Abstract
Process Economics Program Report 247
GAS TO LIQUIDS UPDATE
(December 2002)

Proven world natural gas reserves, which currently exceed 5,000 trillion cubic feet (TCF), have been growing at a faster rate than proven oil reserves. These gas reserves currently represent about 83% of the energy equivalence of proven oil reserves, of which about 75% is considered to be the less desirable heavy crude. In some remote locations, wellhead costs of natural gas have been estimated to be below $0.25/MMBtu, while the cost of reinjecting "associated" gas from crude oil production as an alternative to flaring may greatly exceed its value. About 3,000 TCF of such gas reserves is considered to be "stranded"; i.e., accessible by drilling but located too far from potential markets for economical transportation to those markets.

The chemical conversion of methane to liquid fuels and other higher value products or derivatives which may be more cost effective to transport long distances from remote gas sources has therefore attracted renewed interest. Even though Fischer-Tropsch (FT) synthesis is a technically proven gas-to-liquids (GTL) technology, the conversion of natural gas to liquid fuels such as diesel and gasoline as opposed to higher value chemical products such as chemical grade methanol has only relatively recently been perceived to be a potentially viable commercial proposition. Recent advances in FT synthesis technologies, particularly with regard to natural gas reforming and catalytic partial oxidation, coupled with anticipated increased demand for "clean" diesel fuel appear to be enhancing the economic viability of this route to GTL.

The focus of this report is a comparative techno-economic evaluation of three leading technologies for FT based GTL diesel production, currently under development by the following companies – Sasol, ConocoPhillips, and BP. We also briefly survey the status of FT based GTL technology development by other leading technology developers. The scope of this report includes an assessment of market trends for petroleum-based products as well as future transportation fuel specifications, in addition to a geographical breakdown of natural gas reserves with wellhead costs estimated for various locations.
GAS TO LIQUIDS UPDATE

by GEORGE J. APANEL

December 2002

A private report by the
PROCESS ECONOMICS PROGRAM

Menlo Park, California 94025
SRIC agrees to assign professionally qualified personnel to the preparation of the Process Economics Program’s reports and will perform the work in conformance with generally accepted professional standards. No other warranties expressed or implied are made. Because the reports are of an advisory nature, neither SRIC nor its employees will assume any liability for the special or consequential damages arising from the Client’s use of the results contained in the reports. The Client agrees to indemnify, defend, and hold SRIC, its officers, and employees harmless from any liability to any third party resulting directly or indirectly from the Client’s use of the reports or other deliverables produced by SRIC pursuant to this agreement.

For detailed marketing data and information, the reader is referred to one of the SRI Consulting programs specializing in marketing research. THE CHEMICAL ECONOMICS HANDBOOK Program covers most major chemicals and chemical products produced in the United States and the WORLD PETROCHEMICALS PROGRAM covers major hydrocarbons and their derivatives on a worldwide basis. In addition the SRIC DIRECTORY OF CHEMICAL PRODUCERS services provide detailed lists of chemical producers by company, product, and plant for the United States, Western Europe, Canada, and East Asia, South America and Mexico.
Heat Exchange Reforming (HER) .......................................................................................... 5-5

CONTENTS (Continued)

“Compact” Reforming (CPR) .......................................................................................... 5-5
FISCHER-TROPSCH SYNTHESIS TECHNOLOGY (FTS) .................................................. 5-6
Other Catalysts for FTS ................................................................................................. 5-7
FTS Product Distribution .............................................................................................. 5-7
HYDROCRACKING REQUIREMENTS FOR FT DIESEL PRODUCTION ...................... 5-10
FT Naphtha Conversion Options .................................................................................. 5-10
SUMMARY OF PRINCIPAL GTL TECHNOLOGY DEVELOPERS ............................... 5-10
Sasol’s Technology ....................................................................................................... 5-11
Shell Middle Distillates Synthesis Process (SMDS) ....................................................... 5-13
Syntroleum’s GTL Technology ..................................................................................... 5-14
ExxonMobil’s AGC-21 Technology ............................................................................. 5-15
ConocoPhillips’ GTL Technology .............................................................................. 5-16
BP’s GTL Technology ................................................................................................. 5-16

6 FISCHER-TROPSCH DIESEL VIA SASOL AUTOTHERMAL REFORMER ........... 6-1

PROCESS DESCRIPTION .......................................................................................... 6-1
Section 100—Syngas Generation .................................................................................. 6-3
    Autothermal Reforming .......................................................................................... 6-3
    CO2 Removal ......................................................................................................... 6-4
    Hydrogen Skimming ............................................................................................. 6-4
Section 200—Fischer-Tropsch Synthesis and Hydrocracking ...................................... 6-4
    Fischer-Tropsch Conversion ................................................................................ 6-4
    Hydrocraking ....................................................................................................... 6-5
Section 300—Product Separation ............................................................................... 6-5
Steam Distribution and Utility Balance ....................................................................... 6-6
PROCESS DISCUSSION ............................................................................................ 6-15
Size Selection ............................................................................................................. 6-15
CONTENTS (Continued)

Process Selection....................................................................................................... 6-15
Reformer............................................................................................................... 6-15
F-T Reaction......................................................................................................... 6-16
H2 Separation....................................................................................................... 6-17
Materials of Construction............................................................................................ 6-17
PROCESS COST ....................................................................................................... 6-17
Capital Investment...................................................................................................... 6-17
Operating Cost ........................................................................................................... 6-21

7 CONOCO CATALYTIC PARTIAL OXIDATION (CPOX) .......................................... 7-1
PROCESS DESCRIPTION ........................................................................................ 7-1
Section 100—Syngas Generation .............................................................................. 7-3
Catalytic Partial Oxidation Reforming (CPPOX) .................................................. 7-3
CO2 Removal and Hydrogen Skimming .............................................................. 7-3
Section 200—Fischer-Tropsch Synthesis and Hydrocracking................................... 7-4
Fischer-Tropsch Conversion ................................................................................ 7-4
Hydrocraking ........................................................................................................ 7-4
Section 300—Product Separation .............................................................................. 7-4
Steam Distribution and Utility Balance ............................................................... 7-4
PROCESS DISCUSSION........................................................................................... 7-11
Size Selection............................................................................................................. 7-11
Process Selection....................................................................................................... 7-11
Reformer............................................................................................................... 7-11
Materials of Construction............................................................................................ 7-15
PROCESS COST ....................................................................................................... 7-15
Capital Investment...................................................................................................... 7-15
Operating Cost ........................................................................................................... 7-19

8 BP COMPACT REFORMER (CREF) ........................................................................ 8-1
CONTENTS (Concluded)

PROCESS DESCRIPTION .................................................................................................. 8-1
Section 100—Syngas Generation .................................................................................. 8-3
    Compact Reforming (CREF) .................................................................................... 8-3
Section 200—Fischer-Tropsch Synthesis and Hydrocracking ...................................... 8-4
    Fischer-Tropsch Conversion .................................................................................. 8-4
    Hydrocraking ....................................................................................................... 8-4
Section 300—Product Separation ............................................................................... 8-4
Steam Distribution and Utility Balance ....................................................................... 8-5
PROCESS DISCUSSION ................................................................................................ 8-11
Size Selection ............................................................................................................. 8-11
Process Selection ....................................................................................................... 8-11
    Reformer .............................................................................................................. 8-11
Materials of Construction ........................................................................................... 8-11
PROCESS COST .......................................................................................................... 8-11
Capital Investment ...................................................................................................... 8-11
Operating Cost ........................................................................................................... 8-11

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 COMPANY ........................................... D-1
APPENDIX E: PROCESS FLOW DIAGRAM ............................................................... E-1
<table>
<thead>
<tr>
<th>Illustration</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>General GTL Processing Scheme</td>
</tr>
<tr>
<td>4.1</td>
<td>World Primary Energy Demand by Fuel</td>
</tr>
<tr>
<td>4.2</td>
<td>World Refined Product Demands 2000-2015</td>
</tr>
<tr>
<td>4.3</td>
<td>World Consumption of Gasoline and Diesel Fuels</td>
</tr>
<tr>
<td>4.4</td>
<td>World Fuel Oil Consumption</td>
</tr>
<tr>
<td>4.5</td>
<td>Spot Gulf Coast Crude Oil and Product Prices</td>
</tr>
<tr>
<td>4.6</td>
<td>Refinery Block Flow</td>
</tr>
<tr>
<td>4.7</td>
<td>Trend of API Gravity and Sulfur Content For US Crudes</td>
</tr>
<tr>
<td>4.8</td>
<td>API Gravity Trend For Crude Oil in Major Consuming Regions</td>
</tr>
<tr>
<td>4.9</td>
<td>Transportation Costs of Oil, Gas and Methanol</td>
</tr>
<tr>
<td>5.1</td>
<td>FT Product vs. Carbon Number</td>
</tr>
<tr>
<td>5.2</td>
<td>FT Carbon Number Distribution</td>
</tr>
<tr>
<td>5.3</td>
<td>FT Distillate Cut Distribution</td>
</tr>
<tr>
<td>5.4</td>
<td>Sasol's Reactor Scale-Up Experience</td>
</tr>
</tbody>
</table>
# TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>GTL Diesel Investment Comparison Total Capital Investment</td>
<td>2-4</td>
</tr>
<tr>
<td>2.2</td>
<td>GTL Diesel Cost Comparison Production Costs</td>
<td>2-5</td>
</tr>
<tr>
<td>4.1</td>
<td>World Refined Product Demands</td>
<td>4-3</td>
</tr>
<tr>
<td>4.2</td>
<td>Natural Gas Production, Consumption and Reserves</td>
<td>4-11</td>
</tr>
<tr>
<td>4.3</td>
<td>Worldwide LNG Plant Summary For 1995</td>
<td>4-14</td>
</tr>
<tr>
<td>4.4</td>
<td>Estimated Natural Gas Supply Costs at the Wellhead</td>
<td>4-15</td>
</tr>
<tr>
<td>4.5</td>
<td>Unleaded Gasoline Sulfur Limits for Major Consuming Nations</td>
<td>4-16</td>
</tr>
<tr>
<td>4.6</td>
<td>Diesel Fuel Specifications</td>
<td>4-17</td>
</tr>
<tr>
<td>4.7</td>
<td>Summary of GTL and Related Synfuel Projects</td>
<td>4-18</td>
</tr>
<tr>
<td>6.1</td>
<td>Ft Diesel via Sasol ATR Process Design Basis</td>
<td>6-2</td>
</tr>
<tr>
<td>6.2</td>
<td>Ft Diesel via Sasol ATR Process Material Balance</td>
<td>6-7</td>
</tr>
<tr>
<td>6.3</td>
<td>Ft Diesel via Sasol ATR Process Major Equipment</td>
<td>6-12</td>
</tr>
<tr>
<td>6.4</td>
<td>Ft Diesel via Sasol ATR Process Utilities Summary</td>
<td>6-18</td>
</tr>
<tr>
<td>6.5</td>
<td>Ft Diesel via Sasol ATR Process Total Capital Investment</td>
<td>6-19</td>
</tr>
<tr>
<td>6.6</td>
<td>Ft Diesel via Sasol ATR Process Capital Investment By Section</td>
<td>6-20</td>
</tr>
<tr>
<td>6.7</td>
<td>Ft Diesel via Sasol ATR Process Production Costs</td>
<td>6-22</td>
</tr>
<tr>
<td>7.1</td>
<td>Ft Diesel via Conoco CPOX Process Design Basis</td>
<td>7-2</td>
</tr>
<tr>
<td>7.2</td>
<td>Ft Diesel via Conoco CPOX Process Material Balance</td>
<td>7-6</td>
</tr>
<tr>
<td>7.3</td>
<td>Ft Diesel via Conoco CPOX Process Major Equipment</td>
<td>7-12</td>
</tr>
<tr>
<td>7.4</td>
<td>Ft Diesel via Conoco CPOX Process Utilities Summary</td>
<td>7-16</td>
</tr>
</tbody>
</table>
TABLES (Concluded)

7.5 Ft Diesel via Conoco CPOX Process
Total Capital Investment............................................................... 7-17

7.6 Ft Diesel via Conoco CPOX Process
Investment by Section ................................................................. 7-18

7.7 Ft Diesel via Conoco CPOX Process
Production Costs ........................................................................... 7-20

8.1 Ft Diesel via Bp CREF Process
Design Basis.................................................................................. 8-2

8.2 Ft Diesel via Bp CREF Process
Material Balance........................................................................... 8-6

8.3 Ft Diesel via Bp CREF Process
Major Equipment ........................................................................ 8-13

8.4 Ft Diesel via Bp CREF Process
Utilities Summary.......................................................................... 8-16

8.5 Ft Diesel via Bp CREF Process
Total Capital Investment............................................................... 8-17

8.6 Ft Diesel via Bp CREF Process
Investment by Section ................................................................. 8-18

8.7 Ft Diesel via Bp CREF Process
Production Costs ........................................................................... 8-19