent of specific catalyst packing
- distillation column hydraulics and mass transfer not affected by catalyst structure
- high *Da*/*N*-ratio achievable

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see e.g.: Aittamaa, J., Eilos, I., Jakkula, J., Lindqvist, P., US 5 637 777 (1997)

Catalytic Packings: Aspects of Selection

Reaction Rate
(Catalyst Holdup: ε_{cat})

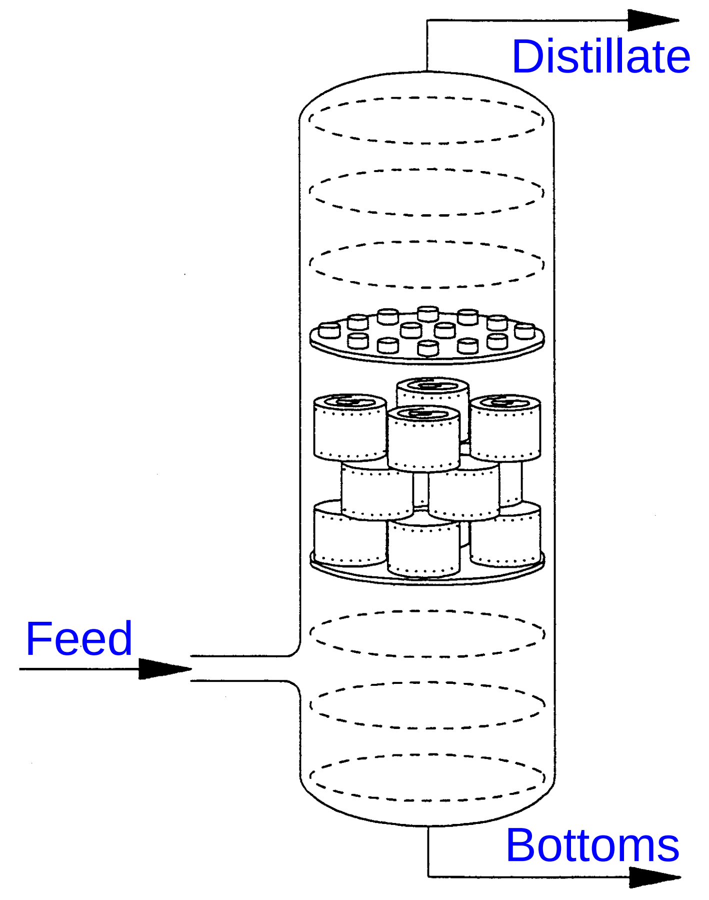
Catalytic Packing

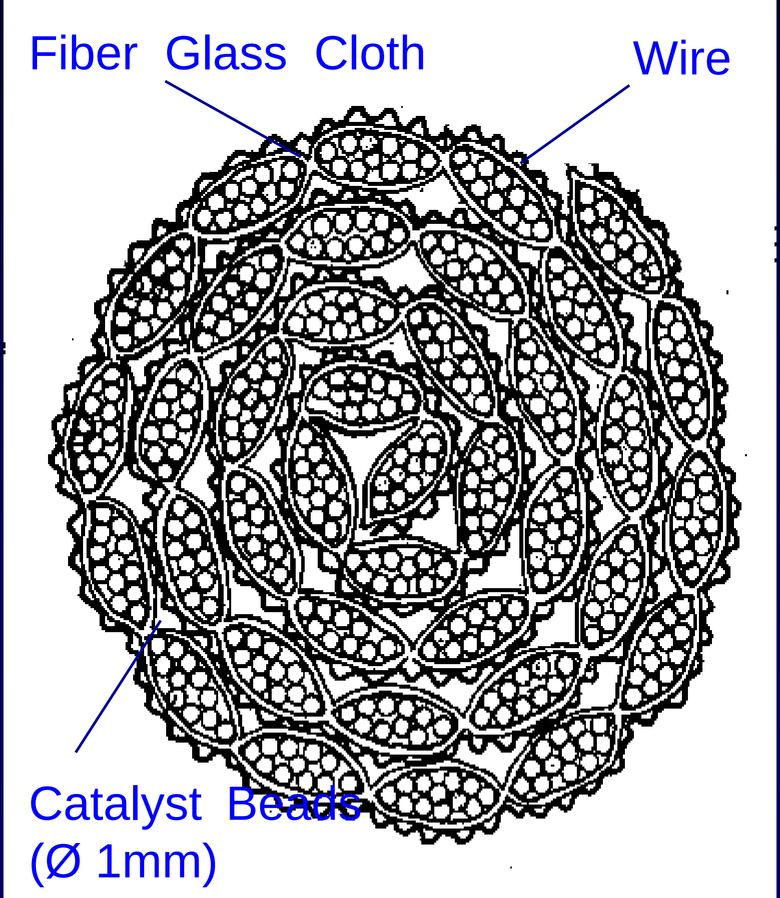
in CD Columns

Hydraulic Capacity
(Void Fraction: $1 - \varepsilon_{cat}$)

Mass Transfer
Efficiency
(Number of Theoretical
Stages: NTSM)

Catalytic Bales (CD Tech)





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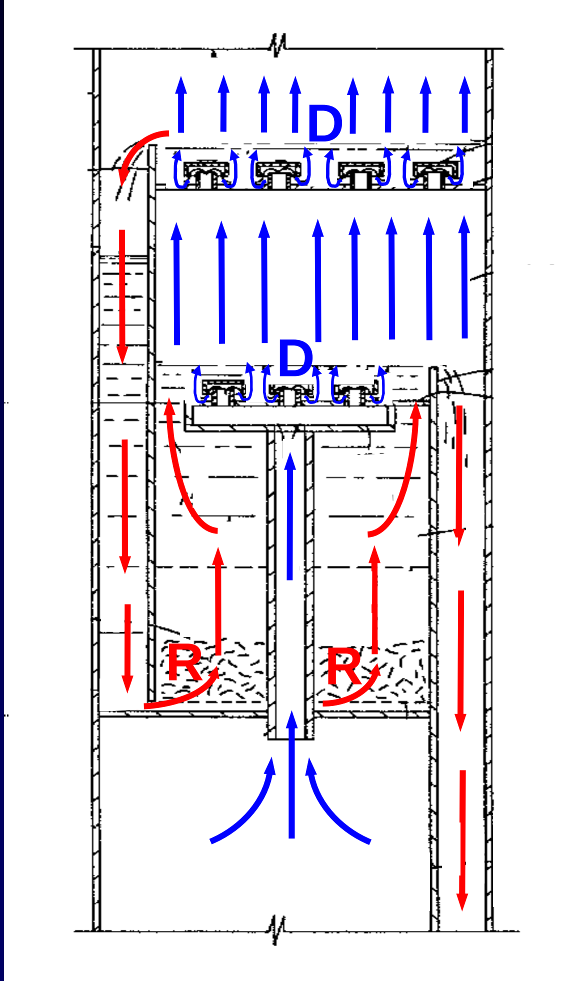
see e.g. Smith, L. A. *et al.*, EP 466954 A1 (1990)

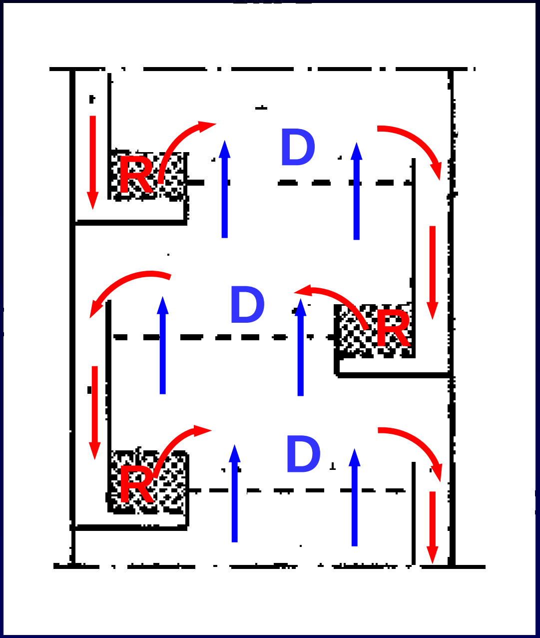
Catalytic Distillation Trays

CR & L



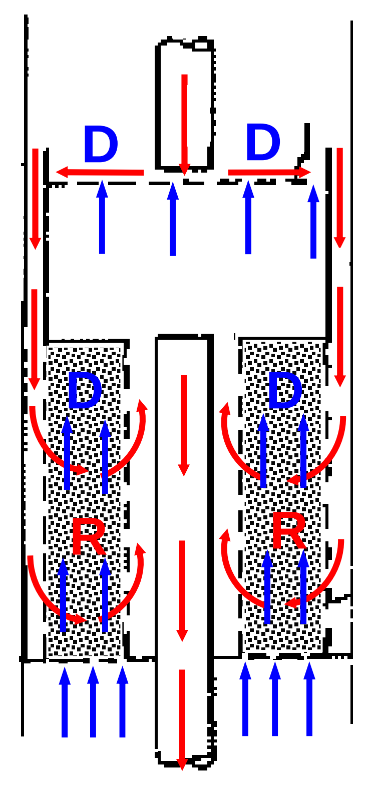
Jones Jr., Edward M., US 5130102 (1992)

IFP



Lionel, A. *et al.*, US 5368691 (1994)

SNAMPROGETTI



Domenico, S. *et al.*, US 5493059 (1996)

Structured Catalytic Packings

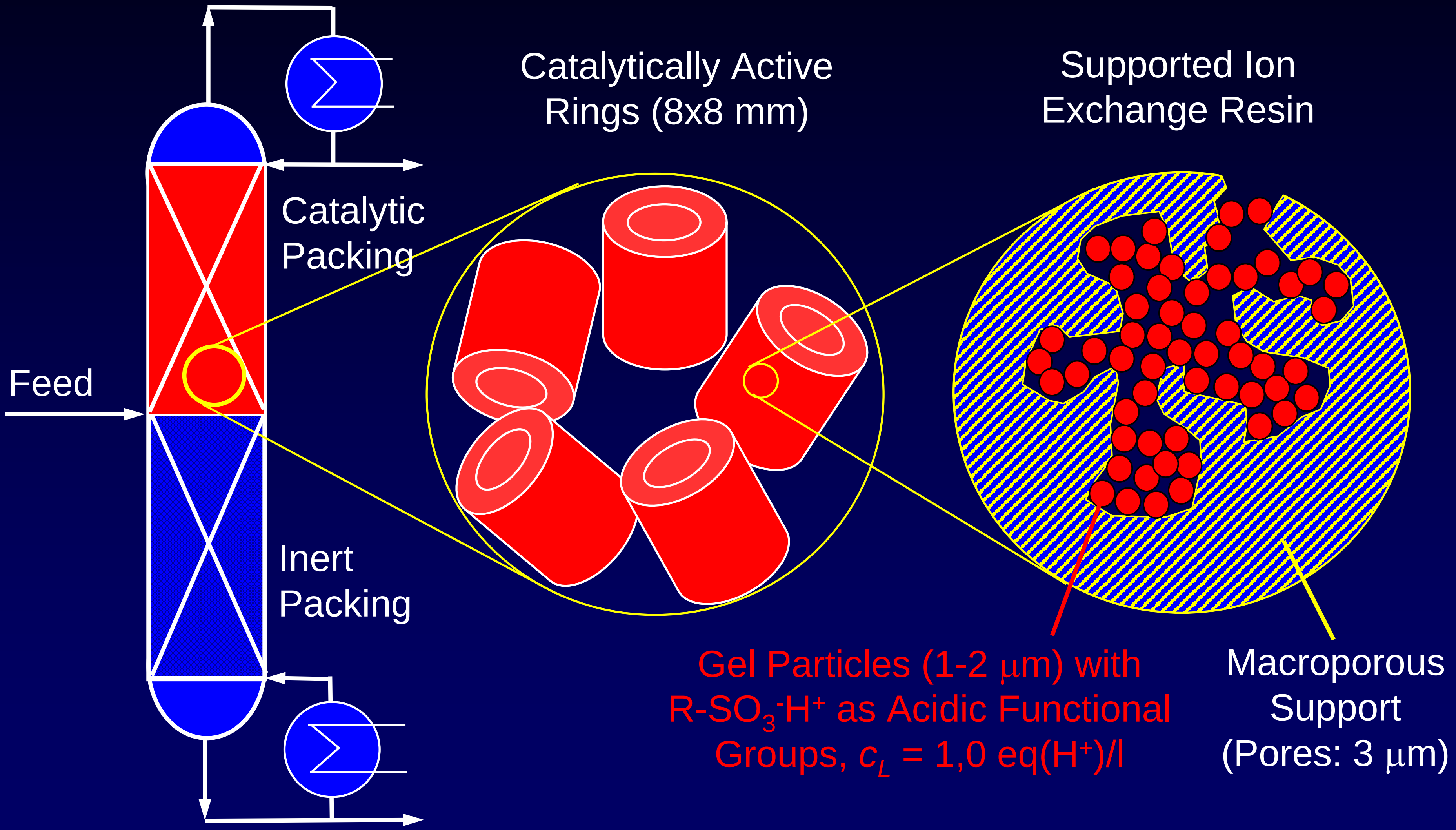
KATAPAK-S (Sulzer Chemtech)

MULTIPAK (Julius Montz)

Stringaro, J.P., EP 631813 A1 (1993)

Gorak, A., Kreul., L. U., DE 197 01 045 A1 (1998)

Catalytic Distillation Process for Fuel Ether Production (TU Clausthal)



Feed

Catalytic Packing

Inert Packing

Catalytically Active Rings (8x8 mm)

Supported Ion Exchange Resin

Gel Particles (1-2 μm) with R-$SO_3^-H^+$ as Acidic Functional Groups, c_L = 1,0 eq(H^+)/l

Macroporous Support (Pores: 3 μm)

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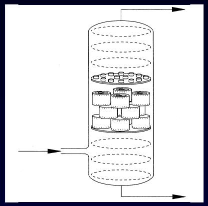
see e.g.: Hoffmann, U. *et al.*, DP 4234779.3 (1992); Sundmacher, K. and Hoffmann, U. (1996) *Chem. Eng. Sci.* 51, 2359-2368.

Some Properties of Catalytic Packings

				Katapak
Void Fraction	$[m^3/m_{col}^3]$	0.49	0.75[*]	0.75[*]
Catalyst Loading	$[m_{cat}^3/m_{col}^3]$	0.51	0.20[*]	0.20[*]
Catalyst Surface-to-Volume Ratio	$[m_{cat}^2/m_{cat}^3]$	1129	4000[*]	4000[*]
Packing Surface-to-Volume Ratio	$[m_{cat}^2/m_{col}^3]$	576	800[*]	800[*]

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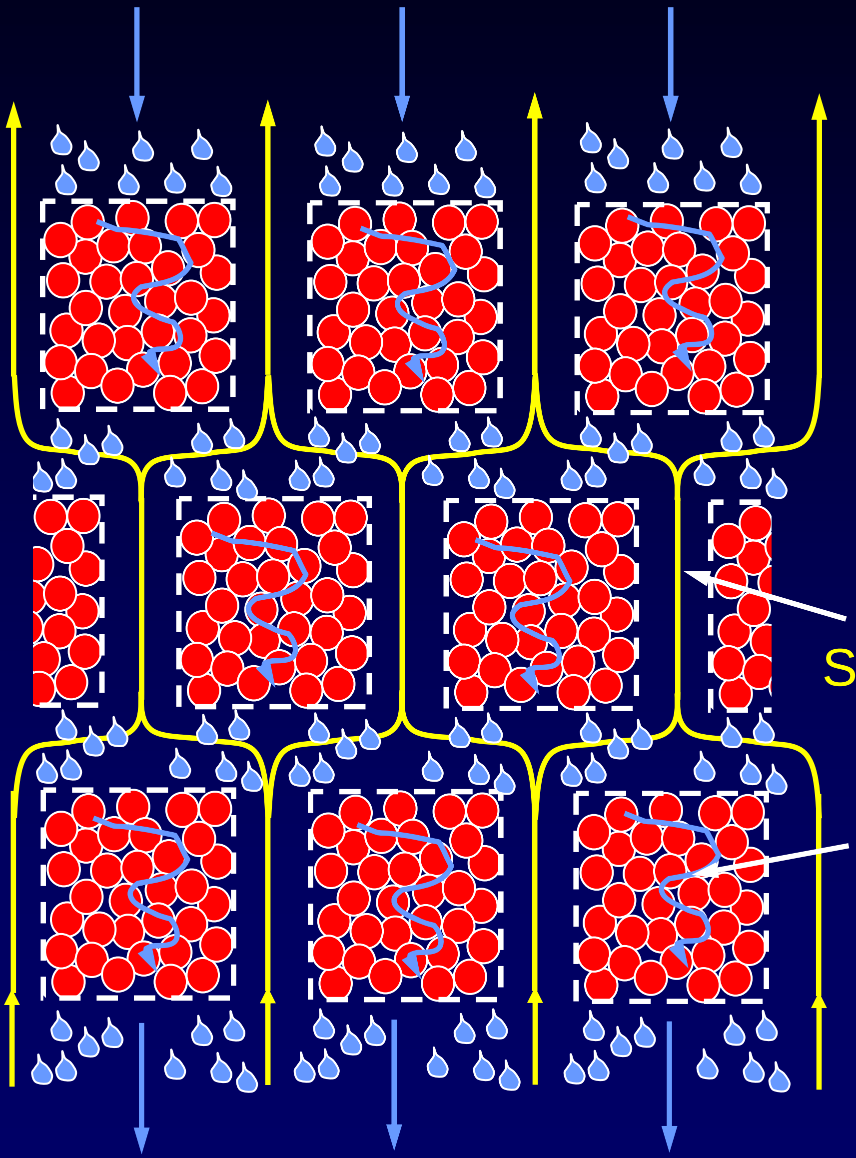
[*] See: Lebens, P. J. M., Kapteijn, F., Sie, T.N., Moulijn, J.A., *Chem. Eng. Sci.* 54 (1997) 1359-1365.

Three-Levels-of-Porosity Concept

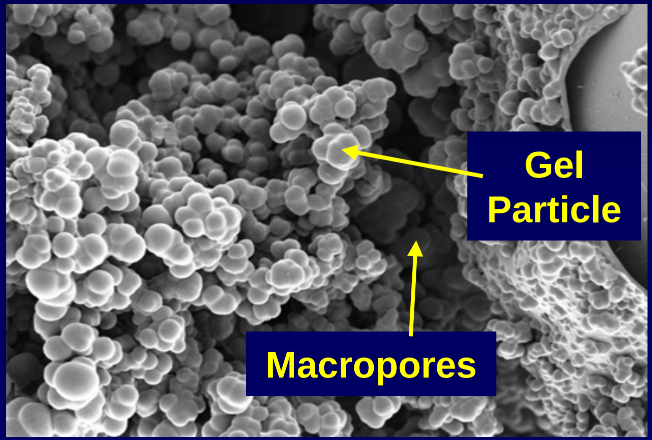


Three Pore Levels:

I. Pores <u>inside</u> catalytic particles

II. mm-Pores <u>between</u> catalytic particles

III. cm-Pores between the catalytic pockets



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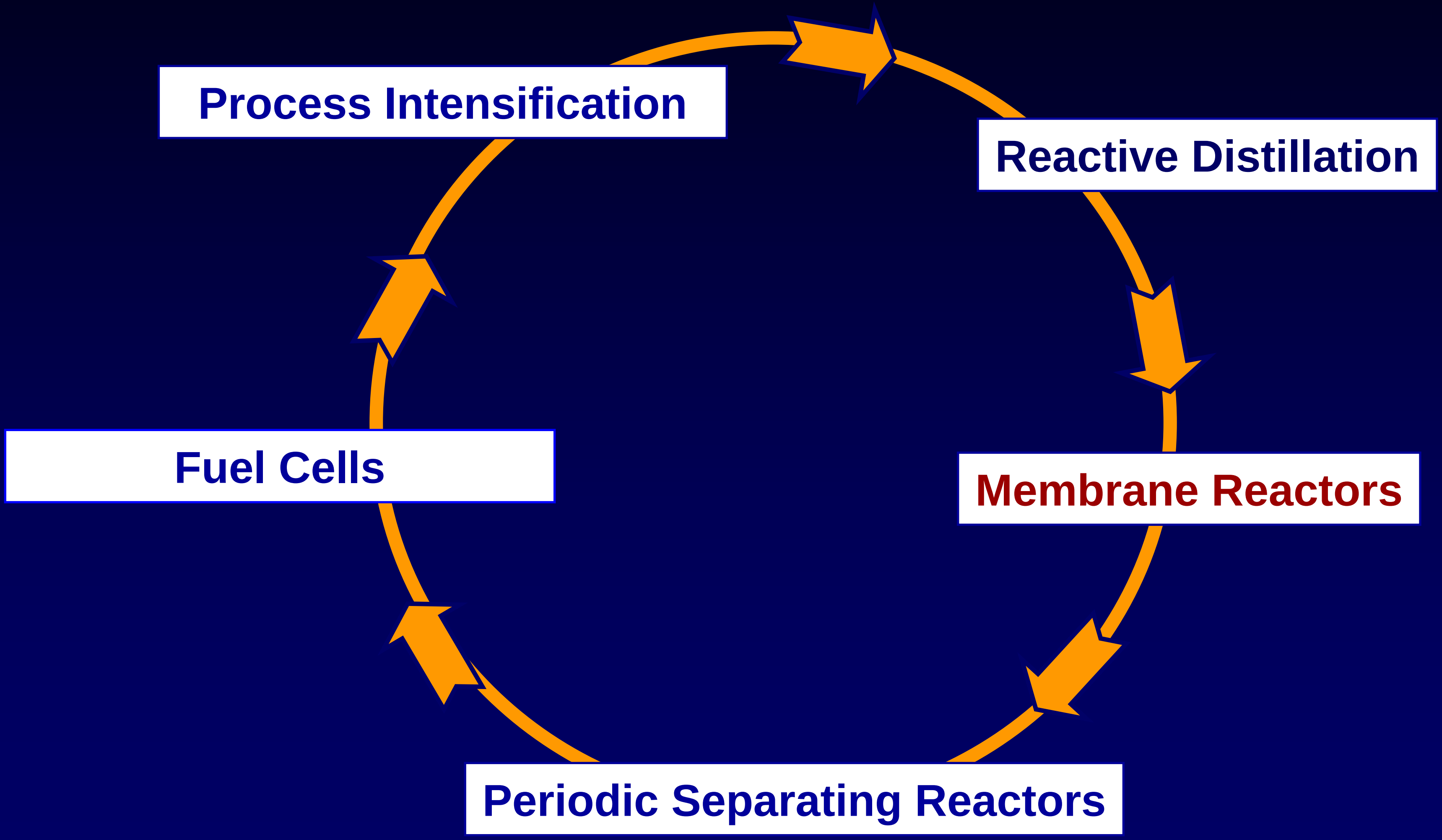
see e.g.: Krishna, R., Sie, S.T., *Chem. Eng. Sci* **49** (1994) 4029-4065.

Summary RD

- Reduced downsteam processing
- Overcoming limitations of thermodynamic equilibrium
- Breaking of azetropes
- Increasing selectivity
- Utilisation of the ΔH_r for evaporation
- Separation of isomeric mixtures

- Compatible *T-p* range
- Very slow reactions
- Gas-liquid reaction (high T and p)
- Catalyst life time

Integrated Catalytic Processes –Lecture Outline



Process Intensification

Reactive Distillation

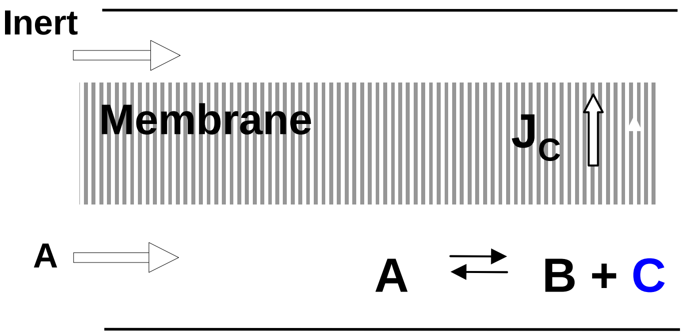
Membrane Reactors

Periodic Separating Reactors

Fuel Cells

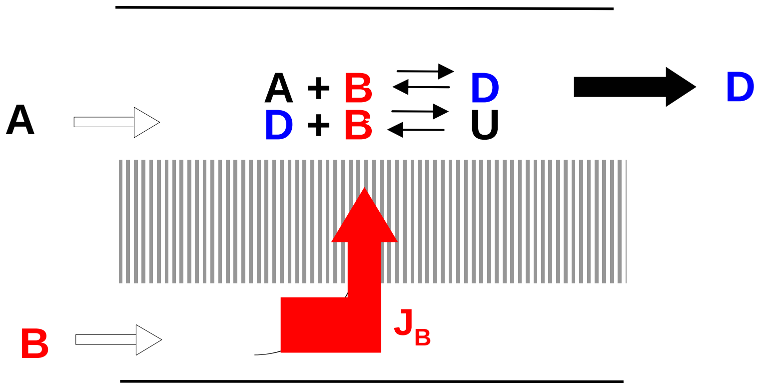
Catalytic Membrane Processes

Selective product removal („Extractor“)



- enhanced conversion of reversible reactions

Controlled reactant dosing („Distributor“)



- dosing of critical reactants
- selectivity improvements
- cleaning of B from impurities

Advantages:

- „overcome“ equilibrium
- suppress unwanted subseq. reaction
- controlled reaction, hot spots
- cogeneration of electric power (EMR)

Challenges:

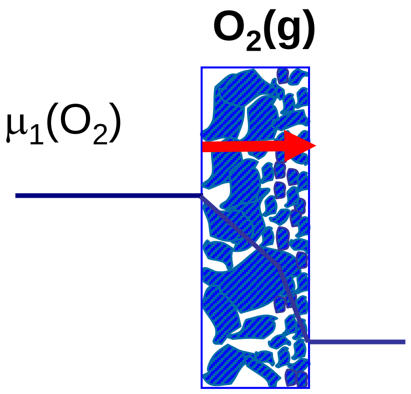
- reactor size/productability
- materials
- costs
- optimal dosing

Electrochemical Membrane Reactor

Porous Membranes

- gaseous oxygen
- nonselective
- permselective microporous

- alumina
- silica
- zeolites

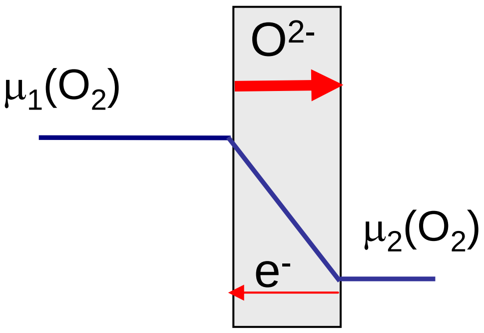


Ceramic Dense Membranes

- oxygen transfer as ion O^{2-}
- good permselectivity towards oxygen
- reactor efficiency limited by permeability (T!)

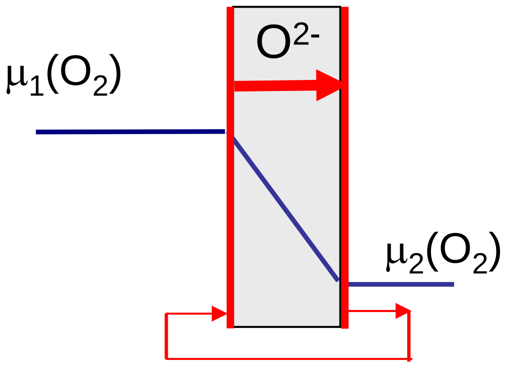
Mixed Ion Electron Conducting Membranes

- σ_{ion} and σ_{el} high
- internal circuit for electrons
- simple construction as reactor

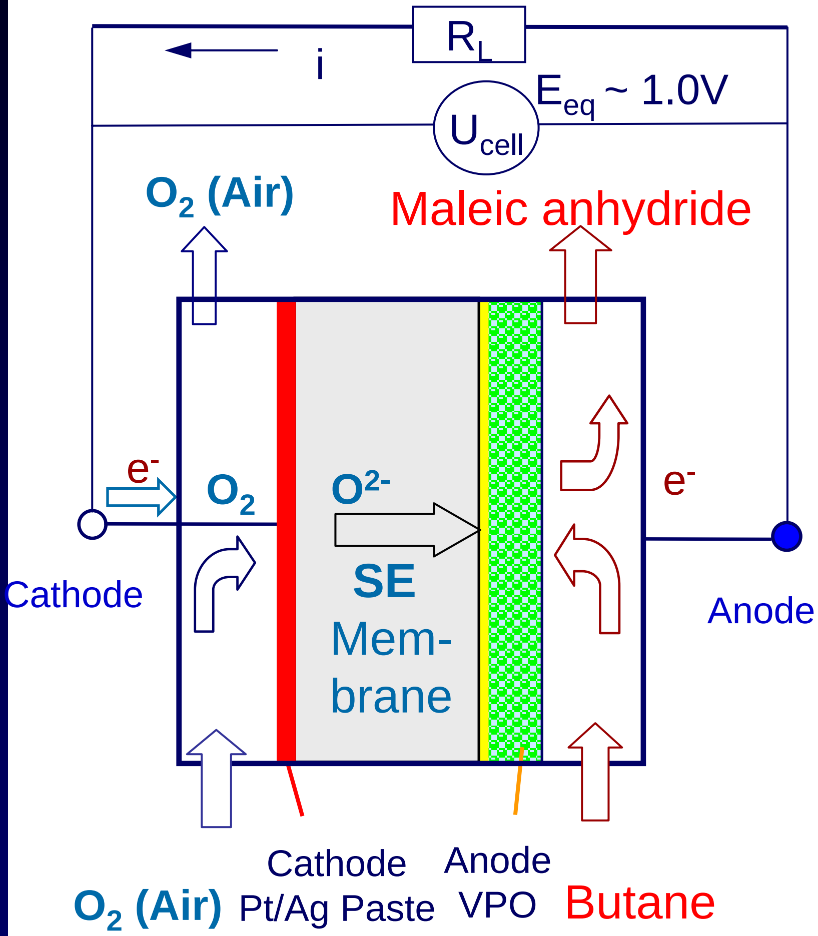


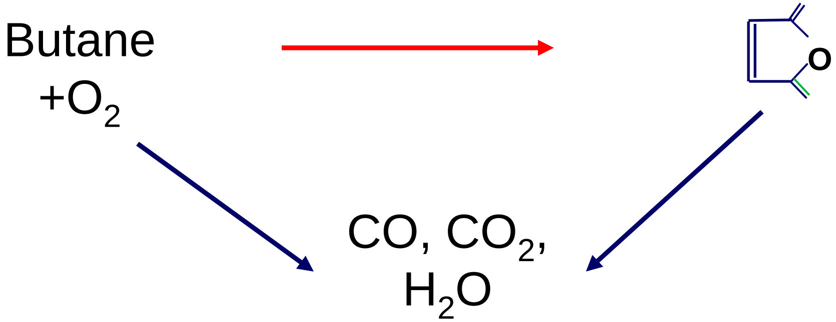
Oxygen Ion Conducting Solid Electrolytes (SE)

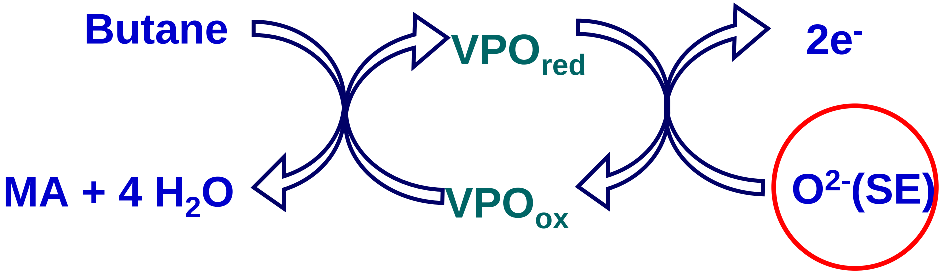
- σ_{ion} high and σ_{el} low
- external circuit for electrons
- complex construction



EMR in Butane Partial Oxidation





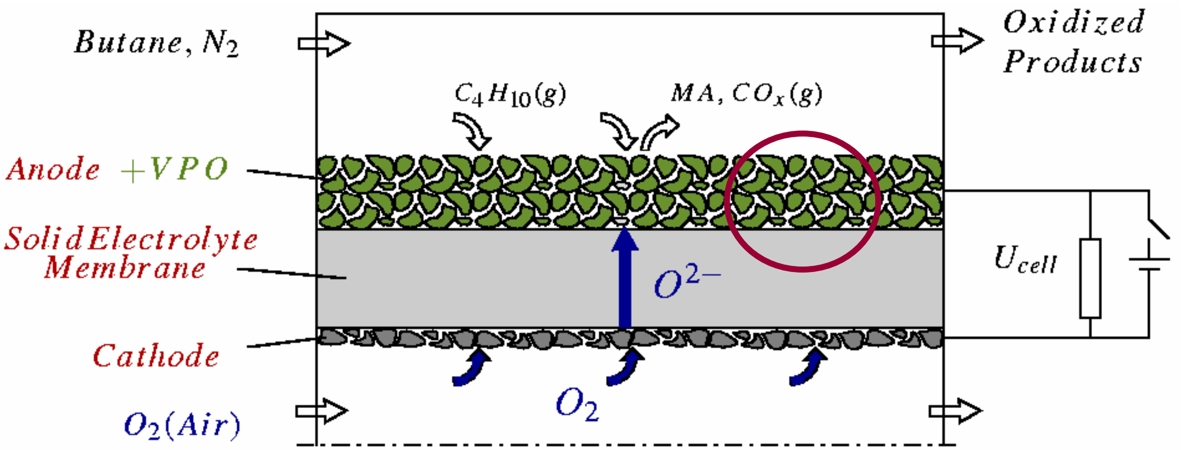


<u>Electrochemical process:</u>

- **reoxidation of catalyst electrochemically**

+ control of catalyst oxidation state
+ no gas phase oxygen
+ total oxidation suppressed

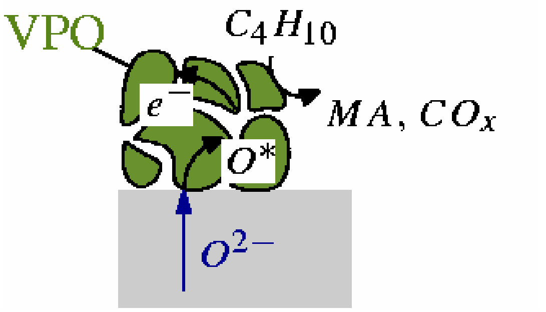
EMR Electrode Construction



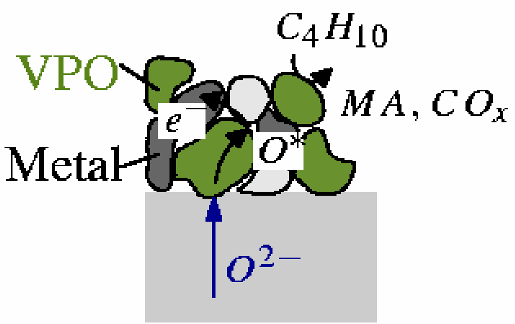
Advantages:

- **no prior air separation units**
- **faradaic coupling of oxygen feed to cell current**
  → forced periodic operation
- **driving force $\Delta_R G \sim U^0_{cell}$ (fuel cell mode)**
  → cogeneration of electricity

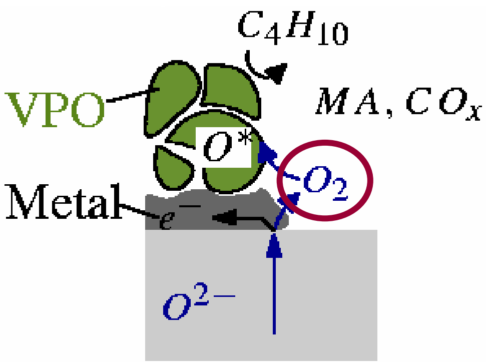
Optimal case: Anode mixed (O^{2-} and e^-) conducting



Composite anode



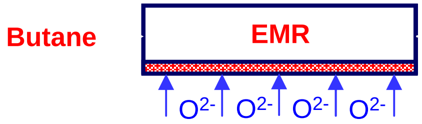
Present study:

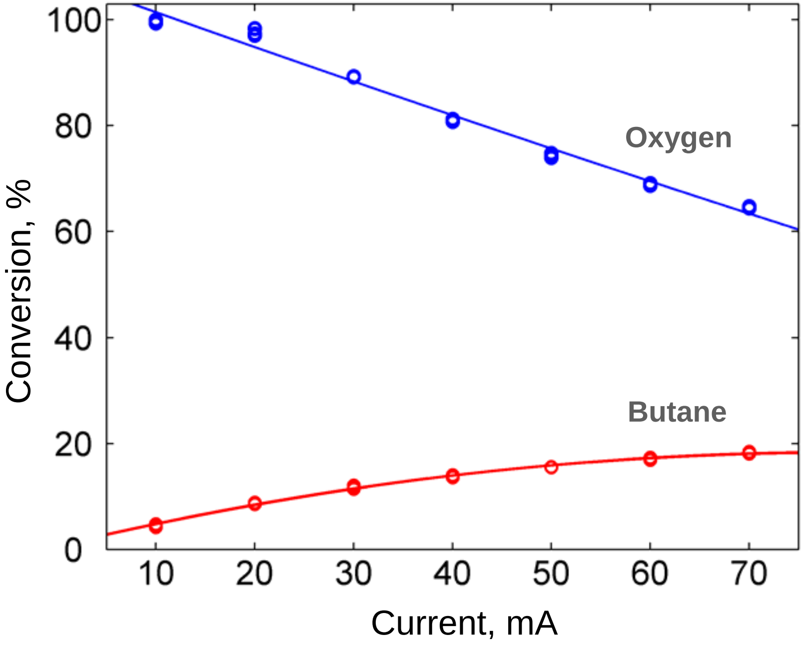


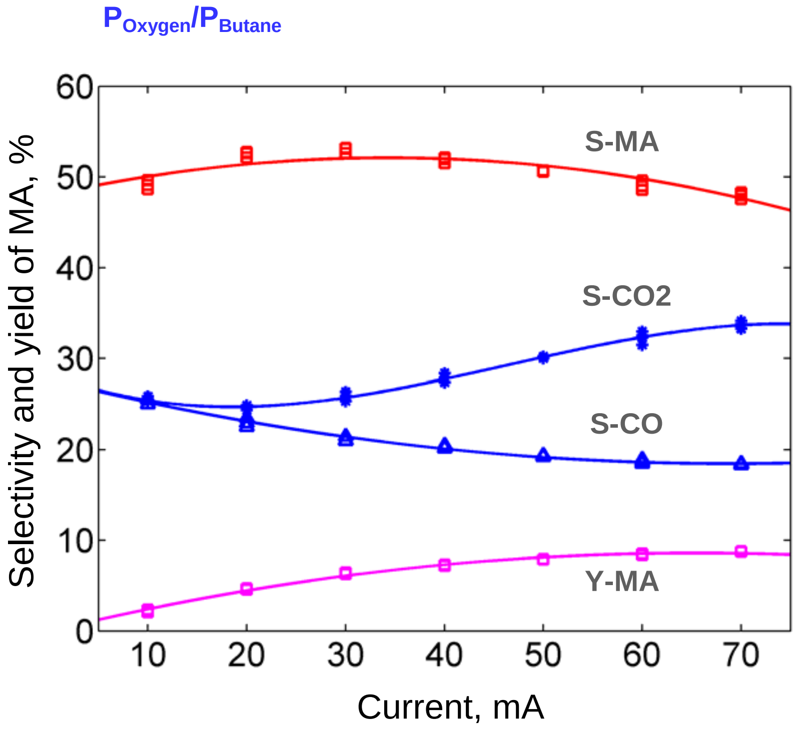
Current Effect in EMR

Experimental condition:

T=480 ˚C; P_{Butane}=0.55 kPa; F=35 ml/min; I=0.44-3.1 mA/cm^2



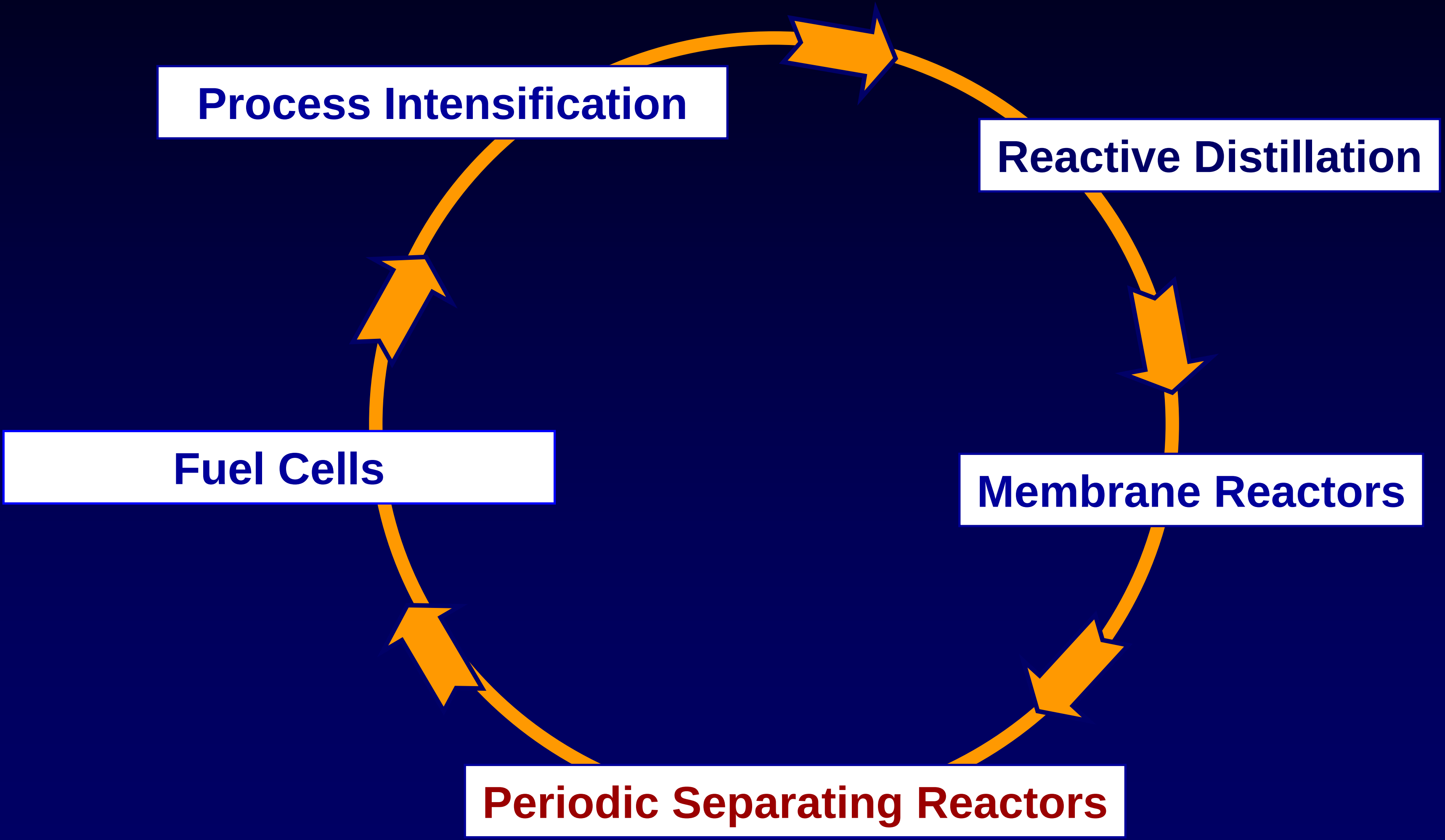




- **High current is favorable for butane conversion and MA yield**
- **S_{MA} has a maximum w.r.t. current**

Ye, Rihko-Struckmann, Munder, Sundmacher. *Appl. Catal. A: General*, 2005, **285**(1-2):86-95

Integrated Catalytic Processes –Lecture Outline



Process Intensification

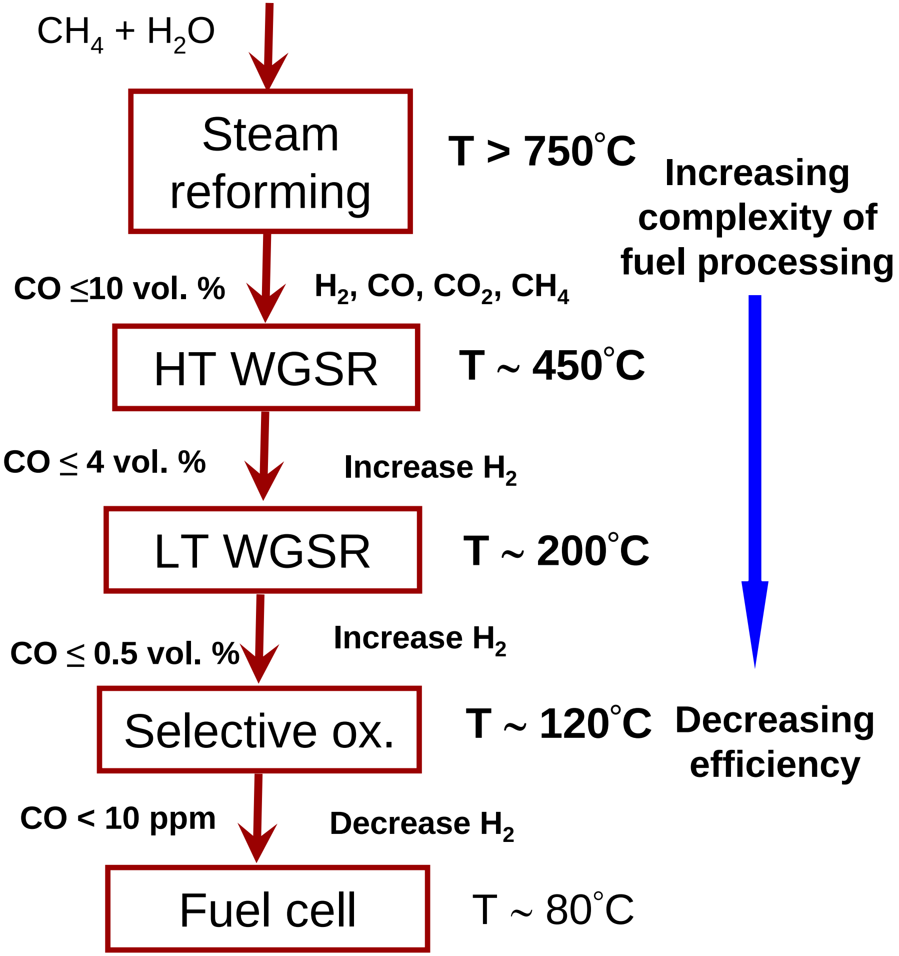
Reactive Distillation

Membrane Reactors

Periodic Separating Reactors

Fuel Cells

Water Gas Shift (WGS) Reaction



$CH_4 + H_2O$

Steam reforming

T > 750°C

CO ≤10 vol. %

H_2, CO, CO_2, CH_4

HT WGSR

T ~ 450°C

CO ≤ 4 vol. %

Increase H_2

LT WGSR

T ~ 200°C

CO ≤ 0.5 vol. %

Increase H_2

Selective ox.

T ~ 120°C

CO < 10 ppm

Decrease H_2

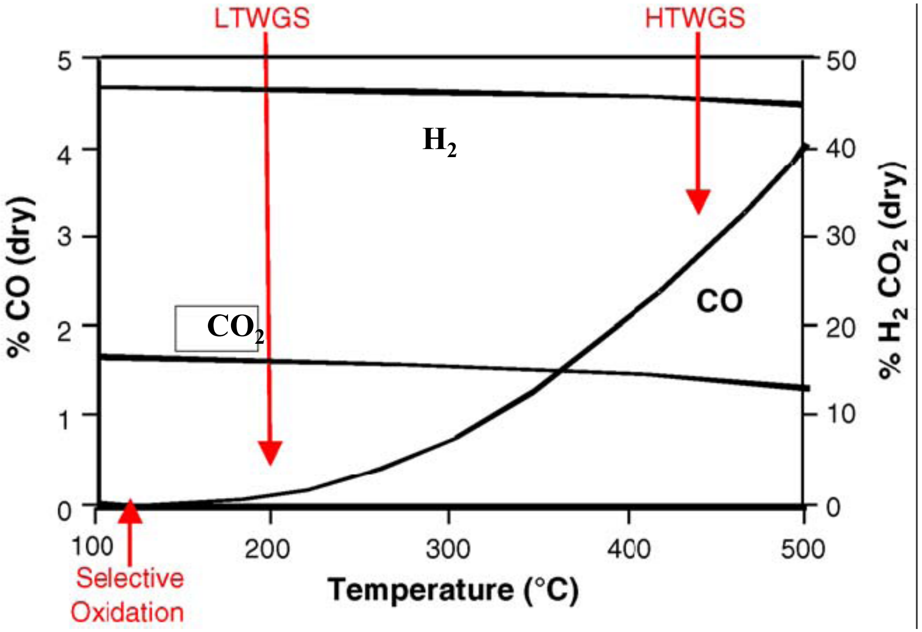
Fuel cell

T ~ 80°C

Increasing complexity of fuel processing

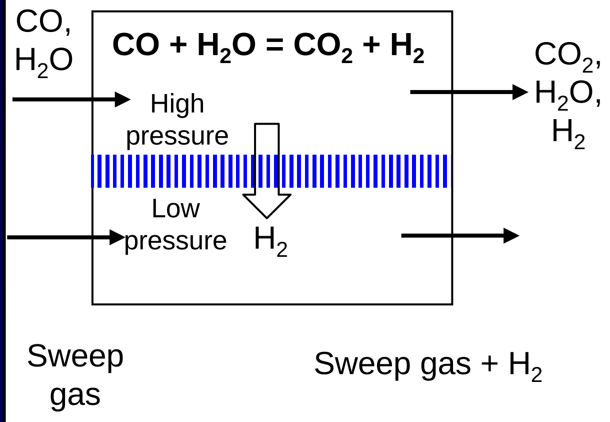
Decreasing efficiency

Equilibrium concentrations in WGS as a function of temperature

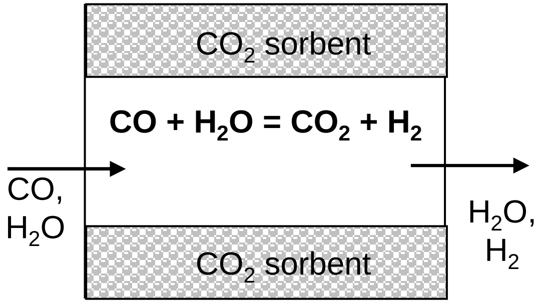


Hydrogen Purification- single step processes

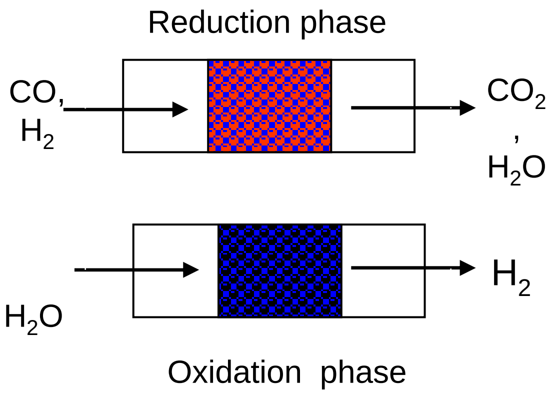
WGS with H_2-separating membrane



WGS with CO_2 capture



WGS with periodic separating reactor



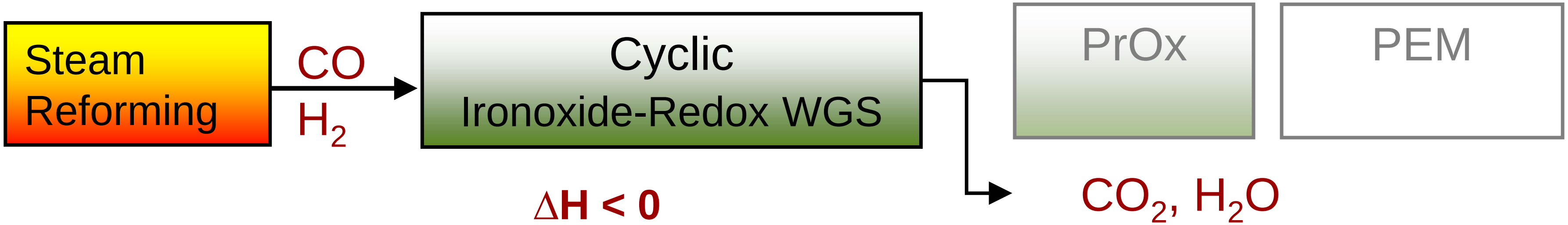
$CO + H_2O = CO_2 + H_2$

Rune Bredesen, et al., Chemical Engineering and Processing 43 (2004) 1129

Periodic Separating Reactor

Phase 1: Reduction of Iron oxide

Gas (CO, H_2) + $Fe_3O_4 \rightarrow FeO_X + CO_2 + H_2O$

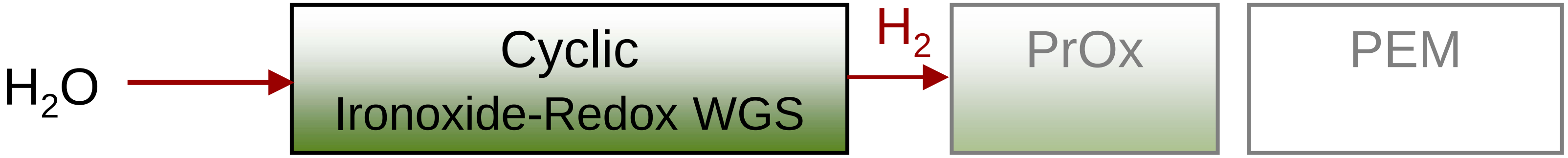


ΔH < 0

Phase 2: Re-Oxidation with Steam

$H_2O + FeO_X \rightarrow Fe_3O_4 + H_2$

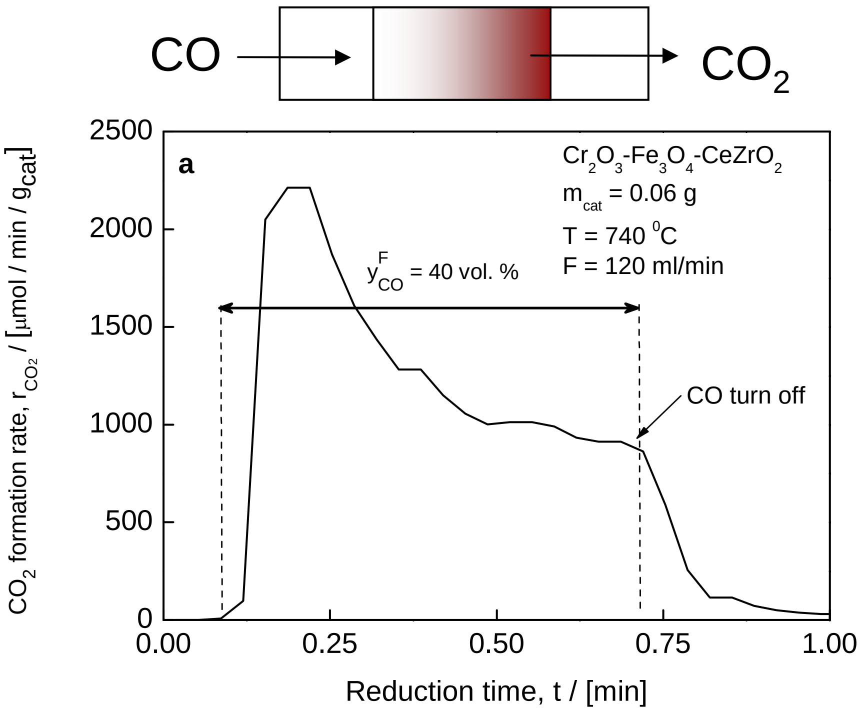
Overall reaction
$CO + H_2O \rightarrow CO_2 + H_2$
ΔH = – 41kJ/mol



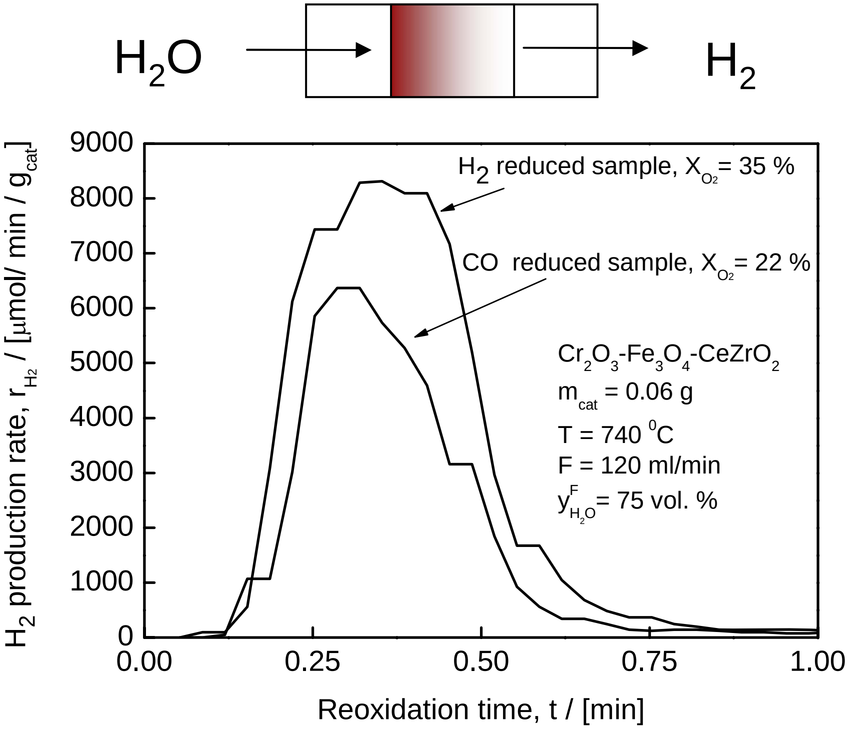
ΔH > 0

Feasibility of Cyclic WGS

Reduction with CO

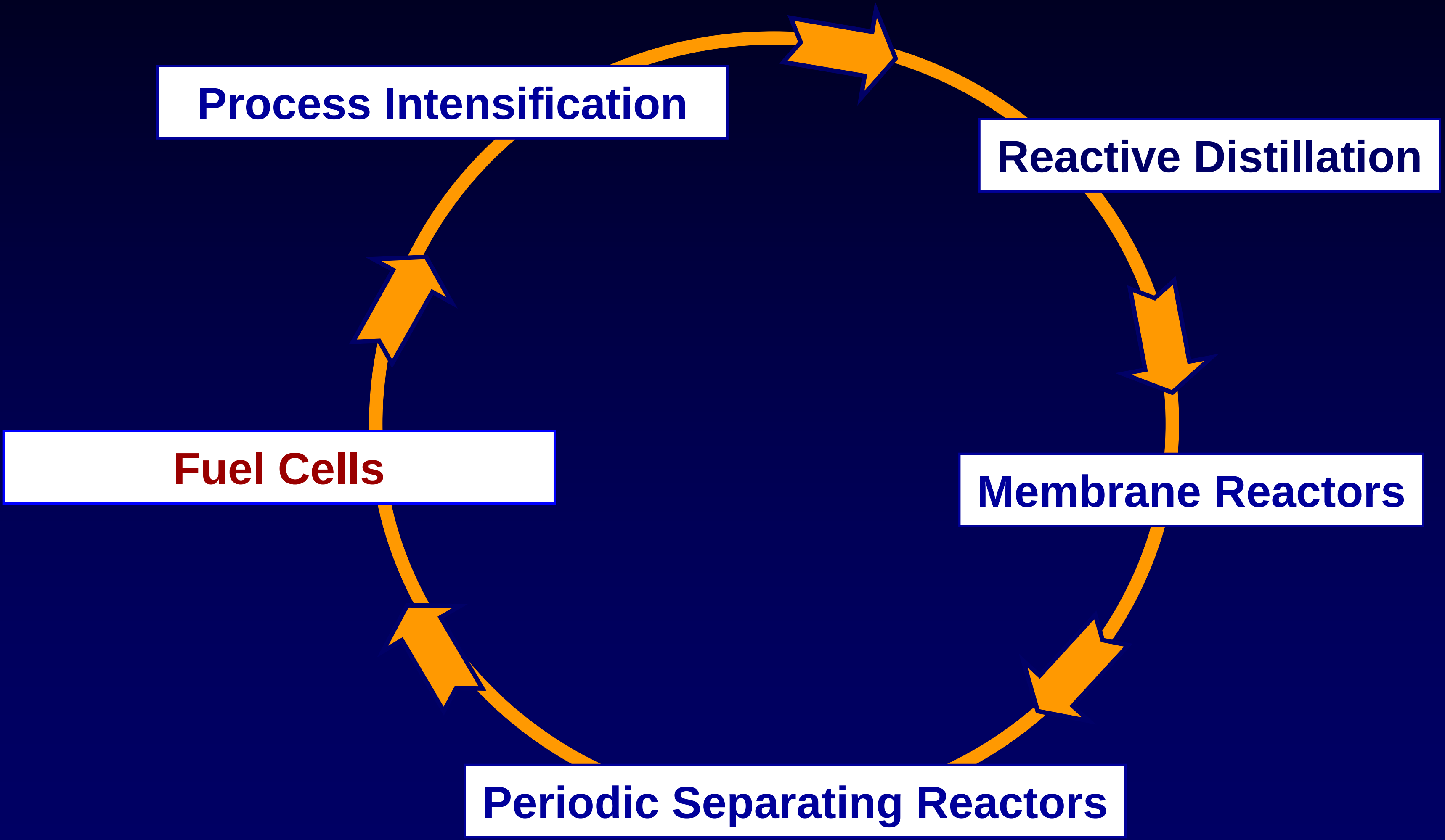


Re-Oxidation with H_2O



Galvita, V., Sundmacher, K., Appl. Catal. 289 (2005) 121

Integrated Catalytic Processes –Lecture Outline



Process Intensification

Reactive Distillation

Membrane Reactors

Periodic Separating Reactors

Fuel Cells

HT Fuel Cells

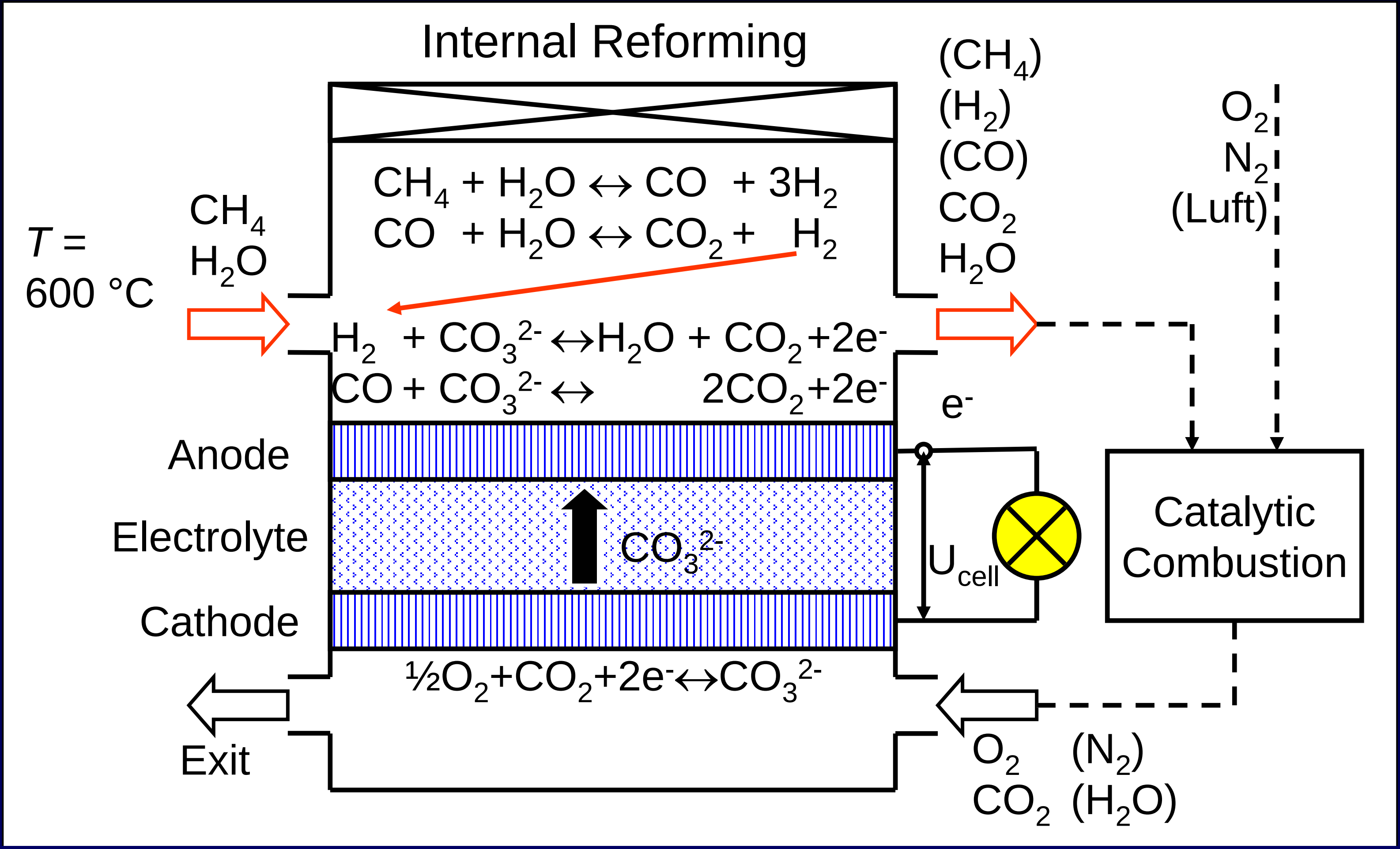
HotModule in Magdeburg University

- Developed by MTU CFC Solutions GmbH

- Start in October 2002
- Molten-Carbonate Fuel Cell (MCFC)
- Feed natural gas

HotModule bei der IPF in Magdeburg

Optimized Internal Reforming in MCFC



Internal Reforming

T = 600 °C

CH_4
H_2O

$CH_4 + H_2O \leftrightarrow CO + 3H_2$
$CO + H_2O \leftrightarrow CO_2 + H_2$

$H_2 + CO_3^{2-} \leftrightarrow H_2O + CO_2 + 2e^-$
$CO + CO_3^{2-} \leftrightarrow 2CO_2 + 2e^-$

(CH_4)
(H_2)
(CO)
CO_2
H_2O

O_2
N_2
(Luft)

e^-

Anode

Electrolyte

Cathode

CO_3^{2-}

U_{cell}

Catalytic Combustion

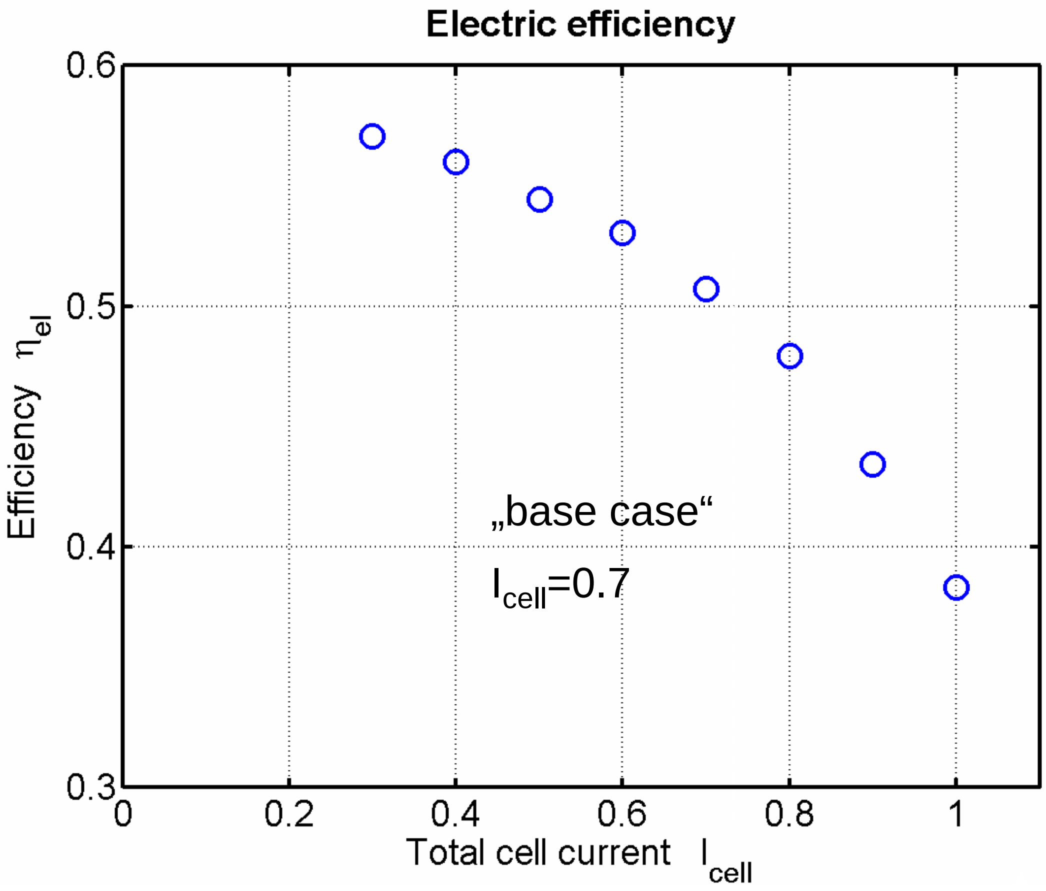
$\frac{1}{2}O_2 + CO_2 + 2e^- \leftrightarrow CO_3^{2-}$

Exit

O_2 (N_2)
CO_2 (H_2O)

- Mass coupling (reforming + WGS + electrochemical Oxidation
- Energetical coupling (ΔHr)

Optimization of operating conditions



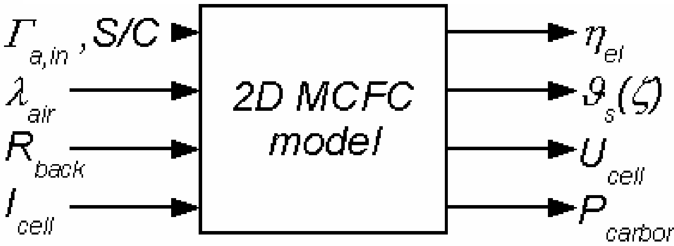
Electric efficiency

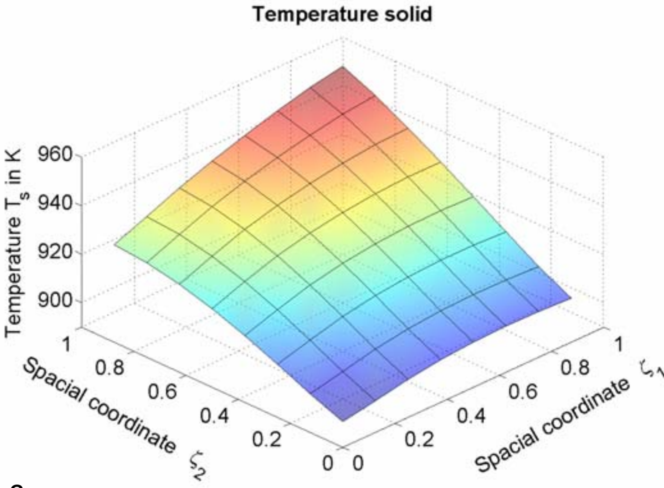
„base case“

I_{cell}=0.7

146.5 mA/cm²

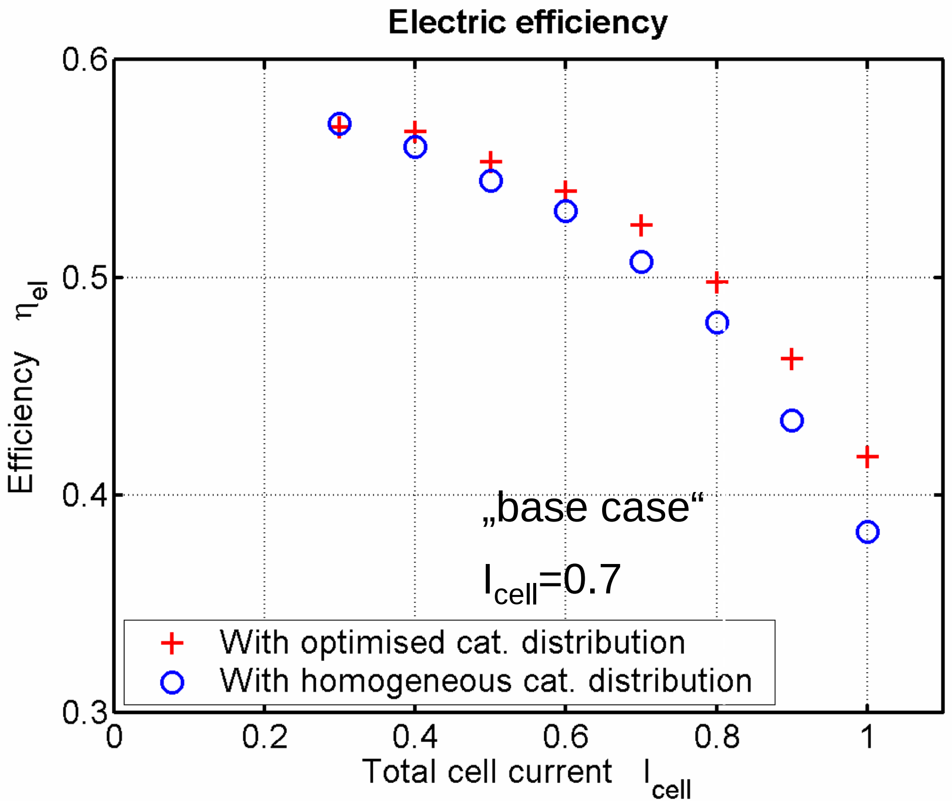
$$\eta_{el}\left(\Gamma_{a,in}, S/C, \lambda_{air}, R_{back}\right) \to \max!$$





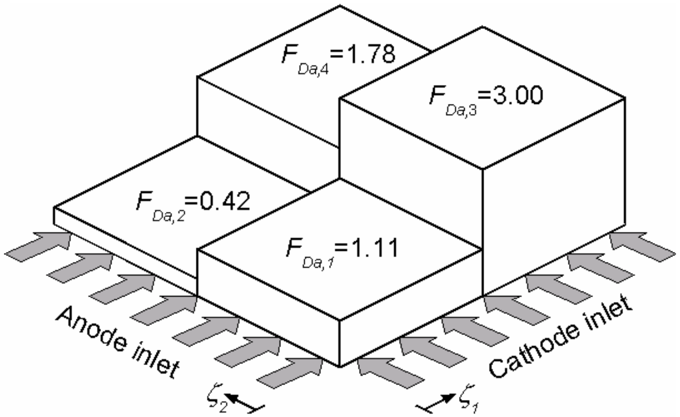
Temperature solid

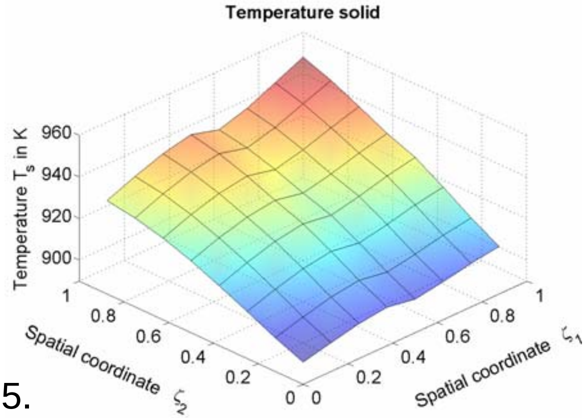
Optimization of reforming catalyst distribution



146.5 mA/cm²

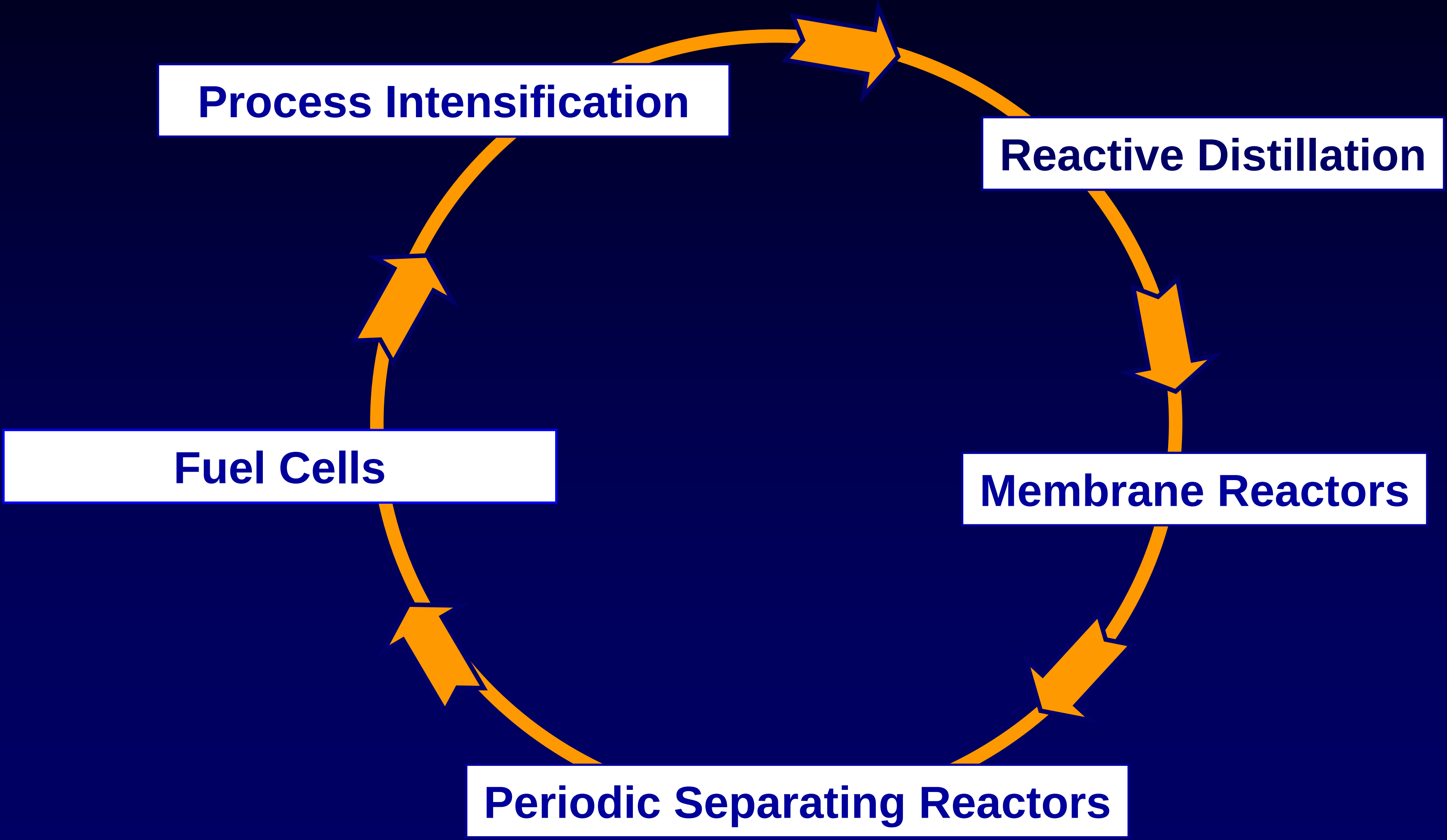
$$\eta_{el}\left(\Gamma_{a,in}, S/C, \lambda_{air}, R_{back}, F_{Da}\right) \rightarrow \max!$$





P. Heidebrecht, Fortschritt-Berichte, VDI-Verlag, Düsseldorf, 2005.
P. Heidebrecht, K. Sundmacher, Ind. Eng. Chem. Res.44 (10), 2005

Integrated Catalytic Processes –Lecture Outline



Process Intensification

Reactive Distillation

Membrane Reactors

Periodic Separating Reactors

Fuel Cells

Modern Methods in Heterogeneous Catalysis Research
Fritz Haber Institute, Berlin, 24 November 2006

Acknowledgements

Many thanks for scientific co-operation with

- Prof. A.Seidel-Morgenstern, A. Tota (MR)

- Prof. K. Sundmacher
- Dr. Zhiwen Qi (RD)
- M. Chalakova (RD)
- Dr. V. Galvita (C - WGS)
- Dr. Ye, B. Munder, L. Chalakov (EMR)
- Dr. P. Heidebrecht (MCFC)