## Chlor-Alkali

### Table of Contents

A Report by NexantThinking™

Process Evaluation/Research Planning (PERP) Program

PERP Report 2016-5 – Published July 2016

www.nexantthinking.com

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Executive Summary</td>
</tr>
<tr>
<td>1.1</td>
<td>OVERVIEW OF TECHNOLOGY</td>
</tr>
<tr>
<td>1.2</td>
<td>TECHNOLOGY LICENSORS</td>
</tr>
<tr>
<td>1.2.1</td>
<td>Asahi Kasei Chemicals Corporation</td>
</tr>
<tr>
<td>1.2.2</td>
<td>ThyssenKrupp Uhde Chlorine Engineers</td>
</tr>
<tr>
<td>1.2.3</td>
<td>INEOS Technologies</td>
</tr>
<tr>
<td>1.2.4</td>
<td>BlueStar Chemical Machinery Company Limited</td>
</tr>
<tr>
<td>1.3</td>
<td>ENVIRONMENTAL REGULATIONS</td>
</tr>
<tr>
<td>1.3.1</td>
<td>Mercury and Mercury Cell Process</td>
</tr>
<tr>
<td>1.4</td>
<td>PROCESS ECONOMICS</td>
</tr>
<tr>
<td>1.5</td>
<td>GLOBAL CHLORINE SUPPLY AND DEMAND</td>
</tr>
<tr>
<td>1.5.1</td>
<td>Global Chlorine Demand</td>
</tr>
<tr>
<td>1.5.2</td>
<td>Global Chlorine Supply</td>
</tr>
<tr>
<td>1.5.3</td>
<td>Global Chlorine Supply/Demand Balance</td>
</tr>
<tr>
<td>1.5.4</td>
<td>North America Chlorine Supply/Demand Balance</td>
</tr>
<tr>
<td>1.5.5</td>
<td>Western Europe Chlorine Supply/Demand Balance</td>
</tr>
<tr>
<td>1.5.6</td>
<td>Asia Pacific Chlorine Supply/Demand Balance</td>
</tr>
<tr>
<td>1.5.7</td>
<td>Rest of the World Chlorine Supply/Demand Balance</td>
</tr>
<tr>
<td>1.6</td>
<td>GLOBAL SODIUM HYDROXIDE SUPPLY AND DEMAND</td>
</tr>
<tr>
<td>1.6.1</td>
<td>Global Sodium Hydroxide Demand</td>
</tr>
<tr>
<td>1.6.2</td>
<td>Global Sodium Hydroxide Supply</td>
</tr>
<tr>
<td>1.6.3</td>
<td>Global Sodium Hydroxide Supply/Demand Balance</td>
</tr>
<tr>
<td>1.6.4</td>
<td>North America Sodium Hydroxide Supply/Demand Balance</td>
</tr>
<tr>
<td>1.6.5</td>
<td>Western Europe Sodium Hydroxide Supply/Demand Balance</td>
</tr>
<tr>
<td>1.6.6</td>
<td>Asia Pacific Sodium Hydroxide Supply/Demand Balance</td>
</tr>
<tr>
<td>1.6.7</td>
<td>Rest of the World Sodium Hydroxide Supply/Demand Balance</td>
</tr>
<tr>
<td>2</td>
<td>Introduction</td>
</tr>
<tr>
<td>2.1</td>
<td>TECHNOLOGY LICENSORS</td>
</tr>
<tr>
<td>2.1.1</td>
<td>Asahi Kasei Chemicals Corporation</td>
</tr>
<tr>
<td>2.1.2</td>
<td>ThyssenKrupp Uhde Chlorine Engineers</td>
</tr>
</tbody>
</table>
2.1.3 INEOS Technologies .......................................................... 15
2.1.4 BlueStar Chemical Machinery Company Limited ...................... 15
2.2 MAJOR PRODUCERS .................................................................. 16
2.3 CHARACTERISTICS AND PROPERTIES ...................................... 16
2.4 ENVIRONMENTAL REGULATIONS ............................................. 17
2.4.1 Mercury and Mercury Cell Process .......................................... 17
3 Background ................................................................................. 18
3.1 ELECTROCHEMICAL BASIC THEORY OUTLINED ...................... 18
3.1.1 Thermodynamics ................................................................. 20
3.1.2 Kinetics ............................................................................. 21
3.1.3 Bubbles ............................................................................. 22
3.1.4 Summary ........................................................................... 22
3.2 PARASITIC LOSS REACTIONS................................................... 23
3.3 BRINE SUPPLY ...................................................................... 23
3.3.1 Calcium, Magnesium, and Trace Metals ................................. 24
3.3.2 Sulfates ............................................................................. 25
3.3.3 Fluorides, iodides, and Organics ......................................... 25
3.3.4 Chlorine ........................................................................... 26
3.3.5 Brine Treatment Unit .......................................................... 26
3.3.6 Waste Brine ...................................................................... 29
3.4 ELECTRICITY SUPPLY ............................................................ 30
3.5 PIPING .................................................................................. 30
3.6 WATER .................................................................................. 31
3.7 ELECTRODE CONFIGURATION (BIPOLAR VERSUS MONOPOLAR) .... 31
3.8 LEAKAGE CURRENT ............................................................... 33
3.9 ELECTRODES (MATERIAL OF CONSTRUCTION) ...................... 34
3.9.1 Anodes ............................................................................ 34
3.9.2 Cathodes ......................................................................... 35
4 Chlor-Alkali Technologies .............................................................. 36
4.1 MERCURY CELLS ................................................................. 37
4.2 DIAPHRAGM CELLS ................................................................. 41
4.3 MEMBRANE CELLS ................................................................ 45
4.3.1 Asahi Kasei Chemicals Corporation ...................................... 49
4.3.2 ThyssenKrupp Uhde Chlorine Engineers ................................ 50
4.3.3 INEOS Technologies .......................................................... 52
4.3.4 BlueStar (Beijing) Chemical Machinery Company Limited .... 53
4.4 FUEL CELL INTEGRATED SYSTEMS ........................................ 53
4.5 OXYGEN DEPOLARIZED CATHODES ...................................... 56
4.6 ELECTRICAL ENERGY CONSUMPTIONS AND HEATING ............ 60
4.7 HYDROGEN PROCESSING ....................................................... 61
4.8 CHLORINE PROCESSING ......................................................... 61
4.8.1 Cooling .............................................................................. 62
4.8.2 Drying ............................................................................................................. 63
4.8.3 Compression ................................................................................................... 63
4.8.4 Liquefaction .................................................................................................... 63
4.8.5 Materials of Construction ............................................................................. 63
4.8.6 Storage and Shipping..................................................................................... 64
4.9 SODIUM HYDROXIDE PROCESSING ................................................................. 64
4.9.1 Mercury Cell .................................................................................................. 66
4.9.2 Diaphragm Cell ............................................................................................. 66
4.9.3 Membrane Cell ............................................................................................. 66
4.9.4 Concentrated and Solid Sodium Hydroxide .................................................. 66
4.9.5 Materials of Construction ............................................................................. 67
4.9.6 Storage and Shipping..................................................................................... 67
4.10 EFFLUENT PROCESSING .................................................................................. 67
5 Developing Technologies and Recent Patents ..................................................... 71
5.1 ELECTROCHEMICAL ......................................................................................... 71
5.1.1 Electrolysis of KCl ......................................................................................... 71
5.1.2 Electrolysis of Molten Salts ......................................................................... 71
5.1.3 Electrolysis of HCl ......................................................................................... 72
5.2 CHEMICAL .......................................................................................................... 75
5.2.1 Catalytic Oxidation ....................................................................................... 75
5.3 RECENT PATENT DEVELOPMENTS ................................................................. 78
5.3.1 Axiall (PPG Industries) ................................................................................. 78
5.3.2 DOW ............................................................................................................... 78
5.3.3 ThyssenKrupp Uhde Chlorine Engineers ...................................................... 80
5.3.4 De Nora .......................................................................................................... 80
5.3.5 Uhdenora ....................................................................................................... 81
6 Process Economics ................................................................................................ 83
6.1 COSTING BASIS ................................................................................................ 83
6.1.1 Investment Basis ............................................................................................ 83
6.1.2 Pricing Basis .................................................................................................. 83
6.1.3 Cost of Production Basis .............................................................................. 85
6.2 COST OF PRODUCING CHLOR-ALKALI VIA MERCURY CELL ................... 86
6.3 COST OF PRODUCING CHLOR-ALKALI VIA DIAPHRAGM CELL ................. 88
6.4 COST OF PRODUCING CHLOR-ALKALI VIA MEMBRANE CELL TECHNOLOGY ................................................................. 90
6.5 COST OF PRODUCING CHLOR-ALKALI VIA MEMBRANE CELL WITH OXYGEN DIFFUSION CATHODE ................................................................. 95
6.6 ESTIMATE OF COST FOR PRODUCING CHLOR-ALKALI VIA MEMBRANE CELL WITH INTEGRATED FUEL CELL ................................................................. 98
6.7 COMPARISON OF TECHNOLOGIES .............................................................. 101
6.8 ECONOMIC SENSITIVITY ANALYSES .......................................................... 104
6.8.1 Sensitivity of Sodium Chloride Feedstock Price on Production Cost .......... 104
6.8.2 Sensitivity of Electricity Price on Production Cost ........................................ 105
7 Commercial Applications ................................................................. 112
  7.1 CHLORINE ................................................................................. 112
  7.2 SODIUM HYDROXIDE (CAUSTIC SODA) ...................................... 113
8 Regional Market Analysis ................................................................. 114
  8.1 GLOBAL .................................................................................. 114
    8.1.1 Chlorine Demand ................................................................. 114
    8.1.2 Chlorine Supply ................................................................. 115
    8.1.3 Chlorine Supply/Demand Balance ........................................ 116
    8.1.4 Sodium Hydroxide Demand ................................................ 117
    8.1.5 Sodium Hydroxide Supply ................................................... 118
    8.1.6 Sodium Hydroxide Supply/Demand Balance ......................... 118
  8.2 NORTH AMERICA ................................................................. 119
    8.2.1 Chlorine Demand ................................................................. 119
    8.2.2 Chlorine Supply ................................................................. 120
    8.2.3 Chlorine Supply/Demand Balance ........................................ 121
    8.2.4 Sodium Hydroxide Demand ................................................ 122
    8.2.5 Sodium Hydroxide Supply ................................................... 123
    8.2.6 Sodium Hydroxide Supply/Demand Balance ......................... 123
  8.3 WESTERN EUROPE .............................................................. 124
    8.3.1 Chlorine Demand ................................................................. 124
    8.3.2 Chlorine Supply ................................................................. 124
    8.3.3 Chlorine Supply/Demand Balance ........................................ 127
    8.3.4 Sodium Hydroxide Demand ................................................ 128
    8.3.5 Sodium Hydroxide Supply ................................................... 128
    8.3.6 Sodium Hydroxide Supply/Demand Balance ......................... 128
  8.4 ASIA PACIFIC ........................................................................... 129
    8.4.1 Chlorine Demand ................................................................. 129
    8.4.2 Chlorine Supply ................................................................. 129
    8.4.3 Chlorine Supply/Demand Balance ........................................ 140
    8.4.4 Sodium Hydroxide Demand ................................................ 141
    8.4.5 Sodium Hydroxide Supply ................................................... 141
    8.4.6 Sodium Hydroxide Supply/Demand Balance ......................... 141
  8.5 ROW .................................................................................... 142
    8.5.1 Chlorine Supply ................................................................. 142
    8.5.2 Chlorine Supply/Demand Balance ........................................ 145
    8.5.3 Sodium Hydroxide Supply ................................................... 145
    8.5.4 Sodium Hydroxide Supply/Demand Balance ......................... 146
Appendix

A  Definitions of Capital Cost Terms Used in Process Economics                A-1
B  Definitions of Operating Cost Terms Used in Process Economics           B-1
C  PERP Program Title Index (2007 - 2016)                                  C-1

Figure

1.1  The Chlor-Alkali Value Chain ............................................................. 1
1.2  Comparison of Costs of Production for Conventional Technologies ........ 4
1.3  Comparison of Cost of Electrical Energy Conventional Technologies ...... 5
1.4  Regional Comparison of Chlor-Alkali Costs for Bipolar Membrane Cell Technology ........... 5
1.5  Comparison of Electricity Conserving Technologies ............................... 6
1.6  Global Chlorine Demand by Application, 2015 ...................................... 8
1.7  Global Chlorine Capacity by Region, 2015 ........................................... 8
1.8  Global Sodium Hydroxide Demand by Application, 2015 .......................... 11
2.1  The Chlor-Alkali Value Chain ............................................................. 14
3.1  Electrode Potential – pH Relationship of Part of the Chlorine – Water System .... 20
3.2  Chlorine Activity-pH Diagram ............................................................. 26
3.3  Brine Preparation Process Block Diagram .............................................. 27
3.4  Simplified Representation of Monopolar and Bipolar Electrolyzer Configuration ........ 32
3.5  Manifolding Option to Increase Path Length ........................................... 34
4.1  Global Mercury Cell Chlor-Alkali Plants Capacity .................................. 37
4.2  Mercury Cell Process Block Flow Diagram ............................................ 38
4.3  Schematic of a Mercury Cell ............................................................... 39
4.4  Schematic of Hg-Na Amalgam Decomposer with De Nora Improvement ......... 40
4.5  Diaphragm Cell Process ...................................................................... 42
4.6  Schematic Representation of a Diaphragm Cell ....................................... 43
4.7  Membrane Cell Process Block Flow Diagram ......................................... 46
4.8  Schematic of a Membrane Cell ............................................................ 47
4.9  Proton Exchange Membrane Fuel Cell .................................................. 54
4.10 Schematic Representation of Membrane Cell with an Oxygen Diffusion Electrode ........ 57
4.12 Chlorine Handling Block Flow Diagram ................................................... 62
4.13 Treatment of the Sodium Hydroxide Solution from Various Electrolysis Cells .... 65
4.14 Schematic Diagram for the Extraction of Mercury from Brine Sludge .......... 69
5.1  Aqueous HCl Electrolysis Comparison .................................................... 72
5.2 DuPont Anhydrous HCl Process................................................................. 74
5.3 Sumitomo Chemical Process....................................................................... 77
6.1 Comparison of Costs of Production for Conventional Technologies......... 101
6.2 Comparison of Cost of Electrical Energy Conventional Technologies........ 102
6.3 Regional Comparison of Chlor-Alkali Costs for Bipolar Membrane Cell Technology .... 102
6.4 Comparison of Electricity Conserving Technologies.................................. 103
6.5 Sensitivity of Cost of Production to Price of Sodium Chloride.................. 104
6.6 Cost of Production Sensitivity to Variation in Power Pricing..................... 105
6.7 Variation in Cost of Production with Plant Scale........................................ 106
6.8 Variation in Cost of Production with Value of Hydrogen in Western Europe .... 107
6.9 Variation in Cost of Production with Value of Hydrogen in China.................. 108
6.10 Sensitivity to Total Project Investment, Percentage of Base Case................ 109
6.11 Cost of Production of Membrane Technology Time Series, Western Europe .... 110
6.12 Cost of Production of Membrane Technology Time Series, China............... 111
8.1 Global Chlorine Demand by Application, 2015 ........................................ 115
8.2 Global Chlorine Capacity by Region, 2015............................................... 116
8.3 Global Chlorine Supply and Demand......................................................... 117
8.4 Global Sodium Hydroxide Demand by Application, 2015.......................... 118
8.5 Global Sodium Hydroxide Supply and Demand......................................... 119
8.6 North America Chlorine Supply and Demand............................................ 122
8.7 North America Sodium Hydroxide Supply/Demand Balance......................... 123
8.8 Western Europe Chlorine Supply and Demand........................................... 127
8.9 Western Europe Sodium Hydroxide Supply/Demand Balance......................... 128
8.10 Asia Pacific Chlorine Supply/Demand Balance.......................................... 140
8.11 Sodium Hydroxide Supply/Demand Balance............................................ 141
8.12 ROW Chlorine Supply/Demand Balance.................................................. 145
8.13 ROW Sodium Hydroxide Supply/Demand Balance.................................... 146
Table

| 1.1 | Regional Demand for Chlorine | 7 |
| 1.2 | Global Chlorine Supply and Demand | 9 |
| 1.3 | North America Chlorine Supply and Demand | 9 |
| 1.4 | Western Europe Chlorine Supply and Demand | 9 |
| 1.5 | Asia Pacific Chlorine Supply/Demand Balance | 10 |
| 1.6 | ROW Chlorine Supply/Demand Balance | 10 |
| 1.7 | Regional Demand for Sodium Hydroxide | 10 |
| 1.8 | Global Sodium Hydroxide Supply and Demand | 11 |
| 1.9 | North America Sodium Hydroxide Supply/Demand Balance | 12 |
| 1.10 | Western Europe Sodium Hydroxide Supply/Demand Balance | 12 |
| 1.11 | Sodium Hydroxide Supply/Demand Balance | 12 |
| 1.12 | ROW Sodium Hydroxide Supply/Demand Balance | 13 |
| 2.1 | Key Physical and Thermodynamic Properties of Chlorine | 16 |
| 2.2 | Key Physical and Thermodynamic Properties of Sodium Hydroxide | 17 |
| 3.1 | Typical Specifications for Feed Brine to Electrolyzers | 28 |
| 3.2 | Salt Loss in Waste Brines Purge | 30 |
| 3.3 | Demineralized Water Specifications | 31 |
| 3.4 | Monopolar versus Bipolar Cell Configurations | 33 |
| 4.1 | Product Quality for Typical Membrane Cell Technology | 49 |
| 4.2 | General Operating Characteristics for a Selection of Fuel Cell Technologies | 56 |
| 4.3 | Product Quality and Service Life for Typical Membrane Cell Technology with Oxygen Depolarized Cathode | 60 |
| 6.1 | Pricing Used in Cost of Production Tables | 84 |
| 6.2 | Cost of Production Estimate for Chlor-Alkali Process: Mercury Cell; Western Europe Basis | 87 |
| 6.3 | Cost of Production Estimate for Chlor-Alkali Process: Bipolar Membrane Cell; Western Europe Basis | 89 |
| 6.4 | Cost of Production Estimate for Chlor-Alkali Process: Monopolar Membrane Cell; Western Europe Basis | 91 |
| 6.5 | Cost of Production Estimate for Chlor-Alkali Process: Bipolar Membrane Cell; Western Europe Basis | 92 |
| 6.6 | Cost of Production Estimate for Chlor-Alkali Process: Bipolar Membrane Cell; China Basis | 93 |
| 6.7 | Cost of Production Estimate for Chlor-Alkali Process: Bipolar Membrane Cell; USGC Basis | 94 |
| 6.8 | Cost of Production Estimate for Chlor-Alkali Process: Membrane Cell with Gas Diffusion Cathode; Western Europe Basis | 96 |
| 6.9 | Cost of Production Estimate for Chlor-Alkali Process: Membrane Cell with Gas Diffusion Cathode; China Basis | 97 |
| 6.10 | Cost of Production Estimate for Chlor-Alkali Process: Membrane Cell with Integrated Fuel Cell; Western Europe Basis | 99 |
6.11 Cost of Production Estimate for Chlor-Alkali Process: Membrane Cell with Integrated Fuel Cell; China Basis ........................................... 100
6.12 Cost of Production of Membrane Technology Time Series, Western Europe .............................. 110
6.13 Cost of Production of Membrane Technology Time Series, China ........................................... 111
8.1 Regional Demand for Chlorine ........................................................................................................ 114
8.2 Global Chlorine Supply and Demand ................................................................................................. 116
8.3 Regional Demand for Sodium Hydroxide .......................................................................................... 117
8.4 Global Sodium Hydroxide Supply and Demand ............................................................................... 118
8.5 North America Chlor-Alkali Capacity, 2015 ....................................................................................... 120
8.6 North America Chlorine Supply and Demand .................................................................................. 122
8.7 North America Sodium Hydroxide Supply/Demand balance .............................................................. 123
8.8 Western Europe Chlor-Alkali Capacity, 2015 .................................................................................... 125
8.9 Western Europe Chlorine Supply and Demand ................................................................................ 127
8.10 Western Europe Sodium Hydroxide Supply/Demand Balance .......................................................... 128
8.11 Asia Pacific Chlorine Capacity, 2015 ................................................................................................ 130
8.12 Asia Pacific Chlorine Supply/Demand Balance ................................................................................ 140
8.13 Sodium Hydroxide Supply/Demand Balance .................................................................................. 141
8.14 ROW Chlorine Capacity, 2015 ........................................................................................................ 142
8.15 ROW Chlorine Supply/Demand Balance ........................................................................................ 145
8.16 ROW Sodium Hydroxide Supply/Demand Balance ......................................................................... 146
Nexant Thinking™

Process Evaluation/Research Planning

The NexantThinking™ Process Evaluation/Research Planning (PERP) program is recognized globally as the industry standard source for information relevant to the chemical process and refining industries. PERP reports are available as a subscription program or on a single report basis.

Contact Details:

**New York:** Marcos Nogueira Cesar, Vice President, Global Products, E&CA: Nexant Thinking™
Phone: + 1-914-609-0324, e-mail: mcesar@nexant.com

**London:** Sonia Ouertani, Client Services Coordinator, NexantThinking™
Phone: + 44-207-950-1587, e-mail: souertani@nexant.com

Nexant, Inc. (www.nexant.com) is a leading management consultancy to the global energy, chemical, and related industries. For over 38 years, Nexant has helped clients increase business value through assistance in all aspects of business strategy, including business intelligence, project feasibility and implementation, operational improvement, portfolio planning, and growth through M&A activities. Nexant has its main offices in San Francisco (California), White Plains (New York), and London (UK), and satellite offices worldwide.

Copyright © by Nexant Inc. 2016. All Rights Reserved.