Abstract
Process Economics Program Report 103A
LIQUEFIED NATURAL GAS
(November 2004)

Global trade of liquefied natural gas (LNG) has more than doubled during the last decade, and currently accounts for almost 30% of the internationally traded volumes of natural gas. The growth in LNG flows has resulted from a combination of several factors. On the demand side, LNG imports have been driven by the increasing use of natural gas for power generation, declining production of natural gas in developed regions, and restructuring of the gas and electricity industries in Asia and Europe. From a supply perspective, LNG exports have been driven mainly by the desire to monetize the abundant gas reserves in countries such as Qatar, Algeria, Nigeria and Indonesia, and by significant reductions in LNG production costs. The trends in most of these factors are expected to continue over the next decade, and could support average LNG growth rates in the range of 7 to 9% per year.

Since the liquefaction plant is the most capital-intensive stage in the LNG chain, significant efforts have been made in recent years to improve the liquefaction technology and to achieve economies of scale. LNG train capacity has been increasing from a typical 1.5 MTPA (million metric tons per year) in the 1970s to a current installed range of 3 to 4 MTPA. During this decade, the trend will be toward even larger plants. Recent expansion projects and new greenfield plants have been commissioned with train capacities from 5 up to 8 MTPA. Air Products’ two-cycle refrigeration process, using propane and a mixed refrigerant, has been the dominant technology for baseload LNG production worldwide. However, several new competing processes are now available, including those by Axens-IFP, ConocoPhillips, Shell, and Statoil-Linde.

The focus of this report is a comparative techno-economic evaluation of three processes for baseload LNG production, using triple mixed, dual mixed, and single mixed refrigeration cycles, respectively. We also examine recent commercial and technology developments in the production, shipping and regasification of LNG. Our analysis indicates that the selection of process technology has an impact, although not dramatic, on the capital investment and operating costs of the liquefaction plant. Each type of technology seems to be most competitive within a certain range of train sizes. As a result, we expect that a variety of liquefaction processes, rather than a single standard technology, will play a role in the LNG industry.
# CONTENTS

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

2 SUMMARY ................................................................................................................. 2-1
   GENERAL ASPECTS................................................................................................. 2-1
   TECHNICAL ASPECTS ............................................................................................. 2-1
   PROCESS ECONOMICS........................................................................................... 2-3

3 INDUSTRY STATUS.................................................................................................. 3-1
   WORLD LNG TRADE................................................................................................. 3-1
   LNG Market Structure............................................................................................... 3-1
   REGIONAL LNG DEMAND ..................................................................................... 3-4
      Asia Pacific ........................................................................................................... 3-4
      Europe .................................................................................................................. 3-4
      North America and the Caribbean ........................................................................ 3-6
   REGIONAL LNG SUPPLY ......................................................................................... 3-8
      Africa ..................................................................................................................... 3-8
      Asia-Pacific .......................................................................................................... 3-8
      Middle East .......................................................................................................... 3-14
      Europe .................................................................................................................. 3-14
      Americas .............................................................................................................. 3-14
   VALUE CHAIN ECONOMICS .................................................................................... 3-15
      Gas Production .................................................................................................... 3-15
      Liquefaction ......................................................................................................... 3-15
      Shipping ................................................................................................................. 3-15
      Regasification ...................................................................................................... 3-16
      Total Chain Costs ................................................................................................ 3-16
   ALTERNATIVES TO LNG ........................................................................................ 3-17
      Pipelines ............................................................................................................... 3-17
CONTENTS (Continued)

Compressed Natural Gas (CNG) ................................................................. 3-17
Natural Gas Hydrate (NGH) ....................................................................... 3-18
Gas to Liquids (GTL) .................................................................................. 3-18
Methanol .................................................................................................... 3-19
Dimethyl Ether (DME) ................................................................................ 3-19

4 LNG TECHNOLOGY REVIEW ........................................................................ 4-1

DEVELOPMENTS IN LIQUEFACTION TECHNOLOGY .................................. 4-1
Commercial Liquefaction Processes ............................................................. 4-3
  Propane Pre-cooled Mixed Refrigerant (C3MR) Process ......................... 4-3
  Pure Component Cascade Process ............................................................ 4-5
  Single Mixed Refrigerant (SMR) Process .................................................. 4-7
  Shell Dual Mixed Refrigerant (DMR) Process .......................................... 4-8
  Axens-IFP Liquefin Process ................................................................... 4-9
  Statoil/Linde Mixed Fluid Cascade (MFC) Process ............................... 4-11
  APCI AP-X Process ................................................................................ 4-12
OFFSHORE LNG PRODUCTION .................................................................. 4-13
Offshore Liquefaction Technology ............................................................... 4-14
LNG SHIPPING .......................................................................................... 4-16
Vessel Design ............................................................................................... 4-16
LNG Ship Size ............................................................................................. 4-16
Power Generation Alternatives ................................................................. 4-17
LNG REGASIFICATION .............................................................................. 4-17
Storage Tanks ............................................................................................. 4-18
LNG Vaporizers ........................................................................................ 4-18
Heat Integration with Power Plants ........................................................... 4-18
Offshore Regasification ............................................................................. 4-19
BTU Stabilization Methods ......................................................................... 4-20
## CONTENTS (Continued)

### 5 LNG BY THE TRIPLE MIXED REFRIGERANT PROCESS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROCESS DESCRIPTION</td>
<td>5-1</td>
</tr>
<tr>
<td>Feed Pretreatment</td>
<td>5-1</td>
</tr>
<tr>
<td>Liquefaction</td>
<td>5-2</td>
</tr>
<tr>
<td>NGL Separation</td>
<td>5-2</td>
</tr>
<tr>
<td>PROCESS DISCUSSION</td>
<td>5-12</td>
</tr>
<tr>
<td>Feed Pretreatment</td>
<td>5-12</td>
</tr>
<tr>
<td>Refrigeration Cycles</td>
<td>5-12</td>
</tr>
<tr>
<td>Selection of Compressors and Drivers</td>
<td>5-12</td>
</tr>
<tr>
<td>Cryogenic Heat Exchangers</td>
<td>5-14</td>
</tr>
<tr>
<td>Liquid Expansion Turbines</td>
<td>5-14</td>
</tr>
<tr>
<td>NGL Separation</td>
<td>5-14</td>
</tr>
<tr>
<td>Materials of Construction</td>
<td>5-14</td>
</tr>
<tr>
<td>COST ESTIMATES</td>
<td>5-14</td>
</tr>
<tr>
<td>Capital Costs</td>
<td>5-15</td>
</tr>
<tr>
<td>Production Costs</td>
<td>5-15</td>
</tr>
</tbody>
</table>

### 6 LNG BY THE DUAL MIXED REFRIGERANT PROCESS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>PROCESS DESCRIPTION</td>
<td>6-1</td>
</tr>
<tr>
<td>Feed Pretreatment</td>
<td>6-1</td>
</tr>
<tr>
<td>Liquefaction</td>
<td>6-1</td>
</tr>
<tr>
<td>NGL Separation</td>
<td>6-2</td>
</tr>
<tr>
<td>PROCESS DISCUSSION</td>
<td>6-11</td>
</tr>
<tr>
<td>Refrigeration Cycles</td>
<td>6-11</td>
</tr>
<tr>
<td>Selection of Compressors and Drivers</td>
<td>6-11</td>
</tr>
<tr>
<td>Cryogenic Heat Exchangers</td>
<td>6-12</td>
</tr>
<tr>
<td>Other Items</td>
<td>6-13</td>
</tr>
</tbody>
</table>
ILLUSTRATIONS

3.1 World LNG Imports, 1970-2003 ................................................................. 3-2
4.1 LNG Train Capacity Trend ........................................................................... 4-2
4.2 APCI’s Propane Pre-cooled Mixed Refrigerant Process............................ 4-4
4.3 Phillips Pure Component Cascade Process .................................................. 4-6
4.4 PRICO Single Mixed Refrigerant Process ..................................................... 4-8
4.5 Shell Dual Mixed Refrigerant Process .......................................................... 4-9
4.6 Axens-IFP Liquefin Process ........................................................................ 4-10
4.7 Statoil-Linde Mixed Fluid Cascade Process ............................................... 4-12
4.8 APCI AP-X Process .................................................................................... 4-13
4.9 BHP-Linde Nitrogen Cycle Process ............................................................ 4-15
5.1 Liquefied Natural Gas by the Triple Mixed Refrigerant Process .......... E-3
5.2 Liquefied Natural Gas by the Triple Mixed Refrigerant Process
Compressor and Turbine Layouts ................................................................. 5-13
5.3 Liquefied Natural Gas by the Triple Mixed Refrigerant Process
Effect of Feed Gas Price Production Cost and Product Value .................. 5-21
5.4 Liquefied Natural Gas by the Triple Mixed Refrigerant Process
Effect of Operating Level and Plant Capacity on Product Value ............... 5-22
6.1 Liquefied Natural Gas by the Dual Mixed Refrigerant Process .............. E-5
6.2 Liquefied Natural Gas by the Dual Mixed Refrigerant Process
Compressor and Turbine Layouts ................................................................. 6-12
6.3 Liquefied Natural Gas by the Dual Mixed Refrigerant Process
Effect of Feed Gas Price Production Cost and Product Value ................ 6-20
6.4 Liquefied Natural Gas by the Dual Mixed Refrigerant Process
Effect of Operating Level and Plant Capacity on Product Value ............... 6-21
7.1 Liquefied Natural Gas by the Single Mixed Refrigerant Process ............ E-7
7.2 Liquefied Natural Gas by the Single Mixed Refrigerant Process
Compressor and Turbine Layouts ................................................................. 7-12
7.3 Liquefied Natural Gas by the Single Mixed Refrigerant Process
Effect of Feed Gas Price Production Cost and Product Value ................ 7-19
7.4 Liquefied Natural Gas by the Single Mixed Refrigerant Process
Effect of Operating Level and Plant Capacity on Product Value ............... 7-20
# TABLES

2.1 LNG Chain – Typical Cost Range ........................................................................ 2-3
2.2 Baseload Liquefaction of Natural Gas
Comparison of Process Economics ........................................................................ 2-5
2.3 Baseload Liquefaction of Natural Gas
Summary of Results .............................................................................................. 2-6
3.1 LNG Importing Countries, 2003 ............................................................................. 3-3
3.2 LNG Exporting Countries, 2003 ............................................................................ 3-3
3.3 World Regasification Capacity ........................................................................ 3-5
3.4 U.S. LNG Import Terminals and Projects with Pending Applications as of
July 2004 ............................................................................................................... 3-7
3.5 Proved Natural Gas Reserves, as of End 2003 .................................................... 3-9
3.6 World Natural Gas Liquefaction Plants ................................................................. 3-10
3.7 Typical LNG Shipping Costs for the United States ............................................. 3-16
3.8 Cost Reductions in the LNG Chain
Basis: Middle East to Far East LNG Project ......................................................... 3-17
4.1 Gas Turbine Drivers for Baseload LNG ................................................................. 4-2
4.2 Liquefaction Processes ......................................................................................... A-3
5.1 Liquefied Natural Gas by the Triple Mixed Refrigerant Process
Design Bases and Assumptions ............................................................................ 5-4
5.2 Liquefied Natural Gas by the Triple Mixed Refrigerant Process
Stream Flows ......................................................................................................... 5-5
5.3 Liquefied Natural Gas by the Triple Mixed Refrigerant Process
Major Equipment ................................................................................................... 5-8
5.4 Liquefied Natural Gas by the Triple Mixed Refrigerant Process
Utilities Summary ................................................................................................ 5-11
5.5 Liquefied Natural Gas by the Triple Mixed Refrigerant Process
Total Capital Investment ....................................................................................... 5-16
5.6 Liquefied Natural Gas by the Triple Mixed Refrigerant Process
Capital Investment by Section ............................................................................. 5-17
5.7 Liquefied Natural Gas by the Triple Mixed Refrigerant Process
Production Costs ................................................................................................... 5-18
<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.1</td>
<td>Liquefied Natural Gas by the Dual Mixed Refrigerant Process Design Bases and Assumptions</td>
<td>6-3</td>
</tr>
<tr>
<td>6.2</td>
<td>Liquefied Natural Gas by the Dual Mixed Refrigerant Process Stream Flows</td>
<td>6-4</td>
</tr>
<tr>
<td>6.3</td>
<td>Liquefied Natural Gas by the Dual Mixed Refrigerant Process Major Equipment</td>
<td>6-7</td>
</tr>
<tr>
<td>6.4</td>
<td>Liquefied Natural Gas by the Dual Mixed Refrigerant Process Utilities Summary</td>
<td>6-10</td>
</tr>
<tr>
<td>6.5</td>
<td>Liquefied Natural Gas by the Dual Mixed Refrigerant Process Total Capital Investment</td>
<td>6-15</td>
</tr>
<tr>
<td>6.6</td>
<td>Liquefied Natural Gas by the Dual Mixed Refrigerant Process Capital Investment by Section</td>
<td>6-16</td>
</tr>
<tr>
<td>6.7</td>
<td>Liquefied Natural Gas by the Dual Mixed Refrigerant Process Production Costs</td>
<td>6-17</td>
</tr>
<tr>
<td>7.1</td>
<td>Liquefied Natural Gas by the Single Mixed Refrigerant Process Design Bases and Assumptions</td>
<td>7-3</td>
</tr>
<tr>
<td>7.2</td>
<td>Liquefied Natural Gas by the Single Mixed Refrigerant Process Stream Flows</td>
<td>7-4</td>
</tr>
<tr>
<td>7.3</td>
<td>Liquefied Natural Gas by the Single Mixed Refrigerant Process Major Equipment</td>
<td>7-7</td>
</tr>
<tr>
<td>7.4</td>
<td>Liquefied Natural Gas by the Single Mixed Refrigerant Process Utilities Summary</td>
<td>7-10</td>
</tr>
<tr>
<td>7.5</td>
<td>Liquefied Natural Gas by the Single Mixed Refrigerant Process Total Capital Investment</td>
<td>7-14</td>
</tr>
<tr>
<td>7.6</td>
<td>Liquefied Natural Gas by the Single Mixed Refrigerant Process Capital Investment by Section</td>
<td>7-15</td>
</tr>
<tr>
<td>7.7</td>
<td>Liquefied Natural Gas by the Single Mixed Refrigerant Process Production Costs</td>
<td>7-16</td>
</tr>
</tbody>
</table>