Flow chemistry
“Flow chemistry”, sometimes referred to as “plug flow” or “continuous flow chemistry” is the process of performing chemical reactions in a tube or pipe. Reactive components are pumped together at a mixing junction and flowed down a temperature-controlled pipe or tube. This provides some major advantages such as faster reactions, cleaner products, safer reactions and easy scale-up.

Electrochemistry
“Electrochemistry” is the branch of chemistry concerned with the interrelation of electrical and chemical changes that are caused by the passage of current.

Electrochemical reactor (Electrochemical cell)
An electrochemical cell is a device that can generate electrical energy from the chemical reactions occurring in it, or use the electrical energy supplied to it to facilitate chemical reactions in it. These devices are capable of converting chemical energy into electrical energy, or vice versa.

Electrochemical flow reactor
Is there anyway to combine features of electrochemistry and flow chemistry to a tool in which could take advantage both of them? The answer is absolutely yes and here comes the electrochemical flow reactor.
### Electrochemical Flow Reactor

#### Reactors for electrosynthesis

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</tr>
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<td>Surface-to-Volume Ratio ((A/V))</td>
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</tr>
<tr>
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<td>fast</td>
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<td>fast</td>
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<tr>
<td>Scale-up Mass Transfer</td>
<td>slow</td>
<td>fast</td>
</tr>
<tr>
<td>Scale-up Heat Transfer</td>
<td>slow</td>
<td>fast</td>
</tr>
<tr>
<td>Scale-up Safety Level</td>
<td>low</td>
<td>high</td>
</tr>
<tr>
<td>Integrated Heat Exchanger</td>
<td>not applicable</td>
<td>applicable</td>
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<td>Precise Temperature Control</td>
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<tr>
<td>Reagent Solubility</td>
<td>soluble, insoluble</td>
<td>soluble (only)</td>
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<tr>
<td>Electrode Deposition</td>
<td>likely</td>
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</tr>
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<td>Electrode Potential Distribution</td>
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<td>uniform</td>
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<td>Scale-up Strategy</td>
<td>dimension enlarge</td>
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<tr>
<td>Residence Time Control</td>
<td>not applicable</td>
<td>applicable</td>
</tr>
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<td>Scale-up Set up</td>
<td>easy</td>
<td>complex</td>
</tr>
<tr>
<td>Scale-up Reoptimization</td>
<td>complex</td>
<td>minimal, easy</td>
</tr>
<tr>
<td>Space Requirement</td>
<td>large space</td>
<td>small space</td>
</tr>
</tbody>
</table>

**List of Symbols:**

- \(\Delta U\): Ohmic potential drop of cell (V)
- \(I\): Cell Current (A)
- \(R_{\text{drop}}\): Electrolyte ohmic resistance (Ω)
- \(A_e\): Electrode Surface (m²)
- \(d\): Interelectrode Distance (m)
- \(k_m\): Mass transfer velocity (m s⁻¹)
- \(\kappa\): Conductivity (S m⁻¹)
- \(i\): Current density (A m⁻²)
- \(Q\): Heat generation flux (J)
- \(E_c\): Cell voltage (V)
- \(E_{\text{ext}}\): Equilibrium potential (V)
- \(\eta\): Overpotential (V)

**Rate controlling steps in electrochemistry**

- Charge Transfer Controlled
- Mass Transfer Controlled

**Joule’s First Law:**

\[
Q = I^2 R_{\text{drop}} t
\]

**Conversion (%)**

\[
X = 1 - \exp\left(-\frac{k_m A_e I}{V \kappa t}\right)
\]

**Equations**

\[
\Delta U = I R_{\text{drop}} = I \frac{1}{A_e \kappa} \frac{d}{k_m} = \frac{i d}{A_e \kappa}
\]

\[
\Delta U = \text{Ohmic potential drop of cell (V)}
\]

**Factors to Consider**

- Diffusive Distance
- Travel Time (to electrode)
- Ohmic Potential Drop
- Power of Heating
- Energy Cost
- Electrolyte Loading
- Surface-to-Volume Ratio \((A/V)\)
- Conversion Rate
- Heat Exchange
- Scale-up Mass Transfer
- Mass Transfer Mode
- Conversion Time
- Scale-up Heat Transfer
- Scale-up Safety Level
- Integrated Heat Exchanger
- Precise Temperature Control
- Reagent Solubility
- Electrode Deposition
- Electrode Potential Distribution
- Scale-up Strategy
- Residence Time Control
- Scale-up Set up
- Scale-up Reoptimization
- Space Requirement
**Electrochemical Flow Reactor**

**Flow mode**

- Flow-by (planar)
- Flow-by (porous)
- Flow-through (porous)
- Flow-across (porous)
- Interdigitated (porous)
- Flow-by (planar)
- Flow-through (planar)

**Flow type**

- Laminar flow (every fluid molecule followed a straight path)
  - \( R_e < 2100 \)
- Turbulent flow (every fluid molecule has an irregular path)
  - \( R_e > 4000 \)

**Flow field (channel)**

- Empty channel
- Parallel
- Interdigitated
- Pin-type
- Spiral
- Single serpentine
- Multiple serpentine

**General electrical connection**

- Monopolar electrodes in parallel connection
- Monopolar electrodes in series connection
- Bipolar electrodes in series connection

**Divided cell electrical connection**

- Monopolar mode
- Bipolar mode

**Undivided cell electrical connection**

- Monopolar mode
- Bipolar mode

**Reynolds number:**

\[
R_e = \frac{\rho UD}{\mu}
\]

- The velocity of the flow (U)
- The diameter of the tube (D)
- The density of the fluid (\( \rho \))
- The fluid's dynamic viscosity (\( \mu \))

**Laminar flow**

- Every fluid molecule followed a straight path

**Turbulent flow**

- Every fluid molecule has an irregular path
Ready-made flow reactors on the world market

**Electrochemical Flow Reactor**

**Filter-Press flow cell (FM01-LC marketed by ICI)**

- **Advantages:**
  - High mass transport rates
  - Uniform potential and current distributions
  - Simplicity of design, installation, and maintenance
  - Low capital and running costs
  - Easy integration with other process needs
  - Easy scalability (ranging from laboratory pilot scale to industrial scale) by increasing electrode size or by constructing stacks of multiple cells
  - Flexibility of cell architecture (divided cell/undivided cell)
  - Well defined fluid flow and mass transfer in a rectangular flow channel
  - Easy adjustment of electrode distance
  - Ability to install different electrode and channel configuration

- **Performance improvement:**
  - Greater flow turbulence due to better electrolyte agitation
  - Improved local turbulence using a roughened electrode surface or using a 2D/3D porous electrodes
  - Improved local turbulence by introducing polymer mesh
  - A higher flow rate through channel

**Pipe cell**

- **Concentric electrode**
- **0.5-3 mm IE gap**

**Disk stack cell**

- Bipolar connection
- Thin polymer spacer
- up to 100 disks

In 1990s BASF used this cell for commercial production of adiponitrile, dimethylsebacate, 4-tert-butylbenzaldehyde, and dimethoxyhydrofuran.

In 1970s the cell was used for methoxylation and acetoxylation of toluenes, alkylamides, and N-heterocycles, as well as dehydrocoupling of aromatic rings, for a scale of 1-5 mol and completed in 1-10 h.
Norvatis dehalogenation

\[
\text{Br} \quad \text{COOH} \quad \text{Br} \quad \text{COOH}
\]

2.7 g, 70%, 99% ee
Key Intermediate for NSSA Inhibitors

Flow Parameters (16 mmol):
- \( Q = 20 \text{ F} \)
- \( CD = 15 \text{ mA/cm}^2 \)
- \( V_f = 0.6 \text{ mL/min} \)
- \( I = 1.2 \text{ A (C.C)} \)
- \( S = 80 \text{ cm}^2 \)
- \( T_{\text{cat}} = 25 \text{ °C} \)
- Anode: Graphite
- Anolyte: DMF, MTES, MeOH
- Cathode: CuSn7Pb15
- Catholyte: DMF, MTES

Divided cell, single pass

(1) Total view of the flow cell, (2) cross section of the hole cell, (3) anodic half-cell and Nafion separator, (4) cathodic half-cell: (a) cathode, CuSn7Pb15; (b) anode, graphite; (c) Nafion membrane; (d) inlets for electrolyte; (e) outlets for electrolyte; (f) contacts for cooling media.

Explosion drawing of flow reactor

Parallel
Flow mode:
Flow-by planar
Flow regime:
Laminar
Electrode type:
2D planar
Electric connection:
Monopolar
Cell division:
Divided

Stainless steel plate
Anodic half-cell
Cathodic half-cell
Stainless steel framework
Teflon spacer grid
Graphite foil
EPDM sealing
EPDM seals
Teflon framework
Teflon hose connector
Screws to fix the cathode
Power connector
Nafion membrane
teflon screws for anode fixation and sealing of power connection

S=80 cm²
Electrochemical Flow Reactor

Redox-neutral reaction

\[
\begin{align*}
\text{CN} & \quad \text{R}_1 \quad \text{EWG} \\
\text{R}_1 & \quad \text{EWG} \\
\text{Br} & \quad \text{R}_2 \quad \text{COOH}
\end{align*}
\]

Mediator 10 mol\%

\[
\begin{align*}
\text{(+)}\text{GC/GC(-)} \\
\text{TsoH, LiClO}_4 \\
\text{DMSO}
\end{align*}
\]

> 15 example 49%-80%

NiCl\(_2\) glyme 5 mol\%
dtbppy 5 mol\%

\[
\begin{align*}
\text{(+)}\text{GC/GC(-)} \\
\text{MeCN}
\end{align*}
\]

3 example 63%-86%

Ni(bpy)Cl\(_2\), Bu\(_4\)NBF\(_4\), DMF

\[
\begin{align*}
\text{(+)}\text{FeNi/Ni form(-)} \\
80 ^\circ \text{C} \\
40 \text{ mA} \\
2.5 \text{ mL/min} \\
1.2 \text{ F/mol}
\end{align*}
\]

2.65 g, 87%

Flow parameters: Flow-by, undivided cell, single pass, d= 25 µm, monopolar connection, empty channel

Deprotection

\[
\begin{align*}
\text{O} & \quad \text{R} \\
\text{H} & \quad \text{O} \\
\text{OH} & \quad \text{Noc}
\end{align*}
\]

\[
\begin{align*}
\text{(+)}\text{Pt/Pt(-)} \\
\text{H}_2\text{O/DMF (1:5 v/v)} \\
92 \text{ s, } 20 ^\circ \text{C}
\end{align*}
\]

R= H, 61%
R= OMe, 43%
R= CO\(_2\)Me, 50%

Flow parameters: Undivided cell, single pass, flow-by, CD= 16.7 mA/cm\(^2\), \(v_f= 15 \mu\text{L/min}\)


Chemoselective cathodic reduction

\[
\begin{align*}
\text{Cl} & \quad \text{OC} \\
\text{PhCHO} & \quad \text{cathodic reduction} \\
3.73 \text{ F/mol} \\
10 \text{ mA/cm}^2 \\
0.02 \text{ mL/min}
\end{align*}
\]

\[
\begin{align*}
\text{γ-adduct} & \quad \text{α-adduct}
\end{align*}
\]

Undivided cell, single pass


Mo, Y. et al Science 2020, 368, 1352.
**Electrochemical Flow Reactor**

### Sulfonamide synthesis

\[
\text{SH} + \text{H}_2\text{NCO}_2\text{Me} \rightarrow \text{SO}_2\text{Me} + \text{H}_2 \quad (\text{81\% yield})
\]

**Batch**: 100 mol\% Me$_4$NBF$_4$, d=1.0 cm, 24 h, 1.0 mmol, 55\% yield

**Flow**: Undivided cell, single pass, 10 mol\% Me$_4$NBF$_4$, V=3.2 V, CD=5.6 mA/cm$^2$, d=250 µm, $t_R$=5.0 min, 1.0 mmol, 81\% yield (10.0 mmol, 80\% yield)


### Anodic Methoxylation (Shono Oxidation)

\[
\text{MeOH} \rightarrow \text{OMe} + \text{CO}_2\text{Me} \quad (57\% \text{ yield}), \quad \text{MeOH} \rightarrow \text{OMe} + \text{CO}_2\text{Me} \quad (40\% \text{ yield})
\]

**Flow Parameters**: Undivided cell, single pass, d=75 µm, PTFE membrane ($\phi=3.0 \mu$m), $v_f=2$ mL/h, I=11 mA (C.C), no electrolyte


### Cation flow synthesis

\[
\text{NCO}_2\text{Me} + \text{TMS} \rightarrow \text{NCO}_2\text{Me} + \text{CO}_2\text{Me} \quad (69\% \text{ yield})
\]

**Flow Parameters**: Divided cell, single pass, PTFE membrane with ($\phi=0.1 \mu$m), I=14 mA (C.C), $v_f=2.1$ mL/h


### Isoindolinone synthesis

\[
\text{N-Ph} + \text{MeNMe}_2\text{OH} (0.5 \text{ eq}) \rightarrow \text{N-Ph} \quad (75\%, E/Z=9:1)
\]

**Flow**: 1.5 h, 95\%, 3:3:1 d.r., no supporting electrolyte

**Batch**: 6 h, 51\%, 3:1 d.r., NBF$_4$ 0.1M

**Flow Parameters**: Undivided cell, single pass, Q=3 F, I=24 mA (C.C), V=1-2 V, $v_f=0.1$ mL/min, 3D printed reactor (0.205 mL), serpentine channel, d=0.75 mm


### In situ α-Quinones

**Flow Parameters**: Undivided cell, single pass, d=80 µm, $v_f=0.1$ mL/min, Q=2.8 F, I=4.5 mA (C.C), CD=1.5 mA/cm$^2$

*Tanaka, K. et al Synlett 2019, 30, 1194.*

**Flow Parameters**: Undivided cell, single pass, d=80 µm, $v_f=6.0$ mL/h, I=4.5 mA (C.C), CD=1.5 mA/cm$^2$

**Difluoro- and Trifluoromethylation**

\[
\begin{align*}
\text{RFCO}_2\text{H} \ (0.7 \text{ eq})
\end{align*}
\]

\[
\begin{align*}
\text{RF} &= \text{CF}_3 \\
\text{RF} &= \text{CHF}_2 \\
\text{(+Pt)}(\cdot)\text{Pt}
\end{align*}
\]

Et$_3$N, 10 mol%  
MeCN: H$_2$O (7:1 v/v)

**Flow Parameters:** Undivided cell, single pass, FEP channel, \(d=254 \mu\text{m}, I=50 \text{ mA (C.C)}, \text{CD}= 28 \text{ mA/cm}^2, \text{Vf}= 20 \text{ µL/min}, t_R= 69\text{s}

\[
\begin{align*}
\text{RFCO}_2\text{H} \ (3.0 \text{ eq})
\end{align*}
\]

\[
\begin{align*}
\text{RF} &= \text{CF}_3 \\
\text{RF} &= \text{CHF}_2 \\
\text{(+Pt)}(\cdot)\text{Pt}
\end{align*}
\]

Et$_3$N, 10 mol%  
MeCN: H$_2$O (7:1 v/v)

**Flow Parameters:** Undivided cell, single pass, FEP channel, \(d=254 \mu\text{m}, I=10 \text{ mA (C.C)}, \text{CD}= 2.4 \text{ mA/cm}^2, \text{Vf}= 5 \text{ µL/min}, t_R= 10.5 \text{ min}

\[
\begin{align*}
\text{RFCO}_2\text{H} \ (16.0 \text{ eq})
\end{align*}
\]

\[
\begin{align*}
\text{RF} &= \text{CF}_3 \\
\text{RF} &= \text{CHF}_2 \\
\text{(+Pt)}(\cdot)\text{Pt}
\end{align*}
\]

Et$_3$N, 10 mol%  
MeCN: H$_2$O (7:1 v/v)

**Flow Parameters:** Undivided cell, single pass, FEP channel, \(d=254 \mu\text{m}, I=200 \text{ mA (C.C), CD}= 111 \text{ mA/cm}^2, \text{Vf}= 50 \text{ µL/min}, t_R= 28\text{s}

**Domino-oxidation-reduction**

\[
\begin{align*}
\text{(+)} \text{Graphite}
\end{align*}
\]

\[
\begin{align*}
-2e^-, -2H^+
\end{align*}
\]

MTPS (0.012 M)  
MeCN/H$_2$O (11:1 v/v)

**Flow Parameters:** Undivided cell, single pass, (+)C/(-)Pb, \(d=0.12 \text{ mm}, \text{Vf}= 8.5 \text{ mL/h, I}=60 \text{ mA (C.C), Q}= 2.18 \text{ F, CD}= 5 \text{ mA/cm}^2, \text{no electrolyte}

- Byproducts (mono- and 2-fold dehalogenated product) control by lowering IE

\[
\begin{align*}
\text{(-)} \text{Lead}
\end{align*}
\]

\[
\begin{align*}
+2e^-, +2H^+, -H_2O
\end{align*}
\]

- Batch: 41%


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**Electrochemical Flow Reactor**

**Baran Lab Group Meeting**  
06/13/2020

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Electrochemical Flow Reactor

**Longrui Chen**

**Baran Lab Group Meeting**  
06/13/2020

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### Dehydrogenative C–S Bond Formation

![Chemical structure](image)

**Flow Parameters:** Undivided cell, single pass, $d = 250 \mu m$, $v_\text{f} = 0.2 \text{ mL/min}$, $CD = 4.88 \text{ mA/cm}^2$, $Q = 2.5$  
F, no supporting electrolyte

---

### Hydrogenation (Furfural reduction)

![Chemical structure](image)

**Flow Parameters:** Undivided cell, single pass, $v = 0.075 \text{ mL/min}$, $t_b = 10 \text{ min}$, $V = 2.9 \text{ V (C.V.)}$, current efficiency 90%

---

### C-C bond coupling

![Chemical structure](image)

**Flow Parameters:** Undivided cell, single pass, $d = 160 \mu m$, $v_\text{f} = 15 \mu L/min$, $V= 4.4 \text{ V}$, $t_b = 5 \text{ min}$

---

### Sulfonyl Fluoride Synthesis

![Chemical structure](image)

**Flow Parameters:** Undivided cell, single pass, $d = 250 \mu m$, $T$-mixer, $v_\text{f} = 0.15 \text{ mL/min}$, $V = 3.3 \text{ V (C.V.)}$

---

### Flow reactor laboratory scale-up

**Birch reaction**

![Reaction scheme](image)

**Flow Parameters:** Undivided cell, single pass, $d = 250 \mu m$, $v_\text{f} = 0.15 \text{ mL/min}$, $V = 4-4.4 \text{ V}$, $t_b = 5 \text{ min}$

---

### Oxidative cyclization

![Reaction scheme](image)

**Flow Parameters:** Undivided cell, single pass, $d = 250 \mu m$, $v_\text{f} = 0.2 \text{ mL/min}$, CD = 4.88 mA/cm², $Q = 2.5$  
F, no supporting electrolyte

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**Electrochemical Flow Reactor**

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**Amination**

N-Boc-piperidine (1.5 eq.)
NIBr₂ (10 mol%), bpy (50%)
NaBr (0.2), DBU 2.0 (eq)

DMA, (+)/(-)C

I=2.5 A (C.C)

Undivided cell

100 g scale

Byproduct controlled by cathode overpotential

- 2 kA/m² current density, 3.8 V per cell
- Current efficiency 95%
- Interelectrode gap 2 mm
- Total energy use 2.5 kWh/kg (6.0 kWh/kg as of corresponding undivided cell)
- 0.347 million metric ton/year production (2010)
- QS adsorbed on the cathode in preference to protons or water


**Monsanto adiponitrile process**

Quaternary ammonium salt (QS)

CN + H₂O

(+)/(-)Cd

O₂

key intermediate of nylon-6,6

- First commercial example of paired organic electrosynthesis
- Product on both anode and cathode
- 200% Bipolar disk stack cell
- 4000 metric ton/year production
- MeOH as both reagent and solvent

BASF phthalide and dimethylacetal process

- 0.347 million metric ton/year production (2010)
- Current density 1 kA/m² at a cell voltage 4-7 V

**Flow reactor in commercial production**

Monsanto adiponitrile process

- First commercial example of paired organic electrosynthesis
- Product on both anode and cathode
- 200% Bipolar disk stack cell
- 4000 metric ton/year production
- MeOH as both reagent and solvent

BASF phthalide and dimethylacetal process

- First commercial example of paired organic electrosynthesis
- Product on both anode and cathode
- 200% Bipolar disk stack cell
- 4000 metric ton/year production
- MeOH as both reagent and solvent

- Current density 1 kA/m² at a cell voltage 4-7 V

**Monsant EHD Flow reactor**

- Biopar disk stack cell with recycle mode
- Current density 300-500 A/m² with a cell 4-6V
- More than 3500t/year production
- Conversion > 90%, yield > 80%, selectivity > 85%


- 3000 metric tons per year world market
- 100% conversion and 90% current efficiency
- Current density 2500 A/m²
- Filter press divided cell


**BASF p-Anisaldehyde process**

Anode:

Cathode:

4 CH₃OH → 4 CH₃O⁻ + 2 H₂

- Biopar disk stack cell with recycle mode
- Current density 300-500 A/m² with a cell 4-6V
- More than 3500t/year production
- Conversion > 90%, yield > 80%, selectivity > 85%


**Nipon Chemical L-Cystine process**

- 3000 metric tons per year world market
- 100% conversion and 90% current efficiency
- Current density 2500 A/m²
- Filter press divided cell

Longrui Chen  

**Electrochemical Flow Reactor**

**List of Typical Industrial Processes Based on Organic Electrosynthesis**

<table>
<thead>
<tr>
<th>Product</th>
<th>Raw Material</th>
<th>Company</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Commercial processes</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acetoin</td>
<td>Butanone</td>
<td>BASF</td>
</tr>
<tr>
<td>Acetylenedicarboxylic acid</td>
<td>1,4-Butynediol</td>
<td>BASF</td>
</tr>
<tr>
<td>Adipin dimethyl acetel</td>
<td>Cyclohexanone</td>
<td>BASF</td>
</tr>
<tr>
<td>Adiponitrile</td>
<td>Acrylonitrile</td>
<td>BASF, Monsanto</td>
</tr>
<tr>
<td>4-Aminomethylpyridine</td>
<td>4-Cyanopyridine</td>
<td>Reilly Tar</td>
</tr>
<tr>
<td>Anthraquinone</td>
<td>Anthracene</td>
<td>L. B. Holliday, ECRC</td>
</tr>
<tr>
<td>Azobenzene</td>
<td>Nitrobenzene</td>
<td>Johnson Matthey Co.</td>
</tr>
<tr>
<td>Bleached montan wax</td>
<td>Raw montan wax</td>
<td>Clariant</td>
</tr>
<tr>
<td>Calcium gluconate</td>
<td>Glucose</td>
<td>Sandoz, India</td>
</tr>
<tr>
<td>Calcium lactobionate</td>
<td>Lactose</td>
<td>Sandoz, India</td>
</tr>
<tr>
<td>5,Carboxymethylpyruvate</td>
<td>Cysteine + chloroacetic acid</td>
<td>Spain</td>
</tr>
<tr>
<td>1-Cysteine</td>
<td>L-Cysteine</td>
<td>Wacker Chemie AG</td>
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<tr>
<td>Diacetone-2-ketogulonic acid</td>
<td>Diacetone-1-sorbos</td>
<td>Hoffmann-La Roche</td>
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<tr>
<td>Dialdehyde starch</td>
<td>Starch</td>
<td>CECRI</td>
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<tr>
<td>1,4-Dihyronaphthalene</td>
<td>Naphthalene</td>
<td>Clariant</td>
</tr>
<tr>
<td>2,5-Dimethoxy-2,5-dihydrofuran</td>
<td>Furan</td>
<td>BASF</td>
</tr>
<tr>
<td>2,5-Dimethoxy-2,5-dihydrofuran-1-ethanol</td>
<td>Furfuryl-1-ethanol</td>
<td>Otsuka</td>
</tr>
<tr>
<td>Dimethylsulphate</td>
<td>Monomethyladipate</td>
<td>Asahi Chemical</td>
</tr>
<tr>
<td>Glucic acid</td>
<td>Glucose</td>
<td>Sandoz, India</td>
</tr>
<tr>
<td>Hexahydropropylene oxide</td>
<td>Hexahydropropylene</td>
<td>Clariant</td>
</tr>
<tr>
<td>m-Hydroxybenzyl alcohol</td>
<td>m-Hydroxybenzic acid</td>
<td>Otsuka</td>
</tr>
<tr>
<td>p-Anisaldehyde</td>
<td>p-Methoxybenzene</td>
<td>BASF</td>
</tr>
<tr>
<td>Perfluorinated hydrocarbons</td>
<td>Alkyl substrates</td>
<td>3M, Bayer, Clariant</td>
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<tr>
<td>Polyisobutanes</td>
<td>Chlorosilanes</td>
<td>Osaka Gas</td>
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<tr>
<td>Salicylic aldehyde</td>
<td>o-Hydroxybenzoic acid</td>
<td>India</td>
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<tr>
<td>Succinic acid</td>
<td>Maleic acid</td>
<td>CERCI, India</td>
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<tr>
<td>3,4,5-Trimethoxy benzaldehyde</td>
<td>3,4,5-Trimethoxy tolune</td>
<td>Otsuka Chemical</td>
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<tr>
<td>3,4,5-Trimethoxytoly alcohol</td>
<td>3,4,5-Trimethoxy tolune</td>
<td>Otsuka Chemical</td>
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<table>
<thead>
<tr>
<th>Product</th>
<th>Raw Material</th>
<th>Company</th>
</tr>
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<tbody>
<tr>
<td>1-Acetoxynaphthalene</td>
<td>Naphthalene</td>
<td>BASF</td>
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<tr>
<td>2-Aminobenzyl alcohol</td>
<td>Anthranilic acid</td>
<td>BASF</td>
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<tr>
<td>Anthraquinone</td>
<td>Naphthalene, butadiene</td>
<td>Hydro Quebec</td>
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<tr>
<td>Arabinose</td>
<td>Glucoante</td>
<td>Electrolysis Co.</td>
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<tr>
<td>1,2,3,4-Butanetetraoxyacid</td>
<td>Dimethyl maleate</td>
<td>Monsanto</td>
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<td>Cefibuten</td>
<td>Cephalosporin C</td>
<td>Electrolysis Co.</td>
</tr>
<tr>
<td>3,6-Dichloropicolic acid</td>
<td>3,4,5,6-Tetracloropicolic acid</td>
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<td>Ditoliolidionion salts</td>
<td>p-Iodomonolene, tolune</td>
<td>Eastman Chemical</td>
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<td>Ethylene glycol</td>
<td>Formaldehyde</td>
<td>Electrolysis Co.</td>
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<td>Glyoxylic acid</td>
<td>Oxalic acid</td>
<td>Rhone Poulenc</td>
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<td>Hydroxymethylbenzoic acid</td>
<td>Dimethyl terephthalate</td>
<td>Clariant</td>
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<tr>
<td>Monochloroacetic acid</td>
<td>Tri- and dichloroacetic acid</td>
<td>Clariant</td>
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<tr>
<td>Nitrobenzene</td>
<td>p-Aminophenol</td>
<td>India, Monsanto</td>
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<tr>
<td>5-Nitronaphthoquinone</td>
<td>1-Nitronaphthalene</td>
<td>Hydro Quebec</td>
</tr>
<tr>
<td>Partially fluorinated hydrocarbons</td>
<td>Alkanes and alkenes</td>
<td>Philips Petroleum</td>
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<td>Pinacol</td>
<td>Acetone</td>
<td>Diamond Shamrock</td>
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<td>Propionic acid</td>
<td>Propargyl alcohol</td>
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<td>Propylene oxide</td>
<td>Propylene</td>
<td>Kellog, Shell</td>
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<tr>
<td>Substituted benzaldehydes</td>
<td>Substituted toluenes</td>
<td>Hydro Quebec</td>
</tr>
</tbody>
</table>

**Important parameters for industrial scale up:**
- Yield of the desired product
- Rate of production
- Energy consumption
- Capital cost

**Challenges to commercialization**
- High energy costs
- Pollution constrains
- Low product selectivity

Parameters and choices regarding the design features in e-chem flow reactors

- **Type of cell division**: Divided/undivided
- **Separator manufacture**: Cast, Extruded, Composite, Reinforced
- **Electrode type**: 2D/3D, Bare/coated, Metal/ceramic/carbon, Composite, Monopolar/bipolar
- **Electrode shape**: Rectangular, Trapezoidal, Circular, Other
- **Electrolyte manifolds**: Simple tubular, Distributed manifold, Internal/external, Jet/calming zone
- **Electrode flow configuration**: Flow-by, Flow-through, Flow-across
- **Electrode flow fields**: Conventional, Serpentine, Interdigitated

**Performance indicators include:**
- $k_m$, Mass transfer coefficient for 2D electrode
- $k_m A_e$, Volumetric Mass transfer coefficient for 3D electrode
- $X_a$, Fractional conversion of reactant
- STY, The space time yield of an electrosynthesis cell
- NSV, The normalised space velocity of environmental treatment cell

**Hydraulics parameters include:**
- $Q$, Volumetric flow rate of electrolyte, cm$^3$/s
- $v$, Mean linear flow velocity past the electrode surface, cm/s
- $P$, Pressure, Pa
- $R_e$, Renard's number

**Requirements of good flow cell:**
- High productivity
- Good mass transport
- Good temperature control
- Low electrical resistance
- Ease of operation
- Safety in operation
- Ability to deal with gaseous products and reactants
- Minimum cost