FLUE GAS CO$_2$ CAPTURE

(CO$_2$ CAPTURE TECHNOLOGY OF KS-1)

Mitsubishi Heavy Industries, Ltd.
Process Flow for Amine Absorption

Flue Gas

- Flue Gas Cooler
- C.W.

ABSORBER

Flue Gas Outlet

C.W.

STRIPPER

CO₂

Purity: 99.9%

C.W.

Reboiler

Steam
Amine Reaction Mechanism

**Mono-ethanol Amine (MEA)**

\[ 2 \text{R-NH}_2 + \text{CO}_2 \rightleftharpoons \text{R-NH}_3^+ + \text{R-NH-COO}^- \]
\[ \text{R-NH}_2 + \text{CO}_2 + \text{H}_2\text{O} \rightleftharpoons \text{R-NH}_3^+ + \text{HCO}_3^- \]

**Sterically Hindered Amine (KS-1)**

\[ 2 \text{R-NH}_2 + \text{CO}_2 \rightleftharpoons \text{R-NH}_3^+ + \text{R-NH-COO}^- \]
\[ \text{R-NH}_2 + \text{CO}_2 + \text{H}_2\text{O} \rightleftharpoons \text{R-NH}_3^+ + \text{HCO}_3^- \]
MHI and Kansai Electric initiated R&D since 1990.

- Laboratory tests
- Bench scale tests
- Pilot plant tests
- Data collection and analysis from commercial plants
Solubility of CO$_2$ in KS-1 and MEA Solution

CO$_2$ Partial Pressure vs CO$_2$ Loading (mol.CO$_2$/mol.Amine) chart showing the absorption and regeneration regions for MEA and KS-1 solutions.
Heat of Dissociation
(Heat of Absorption)

CO₂ Loading (mol.CO₂/mol.Amine)
Deteriorated Product of MEA and KS-1

- KS-1 Commercial
- KS-1 Pilot
- MEA Pilot

Heat Stable Salts (wt%) vs. Running Time (hours)

Base
Corrosion Test Result

<table>
<thead>
<tr>
<th></th>
<th>Test 1</th>
<th>Test 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEA</td>
<td>93.0</td>
<td>76.4</td>
</tr>
<tr>
<td>MEA + inhibitor</td>
<td>9.5</td>
<td>8.3</td>
</tr>
<tr>
<td>KS-1</td>
<td>3.1</td>
<td>3.6</td>
</tr>
</tbody>
</table>

Test condition: 130°C, in the presence of O₂

(Unit: mils per year)
KS-1 Process Excellency

- Lower Dissociation Heat
- Higher CO₂ Loading
- Lower Degradation
- Lower Corrosion

- Low Regeneration Energy
- Low Solvent Circulation Flow Rate
- Minimal Reclaiming Requirement
- Corrosion Inhibitor Not Required
## Process Comparison

<table>
<thead>
<tr>
<th></th>
<th>MEA</th>
<th>KS-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solution Circulation Rate</td>
<td>1</td>
<td>0.6</td>
</tr>
<tr>
<td>Regeneration Energy</td>
<td>1</td>
<td>0.8</td>
</tr>
<tr>
<td>Degradation of the Solvent</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Solvent Loss</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Corrosion Inhibitor</td>
<td>YES</td>
<td>NO</td>
</tr>
</tbody>
</table>
# Performance of Amine CO₂ Capture Process
*(Comparison Basis of KS-1 and MEA)*

<table>
<thead>
<tr>
<th>1. Flue Gas Sources:</th>
<th>Coal Fired (CO₂ Conc. = 12%[d])</th>
<th>Gas/Oil Fired (CO₂ Conc. = 9%[d])</th>
<th>Gas Turbine (CO₂ Conc. = 3%[d])</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Utility Unit Rate:</td>
<td>LP Steam 3.0 US /MMBTU</td>
<td>Electricity 5 US /Kwh</td>
<td>C.W. 1 US /T</td>
</tr>
<tr>
<td>3. Solvent Price:</td>
<td>KS-1 6.5 US /kg</td>
<td>MEA 1.8 US /kg</td>
<td></td>
</tr>
<tr>
<td>4. Plant Depreciation:</td>
<td>15-Years</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
CO₂ Capture Cost of KS-1 Process

(US$/T-CO₂)

- **G/T** (CO₂ = 3%)
- **Boiler** (CO₂ = 9%)
- **Coal** (CO₂ = 12%)

**Categories:**
- Operation & Maintenance
- Solvent
- Cooling Water
- Electricity
- LP Steam
MHI’s Experience

PILOT PLANT

Location : Nanko Power Plant, Osaka, Japan

Capacity : Flue Gas 600 Nm³/H
           CO₂ Capture Rate 2 Ton/D

Start Up : April, 1991

Research Items
           : New Solvent Development
           : New Packing Development (KP-1)
           : System Improvement
MHI’s Experience (KS-1)

160 T/D CO₂ Capture Plant

Client : Petronas Fertilizer (Keda) Sdn. Bhd.

• Location : Kedah Darul Aman, Malaysia

• Feed Gas : Steam Reformer Flue Gas

• Capacity : Flue Gas  47,000 Nm³/H
  (Max. Capacity = 210 T/D)

• Use of CO₂ : Urea Production

• Start Up : October 1999
Large Scale CO₂ Capture Plant (Conceptual)
**DELIVERED CO₂ REQUIREMENTS FOR EOR**

**CO₂ Purity:** 94% or above

- **CH₄, C₂H₆ below 4%**
- **N₂ below 5%**
- **H₂S below 100 ppmv.**

**Amount CO₂ required:** 3 - 20 MSCF/bbl of oil

- **If CO₂ requirement is between 3 - 8 MSCF/bbl, EOR may be economical.**

**CO₂ Delivery Pressure:** 2,000 psig at inlet of pipeline

- **CO₂ is then compressed further to suit wellhead pressure.**
A comprehensive economic study has been carried out on CO$_2$ recovery plants in the Middle East area for the purpose of EOR based on the following parameters:

(1) Capacity of CO$_2$ Recovery Unit

(2) Utility Cost
   - Fuel gas
   - Cooling water
   - Electricity

(3) Other Operational Requirements
   - Pipeline cost
## CASES

<table>
<thead>
<tr>
<th>Cases</th>
<th>CO₂ Content</th>
<th>CO₂ Recovery Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler Case-1</td>
<td>8.5 vol%</td>
<td>100 MMSCFD</td>
</tr>
<tr>
<td>Boiler Case-2</td>
<td>8.5 vol%</td>
<td>60 MMSCFD</td>
</tr>
<tr>
<td>Gas Turbine Case-1</td>
<td>3.0 vol%</td>
<td>90 MMSCFD</td>
</tr>
<tr>
<td>Gas Turbine Case-2</td>
<td>3.0 vol%</td>
<td>50 MMSCFD</td>
</tr>
</tbody>
</table>
**Figure-1**

Gas Turbine Case

**Figure-2**

Boiler Case

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**Scope of the Study**

- **Aux. Boiler**
- **Steam**
- **CO₂ Recovery**
- **CO₂ Compression & Dehydration**
- **2000 psig**
- **To CO₂ Pipeline**

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**Aux. Boiler**

- **Steam**
- **CO₂ Recovery**
- **CO₂ Compression & Dehydration**
- **2000 psig**
- **To CO₂ Pipeline**

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MITSUBISHI HEAVY INDUSTRIES, LTD.
(1) Initial investment cost of CO$_2$ recovery, compression, auxiliary utilities

(2) Location area: Middle East

(3) Depreciation: 10% per year

*CAPEX = Capital Expenditure*
# OPEX*

- Operator cost
- Maintenance cost
- General charge
- Utility cost

<table>
<thead>
<tr>
<th></th>
<th>Study Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Gas (US$/106BTU)</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td>(Base)</td>
<td></td>
</tr>
<tr>
<td>Cooling Water (US$/T)</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>2.0</td>
</tr>
<tr>
<td>(Base)</td>
<td></td>
</tr>
<tr>
<td>Electricity (US$/Kwh)</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>4.0</td>
</tr>
<tr>
<td>(Base)</td>
<td></td>
</tr>
</tbody>
</table>

*OPEX = Operative Expenditure*
## BASE CASE STUDY RESULTS

<table>
<thead>
<tr>
<th>Base Case</th>
<th>CO₂ Content</th>
<th>Recovery Capacity</th>
<th>On Stream Factor</th>
<th>CAPEX (US$/MSCF)</th>
<th>OPEX (US$/MSCF)</th>
<th>Cost Total (US$/MSCF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boiler Case-1</td>
<td>8.5</td>
<td>100</td>
<td>90%</td>
<td>0.472</td>
<td>0.444</td>
<td>0.916</td>
</tr>
<tr>
<td>Boiler Case-2</td>
<td>8.5</td>
<td>60</td>
<td>90%</td>
<td>0.533</td>
<td>0.515</td>
<td>1.048</td>
</tr>
<tr>
<td>Gas Turbine Case-1</td>
<td>3.0</td>
<td>90</td>
<td>90%</td>
<td>0.609</td>
<td>0.830</td>
<td>1.439</td>
</tr>
<tr>
<td>Gas Turbine Case-2</td>
<td>3.0</td>
<td>50</td>
<td>90%</td>
<td>0.609</td>
<td>0.838</td>
<td>1.446</td>
</tr>
</tbody>
</table>
RELATIONSHIP BETWEEN CO₂ DELIVERY COST AND CO₂ RECOVERY PLANT CAPACITY

Note:
- Fuel gas: 1.0 / MMBTU
- Electricity: 2.0 / kWh
- Cooling water: 1.5 / T
- Industrial water: 2.0 / T
- Pipeline Cost (Not included)
RELATIONSHIP BETWEEN CO₂ DELIVERY COST AND FUEL GAS COST

Note:
- Electricity: $2.0/\text{kWh}$
- Cooling water: $1.5/T$
- Industrial water: $2.0/T$
- Pipeline Cost (Not included)
RELATIONSHIP BETWEEN CO₂ DELIVERY COST AND COOLING WATER COST

Note:
- Fuel gas: 1.0 /MMBTU
- Electricity: 2.0 /kWh
- Industrial water: 2.0 /T
- Pipeline Cost (Not included)
PIPELINE COST

PIPEDLINE

CO₂ transportation from flue gas CO₂ recovery plant to Oil fields

PIPEDLINE COSTS

6 US $ MSCF/100 km (Middle East base)

EXAMPLE

CO₂ recovery and compression cost: 1.0 $/MSCF
100km pipeline cost: 0.06 $/MSCF

Total 1.06 $/MSCF
BENEFITS OF USING CO$_2$ RECOVERED FROM FLUE GAS FOR EOR

CO$_2$ EOR  $\rightarrow$  CO$_2$ can be stored in the oil reservoir

$\downarrow$

Reduction of CO$_2$ emissions

Application of JI*1) or CDM*2) will result in CO$_2$ credit surplus

*1) JI = Joint Implementation
*2) CDM = Clean Development Mechanism
CONCLUSION

Projects for flue gas CO₂ recovery and the utilization of CO₂ for EOR will become economical for the circumstances stated below:

I. Larger CO₂ recovery plant for sources with higher CO₂ content with cheap utility cost will give attractive CO₂ delivery cost.

II. If JI or CDM can trade CO₂ emission rights, financial benefits can be enjoyed for the projects.