Abstract
Process Economics Program REPORT 29F
ETHYLENE BY NONCONVENTIONAL PROCESSES
(August 1998)

This report reviews recent developments in nonconventional ethylene technologies and evaluates commercial technologies and processes in R&D.

Among commercial processes, the use of low-value refinery gas as a feedstock allows recovery of valuable products; however, refinery gas supplies for ethylene production are limited. The metathesis process for converting propylene to ethylene or the reverse reaction entails a low processing cost, but the relative propylene/ethylene price has a major impact on process economics. Ethanol dehydration, although requiring low capital investment, is waning in popularity because of the rising cost of ethanol, capacity limitations, and competition from steam cracking.

Promising nonconventional processes in R&D follow. UOP/Hydro's Methanol-to-Olefins process requires a low capital investment, but methanol production is capital-intensive. The shock wave reactor provides precise temperature history control, is compact, eliminates high-temperature gradients through the wall, and decouples heat addition from the chemical reaction, thus allowing high pyrolysis temperatures; however, further development and testing are needed. Promising catalytic cracking developments include Vniios' (Russia) process and R&D conducted by the Japanese Ministry of International Trade and Industry. Ethane dehydrogenation in membrane reactors shifts the chemical equilibrium in favor of ethane conversion at several times the normal rate, and its capital and production costs are competitive with those of conventional processes; however, a major uncertainty is scale-up of the reactors. Light alkanes oxidative dehydrogenation removes the equilibrium limitation by oxidizing the hydrogen product while providing the heat required; however, oxygen also converts alkanes and dehydrogenation products to CO₂ and other oxygenated compounds; suitable catalysts and novel reactors could mitigate the problem. Broken Hill Proprietary and Commonwealth Scientific & Industrial Research Organisation’s OXCO process combines methane oxidative coupling with steam cracking; OXCO's per pass yields of both ethylene and propylene are higher than those of methane oxidative coupling.

Less promising developments include ethylene and vinyl chloride coproduction, ethylene and acetic acid coproduction, fluidized or circulating bed cracking, thermal cracking with partial combustion, hydropyrolysis, and other methane-based processes.

This report should prove useful not only to provide an overview and understanding of various nonconventional processes, but also for monitoring and/or investing in the emerging alternative technologies.
<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACR</td>
<td>Advanced Cracking Reactor</td>
</tr>
<tr>
<td>AET</td>
<td>Advanced Extraction Technologies</td>
</tr>
<tr>
<td>BHP</td>
<td>Broken Hill Proprietary</td>
</tr>
<tr>
<td>CMHC</td>
<td>Coupled methanol/hydrocarbon cracking</td>
</tr>
<tr>
<td>CSIRO</td>
<td>Commonwealth Scientific &amp; Industrial Research Organisation</td>
</tr>
<tr>
<td>CTIP</td>
<td>Compagnia Tecnica Internazionale Progetti</td>
</tr>
<tr>
<td>CTP</td>
<td>Centro de Tecnología Promon</td>
</tr>
<tr>
<td>DCC</td>
<td>Deep Catalyst Cracking</td>
</tr>
<tr>
<td>EDC</td>
<td>Ethylene dichloride</td>
</tr>
<tr>
<td>FCC</td>
<td>Fluidized catalytic cracking</td>
</tr>
<tr>
<td>FCCU</td>
<td>Fluidized catalytic cracking units</td>
</tr>
<tr>
<td>FT</td>
<td>Fischer-Tropsch</td>
</tr>
<tr>
<td>GHSV</td>
<td>Gas hourly space velocity</td>
</tr>
<tr>
<td>GTO</td>
<td>Gas-to-olefins</td>
</tr>
<tr>
<td>HT</td>
<td>Haldor Topsøe</td>
</tr>
<tr>
<td>IFP</td>
<td>Institut Français du Pétrole</td>
</tr>
<tr>
<td>JCIA</td>
<td>Japan Chemical Industry Association</td>
</tr>
<tr>
<td>JGC</td>
<td>Japan Gas Co.</td>
</tr>
<tr>
<td>KTI</td>
<td>Kinetics Technology International</td>
</tr>
<tr>
<td>LHSV</td>
<td>Liquid hourly space velocity</td>
</tr>
<tr>
<td>LPG</td>
<td>Liquefied petroleum gas</td>
</tr>
<tr>
<td>LPR</td>
<td>Low-Pressure Recovery Process</td>
</tr>
<tr>
<td>MITI</td>
<td>Ministry of International Trade and Industry, Japan</td>
</tr>
<tr>
<td>MTE</td>
<td>Methane-to-Ethylene Process</td>
</tr>
<tr>
<td>MTO</td>
<td>Methanol-to-Olefins</td>
</tr>
<tr>
<td>OCT</td>
<td>Olefins Conversion Technology</td>
</tr>
<tr>
<td>ODH</td>
<td>Oxidative dehydrogenation</td>
</tr>
<tr>
<td>Term</td>
<td>Definition</td>
</tr>
<tr>
<td>----------</td>
<td>-----------------------------------------------------------</td>
</tr>
<tr>
<td>OGR</td>
<td>Off-gas recovery process</td>
</tr>
<tr>
<td>Oxychem</td>
<td>Occidental Chemical Corporation</td>
</tr>
<tr>
<td>PSA</td>
<td>Pressure swing adsorption</td>
</tr>
<tr>
<td>QC</td>
<td>Quick Contact</td>
</tr>
<tr>
<td>SAPO</td>
<td>Silica alumina-phosphate synthetic molecular sieve</td>
</tr>
<tr>
<td>SAS</td>
<td>Sasol Advanced Synthol</td>
</tr>
<tr>
<td>SD</td>
<td>Scientific Design</td>
</tr>
<tr>
<td>SHOP</td>
<td>Shell Higher Olefins Process</td>
</tr>
<tr>
<td>SWR</td>
<td>Shock wave reactor</td>
</tr>
<tr>
<td>THR</td>
<td>Total Hydrocarbon Reforming Process</td>
</tr>
<tr>
<td>TRC</td>
<td>Thermal Regeneration Cracking</td>
</tr>
<tr>
<td>UCC</td>
<td>Union Carbide</td>
</tr>
<tr>
<td>USC</td>
<td>The University of Southern California</td>
</tr>
<tr>
<td>VCM</td>
<td>Vinyl chloride monomer</td>
</tr>
<tr>
<td>Vniios</td>
<td>All-Union Institute for Organic Synthesis, Russia</td>
</tr>
<tr>
<td>WHSV</td>
<td>Weight hourly space velocity</td>
</tr>
</tbody>
</table>
## CONTENTS

GLOSSARY ............................................................................................................. xvii

1  INTRODUCTION ........................................................................................................ 1-1

2  SUMMARY .................................................................................................................. 2-1

   GENERAL ASPECTS .......................................................................................... 2-1

   Ethylene Feedstocks ......................................................................................... 2-1

   Ethylene Production ......................................................................................... 2-2

   Ethylene Consumption ...................................................................................... 2-2

   TECHNICAL ASPECTS .................................................................................... 2-2

   Ethylene from Ethane by a Conventional Process .......................................... 2-3

   Ethylene from Propane by a Conventional Process ........................................ 2-3

   Ethylene from Light Naphtha by a Conventional Process ............................. 2-4

   Ethylene from Ethanol by Catalytic Dehydration .......................................... 2-14

   Ethylene Recovery from Refinery Gas ............................................................ 2-14

   Charging into a Conventional Ethylene Plant ................................................. 2-14

   The Expander Process ...................................................................................... 2-14

   Low-Pressure Cryogenic Recovery ................................................................ 2-14

   Solvent Absorption ............................................................................................ 2-15

   Salt Complexing Absorption ............................................................................ 2-15

   Pressure Swing Adsorption ............................................................................. 2-15

   Ethylene from Propylene or Butylenes by Metathesis ..................................... 2-15

   Ethylene by Catalytic Cracking ........................................................................ 2-16

   The Unios Process ............................................................................................... 2-16

   Toyo Engineering’s Process ............................................................................... 2-16

   Asahi Chemical’s Process .................................................................................. 2-17

   MITI’s Project ...................................................................................................... 2-17

   Ethylene from Ethane by Catalytic Dehydrogenation in Membrane Reactors .... 2-17

   Ethylene from Ethane by Oxidative Dehydrogenation ..................................... 2-17

   Ethylene from Propane/Butane by Oxidative Dehydrogenation ..................... 2-18

   Ethylene Coproduction with Acetic Acid by Oxidative Dehydrogenation ........ 2-18

   Ethylene Coproduction with Vinyl Chloride by Chloro-Dehydrogenation ....... 2-18
CONTENTS (Continued)

2 SUMMARY (Concluded) .................................................................................................................... 2-1
Ethylene by Fluidized or Circulating Bed Cracking ................................................................. 2-19
   The Lurgi Sand Cracker ............................................................................................................ 2-19
   BASF's Fluidized Coke/Flow Cracking ................................................................................. 2-19
   The KK Process ....................................................................................................................... 2-19
   The Ube Process ....................................................................................................................... 2-20
Quick Contact Reaction System/Thermal Regenerative Cracking ............................................. 2-20
Ethylene by Thermal Cracking with Partial Combustion ......................................................... 2-20
   The Advanced Cracking Reactor Process .............................................................................. 2-20
   Ethylene from Light Crude by Dow's Partial Combustion Process .................................... 2-21
   Ethylene by Hydropyrolysis .................................................................................................... 2-21
   Ethylene from Ethane using the Shock Wave Reactor .......................................................... 2-21
   Ethylene from Methane, Directly or via Methanol ............................................................... 2-22
      Ethylene from Methane by Direct Pyrolysis ........................................................................ 2-22
      Ethylene from Methane by Oxidative Coupling ............................................................... 2-22
      Ethylene from Methanol ....................................................................................................... 2-23
   Ethylene from Syngas by Modified Fischer-Tropsch Process ............................................... 2-23
   Ethylene by Ethanol Dehydration via Methanol Homologation .......................................... 2-24
   Ethylene from Methane via Methyl Chloride ........................................................................ 2-24
ECONOMICS ASPECTS ................................................................................................................. 2-24
CONCLUSIONS ............................................................................................................................. 2-26

3 ETHYLENE FROM ETHANOL BY CATALYTIC DEHYDRATION ............................................. 3-1
   INDUSTRY STATUS .................................................................................................................. 3-1
   CHEMISTRY ............................................................................................................................. 3-3
   PROCESS REVIEW ................................................................................................................... 3-3
   Halcon/SD ............................................................................................................................... 3-3
   Japan Gas/Nikki Chemical ..................................................................................................... 3-4
   ABB Lummus .......................................................................................................................... 3-4
   Petrobras ................................................................................................................................ 3-4
   Others .................................................................................................................................... 3-5
   Product Separation ................................................................................................................. 3-5
CONTENTS (Continued)

3 ETHYLENE FROM ETHANOL BY CATALYTIC DEHYDRATION (Concluded)
ETHYLENE FROM ETHANOL BY FLUIDIZED-BED CATALYTIC DEHYDRATION ........3-6
Process Description ....................................................................................................................3-6
  Section 100—Reaction ...........................................................................................................3-6
  Section 200—Product Separation ..........................................................................................3-6
Process Discussion ....................................................................................................................3-12
Cost Estimates ..........................................................................................................................3-12
  Capital Costs ........................................................................................................................3-12
  Production Costs ..................................................................................................................3-12
ETHYLENE FROM ETHANOL BY CATALYTIC DEHYDRATION
IN FIXED-BED REACTORS .................................................................3-14
Economic Comparison ..............................................................................................................3-14

4 ETHYLENE RECOVERY FROM REFINERY GAS .................................................................4-1
INDUSTRY STATUS .................................................................................................................4-1
PROCESS REVIEW ..................................................................................................................4-3
  Charging into a Conventional Ethylene Plant .......................................................................4-3
  The Expander Process .........................................................................................................4-3
Low-Pressure Cryogenic Recovery ..........................................................................................4-4
Solvent Absorption ..................................................................................................................4-4
Salt Complexing Absorption ....................................................................................................4-4
Pressure Swing Adsorption ......................................................................................................4-5
PROCESS EVALUATION ..........................................................................................................4-5
PROCESS STATUS ....................................................................................................................4-6

5 ETHYLENE FROM PROPYLENE OR BUTYLENES BY METATHESIS ..................................5-1
INDUSTRY STATUS .................................................................................................................5-1
CHEMISTRY ..........................................................................................................................5-1
PROCESS REVIEW ..................................................................................................................5-2
  Phillips Petroleum ...............................................................................................................5-2
  Institut Français du Pétrole ..................................................................................................5-3
  ARCO Chemical ..................................................................................................................5-3
Others ......................................................................................................................................5-3
CONTENTS (Continued)

5 ETHYLENE FROM PROPYLENE OR BUTYLENES BY METATHESIS (Concluded)
   PROCESS EVALUATION ........................................................................................................... 5-4
   Propylene from Ethylene and Butylenes ............................................................................... 5-4
   Ethylene and Butylenes from Propylene ............................................................................... 5-4

6 ETHYLENE BY CATALYTIC CRACKING ........................................................................... 6-1
   CHEMISTRY .......................................................................................................................... 6-1
   PROCESS REVIEW ............................................................................................................... 6-1
   The Vniios Process ............................................................................................................... 6-2
   Toyo Engineering’s Process .................................................................................................. 6-2
   Asahi Chemical’s Process ...................................................................................................... 6-3
   MITI’s Project ....................................................................................................................... 6-3
   PROCESS EVALUATION ....................................................................................................... 6-4
   PROCESS STATUS .................................................................................................................. 6-4

7 ETHYLENE FROM ETHANE BY CATALYTIC DEHYDROGENATION ................................ 7-1
   IN MEMBRANE REACTORS ................................................................................................. 7-1
   CHEMISTRY .......................................................................................................................... 7-1
   PROCESS REVIEW ............................................................................................................... 7-3
   The USC Process .................................................................................................................... 7-3
   Membrane Reactor Design ................................................................................................. 7-3
   Process Parameters ............................................................................................................ 7-5
   Others ................................................................................................................................... 7-5
   PROCESS DESCRIPTION ..................................................................................................... 7-7
   Section 100—Reaction and Quenching ................................................................................. 7-7
   Section 200—Compression and Hydrogen Separation ......................................................... 7-8
   Section 300—Ethylene Separation ....................................................................................... 7-8
   Section 400—Propylene Refrigeration .................................................................................. 7-9
   PROCESS DISCUSSION ....................................................................................................... 7-16
   COST ESTIMATES .................................................................................................................. 7-16
   Capital Costs ........................................................................................................................ 7-16
   Production Costs .................................................................................................................. 7-17
   ECONOMICS COMPARISON .............................................................................................. 7-17
   PROCESS STATUS .................................................................................................................. 7-18
### CONTENTS (Continued)

9 **ETHYLENE FROM PROPANE/BUTANE BY OXIDATIVE DEHYDROGENATION** (Concluded)
   - Ethylene from LPG by ODH Using Rare Earth-Alkali-Halogen Catalyst ........................................ 9-6
   - PROCESS STATUS ....................................................................................................................... 9-7

10 **ETHYLENE COPRODUCTION WITH ACETIC ACID BY OXIDATIVE DEHYDROGENATION** ........................................... 10-1
    - CHEMISTRY ............................................................................................................................ 10-1
    - PROCESS REVIEW .................................................................................................................. 10-1
    - PROCESS EVALUATION ......................................................................................................... 10-2
    - PROCESS STATUS ................................................................................................................... 10-3

11 **ETHYLENE COPRODUCTION WITH VINYL CHLORIDE BY CHLORO-DEHYDROGENATION** ................................... 11-1
    - CHEMISTRY ............................................................................................................................ 11-1
    - PROCESS REVIEW .................................................................................................................. 11-1
    - PROCESS EVALUATION ......................................................................................................... 11-2
    - PROCESS STATUS ................................................................................................................... 11-5

12 **ETHYLENE BY FLUIDIZED OR CIRCULATING BED CRACKING** ..................................................................................... 12-1
    - PROCESS REVIEW .................................................................................................................. 12-1
    - Lurgi’s Sand Cracker ................................................................................................................ 12-1
    - BASF’s Fluidized Coke/Flow Cracking ....................................................................................... 12-4
    - The KK Process ....................................................................................................................... 12-4
    - The Ube Process ..................................................................................................................... 12-8
    - Quick Contact Reaction System/Thermal Regenerative Cracking ............................................. 12-8
    - Other New Developments ........................................................................................................ 12-11
    - PROCESS EVALUATION ......................................................................................................... 12-11
    - PROCESS STATUS ................................................................................................................... 12-12

13 **ETHYLENE BY THERMAL CRACKING WITH PARTIAL COMBUSTION** ........................................................................... 13-1
    - THE ADVANCED CRACKING REACTOR PROCESS ................................................................. 13-1
    - Process Review ....................................................................................................................... 13-1
    - Process Evaluation .................................................................................................................. 13-3
    - Process Status ......................................................................................................................... 13-4
CONTENTS (Continued)

13 ETHYLENE BY THERMAL CRACKING WITH PARTIAL COMBUSTION (Concluded)
   ETHYLENE FROM LIGHT CRUDE BY DOW’S PARTIAL COMBUSTION PROCESS... 13-7
   Process Review .................................................................................................. 13-7
   Process Evaluation ............................................................................................ 13-7
   Process Status .................................................................................................... 13-7
14 ETHYLENE BY HYDROPYROLYSIS ........................................................................ 14-1
   PROCESS REVIEW ............................................................................................ 14-1
   PROCESS EVALUATION ..................................................................................... 14-1
   PROCESS STATUS .............................................................................................. 14-2
15 ETHYLENE FROM ETHANE BY SHOCK WAVE REACTOR ...................................... 15-1
   PROCESS REVIEW ............................................................................................ 15-1
   PROCESS EVALUATION ..................................................................................... 15-3
   PROCESS STATUS .............................................................................................. 15-3
16 ETHYLENE FROM METHANE DIRECTLY OR VIA METHANOL .............................. 16-1
   PROCESS REVIEW ............................................................................................ 16-1
   Ethylene from Methane by Direct Pyrolysis ...................................................... 16-1
   Ethylene from Methane by Oxidative Coupling .............................................. 16-2
      The ARCO Process ......................................................................................... 16-2
      The Oxpyrolysis Process ............................................................................... 16-3
      The OXCO Process ....................................................................................... 16-4
      The Lawrence Berkeley Laboratory Process .............................................. 16-4
      The Vniios Process ....................................................................................... 16-5
   Ethylene from Methanol .................................................................................. 16-5
      The Mobil MTE Process ............................................................................... 16-5
      The UOP/Hydro MTO Process ..................................................................... 16-6
   Coupled Methanol/Hydrocarbon Cracking ...................................................... 16-6
      The IFP Process ............................................................................................. 16-7
   Ethylene from Syngas by the Modified Fischer-Tropsch Process ...................... 16-7
   Ethylene by Ethanol Dehydration via Methanol Homologation ...................... 16-7
   ETHYLENE FROM METHANE VIA METHYL CHLORIDE ................................. 16-12
   PROCESS EVALUATION ................................................................................... 16-12
   PROCESS STATUS ............................................................................................ 16-13
CONTENTS (Concluded)

APPENDIX A: PATENT SUMMARY TABLES .......................................................... A-1
APPENDIX B: LITERATURE SUMMARY TABLES ......................................... B-1
APPENDIX C: DESIGN AND COST BASES .................................................. C-1
APPENDIX D: CITED REFERENCES ................................................................. D-1
APPENDIX E: PATENT REFERENCES BY COMPANY .................................. E-1
APPENDIX F: PROCESS FLOW DIAGRAMS ................................................. F-1
ILLUSTRATIONS

2.1 Ethylene by Nonconventional Processes: Commercial Processes Other than Steam Cracking ...................................................... 2-3
2.2 Ethylene by Nonconventional Processes: Nonmethane-Based ................................................................. 2-5
2.3 Ethylene by Nonconventional Processes: Methane-Based .............................................................................. 2-6
2.4 Comparison of Capital investment, Variable Costs, and Production Costs for Ethylene Production by Different Processes ........................................................................ 2-27
3.1 Ethylene from Ethanol by Fluidized-Bed Catalytic Dehydration ...................................................................... F-3
3.2 Ethylene from Ethanol by Fluidized-Bed Catalytic Dehydration Effect of Operating Level and Plant Capacity on Product Value ..................................................................... 3-19
3.3 Ethylene from Ethanol by Fluidized-Bed Catalytic Dehydration Total Fixed Capital for Different Processes and Feedstocks ................................................................. 3-20
3.4 Ethylene from Ethanol by Fluidized-Bed Catalytic Dehydration Product Value for Different Processes and Feedstocks ............................................................................. 3-21
7.1 Ethylene from Ethane by Catalytic Dehydrogenation in Membrane Reactors Comparison of Conversions ........................................................................................................ 7-2
7.2 Ethylene from Ethane by Catalytic Dehydrogenation in Membrane Reactors Reactor Design .............................................................. ............................................................................. 7-4
7.3 Ethylene from Ethane by Catalytic Dehydrogenation in Membrane Reactors Reactor Layout .............................................................................................. 7-6
7.4 Ethylene from Ethane by Catalytic Dehydrogenation in Membrane Reactors .................................................. F-5
7.5 Ethylene from Ethane by Catalytic Dehydrogenation in Membrane Reactors Effect of Operating Level and Plant Capacity on Product Value ........................................................................ 7-24
7.6 Ethylene from Ethane by Catalytic Dehydrogenation in Membrane Reactors Total Fixed Capital for Different Processes and Feedstocks ........................................................................ 7-25
7.7 Ethylene from Ethane by Catalytic Dehydrogenation in Membrane Reactors Product Value by Different Processes and Feedstocks ............................................................................. 7-26
8.1 Ethylene from Ethane by Oxidative Dehydrogenation Model of Surface Reactions ........................................................................................................................................................................... 8-2
8.2 Ethylene from Ethane by Oxidative Dehydrogenation Ethane Conversion versus Ethylene Selectivity ........................................................................................................................................................................... 8-7
8.3 Ethylene from Ethane by Oxidative Dehydrogenation ......................................................................................... F-9
8.4 Ethylene from Ethane by Oxidative Dehydrogenation Effect of Operating Level and Plant Capacity on Product Value ........................................................................................................... 8-33
8.5 Ethylene from Ethane by Oxidative Dehydrogenation Total Fixed Capital for Different Processes and Feedstocks ........................................................................................................... 8-34
8.6 Ethylene from Ethane by Oxidative Dehydrogenation Product Value by Different Processes and Feedstocks ........................................................................................................................................................................... 8-35
ILLUSTRATIONS (Concluded)

9.1 Ethylene from Propane/Butane by Oxidative Dehydrogenation
Model of Surface Reactions.................................................................9-3

11.1 Ethylene Coproduction with Vinyl Chloride
Block Flow Diagram............................................................................11-3

12.1 Lurgi Sand Cracker........................................................................12-3
12.2 BASF Fluidized Coke Cracking....................................................12-5
12.3 BASF Fluidized Flow Cracking......................................................12-6
12.4 The KK Process.............................................................................12-7
12.5 The Ube Process...........................................................................12-9
12.6 Quick Contact Reaction System....................................................12-10
13.1 The Advanced Cracking Reactor Process....................................13-2
15.1 Schematic of Shock Wave Reactor and Gas Temperature Profiles...........15-2
TABLES

2.1 Technical Aspects of Ethylene Processes ................................................................. 2-7
3.1 Producers and Capacities of Ethylene from Ethanol ................................................... 3-2
3.2 Ethylene from Ethanol by Fluidized-Bed Catalytic Dehydration
   Patent Summary ........................................................................................................ A-3
3.3 Ethylene from Ethanol by Fluidized-Bed Catalytic Dehydration
   Literature Summary .................................................................................................. B-3
3.4 Ethylene from Ethanol by Fluidized-Bed Catalytic Dehydration
   Design Bases and Assumptions ............................................................................. 3-7
3.5 Ethylene from Ethanol by Fluidized-Bed Catalytic Dehydration
   Stream Flows ......................................................................................................... 3-8
3.6 Ethylene from Ethanol by Fluidized-Bed Catalytic Dehydration
   Major Equipment .................................................................................................. 3-9
3.7 Ethylene from Ethanol by Fluidized-Bed Catalytic Dehydration
   Utilities Summary .................................................................................................. 3-11
3.8 Ethylene from Ethanol by Fluidized-Bed Catalytic Dehydration
   Total Capital Investment ..................................................................................... 3-15
3.9 Ethylene from Ethanol by Fluidized-Bed Catalytic Dehydration
   Capital Investment by Section ............................................................................ 3-16
3.10 Ethylene from Ethanol by Fluidized-Bed Catalytic Dehydration
    Production Costs .................................................................................................. 3-17
4.1 Producers and Capacities of Ethylene from Refinery Gas ....................................... 4-2
4.2 Comparison of Ethylene Recovery from Refinery Gas and Ethane Steam Cracking
    Production Costs .................................................................................................. 4-7
6.1 Ethylene by Catalytic Cracking
   Patent Summary ................................................................................................... A-6
6.1 Ethylene by Catalytic Cracking
   Literature Summary ................................................................................................ B-6
7.1 Ethylene from Ethane by Catalytic Dehydrogenation in Membrane Reactors
   Patent Summary .................................................................................................... A-9
7.2 Ethylene from Ethane by Catalytic Dehydrogenation in Membrane Reactors
   Literature Summary ................................................................................................ B-7
7.3 Ethylene from Ethane by Catalytic Dehydrogenation in Membrane Reactors
   Design Bases and Assumptions ........................................................................... 7-10
7.4 Ethylene from Ethane by Catalytic Dehydrogenation in Membrane Reactors
   Stream Flows ......................................................................................................... 7-11
7.5 Ethylene from Ethane by Catalytic Dehydrogenation in Membrane Reactors
   Major Equipment .................................................................................................. 7-13
<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.6</td>
<td>Ethylene from Ethane by Catalytic Dehydrogenation in Membrane Reactors Utilities Summary</td>
</tr>
<tr>
<td>7.7</td>
<td>Ethylene from Ethane by Catalytic Dehydrogenation in Membrane Reactors Total Capital Investment</td>
</tr>
<tr>
<td>7.8</td>
<td>Ethylene from Ethane by Catalytic Dehydrogenation in Membrane Reactors Capital Investment by Section</td>
</tr>
<tr>
<td>7.9</td>
<td>Ethylene from Ethane by Catalytic Dehydrogenation in Membrane Reactors Production Costs</td>
</tr>
<tr>
<td>8.1</td>
<td>Ethylene from Ethane by Oxidative Dehydrogenation Patent Summary</td>
</tr>
<tr>
<td>8.2</td>
<td>Ethylene from Ethane by Oxidative Dehydrogenation Literature Summary</td>
</tr>
<tr>
<td>8.3</td>
<td>Ethylene from Ethane by Oxidative Dehydrogenation Design Bases and Assumptions</td>
</tr>
<tr>
<td>8.4</td>
<td>Ethylene from Ethane by Oxidative Dehydrogenation Stream Flows</td>
</tr>
<tr>
<td>8.5</td>
<td>Ethylene from Ethane by Oxidative Dehydrogenation Major Equipment</td>
</tr>
<tr>
<td>8.6</td>
<td>Ethylene from Ethane by Oxidative Dehydrogenation Utilities Summary</td>
</tr>
<tr>
<td>8.7</td>
<td>Ethylene from Ethane by Oxidative Dehydrogenation Total Capital Investment</td>
</tr>
<tr>
<td>8.8</td>
<td>Ethylene from Ethane by Oxidative Dehydrogenation Capital Investment by Section</td>
</tr>
<tr>
<td>8.9</td>
<td>Ethylene from Ethane by Oxidative Dehydrogenation Production Costs</td>
</tr>
<tr>
<td>9.1</td>
<td>Ethylene from Propane by Oxidative Dehydrogenation Patent Summary</td>
</tr>
<tr>
<td>9.2</td>
<td>Ethylene from Propane by Oxidative Dehydrogenation Literature Summary</td>
</tr>
<tr>
<td>9.3</td>
<td>Ethylene from Propane by Oxidative Dehydrogenation Production Costs</td>
</tr>
<tr>
<td>10.1</td>
<td>Ethylene and Acidic Acid from Ethane by Oxidative Dehydrogenation Patent Summary</td>
</tr>
<tr>
<td>10.2</td>
<td>Ethylene and Acidic Acid from Ethane by Oxidative Dehydrogenation Literature Summary</td>
</tr>
<tr>
<td>10.3</td>
<td>Ethylene Coproduction with Acetic Acid by the Ethoxene® Process Production Costs</td>
</tr>
<tr>
<td>11.1</td>
<td>Ethylene and Vinyl Chloride from Ethane by Chloro-Dehydrogenation Patent Summary</td>
</tr>
</tbody>
</table>
TABLES (Concluded)

11.2 Ethylene and Vinyl Chloride from Ethane by Chloro-Dehydrogenation
Production Costs........................................................................................................... 11-6

12.1 Fluidized/Circulating Bed Cracking Processes for Ethylene Production .......... 12-2

13.1 Comparison of the Advanced Cracking Reactor and a Conventional Ethylene Process
Consumption and By-Production ....................................................................................... 13-5

13.2 Comparison of the Advanced Cracking Reactor and Naphtha Steam Cracking
Production Costs........................................................................................................... 13-6

13.3 Comparison of Dow’s Partial Combustion Process and Naphtha Steam Cracking
Production Costs........................................................................................................... 13-8

14.1 Comparison of the Hydropyrolysis and a Conventional Ethylene Process
Material Consumption and By-Production....................................................................... 14-3

16.1 Ethylene from Methane by Oxidative Coupling (the ARCO Process)
Production Costs........................................................................................................... 16-14

16.2 Ethylene from Methanol by the Mobil MTE Process
Production Costs........................................................................................................... 16-15

16.3 Ethylene from Methanol by the UPO/Hydro MTO Process
Production Costs........................................................................................................... 16-16

16.4 Ethylene from Syngas by Modified Fischer-Tropsch Synthesis
Production Costs........................................................................................................... 16-17