Abstract
Process Economics Program Report 2H
PROPYLENE OXIDE
(September 2003)

This supplementary report presents the industry status of propylene oxide (PO) and reviews recent developments in PO manufacturing technologies since PEP Report 2G, *Propylene Oxide*, issued in December 2001. In this Report we focus on the review and technoeconomic evaluation of PO using hydrogen peroxide and PO by direct epoxidation processes.

We present technoeconomic evaluations of our interpretation of BASF’s and Degussa’s PO using hydrogen peroxide and AIST-Nippon Shokubai’s PO by direct epoxidation processes. We also update the process economics of our interpretation of Lyondell's and Huntsman's PO/t-butyl alcohol processes, Lyondell's and Shell's PO/styrene processes, Sumitomo's PO by using cumene hydroperoxide process, and the chlorohydrin processes using lime and using cell liquor. In addition, we compare the technical aspects and economics of the above mentioned processes.

Overall, this PO report encompasses the latest technologies and process economics and provides a basis for insight into technical trends, environmental issues, and the selection of technologies.
CONTENTS (Continued)

4 PROPYLENE OXIDE/t-BUTYL ALCOHOL BY HYDROPEROXIDATION USING t-BUTYL HYDROPEROXIDE ................................................................. 4-1

PO/TBA BY THE LYONDELL PROCESS USING TBHP ................................... 4-1
Process Description .......................................................................................... 4-1
Process Discussion ........................................................................................... 4-15
Cost Estimates ................................................................................................. 4-16

PO/TBA BY THE HUNTSMAN PROCESS USING TBHP .................................. 4-24
Process Description .......................................................................................... 4-24
Process Discussion ........................................................................................... 4-37
Cost Estimates ................................................................................................. 4-37

COMPARISON OF PO/TBA PROCESSES ......................................................... 4-45

5 PROPYLENE OXIDE/STYRENE BY HYDROPEROXIDATION USING ETHYLBENZENE HYDROPEROXIDE ......................................................... 5-1

PO/SM BY THE LYONDELL PROCESS USING EBHP .................................... 5-1
Process Description .......................................................................................... 5-1
Process Discussion ........................................................................................... 5-19
Cost Estimates ................................................................................................. 5-20

PO/SM BY THE SHELL PROCESS USING EBHP ............................................ 5-26
Process Description .......................................................................................... 5-26
Process Discussion ........................................................................................... 5-26
Cost Estimates ................................................................................................. 5-42

COMPARISON OF PO/SM PROCESSES ......................................................... 5-50

6 PROPYLENE OXIDE BY HYDROPEROXIDATION USING CUMENE HYDROPEROXIDE .............................................................. 6-1

PO BY THE SUMITOMO PROCESS USING CHP ............................................. 6-1
Process Description .......................................................................................... 6-1
Process Discussion ........................................................................................... 6-16
Cost Estimates ................................................................................................. 6-16

COMPARISON OF PO BY DIFFERENT HYDROPEROXIDATION PROCESSES .... 6-23
CONTENTS (Continued)

7 PROPYLENE OXIDE BY HYDROPEROXIDATION USING HYDROGEN PEROXIDE ................................................................. 7-1

PROCESS REVIEW ........................................................................................................... 7-1
Integration of PO Production and Hydrogen Peroxide Preparation ............................. 7-4
Process Configurations ................................................................................................. 7-4
Catalysts for Propylene Epoxidation with Hydrogen Peroxide................................. 7-4
Catalyst Regeneration ................................................................................................. 7-6
Propylene Epoxidation with Hydrogen Peroxide ....................................................... 7-7
Separation of Epoxidation Product and Propylene Oxide Purification....................... 7-8
PO BY THE BASF PROCESS USING HYDROGEN PEROXIDE ............................... 7-8
Process Description ....................................................................................................... 7-9
Process Discussion ....................................................................................................... 7-10
Cost Estimates .............................................................................................................. 7-12
PO BY THE DEGUSSA PROCESS USING HYDROGEN PEROXIDE....................... 7-25
Process Description ....................................................................................................... 7-25
Process Discussion ....................................................................................................... 7-26
Cost Estimates .............................................................................................................. 7-27
COMPARISON OF PO USING HP AND PO/SM USING EBHP PROCESSES... 7-41

8 PROPYLENE OXIDE BY DIRECT EPOXIDATION ...................................................... 8-1

PROCESS REVIEW ........................................................................................................... 8-1
Propylene Epoxidation with Molecular Oxygen .......................................................... 8-1
PO by Propylene Epoxidation with Molecular Oxygen and Hydrogen ..................... 8-4
Propylene Epoxidation with Molecular Oxygen and CO or NO ................................. 8-11
Propylene Epoxidation with Oxygen-Containing Compounds .................................. 8-11
PO BY THE DIRECT EPOXIDATION OF AIST-NIPPON SHOKUBAI ................. 8-11
Process Description ....................................................................................................... 8-11
Process Discussion ....................................................................................................... 8-19
Cost Estimates .............................................................................................................. 8-20
CONTENTS (Concluded)

8 PROPYLENE OXIDE BY DIRECT EPOXIDATION (CONCLUDED)
   COMPARISON OF PO BY DIRECT EPOXIDATION, PO USING HP, AND
   PO/SM USING EBHP PROCESSES ................................................................. 8-26

9 PROPYLENE OXIDE BY THE CHLOROHYDRIN PROCESS .............................. 9-1
   THE CHLOROHYDRIN PROCESS USING LIME (CONVENTIONAL) ............... 9-1
   Process Description ....................................................................................... 9-2
   Process Discussion ......................................................................................... 9-12
   Cost Estimates ............................................................................................... 9-12
   THE CHLOROHYDRIN PROCESS USING CELL LIQUOR FOR
   SAPONIFICATION ............................................................................................. 9-18
   Process Description ....................................................................................... 9-18
   Process Discussion ......................................................................................... 9-28
   Cost Estimates ............................................................................................... 9-28
   COMPARISON OF DIFFERENT VERSIONS OF THE CHLOROHYDRIN
   PROCESS ......................................................................................................... 9-34

APPENDIX A: PATENT SUMMARY TABLES .................................................... A-1

APPENDIX B: DESIGN AND COST BASES .................................................... B-1

APPENDIX C: CITED REFERENCES .................................................................. C-1

APPENDIX D: PATENT REFERENCES BY ASSIGNEE .................................... D-1

APPENDIX E: PROCESS FLOW DIAGRAMS ................................................... E-1
ILLUSTRATIONS

3.1 Historical Prices of Propylene Oxide ................................................................. 3-12
3.2 Propylene Oxide Consumption Patterns ............................................................. 3-13
4.1 PO/TBA by the Lyondell Process Using TBHP
   Process Flow Diagram .......................................................................................... E-3
4.2 PO/TBA by the Lyondell Process Using TBHP
   Effect of Operating Level and Plant Capacity on Product Value ....................... 4-22
4.3 PO/TBA by the Lyondell Process Using TBHP
   Effect of Raw Material Costs and Coproduct Credit on Product Value ............... 4-23
4.4 PO/TBA by the Huntsman Process Using TBHP
   Process Flow Diagram .......................................................................................... E-7
4.5 PO/TBA by the Huntsman Process Using TBHP
   Effect of Operating Level and Plant Capacity on Product Value ....................... 4-43
4.6 PO/TBA by the Huntsman Process Using TBHP
   Effect of Raw Material Costs and Coproduct Credit on Product Value ............... 4-44
5.1 PO/SM by the Lyondell Process Using EBHP
   Process Flow Diagram .......................................................................................... E-11
5.2 PO/SM by the Lyondell Process Using EBHP
   Effect of Operating Level and Plant Capacity on Product Value ....................... 5-26
5.3 PO/SM by the Lyondell Process Using EBHP
   Effect of Raw Material Costs and Coproduct Credit on Product Value ............... 5-27
5.4 PO/SM by the Shell Process Using EBHP
   Process Flow Diagram .......................................................................................... E-15
5.5 PO/SM by the Shell Process Using EBHP
   Effect of Operating Level and Plant Capacity on Product Value ....................... 5-48
5.6 PO/SM by the Shell Process Using EBHP
   Effect of Raw Material Costs and Coproduct Credit on Product Value ............... 5-49
6.1 PO by the Sumitomo Process Using CHP
   Process Flow Diagram .......................................................................................... E-19
6.2 PO by the Sumitomo Process Using CHP
   Effect of Operating Level and Plant Capacity on Product Value ....................... 6-22
6.3 Comparison of PO by Hydroperoxidation Processes
   Effect of Raw Material Prices and Coproduct Credits ........................................... 6-25
7.1 PO by the BASF Process Using HP
   Process Flow Diagram .......................................................................................... E-23
7.2 PO by the BASF Process Using HP
   Effect of Operating Level and Plant Capacity on Product Value ....................... 7-24
**ILLUSTRATIONS (Concluded)**

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.3</td>
<td>PO by the Degussa Process Using HP</td>
<td>E-25</td>
</tr>
<tr>
<td></td>
<td>Process Flow Diagram</td>
<td></td>
</tr>
<tr>
<td>7.4</td>
<td>PO by the Degussa Process Using HP</td>
<td>7-40</td>
</tr>
<tr>
<td></td>
<td>Effect of Operating Level and Plant Capacity on Product Value</td>
<td></td>
</tr>
<tr>
<td>7.5</td>
<td>Comparison of PO by Using HP and PO/SM Using EBHP Processes</td>
<td>7-43</td>
</tr>
<tr>
<td></td>
<td>Effect of Raw Material Prices and Coproduct Credits</td>
<td></td>
</tr>
<tr>
<td>8.1</td>
<td>Effect of Pt/Pd Catalyst Reduction Condition on PO Yield</td>
<td>8-7</td>
</tr>
<tr>
<td>8.2</td>
<td>Effect of Pt Loading in Pt/Pd Catalyst on PO Yield</td>
<td>8-7</td>
</tr>
<tr>
<td>8.3</td>
<td>Effect of Alkali Loading in Pt/Pd Catalyst on PO Yield</td>
<td>8-8</td>
</tr>
<tr>
<td>8.4</td>
<td>PO by Direct Epoxidation of AIST-Nippon Shokubai</td>
<td>E-27</td>
</tr>
<tr>
<td></td>
<td>Process Flow Diagram</td>
<td></td>
</tr>
<tr>
<td>8.5</td>
<td>PO by Direct Epoxidation of AIST-Nippon Shokubai</td>
<td>8-25</td>
</tr>
<tr>
<td></td>
<td>Effect of Operating Level and Plant Capacity on Product Value</td>
<td></td>
</tr>
<tr>
<td>8.6</td>
<td>Comparison of PO by Direct Epoxidation, PO Using HP and PO/SM Using</td>
<td>8-28</td>
</tr>
<tr>
<td></td>
<td>EBHP Processes: Effect of Raw Material Prices and Coproduct Credits</td>
<td></td>
</tr>
<tr>
<td>9.1</td>
<td>PO by the Chlorohydrin Process Using Lime</td>
<td>E-29</td>
</tr>
<tr>
<td></td>
<td>Process Flow Diagram</td>
<td></td>
</tr>
<tr>
<td>9.2</td>
<td>PO by the Chlorohydrin Process Using Cell Liquor</td>
<td>E-33</td>
</tr>
<tr>
<td></td>
<td>Process Flow Diagram</td>
<td></td>
</tr>
</tbody>
</table>
# TABLES

2.1 Economics of Propylene Oxide Processes ......................................................... 2-13
3.1 Historical and Projected World Propylene Oxide Capacity, Production, and Consumption, by Region ................................................................. 3-8
3.2 Year-End Capacities of Propylene Oxide Plants Worldwide............................ 3-9
4.1 PO/TBA by the Lyondell Process Using TBHP Design Bases and Assumptions .................................................................................................................... 4-4
4.2 PO/TBA by the Lyondell Process Using TBHP Stream Flows ................................................................. 4-6
4.3 PO/TBA by the Lyondell Process Using TBHP Summary of Waste Streams ................................................................. 4-10
4.4 PO/TBA by the Lyondell Process Using TBHP Major Equipment .......... 4-11
4.5 PO/TBA by the Lyondell Process Using TBHP Utilities Summary .............. 4-14
4.6 PO/TBA by the Lyondell Process Using TBHP Capital Investment ......... 4-17
4.7 PO/TBA by the Lyondell Process Using TBHP Capital Investment by Section ................................................................. 4-18
4.8 PO/TBA by the Lyondell Process Using TBHP Production Costs ............. 4-20
4.9 PO/TBA by the Huntsman Process Using TBHP Design Bases and Assumptions .................................................................................................................... 4-26
4.10 PO/TBA by the Huntsman Process Using TBHP Stream Flows .............. 4-28
4.11 PO/TBA by the Huntsman Process Using TBHP Summary of Waste Streams ................................................................. 4-32
4.12 PO/TBA by the Huntsman Process Using TBHP Major Equipment .......... 4-33
4.13 PO/TBA by the Huntsman Process Using TBHP Utilities Summary .......... 4-36
4.14 PO/TBA by the Huntsman Process Using TBHP Capital Investment ......... 4-38
4.15 PO/TBA by the Huntsman Process Using TBHP Capital Investment by Section ................................................................. 4-39
4.16 PO/TBA by the Huntsman Process Using TBHP
Production Costs ................................................................. 4-41

5.1 PO/SM by the Lyondell Process Using EBHP
Design Bases and Assumptions ........................................... 5-4

5.2 PO/SM by the Lyondell Process Using EBHP
Stream Flows ........................................................................ 5-7

5.3 PO/SM by the Lyondell Process Using EBHP
Summary of Waste Streams .................................................. 5-13

5.4 PO/SM by the Lyondell Process Using EBHP
Major Equipment ................................................................. 5-14

5.5 PO/SM by the Lyondell Process Using EBHP
Utilities Summary ................................................................. 5-18

5.6 PO/SM by the Lyondell Process Using EBHP
Capital Investment ................................................................. 5-21

5.7 PO/SM by the Lyondell Process Using EBHP
Capital Investment by Section .............................................. 5-22

5.8 PO/SM by the Lyondell Process Using EBHP
Production Costs ................................................................. 5-24

5.9 PO/SM by the Shell Process Using EBHP
Design Bases and Assumptions ............................................. 5-29

5.10 PO/SM by the Shell Process Using EBHP
Stream Flows ......................................................................... 5-31

5.11 PO/SM by the Shell Process Using EBHP
Summary of Waste Streams .................................................. 5-36

5.12 PO/SM by the Shell Process Using EBHP
Major Equipment ................................................................. 5-37

5.13 PO/SM by the Shell Process Using EBHP
Utilities Summary ................................................................. 5-41

5.14 PO/SM by the Shell Process Using EBHP
Capital Investment ................................................................. 5-43

5.15 PO/SM by the Shell Process Using EBHP
Capital Investment by Section .............................................. 5-44

5.16 PO/SM by the Shell Process Using EBHP
Production Costs ................................................................. 5-46

6.1 PO by the Sumitomo Process Using CHP
Design Bases and Assumptions ............................................. 6-4
<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.2</td>
<td>PO by the Sumitomo Process Using CHP Stream Flows</td>
<td>6-6</td>
</tr>
<tr>
<td>6.3</td>
<td>PO by the Sumitomo Process Using CHP Summary of Waste Streams</td>
<td>6-11</td>
</tr>
<tr>
<td>6.4</td>
<td>PO by the Sumitomo Process Using CHP Major Equipment</td>
<td>6-12</td>
</tr>
<tr>
<td>6.5</td>
<td>PO by the Sumitomo Process Using CHP Utilities Summary</td>
<td>6-15</td>
</tr>
<tr>
<td>6.6</td>
<td>PO by the Sumitomo Process Using CHP Capital Investment</td>
<td>6-17</td>
</tr>
<tr>
<td>6.7</td>
<td>PO by the Sumitomo Process Using CHP Capital Investment by Section</td>
<td>6-18</td>
</tr>
<tr>
<td>6.8</td>
<td>PO by the Sumitomo Process Using CHP Production Costs</td>
<td>6-20</td>
</tr>
<tr>
<td>6.9</td>
<td>Comparison of PO by Hydroperoxidation Processes</td>
<td>6-24</td>
</tr>
<tr>
<td>7.1</td>
<td>PO by Hydroperoxidation Using Hydrogen Peroxide Patent Summary</td>
<td>A-3</td>
</tr>
<tr>
<td>7.2</td>
<td>PO by the BASF Process Using HP Design Bases and Assumptions</td>
<td>7-11</td>
</tr>
<tr>
<td>7.3</td>
<td>PO by the BASF Process Using HP Stream Flows</td>
<td>7-13</td>
</tr>
<tr>
<td>7.4</td>
<td>PO by the BASF Process Using HP Summary of Waste Streams</td>
<td>7-15</td>
</tr>
<tr>
<td>7.5</td>
<td>PO by the BASF Process Using HP Major Equipment</td>
<td>7-16</td>
</tr>
<tr>
<td>7.6</td>
<td>PO by the BASF Process Using HP Utilities Summary</td>
<td>7-18</td>
</tr>
<tr>
<td>7.7</td>
<td>PO by the BASF Process Using HP Capital Investment</td>
<td>7-19</td>
</tr>
<tr>
<td>7.10</td>
<td>PO by the Degussa Process Using HP Design Bases and Assumptions</td>
<td>7-28</td>
</tr>
<tr>
<td>7.11</td>
<td>PO by the Degussa Process Using HP Stream Flows</td>
<td>7-29</td>
</tr>
<tr>
<td>Table Number</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------------</td>
<td>------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>7.8</td>
<td>PO by the BASF Process Using HP Capital Investment by Section</td>
<td>7-20</td>
</tr>
<tr>
<td>7.9</td>
<td>PO by the BASF Process Using HP Production Costs</td>
<td>7-22</td>
</tr>
<tr>
<td>7.12</td>
<td>PO by the Degussa Process Using HP Summary of Waste Streams</td>
<td>7-31</td>
</tr>
<tr>
<td>7.13</td>
<td>PO by the Degussa Process Using HP Major Equipment</td>
<td>7-32</td>
</tr>
<tr>
<td>7.14</td>
<td>PO by the Degussa Process Using HP Utilities Summary</td>
<td>7-34</td>
</tr>
<tr>
<td>7.15</td>
<td>PO by the Degussa Process Using HP Capital Investment</td>
<td>7-35</td>
</tr>
<tr>
<td>7.16</td>
<td>PO by the Degussa Process Using HP Capital Investment by Section</td>
<td>7-36</td>
</tr>
<tr>
<td>7.17</td>
<td>PO by the Degussa Process Using HP Production Costs</td>
<td>7-38</td>
</tr>
<tr>
<td>7.18</td>
<td>Comparison of PO Using HP and PO/SM Using EBHP Processes Technical Aspects and Base-Case Process Economics</td>
<td>7-42</td>
</tr>
<tr>
<td>8.1</td>
<td>PO by the Direct Epoxidation of AIST-Nippon Shokubai Patent Summary</td>
<td>A-5</td>
</tr>
<tr>
<td>8.2</td>
<td>PO by the Direct Epoxidation of AIST-Nippon Shokubai Design Bases and Assumptions</td>
<td>8-12</td>
</tr>
<tr>
<td>8.3</td>
<td>PO by the Direct Epoxidation of AIST-Nippon Shokubai Stream Flows</td>
<td>8-13</td>
</tr>
<tr>
<td>8.4</td>
<td>PO by the Direct Epoxidation of AIST-Nippon Shokubai Summary of Waste Streams</td>
<td>8-15</td>
</tr>
<tr>
<td>8.5</td>
<td>PO by the Direct Epoxidation of AIST-Nippon Shokubai Major Equipment</td>
<td>8-16</td>
</tr>
<tr>
<td>8.6</td>
<td>PO by the Direct Epoxidation of AIST-Nippon Shokubai Utilities Summary</td>
<td>8-18</td>
</tr>
<tr>
<td>8.7</td>
<td>PO by the Direct Epoxidation of AIST-Nippon Shokubai Capital Investment</td>
<td>8-21</td>
</tr>
<tr>
<td>8.8</td>
<td>PO by the Direct Epoxidation of AIST-Nippon Shokubai Capital Investment by Section</td>
<td>8-22</td>
</tr>
<tr>
<td>8.9</td>
<td>PO by the Direct Epoxidation of AIST-Nippon Shokubai Production Costs</td>
<td>8-23</td>
</tr>
</tbody>
</table>
TABLES (Concluded)

8.10 Comparison of PO by Direct Epoxidation, PO Using HP and PO/SM Using EBHP Processes: Technical Aspects and Base-Case Process Economics .......................... 8-27

9.1 PO by the Chlorohydrin Process Using Lime Design Bases and Assumptions .................................................................................................................. 9-3

9.2 PO by the Chlorohydrin Process Using Lime Stream Flows ................................................................................................................................. 9-4

9.3 PO by the Chlorohydrin Process Using Lime Summary of Waste Streams ........................................................................................................... 9-8

9.4 PO by the Chlorohydrin Process Using Lime Major Equipment ....................................................................................................................... 9-9

9.5 PO by the Chlorohydrin Process Using Lime Utilities Summary ....................................................................................................................... 9-11

9.6 PO by the Chlorohydrin Process Using Lime Capital Investment .................................................................................................................... 9-13

9.7 PO by the Chlorohydrin Process Using Lime Capital Investment by Section .......................................................................................... 9-14

9.8 PO by the Chlorohydrin Process Using Lime Production Costs .................................................................................................................. 9-16

9.9 PO by the Chlorohydrin Process Using Cell Liquor Design Bases and Assumptions ................................................................................... 9-19

9.10 PO by the Chlorohydrin Process Using Cell Liquor Stream Flows ........................................................................................................... 9-20

9.11 PO by the Chlorohydrin Process Using Cell Liquor Summary of Waste Streams ...................................................................................... 9-24

9.12 PO by the Chlorohydrin Process Using Cell Liquor Major Equipment ...................................................................................................... 9-25

9.13 PO by the Chlorohydrin Process Using Cell Liquor Utilities Summary ....................................................................................................... 9-27

9.14 PO by the Chlorohydrin Process Using Cell Liquor Capital Investment .................................................................................................. 9-29

9.15 PO by the Chlorohydrin Process Using Cell Liquor Capital Investment by Section .................................................................................. 9-30

9.16 PO by the Chlorohydrin Process Using Cell Liquor Production Costs ...................................................................................................... 9-32

9.17 Comparison of Different Versions of the Chlorohydrin Process for PO Production .................................................................................. 9-35