Clean Coal Technologies in Japan
Technological Innovation in the Coal Industry

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Preface

In 2006, the New Energy and Industrial Technology Development Organization (NEDO) prepared a guide which reviewed the history of "Clean Coal Technology" (CCT) in Japan, systematically described the latest status of CCT, and provided useful material for future novel technological innovation. This brochure is a revised version of the original guide, updated with the latest data and information. NEDO hopes this brochure will be helpful in elucidating why Japan’s CCT is an attractive technology in the increasingly complex arena of coal utilization resulting from global warming concerns and other environmental issues. NEDO also hopes this brochure will encourage rapid progress in CCT development and the establishment of innovative clean coal utilization systems.

This guide will describe how CCT development in Japan has reached the highest level of technological superiority in the world, making the technology highly attractive to Asian countries that depend on coal as an energy resource. In Japan, coal consumption has rapidly increased since 1998. Gross electric power generation efficiency has also been increasing from approximately 38% to 43% over the past two decades. In addition, emissions of CO₂, SOx and NOx per electric power in Japanese thermal power plants are far below the level of other industrialized countries. Due to these factors, CCT is expected to play a key role in maintaining both CO₂ reduction and GDP growth.

Technological innovation has no boundaries and significant progress can be achieved by sustainable, patient and consistent efforts. NEDO is confident this publication will contribute to CCT development and we look forward to the emergence of dramatic technological innovations in the coal industry.
### Coal classification by degree of carbonization (JIS M1002)

<table>
<thead>
<tr>
<th>Classification</th>
<th>Heating value (kcal/kg (dry basis))</th>
<th>Fuel ratio</th>
<th>Caking property</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anthracite</td>
<td>-</td>
<td>4.0 or greater</td>
<td>Non-caking</td>
</tr>
<tr>
<td>Bituminous coal</td>
<td>8,400 or greater</td>
<td>1.5 or greater</td>
<td>Strong-caking</td>
</tr>
<tr>
<td></td>
<td>8,100 or greater less than 8,400</td>
<td>1.5 or less</td>
<td>Strong-caking</td>
</tr>
<tr>
<td>Subbituminous coal</td>
<td>7,800 or greater less than 8,100</td>
<td>-</td>
<td>Weak-caking</td>
</tr>
<tr>
<td></td>
<td>7,300 or greater less than 7,800</td>
<td>-</td>
<td>Weak-caking</td>
</tr>
<tr>
<td>Brown coal</td>
<td>6,800 or greater less than 7,300</td>
<td>-</td>
<td>Non-caking</td>
</tr>
<tr>
<td></td>
<td>5,800 or greater less than 6,800</td>
<td>-</td>
<td>Non-caking</td>
</tr>
</tbody>
</table>

### Coal classification by utilization (expressed as coal)

<table>
<thead>
<tr>
<th>Source: TEXT report</th>
<th>Source: Trade Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anthracite</td>
<td>Anthracite</td>
</tr>
<tr>
<td>Coking coal A</td>
<td>Strong-caking coal for coke</td>
</tr>
<tr>
<td>Coking coal B</td>
<td>Other coal for coke</td>
</tr>
<tr>
<td>Coking coal C</td>
<td>Other</td>
</tr>
<tr>
<td>Coking coal D</td>
<td>Other</td>
</tr>
<tr>
<td>Steam coal A</td>
<td>Other</td>
</tr>
<tr>
<td>Steam coal B</td>
<td>Other</td>
</tr>
<tr>
<td>Steam coal C</td>
<td>Other</td>
</tr>
</tbody>
</table>

---

### Exploration, mining, safety and preparation
- Coal mine
- Coal preparation plant
- Coal train
- Coal tanker

### Crushing, transportation and storage
- EAGLE
- DME
- SCOPE21
- Coal train
- Power plant
- Yokohama Landmark Tower
- Cement plant
- Iron works
- Chemical plant
- CO2 reduction
- Flue gas treatment
- Flue gas desulfurization facility
- Enhanced Oil Recovery (EOR) by CO2

### Processing, reforming and converting
- Exploration, mining, safety and preparation
- Crushing, transportation and storage
- Processing, reforming and converting
- Environmental countermeasures
  - Utilization
  - Source: Trade Statistics
  - Anthracite
    - Ash content of 8% or less
    - Ash content exceeding 8%
  - Bituminous coal
    - Ash content of 8% or less
    - Ash content exceeding 8%

### A. Multi-purpose coal utilization technologies

- A-01. Coal gasification and hydrogenation technologies
  - Hydrogen from coal process (HYCOL)
  - Multi-purpose coal gasification technology development (EAGLE)
  - Twin IHG gasifier (IGGAR) technology for brown coal utilization

- A-02. Liquefaction technologies
  - Coal liquefaction technology development in Japan
  - Bituminous coal liquefaction technology (NEDOL)
  - Brown coal liquefaction technology (BCL)
  - Dimethyl ether (DME) production technology

- A-03. Pyrolysis technologies
  - Multi-purpose coal conversion technology (CPX)
  - Efficient co-production with coal flash partial hydropyrolysis technology (ECOPRO®)

- A-04. Powdering, fluidization and co-utilization technologies
  - Coal hot water slurrification technology
  - Brown coal production technology
  - Briquette production technology
  - Coal pulverizing technology

- A-05. De-ashing and reforming technologies
  - Production of coking additives for coke production from low-rank coal (Hyper-coal)
  - Low-rank coal upgrading technology (UBC process)
  - Efficient brown coal drying technology
  - Brown coal advanced utilization technology
  - Brown coal upgrading technology

- A-06. Combustion technologies
  - Coal and woody biomass co-firing technology
  - Efficient combustion and coal co-firing support system

- A-10. Other
  - Modeling and Simulation Technologies for Coal Gasification
Coal production and consumption by country (Total coal production worldwide in 2013: 7,031 million tons; Total coal consumption worldwide in 2013: 6,747 million tons) and Japanese coal imports (Japan's total coal imports in 2013: 209 million tons).

## World reserves of coal, oil, and natural gas resources (Unit: 100 million tons oil equivalent)

<table>
<thead>
<tr>
<th>Region</th>
<th>Coal</th>
<th>Oil</th>
<th>Natural gas</th>
<th>Uranium</th>
</tr>
</thead>
<tbody>
<tr>
<td>World reserves</td>
<td>891.5 billion tons</td>
<td>1,687.9 billion barrels</td>
<td>185.7 trillion m³</td>
<td>5.9 million tons</td>
</tr>
<tr>
<td>North America</td>
<td>27.5%</td>
<td>13.6%</td>
<td>6.3%</td>
<td>12%</td>
</tr>
<tr>
<td>Latin America</td>
<td>1.6%</td>
<td>19.5%</td>
<td>4.1%</td>
<td>5.0%</td>
</tr>
<tr>
<td>Europe</td>
<td>9.6%</td>
<td>0.8%</td>
<td>2.0%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Former Soviet Union</td>
<td>25.2%</td>
<td>8.0%</td>
<td>28.5%</td>
<td>25%</td>
</tr>
<tr>
<td>Middle East</td>
<td>0.0%</td>
<td>47.9%</td>
<td>43.2%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Africa</td>
<td>3.7%</td>
<td>7.7%</td>
<td>7.6%</td>
<td>21%</td>
</tr>
<tr>
<td>Asia Pacific</td>
<td>32.3%</td>
<td>2.5%</td>
<td>8.2%</td>
<td>34%</td>
</tr>
</tbody>
</table>

### Local reserves

<table>
<thead>
<tr>
<th>Region</th>
<th>Coal</th>
<th>Oil</th>
<th>Natural gas</th>
<th>Uranium</th>
</tr>
</thead>
<tbody>
<tr>
<td>North America</td>
<td>27.5%</td>
<td>13.6%</td>
<td>6.3%</td>
<td>12%</td>
</tr>
<tr>
<td>Latin America</td>
<td>1.6%</td>
<td>19.5%</td>
<td>4.1%</td>
<td>5.0%</td>
</tr>
<tr>
<td>Europe</td>
<td>9.6%</td>
<td>0.8%</td>
<td>2.0%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Former Soviet Union</td>
<td>25.2%</td>
<td>8.0%</td>
<td>28.5%</td>
<td>25%</td>
</tr>
<tr>
<td>Middle East</td>
<td>0.0%</td>
<td>47.9%</td>
<td>43.2%</td>
<td>0.0%</td>
</tr>
<tr>
<td>Africa</td>
<td>3.7%</td>
<td>7.7%</td>
<td>7.6%</td>
<td>21%</td>
</tr>
<tr>
<td>Asia Pacific</td>
<td>32.3%</td>
<td>2.5%</td>
<td>8.2%</td>
<td>34%</td>
</tr>
</tbody>
</table>

### Annual production rate

<table>
<thead>
<tr>
<th>Region</th>
<th>Coal</th>
<th>Oil</th>
<th>Natural gas</th>
<th>Uranium</th>
</tr>
</thead>
<tbody>
<tr>
<td>World reserves</td>
<td>3.88 billion tons</td>
<td>31.7 billion barrels</td>
<td>3.4 trillion m³</td>
<td>0.059 million tons</td>
</tr>
<tr>
<td>R/P</td>
<td>113 years</td>
<td>53.3 years</td>
<td>55.1 years</td>
<td>100 years</td>
</tr>
</tbody>
</table>

Source: Oil, natural gas, and coal data source: BP Statistics 2014
Uranium: URANIUM 2014

---

## Proven reserves and R/P (ratio of reserves to production) of major energy resources

### World reserves of coal, oil, and natural gas resources (Unit: 100 million tons oil equivalent)

![Worldwide Energy Reserves Map](source: BP 2014)
Coal production and consumption by country (Total coal production worldwide in 2013: 7,031 million tons; Total coal consumption worldwide in 2013: 6,747 million tons) and Japanese coal imports (Japan’s total coal imports in 2013: 209 million tons)

World reserves of coal, oil, and natural gas resources (Unit: 100 million tons oil equivalent)

Coal demand trend in Japan (Unit: 10,000 tons)

Clean Coal Technologies in Japan
### Part 1 CCT Classification

#### CCT in Japanese Industries

**Location of coal-fired power plants**

Figures in parentheses indicate power generation capacity (MW) at the end of 2013.

#### Power Generation Field

![Image of coal-fired power plants]

**Location of iron works**

Figures in parentheses indicate crude steel production (tons) at the end of 2011.

#### Iron making field

![Image of iron making field]

---

The content includes a detailed analysis of coal consumption and generated power in the power generation sector, as well as a breakdown of iron making field production. The diagrams illustrate the distribution of coal-fired power plants and iron works in Japan, highlighting their locations and capacities.
### Cement production field

Figures in parentheses indicate clinker production capacity (1000 tons/yr) at the end of 2013.

- **Myojo Cement (Itoigawa)** (1,670)
- **Denki Kagaku Kogyo (Nanyo)** (493)
- **Ube Industries (Ube)** (6,745)
- **Tosoh (Nanyo)** (1,166)
- **Tosoh (Yokkaichi)** (493)
- **Tosoh (Nanyo)** (1,166)
- **Tosoh (Yokkaichi)** (493)
- **Showa Denko (Oita)** (615)
- **Mitsubishi Chemical (Kashima)** (778)
- **Mitsui Chemicals (Ichihara)** (553)
- **Idemitsu Petrochemical (Chiba)** (374)
- **Sumitomo Chemical (Anegasaki, Sodegaura)** (380)
- **Maruzen Petrochemical (Ichihara)** (480)
- **Keihin Ethylene (Kawasaki)** (690)
- **Tonen Chemical (Kawasaki)** (491)
- **Mitsubishi Chemical (Yokkaichi)** (493)

### Coal chemicals and other fields

Figures in parentheses indicate ethylene production capacity (1000 tons/yr) at the end of 2012.

- **Mitsubishi Chemical (Mizushima)** (431)
- **Mitsui Chemicals (Iwakuni-otake)** (443)
- **Mitsubishi Chemical (Kashima)** (778)
- **Maruzen Petrochemical (Ichihara)** (480)
- **Kohtin Ethylene (493)
- **Mitsui Chemicals (ichihara)** (553)
- **Idemitsu Petrochemical (Chiba)** (374)
- **Nippon Oil & Energy (Kawasaki)** (404)
- **Mitsubishi Chemical (Yokkaichi)** (493)
- **Mitsubishi Chemicals (Osaka)** (615)

### Location of chemical complexes

Coal energy supply, GDP, and CO₂ emissions in Japan

### Location of cement plants

Coal consumption in cement production sector and cement production
Efforts to reduce CO₂ emissions

The Kyoto Protocol went into effect on February 16, 2005 requiring Japan to reduce greenhouse gas emissions by 6 percent from the 1990 level between 2008 and 2012 including reductions to carbon dioxide, methane, nitrous oxide and alternative CFC emissions. Among these greenhouse gases, carbon dioxide (CO₂) has the greatest impact on the environment. To reduce emissions of CO₂ Japan, with the most highly advanced clean coal technologies in the world, is promoting further technological developments, including:

1. Reduction of CO₂ generation by enhancing coal utilization efficiency.
2. Control of CO₂ emissions generated through direct coal burning by utilizing the carbon component in coal for material production, and
3. CO₂ capture in flue gas and storage.
Japan also promotes the reduction of CO₂ emissions through international cooperation using the Kyoto Mechanisms.

**Improvement of electric power generation efficiency by advanced technology**

**Co-production**

**CO₂ capture and storage**

- Separation and capture
  - Chemical absorption
  - Physical adsorption
  - Membrane separation
  - Oxygen burning
- Transportation
  - Land: liquefied CO₂ pipelines
  - Marine: liquefied CO₂ transport ships
- Capture and Sequestration
  - Underground: aquifer, coal seam
  - Ocean: dissolution, diffusion, hydrate (on the sea floor)

**Energy-derived CO₂ emission trend in Japan**

**CO₂ emissions in major countries (million tons)**

<table>
<thead>
<tr>
<th>Country</th>
<th>1990</th>
<th>2000</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S.</td>
<td>5,032</td>
<td>5,608</td>
<td>5,454</td>
<td>5,523</td>
<td>5,691</td>
</tr>
<tr>
<td>Canada</td>
<td>466</td>
<td>546</td>
<td>574</td>
<td>609</td>
<td>654</td>
</tr>
<tr>
<td>Western Europe</td>
<td>4,193</td>
<td>4,223</td>
<td>4,097</td>
<td>4,151</td>
<td>4,257</td>
</tr>
<tr>
<td>Russia</td>
<td>2,368</td>
<td>1,595</td>
<td>1,749</td>
<td>1,945</td>
<td>2,018</td>
</tr>
<tr>
<td>China</td>
<td>2,270</td>
<td>7,885</td>
<td>11,532</td>
<td>14,028</td>
<td>14,911</td>
</tr>
<tr>
<td>India</td>
<td>669</td>
<td>1,958</td>
<td>2,109</td>
<td>2,693</td>
<td>3,326</td>
</tr>
<tr>
<td>Japan</td>
<td>1,047</td>
<td>1,176</td>
<td>1,220</td>
<td>1,215</td>
<td>1,150</td>
</tr>
<tr>
<td>World total</td>
<td>21,452</td>
<td>31,183</td>
<td>36,446</td>
<td>41,464</td>
<td>45,453</td>
</tr>
</tbody>
</table>

**CO₂ emissions per generated power unit in major countries**

<table>
<thead>
<tr>
<th>Country</th>
<th>1990</th>
<th>2000</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S.</td>
<td>0.51</td>
<td>0.47</td>
<td>0.44</td>
</tr>
<tr>
<td>Germany</td>
<td>0.07</td>
<td>0.17</td>
<td>0.41</td>
</tr>
<tr>
<td>France</td>
<td>0.47</td>
<td>0.47</td>
<td>0.47</td>
</tr>
<tr>
<td>Canada</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Italy</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Japan</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Clean Coal Technologies in Japan**

**Flue gas treatment technologies**

Emission reduction technology to remove dust, sulfur oxides, and nitrogen oxides in flue gas has been developed by improving gas treatment performance, dust separator efficiency and coal combustion method.

- **Electrostatic precipitator-EP**
  Flue gas containing ash and dust passes between two electrodes that are charged by a high voltage current. The dust carrying negative charge are attracted toward the electrode carrying positive charge. The ash and dust deposited on the electrode are tapped periodically, and are collected in the lower section of the electrostatic precipitator. The principle is the same as the phenomenon where paper and dust adhere to a celluloid board that has been electrostatically charged by rubbing.

- **Flue gas desulfurizer-FGD**
  Powdered limestone is used to prepare a water-based mixture (limestone slurry). The mixture is injected into the flue gas where the limestone reacts with the sulfur oxides in the flue gas to form calcium sulfite, which is further reacted with oxygen to form gypsum. The gypsum is then separated as a product.

- **Selective catalytic NOx reduction-SCR**
  Ammonia is injected into the flue gas containing nitrogen oxides. The gas mixture is introduced to a metallic catalyst (a substance which induces chemical reactions). The nitrogen oxides in the flue gas then decompose into nitrogen and water under the catalyst.

**Reaction formulae**

$$4\text{NO} + 4\text{NH}_3 + \text{O}_2 \rightarrow 4\text{N}_2 + 6\text{H}_2\text{O}$$

$$6\text{NO}_2 + 8\text{NH}_3 \rightarrow 7\text{N}_2 + 12\text{H}_2\text{O}$$

**Emissions of SOx and NOx per generated power in major countries**

Source: The Federation of Electric Power Companies of Japan

<table>
<thead>
<tr>
<th>Country</th>
<th>SOx (g/kWh)</th>
<th>NOx (g/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S.</td>
<td>3.3</td>
<td>3.4</td>
</tr>
<tr>
<td>Germany</td>
<td>1.2</td>
<td>1.6</td>
</tr>
<tr>
<td>France</td>
<td>1.4</td>
<td>0.8</td>
</tr>
<tr>
<td>Canada</td>
<td>1.4</td>
<td>0.8</td>
</tr>
<tr>
<td>Italy</td>
<td>0.8</td>
<td>0.6</td>
</tr>
<tr>
<td>Japan (2005)</td>
<td>0.2</td>
<td>0.2</td>
</tr>
</tbody>
</table>

**Effective coal ash utilization technologies**

Ash generated during coal combustion can be effectively used as a raw material for cement and other products. The use of ash for multiple purposes is under study.

**Coal preparation technologies**

Reducing sulfur oxide emissions during coal utilization is an important environmental conservation challenge. Coal washing is an environmental control technology that removes iron pyrite particles and ash from coal.
In an effort to disseminate and promote Japan’s efficient coal usage technologies overseas, NEDO has conducted Coal Feasibility Studies (Coal FS) since FY 2011. These studies examine the feasibility for Japanese companies to deploy Japan’s high-efficiency power generation technologies, low-rank coal utilization technologies, operation management technologies, and high-efficiency coal usage systems such as CO2 capture and storage (CCS) and others internationally. From a global CO2 emissions reduction perspective, it is undesirable to have more low-efficiency coal-fired power plants built in coal-dependent countries leading to increased CO2 emissions. The object of the studies is to disseminate Japan’s high-efficiency technologies that are less burdensome to the environment, and to develop projects that are optimal for both the host country and Japan as well beneficial for the global environment.

Object of the studies >>> Reduction of global CO2 emissions and the environmental burden/Japan’s economic growth

[1] Support is provided to studies that are difficult for the private sector accomplish independently.
[2] Support is also provided to studies that verify the applicability of Japanese technologies to the type of coal in a host country.
[3] Results of Coal FS are shared to host country governments and companies at international events and bilateral/multilateral dialogues in order to win endorsement for Japan’s technologies based on their excellence and efficiency.
2. Low-rank Coal Utilization Promotion

Although steam coal has been widely used, its reserves are decreasing and maintaining a stable supply is becoming challenging due to increasing demands on coal-producing nations. Under this circumstance, it is increasingly necessary to expand the use of low-rank coal, which has abundant reserves.

There are potentially large markets worldwide for the utilization of low-rank coal. Many drying and upgrading technologies have been explored and demonstrated, but due to low added value of these products, it has been considered difficult to make profitable business. Various studies have been conducted regarding the production of hydrogen, synthetic natural gas (SNG), urea, methanol, and other higher value products, and the possibility of commercialization has been confirmed. However, these products have yet to be commercialized because sufficient cost reduction has not been achieved to make them fully competitive with existing products.

Beginning in FY2013, NEDO targeted projects that aim to manufacture chemical products with greater added values, or to upgrade coal at coal mining sites. NEDO prepares business models for these projects encompassing mines, manufacturing plants, transportation infrastructure, and product consumers.

NEDO also conducts feasibility studies for turning these business models into reality by identifying economic and technological hurdles and developing solutions, thus helping realization through technical development.

<table>
<thead>
<tr>
<th>Country</th>
<th>Subject coal</th>
<th>Product</th>
<th>CO₂ measure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indonesia</td>
<td>Sumatra’s brown coal</td>
<td>Synthetic natural gas</td>
<td>CO₂/EOR</td>
</tr>
<tr>
<td>Indonesia</td>
<td>Kalimantans’s brown coal</td>
<td>Blast furnace injected coal</td>
<td>-</td>
</tr>
<tr>
<td>Australia</td>
<td>Victoria’s brown coal</td>
<td>Reform coal (steel coal altern-tive)</td>
<td>-</td>
</tr>
<tr>
<td>Australia</td>
<td>Victoria’s brown coal</td>
<td>H₂</td>
<td>-Aquitfer CCS</td>
</tr>
<tr>
<td>China</td>
<td>Inner Mongolia’s brown coal</td>
<td>Synthetic natural gas</td>
<td>-</td>
</tr>
</tbody>
</table>
A-01-01. Hydrogen-from-Coal Process (HYCOL)

The Hydrogen-from-Coal Process (HYCOL) is a gasification technology utilizing a spouted bed in which pulverized coal is gasified with oxygen under high temperatures and high pressure. Through the gasifier, medium calorific gas, rich in hydrogen and carbon monoxide, is obtained. The technology is called the ‘HYCOL process.’ Through the shift reaction, the gas yields carbon monoxide and converts steam to carbon dioxide and hydrogen. After separating the carbon dioxide, the gas is purified to become high-purity hydrogen.

Hydrogen is used in oil refineries and in the chemical industry, as well as in the coal liquefaction process. Additionally, the gas containing carbon monoxide is expected to have a wide range of uses as a raw material for synthetic chemical products, as a fuel for fuel cells, and as a fuel in various industries.

The HYCOL process has the following features:
1. The process uses a dry-feed, two-stage, swirl-flow entrained-bed gasifier. Pulverized coal, pressurized in a lock hopper, is fed to the gasifier. Four burners are located in each stage so as to form a swirl-flow. The oxygen feed rate at the upper stage and lower stage are separately controlled. Throughout the operation, high thermal efficiency is attained, and high throughput capacity is ensured.
2. Slag self-coating technology was applied to the water-cooled wall. This technology extends the life of the gasifier wall.
3. A new type of coal distributor was developed. This technology can distribute coal to multiple burners equally.
4. Ash in coal is melted in the gasifier. The melted ash is discharged through the slag tap hole located in the bottom of gasifier. As a result of the swirl gas flow, a high temperature is maintained at the slag tap hole, ensuring a stable slag tapping.
5. The unreacted char, discharged along with gas from the gasifier, is separated by a cyclone or other device. The recovered char is recycled to the gasifier via high-temperature lock hopper system and subsequently gasified completely.
6. Ash in the coal is recovered as slag, which does not elute toxic components. Sulfur and nitrogen components, in the form of H₂S and NH₃, respectively, can be captured by existing technologies quite easily.

To test the process, a pilot plant with a coal throughput of 50 tons/day was constructed at Sodegaura, Chiba. The operational study of the pilot plant was conducted from 1991 to 1994. The performance target was achieved, and the world’s most advanced gasification technology was established.
Figure 1 Process flowchart of pilot plant

Table 1 Pilot plant: Specifications and target performance

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal throughput</td>
<td>Max. 50 tons/day</td>
</tr>
<tr>
<td>Gasification agent</td>
<td>Oxygen</td>
</tr>
<tr>
<td>Gasification pressure</td>
<td>30 kg/cm²(G)</td>
</tr>
<tr>
<td>Gasification temperature</td>
<td>1,500-1,800°C</td>
</tr>
<tr>
<td>O₂/Coal</td>
<td>0.8-0.9 (weight ratio)</td>
</tr>
<tr>
<td>Produced gas volume</td>
<td>Approximately 91 kNm³/day</td>
</tr>
<tr>
<td>Gas composition (design)</td>
<td>CO 61%</td>
</tr>
<tr>
<td></td>
<td>H₂ 31%</td>
</tr>
<tr>
<td></td>
<td>CO₂ 3%</td>
</tr>
<tr>
<td>Carbon conversion</td>
<td>98% or greater</td>
</tr>
<tr>
<td>Cold gas efficiency</td>
<td>78% or greater</td>
</tr>
</tbody>
</table>
A-01-02. Multi-purpose Coal Gasification Technology Development (EAGLE)

New Energy and Industrial Technology Development Organization, and J-POWER

METI-subsidized project, NEDO-joint research


Technology Overview

1. Summary of technology

The purpose of EAGLE (Coal Energy Application for Gas, Liquid and Electricity) is to reduce the environmental burden, particularly due to global warming gas emissions. The EAGLE project aims to establish a coal gasification system utilizing the most advanced oxygen-blown, two-stage swirl-flow gasifier that allows the highly-efficient production of synthetic gas (CO+H₂) which can be widely used as a raw material for chemicals, hydrogen production, synthetic liquid fuel, electric power generation and other purposes. This gasifier, combined with gas turbines, steam turbines, and fuel cells, will provide an integrated coal gasification fuel cell combined-cycle system (IGFC) that is expected to reduce CO₂ emissions by up to 30% compared to existing thermal power plants.

2. Development targets and technology to be developed

The EAGLE project’s development targets are shown in Table 1. When utilizing coal-gasified gas for fuel cell power generation or the production of synthetic fuel, hydrogen, or chemical fertilizers, sulfur compounds and other impurities contained in the gas may contaminate the fuel cells and the reactor catalyst and degrade their performance. The EAGLE project, therefore, sets targets to meet the purity levels required by fuel cells and catalysts. Since there have been few reports published on the matter, particularly on the effects of fuel cell contaminating materials (including halogens), the project set target levels with reference to reports by the U.S. Department of Energy (DOE), the MCFC Association of Japan, and other organizations.

3. Key feature of pilot plant

In this project, a pilot test plant (Photo 1) with a coal processing capacity of 150 tons/day was built at J-POWER’s Wakamatsu Research Institute. Operational testing has been ongoing since 2002. Figure 1 shows a flowchart of the pilot test plant, and Table 2 provides the specifications of the major systems. The test plant consists of the following systems: coal pretreatment, coal gasification, air separation, gas purification, effluent treatment, and produced gas combustion, as well as a gas turbine.

Table 1 Development targets (Step-1)

<table>
<thead>
<tr>
<th>Item</th>
<th>Development target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal gasification performance</td>
<td>Carbon conversion rate: 98% or higher</td>
</tr>
<tr>
<td></td>
<td>Cold gas efficiency: 78% or higher</td>
</tr>
<tr>
<td></td>
<td>Gas calorific value (higher): 10,000 kJ/m³N or higher</td>
</tr>
<tr>
<td>Gas purification performance</td>
<td>Sulfur compounds: 1 ppm or less</td>
</tr>
<tr>
<td></td>
<td>Halogen compounds: 1 ppm or less</td>
</tr>
<tr>
<td></td>
<td>Ammonia: 1 ppm or less</td>
</tr>
<tr>
<td></td>
<td>Dust: 1 mg/m³N</td>
</tr>
<tr>
<td>Miscellaneous</td>
<td>Continuous operation: 1,000 hr or longer</td>
</tr>
<tr>
<td></td>
<td>Acquisition of gasification data for 5 or more coal types</td>
</tr>
<tr>
<td></td>
<td>Acquisition of scale-up data</td>
</tr>
</tbody>
</table>

Table 2 Specifications of major equipment

<table>
<thead>
<tr>
<th>Item</th>
<th>Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal gasifier</td>
<td>Oxygen-blown, single-chamber, two-stage swirling-flow entrained bed gasifier</td>
</tr>
<tr>
<td>Coal processing capacity</td>
<td>150t/d (6.3t/hr)</td>
</tr>
<tr>
<td>Gasification temperature</td>
<td>1,200°C to 1,600°C</td>
</tr>
<tr>
<td>Gasification pressure</td>
<td>2.5 MPa</td>
</tr>
<tr>
<td>Gas refinery</td>
<td>Wet chemical absorption type</td>
</tr>
<tr>
<td>Absorbing solution</td>
<td>Methyl diethanolamine (MDEA)</td>
</tr>
<tr>
<td>Processing capacity</td>
<td>Approx. 14,800 m³N/hr</td>
</tr>
<tr>
<td>Sulfur recovery unit</td>
<td>Wet limestone-gypsum method</td>
</tr>
<tr>
<td>Air separation system</td>
<td>Pressurized oxygen separation type</td>
</tr>
<tr>
<td>Air pressure</td>
<td>1.09 MPa</td>
</tr>
<tr>
<td>Air processing capacity</td>
<td>Approx. 27,500 m³N/hr</td>
</tr>
<tr>
<td>Oxygen production</td>
<td>Approx. 4,600 m³N/hr</td>
</tr>
<tr>
<td>Oxygen purity</td>
<td>95%</td>
</tr>
<tr>
<td>Gas turbine</td>
<td>Open simple-cycle, single-shaft type</td>
</tr>
<tr>
<td>Output</td>
<td>8,000kW</td>
</tr>
</tbody>
</table>

Figure 1 Flowchart of EAGLE 150 t/d pilot plant
Clean Coal Technologies in Japan

4. Timetable and progress

This project was a joint-effort between the New Energy and Industrial Technology Development Organization (NEDO) and J-POWER. In Step 1, as shown in Table 3, performance goals were achieved by 2005 before the end of the project period. For cold gas efficiency, the target was achieved and exceeded at a rate of 82% or higher. Moreover, all other goals were achieved, including the continuous operation of 1,000 hours or longer, ensuring compatibility with multiple coal types (acquisition of gasification data for 5 or more coal types), and the acquisition of scalability (x10 scale-up) data.

The EAGLE project was later extended as shown in the development timeline in Figure 2. In Step 2, a pilot plant was improved for a more advanced gasification test (2007-2009). In studies involving coal with high ash fusion temperature, gasification tests of three new coal types were conducted. A chemical absorption test facility using MDEA (methyl di-ethanol amine) was added for CO₂ capture. The goals were achieved with a CO₂ capture rate of 90% or higher and a 99% or higher purity of captured CO₂, as well as the verification of an energy-efficient solvent recycling process.

In Step 3, testing facilities were remodeled for the development of an innovative CO₂-capturing coal gasification technology (2010 – June 2014). Physical absorption testing equipment was added for CO₂ capture testing, and the goals were achieved with a 98% or higher purity of captured CO₂ and improved power generation efficiency (10% increase over the result of the chemical absorption process of Step 2).

The EAGLE project completed all of its studies in June 2014, having achieved all of its initial goals in each step. The summaries of CO₂ capture tests in Step 2 and Step 3 are provided in section C-06-03, Pre-combustion CO₂ recovery technologies from coal gasification (Pre-Combustion), of this document.

5. Future plans

The successful results of the EAGLE project are being applied to the Osaki CoolGen Project, which is now under construction. This project aims to establish an IGCC/IGFC system using oxygen-blown gasification technologies.

EAGLE technology can be effectively used in an integrated coal gasification combined cycle (IGCC) power generation system, which combines a gas turbine generation system and a steam turbine generation system, and will applied to a fuel cell combined-cycle system (IGFC), shown in Figure 3. This system represents the most efficient power generation option using coal. IGFC is expected to dramatically improve power generation efficiency relative to conventional pulverized coal-fired power generation systems, and to be the ultimate power generation system, with efficiency exceeding 55%. EAGLE plants using oxygen-blown coal gasifiers produce coal-gasified gas with a substantially higher CO and H₂ composition. Utilization of this gas allows for the efficient production of liquid fuels or chemical feedstocks.

EAGLE technology will also meet the demands of an increasingly hydrogen-based society.

References

Brown coal and, low-rank coals can be gasified under lower temperature and at atmospheric pressure. TIGAR comprises a combination of gasification which is an endothermic reaction, and combustion, which is an exothermic reaction. It uses a fluidized-bed system with a moving medium (sand) circulation between the gasifier and the combustor. Because the gasifier has a fluidized bed, there is no need for preliminary drying, slurrying, and transport gas.

As a result of these challenges, the goal is to develop brown coal gasification technology for use locally in coal-producing countries. This technology is low in cost and offers ease of handling and plant maintenance.

Brown coal and other low-rank coal reserves are found in large quantities in Indonesia, Germany and Australia. These types account for one half of the total coal reserves. It is therefore necessary from a global energy security perspective to develop an efficient application technology for brown coal and other low-rank coals. Due to its high inherent moisture content and spontaneous combustion property, brown coal’s use has been limited. The twin IHI gasifier (TIGAR) illustrated in Figure 1 can apply to not only brown coal, but also to co-utilization of biomass. It serves to use brown coal as a substitute fuel for natural gas and petroleum, and reduces CO₂ emissions compared to existing brown coal utilization technologies.

As the process takes place under atmospheric pressure and at a low temperature, it does not require expensive heatproof material or a pressure-proof mechanisms. The use of commonly available parts lowers both initial and maintenance costs. Introduction of the technology to Indonesia and other coal-producing nations will encourage the use of brown coal as a substitute to existing energy resources such as natural gas. This will contribute to energy security as it mitigates energy demand of coal-producing countries, increases their export capacity of high-rank coal and LNG, and would enable them to export high-rank coal to Japan.

**Technology Overview**

1. **Purpose of technology development**
   This technology aims to develop an efficient gasification system for brown coal (ignite). The inherently high moisture content and spontaneous combustion characteristics of brown coal cause problems in its transportation and storage.

2. **Needs and benefits**
   Brown coal and other low-rank coal reserves are found in large quantities in Indonesia, Germany and Australia. These types account for one half of the total coal reserves. It is therefore necessary from a global energy security perspective to develop an efficient application technology for brown coal and other low-rank coals. Due to its high inherent moisture content and spontaneous combustion property, brown coal’s use has been limited. The twin IHI gasifier (TIGAR) illustrated in Figure 1 can apply to not only brown coal, but also to co-utilization of biomass. It serves to use brown coal as a substitute fuel for natural gas and petroleum, and reduces CO₂ emissions compared to existing brown coal utilization technologies.

3. **Key technology and features**
   Brown coal and, low-rank coals can be gasified under lower temperature and at atmospheric pressure. TIGAR comprises a combination of gasification which is an endothermic reaction, and combustion, which is an exothermic reaction. It uses a fluidized-bed system with a moving medium (sand) circulation between the gasifier and the combustor. Because the gasifier has a fluidized bed, there is no need for preliminary drying, slurrying, and transport gas.

   TIGAR is based on the circulating fluidized-bed system that has already been successfully used in industrial boilers and other applications, and that is being promoted by coal-producing and other countries. As it is a gasification process under lower temperature and atmospheric pressure, it has favorable operations and maintenance characteristics. Furthermore, it is not only applicable for brown coal, but also for biomass and many other low-rank fuels.

4. **Progress and development timeline**
   The TIGAR development plan is illustrated in Table 1. Following a bench-scale gasifier test of 0.1 t/d (FY2005-FY2006), initial goals were achieved in the 6t/d pilot gasifier test operation (FY2010-FY2011). These initial goals included the confirmation of plant performance, environmental acceptability, and operational stability. A demonstration plant (50 t/d) has been under construction in Indonesia since 2012. Figure 2 shows a conceptual drawing and Photo 1 reveals the state of construction. Beginning in 2015, the prototype plant will demonstrate the technology’s ability to transform low-rank coal into many different products including fuel and chemical feedstocks, aiming towards commercial use. After the demonstration stage is complete, the first commercial unit will be built for a fertilizer plant in Indonesia in where the fertilizer is now made using natural gas. TIGAR will then be promoted for fuel and chemical feedstock applications in brown coal-producing countries.
5. Technology to be developed

(1) Establish a scale-up method
Based on the results of the pilot reactor (6 t/d of coal supply), a demonstration plant (50 t/d) will be built and tested while the performance data is reviewed.

(2) Establish gas purification process
Technologies need to be developed to process and purify tar generated through low-temperature gasification. Tar is formed due to a relatively low temperature of gasification. The process to treat and purify tar needs to be tested at the demonstration unit scale to verify its performance and operation. Additionally, technologies to limit the formation of tar by gasifier and other processing technologies will be researched and developed.

(3) Verify reliability
Through long-term operation (several thousand hours), ease of handling, durability and maintainability will be verified.

(4) Other
Cost reduction will be studied for greater competitiveness.
A-02-01. Coal Liquefaction Technology Development in Japan

Technology Overview

1. Background of coal liquefaction technology development
Since the Industrial Revolution, coal has been an important source of energy. Coal consumption surpassed that of firewood and charcoal for the first time in the latter half of the nineteenth century, making coal a major source of energy. In Japan, coal also became a primary energy source in the twentieth century. In the 1960s, however, coal’s preeminence gradually faded as it was replaced by easier-to-use oil. It was after the oil crises of 1973 and 1978 that coal regained importance. With the oil crises as a turning point, the development of oil-alternative energy, particularly coal utilization technology, came into the spotlight amid calls for a diversification of energy sources. During that time, the liquefaction of coal, which had been positioned as the strongest oil-alternative energy contender because of huge coal reserves, was undergoing development in many countries. Research in Germany and the United States involved pilot plants with the capacity to treat hundreds of tons of coal per day. In Japan, development of coal liquefaction technology was also being promoted under the Sunshine Project, led by the New Energy and Industrial Technology Development Organization (NEDO). Despite being a decade or so behind Germany and the United States, slow but steady development progress in Japan led to the successful completion of a 150 t/d-scale pilot plant for the liquefaction of bituminous coal in 1998. This drew Japan equal with Germany and the United States and also established state-of-the-art coal liquefaction technology.

2. History of coal liquefaction technology development in Japan
2.1 Beginnings of coal liquefaction technology development
Between approximately 1920 and 1930, the South Manchurian Railway Co., Ltd. started basic research on coal liquefaction using the Bergius Process, and around 1935 it initiated operation of a bench-scale PDU (process development unit) plant. Based on this research, a plant with an annual production capacity of 20,000 tons of coal oil was built at the Wushun coal mine, China, which operated until 1943. In parallel, Korean Artificial Petroleum Co., Ltd. succeeded, between 1938 and 1943, in the continuous operation of a direct coal liquefaction plant capable of treating 100 t/d of coal at its Agochi factory. The production of coal oil at both of the above-mentioned plants was suspended due to military requests that the plants be used for the hydrogenation of heavy oil or to produce methanol. Around 1930, in addition to the direct coal liquefaction method (Bergius Process), a second process, known as the Fischer-Tropsch Process, was used as an indirect coal liquefaction method to study coal liquefaction technology and to produce synthetic oil. The Fischer-Tropsch Process was introduced to Japan following its announcement in Germany in 1935, and construction of a plant began in Mike in 1937. This oil synthesis plant was completed in 1940, with an annual production capacity of 30,000 tons of coal oil. Production of synthetic oil continued until the end of World War II.

2.2 Post-war research on coal liquefaction
Immediately after the war, the U.S. Armed Forces Headquarters banned coal liquefaction research in Japan, alleging that it was military research. In 1955, coal liquefaction research was resumed at national laboratories and universities. This was not, however, research on coal oil production, but research on the production of chemicals from the high-pressure hydrocracking of coal. This research continued until around 1975. The Sunshine Project was inaugurated in 1974 on the heels of the first oil crisis, encouraging efforts to devise liquefaction technology unique to Japan as part of an oil-alternative energy development program. Under the Sunshine Project, technological development was pursued for three coal liquefaction processes (Solvolyisis, Solvent Extraction, and Direct Hydrogenation) to liquefy bituminous coal. The R&D of brown coal liquefaction processes began at the end of 1980.

2.3 Amalgamation of three coal liquefaction processes
With the oil crises as an impetus, coal liquefaction technology development was incorporated for further promotion into the Sunshine Project due to Japan’s international obligations, the need for a large, stable supply of liquid fuel, and as part of efforts

Table 1 History of NEDOL Process

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
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<tbody>
<tr>
<td>1979</td>
<td>Sunshine Project started (July 1974)</td>
</tr>
<tr>
<td>1980</td>
<td>NEDO established (Oct. 1, 1980)</td>
</tr>
<tr>
<td>1981</td>
<td>NEDO established (Oct. 1, 1980); Coal Technology Development Office assumes responsibility for three liquefaction processes.</td>
</tr>
<tr>
<td>1982</td>
<td>Construction of 300 t/d plant began.</td>
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<tr>
<td>1983</td>
<td>Construction of 300 t/d plant completed.</td>
</tr>
<tr>
<td>1984</td>
<td>Construction of 300 t/d plant completed.</td>
</tr>
<tr>
<td>1985</td>
<td>Construction of 150 t/d plant started.</td>
</tr>
<tr>
<td>1986</td>
<td>Coal trial run-1 (March 26, 1987)</td>
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<td>1987</td>
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<td>2000</td>
<td>Coal trial run-15 (March 31, 2001)</td>
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</tbody>
</table>
to increase diversification of energy sources and develop oil-alternative energy. In 1983, NEDO (formerly New Energy Development Organization and now known as New Energy and Industrial Technology Development Organization) assembled their R&D results to date from the three bituminous coal liquefaction processes. The major results were as follows:

1. Results of Direct Hydrogenation Process: Under certain reaction conditions, the higher the liquid yield rate, the better the catalyst function.

2. Results of Solvent Extraction Process: Hydrogen offers liquefaction under mild conditions.

3. Results of Solvolysis Liquefaction Process: To focus on the acquisition of light oil, it is effective to thicken the circulation solvent.

These three processes were amalgamated on the strength of their features into the NEDOL Process.

### 3. Future of coal liquefaction

As China anticipates facing a tight supply-demand balance of oil in the future, the country has been proactive towards the development and introduction of coal liquefaction technology. As part of international cooperation efforts, NEDO installed a 0.1 t/d liquefaction device in China in 1982 and has been engaged in liquefaction studies, exploration of solvents, and educational activities to technicians. At China’s request, NEDO collaborated on a feasibility study of a coal liquefaction plant using Heilongjiang Yilan bituminous coal beginning in 1997. Also at the request of China, NEDO is working with Shangwan coal in both Shaanxi and Inner Mongolia. This coal appears promising as a cheaper energy source, and its reserves are estimated to be about 200 billion tons. Indonesia is poised to become an oil importer in the near future. In 1992, the Indonesian government requested cooperation from Japan on coal liquefaction research for Indonesian brown coal. In response, NEDO signed a Memorandum of Understanding with the Indonesian Agency for the Assessment and Application of Technology (BPPT) on coal liquefaction research cooperation and started new brown coal liquefaction technology development aiming to establish a commercial plant utilizing Indonesian brown coal.

Coal liquefaction R&D that began with the Sunshine Project in 1973 moved from the research stage to the deployment stage following the end of the pilot plant’s operations. It is believed that the technology will be introduced through international cooperation with coal producers, particularly China and Indonesia.

China, the United States, Germany, and Japan are all exploring potential locations of a liquefaction plant. While liquefaction technology has not yet been deployed in Japan due to economic considerations, China is more actively engaged in the development and introduction of liquefaction technology, mainly in Inner Mongolia, due to an anticipated future shortage of oil supply in the country.

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**Figure 1 Basic philosophy of NEDOL Process**

**Figure 2 Coal liquefaction deployment considered in China**
A-02-02. Bituminous Coal Liquefaction Technology (NEDOL)

**Technology Overview**

1. Overview of NEDO Process development

The conceptual design of a 250 t/day pilot plant (PP) began in FY1984. Owing to changes in economic conditions, however, the scale was altered and design of a 150 t/d PP began in FY1988. As a support study to the pilot plant, the operational study of a 1 t/d process support unit (PSU) was carried out. The 1 t/d PSU, constructed in FY1988 at Kimitsu Ironworks of Nippon Steel Corp., consisted of four stages: coal storage and pretreatment, liquefaction reaction, liquefied coal distillation, and solvent hydrogenation. Over the ten-year period from FY1989 to FY1998, a joint study team from Nippon Steel Corp., Mitsui Coal Liquefaction Co., Ltd., and Nippon Coal Oil Co., Ltd. conducted operational studies on nine coal types under 72 liquefaction conditions. Through the 26,949 cumulative hours of operations, the stability and the overall operability of the NEDOL Process was confirmed. Additionally, the optimization of the process was established. Finally, the design data necessary for the scale-up was acquired. Construction of the 150 t/d pilot plant was launched in 1991 at Sumitomo Metal Industries, Ltd.’s Kashima Steelworks (Kashima City, Ibaraki), which required nearly five years for completion. The pilot plant consisted of five main facilities: the coal treatment unit, the liquefaction reaction unit, the liquefied coal distillation unit, the solvent hydrogenation unit, and the hydrogen production unit.

2. Evaluation of NEDO process development

Figure 1 shows the progress of coal liquefaction technology from before World War II to the present, expressed by the relation between the severity of the liquefaction reaction and the yield of coal-liquefied oil by generation. As noted in Figure 1, the NEDOL Process is competitive with processes in Europe and the United States in terms of technology, economics, and operational stability. As a result, the NEDOL Process is one of the most advanced processes and is expected to enter the commercialization stage shortly.

![Fig. 1 Relation between the severity of liquefaction reaction and the yield of coal-liquefied oil](image)

![Fig. 2 Bituminous coal liquefaction process flowchart](image)
3. Features of NEDOL process

The NEDOL Process is a coal liquefaction process developed exclusively in Japan. The process has integrated the advantages of three bituminous liquefaction processes (Direct Hydrogenation Process, Solvent Extraction Process, and Solvolysis Process) to provide superiority in both technology and economics. The advantages of the NEDOL Process include:

1. Attaining high liquid yield under mild liquefaction reaction conditions owing to the iron-based fine powder catalyst and to the hydrogen-donating solvent
2. Producing coal-liquefied oil that is rich in light distillate
3. Assuring high process stability through plant composition of reliable elements
4. Applicability to a wide range of coal ranks, from sub-bituminous coal to low coalification grade bituminous coal

<table>
<thead>
<tr>
<th>Liquefaction catalyst</th>
<th>Hydrogenation catalyst</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catalyst composition Fe (wt%)</td>
<td>Ni-Mo/Al2O3</td>
</tr>
<tr>
<td>S (wt%)</td>
<td>Specific surface area (m²/g) 190</td>
</tr>
<tr>
<td>Other (wt%)</td>
<td>Micropore volume (m³/g) 0.7</td>
</tr>
<tr>
<td>Specific surface area (m²/g)</td>
<td>Mean micropore size (nm) 14.5</td>
</tr>
<tr>
<td>Size of pulverized catalyst [D₅₀] m</td>
<td></td>
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<tr>
<td>0.7-0.8</td>
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</tbody>
</table>

4. Typical reaction conditions of NEDOL process

<table>
<thead>
<tr>
<th>Liquefaction reaction</th>
<th>Solvent hydrogenation reaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature 450°C</td>
<td>Temperature 320°C</td>
</tr>
<tr>
<td>Pressure 170kg/cm²-G</td>
<td>Gas/solvent ratio 500Nm³/t</td>
</tr>
<tr>
<td>Type of catalyst Iron-base fine powder catalyst</td>
<td>Hydrogen concentration in recycle gas 90 vol%</td>
</tr>
<tr>
<td>Added amount of catalyst 3 wt%(dry coal basis)</td>
<td>Kind of catalyst Ni-Mo/Al₂O₃</td>
</tr>
<tr>
<td></td>
<td>LHSV 1 hr⁻¹</td>
</tr>
<tr>
<td>Slurry concentration 40 wt% (dry coal basis)</td>
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<tr>
<td>Slurry retention time 60 min</td>
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<tr>
<td>Gas/solvent ratio 700Nm³/t</td>
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<tr>
<td>Hydrogen concentration in recycle gas 85 vol%</td>
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5. Pilot plant: Objectives and achievements

Development objectives | Target | Achievements |
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<tbody>
<tr>
<td>1. Yield of coal-liquefied oil</td>
<td>For standard coal, 50 wt% or higher yield of light to medium oils, and 54 wt% of higher total yield</td>
<td>With standard coal, attained 51 wt% yield of light to medium oils, and 58 wt% of total yield</td>
</tr>
<tr>
<td>2. Slurry concentration</td>
<td>40-50 wt% of coal concentration in slurry</td>
<td>Stable operation achieved at 50 wt% of coal concentration in slurry</td>
</tr>
<tr>
<td>3. Added amount of catalyst</td>
<td>2.3 wt% (dry-coal basis) of added amount of iron sulfide-base catalyst</td>
<td>Operation conducted in a range from 1.5 to 3 wt% of added amount of iron sulfide-base catalyst</td>
</tr>
<tr>
<td>4. Continuous operation time</td>
<td>1,000 hours or more for standard coal</td>
<td>Continuous operation of 80 days (1,920 hours) achieved with standard coal</td>
</tr>
<tr>
<td>5. Range of applicable coal grades</td>
<td>Three coal ranks or more</td>
<td>Operation conducted with a wide range of coalification ranks, namely Adaro coal, Tanjitohalm coal, and Ikijima coal</td>
</tr>
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6. Research and development timetable of NEDOL process pilot plants

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<tr>
<td>250 t/d PP design</td>
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<tr>
<td>150 t/d PP design</td>
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<td>Construction</td>
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7. Research and development results

All the acquired data, including pilot plant data, basic research data, and support study data, was summarized in a technology package to prepare for practical application. At the December 22, 1999 meeting of the Development and Assessment Committee for Bituminous Coal Liquefaction Technology in the Assessment Work Group of the Industrial Technology Council, the NEDOL Process was highly evaluated. The committee assessed that “The NEDOL Process is at the highest technology level in the world, and has reached the stage where worldwide deployment is expected.” As a result of this assessment, the development of coal liquefaction technology in Japan moved from the research stage into the practical application stage. Furthermore, development of materials and new processes are expected to significantly influence development in other industries. Internationally, the Shenhua Group completed a 6,000 t/day capacity coal liquefaction plant (1 million t/year in coal-liquefied oil) in 2009 in Ordos City in Inner Mongolia, China. This system has been improved and is the only continuously operating plant in the world.

References

2) "Development of Coal Liquefaction Technology - A Bridge for Commercialization," Nippon Coal Oil Co., Ltd.
A-02-03. Brown Coal Liquefication Technology (BCL)

New Energy and Industrial Technology Development Organization; Kobe Steel, Ltd.; Nissho Iwai Corp.; Mitsubishi Chemical Corp.; Cosmo Oil Co., Ltd.; Idemitsu Kosan Co., Ltd.; and Nippon Brown Coal Liquefaction Co., Ltd.

NEDO-commissioned project
FY1981 – FY2002 (21 years)

Technology Overview

1. Background and process overview

Economically recoverable coal reserves are expected to total about one trillion tons globally, and approximately half of these reserves are comprised of low-rank coal such as sub-bituminous coal and brown coal. Coal has a larger ratio of reserves to production (R/P) than that of oil and natural gas. For the effective utilization of coal, however, the effective use of low-rank coal is essential. Low-rank coal contains a large amount of water, but unlike bituminous coal and other higher-rank coals, it has a spontaneous combustion property in a dry state. Consequently, brown coal liquefaction technology development has progressed so it can contribute to a stable supply of energy in Japan either by converting the difficult-to-use low-rank coal into an easy-to-handle and useful product, or by using it to produce transportation fuels such as gasoline and diesel oil. As shown in Figure 1, the BCL process has four stages:

1. The slurry dewatering stage, where water is efficiently removed from low-rank coal
2. The liquefaction stage, where liquefied oil production yield is increased by using a highly active limonite catalyst and bottom recycling technology
3. The in-line hydrotreatment stage, where the heteroatoms (sulfur-containing compounds, nitrogen-containing compounds, etc.) in the coal-liquefied oil are removed to obtain high-quality gasoline, diesel oil, and other light fractions
4. The solvent de-ashing stage, where the ash in coal and the added catalysts are efficiently discharged from the process.

In Asian countries, economic growth has caused a steady increase in energy demand, and countries possessing low-rank coal resources, such as Indonesia, anticipate commercialization of BCL technology.
2. Development objectives and technology to be developed

A pilot plant (Photo 1) study conducted under the governmental cooperation of Japan and Australia set the following technical targets:

1. High liquefied oil production efficiency: 50% or greater;
2. Long-term continuous operation: 1,000 hours or greater;
3. High de-ashing performance: 1,000 ppm or less; and
4. Establishment of a new slurry dewatering process.

Following four years of operation and study (1987-1990), all of the above targets were achieved. Furthermore, scale-up data necessary to construct commercial liquefaction plants and operational knowledge were obtained through pilot plant operation. During the study period, however, oil prices were low and supplies were stable worldwide. Thus, further improvements in the economics of the coal liquefaction process were required to make commercialization feasible. Additionally, cleaner liquefied oil was demanded as a result of increased environmental concerns. Accordingly, a bench-scale plant (0.1 t/d) in Kobe Steel, Ltd.’s Takasago Works was constructed to conduct a study aiming to improve the process. Results of the study included the development of a limonite catalyst, which was an extremely active catalyst compared to existing liquefaction catalysts that possessed superior handling properties, such as excellent crushing characteristics. Additional improvements included a method to maintain catalytic activity through bottom recycling technology, an in-line hydrotreatment technology that significantly improved the quality of coal-liquefied oil, and various other improvements that increased operational reliability. Through the development work, an improved BCL process (sown in Figure 1 above) was established that significantly improved the economics, reliability, and environmental compatibility of the brown coal liquefaction process.

3. Progress and development results

Following the signing of a memorandum of understanding on cooperative coal liquefaction research between the Agency for the Assessment and Application of Technology of Indonesia and the New Energy and Industrial Technology Development Organization (NEDO), a study team carried out surveys and liquefaction tests of low-rank coal in Indonesia beginning in 1994 to screen candidate coals for liquefaction. Furthermore, the team endeavored to increase the technical abilities of the Indonesian engineers through technical training and the supply of liquefaction testing equipment. In 1999, the study team selected three candidate sites for a liquefaction plant in Indonesia and carried out a feasibility study, which included an economic evaluation. The feasibility study revealed that coal liquefaction would be economically feasible based on current oil price levels.

4. Issues and prospects for practical use

As energy demand in Asian countries is rapidly increasing due to steady economic growth, brown coal liquefaction technology that utilizes low-rank coal will play an important role. Its practical application is particularly desired in areas that lack transportation fuel. However, many factors influence the prospects of putting this technology into practical use including its economic viability as well as the policies, legal system, labor considerations, environmental concerns, management methodology, and decision making of the individual country.

References

A. Multi-purpose Coal Utilization Technologies

Part 2 CCT Overview

A-02-04. Dimethyl Ether (DME) Production Technology


METI-subsidized project FY2002 – FY2006 (5 years)

Technology Overview

1. Background and process overview

Dimethyl ether (DME) is a clean energy source with a low environmental impact as it generates no sulfur oxide or soot during combustion. Owing to its non-toxicity and easy liquefaction properties, DME is easy to handle and therefore can be used as a domestic-sector fuel (substitute for liquefied petroleum gas, transportation fuel (diesel vehicles, fuel cell vehicles), power plant fuel (thermal plants, cogeneration plants, stationary fuel cells), and as a raw material for chemical products.

Currently, DME is produced by dehydrating methanol. Approximately ten thousand tons per year are produced in Japan, and 150 thousand tons per year are produced worldwide. DME’s main use is as a spray propellant. Given the above-described superior properties, if DME were to become widely available in large amount at a reasonable price, DME could be used as a fuel in a wide variety of fields.

2. Development objectives and technology to be developed

The objective of this study was the development of a process to directly synthesize DME from syngas, which is a mixture of H₂ and CO (Chemical reaction (1)). Existing technology produced DME through the dehydration of methanol (Chemical reaction (3)). However, the scale of existing plants was rather small, making scaling-up an issue to produce DME as a commercial fuel. In addition, the equilibrium conversion of the methanol synthesis reaction (Chemical reaction (2)) is relatively low, as show in Figure 1. Because the methanol synthesis equilibrium limitation can be avoided in the direct DME synthesis reaction (1); a higher conversion rate can be achieved.

The equilibrium conversions for methanol synthesis and direct DME synthesis are given in Figure 1. Since direct synthesis produces the maximum conversion with a syngas composition of H₂/CO=1, the process is suitable for the syngas produced from coal gasification (H₂/CO=0.5-1).

The targets of the development study included the following:

[1] DME production rate: 100 tons/day or greater, syngas total conversion: 95% or greater, DME selectivity: 90% or greater, DME purity: 99% or greater;
[2] Establishing scale-up technology;
[3] Optimizing entire system; and

Chemical reaction:

(1) 3CO + 3H₂ → CH₃OCH₃ + CO₂

(2) CO + 2H₂ → CH₃OH

(3) 2CH₃OH → CH₃OCH₃ + H₂O

3. Progress and development results

The development of the direct synthesis process has been developed by JFE. The first step was the search for a direct synthesis catalyst. The second step was a test using small bench plant (5 kg/day). The third step was an operation using a 5 ton/day pilot plant (Photo 1) constructed with the aid of the Ministry of Economy, Trade and Industry (METI).1,2) The fourth step was a demonstration using a 100 ton/day plant (Photo 2) also constructed with the aid of METI. This demonstration plant was completed in November 2003 and had six long-term continuous operation runs over 2 to 5 month periods from the end of 2003 to 2006. The total production of DME by the demonstration plant reached approximately 19,000 tons.
4. Issues and prospects for practical use

DME is already utilized as a fuel on a small-scale in an inland area of China. In Japan, several companies are pursuing activities toward the practical application of DME as a fuel including:
- DME International Co., Ltd.
- Japan DME Co., Ltd. (which was established by Mitsubishi Gas Chemical Co., Inc.)
- Mitsubishi Heavy Industries, Ltd.
- JGC, and Itochu Corp.
- Mitsui & Co., Ltd.
- Toyo Engineering Corp (which adopted the methanol dehydration process)

These activities aimed to supply DME products by 2006, and in all cases planned to use natural gas as the feedstock due to its small initial investment requirements.

In future iterations, the feedstock could switch to coal, which has larger reserves than natural gas. When coal is used, CO₂ is generated from the direct synthesis chemical reaction (1) and is subsequently separated at very high purity level through a purification process. Once CO₂ capture and storage technology is established, DME can be produced from coal as a fuel in low CO₂ load (See Figure 2).

Japan does not yet have a commercial-scale DME plant that offers competitive prices. The DME production process has a higher thermal efficiency than the GTL process, but its commercialization requires further improvement in energy and carbon conversion efficiency. It also requires assurance of durability over long-term operations, development of DME-resistant sealing materials, and proof of plant reliability.

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**References**

1) Tsunao Kamijo et al., Lecture papers of The 8th Coal Utilization Technology Congress, Tokyo, pp. 194-205, 1998.
Part 2 CCT Overview
A. Multi-purpose Coal Utilization Technologies

A-03-01. Multi-purpose Coal Conversion Technology (CPX)

Japan Coal Energy Center; Nippon Steel Engineering Co., Ltd.; JFE Steel Corp.; Sumitomo Metal Industries, Ltd.; Kobe Steel Ltd.; Ube Industries, Ltd.; Idemitsu Kosan Co., Ltd.; Nippon Steel Chemical Co., Ltd.

METI-subsidized project
FY1996 – FY2000 (5 years)

Technology Overview

1. Technological features

In an attempt to develop more versatile uses for coal, the aim of this project was to develop multi-purpose coal conversion technology with excellent efficiency, economic feasibility, and environmental-friendliness. The main uses for the converted coal would be as medium-calorie gas for industrial fuel and as liquid products to serve as feedstocks for chemical production.

The technological objectives were as follows:

[1] Moderate operational conditions
- A pyrolysis reactor operating at temperatures of 600-950°C.
- A reaction pressure of less than 1 MPa, much lower than the coal liquefaction (several ten MPa order) or hydro-gasification processes (a few MPa order)

[2] High overall thermal efficiency
- Flash pyrolysis of coal combined with char gasification, thereby improving thermal efficiency of the process

[3] Coal flexibility
- Utilizing lower grades of coal, from sub-bituminous to highly volatile bituminous coal, as primary material to enable high gas/tar yields

[4] Efficient separation of coal ash
- Coal ash discharged from gasifier as molten slag and then granulated within a water bath

[5] Multiple products
- Among products, gas can be used as industrial fuel, liquids (light oil/tar) can be used as feedstocks for chemicals, solid char can be used as fuel or a reductant, and slag can be used as a raw material for cement production
- Heating value of gas produced from the process to approach approximately 3,500 kcal/Nm³
- Total yield of gas and liquid (light oil/tar): 70% or more of coal input

[6] Yield control of products
- A change in pyrolysis temperature (600-950°C) or type of coal allows product yields to be adjusted accordingly

Figure 1 Process flow diagram
2. Summary of technology

This conversion process is characterized by higher overall thermal efficiency. It is achieved through a compact, low-pressure char/oxygen gasification system that combines the flash pyrolysis of coal and the partial recycling of pyrolyzed char to reuse the sensible heat. The char gasification gas acts as a heat source for the flash heating/pyrolysis reaction of pulverized coal (Figure 1). The entrained-bed coal flash pyrolysis process has been developed to produce high-calorific gas such as coke-oven gas (COG), and liquids (tar and oil). The heat from the char gasifier effects co-production in the pyrolysis reactor. Pulverized and dried coal (of about 50 μm in size) is injected into the pyrolysis reactor and mixed with 600-950°C gas at several atmospheres of pressure. In a reaction lasting two seconds, the coal is rapidly heated and pyrolyzed. Part of the char produced in pyrolysis reactor is recycled to the hot gas generation section (char gasifier) to be partially oxidized by oxygen and steam, thus allowing a gas stream approximately at a temperature of 1500-1600°C, mainly composed of CO and H₂, to be generated so that the sensible heat of the gas can be used at the pyrolysis reaction. The pyrolysis reactor employs an up-flow system where the hot gas generated at char gasifier is fed from the lower part of the reactor. After coal is mixed with hot gas, the product (char and pyrolyzed gas) leaves from upper part of pyrolysis reactor. A portion of the solid product (char) separated at the cyclone is recycled to the char gasifier and the remainder is recovered as a product following heat recovery. Heat is recovered from the gas containing pyrolyzed products until it cools down to approximately 350°C through an indirect heat exchange with thermal oil, while tar passes the venturi scrubber/tar cooler to be recovered. Pyrolysis gas is available for use as industrial-purpose fuel gas after purification, and can be applied in processes such as light oil (BTX) recovery and desulfurization.

At the pilot plant (Photo 1), built within the Yahata Works of Nippon Steel Corp., tests were conducted mainly to evaluate and verify the process components and total system technologies in an effort to establish the technological basis for commercialization. Additionally, data was obtained to aid in the design of an actual plant (1,000 t/d) and to evaluate its economic feasibility. In a period of two years, beginning in 1999, ten total tests were conducted, achieving a maximum of 210 hours of stable, continuous operation. During this period, it was verified that the product yield was able to be controlled by pyrolysis temperatures (Figure 2).

Technology for producing high-calorie gas, char, and liquid components (BTX, etc.) through flash pyrolysis of coal was developed at this pilot facility, which had a processing capacity of 100 t/d of coal. This component technology was later successfully incorporated into ECOPRO (Efficient Co-production with Coal Flash Partial Hydropyrolysis) technology.
A-03-02. Efficient Co-production with Coal Flash Partial Hydropyrolysisisc Technology (ECOPRO®)


FY1996 – FY1999(4 years), FY2003 – FY2008(6 years), FY2010 – FY2011(2 years), FY 2014(1 year)

Technology Overview

1. Technological objective

ECOPRO® is an efficient coal conversion technology that combines coal gasification (partial oxidation) and pyrolysis. Using brown and other under-utilized coals, it aims to supply chemical feedstocks and fuels instead of oil and natural gas.

2. Needs and benefits of the project

It is critical to develop technologies for the efficient use of coal, including under-utilized brown coal and other low-rank coals. The strategic goals supported by this project are to secure and stabilize energy supplies for Japan, and to address global environmental issues. ECOPRO® allows for the efficient use of brown coal and other low-rank coals, and endeavors to supply chemical feedstocks and clean fuel as a substitute for oil and natural gas supplies.

3. Technology Overview

ECOPRO® is comprised of upper and lower reaction zones. Coal and oxygen are blown into the lower reactor, where partial oxidation occurs. Pyrolysis occurs in the upper reactor into which coal is blown without oxygen and is heated by the sensible heat of gas generated by the lower reactor. Ash melting and separation, carbonization, and char gasification take place in the lower reactor while coal pyrolysis takes place in the upper reactor through interaction with a gas stream of approximately 1300°C from the lower reactor. Char is mostly recycled and gasified in the lower reactor. As char residence time in the reactor is relatively short, this system is suitable for gasification of low-rank coal whose char is easy to gasify. As pyrolysis takes place in the upper reactor, the synthesized gas contains a large amount of methane, which reduces heat loss of methanation process. Therefore, ECOPRO® is suitable for a synthetic natural gas (SNG) production process. Using Indonesian sub-bituminous coal, a 20 t/d pilot plant has achieved 85% cold gas efficiency.

4. Progress and development timeline

Following the construction and successful trial of the 20 t/d pilot plant in Japan from 2003-2008, an ECOPRO® technology demonstration feasibility study on using Victorian brown coal in Australia was conducted in 2010-2011. Figure 1 provides an overview of ECOPRO technology and Photo 1 shows the pilot plant. A feasibility study for a potential demonstration project using unusable coal in China began in 2013.

5. Technological issues

(1) Establish gasifier scale-up technology
Based on the results of the pilot reactor (20 t/d coal supply), a demonstration plant (200~500t/d) needs to be constructed. Energy efficiency, various operational performance and reliability should also be verified.

(2) Achieve applicability to various coals
Demonstrated operation should be conducted in coal-producing countries using brown coal and other unusable coals to verify applicability.
Clean Coal Technologies in Japan

A-04-01. Coal Cartridge System (CCS)

Idemitsu Kosan Co., Ltd.

Project Type: METI-subsidized project

Development Period: Since early 1980s

1. System overview

The Coal Cartridge System (CCS) supplies imported coal to medium- to small-lot consumers who use several thousand tons of coal per year, but for whom it is difficult to directly import coal. Through CCS, the imported coal is blended into suitable qualities and supplied to consumers as pulverized coal. This system was subjected, under a 3-year program starting in 1985, to demonstration tests at manufacture/supply and combustion bases in an attempt to establish the reliability of CCS with regards to coal blending and meeting the consumers’ quality requirements. As a result, the first Japanese CCS center, with a capacity to produce 200 thousand tons per year, was built in 1991 and the operation of two CCS based boilers commenced.

2. Features

In a typical pulverized coal-fired system, coal is stored in a stockyard and pulverized in a mill prior to being fed to a boiler. In CCS, however, the additional steps of grinding the blended coal, loading the pulverized coal onto tank lorries, delivery, and unloading into consumers’ coal silos are performed. Following these steps, the coal is then supplied to boilers. In this system, all processes are completed within a sealed environment. This environment-friendly process not only eliminates the problem of the dispersion of coal dust, but also enables smoother operation through easier control of coal flow rate and boiler load change. CCS provides several benefits to consumers. They do not need a mill or a coal yard since the pulverized coal can be stored in a silo. CCS also reduces capital investments because of the compact equipment configuration, provides labor savings, and has a lower environmental impact. Overall, CCS is a pulverized coal utilization system featuring improved coal handling and a sealed-carriage system.

3. Technical data

The properties of CCS coal are shown in Table 1.

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<tr>
<th>Brand</th>
<th>Moisture Wt%</th>
<th>Ash Wt%</th>
<th>Volatiles Wt%</th>
<th>Fixed carbon Wt%</th>
<th>Fuel ratio</th>
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</tr>
</tbody>
</table>

Figure 1 Process flow of CCS coal production/supply facility

4. Process flow

Figure 1 shows a process flow diagram and system overview of a CCS coal production and supply facility.

5. Progress of commercialization

The only CCS operation in Japan is at Idemitsu Kosan’s Aichi Refinery CCS Center. CCS is a coal utilization system where coal is pulverized and delivered to consumers’ silos by lorries (quoted from Idemitsu Kosan’s website).
A-04-02. Brown Coal Hot Water Slurrification Technology

JGC Corporation
CCUJ-subsidized project, NEDO-subsidized project
FY1991 – FY1995 (5 years),
FY2010 – FY2013 (4 years),
(Placed under the authority of JOGMEC beginning in September 2012)
FY2014 – FY2015 (2 years)

Technology Overview

1. Technological objectives
In an effort towards more efficient utilization of and upgrading low-rank coal, technology is being developed to use inherent moisture within the coal itself to create a slurry fluid (JCF®, JGC Coal Fuel). This slurry fluid which is easy to transport and handle than the original coal. JCF® applications include oil and gas substitutes for boiler fuel and coal gasification feedstocks. Deployment of this technology in coal-producing countries will lead to an increase in the domestic and international supply of high-rank coal, oil, and gas fuel. This technology is being developed for market introduction by 2020.

2. Needs and benefits of the project
As energy demands in Asia and other developing countries rise, so does the need to better utilize brown coal as an alternative fuel to costly oil and gas. This technology addresses the drawbacks (e.g. spontaneous combustion, high moisture content) to using brown coal. Because the fuel (JCF) produced by this technology has abundant volatile matter, small particle size, and speedy combustion properties, its anticipated applications include use as boiler fuel, as well as low-speed diesel power generation and gasified fuel.

3. Component technology
The JCF process upgrades low-rank coal (LRC), such as sub-bituminous and brown coal, through hot water treatment (HWT). This process uses high-pressure, high-temperature water to remove oxygen and moisture from LRC and subsequently converts it into a coal-water slurry with a small amount of additives. Brown coal is limited to use near its source mines as it is prone to spontaneous combustion and has high moisture content. By upgrading its properties to the equivalent of sub-bituminous coal through slurrification, it can be made into a transportable fuel. As shown in Figure 2, it is believed that the aromatic compound of LRC changes to a hydrophobic state in the subcritical hot water, and thus dehydration takes place. As the dehydration in hot water negates the latent heat for vaporization, this technology boasts greater heat efficiency than other drying technologies. Figure 3 shows the process flow of the demonstration plant. Figure 4 shows the schematic flow diagram of the JCF process in which the Coal Water Mixture (CWM) technology is applied.

![Figure 1 Conditions for HWT upgrading](image1)
![Figure 2 Schematic diagram of HWT upgrading](image2)
4. Progress and development timeline

- FY2010 – FY2013: JCF production demonstration at 10,000 t/year demonstration plant (Karawang, Indonesia)
- FY2014 – FY2015: Power generation demonstration using JCF produced at the demo plant in place of diesel power generation for isolated island (Karawang, Indonesia)
- 2016 and onwards: Commercialization planned (Figure 5)

5. Technological issues

- Cost-competitive production of brown coal hot water slurry through optimization of various production unit requirements and devices (Figure 6)
- of raw material coal for commercialization, plant scale-up, stable production of fuels compatible with many coal ranks, and stable power generation (improved reliability as fuel).
- Commercialization and broadening application through the expansion of compatible coal ranks, accumulation of storage/transportation data, and sample shipments.
A-04-03. Briquette Production Technology

<table>
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### Technology Overview

#### 1. Background

Global warming, caused by CO₂ and other substances, has become an international concern in recent years. To protect forestry resources, which act as major absorbers of CO₂, controlling ever-increasing deforestation along with mitigating the increase in the consumption of wood fuels, such as firewood and charcoal, is an urgent issue.

To these ends, the development of a substitute fuel for charcoal is necessary. Briquette production technology, a type of clean coal technology, can serve as a global warming countermeasure and help prevent flooding by conserving forestry resources through the provision of a stable supply of briquettes as alternatives to conventional charcoal and firewood.

#### 2. Carbonized briquettes

##### (1) Process overview

The coal briquette carbonization production process consists of a carbonization stage and a forming stage. Figure 1 shows the basic process flow.

In the carbonization stage, an internal-heating, low-temperature fluidized-bed carbonization furnace (approximately 450°C) produces smokeless semi-coke containing approximately 20% volatile matter. The carbonization furnace has a simple structure, with no gas distributor or agitator, making it easy to operate and maintain.

In the forming stage, the smokeless semi-coke and auxiliary raw materials, hydrated lime and clay, are well mixed at a predetermined mixing ratio. After pulverizing, the mixture is blended with a caking additive while water is added to adjust the water content of the mixture. The mixture is kneaded to uniformly distribute the caking additive, and to increase the viscosity in order to make the forming of the briquettes easy. The mixture is then introduced into the molding machine to prepare the briquettes. The briquettes then are dried and cooled.

##### (2) Carbonization stage

The raw coal (10% or lower surface water content, 5-50 mm particle size) is preliminarily dried in a rotary dryer. The gas exhaust from the dryer passes through a multi-cyclone to remove the dust before venting the gas to the atmosphere. Figure 2 shows a cross-sectional view of the internal-heating, low-temperature fluidized-bed carbonization furnace, which is the most efficient process for carbonizing semi-coke and one which retains approximately 20% of the volatile matter in the semi-coke.

The pre-dried raw coal is injected to the middle section of the furnace, and is subjected to fluidization carbonization. The semi-coke is discharged from the top of the furnace together with the carbonization gas. The semi-coke is separated from the carbonization gas by the primary cyclone and the secondary cyclone.

After cooling, the semi-coke is transferred to a stockyard, and the carbonization gas is supplied to the refractory-lined combustion furnace, where the carbonization gas is mixed with air to combust. The generated hot gas is injected into the raw coal dryer and to the briquette dryer to use as the heat source for the preliminary drying of the raw coal and the drying of the formed oval briquettes.

---

Figure 1 Process flow of briquette production

Figure 2 Cross-sectional view of carbonization furnace
Bio-briquettes are a type of solid fuel, prepared by blending coal with 10-25% biomass, such as wood, bagasse (fibrous residue of processed sugar cane stalks), straw, and corn stalks. A desulfurizing agent, Ca(OH)₂, is also added in an amount corresponding to the sulfur content of the coal. Owing to the high-pressure briquetting (1-3 t/cm²), the coal particles and the fibrous biomass material in the bio-briquette strongly intertwine and adhere to each other. As a result, they do not separate from each other during combustion, and the low ignition temperature and low calorific value combust cleanly. As a result, the bio-briquette has superior combustion-sustaining properties, and will not die out in a stove or other heater when the air supply is decreased. This makes adjusting the combustion rate relatively simple.

Since fibrous biomass is intertwined with the coal particles, the agent effectively reacts with the sulfur in the coal to fix about 60-80% of the sulfur into the ash. Many coal ranks can be used for this process including bituminous coal, sub-bituminous coal, and brown coal. In particular, the bio-briquettes produced from low-grade coal containing large amounts of ash and having low calorific value combust cleanly. As a result, the bio-briquette technology is an effective technology to produce clean fuel for household heaters and small industrial boilers.

(1) Bio-briquette production process

Figure 3 shows the basics of the bio-briquette production process. The raw materials, coal and biomass, are pulverized to a size of approximately 3 mm or smaller, and then dried. The dried mixture is further blended with a desulfurizing agent, Ca(OH)₂. The mixture is formed by compression molding in a high-pressure briquetting machine. Powder coal may be utilized without being pulverized. A small amount of binder may be added to some coal ranks.

The production process does not involve high temperatures, and is centered on a dry, high-pressure briquetting machine. The process has a simple flow, which is safe and which does not require skilled operating technique. Owing to the high-pressure briquetting process, the coal particles and the biomass strongly intertwine and adhere to each other, thus the process produces rigid formed coal, which does not separate during combustion.

(2) Bio-briquette characteristics

[1] Bio-briquette combustion decreases the generation of dust and soot to one-fifth to one-tenth that of direct coal combustion. Direct coal combustion exhibits an increased generation of dust and soot because the volatile matter released at low temperatures (200-400°C) does not completely combust. On the contrary, bio-briquettes simultaneously combust the low ignition point biomass, which permeates the coal particles, and improves the combustion of volatile matter from coal at low combustion temperatures. As a result, the amount of generated dust and soot is significantly reduced.

[2] Bio-briquettes prepared by blending biomass with coal have a significantly shorter ignition time. Additionally, due to the low caking property of bio-briquettes, sufficient air flow can be maintained in a stove during continuous combustion. As a result, the bio-briquettes have superior combustion-sustaining properties, and will not die out in a stove or other heater when the air supply is decreased. This makes adjusting the combustion rate relatively simple.

[3] Since fibrous biomass is intertwined with the coal particles, there is no fear of ash adhering and forming clinker-lumps during combustion. Instead, the ash falls in particle form through the grate of stove. Therefore, aeration is maintained to stabilize the combustion state. Furthermore, since no clinker is formed, the ash contains very small amounts of unburned coal.

[4] The bio-briquettes are formed under high compressive force. Because of this, the desulfurizing agent and the coal particles strongly adhere to each other, and they effectively react during combustion. With the addition of a desulfurizing agent at a ratio of approximately 1.2-2 of Ca/S, 60-80% of the sulfur in the coal is fixed in the ash.

3. Bio-briquettes

Figure 3 shows the basics of the bio-briquette production process. The raw materials, coal and biomass, are pulverized to a size of approximately 3 mm or smaller, and then dried. The dried mixture is further blended with a desulfurizing agent, Ca(OH)₂. The mixture is formed by compression molding in a high-pressure briquetting machine. Powder coal may be utilized without being pulverized. A small amount of binder may be added to some coal ranks. The production process does not involve high temperatures, and is centered on a dry, high-pressure briquetting machine. The process has a simple flow, which is safe and which does not require skilled operating technique. Owing to the high-pressure briquetting process, the coal particles and the biomass strongly intertwine and adhere to each other, thus the process produces rigid formed coal, which does not separate during combustion.

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4. Present status

Carbonized briquettes have not been produced in or imported to Japan due to cost-competitiveness and safety concerns (e.g. spontaneous combustion during transportation).

Bio-briquettes were studied in China for environmental measures, but have not been commercialized to date.
A-04-04. Coal Pulverizing Technology

## Technology Overview

### 1. Objectives
To improve plant efficiency and reduce environmental load by reducing the size of pulverized coal.

### 2. Needs and benefits of the project
Reduction of CO₂ and NOx emissions is a critical challenge for coal-fired power plants. More finely pulverized coal will improve plant efficiency and reduce NOx emissions. To meet NOx reduction requirements, combustion improvement possesses significant potential to reduce NOx emissions while consuming less catalysts and ammonia in DeNOx equipment. While low NOx burners and in-furnace NOx reduction technology have been highly effective in reducing NOx emissions, pulverization technologies have also been developed to further reduce emissions.

### 3. Technology and experience
Mitsubishi Hitachi Power Systems, Ltd. has been developing and improving pulverizers that they believe to have an important role in reducing NOx and unburned carbon. The company has two product lines of advanced pulverizers: MV Mill (formerly by Mitsubishi Heavy Industries) and MPS Mill (formerly by Bubcock-Hitachi) shown in Figure 1. Adjusting the rotational speed of the rotary classifier and grinding load can address a wide range of pulverizing demands for various ranks of coal, such as smokeless, high-moisture, and high-ash content coal, as well as petroleum oil coke. Excellent classification efficiency leads to a minimum amount of coarse powder in powdered coal, significantly reducing unburned fuel loss. By lowering the rate of excess air for combustion, it is possible to improve plant efficiency (CO reduction). Furthermore, the grinding load, grinding table rpm, and air rate may be optimized to enable operation at a wider load range (100 – 30%).

The pulverizers also have excellent responsiveness to load change. Many of these pulverizers are installed in Japan and overseas for commercial and industrial thermal power generation. IHI developed ultrafine pulverization technology through optimizing the shape of the mill (shown in Figure 4), and increasing rotary classifier rpm and loading pressure. The company assessed the economy of fine pulverization based on the result of a demonstration unit installed in a power plant. The demonstration study reveals that fine pulverization reduces overall auxiliary power. Although it increases the grinding power, it also reduces fan power because improved combustion lowers oxygen concentration in flue gas. NOx reduction lowers the quantity of ammonia used for NOx reduction. Moreover, as coal usage decreases, boiler efficiency increases. Fine pulverization reduces overall operating cost. The result of this demonstration study led to the installation of the unit at a newly constructed plant.

![Figure 1 Mitsubishi Hitachi Power Systems coal pulverizers](image-url)
Clean Coal Technologies in Japan

4. Recent R&D trend

(1) Optimization of the grinding component and pulverization assessment methodology of less-grindable, high-moisture-content coal

The Central Research Institute of Electric Power Industry examined the relationship among pulverization work index*, Hardgrove Grindability Index (HGI), and surface moisture. As the study showed that the surface moisture of coal had a significant impact on grinding power, the Institute developed a pulverization work index calculation method that takes surface moisture into account.

The objective was to promote the utilization of hard-to-grind coal and expand the coal ranks that may be used within the system. This method helps to evaluate the optimal pulverized particle diameter in relation to the characteristics of coal.

Pulverization work index increases as HGI decreases. The greater the weight of surface moisture to the weight of dry coal (surface moisture content), the more slippery the roller becomes. This slipperiness lowers grinding efficiency, which in turn increases the pulverization work index.

IHI achieved ultrafine pulverization through optimizing mill shape and increasing rotary classifier rpm and loading pressure. A combustion study was conducted using conventional pulverized coal (average particle size of about 40 µm) and superfine pulverized coal (about 20 µm) (fuel ratio 2.25) in a 12 MWt capacity test furnace. Compared to conventional pulverized coal, superfine pulverized coal can reduce NOx emissions from combustion by 20% as it reduces exhaust gas oxygen concentration.

Figure 2 Relation between rotary classifier and pulverization in MV Mill

Figure 3 MPS Mill particle size distribution
Pulverized coal product contains few crude particles above mesh size of 100.

Figure 4 IHI Mill for ultrafine pulverized coal
IHI achieved ultrafine pulverization through optimizing mill shape and increasing rotary classifier rpm and loading pressure.

Figure 5 Effect of superfine pulverization on NOx and unburned carbon in ash

A combustion study was conducted using conventional pulverized coal (average particle size of about 40 µm) and superfine pulverized coal (about 20 µm) (fuel ratio 2.25) in a 12 MWt capacity test furnace. Compared to conventional pulverized coal, superfine pulverized coal can reduce NOx emissions from combustion by 20% as it reduces exhaust gas oxygen concentration.

Figure 6 Effect of coal HGI and water content on roller mill grindability
Pulverization work index increases as HGI decreases. The greater the weight of surface moisture to the weight of dry coal (surface moisture content), the more slippery the roller becomes. This slipperiness lowers grinding efficiency, which in turn increases the pulverization work index.
A05-01. Production of Caking Additives for Coke Production from Low-Rank Coal (Hyper-coal)

Kobe Steel, Ltd.; and National Institute of Advanced Industrial Science and Technology
NEDO-commissioned project
FY1999 – FY2001 (3 years), FY2002 – FY2007 (6 years)

Technology Overview

1. Objectives
The objective is to establish technology that produces effective and economic caking additives for coke production in response to the anticipated mid- to long-term shortage of heavy coking coal and its price rise.

2. Needs and benefits of the project
The price of coking coal for steel making fluctuates significantly with supply and demand. Coking coal prices stayed relatively low in 2014, but in the medium to long term, it is expected to rise steeply. As a means to address these price fluctuations, it is necessary to have technology to produce caking additives for coke’s production from steam coal or even lower-ranked brown coal. Ideally, coke of equal or better quality to that which is currently available, can be produced by using less expensive low-rank coal and a caking additive in the raw material blend during production. Use of such a caking additive would make it possible to use more types of coal for steel-making cokes. Moreover, by utilizing higher-strength cokes, coke use in furnaces may be reduced, and CO emissions from steel making may also be mitigated. Additionally, cost reduction may be achieved by replacing strongly caking coal (expensive) with slightly caking coal (inexpensive) and steam coal. The market size is projected to be 2 million tons/year assuming that 5% of the 40 million tons/year of coking coal used for steel production will be replaced with upgraded coal made using caking additives.

3. Component technology
This process utilizes de-ashing technology, which was developed as part of Japan’s brown coal liquefaction (BCL) technology. Also, the experience and expertise gained at coal liquefaction pilot plants is applied. As shown in Figure 1, coking coal is extracted in a heated solvent, then the insoluble content and ash are moved through gravity settling, and then the solvent is recovered. The process significantly reduces ash content and produces a caking additive (hyper-coal) that has excellent fluidity and caking properties.

Production method: Solvent with a high affinity to coal is used to extract coal unnecessary ash content is removed

Figure 1 Hyper-coal schematic chart
(Source: NEDO, “Hyper-coal-based High-efficiency Combustion Technology”)
4. Progress and development timeline

Beginning around 2016, a demonstration study is planned for commercialization of the technology to produce caking additives for coke production as shown in Table 1. The ultimate goal is to be operable on a semi-commercial scale by approximately 2020. Other technologies have been developed to utilize hyper-coal technology. For instance, an innovative binder was developed through a 2009-2012 METI subsidized project: “Development of Innovative Steel Making Process” (Ferro Coke). A high-performance caking additive is currently being developed under an ongoing METI-NEDO-commissioned project entitled “Course 50.”

<table>
<thead>
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<td>Caking additive production technology (economic evaluation, preliminary process/plant design)</td>
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<td>Caking additive production technology (Detailed plant design, plant construction/operation, production of caking additives)</td>
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<td>Technology for coke production using caking additives (basic study)</td>
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<td>Technology for coke production using caking additives (test by actual coke oven)</td>
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<tr>
<td>Byproduct coal utilization technology (combustion study)</td>
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<tr>
<td>Determination of commercialization feasibility</td>
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</table>

5. Technological challenges

Issues remaining in hyper-coal production technology include the establishment of optimal extraction conditions to coal rank and application, and the establishment of scale-up technology for a commercial unit. A demonstration is needed on an actual reactor for coke property improvement by blending hyper-coal into coke materials. Additionally, achieving a high yield from low-rank coal through bench and demonstration plants in the hyper-coal process is required.

When low-rank coal is used as raw material, a plant is often constructed near (or adjacent to) a coalmine or a nearby coke oven. As such, it is all the more important to maintain a favorable relationship with coal-producing countries through comprehensive dialogue covering technical and institutional aspects.
### A-05-02. Low-rank Coal Upgrading Technology (UBC Process)

**Japan Coal Energy Center; Kobe Steel, Ltd.**

**Project Type**
METI-subsidized project

**Development Period**
FY2001 – FY2002 (2 years), FY2006 – FY2010 (5 years)

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#### Technology Overview

#### 1. Objectives

The objective is to introduce this technology to coal-producing nations in order to enable production of economic fuel, low in ash and sulfur content, for import to Japan.

Also, by introducing upgraded low-rank coal for power generation near its production source, the project aims to lower coal-producing countries’ demands for imported steam coal, further contributing to stable availability of coal for importation to Japan.

#### 2. Needs and benefits of the project

Low-rank coal accounts for one half of global coal reserves. Low-rank coal use through the application of upgrading technology is critical for effective utilization of energy resources, and to ensure a more stable coal supply for Japan. The use of low-rank coal is currently limited due to its high moisture content, low calorific value, and spontaneous combustibility. Upgrading technologies to overcome these drawbacks are quite beneficial.

Indonesia plays an important role as a coal supplier to Japan. Most Indonesian coals are low-rank, but they are also low in ash and sulfur content, which are characteristics that are beneficial for the environment. Introduction of this technology contributes to a more stable coal supply to Japan, reduction of disposed ash, as well as CO₂ emission reduction due to improved combustion efficiency.

#### 3. Component technology

Low-rank coal is dewatered as it is pulverized, mixed with circulating oil (normally light petroleum oil) into slurry, and then heated. With the addition of a small amount of heavy oil (such as asphalt), the oil adheres to the surface and pores of low-rank coal. This prevents spontaneous combustion and the re-absorption of moisture. Coal upgraded in this manner has a calorific value equivalent to that of bituminous coal and is very stable.

This technology can even upgrade low-rank coal of approximately 60% water content into stable coal as shown in Figure 1. It is a much more economic technology as its process takes place at a lower temperature and under lower pressure than other steam or non-steam processes. Energy consumption is minimized by the use of the latent heat of separated moisture (vapor), and moderate processing conditions without chemical reaction that makes the wastewater treatment easy. As shown in Figure 3, the resulting upgraded coal has excellent combustibility and significantly less unburned carbon than bituminous coal.

---

![Figure 1 Outline of low-rank coal upgrading](Image)

(Source: JCOAL Operation Report, December 2010.)

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**Part 2 CCT Overview**

**A. Multi-purpose Coal Utilization Technologies**
4. Progress and development timeline

A large-scale demonstration project was run until 2010, producing approximately 50,000 tons of upgraded brown coal over 4,000+ hours of operation. The project established the technology as being ready for commercialization by ensuring stable operation, providing scale-up technology, and assessing combustibility and ease of handling of the upgraded coal through combustion tests in a full-scale boiler.

Since 2011, efforts have been made to spread this technology through construction and operation of commercial plants. Both upgraded briquettes for export and powder for local power generation are anticipated types of products for commercialization.

5. Technological Issues

While some milestones have been reached in plant cost reduction, remaining challenges include further cost reduction and operation of commercial plants in coal-producing countries.
A-05-03. Efficient Brown Coal Drying Technology

<table>
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<tr>
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<tr>
<td>Development Periods</td>
<td>FY2010 – FY2012 (3 years)</td>
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Technology Overview

1. Objectives
The objective is to develop a system to be installed in a pulverized coal-fired power plant or upstream of IGCC, which efficiently dewater low-rank coal with high moisture content, significantly increasing power generation efficiency and reducing CO₂ emissions.

2. Needs and benefits of the project
Low-rank coal, such as sub-bituminous and brown coal, accounts for one half or more of worldwide coal reserves. Due to its high water content, low-rank coal has poor combustion efficiency when used in a boiler (shown in Figure 1). Once it is dried, low-rank coal is prone to spontaneous combustion, which complicates transportation. At the brown coal-fired power plants of today, the coal is simultaneously pulverized and dried by a mill and then fed to a boiler. As water within the brown coal turns to vapor in the furnace and is discharged out of the system as exhaust gas, the latent heat of evaporation is lost, which leads to a lower power generation efficiency. Efficient dewatering of brown coal is one of the major factors that determine the usability of brown coal.

At conventional pulverized brown coal-fired power plants, power generation efficiency may be significantly improved by installing an efficient brown coal dryer system, developed for commercialization through this project, in the upstream side of a boiler. At an integrated coal gasification combined cycle (IGCC) power plant, the use of this technology would enable the use of a state-of-the-art gas turbine. When using bituminous coal, power generation efficiency is expected to rise to approximately 46-48% (HHV base). When an efficient drier system is used for brown coal-fired IGCC, coal consumption and CO₂ emissions may be significantly reduced. For example, at an existing 500 MW brown coal-fired power plant, CO₂ emission is estimated to be about 1,050 kg-CO₂/MWh-Gross at the present power generation efficiency. When brown coal-fired IGCC is able to reach the efficiency of 43%, CO₂ emissions decrease to 730 kg-CO₂/MWh-Gross, achieving an approximate 30% emissions reduction.

---

**Loy Yang Power Plant Flowchart**


**Figure 1 Loss due to moisture at a pulverized brown coal-fired power plant**

3. Component technology

To resolve the above-mentioned issue, an efficient brown coal drying system is being developed. This system will be equipped with a steam fluidized-bed drying system (shown in Figure 2) that uses steam as a fluidizing medium.

Some of this steam is recompressed by a latent heat recovery system to raise the saturated vapor temperature and is used as the heating source in the dryer (steam fluidized-bed plug flow drying technology, self-heat recuperation latent heat recovery technology).

![Figure 2 Efficient brown coal drying system](image)

4. Progress and development timeline

Development is underway for scale-up and efficiency improvement with the following specific goals:

- **[1]** Scale-up (drying capacity): 120 t/h. when used in 500 MW-class gasifier (480 t/h comprised of 4 systems)
- **[2]** Increased efficiency – latent heat recovery rate: 50% or greater: recovering 50% or more of the latent heat of steam generated from brown coal

A market launch in the 2020s is aimed for. In 2010, MHI completed the design, manufacture and construction of a process development unit (PDU) and conducted tests in 2011-2012.

In 2012, MHI conducted a demonstration test feasibility study and conducted a basic design for a 200 t/d demonstration unit.

Remaining issues for the technology’s deployment include funding for the demonstration test as the next step, and ultimately securing a local business partner for construction and operation of a mine-mouth project.

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<tr>
<td>Demonstration test FS</td>
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5. Technological Issues

In developing this brown coal-drying technology, the issues below need to be resolved. After three years of development, this technology looks promising, although it needs to be verified in future demonstration testing.

- **[1]** Ensure safety against spontaneous combustion throughout the facility
- **[2]** Determine an optimal particle size (for crushing, handling, drying, and powdering prevention)
- **[3]** Reduce operating cost by selecting an optimal system including latent heat recovery
- **[4]** Establish scale-up technology to a large-capacity commercial unit
A. Multi-purpose Coal Utilization Technologies

Part 2 CCT Overview

A-05-04. Brown Coal Advanced Utilization Technology

Mitsubishi Heavy Industries, Ltd. (MHI)
METI-subsidized project
FY2010 – FY2012(3 years)

Technology Overview

1. Objectives
The objective is to develop technology to upgrade Australian brown coal by improving its calorific value and stabilizing its quality on site so that it can be exported to Japan as fuel for power generation at existing power plants.

2. Needs and benefits of the project
Coal is an important fuel for base load power sources with a stable supply and superior value due to the abundance of its reserves. As coal demand in China, India and other emerging countries drastically increases, competition to acquire these resources will intensify worldwide. High-rank coal such as bituminous coal is the fuel of choice for thermal power plants today, and its ratio of reserve to production is quickly shrinking. This raises concerns for the ongoing balance of supply and demand as well as the price stability of coal. It is critical to utilize low-rank coal since it accounts for a half or more of worldwide coal reserves. This is especially important from a viewpoint of stability and the long-term use of coal in Japan. However, brown coal that accounts for about 40% of low-rank coal reserves has high inherent water content, is low in calorific value, and is prone to spontaneous combustion. These properties make it difficult to store or to transport it over long distances. Therefore, technology needs to be developed to help utilize brown coal efficiently.

About a quarter of worldwide brown coal reserves are located in Victoria, a state in southeast Australia. Due to the abundance of these reserves and its low ash content, Victorian brown coal may guarantee a long-term, stable source of fuel for coal-fired power plants while reducing the amount of ash disposed as waste.

3. Overview of technological development
Moisture content must be reduced, and calorific value and transportation efficiency must be improved to enable the use of Australian brown coal in Japanese power plants. Moreover, risks of spontaneous combustion must be mitigated to ensure safety. For these purposes, research is underway for upgrading processes and respective component technologies as shown in Figure 1.

In this particular process, a dryer reduces the moisture content to an appropriate level, and a subsequent carbonization step increases the calorific value of the dried brown coal. The coal is then molded into a certain size to improve safety and efficiency during transportation and storage.

Figure 1 Upgrading process
Clean Coal Technologies in Japan

4. Status of technological development

In 2009, Kyushu Electric Power Company (KEPCO) signed a letter of intent (LOI) with the state government of Victoria, Australia to collaborate on the strategic research and development of brown coal utilization technology, establishing a research partnership framework between Japan and Australia. KEPCO also initiated the basic research on brown coal upgrading technology, including brown coal drying technology, in a joint research project (laboratory test) with Kyushu University. Subsequently, KEPCO conducted a pilot study in collaboration with other coal users. Research efforts are underway to establish the deployment of brown coal upgrading technology.

• Assessment of upgraded coal in laboratory test

In the joint research with Kyushu University, Australian brown coal was dried and carbonized, and the resulting upgraded coal was found to have properties equivalent to those of bituminous coal as shown in Table 1.

<table>
<thead>
<tr>
<th>Moisture (%)</th>
<th>Australian brown coal</th>
<th>Upgraded coal</th>
<th>Bituminous coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>55.9</td>
<td>6.4</td>
<td>2.7</td>
<td></td>
</tr>
<tr>
<td>Gas content (%)</td>
<td>24.0</td>
<td>26.3</td>
<td>27.3</td>
</tr>
<tr>
<td>Carbon content (%)</td>
<td>19.5</td>
<td>64.8</td>
<td>55.3</td>
</tr>
<tr>
<td>Ash content (%)</td>
<td>0.6</td>
<td>2.5</td>
<td>14.7</td>
</tr>
<tr>
<td>Combustion ratio</td>
<td>0.8</td>
<td>2.5</td>
<td>2.0</td>
</tr>
</tbody>
</table>

• Pilot study results and issues

Aiming for the practical application of upgrading technology verified in this laboratory test, a pilot study was conducted in 2013 to verify component technologies. A certain level of development feasibility was confirmed with application technologies to realize the upgrading. The pilot study also identified technical issues to be resolved in the areas of molding, safety, and combustibility of upgraded coal.

5. Future plan

The next technological development phase is a demonstration study, followed by commercialization. To reach that stage, some issues must be identified and addressed, such as transportation infrastructure to move upgraded coal from Australia.

Before this stage, successful upgrading technology must first be established. Therefore the priority is placed on resolving technical issues mentioned above.

![Figure 2 Development timeline]
A-05-05. Brown Coal Upgrading Technology

**Research and Development**
Ube Industries, Ltd., Marubeni Corp.

**Project Type**
Voluntary project

**Development Period**
Under development since FY2012

## Technology Overview

### 1. Objectives

The objective of this project is to upgrade brown coal near coal mines in Indonesia and other coal-producing countries, and to supply upgraded coal with properties equivalent to those of sub-bituminous coal, with regards to handling and price, to Japan and other Asian customers.

### 2. Needs and benefits of the project

Emerging countries are trying to secure low-rank coal mining rights in Indonesia and other coal-producing countries. Developing low-rank coal upgrading technology early will be a road for Japan to acquire resource interests and help secure stable sources of coal supply. More effective use of underutilized brown coal in Indonesia and other areas will prolong the lifespan of bituminous coal, which is being depleted. The realization of this integral technology is urgent and imperative to the sustainability of Japan’s coal supply.

Use of sub-bituminous coal is recognized and established in the market in terms of quantity and price (more than 10 million ton is imported and used in Japan every year). Supplying upgraded coal equivalent to sub-bituminous coal at competitive prices would meet the potential needs of customers and brown coal suppliers. By combining it with the acquisition of interest in low-rank coal, the technology will further contribute to Japan’s energy security.

### 3. Component technology

The upgrading process is comprised of crushing, drying, pulverizing, and molding steps. As this process is entirely comprised of established technologies and uses conventional equipment, the capital cost can be minimized. The R&D is focused on the ease of handling the product at the levels of existing sub-bituminous coal. In order to achieve this, the size and surface area of raw material particles, moisture content, as well as density and strength of the briquettes were optimized to reduce powering and self-heating characteristics (Figure 1). As moisture is limited to the level of sub-bituminous coal (18-25%), heat loss caused by reabsorption of water is also minimized. Table 1 shows typical properties of upgraded coal. For this process, the steps of crushing, drying, and pulverizing can be shared with an existing pulverized-coal boiler. Applying this technology to existing mine-mouth power generation provides a deliverable in the form of electricity to the local area, while high-quality coal would be available for export to other external consumers.
4. Progress and development timeline

The principle of this technology was confirmed, and scale-up data on upgrading conditions and the demonstration facility were obtained through bench-scale testing and a pilot study. The project aims for commercialization by approximately 2020, coinciding with an anticipated shortage of Indonesian sub-bituminous coal supply. The ultimate aim is to produce 1 million tons/year of upgraded coal, which will be supplied to consumers in Japan and other Asian countries at competitive prices.

5. Technological issues

The following issues need to be resolved through long-term demonstrative operation at a demonstration facility:

- Demonstration of operation using existing coal chains (transport, handling, and combustion)
- Technological transfer to Indonesia and other coal-producing countries for implementation

Table 1 Representative properties of upgraded goal

<table>
<thead>
<tr>
<th></th>
<th>Indonesian brown coal</th>
<th>Upgraded</th>
<th>(vs.) Indonesian sub-bituminous coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total moisture (% arb)</td>
<td>48.0</td>
<td>22.0</td>
<td>26.9</td>
</tr>
<tr>
<td>Air-dried moisture (% arb)</td>
<td>15.0</td>
<td>15.0</td>
<td>16.4</td>
</tr>
<tr>
<td>Ash (% arb)</td>
<td>3.7</td>
<td>3.7</td>
<td>2.3</td>
</tr>
<tr>
<td>Volatile content (% arb)</td>
<td>41.8</td>
<td>41.8</td>
<td>42.1</td>
</tr>
<tr>
<td>Fixed carbon (% arb)</td>
<td>39.5</td>
<td>39.5</td>
<td>39.2</td>
</tr>
<tr>
<td>Total sulfur (% db)</td>
<td>0.19</td>
<td>0.19</td>
<td>0.14</td>
</tr>
<tr>
<td>GAR calorific value (kcal/kg)</td>
<td>3300</td>
<td>4950</td>
<td>4990</td>
</tr>
</tbody>
</table>

Figure 2 Principle of upgrading
A-06-01. Coal and Woody Biomass Co-firing Technology

Babcock-Hitachi K.K.
NEDO-joint project
FY2010-FY2013 (4 years)

### Technology Overview

#### 1. Objectives
When the biomass co-firing ratio is increased on an existing coal-fired power plant, a special mill (pulverizer) must be added for biomass use. This results in issues such as an auxiliary power requirement increase and an expanded physical footprint. In order to address these issues, a system is being developed to provide a low-cost method for construction to modify facilities, and a high biomass co-firing ratio combustion method. As a means to achieve this, some but not all coal mills are repurposed as dedicated biomass mills. Essentially, a system is built to incorporate an additional dedicated biomass pulverization function.

#### 2. Needs and benefits of the project
Woody biomass is renewable energy and is considered carbon neutral. Woody biomass is more extensively available than fossil fuels, and even Japan has biomass reserves. Therefore, an expansion of biomass utilization is anticipated. One way to use biomass is to co-fire woody biomass with coal in power production applications.

In order to increase the biomass to coal ratio, a dedicated mill (pulverizer) needs to be added and which necessitates auxiliary power and securing installation space. Efforts are being made to develop a combustion system using existing mills as a means to decrease costs associated with constructing and modifying facilities and to ensure a high biomass to coal co-firing ratio.

#### 3. Component technology

1. **Biomass pulverizing mill**
   By converting existing coal mills, elemental test evaluations were conducted on multiple types of biomasses including grass and woody materials. Proposals were made for the appropriate structure to achieve the target co-firing ratio, and both safety (explosion-proofing) and corrosiveness were evaluated.

2. **Dedicated biomass burners**
   Combustion performance was evaluated for switchgrass using a single burner pilot plant for the combustion of biomass at the pilot scale.

3. **Biomass co-firing system**
   A large-scale combustion facility was used in tests to demonstrate that there are no combustion problems in the boiler operation.

4. **Projection of actual boiler performance and feasibility study of the system**
   When compared with the combustion of coal, the increase in gas temperature and gas flow rate are a few degrees C and a few percentage points respectively. This performance was within a range where it would not cause problems in a commercial plant.

#### 4. Progress and development timeline
A development roadmap is outlined in Table 1. In 2010, this technology was launched as the NEDO project, Development of strategic next-generation biomass energy technologies, and developed as NEDO joint study.
Clean Coal Technologies in Japan

5. Main outcomes

Table 2 shows study results of the target biomass co-firing ratio of 25 cal%. The system shown in Figure 1 was used in the test. The pulverization and combustion characteristics were obtained, and it is confirmed that a biomass co-firing ratio of 25 cal% will be achievable at an existing coal-firing power plant.

Table 2 Study results of biomass co-firing ratio

<table>
<thead>
<tr>
<th>Case</th>
<th>Dedicated pulverization mill</th>
<th>Feedstock type</th>
<th>Mixed pulverization mill</th>
<th>Feedstock type</th>
<th>Feasibility</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td></td>
<td></td>
<td>20</td>
<td>Chip (forestall residue)</td>
<td>No (mixed pulverization load too large)</td>
<td>Initially planned case 5 cal%/boiler for mixed pulverization is equivalent to 6.25 cal%/mill.</td>
</tr>
<tr>
<td>B</td>
<td></td>
<td></td>
<td>20</td>
<td>Pellet (switchgrass)</td>
<td>Yes</td>
<td>Case A alternate</td>
</tr>
<tr>
<td>C</td>
<td></td>
<td></td>
<td>22.68</td>
<td>Chip (forestall residue scraps)</td>
<td>Yes (dedicated pulverization load restrained)</td>
<td>Heat input for dedicated pulverization was greater than planned. 2.32 cal%/boiler for mixed pulverization is equivalent to 3 cal%/mill.</td>
</tr>
<tr>
<td>D</td>
<td></td>
<td></td>
<td>25</td>
<td>0</td>
<td>Yes (dedicated pulverization load restrained)</td>
<td>Heat input for dedicated pulverization was greater than planned.</td>
</tr>
<tr>
<td>E</td>
<td></td>
<td></td>
<td>20</td>
<td>Chip (forestall residue scraps)</td>
<td>No (mixed pulverization load too large)</td>
<td>Initially planned case 5 cal%/boiler for mixed pulverization is equivalent to 6.25 cal%/mill.</td>
</tr>
<tr>
<td>F</td>
<td></td>
<td></td>
<td>20</td>
<td>Pellet (wood [pine])</td>
<td>Yes</td>
<td>Case E alternate</td>
</tr>
<tr>
<td>G</td>
<td></td>
<td></td>
<td>20.68</td>
<td>Chip (forestall residue)</td>
<td>Yes (dedicated pulverization load restrained)</td>
<td>Heat input for dedicated pulverization was greater than planned. 5 cal%/boiler for mixed pulverization is equivalent to 6.25 cal%/mill.</td>
</tr>
<tr>
<td>H</td>
<td></td>
<td></td>
<td>25</td>
<td>0</td>
<td>Yes (dedicated pulverization load restrained)</td>
<td>Heat input for dedicated pulverization was greater than planned.</td>
</tr>
</tbody>
</table>

(Source: Babcock-Hitachi K.K.)
A-06-02. Efficient Combustion and Coal Co-firing Support System

Idemitsu Kosan Co., Ltd.  
Voluntary project  
Since 1980s

1. Objectives
The objective of the project is to support efficient and trouble-free operation of pulverized-coal boilers by identifying conditions for optimal operation and coal blend. The coal assessment system (shown in Figure 1) is a computer software program to support the use of more coal types by projecting plant performance quantitatively when utilizing new coal or a new blended coal. This combustion simulation diagnoses a boiler’s combustion state and determines its optimal operating conditions to achieve less-unburned carbon and lower NOx emissions. It also addresses issues caused by ash deposition.

2. Needs and benefits of the project
Many types of coal are used in Japan, but more sub-bituminous coal (with different characteristics from conventional coal) has been used in recent years. When using a different rank of coal from designed coal in a boiler, it is critical to examine the combustion efficiency, potential problems, and changes to environmental performance resulting from the new coal use. Also, decisions must be made on whether or not a new coal type is applicable to that boiler or what coal blend ratio is optimal. Idemitsu developed a software named “Coal Assessment System” which instantly evaluates various parameters including handling, combustibility and environmental compatibility. The combustion simulation shown in Figure 3 minutely analyzes combustion states in the boiler, and provides solutions to increase boiler efficiency such as reducing unburned carbon, improving environmental compatibility (reducing NOx) and preventing troubles (i.e. ash deposition). By changing the airflow rate and direction for each burner layer, unburned carbon and NOx emissions can be reduced and troubles of slagging can be resolved as shown in Figure 4.

Figure 1 Coal Assessment System overview
At coal-firing power plants, performance needs to be evaluated from many perspectives including self-heating, handling, grinderbility, combustibility, slagging, NOx generation, and electric precipitation among others. New coal is assessed and an optimal blend ratio is suggested from the analysis of the relationship between coal properties and practical characteristics. In addition to this, the experimental findings and actual plant data are fully utilized to evaluate the coal and its optimal blend ratio.

### 3. Component technology

**[Coal Assessment System]**

At coal-firing power plants, performance needs to be evaluated from many perspectives including self-heating, handling, grinderbility, combustibility, slagging, NOx generation, and electric precipitation among others. New coal is assessed and an optimal blend ratio is suggested from the analysis of the relationship between coal properties and practical characteristics. In addition to this, the experimental findings and actual plant data are fully utilized to evaluate the coal and its optimal blend ratio.

**[Combustion Simulation]**

Commercially available CFD (Computational Fluid Dynamics) software (FLUENT) was incorporated with an original pulverized-coal combustion model to establish combustion simulation technology that accurately simulates combustion behaviors in actual boilers.

### 4. Progress and development timeline

The development is complete and the product has been launched in the market.
A-10-01. Modeling and Simulation Technologies for Coal Gasification

The consumption of fossil fuels impacts the environment in a variety of ways. There is also an impact on the environment during coal production, transportation, and utilization processes. During utilization, in particular, coal dust, ash dust, acid gases (NOx, SOx), and carbon dioxide are discharged. This raises concerns of what impact the unregulated consumption of coal may ultimately have on the environment. However, technologies to minimize the harmful impact of coal utilization on the environment, collectively called clean coal technology (CCT), are in widespread use in developed countries, including Japan.

The "Basic Research Associate for Innovated Coal Utilization" (BRAIN-C) program is focused on coal gasification technology, and basic coal data from a variety of perspectives has been collected and compiled to ensure its speedy commercialization. Numerical simulation is a very effective tool to predict the characteristics of a pilot or actual production unit and the above-mentioned data is critical to these simulations.

In addition to simulations, it can also prove useful select relevant basic data for evaluation. With this taken into consideration, technology development under BRAIN-C has proceeded in an effort to establish both a useful basic database as well as highly-accurate numerical simulation module.

Figure 1 shows the "BRAIN-C technology map." Results from this project are mainly composed by the following three categories:
(1) An entrained-bed gasification simulator
(2) A predicted model and parameter correlative equations for reaction, heat transfer, fluid dynamics, ash behavior etc.
(3) A coal database

(1) to (3) above are illustrated below. All three results from this project are indispensable for use in both R&D efforts and technology applications. The appropriate utilization of each aspect of the BRAIN-C application allows for full optimization.
2. Entrained-bed gasification simulator

The entrained-bed gasification simulator is based on software for thermal fluid analysis, or computational fluid dynamics (CFD), and is capable of simultaneously analyzing flow, reaction, and heat transfer. It can calculate temperature distribution, ash adhesion locations, gas composition, etc. under the various input data variables such as reactor shapes, operating conditions, coal properties and reaction data (Figure 2).

Highly reliable prediction results can be used for evaluating operating condition validity, reactor design, and other information in advance. In the BRAIN-C program, the coal gasification reaction model shown in Figure 3 is built using CFD combining with the original ash adhesion model shown in Figure 4. Simulation results are then compared with gasifier operating data in coal-based hydrogen production technology (HYCOL or EAGLE) to examine the validity.

![Figure 2 Functions of entrained-bed gasification simulator](image)

![Figure 3 Coal gasification process modeling](image)

![Figure 4 Ash viscosity-based adhesion prediction model](image)
Figure 5 shows an example of the comparative results between observed and simulated data for melting ash (slag) layer position. This shows that the slag layer position predicted by the simulator corresponded well to the observed position, confirming the accuracy of the simulation relative to the actual data.

Figure 6 shows the result of case studies on HYCOL using a gasification simulation. The near-wall temperature and ash viscosity on the wall shown on the left side of Figure 6 are those reproduced by simulation after 1,000 hours of operation. The temperature is high in the bottom area of the furnace, where the slag flows (shown in red in the upper image), and the viscosity is low (shown in blue in the lower image). The temperature of the upper part of the furnace is low (shown in green in the upper image), providing conditions where it is hard for particles to adhere. On the right side of Figure 6, the near-wall temperature and ash viscosity on the wall shown are the result of simulation under intentionally changed operating conditions. For this simulation, the oxygen ratio at the upper level is higher and the oxygen ratio at the bottom level is lower than is shown on the left image. In such cases, it was found that the temperature at the bottom of the furnace decreases (shown in orange) and the low-ash-viscosity region (shown in blue) narrows while the upper part of the furnace becomes hot (the region in red increases) to form a region where it is easier for ash to adhere. This scenario would be categorized as less desirable operating conditions.

By using the gasification simulator in this manner, analysis can be easily made even if gasification conditions are altered. This has resulted in growing expectations for use of the simulator in the next gasification projects.

### 3. Predicted model/parameter correlative equation

The entrained-bed gasification simulator can be applied to various furnace designs and operating conditions, but it is not applicable to all types of coal. It is, therefore, necessary to input coal characteristics into the simulator using coal-type as a parameter. This parameter generally uses the data obtained from basic test equipment. However, this method requires much time and evaluation work. It is desirable to establish a quick means to obtain the parameters. The data could be obtained from a general the analysis of coal or from structural composition data (an advanced model incorporating correlative equations for estimations and experimental conditions). More specifically, a generalized volatilization model and the adhesion determination equation are among the tools used to prepare parameters.

Additionally, a trace elements distribution model and an adhesion determination equation model offer determinations from simulation results and also play an important role. Under the BRAIN-C system, therefore, prediction equations around a gasification simulator have also been developed so that the simulator can be used effectively and quickly.
4. Coal database

When constructing correlation formulas and models, basic experimental data and coal analysis data are both necessary. One major problem with obtaining this data is the fact that characteristics can differ by coal lot or sample, even if the coal brand (coal deposit) is the same. In order to create a highly accurate simulation model, each of the testing laboratories conducting research shown in Figure 1 needed the same coal samples. Figure 7 is a coal sample bank established by the National Institute of Advanced Industrial Science and Technology. By managing test samples in this way, research and development institutions receive standardized samples.

A part of the experimental data utilizing such samples has been uploaded to a server at the Japan Coal Energy Center-JCOAL, as shown in Figure 8. In addition, most of this data is managed in the form of downloadable Excel files (see Figure 9), making it easy to use it in further computations and processing.

5. Dissemination of advances in basic coal utilization technologies

By utilizing basic data and various models, the entrained-bed gasification simulator developed with the BRAIN-C program has made it possible to make predictions that can be applied in practical uses. The BRAIN-C program was completed in 2004, and a system has been put in place to make the program and basic data available so that users can take advantage of the advances developed through this project. A detailed user's manual has been prepared and training seminars have also been conducted.

The system makes it easy to analyze scenarios such as when the gasification conditions have changed, and it has been used in subsequent gasification projects. From 2007 to 2013, the Coal Bank Project was newly implemented as a follow-up to the Zero Emissions Coal Firing Technologies Development Project. It includes:

- a) Development of Technologies for Reducing the Influence of Trace Elements in Coal Utilization Processes
- b) Data Collection Towards the Standardization of High-Precision Analytic Techniques for Trace Elements
- c) Elucidation of Trace Element Behavior in the Combustion Plant.

Although this program was developed focusing on coal gasification technologies, it will be expected to use in other coal utilization processes, because the simulation code itself describes the coal reaction/flow phenomenon by generalized mathematical formulas.
Integrated Gasification Combined Cycle (IGCC)

Integrated gasification combined cycle (IGCC) is a high-efficiency power generation technology that employs coal gas as a fuel for gas turbine. Electric power companies in Japan have undertaken research and development on IGCC technologies at a Nakoso pilot plant (PP) gasifier.\(^1,2,3\) As shown in Figure 1, this gasifier employs a dry-coal feed, oxygen-enriched, air-blown, pressurized two-staged entrained bed. This technology is expected to achieve higher efficiency than current technologies available internationally.

IGCC demonstration tests have been initiated with the aim of demonstrating the reliability, operability, maintainability, and economics of IGCC. IGCC has many advantages over conventional pulverized coal firing, including the following:

1. Improved power generation efficiency: Compared with existing pulverized coal firing system, IGCC may result in a 20% increase in power generation efficiency in commercial operations.
2. Improved environmental performance: Owing to its superior power generation efficiency, IGCC can reduce SOx, NOx, and dust emissions per unit of electric power generated. In addition, CO\(_2\) emissions are equivalent for those at heavy oil-fired power plants.
3. Expansion of usable coal grades: Because IGCC systems can also use coal with low ash melting points (something which existing pulverized coal-fired facilities struggle with), IGCC can broaden the grades of coal employed in coal-fired power generation facilities.
4. Expansion in the effective utilization of ash: Because the coal ash is discharged in the form of a glassy slag, it can serve as a material for civil engineering work.
5. Reduction in water consumption: Because the generated gas is desulfurized directly, it does not require flue gas desulfurization equipment, which consumes large volumes of water. Compared to existing pulverized coal-fired systems, IGCC systems use significantly less water.

2. Specification and goals of IGCC demonstration plant

Figure 2 is a system diagram of an IGCC demonstration plant, Table 1 lists the main specifications and target values, and Figure 3 is a conceptual drawing of the IGCC demonstration plant. The IGCC demonstration plant operates at 250 MW (1,700 t/d of coal) which is at about one-half the capacity of a commercial plant. The gasifier is based on the former Nakoso 250t/d pilot plant gasifier, and gas cleanup is performed using wet-gas purification utilizing methyl di-ethanol amine. The gas turbine is 1200°C-class with a power output of 250 MW.
3. IGCC demonstration tests

The IGCC demonstration testing has been conducted by the Clean Coal Power Research Institute (CCP), which was established by nine power companies and the Electric Power Development Co., Ltd. (J-POWER). The Ministry of Economy Trade and Industry subsidized 30% of the project’s costs, with the remaining 70% shared among eleven entities comprised of the nine CCP power companies, J-POWER, and the Central Research Institute of Electric Power Industry.

4. Timeline and progress to date

Figure 2 shows the timeline of the demonstration project. The operation tests for the demonstration plant were conducted from the second half of 2007 through 2012.

5. Activities to date

The pilot plant test (operating with 250 t/d of coal), which was the initial stage of the demonstration test, was carried out between 1986 and 1996 at the Nakoso power plant located in Iwaki City, Fukushima, and operated by the Joban Joint Power Co., Ltd. The pilot test was commissioned by NEDO and implemented through the joint efforts of J-POWER, the Central Research Institute of Electric Power Industry, and nine power companies. The feasibility of employing IGCC technology was verified through the pilot testing which totaled 4,770 cumulative hours, including 789 hours of continuous operation.

On the basis of this pilot plant success, and following an investigation into possible candidate locations, Joban Joint Power's Nakoso power plant was once again selected as the testing site for the demonstration test. This demonstration test incorporated an optimized system that was selected through a feasibility study conducted by NEDO.

Clean Coal Power Research Institute conducted the demonstration test from 2007 – 2012 using a 250-MW IGCC system. One year after beginning operations, it achieved 2,000 hours of continuous operation. In its third year, a 5,000-hour durability test was completed. Comparing the operation results from this initial stage, the results from Nakoso far surpassed those achieved by four IGCC tests conducted in Europe America in the 1990s. This demonstrates the superiority and reliability of Japan’s IGCC technology.

Following these achievements, the 250MW demonstration plant began commercial operations on April 1, 2013 as a 5th unit in Joban Joint Power's Nakoso thermal power plant, making it the fifth coal-based IGCC commercial facility in the world. In an effort to help rebuild the Fukushima region, TEPCO has announced that it will be establishing state-of-the-art IGCC facilities in Fukushima Prefecture. This project will build two 500MW IGCC plants at Joban Joint Power's Nakoso thermal power plant and Hirono thermal power plant. Operations are expected to begin at these new facilities around 2020.

●References

As there is a pressing need to reduce the amount of CO₂ emitted from coal-fired power generation facilities, this project aims to demonstrate the efficacy of an integrated coal gasification fuel cell combined cycle system (IGFC), which is the most high-efficient coal-fired power generation technologies. Osaki CoolGen Corporation was established in July 2010 to develop IGFC technology. As described below, this project aims to demonstrate and test highly efficient power generation by oxygen-blown IGCC equipment, test CO₂ capture, and test the integration of fuel cells into the process. Simultaneously, NEDO will seek to realize an IGFC system that integrates recent advances in commercial fuel cells.

**[1] First Phase: Oxygen-Blown IGCC Demonstration Test**

In the first phase, utilizing a 166-MW oxygen-blown gasification plant, the key technology for the IGFC system will be established. A demonstration test will be performed on the system testing economic viability, reliability, operability (including startup and shutdown times and load following rate), and performance (power generation efficiency and environmental performance).

**[2] Second Phase: IGCC Demonstration Test with CO₂ Capture**

In the second phase, CO₂ separation and recovery ("capture") equipment will be added to the IGCC demonstration test facilities, and the adaptability to coal-fired power system will be assessed in terms of performance, operability, economic viability, and environmental performance.

**[3] Third Phase: IGFC Demonstration Test with CO₂ Capture**

In the third phase, a fuel cell will be incorporated into the CO₂-capture IGCC system constructed in Phase II. This phase will confirm the feasibility of applying such a system to fuel cells using coal derived gas, and will thereby demonstrate an optimal integrated coal gasification fuel cell combined cycle (IGFC).

It is estimated that coal will be available as an energy resource for 112 years longer than other fossil fuels. It is widely distributed in countries across the world, its supply is stable, and it is highly economical. As a result, for a country with extremely limited energy resources for power generation, such as Japan, coal-fired power generation plays a critical role and accounts for one fourth of the nation's generated power. However, because coal emits far more carbon dioxide per unit heat input than other fossil fuels, global environmental concern have placed constraints on its use as an energy source. These constraints have created a need to develop ways to suppress carbon dioxide emissions during coal-fired power generation. Following the nuclear power plant accident caused by the Tohoku earthquake of March 2011, Japan's revised energy policies identified the need for coal-fired power generation to play an even more important role in the future. Consequently, this IGFC project is critical to support efforts to reduce carbon dioxide emissions while achieving heightened efficiency in coal-fire power generation. Carbon dioxide emissions from a current pulverized coal-fired power (with a net efficiency of 40% (HHV)) come to 0.8 kg-CO₂/kWh, but when IGFC (having a net efficiency of 55% (HHV)) is realized, emissions fall to 0.6 kg-CO₂/kWh. If combined with CCS, a further reduction of approximately 0.1 kg-CO₂/kWh can be achieved.

**[1] Coal Gasification Technology**

This project establishes the coal-flexible and high efficiency gasifier (oxygen-brown), and IGCC and IGFC systems with highly efficient CO₂ capture methods. It aims for a dramatic increase in power generation efficiency using IGCC and IGFC with 1700° C-class gas turbines.

**[2] Gas purification technology**

The desulfurization is based on the wet scrubbing process and the sulfur recovery is based on the limestone/gypsum process. In addition to demonstrating the recovery of sulfur through these methods, the gas purification process is adapted to fuel cells and CO₂ capture technology is applied.
Clean Coal Technologies in Japan

The demonstration tests that will be performed by the Osaki CoolGen Corporation aim to assess and verify the following technical issues:

1. In addition to verifying the scale-up technology for the gasifier, coal flexibility and slag discharge will be assessed and verified.

2. With regards to gas purification, in the EAGLE project, performance tests were performed on trace elements removal devices. Compatibility with fuel cells and CO₂ capture will now being verified with the aim of achieving good environmental performance under commercial applications.

3. In order to accommodate IGFC system, demonstration tests that incorporate high-temperature fuel cell systems will be implemented.

Figure 1 Development timeline

4. Development timeline and current status

Figure 1 shows the development timeline for the project. Civil engineering and construction work began in 2012, and fabrication of gasification and other facilities began in 2013.

5. Technical issues

The demonstration tests that will be performed by the Osaki CoolGen Corporation aim to assess and verify the following technical issues:

1. In addition to verifying the scale-up technology for the gasifier, coal flexibility and slag discharge will be assessed and verified.

2. With regards to gas purification, in the EAGLE project, performance tests were performed on trace elements removal devices. Compatibility with fuel cells and CO₂ capture will now being verified with the aim of achieving good environmental performance under commercial applications.

3. In order to accommodate IGFC system, demonstration tests that incorporate high-temperature fuel cell systems will be implemented.

Figure 2 Configuration of the Equipment in an Integrated Gasification Fuel Cell (IGFC) System

Figure 3 Demonstration plant facilities layout diagram

[3] CO₂ capture technology from the coal gas

The EAGLE project compared pre-combustion CO₂ capture technologies, examining the characteristics of both chemical and physical absorption, and its results indicated the physical absorption method was superior. The IGFC project will further demonstrate its feasibility.


An optimal IGFC system will be demonstrated based on the utilization of coal gasification gas in fuel cells.
B-01-03. Next Generation IGCC with CO₂ Capture

Central Research Institute of Electric Power Industry, Kyushu University
NEDO-commissioned project
FY2008 – FY2014 (7 years)

Technology Overview

1. Objectives
To develop a next-generation coal gasification power generation system that can achieve high efficiencies even with the application of CO₂ capture technology.

2. Needs and benefits of the project
Because coal emits far more carbon dioxide per unit of heat input than other fossil fuels when combusted, global environmental concerns place constraints on its use as an energy source. With regards to coal-fired power generation, even more constraints on carbon dioxide emissions are demanded. In the interest of keeping CO₂ emissions from coal-fired power generation low, there is a need to develop carbon capture and storage (CCS) technology to achieve carbon reductions. However, CCS is inherently detrimental to efficiency in power generation due to the requirement for large additional amounts of energy which also leads to an increase in power generation costs.

In order to curtail these power generation costs and still effectively utilize energy resources while capturing CO₂, a revolutionary power generation system needs to be developed that can achieve power generation efficiencies on the order of 42% HHV. This value is equivalent to those of cutting edge coal-fired power generation systems and the development of such a technology is especially important to Japan, which is dependent on external energy resources.

3. Component technologies
This system is a next-generation IGCC system that can greatly improve the efficiency of a coal gasification system with CCS by partially recycling the discharged CO₂. It is a unique concept that uses the technologies described below and is the first of its kind globally. Its importance stems from achieving high power generation efficiency even while recovering CO₂.

[1] O₂ - CO₂ Blown Gasification:
With known oxygen-blown gasification technologies as a base, recycled CO₂ utilized as a gasification material in a gasification reaction, which improves gasification performance.

[2] Closed cycle O₂-CO₂ combustion gas turbine:
An O₂-CO₂ gas combustion closed gas turbine is a technology that utilizes a part of the combustion gas (CO₂ + H₂O) as a dilution medium. Fuel gas (CO + H₂) is burned by oxygen near its stoichiometric ratio. Because the amount of exhaust gases discharged outside the system is less than in an open cycle, the exhaust heat loss is reduced, and power generation efficiency is improved.

[3] Dry gas purification:
Dry gas purification is a technology that suppresses the heat losses by eliminating impurities in the fuel at high temperature.

Figure 1 Schematic diagram of Next-generation IGCC system featuring CO₂ capture
Clean Coal Technologies in Japan

4. Development schedule and current status

Figure 3 is a diagram of the research and development schedule of the project. Previous basic research was conducted using gasifiers operating on a scale of 3 t/d. The project will be scaled up to proceed with technology verification, and in an aim to begin commercialized operations by 2035.

Because this technology is dependent on the availability of CCS systems, the current plan utilizes a stage gate model in order to flexibly respond to new circumstances while keeping an eye on trends in CSS both abroad and in Japan.

5. Technical issues

This system has consisted of pioneering technologies since the beginning of its development including the individual devices and equipment used to construct the system such as the gasifier, gas turbine, and purification devices. The following outstanding issues will need to be resolved in order to make this system commercially operable, and performance must be verified using full-scale systems to test durability and reliability.

(1) O₂-CO₂ blown gasification
- Appreciation of the gasification characteristics in CO₂-rich environments
- Assessment of the effects of fluctuations in CO₂ concentration levels
(2) Closed cycle O₂-CO₂ combustion gas turbines
- Verification of combustion properties
- Verification of system configuration and performance
(3) Dry gas purification
- Countermeasure for carbon deposit
- Confirmation of the performance of dry desulfurization catalysts
- Understanding the behavior of impurities, besides sulfur, and construction of removal methods
- Scale up technology
B. Technologies for High-Efficiency Applications

B-01-04. Cogeneration Systems

Technology Overview

1. Definition of cogeneration
Cogeneration systems combust fuel (primary energy) and simultaneously extract multiple types of secondary energy through conversions to heat, electricity or other forms.

2. Cogeneration systems
There are two kinds of cogeneration systems. In the first type, a primary engine such as diesel engine, gas engine, or gas turbine generates power. Then, using a boiler, heat is exchanged from the exhaust heat of the primary engines to hot water or steam. In the other type of cogeneration system, steam generated by a boiler generates electric power by driving a steam turbine. Then the extracted steam is used as a process steam, which is employed at a desired pressure. A liquid fuel or gas is typically employed in the former method, and this approach is generally applied to small-scale systems such as those utilized in hotels, supermarkets, and hospitals among others. In contrast, the latter method can utilize a number of fuels (including coal) for the boiler, and this form of cogeneration is typically applied to comparatively large-scale private-use thermal power generation facilities.
Cogeneration systems can also be broadly divided into two categories based on intended use. Supplying electricity (condensing steam turbines) is the primary goal of one category and generating steam (heat) supply (back-pressure steam turbines) is the primary goal of the other.

3. Efficiency
Typically, the power generation efficiency of a coal-fired power plant that extracts only electricity is near 40%. In a cogeneration system, total thermal efficiency, which is the sum of the power generation efficiency and heat recovery efficiency, will differ depending on whether the primary aim is the generation of heat or electricity. Cogeneration systems designed primarily to provide heat can have total thermal efficiencies as high as 80%.

(1) Cogeneration in large-capacity coal-fired power plants
The Kobe power station of Kobe Steel Ltd. is a large-scale coal-fired power-generation facility with a 1,400 MW capacity from two 700 MW units. It entered the electric power wholesaler business as an independent power provider (IPP) and provided all its surplus electricity to the Kansai Electric Power Co. Inc. Unit 1 began commercial operations in April 2002, and Unit 2 began commercial operations in April 2004.
(2) Regional supply of thermal energy

A portion of the steam generated by the power plant supplies up to 40 t/h of steam to four nearby brewing companies. This corresponds to approximately 2\% of the steam that is generated by the boiler, and is a small fraction of the total heat supply. Previously, steam that was produced using multiple boilers at each of the brewing companies was collected in a header and sent to the plant. Now, the steam needed for all brewing companies is extracted from turbine and is fed to a header. Thus, region-wide energy savings is being achieved.

(3) Heat supply conditions

Because the turbine-extracted steam contains trace amounts of hydrazine as rust inhibitor, it cannot be supplied directly to brewery companies as it would be used in processes causing it to come in direct contact with grains. A steam generator that uses the turbine-extracted steam (primary steam) as a heat source is therefore implemented to indirectly produce steam (secondary steam) that is then supplied to the breweries. An overview of the facilities is shown below.

![Aerial view of the power plant](image)

**Figure 2** Aerial view of the power plant

![Schematic of the heat supply facilities](image)

**Figure 3** Schematic of the heat supply facilities

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**References**


B-01-05. Fuel Coproduction Power Generation Systems

Technology Overview

1. Possibilities of fuel coproduction power generation systems

The feasibility of developing revolutionary processes within a single industry, as has been the norm up to now, is beginning to reach its limits. In order to achieve further reductions in CO₂ emissions, it will be necessary to reassess conventional energy and material production systems from their core, not simply seeking improvements in conversion efficiency and energy savings but also developing technologies that optimize both individual processes and the interfaces between processes to achieve systematic and fundamental changes.

Fuel coproduction power generation systems (or “coproduction” for short) use coal as a base for simultaneously producing power fuel and/or chemical raw materials. By utilizing this concept of industrial fusion, it is possible to improve overall energy utilization efficiency. Fields such as power generation, steel manufacture, and chemical production use coal as one of the main energy resources. By forming a core factory that co-produces both energy and chemical raw materials and then co-locating various production factories nearby, a “coal complex” based on the new energy and materials production system can be established. This type of industrial-fusion scheme moves industries from isolated states towards a next-generation hybrid-industry model.

The core technological component of such fuel coproduction power generation systems is coal gasification. By combining a high-efficiency power generation system like IGFC with a process that co-produces a storable fuel, it becomes possible to balance the loads placed on gasifiers while achieving substantial reductions in CO₂ emissions.

In addition, by using the waste heat resources available in a coal complex to produce an endothermic reaction while extracting chemical raw materials from the coal itself, energy efficiency is increased.

![Figure 1 Energy flow](image-url)
2. Co-produced fuel and chemical materials

The types of fuel or chemical materials to be co-produced with power depends on the needs of project stakeholders. Representative examples of coproduction through coal gasification being conducted abroad include the synthetic fuel (GTL) production by the Sasol Group of South Africa, and acetyl chemicals production by the Eastman Chemical Company of North America. Methanol or methane is also produced in China, Europe, and the Americas.

The following chemicals are also being co-produced:

DME: DME can be utilized as clean fuel or raw material in the manufacture of propylene.

Hydrogen: New demand for hydrogen has increased as the hydrogen energy society aims to provide fuel for fuel-cell hybrid vehicles (FCVs) and other applications.

Green gas for steel mills: Green gas is being used to meet the change in energy balance in the steel mills of the future.

3. Coproduction systems

By producing materials and energy simultaneously, coproduction systems have created systems that greatly reduce the energy losses from combustion and dramatically enhance the efficiency of energy utilization.

Going beyond conventional systems that aim to improve energy conversion efficiency or to utilize the produced heat energy as effectively as possible, coproduction systems are a new form of production system that aim to greatly reduce the consumption of energy and materials by co-producing them. Furthermore, by making the processes clean, hopes are high that coproduction can give rise to economic vitality while simultaneously helping to resolve both energy shortages and environmental concerns. In other words, coproduction systems that simultaneously produce energy in the forms of fuel and electricity deserve close attention from the standpoint of their potential to generate new energy markets and industries.

Because they incorporate a host of comprehensive coal utilization technologies at a high level, coproduction systems based on coal gasification can help to alleviate environmental concerns by dramatically reducing CO2 emissions. Technological developments in such systems achieve a technology revolution in the field of coal utilization, and are expected to bring advances in the development of a recycling society while strengthening international competition. Internationally coproduction can be seen as an example of a technical solution that helps address global environmental issues.
Part 2 CCT Overview

B. Technologies for High-Efficiency Applications


Kawasaki Heavy Industries Ltd., Sumitomo Osaka Cement Co., Ltd.

Voluntary project, METI-subsidized project, NEDO-commissioned project

FY1984 – FY1985 (2 years), FY1986 – FY1992 (7 years),

Technology Overview

1. Features

By effectively utilizing its combustion performance, heat transfer performance, particle diffusion, and granulation characteristics, a fluidized-bed advanced cement kiln system (FAKS) is able to combust low-rank coal efficiently, reduce NOx emissions dramatically, and improve the efficiency from gases and particles discharged. As such, FAKS systems can contribute to global environmental protection and energy conservation while also helping to meet the demand for handling various types and special grades of cement.

2. Technology overview

A fluidized bed advanced cement kiln system consists of a granulated firing kiln and a two-stage cooler and it produces high-quality cement. The granulated firing kiln grinds the powdered raw material to a certain size and then fires the granules at high temperature. The two-stage cooler combines a fluidized-bed quenching cooler and a moving-bed slow-cooling cooler.

The most important technology in this system is the granulation control technology. In order to control granulation, previous conventional technological required that the seed clinker used for seeding be injected from the outside, at which point the high-temperature powdered raw material was then adhered to the seed and grown on it. In contrast, the FAKS system employs the world’s first thermal self-granulation process wherein a portion of the powdered raw material is agglomerated within the granulated kiln to form a seed itself. Then, the remaining powdered raw material is adhered onto that seed and made to grow, thereby achieving granulation control.

To achieve controlled granulation, the granulated firing kiln combines two main technologies: a raw material injection unit and a bottom classification and discharge unit.
3. Demonstration site and application

1) 200-t/d Demonstration

2) 1,000-t/d Demonstration
[1] Demonstration sites:
   Shandong Paoshan Biological Building Materials Co., Ltd.
   Liubo City, Shandong Province, China

4. Demonstration site and field of application

Basic research into the FAKS technology started in 1984 in the form of an independent project conducted by Kawasaki Heavy Industries, Ltd. and Sumitomo Osaka Cement Co., Ltd. Based on their preliminary research findings, work continued in 1986 in the form of a grant for the promotion of coal production and utilization technology sponsored by the Agency of Natural Resources and Energy of the Ministry of International Trade and Industry. In June of 1986, a 20 t/d-scale pilot plant was constructed jointly by the Japan Coal Energy Center, Kawasaki Heavy Industries, Ltd., and Sumitomo Osaka Cement Co., Ltd., to begin testing. In April 1993, basic planning and design of a scaled-up 200 t/d plant was initiated jointly by the Japan Coal Energy Center and the Japan Cement Association. In February 1996, this demonstration plant began testing operations. After the system had passed its operational tests aimed upon verifying commercialization potential, the project was terminated in December 1997.

In May 2005, NEDO launched a joint demonstration project for a 1,000 t/d scale fluidized bed advanced cement kiln system at the Shandong Paoshan Biological Building Materials Co., Ltd. in Liubo City, Shandong Province, China as an International Coal Utilization Project.

5. Future avenues of development

Table 1 below compares the performance of the conventional technology and FAKS when operating a commercial plant at 1,000 t/d. Development of the system was completed via test operations of this scale in Shandong Province, China. FAKS is expected to be adapted to commercial facilities as an innovative cement production technology that can replace conventional technologies. While practical facilities have been established both in China and in Japan on a 3,000 – 5,000 t/d scale, actual cement production in Japan has been on the decline delaying the full-scale practical utilization of the new technology.

Table 1 Comparison of environmental improvement effects of FAKS vs. a rotary kiln type process at a 1,000 t/d plant

<table>
<thead>
<tr>
<th>Emissions levels</th>
<th>Rotary kiln method</th>
<th>Fluidized bed method</th>
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<tbody>
<tr>
<td>NO₂</td>
<td></td>
<td></td>
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<tr>
<td>Conversion value with 1% O₂ and 10% O₂ in coal</td>
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<tr>
<td>Emissions (mg/Nm³)</td>
<td>708</td>
<td>476</td>
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<tr>
<td>Annual emissions (t-NO₂/y)</td>
<td>341</td>
<td>233</td>
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<tr>
<td>CO₂ emissions due to coal and electricity*</td>
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<tr>
<td>Emissions (g/Nm³)</td>
<td>245</td>
<td>220</td>
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<tr>
<td>Annual emissions (t-CO₂/y)</td>
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<td>108x10³</td>
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Basis of calculation

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<th>t-clinker/d</th>
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<th>t-clinker/d</th>
<th>t-cement/d</th>
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<td>Production capacity</td>
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<tr>
<td>Annual days of operation</td>
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<tr>
<td>Heat consumption</td>
<td>3,411x10³</td>
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<tr>
<td>Power consumption</td>
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<tr>
<td>Exhaust gas from firing system</td>
<td>1.46</td>
<td>1.49</td>
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<td>Lower calorific value of coal</td>
<td>25,116</td>
<td>25,116</td>
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* Based on IPCC: Guideline for National Greenhouse Gas Inventories, Reference Manual (carbon emissions coefficient = 26.8 t-C/TJ / oxidized carbon fraction = 0.98).

References

Part 2 CCT Overview
B. Technologies for High-Efficiency Applications

B-05-02. New Scrap Recycling (NSR) Systems

Japan Coal Energy Center, Nippon Sanso Corporation, NKK Corporation
METI-subsidized project
FY1992 – FY1997 (6 years)

Technology Overview

1. Features
In Japan, some 30 million tons of iron scrap is recycled annually. Most of this is melted in arc furnaces, which consume large quantities of power. The energy efficiency of an arc furnace is typically as low as 25% on a primary energy conversion basis, taking power generation and delivery efficiencies into account. Unsurprisingly, industry professionals have identified the need for a melting process that achieves higher energy efficiency. The new scrap recycling (NSR) process is an “electricity less” melting technology that melts iron such as metal scrap by using the high-temperature energy obtained by combusting powdered coal using oxygen. NSR has been developed with the aim of dramatically improving energy efficiency over that in conventional technologies.

2. Development timeline
The NSR process was developed jointly by the Japan Coal Energy Center, Nippon Sanso Corporation, and NKK Corporation (currently known as the JFE Steel Corporation). The main development issue was finding a furnace structure and burner placement for high efficiency melting. Studies were initiated using batch smelters, and based on the preliminary results, a continuous melting furnace was developed with the aim of attaining higher energy efficiencies.

Table 1 Development timeline

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<td>Preliminary research</td>
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<td>Batch-furnace</td>
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<td>Bench scale (1t/batch)</td>
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<td>Pilot scale (5t/batch)</td>
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<tr>
<td>Continuous furnace (pilot plant scale : 6t/hr)</td>
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3. Overview of process and study results
Figure 1 shows an overview of the processes employed in a continuous melting furnace. The melting furnace is configured from three zones having their own functions: a melting region, a hot well and a holding unit. A pulverized coal/oxygen burner is placed in each of those regions. The oxygen supplied to each of the burners is heated to 400° - 600°C by means of an oxygen preheating unit, and the pulverized coal is combusted using that high-temperature oxygen.

Figure 1 NSR process flow

Figure 2 Pilot plant facilities (6t / hr)
Due to the high-temperature oxygen, even when using pulverized coal having a slow combustion speed, it is possible to achieve high combustion speeds and efficiencies that are equivalent to liquid fuels such as heavy oil. The melting section is shaped like a shaft, and feed scrap that is charged from the furnace top is melted directly by the burner flames at the bottom of the furnace. Once melted, the feed flows sequentially into the hot well section and holding unit. In the hot reservoir section, the molten steel is kept heated and powdered coke is blown into the furnace to control the carbon concentration in the molten steel. In the holding unit, the molten steel is retained for a certain amount of time, then suddenly heated to 1600°C, and then tapped using an electric furnace method. In the hot well section and holding unit, molten steel-agitating gas is blown in from the furnace bottom, thus helping to promote heat transfer from the flames to the molten steel while also facilitating a slag-metal reaction. The combustion gases from each section pass through the entire melting section, and are discharged from top of the furnace. During this process, the heat of gas is utilized for to preheat feed material in the melting section. Feed material is continuously supplied from top of the furnace and melted, while the tapping of steel in the holding unit is performed intermittently. Thanks to these processes, it is possible to efficiently utilize the heat transfer characteristics of an oxygen burner, and consequently, melting is highly efficient. Figure 3 compares the melting energies used in this process against those used when employing an arc furnace.

The power (including electricity needed to oxygen production) was converted to the primary energy equivalent including losses in power generation and power transmission. Compared to conventional arc furnace methods, superb results can be attained as a 40% reduction in melting energies. Moreover, the production of dioxin is greatly suppressed by mean of control of the atmosphere in the furnace, and the dust emission is reduced tremendously as well.

### 4. Practical applications

Design of a full-scale system has been achieved, but due to unfavorable economic conditions in the electric furnace industry, this technology has yet to be fully implemented. The process, however, remains one of the few non-electric-power melting technologies, and it has the major advantage of not being affected by the electricity infrastructure. Future avenues of research include looking into the feasibility of follow-up implementations both in Japan and abroad.

**References**

Part 2 CCT Overview

B. Technologies for High-Efficiency Applications

B-06-01. Pulverized Coal-Fired Power Generation Technologies (USC)

Technology Overview

1. Pulverized coal-fired power generation systems

Pulverized coal-fired power generation systems, such as the one shown in Figure 1, are widely used due to the fact that they are a well-established, highly reliable technology. In 1983, Chubu Electric Power’s Hekinan Thermal Power Plant No.3 unit (700 MW), the first ultra-super critical (USC) plant in Japan, began operations. In 2000, J-POWER’s Tachibanawan Units No. 1 and No. 2, each of which were 1,050 MW, were operated at 600° and 610° C. The Isogo New Unit No. 2 of J-POWER, which began operation in 2009, used a primary steam temperature of 600° and a reheating steam temperature of 620° C. In total, 25 USC plants are in commercial operation. Their total output capacity is 19,960 MW, which accounts for 52.1 % of the total capacity of all coal-fired power stations. Because Japan has accomplished such success in the development of USC systems, it is expected that there will be an accelerating trend towards the implementation of coal-fired USC technologies elsewhere throughout the world. Future challenges in this field will be utilizing more grades of coal, improving power generation efficiency, enhancing environmental friendliness, and improving load operability.

In efforts to achieve near-zero emissions, total air control systems have been made great progress. These systems are comprised of furnace denitrification low-NOx burners, SCR technology and FGD technology.

2. Efficiency enhancements

Improving the thermal efficiency of power generation plants is a major issue from both an economic standpoint through reducing power generation costs, and also in efforts to reduce the production of CO2. At large-scale thermal power plants in particular, steam conditions have been remarkably enhanced to operate at higher temperatures and pressures. Figure 2 shows the trend in steam conditions over the past century. In 1989, the Chubu Electric Power Co.’s Kawagoe No. 1 unit (700MW) adopted main steam pressure at 31.0 MPa, with main/reheat/reheat steam temperatures at 566°C/566°C/566°C. In 1993, Chubu Electric’s Hekinan No. 3 (700MW) adopted main steam pressure at 24.1 MPa, with main and reheating steam temperatures of 538°C and 593°C respectively, making it the highest reheating steam temperature in Japan. Subsequently, Chugoku Electric Power Co., Inc.’s Misumi No. 1 (1,000MW) and Tohoku Electric Power Co., Inc.’s Haramachi No. 2 (1,000MW)
Various combustion technologies have been developed and put to use in order to accommodate Japan's needs to achieve high-efficiency combustion while meeting the country's strict environmental guidelines. The air quality levels of dust and NOx depend on the performance of flue gas processing downstream from combustion. The emissions achieved at boiler level are the world's lowest. Because the NOx and dust controls are similar, the discussion that follows will focus mainly on NOx combustion technologies. Low NOx combustion technologies can be roughly divided into two categories: low NOx burners and intra-furnace denitration processes.

(1) Low-NOx Combustion in Coal Burners
The latest burners produced by major boiler manufacturers have differing structures and configurations, but they all strive to achieve better ignition and denitration within the flames. In this regard, thick/thin density control of pulverized coal and multilevel injections of air are considered fundamental. Burner configurations from the major manufacturers are shown in Figures 4 - 7.

(2) Intra-Furnace Denitration
Intra-furnace denitration is a two-stage process.
In the first stage, NOx is reduced by using unburnt hydrocarbons in the combustion gas. In the second stage, any remaining unburned matter (hydrocarbons) is completely combusted using an additional injection of air.
Part 2 CCT Overview

B. Technologies for High-Efficiency Applications

B-06-02. Atmospheric Circulating Fluidized-Bed Combustion Technology (CFBC)

Technology Overview

1. Features
Circulating atmospheric fluidized-bed boilers have the following characteristics:

[1] Compatibility with a Wide Range of Fuels
Whereas conventional boilers for power generation can only use fossil fuels such as high-rank coal, oil, or gas, circulating fluidized-bed boilers can burn a variety of fuels, including low-rank coal, biomass, sludge, waste plastic, and waste tires.

[2] Low Pollution
CFBC technology can greatly reduce the emissions of NOx, SOx, and environmental pollutants without special emission removal equipment. In the case of fluidized bed boilers, desulfurization is mainly carried out within the furnace by using limestone as the main bed material. As for denitration, in contrast with pulverized coal boilers which operate in a temperature range of 1400° - 1500° C, circulating fluidized boilers operate at 850° - 900° C. Because thermal NOx production is highly temperature-dependent, this translates to a significant reduction in NOx production. In addition, thanks to its two-stage combustion process, involving a reduction of combustion at the fluidized bed and an oxidizing combustion at the freeboard, it is also possible to achieve low NOx production. Further still, unburned carbon is collected by a high-temperature cyclone that is located at the boiler exit and is then recycled for the boiler. This recirculation process also enhances denitration efficiency.

[3] High Combustion Efficiency
Thanks to improvements in the combustion time brought about by circulating fluids, CFBC systems can attain high combustion efficiency.

[4] Space Savings and Ease of Maintenance
CFBC systems save space over other systems because they simply do not need separate equipment for desulfurization, denitration, or fuel pulverization. Therefore, they are able to operate with relatively hassle-free maintenance.

2. Technology overview
Figure 1 shows a typical CFBC process flow, and Figure 2 shows a typical configuration of a CFBC. A CFBC system is largely composed of the boiler unit and a high-temperature cyclone. The velocity of gas within the furnace is rather high, around 4 - 8 m/s. Char and a fluidized medium with a large particle diameter are collected from within the exhaust gas by the high-temperature cyclone and returned to the boiler unit. This recycling process keeps the bed temperature high and increases denitration efficiency.

In addition, to improve boiler efficiency, an economizer, which consists of air heaters for combustion air and fluidizing air are installed in the heat recovery section. Most of this boiler technology originates overseas, as the main manufacturers in this field are Foster Wheeler (U.S.), Lurgi (Germany), Steinmuller (Germany), ALSTOM (Finland), and Babcock & Wilcox (U.S.).
Clean Coal Technologies in Japan

Atmospheric circulating fluidized-bed boilers are comprised of technologies that have been imported from abroad since 1986. CFBC is a technology that was introduced from abroad in the form of coal-fired boilers for use mainly by steel makers and paper manufacturers. Later, the technology was disseminated to China under the Green Aid Plan (GAP).

Future concerns include the need to reduce initial costs and further improve efficiency in boilers where RDF, industrial waste products, and wood-based biomass are employed as fuel.
B-06-03. Atmospheric Internal Circulating Fluidized-Bed Combustion Technology (ICFBC)

Japan Coal energy Center, Ebara Corporation, Idemitsu Kosan Co., Ltd.
METI-subsidized project
FY1987 – FY1993 (7 years)

Technology Overview

1. Features
Atmospheric internal circulating fluidized-bed combustion technology has the following essential characteristics:

I) Temperatures in the fluidized bed are uniform thanks to the swirling flow of sand.

II) Non-combustibles are easily discharged due to the fact that sand is agitated vigorously.

III) The temperature of the fluidized bed can be controlled by adjusting the amount of heat recovered from the fluidized bed.

As a result, ICFBC technology has the following advantages:

[1] Ability to accommodate multiple fuel types
Much like the previously described CFBC technology, ICFBC systems can use not just fossil fuels such as high-rank coal, oil, and gas but also low-grade coal, biomass, sludge, waste plastic, and waste tires.

[2] Bed temperature control
Because the overall heat-transfer coefficient varies almost linearly with the change in air flow rates in the heat recovery chamber, it is easy to adjust the amount of heat that is recovered by simply modifying the air flow rate. In addition, because it is possible to control the temperature of the fluidized bed by adjusting the amount of recovered heat, and because that is accomplished by simply modifying the air flow rate, it is extremely simple to control the load. Such simple control is a major advantage of ICFBC technology.

[3] Low pollution
In ICFBC systems, NOx and SOx emissions are greatly reduced without the need for special environmental equipment. In the case of fluidized bed boilers, desulfurization takes place mainly inside the furnace. With ICFBC systems, however, because there are no heat transfer tubes in the fluidized region, there is no abrasion on the heat transfer tubes within the bed, and so silica sand can be used in the fluidized medium instead of soft limestone. For that reason, only minimal amounts of limestone are needed as intra-furnace desulfurization agents. Although efficiency will vary depending on the coal rank, amount of limestone employed, and temperature of the fluidized bed, the desulfurization efficiency of ICFBC systems approaches 90% at a Ca/S molar ratio of 2.0 or thereabouts. Denitration is performed using a two-stage combustion process that involves a combustion reducing step in the fluidized bed section and an oxidizing combustion step in the freeboard section. Carbon that is not burned in the boiler is collected by a high-temperature cyclone installed at the exit of the boiler and circulated back to the boiler, thereby enhancing denitration efficiency.

[4] Space savings and ease of maintenance
Just as with CFBC systems, ICFBC systems do not require separate equipment for desulfurization, denitration, and fuel pulverization. Therefore, they are able to operate with relatively hassle-free maintenance.

2. Technology overview
Figure 1 shows an overview of an ICFBC system. The fluidized bed is divided into a main combustion cell, heat exchange cell, and a partition wall, thereby forming a circulating flow inside the main combustion chamber and another circulating flow between the heat recovery chamber and main combustion chamber. In addition, a circulating flow that returns unburned char and unreacted limestone to the boiler from the cyclone at the boiler exit is also formed. The fluidizing medium is silica sand.

[1] The swirling flow within the main combustion chamber is created by dividing the window box into three sections. In the center section only a small amount of flowing air is introduced, resulting in a weak fluidized bed (moving layer). Meanwhile, large quantities of air are injected from the two end sections, resulting in a vigorous fluidized bed. As a result, the center of the main...
combustion chamber acquires a slow, downward moving bed, while the fluidizing material that is vigorously blown upward from the two ends settles in the center section, and then ascends at both end sections, thereby creating a swirling flow.

[2] The circulating flow between the main combustion chamber and the heat recovery chamber is formed by the actions described below. A portion of the fluidizing material that is vigorously blown up at both end sections of the main combustion chamber is diverted above the inclined partition wall with the direction of flow toward the heat recovery chamber. The heat recovery chamber forms a weak fluidized bed (downward moving layer) by means of the circulating layer air blown in from underneath. As a result, the fluidized medium is circulated first from the main combustion chamber to the heat recovery chamber, and then from the heat recovery unit back to the main combustion chamber. Because heat transfer tubes are provided inside the heat recovery chamber, the thermal energy from within the main combustion chamber is recovered via the circulating flow.

[3] After char, scattered fluidizing medium, and unreacted limestone have been collected using a cyclone or similar mechanism, the circulating flow from the cyclone at boiler exit is returned to the main combustion chamber or heat recovery chamber by means of a screw conveyor or pneumatic transport. This is extremely effective in raising the combustion efficiency, reducing NOx production, and improving desulfurization efficiency.

3. Implementation sites and field of application

Examples of sites where coal-fired ICFBC systems are being implemented include Ebara Qingdao (10 t/hr), Jiangsan, China (35 t/hr), and Nippon Paper Industries’ Nakoso plant (104 t/hr). Examples of sites where ICFBCs run with industrial waste as the fuel include Toyota Motor's Motomachi plant (70 t/hr), Bridgestone's Tochigi plant (27 t/hr), Daishowa Paper Mfg.'s Fuji plant (62 t/hr), Bridgestone's Amaki plant (7.2 t/hr), and Tohoku Paper Mfg.'s Akita plant (61.6 t/hr). In Shizuoka, Chugai Pharmaceutical is operating an ICFBC plant running off of RDF fuel (3.7 t/hr). Photo 1 shows the exterior of an ICFBC facility.

The first ICFBC established using biomass for fuel was the Kaminoike Biomass Power Station (106 t/h) run by Kaminoike Bioenergy. Shirakawa Wood Power Co. followed suit with its Daishin Power Station (58 t/h), and ORIX Corporation is running the Agatsuma Biomass Power Plant.

4. Implementation period

The development of the internal circulating fluidized-bed combustion technology (ICFBC) was launched in 1987. Over the course of the following six years, from 1988 to 1993, the Ministry of International Trade and Industry conducted a Coal Utilization Technology Promotion Grant project entitled ‘Study of Fluidized-Bed Combustion Technology’ that helped to validate ICFBC through a low-polluting, small-scale fluidized bed boiler operating at high-efficiency and capable of employing multiple grades of coal.

5. Progress to-date and future issues

Although ICFBC was initially developed to combust industrial waste having a high caloric value, it was further improved for use in coal-fired boilers. A boiler plant was also constructed in Qingdao, a manufacturing base in China, which has abundant coal reserves. In Japan, boilers employing a wood-based biomass as fuel have been realized. Moving forward, a further reduction in investment and startup costs will be needed so that this technology can become widely adopted in Southeast Asia and other areas rich in biomass resources and low-grade coal.
B-06-04. Pressurized Internal Circulating Fluidized-Bed Combustion Technology (PICFBC)

Japan Coal Energy Center; Ebara Corporation
METI-subsidized project
FY1992 – FY1998 (7 years)

Technology Overview

1. Overview
The underlying technology of a pressurized internal circulating fluidized-bed combustion technology (PICFBC) is based on the internal circulating fluidized-bed combustion boiler (ICFBC) described in B-06-03. PICFBC entails installing an ICFBC system within a pressurized vessel.

2. Features
The pressurized internal circulating fluidized-bed boiler (PICFBC) employs the circulation flow technology of ICFBC systems as developed. As such, it can control the load without needing to vary the height of the fluidized bed. In addition, because the heat transfer tubes are not exposed at the freeboard during the load control step, cooling of the combustion gases is avoided. As a result, not only is it possible to minimize the production of CO₂, but it is also easy to maintain the gas turbine inlet temperature. Additionally, because abrasion of the intra-bed heat transfer tubes is reduced, it is possible to employ silica sand for the fluidizing medium while employing only minimal amounts of limestone for intra-furnace desulfurization. This keeps the amount of ash produced down. Because there are no intra-bed heat transfer tubes inside the main combustion chamber, there is no issue with particle blockage due to the presence of intra-bed heat transfer tubes, and it is possible to prevent the agglomeration (solidification of the molten medium) from occurring.

3. Technology overview
Figure 1 shows a schematic diagram of a PICFBC system. A cylindrical ICFBC is placed inside a cylindrical pressurized vessel. Just as with ICFBC systems, silica sand is used as the fluidizing material. The fluidized bed is divided into a main combustion chamber and heat recovery chamber by means of an inclined partition. A swirling flow is formed inside the main combustion chamber, and a circulating flow is formed between the main combustion chamber and the heat recovery chamber. Figure 2 shows a basic flowchart of a hot-model pilot plant implemented in Sodegaura. The coal delivery mechanism embodies two systems: coal water (CWP) that is supplied in the form of a slurry that is mixed with water, and a lock hopper system through which lumps of coal can be injected. Dust in the combustion gases are removed by means of a ceramic high-temperature bag filter.

Figure 1 Schematic diagram of a PICFBC system

Figure 2 Flowchart of a PICFBC system
Clean Coal Technologies in Japan

4. Implementation site and field of application
A PICFBC pilot plant test was conducted on site at Idemitsu Kosan Co., Ltd.’s Coal Research Laboratory in Nakasode, Sodegaura City, Chiba. Potential applications for this technology include steam turbine power generation using the generated steam and gas turbine generation using combustion exhaust gases. IGCC systems at coal-fired thermal power plants are therefore also potential candidates. Photo 1 shows a PICFB 4-MWth hot model installation. Photo 2 shows the exterior of a pressurized two-stage gasification plant that processes 30 t/d of waste plastic. The pressurized two-stage gasification technology can be used to synthesize ammonia from coal and to produce hydrogen for fuel cell power generation. The pressurized two-stage gasification technology has been operating as a commercial plant at Showa Denko’s Kawasaki plant since 2003, processing 195 tons of waste plastic per day.

5. Implementation period
An ICFBC hot model test was performed from 1992 to 1998. The project was conducted jointly by the Center for Coal Utilization and the Ebara Corporation as a Coal Utilization Technology Promotion Grant project under the auspices of the Ministry of International Trade and Industry. The pressurized two-stage gasification technology was developed jointly with Ube Industries, Ltd. Proof-of-concept operations began in January 2000 with a plant that processed 30 tons/day of waste plastic, and commercial operations were began in January 2001.

6. Technology overview
This technology was developed as a coal-fired PICFBC up to the level of a hot-model experiment at Sodegaura. However, the technology evolved into a pressurized two-stage gasification technology that utilizes a lock hopper system and a thermal load control method in the pressurized fluidized bed. For plants with pressurization systems, future issues of concern include the reliability of the lock hopper system within the fuel delivery system as well as the need for measures to low-temperature corrosion. The technology has yet to be ramped up to a large-scale operation due to the simple fact that user sites have yet to express the need for it on that level.
B-06-05. Coal Partial Combustor Technology (CPC)

Research and Development
Japan Coal Energy Center, Kawasaki Heavy Industries, Ltd.; JFE Steel Corp.; Chubu Electric Power Co., Inc.; and J-POWER

Project Type
METI-subsidized project

Development Period
FY1984 – FY1999 (15 years)

Technology Overview

1. Background and overview of the technology

Given that coal reserves are abundant and spread widely throughout the world, coal supplies are extremely stable, making coal well positioned as an important source of energy for the future. Compared with other fuels such as oil and gas, however, coal contains large amounts of ash and nitrogen. This poses utilization issues: equipment is liable to break down due to the presence of ash, and the vast increase in NOx emissions is environmentally problematic. Moreover, recent years have witnessed increasing international concern over global warming resulting in an urgent need to develop technologies that can reduce CO2 emissions, one of global warming’s major contributors. Given that coal generates large volumes of CO2 per calorific value, the entire world is looking to develop technologies that can use coal in a highly efficient and environmentally friendly way.

A coal partial combustor (CPC) is a technology that minimizes negative environmental impacts while also achieving high efficiencies.

In a CPC, air and coal are blown in at high speed at a tangential direction to a swirling melting furnace. Partial combustion (gasification) occurs at a high temperature and under a high load within a strongly reducing atmosphere. After most of the ash within the coal is melted, separated, and removed, the combustion gas that was produced is then subjected to secondary combustion. There are two variations of CPC technology. The base technology entails operating at atmospheric pressure to produce a clean gas with low calorific value. A further development of CPC is pressurized CPC, which entails applying pressure, making use of a gas turbine, and thereby realizing high-efficiency power generation.

2. Atmospheric pressure coal partial combustor technology

Molten combustion boilers are designed to burn difficult-to-combust coal and to detoxify and reduce the volume of ash emitted from the boiler. Many such boilers are in operation, especially in Europe and America. While molten combustion systems have the merits of high combustion efficiency and the ability to recover ash in the form of a harmless molten slag, they have the shortcoming of high NOx emissions because their combustion takes place at high temperatures.

Atmospheric pressure coal partial combustor technology was developed with the aim of simultaneously achieving low NOx emissions while melting and removing the ash contained in coal. It was launched with the development of coal partial combustion systems. This system installs a CPC directly onto the boiler’s sidewalls. The combustible gas produced by the CPC is injected as into the boiler furnace, where the gas is completely combusted with injected air.

For small to medium-sized coal-fired boilers, CPC can significantly reduce NOx emissions while maintaining a compactness similar to an oil-fired boiler. It also recovers all of the coal ash as molten slag. Figure 1 shows a schematic diagram of an atmospheric pressure CPC boiler.

Figure 1 Schematic diagram of an Atmospheric pressure coal partial combustor (CPC) boiler
3. Pressurized coal partial combustor furnace technology

Pressurized CPC technology entails the application of pressurization to an atmospheric-pressure CPC system. It is designed to be used in combined cycle power generation systems that incorporate gas turbines.

Figure 2 is a schematic flow diagram of a pressurized CPC pilot plant that processes 25 tons of coal per day when operating at an oxygen concentration of 21%. In this experiment, the pilot plant ran the coal gasification production experiment using CPC at a pressure of 20 atm, and its efficacy was thereby confirmed.

4. Future issues and status of implementation

Atmospheric pressure CPC technology has already been successfully developed as low-NOx boilers with molten ash targeting coal, and has been successfully implemented as a low NOx technology for heavy oil ultra-low NOx boilers and in the swirling melting furnaces of a municipal waste gasification melting plant.

As for pressurized CPC technology, now that a pilot plant experiment has been completed, the private sector is currently conducting research and development aimed at future implementations. In addition, these basic technologies have also been added onto gas turbine power generation technologies employing biomass gasification.

5. Progress to-date and future issues

Developments are continuing in the form of ash-melt low-NOx boilers targeting coal, but because the price of petroleum has fallen, the need to convert oil-fired boilers using this technology to coal-fired boilers has declined. Although the objective was to pressurize CPC and to then apply it to gas-turbine-based combined cycle power generation systems, no tests to further scale up the technology have been undertaken following comparisons and explorations vis-à-vis other technologies.

As this technology evolves, it will be applied to low-NOx technologies such as swirling melting furnaces for use as municipal waste gasification furnaces as well as to heavy oil ultra-low NOx boilers.
Part 2 CCT Overview

B. Technologies for High-Efficiency Applications

B-06-06. Pressurized Fluidized Bed Combustion Technology (PFBC)

Japan Coal Energy Center and J-POWER
METI-subsidized project
FY1989 – FY1999 (11 years)

Technology Overview

1. Background and underlying process

(1) The research and development of pressurized fluidized-bed combined power generation technology was conducted at J-POWER's Wakamatsu Coal Utilization Research Center (now known as Wakamatsu Research Institute) using a 71-MWe-PFBC plant, the first PFBC plant in Japan. This test plant was the first in the world to adopt a full-scale ceramic tube filter (CTF) capable of collecting dust from high-temperature, high-pressure gas. Figure 1 shows a flowchart of the overall process of this technology.

(2) Overview of the Facilities:
- Plant output: 71.0 MWe
- Pressurized fluidized-bed combustion boiler (manufactured by ABB and IHI)
- Bubbling pressurized fluidized-bed and coal paste (70% - 75%) feeding method
- Combustion temperature: 860°C
- Combustion air pressure: 1 MPa

2. Development objectives and technology needing development

PFBC technology development objectives
(1) High efficiency combined power generation utilizing pressurized fluidized-bed combustion with a gross efficiency of 43%.
(2) Favorable environmental characteristics—including, SOx reduction based on intra-furnace desulfurization, NOx reduction based on low-combustion temperatures (approximately 860°C), and CO2 reduction resulting from its underlying high efficiency.
(3) Space savings are achieved at the plant installation thanks to a compact pressurized boiler and the elimination of the desulfurization unit. PFBC technological development results

PFBC technological developments have achieved the following:
(1) A gross efficiency of 43% was achieved by employing combined power generation utilizing a pressurized fluidized-bed configuration.
(2) SOx levels of approx. 5 ppm due to intra-furnace desulfurization, NOx levels of approx. 100 ppm due to the use of low combustion temperatures (approximately 860°C), and dust on the order of 1 mg/Nm3 or due to the CTF.
3. Development timeline and progress to-date

Detailed design of the facilities began in 1990, and construction began in August 1992. In October of the same year, installation of equipment and machinery started. In April 1993, test operations began, and in the following September, coal feeding was initiated. In January 1994, a 100% operational load was achieved, in September of that same year, the two-stage cyclone system passed pre-operation inspections, and that December, the CTF system passed pre-operation inspections. Phase 1 of the demonstration test was conducted up until December 1997. Subsequently, the plant was modified to incorporate an ash-recycling PFBC boiler. Phase 2 of the demonstration test was conducted from August 1995 to December 1999. Phase 1 totaled 10,981 hours of operation, and phase 2 totaled 5,156 hours, for a cumulative operating time of 16,137 hours for the test.

In phase 2, 1,508 hours of continuous operation was achieved, making it possible to acquire valuable data and knowledge regarding performance and reliability characteristics. Three power companies—J-POWER, Chugoku Electric Power Co., Ltd., and Hokkaido Electric Power Co., Ltd.—have already utilized the results to expand into the construction of commercial facilities.

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4. Future issues and feasibility outlook

Due to the versatility in the types of fuel that can be used with PFBC technology, such as difficult to combust, low-quality waste, intra-furnace desulfurization, denitration (with or without catalysts), and high-temperature ultra-precision dust removal characteristics can achieved. This is evidenced by SOx levels of 10 ppm or less, NOx levels of 10 ppm or less, and coal dust concentrations of 1 mg/Nm³ or less. Similarly, because of the space savings it can achieve in plant facilities due to the lack of a need for desulfurization devices, PFBC is suitable for urban installations. Pursuit of economic feasibility in implementations of such system will be a topic of future concern.

Of the commercial equipment established by the three power companies, only the Kanda New No. 1 unit PFBC (360MW), which began operations in 2001, is continuing to run, as the other two systems have been discontinued. With the commercialization of USC and the commercialization of IGCC, PFBC has lost some of its competitive edge from the standpoints of price and efficiency, and plans to follow up the Kanda New No. 1 PFBC have dried up. Among other PFBC systems, the Chugoku Electric Power Company’s Osaka Power Station 1 Unit No. 1 was deactivated in December 2011 and the Hokkaido Electric Power Company’s Tomato Atsuma Power Station Unit No. 3. shutdown in October 2005. In both cases, deactivation and shutdown were attributed to their low availability.

References
B. Technologies for High-Efficiency Applications

1. Overview
The development of high-efficiency power generation technology for utilizing coal is an urgent issue from the standpoint of reducing global warming and conserving resources. Advanced pressurized fluidized bed combustion (A-PFBC) technology is an advance over pressurized fluidized bed combustion (PFBC) that combines PFBC with a fluidized bed gasification technology. This increases the gas turbine inlet temperature from approximately 850°C to approximately 1350°C while also making it possible to recover high-temperature stream. The result is higher power generation efficiency—roughly 46% (net efficiency base) compared with 40% in current coal-fired plants. See Figure 1 for a system overview.

2. Development objectives
(1) High-efficiency power generation (net efficiency of 46%)
   • Increase in gas turbine inlet temperature from approx. 850°C to 1350°C
   • Recovery of high-temperature steam (recovery of high-temperature steam using a synthesized gas cooler through the adoption of a high-temperature desulfurization furnace)
(2) Mitigation of gasification conditions (carbon conversion on the order of 85%)
   • Due to its combination with an oxidizing furnace (and thus a perfect complete oxidizing atmosphere), 100% gasification is achieved in the partial oxidizing furnace
(3) Utilization of the benefits of related technologies
   • PFBC technology
   • Various coal gasification technologies
3. Development advances and results

With the aim of readying the above-described system for real-life applications, a small-scale process development test unit (see photo of PDU in Figure 3) was installed at J-POWER's Wakamatsu Research Institute in Kita Kyushu City. PDU test operations began in July 2001. By the end of 2002, the system had logged 1,200 hours of cumulative gasification operations time with 190 hours continuous operation. This PDU test confirmed that the three reactors—namely, the oxidizing furnace, partial oxidizing furnace, and desulfurization furnace—could operate together in an integrated fashion. The test also made it possible to obtain the characteristics of each furnace while deriving data that would be needed to scale up the system. Upcoming development issues will include the validation of a pilot system used in combination with a gas turbine.

(1) Overview of the process development test unit (PDU) test

The objectives of the test were to obtain the operating characteristics and reaction characteristics of the three furnaces (see Figure 2), validate the process, and acquire scale-up data. Objectives specifically included:

- Validating a system that integrates the three types of furnace units
- Confirming the performance of the individual systems (oxidation, gasification, and desulfurization)
- Ascertaining basic operation methods
- Acquiring various characteristics and obtaining scale-up data

Figure 2 PDU: Schematic layout of the three reactors

Table 1 Development timeline of the A-PFBC system

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4. Future issues and outlook for practical implementation

A-PFBC systems have been studied with the aim of improving existing PFBC technology. Specifically, by combining PFBC with a coal gasification process, and by then burning the gas produced through gasification in a gas turbine, A-PFBC systems increase the temperature at the gas turbine inlet so as to increase efficiency. However, just as with PFBC systems, commercialization of this technology may be difficult to achieve given the stiff competition from USC and IGCC systems. Concrete plans for full-scale implementations remain on hold for the time being.

References

"A-PFBC" Preprint for the 13th Coal Utilization Technology Congress. Sponsored by the Center for Coal Utilization (JCOAL).
Part 2 CCT Overview

B. Technologies for High-Efficiency Applications

B-06-08. Advanced Ultra-Supercritical (A-USC) Thermal Power Generation Technologies


NEDO-commissioned project, METI subsidized project

FY2006 – FY2007 (2 years)
FY2008 – FY2016 (9 years)

Technology Overview

1. Development objectives

The main form of coal-fired power generation found in Japan employs a highly efficient technology known as ultra-supercritical (USC) thermal power generation having steam temperatures on the order of 600°C. Technological developments are now underway for an even more efficient technology known as advanced ultra-supercritical (A-USC) thermal power generation, boasting steam temperatures to approximately 700°C. Through the development of A-USC systems, reductions in CO₂ emissions are being achieved, and this in turn should help promote the stable and continuous utilization of coal in the future. As shown in Figure 2, the target of net thermal efficiency is 46% - 48% (HHV). This constitutes a 10% - 15% increase in efficiency over the latest USC systems, while also achieving a 10% - 15% reduction in carbon dioxide emissions. Japan is the world’s leader in technologies for the boiler, turbine, and other main components of A-USC systems, ensuring that the nation will be competitive in the power generation facilities market of the future.

2. Technology overview

Materials resistant to degradation under steam conditions at 700°C, pipe bending and welding technologies, technologies for manufacturing steam turbine rotors, and high-temperature valves are the core technologies needed in this field. Development efforts are underway in earnest to resolve these issues.
3. Current status and development timeline

As shown in Table 1, over a nine-year period from 2008 - 2016, Japan will develop the component technologies required for implementation of A-USC systems. The manufacturer, research institute, and power company have organized an A-USC development promotion committee, and are promoting development using a project-based system. Except for the long-term 100,000-hour creep test, nearly all of the component testing was completed in the first five years of the project. In 2015 and 2016, a test was performed using actual boilers, and a turbine rotor rotation test was also conducted. Going forward, the intention is to introduce machinery for commercial use in the 2020s after having passing through a demonstration test phase.

Looking at international developments, Europe is ten years ahead of Japan in A-USC system development, but due to failures during the demonstration test and a lack of funding, development has stagnated. As for the United States, there are no boiler makers aiming to develop this technology, but they are focusing their efforts on materials development and on the regularization and standardization of materials based on a rich experience in Ni-based alloys. China has recently launched development in this field and is aiming for technological advances in the short term. Their development status will warrant close watching in the future.

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<td>System design / Design technical developments</td>
<td>Basic design, Layout optimization, Cost computations</td>
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<td>Boiler Materials development</td>
<td>Development of new materials for use with large-diameter pipes and heat transfer pipes</td>
<td>Testing of extended high-temperature materials (30,000 - 70,000 hours)</td>
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<td>Verification of the manufacture ability of materials</td>
<td>Development and testing of welding technology / bending test</td>
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<tr>
<td>Turbine Materials development</td>
<td>Creation of material specifications</td>
<td>Testing with life-size components</td>
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<tr>
<td>Large-size welding technology for rotors and casing, and testing</td>
<td>Testing of extended high-temperature materials (30,000 - 70,000 hours)</td>
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<tr>
<td>High-temperature valves Development of materials, components, and configuration</td>
<td>Prototype</td>
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<tr>
<td>Test with actual vessels, rotation test(including high-temperature valves)</td>
<td>Design plan / Facilities design</td>
<td>Equipment manufacture and installation</td>
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<td>Testing and evaluation</td>
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</table>

4. Technology developments

(1) Boiler technology

The development issues to be addressed for boiler technology include the following: manufacturing technologies including pipe materials, pipe processing, and welding; corrosion in materials at high-temperature; confirmation of long-term strength evaluations; and verification during demonstration testing using actual vessels. Of those, one of the most important component developments will be the long duration testing of materials at high temperature, as it is essential to verify the long-term reliability of materials at 700° C. In the actual vessel tests to be performed in 2015 and 2016, comprehensive verifications will be made of the component technologies from the first half of the project. To confirm the lifetime of the materials, an extended high-temperature test will be continued from 2017 onward with the goal of achieving 100,000 total hours of operation.

(2) Steam turbine technology

The aspects of steam turbine technology requiring technological development and verification include the following: materials development for the rotors, casing, vanes, and bolts; structure tests of each component; and manufacturing technologies such as forging, welding, and cutting; evaluations of lifetime and remaining life; and inspection technologies. Rotor materials were developed in advance under a NEDO-commissioned project over the course of two years from 2006 to 2007, in which a turbine manufacturer developed a Ni-based rotor material. In 2008 and after, efforts turned to the scale-up of the Ni-based rotor, welding of Ni-based alloy paired members, and vane member welding technologies for Ni-based alloys and steel materials. This year, a welded rotor for rotation testing use is being manufactured. In the turbine rotation test, strong centrifugal forces will be applied under a high-temperature environment of 700° C. In this way, the reliability of the rotors and vanes under actual conditions will be verified.

(3) High temperature valve technology

Areas requiring technological development and verification for high-temperature valves include the casing material for large valves operating at high-temperature, high-temperature sliding materials for the valve stem, valve seat materials, and packing.

5. Future outlook

In addition to regularizing and standardizing the materials that have been developed and verified, maintenance technologies such as remaining life diagnostic technologies and inspection technologies must be developed. Full-fledged efforts will also be undertaken to help implement A-USC technologies.
B-07-01. Formed Coke Manufacturing Technology

Japan Coal Energy Center and the Japan Iron and Steel Federation

METI-subsidized project

FY1978 – FY1986 (9 years)

**Technology Overview**

1. Overview

   The continuous formed coke manufacturing method uses non-caking coal as the main raw material. The coal is shaped using a binder. It is then carbonized in its formed shape in a carbonizing furnace, where it is dried into coke.

2. Characteristics

   As shown in Figure 1 (following page), the continuous coke forming process is made up of a series of steps that include processing and forming the raw material and then drying and cooling the formed coal. A notable feature is the fact that drying and cooling are performed in a coke-carbonizing furnace, where the material is dried and then cooked. Compared to conventional chamber ovens, this enclosed system has significant advantages in terms of the work environment, work productivity, ease of system startup and shutdown, and space savings.

3. Research results

   [1] Production of formed coke from 100% non-caking coal

   Although the pilot plant normally operated using a blend of 70% non-caking coal and 30% caking coal, operation was also achieved using 100% non-caking coal.


   In the pilot plant, long term operations at full capacity of 200 tons/day, and operations at 300 tons/day (1.5 times large as designed capacity) were achieved. Regarding the heat requirement, 320 Mcal/ton-formed coke was also achieved.

   [3] Extended continuous operation test in a large-scale blast furnace

   The long-term continuous operation was tested over a 74-day period. In this test, a 20% formed coke blend was used at the base operating condition and a 30% blend at maximum was used to confirm that the formed coke could be used in the same way as a conventional chamber oven coke.

4. Research and development timeline

   Table 1 shows the timeline of research and development for this technology.

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<tr>
<td>Component research</td>
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<td>Pilot plant test</td>
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<td>Construction</td>
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<td>Testing operations</td>
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</table>
Clean Coal Technologies in Japan

This technology was employed on a large-sized blast furnace in 1986 and then terminated. At that time, due to the differences in shape, only 30% of the produced coke could be interchanged for conventional chamber oven based coke. For that reason, once development was completed, no steps were taken to bring this technology to commercial operation. However, the formed coke production technology has subsequently been used as a ferro-coke production technology.

5. Future issues and outlook for practical implementation

The formed coal is fed to a carbonization furnace (5), where the coal passes through a low-temperature carbonization zone (6). It is then heated to 1000°C in the high-temperature carbonization zone (7) so that it can undergo carbonization. The speed at which it is heated is controlled to prevent the formed coal from disintegrating due to expansion and contraction. The carbonized coke is cooled to 100°C or below in a cooling zone (8) using ambient temperature gas injected from the bottom of the furnace, and is then discharged from the furnace.

The coke oven gas exiting the top of the furnace at 300 - 350°C is cooled first by a precooler (9) and then by a primary cooler (10). After tar mist is removed (11), most of the gas is circulated back to the furnace. Any surplus gas is extracted from the system for purification and desulfurization, after which it may be used as a clean fuel having a high calorific value of 3,800 kcal/Nm³.

After the tar mist has been removed by the electric precipitator, the gas is heated to approximately 1000°C by the high-temperature gas heating furnace (13), and is then blown into the high temperature carbonization zone (7). After being heated to 450°C by the low-temperature gas heating furnace (14), the gas is used to drive the ejector (15). The ejector draws in the high temperature gas that acquired heat while being used to cool the coke, and the gas is then supplied to the low-temperature carbonization zone (6) at a temperature of approximately 600°C.

The liquid in the gas is led to the decanter (12), where the ammonia liquor and tar are separated by decantation and precipitation. Each of these byproducts is sent to respective existing plants for further treatment. After treatment, the tar is reused as a binder for the formed coke.

Figure 1 Flowchart of continuous formed coke production
B. Technologies for High-Efficiency Applications

1. Overview

In Japan, efforts to inject pulverized coal into blast furnaces were first undertaken in 1981 by Nippon Steel Corporation using their Oita No.1 blast furnace. Although the main reducing material in blast furnaces is coke, starting in the 1960s, blast furnace operators began to use heavy oil as an auxiliary fuel, injecting it through tuyeres to enhance productivity, efficiency, and scale. After the two oil crises, however, the high price of heavy oil forced operators to switch back to using coke exclusively, relying on coke alone as the reducing material. This left companies searching for a way to reduce blast furnace operating costs and stabilize their operation through the introduction of an inexpensive auxiliary fuel that could substitute for heavy oil.

An ARMCO pulverized coal injection system was installed at the Oita No. 1 blast furnace, making it the first in Japan to employ this technology (see Figure 1). This approach has the following advantages.

1. Wear and tear is lower because there are no mechanically rotating components in the high-pressure feeds and injection lines.
2. No recycling of gas, assuring reliable operation.
3. The geometrically symmetrical flow characteristics of fluids are utilized to ensure a uniform distribution of pulverized coal to the tuyeres.
4. To ensure stable blast furnace operations, the drying, pulverization, and collection of coal is conducted in two parallel lines.
5. The velocity of transport air and pressure resistance of equipment are set to preventing fires and explosions.

Although this technology had been deployed successfully overseas, taking into consideration differences in equipment scale, system configuration, and operating conditions in Japan, testing and study was conducted on the following issues with the results being reflected in subsequent system design.

1. Pulverized coal combustion test: This test assessed the effects of various factors, including the brand and size of the pulverized coal, the pressure, temperature and oxygen enrichment of the blast air that is supplied.
2. Model plant test (1 t/h): This test assessed coal processing, transport, and control.
3. Test to inject coal through a single tuyere into an actual furnace: This test evaluated the combustibility at the tuyere of an actual furnace and the sampling of coke in the furnace.
4. Test on the balance of the circumferential distribution of pulverized coal: This test ascertained the powder flow characteristics and measured the distribution accuracy using a full-sized model.

2. Development objectives and areas needing further advance

3. Development status and results

The capacity of the Oita No. 1 blast furnace Unit No. 1 was set to 80 kg/t taking into consideration the rate of heavy oil injection during increased production periods and actual performance results over the long term. Two series of 25 t/d coal mills were equipped. Following startup, the equipment operations and injection operations functioned smoothly, indicating that a stable production system had been established. Following the success of the Oita No. 1 blast furnace, Godo Steel started a proprietary system in 1982. Shortly thereafter, in 1983, Kobe Steel Ltd. installed a Kobelco system at its Kakogawa No. 2 blast furnace and Kobe No. 3 blast furnace incorporating technology from Petrocarb of the U.S. Then, in 1984, full-scale ARMCO systems were incorporated into Nippon Steel's Nagoya No. 1 blast furnace and Nisshin Steel's Kure No. 2 blast furnace. In 1986, pulverized coal injection equipment was installed in 16 blast furnaces throughout Japan, constituting 50% of such furnaces in the nation. By 1996, that number was 25 blast furnaces, and by 1998, all of the nation's blast furnaces were utilizing this technology. This increased the average domestic pulverized coal ratio to 130 kg/t (see Figure 2). Table 1 shows various injection methods being used in blast furnace pulverized coal facilities, and Table 2 shows the highest level attained in Japan for the typical operational index of blast furnaces utilizing pulverized coal injection technology.
Now that the average lifespan for domestic coke ovens has reached approximately 40 years, the importance of pulverized coal injection technology as a means of providing auxiliary fuels is increasing year by year. Compared to coke, which depends on caking coal, hopes for pulverized coal injection are high given that it can facilitate a more elastic utilization of coal resources. Pulverized coal injection technology has the potential to be incorporated into combined injection scenarios where, for example, reduced ores or reducing materials such as biomass or waste plastic are injected into the furnaces via the tuyeres. With such innovations, the technology is expected to develop into a core blast furnace technology that can help address today's concerns surrounding carbon dioxide emissions, energy production, and resource availability.

Although pulverized coal injection into blast furnaces is a technology that had experienced some success internationally, following its test application to a large-scale blast furnace at Nippon Steel's Oita blast furnace No. 1 in 1981, it came to be adopted successively to other blast furnaces within Japan, and by 1998, had been adopted by every blast furnace in the country. As of 2012, average domestic usage reached a 168 kg/t-molten pig iron, which is one half of the 342 kg/t-molten pig iron of coke used.

### Table 1 Pulverized Coal Injection Systems for Blast Furnaces

<table>
<thead>
<tr>
<th>Method</th>
<th>Distribution and transport</th>
<th>Pneumatic delivery</th>
<th>Flow Velocity</th>
<th>Branch pipe flow rate control</th>
<th>Users</th>
<th>Equipment costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petrocarb</td>
<td>Pneumatic delivery from feed tank directly to each tuyere via piping</td>
<td>Low</td>
<td>High</td>
<td>Carrier gas pressure and flow rate (Downtake)</td>
<td>National Steel, Kobe Steel, JFE (NKK)</td>
<td>Moderate</td>
</tr>
<tr>
<td>DENKA</td>
<td></td>
<td>Low</td>
<td>High</td>
<td>Same as above / flow meter</td>
<td>JFE (Kawasaki Steel)</td>
<td>Moderate</td>
</tr>
<tr>
<td>Kuettner</td>
<td></td>
<td>High</td>
<td>Low</td>
<td>Same as above (using uptake)</td>
<td>Thyssen</td>
<td>High</td>
</tr>
<tr>
<td>formerly PW</td>
<td></td>
<td>Medium</td>
<td>Low</td>
<td>Rotary valve</td>
<td>Dunkerque</td>
<td>Moderate</td>
</tr>
<tr>
<td>Simon Macawber</td>
<td></td>
<td>Low</td>
<td>High</td>
<td>Slurry pump</td>
<td>Scunthorpe</td>
<td>High</td>
</tr>
<tr>
<td>ARMCO</td>
<td>Sent from the feed tank to a distributor via a main pipe, and then delivered pneumatically to each tuyere</td>
<td>Low</td>
<td>High</td>
<td>Uniformly distributed to give uniform pressure drop across individual pipes</td>
<td>Nippon Steel Corp., Hoogovens</td>
<td>Low</td>
</tr>
<tr>
<td>new PM</td>
<td></td>
<td>High</td>
<td>Low</td>
<td>Uniformly distributed by throttled pipes</td>
<td>Sidmar, Solac Fod</td>
<td>Low</td>
</tr>
<tr>
<td>Klockner</td>
<td></td>
<td>High</td>
<td>Low</td>
<td>Same as above (using uptake)</td>
<td>Dunkerque, Taranto</td>
<td>Low</td>
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<tr>
<td>Sumitomo Metal Mining Co., Ltd</td>
<td></td>
<td>Low</td>
<td>Low</td>
<td>Rotary feeder / uniform pressure drop distribution</td>
<td>Sumitomo Metal Mining Co., Ltd</td>
<td>Moderate</td>
</tr>
</tbody>
</table>

### Table 2 Highest domestic indices for blast furnaces with pulverized coal injection

<table>
<thead>
<tr>
<th>Month and Year</th>
<th>Steel work and blast furnace</th>
<th>Coal dust ratio kg/t</th>
<th>Coke ratio kg/t</th>
<th>Ratio of reducing material kg/t</th>
<th>Tapping ratio t/d/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum pulverized coal ratio (PCR)</td>
<td>Fukuyama blast furnace No.3</td>
<td>266</td>
<td>289</td>
<td>555</td>
<td>1.84</td>
</tr>
<tr>
<td>Minimum coke ratio (CR)</td>
<td>Kobe blast furnace No.3</td>
<td>214</td>
<td>288</td>
<td>502</td>
<td>2.06</td>
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<tr>
<td>Minimum reducing material ratio (RAR)</td>
<td>Oita blast furnace No.1</td>
<td>122</td>
<td>342</td>
<td>464</td>
<td>1.95</td>
</tr>
<tr>
<td>Maximum tapping ratio</td>
<td>Nagoya blast furnace No.1</td>
<td>137</td>
<td>350</td>
<td>487</td>
<td>2.63</td>
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</tbody>
</table>

## 4. Future issues an implementaion status

Now that the average lifespan for domestic coke ovens has reached approximately 40 years, the importance of pulverized coal injection technology as a means of providing auxiliary fuels is increasing year by year. Compared to coke, which depends on caking coal, hopes for pulverized coal injection are high given that it can facilitate a more elastic utilization of coal resources. Pulverized coal injection technology has the potential to be incorporated into combined injection scenarios where, for example, reduced ores or reducing materials such as biomass or waste plastic are injected into the furnaces via the tuyeres. With such innovations, the technology is expected to develop into a core blast furnace technology that can help address today's concerns surrounding carbon dioxide emissions, energy production, and resource availability.

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### References

Waguri, Shinjiro. Ferrum. vol. 8 (2003), p. 371
B-07-03. Steelmaking with the Direct Iron Ore Smelting (DIOS) Reduction Process

**Research and Development**

Japan Coal Energy Center and the Japan Iron and Steel Federation

**Project Type**

METI-subsidized project

**Development Periods**

FY1988 – FY1995 (8 years)

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### Technology Overview

#### 1. Overview

The direct iron ore smelting (DIOS) reduction process is a technology that can utilize iron ore or powdered or granular non-caking coal iron ore without requiring sintering or coke methods, which are normally required in blast furnaces. Non-caking coal may be fed directly into a smelting reduction furnace, while iron ore must be reduced before being fed into the furnace. The product is molten iron.

#### 2. Features

DIOS technology has many advantages including:

1. Inexpensive raw materials such as non-caking coal and in-house dust may be used.
2. Operating costs are low.
3. It can respond flexibly to fluctuations in production rates.
4. The equipment is compact and the associated investment costs are low.
5. The availability of high-quality iron resources is stable.
6. Coal energy is utilized effectively.
7. Energy may easily be co-produced (cogeneration).
8. Environmental loads are low. Specifically, SOx, NOx, and CO2 emissions are low, coal dust is minimal, and there is no leakage of coke furnace gases.

#### 3. Research results

A feasibility study was conducted on the installation of a commercial plant incorporating blast furnace and DIOS methods at a seaside location. The advantages of the DIOS method over the blast furnace method were demonstrated using a 6,000-ton molten iron model (with annual production of 2 million tons) as outlined below.

- Investment costs were reduced by 35%.
- Molten iron production costs fell by 19%.
- The amount of coal consumed per ton of molten iron production came to 730 - 750 kg, which is nearly equivalent for blast furnace method.
- Net energy consumption fell by 3% - 4%.
- CO2 emissions in the iron making process also decreased by 4% to 5%.

#### 4. Research and development timeline

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<td><strong>Pilot plant test</strong></td>
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<td>Testing operations</td>
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1) **Component Research (FY1988 - FY1990)**

During this phase the core component technologies required to construct a pilot plant were established. These included increasing the thermal efficiency of the smelting reduction furnace (SRF), the development of technology to be integrated with a preliminary reduction furnace (PRF), advances in molten slag discharge technology, and scaling up of the SRF.

2) **Pilot Plant Testing (FY1993 – FY1995)**

Pilot plant testing focused on three main areas of research:

- The feasibility of using powdered and granular ore and coal directly was confirmed, and necessary equipment specifications were determined.
- The equipment and operating specifications needed to achieve high thermal efficiency as an alternative to blast furnaces were ascertained under various raw material conditions.
- A conceptual design of commercial plant, including a water-cooling technology for the furnace, was completed and an economic feasibility study was undertaken. Through their results, the researchers clarified that the equipment and operating conditions would constitute significant advances over blast furnace technology.
A pilot plant test was conducted in 1995 to test the direct iron ore smelting reduction process (DIOS). Although a reduction in CO₂ emissions and other initial targets were achieved, due to high energy unit prices in Japan and because large-scale blast furnaces were widespread throughout the country, commercialization did not take hold. At some new facilities for mid-sized steel manufacturing plants overseas, because the DIOS method proved more economical than using a blast furnace, efforts were made to disseminate the technology in Southeast Asia. At the present time, however, there is no real need for the construction of new steelmaking facilities in Southeast Asia, and a DIOS system has yet to be implemented.

5. Future issues and implementation outlook

Figure 1 Example operation of a DIOS pilot plant (1-ton molten iron)
Part 2 CCT Overview

B. Technologies for High-Efficiency Applications


<table>
<thead>
<tr>
<th>Research and Development</th>
<th>Japan Coal Energy Center and the Japan Iron and Steel Federation</th>
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<tbody>
<tr>
<td>Project Type</td>
<td>METI-subsidized project</td>
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<tr>
<td>Development Periods</td>
<td>FY1994 – FY2003 (10 years)</td>
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Technology Overview

1. Background and process status

Coal is rapidly heated at 350° C to induce low-temperature carbonization and then introduced into a coke oven at 850° C in the SCOPE21 technology. This process can achieve an energy savings of 20% over current methods, where the coke oven is held at 1200° C. Unfortunately, the current process also invites a host of problems. In addition to inherent environmental issues and an energy-intensive configuration, this process limits the rank of coal that can be used, as constraints on coke strength necessitate the use of strongly caking coal. Now that coke ovens in Japan have reached an average lifespan of 30 years and need to be replaced in the near future, there is a need to develop a revolutionary next-generation coke production technology that excels in productivity, energy savings, and environmental friendliness while exhibiting flexibility in the type of coal resources that may be used. Accordingly, efforts are being made to develop a new coke formation technology, As shown in the Figure 1, based on current coke production processes, the SCOPE 21 process is divided into three stages: 1) rapid coal pre-heating, 2) rapid carbonization, and 3) low / medium temperature carbonization. A revolutionary process was developed by pursuing the goals of each step to the fullest while balancing their overall roles. SCOPE 21 is just one large development for new coke processing technologies in the word. Hopes are high that it will one day be put to practical use.

2. Development objectives and technologies to be developed

(1) Increasing the ratio of non-caking powdered coal usage to 50%

The ratio of poor coking coal at present is only 20%. With the aim of increasing that ratio to 50%, work will be undertaken to develop a technology that increases the coal caking quality through rapid preheating and also increases the bulk density of charged coal through drying and briquetting fine coal.

(2) Tripling productivity

With the aim to triple productivity over the current levels, carbonization time will be greatly reduced by increasing the thermal conductivity of the carbonizing chamber's walls and discharging the material at lower temperatures than the existing condition, low/medium temperature carbonization. The resulting insufficient carbonization temperature is compensated for by reheating in the coke dry quenching (CDQ) unit to ensure good product quality.

(3) Reducing NOx emissions by 30% and achieving a smoke-free, odor-free, and dust-free environment

Through hermetically sealed coal transport based on a plug-transport method and the prevention of gas leaks from the coke furnace by intra-furnace pressure control, it will become possible to fully prevent the generation of smoke, dust, and odors that normally accompanies coke production. In addition, low NOx emissions will be sought through improvements to the combustion configuration of the coke oven.

(4) Energy savings of 20%

The energy needed to produce coke will be reduced 20% by increasing the initial carbonization temperature through preheating of the charged coal to a high temperature and by decreasing the coke discharge temperature. Also it becomes easy to recover the sensible heat of the combustion exhaust gas and produced gas through facility downsizing achieved due to high productivity.

3. Development advances and results

Japan Coal Energy Center and the Japan iron and Steel Federation conducted this project jointly. A 6-t/h pilot plant was built at Nippon Steel Corporation's Nagoya Works (see Photo 1), and test operations were conducted.
Energy Savings and Economic Assessment

The SCOPE 21 process was established as a compilation of revolutionary advanced technologies, and as such can achieve energy savings, protect the environment, and facilitate the effective use of coal resources. As a result, it has major economic advantages over conventional processes.

| Facilities cost evaluation: percentages relative to current facilities costs |
|--------------------------|----------|----------------|----------------|
| Current process          | Coke Oven | Pretreatment | Common Environmental Measures |
| SCOPE21                  | 40       | 25           | 19             |
| Current process cost     | 100      | 11           | 84             |

- **Energy Savings**
  - Thanks to direct heating of coal using pretreatment processes and the heat recovery of sensible heat from each process, the coke oven achieves high efficiency, resulting in a 21% energy reduction.
- **Construction Costs**
  - Although environmental countermeasures and coal preprocessing equipment result in a cost increase, the facilities cost reduction for the coke oven creates a major savings, making a 16% reduction in equipment costs possible.
- **Coke Production Costs**
  - While utilities costs for fuel gas and electricity are higher due to coal pretreatment processes, overall coke production costs actually drop by 18% due to reductions in facilities costs and the blending of non-powdered caking coal.

![Image of energy savings assessment](image)

![Image of production costs assessment](image)

<table>
<thead>
<tr>
<th>Table 1 Research and development timeline</th>
</tr>
</thead>
<tbody>
<tr>
<td>------</td>
</tr>
<tr>
<td>Survey and research</td>
</tr>
<tr>
<td>Component technology development</td>
</tr>
<tr>
<td>Component combination testing</td>
</tr>
<tr>
<td>Pilot plant test</td>
</tr>
<tr>
<td>Construction</td>
</tr>
<tr>
<td>Testing operations</td>
</tr>
<tr>
<td>Dismantling</td>
</tr>
</tbody>
</table>

4. Status of implementation

As a substitute for formed coke, which can only be used partially, SCOPE 21 was developed in 2003 as technology to update aging coke furnaces currently running in Japan. In May 2008, operations were performed at Nippon Steel and Sumitomo Metal’s Oita steel plant, which is shown in Photo 2, and Nippon Steel and Sumitomo Metal’s Nagoya steel plant, which is shown in Photo 3. At present, two commercial plants are in operation, contributing to a reduction in CO2 from iron and steel works and enabling the utilization of low-rank coal. Additionally, low-NOx combustion technology may also be applied to conventional, newly constructed coke ovens.

![Photo 2 Oita Coke Oven No.5](image)

![Photo 3 Nagoya Coke Oven No.5](image)

References

Part 2 CCT Overview

B. Technologies for High-Efficiency Applications

## B-07-05. Coke Dry Quenching (CDQ) Systems

### Technology Overview

#### 1. Overview

In order to enhance the thermal efficiency of carbonization, coke ovens are formed in such a way that plate-like coking chambers are alternately arranged in a sandwich-like configuration. The raw material inside the coking chambers is heated to a temperature of 1100°C - 1350°C by combusting blast furnace gas in the combustion chambers located on both sides of the coking chambers beyond the refractory brick. Air is kept out for 12 - 14 hours as carbonization proceeds. During this process, the fixed carbon in the raw material fuses and solidifies to become red-hot coke in the lower portion of the coking chamber, while the volatile matter vaporizes and decomposes, turning into gas. The gas is then collected in the ducts located at the top of the coking chambers. Once carbonization is complete, red-hot coke at a temperature of approximately 1050°C is discharged from the coke oven and conveyed to the top of the chamber, where it is then fed into the circulating gas, which by now has been heated to 800°C or greater, is used to produce high-temperature, high-pressure steam in the boiler. A dust collector removes dust from the gas, and it is sent back to the chambers to be recycled. The steam that was produced is used as process steam for power generation.

![Energy recovery balance](image)

**Figure 1 Energy recovery balance**

### Table 1 Sample of CDQ operation data

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>56t/hr</td>
</tr>
<tr>
<td>Temperature of charged coke</td>
<td>1000-1050°C</td>
</tr>
<tr>
<td>Temperature of discharged coke</td>
<td>200°C</td>
</tr>
<tr>
<td>Gas inlet temperature</td>
<td>170°C</td>
</tr>
<tr>
<td>Gas outlet temperature</td>
<td>800-850°C</td>
</tr>
<tr>
<td>Steam production rate</td>
<td>25t/hr</td>
</tr>
<tr>
<td>Steam pressure</td>
<td>40kgf/cm²</td>
</tr>
<tr>
<td>Steam temperature</td>
<td>440°C</td>
</tr>
<tr>
<td>Total gas volume</td>
<td>84,000Nm³/hr</td>
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</table>

### Table 2 Comparison of CDQ coke quality

<table>
<thead>
<tr>
<th>Item</th>
<th>Wet quenching</th>
<th>Dry quenching</th>
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<tbody>
<tr>
<td>Water content (%)</td>
<td>2-5</td>
<td>0.1-0.3</td>
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<tr>
<td>Ash content (%)</td>
<td>11.35</td>
<td>11.39</td>
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<td>Volatile components (%)</td>
<td>0.50</td>
<td>0.41</td>
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<tr>
<td>Average particle size (mm)</td>
<td>65</td>
<td>55</td>
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<tr>
<td>Powder rate (after cut) (-15 mm)</td>
<td>10</td>
<td>13</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>49</td>
<td>48</td>
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<tr>
<td>DI (％)</td>
<td>83.5</td>
<td>85.5</td>
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<tr>
<td>DI (%)</td>
<td>12.9</td>
<td>17.9</td>
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<td>Strength after small reaction (%)</td>
<td>50</td>
<td>52</td>
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### Table 3 Composition of circulating gas

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<tr>
<th>Gas</th>
<th>CO₂</th>
<th>CO</th>
<th>H₂</th>
<th>N₂</th>
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<tr>
<td></td>
<td>10-15</td>
<td>8-10</td>
<td>2-3</td>
<td>70-75</td>
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### Table 4 CDQ facilities

<table>
<thead>
<tr>
<th>Company</th>
<th>Plant</th>
<th>Targeted furnace units</th>
<th>Coke processing rate (unit)</th>
<th>Plants</th>
<th>Steam (SH)</th>
<th>Pressure (kg/cm²)</th>
<th>Temperature (℃)</th>
<th>Placed in service</th>
<th>Placed</th>
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<tr>
<td>Nippon Steel</td>
<td>Oita</td>
<td>No. 1, 2</td>
<td>190 (1)</td>
<td>Plants</td>
<td>112.0</td>
<td>95</td>
<td>520</td>
<td>Oct. 1988</td>
<td></td>
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<td></td>
<td>Oita</td>
<td>No. 3, 4</td>
<td>180 (1)</td>
<td>Plants</td>
<td>92.5</td>
<td>93</td>
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<td></td>
<td>Yahata</td>
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<td>175 (1)</td>
<td>Plants</td>
<td>120.0</td>
<td>75</td>
<td>495</td>
<td>Feb. 1987</td>
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<td></td>
<td>Nagoya</td>
<td>No. 1, 2</td>
<td>106 (1)</td>
<td>Plants</td>
<td>65.0</td>
<td>117</td>
<td>525</td>
<td>Sept. 1985</td>
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<td>Nagoya</td>
<td>No. 3</td>
<td>96 (1)</td>
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<td></td>
<td>Nagoya</td>
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<td>129 (1)</td>
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<td>71.4</td>
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<td>Jan. 1988</td>
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<td>64</td>
<td>490</td>
<td>Jul. 1981</td>
<td></td>
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<td>JFE Steel</td>
<td>East Japan</td>
<td>No. 5</td>
<td>100 (1)</td>
<td>50.2</td>
<td>52.5</td>
<td>436</td>
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<td></td>
<td>(Chiba)</td>
<td>No. 6, 7</td>
<td>56 (3)</td>
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<td>30.0</td>
<td>25.0</td>
<td>228</td>
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<td>280</td>
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<td>Plants</td>
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<td>280</td>
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<td>99.0</td>
<td>330</td>
<td>Apr. to Sep. 1986</td>
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<td>(Kurashiki)</td>
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<td>130 (1)</td>
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<td>99.0</td>
<td>330</td>
<td>Jan. 1986</td>
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<tr>
<td></td>
<td>West Japan</td>
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<td>125 (1)</td>
<td>69.0</td>
<td>105</td>
<td>540</td>
<td>Apr. 1986</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>(Fukuyama)</td>
<td>No. 5</td>
<td>200 (1)</td>
<td>116.5</td>
<td>85</td>
<td>520</td>
<td>Feb. 1990</td>
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<td></td>
<td>Kagoshima</td>
<td>No. 1ABC</td>
<td>195 (1)</td>
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<td>105.0</td>
<td>545</td>
<td>Mar. 1986</td>
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<td>No. 2AB</td>
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<td>65.0</td>
<td>Plants</td>
<td>105.0</td>
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<td>No. 2CD</td>
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<td>545</td>
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<td>540</td>
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<td>112.0</td>
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<td>Jun. 1987</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>and Chemicals</td>
<td>No. 3, 4</td>
<td>150 (1)</td>
<td>98.0</td>
<td>112.0</td>
<td>556</td>
<td>Oct. 1998</td>
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<td></td>
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<td>58 (1)</td>
<td>31.0</td>
<td>65</td>
<td>490</td>
<td>May 1991</td>
<td></td>
<td></td>
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</table>
2. Characteristics of CDQ systems

The red-hot coke extruded from the coke oven is cooked by spraying it with water. The water used for cooling is vaporized and released into the atmosphere as steam. One drawback to this system is that the thermal energy of the red-hot coke is lost in the form of the heat of vaporization. Another is that it produces airborne coke dust.

In the CDQ system, the red-hot coke is cooked using a gas that circulates within a closed system, and so airborne coke dust is not released into the atmosphere. In addition, the thermal energy of the red-hot coke dust, which is lost in a conventional system, is collected and reused as steam for the boiler. As a result, the CDQ system uses less fossil fuel, produces lower CO₂ emissions, and therefore contributes to the prevention of global warming.

3. Dissemination of Coke Dry Quenching (CDQ) systems

Given that it is an environmentally friendly and energy-efficient technology, CDQ systems have been installed in many steelworks and coke ovens throughout Japan. Thanks to NEDO model projects, the effectiveness of CDQ technology has also been recognized in China. The Chinese government specified that implementing CDQ technology should be one of the targets of the 10th Five-Year Plan in 2000. Steelworks in Hanfang, Beijing, Chengde, and Hangzhou have already introduced Japanese CDQ systems.

### Table 5 Reduction in CO₂ emissions

(Expected energy savings effect: heat collected from produced steam = 604.3 Tcal/year)

<table>
<thead>
<tr>
<th>Scenario</th>
<th>CO₂ emissions (t-CO₂/year)</th>
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<tbody>
<tr>
<td>CO₂ emissions from CDQ project</td>
<td>1,771,569</td>
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<tr>
<td>Baseline CO₂ emissions</td>
<td>1,908,311</td>
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<tr>
<td>Expected reduction of CO₂ emissions</td>
<td>136,742</td>
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</tbody>
</table>

4. Status of Implementation

In the years ahead, crude steel production is expected to increase in Asia, and efforts are underway in India and China to incorporate CDQ technology. As a Clean Development Mechanism project prescribed under the Kyoto Protocol, CDQ is an established technology that can help Japan meet its Kyoto Protocol targets. As of end 2013, this technology has been implemented in 46 out of the 49 coke ovens in Japan. Additionally, because CDQ not only recovers the sensible heat from the red-hot coke but also results in a higher quality product, it is becoming popular outside of Japan in countries such as China and India.
B-07-06. Non-Catalytic Coke Oven Gas (COG) Reform Technology

1. Technology overview
Non-catalytic coke oven gas (COG) reform technology is a technology that is designed to effectively utilize energy while reducing the burden on the environment. It has been developed as a way to manufacture a synthesis gas that can be converted to a clean liquid fuel such as methanol or DME on an industrial scale. This is accomplished by taking high-temperature coal carbonization gas, which is produced in coke ovens and contains tar, and effectively utilizing its sensible heat to reform it through a partial oxidation reaction and a hydrogen atmosphere steam reforming reaction. The two keys to this technology will be a reformer unit that is located at the coke oven outlet and an associated control system.

2. Need for technological development
In recent years, with the surging need for steel worldwide and especially in China, a worldwide shortage of coke and rise in prices has occurred. As a result, Japan is seeking to develop new construction and higher capacity coke ovens. Also, repairs have been conducted to extend the life of aging ovens already in operation. However, there is still a strong desire for technological innovations in the field of coke manufacture.
To avoid the problems caused by tar in conventional coke manufacturing technology, the coke oven gas is rapidly cooled, and the tar component is recovered using an aqueous solution. An unfortunate consequence of this approach is that the sensible heat contained in the high-temperature coke oven gas is not effectively utilized.
Non-catalytic COG reform technology is able to effectively utilize carbon resources at an extremely high level, including the sensible heat available during carbonization in the coke oven gas that is produced as a byproduct of coke production. As such, it is a perfect solution to current challenges where energy and resource utilization are top concerns.

3. Objectives of technological development
By passing the high-temperature coke oven gas through a coke oven and converting most of the tar component into syngas, heat is recovered from that high-temperature gas. In this process, the composition of the gas produced by reforming is controlled so as to be useful in methanol or DME synthesis.

4. Effects of development
For the purpose of methanol production, if this technology is introduced into an existing coke factory that already has gas purification processes, there is no need for tar purification equipment. The only components needed would be for methanol synthesis and certain desulfurization devices. This technology is capable of achieving energy savings.

5. Current issues and future implementation outlook
A pilot plant test has been completed that reforms coke oven gas without the use of catalysts by instead using the sensible heat contained in high-temperature coke oven gas. Remaining technical issues include developing a reformer that can stably process the gas from multiple ovens, further study of such a system, and developing control methods capable of ensuring safe operations.
To help address the need to replace aged coke oven facilities, a pilot plant test for this technology was completed in 2009. Basic plans have been drafted for the next step, namely, that of a verification test. Due to progress in life-extension technologies for coke ovens, the update period has been extended. The majority of the coke ovens in Japan are installed in integrated steel mills, and facilities are typically configured to utilize all of the coke oven gas within the steelmaking plant. When it is not being used to upgrade existing coke oven facilities, however, this technology is difficult to apply, and implementing it in Japan has become difficult. Consequently, a search is under way for a site that will be suitable for conducting a verification test outside of Japan.
China is seen as a prime candidate, but no suitable candidates have identified yet. As a result of global environmental and coke production efficiency concerns, antiquated coke ovens that do not recover byproducts are bound to be abolished. Industry members therefore remain interested in developing coke-related technologies that are suitable for the global environment and that produce products with high added value. Coke production is on the rise in the coal-producing regions in inland China such as Shanxi province. Meanwhile, coke oven gas, which had formerly been used as municipal gas has started to lose ground to natural gas, which has a higher caloric value. Liquid fuels such as methanol and DME, which are manufactured from the syngas produced by this reforming process, would constitute a valuable source of energy for China's inland region, where shortages of liquid fuels are being experienced. Therefore, the marketability of this technology should be very high.
B-07-07. Useful Applications of Coke Oven Gas

Technology Overview

1. Background and overview of technological developments
The coke oven gas (COG), generated during coke production through the carbonization of coal in coke ovens, is primarily used as a heat resource for heating furnaces in steelmaking plants or as a fuel for thermal power generation. The composition of COG is approximately 60% hydrogen, 30% methane, and 10% carbon monoxide. As a result of this diverse composition, COG is not limited to being used merely as fuel, but rather a broad range of applications could be devised. For example, the components could be converted to benzene to serve as a chemical material. This type of innovation not only enhances COG's inherent added value, but would secure upstream material for use in petro-chemistry applications.

Development work has begun with the aim of achieving a technology that can make benzene as a byproduct of COG and CO₂ that is recovered from various other combustion exhaust gases. Benzene is economically competitive as a raw material for chemicals. Unlike benzene production methods that are based on petroleum, this method can be used to produce benzene. This resolves the limitations with complementary products that are an issue in the petrochemical approach, while also reducing the amount of CO₂ emissions that are generated.

2. Component technologies
The first stage in this technology is to produce methane from COG and CO₂, which are recovered from various combustion exhaust gases. Benzene is then produced by the dehydroaromatization reaction of methane. The component technologies of this approach are as follows:

[1] CO₂ recovery technology:
This technology must integrate a process to recover CO₂ from an exhaust gas that is low in CO₂ concentrations, like that generated from a power plant.

[2] Methanation technology:
In the methanation process upstream from the benzene synthesis step, a low-pressure methanation technology must be applied that operates close to the pressure of the benzene synthesis process in order to reduce the energy loss produced by pressure differences.

[3] Technology for direct benzene synthesis from methane:
In this component technology, it is assumed that benzene synthesis will require the use of a catalytic agent. The aim will be to improve the conversion rate and selectivity of the catalyst, which plays a big part in the economics of an industrial plant. Other important issues include the development of a catalyst with a high durability, developing a reaction system operates at a low temperature.

[4] Benzene separation technology:
This component must establish industrial-scale benzene separation technology with operational and equipment safety.

3. Future issues and implementation outlook
The goal of this technology is to add value to COG, maximize benzene production, and reduce CO₂ emissions from the electric power, coal, and petroleum industries. Through cooperation among stakeholders in these industries, it will be possible to secure an extremely desirable petrochemical material.

Presently, studies are underway for catalyst-free coke oven gas reform technologies as described. However, as coke oven gas has extremely high hydrogen content of around 50% - 60%, it could also be used as a source of hydrogen. It is possible that with future advances in hydrogen utilization there will be a need for research on the separation of high-purity hydrogen from COG.
The goal of this technology is to reduce CO₂ emissions from steelmaking plants by 30%. To that end the following advances are needed:

A. Development of a technology that increases the hydrogen content of high-temperature coke oven gas. This hydrogen will reduce the iron ore partially as a substitute for the coke.

B. Development of an innovative carbon dioxide separation and capture technology to be applied to the blast furnace that utilizes the unused heat discharged from the steel mill.

The steel industry accounts for roughly 14% of Japan’s CO₂ emissions, and approximately 70% of the steel industry’s CO₂ emissions are from steelmaking processes that employ a blast furnace. Japan’s steelmaking technology boasts the world’s highest standards of energy efficiency. Therefore, innovative technological developments will be needed to further reduce CO₂ emissions. Such technology could drastically reduce Japan’s total CO₂ emissions.

1. Objectives

The objectives of this technology are to:

reduce the iron ore partially as a substitute for the coke.

2. Demand and effects

The steel industry accounts for roughly 14% of Japan’s CO₂ emissions, and approximately 70% of the steel industry’s CO₂ emissions are from steelmaking processes that employ a blast furnace. Japan’s steelmaking technology boasts the world’s highest standards of energy efficiency. Therefore, innovative technological developments will be needed to further reduce CO₂ emissions. Such technology could drastically reduce Japan’s total CO₂ emissions.

3. Technologies to be developed

(1) A hydrogen utilization technology for iron ore reduction

In order to balance the coke-based reduction rate with that of hydrogen, which has a fast reduction rate, the optimal operating condition of various gases feeding and the raw materials charging into the blast furnace is needed.

(2) Coke oven gas reforming technology

By promoting thermal decomposition of the tar contained in the coke oven gas through the use of a catalyst while also using the thermal energy from the coke oven gas, the amount of hydrogen is increased.

(3) Coke improvement technology

In the COURSE50 concept, the coke feed ratio can be lowered compared with the conventional operation. Therefore, high strength coke is required to maintain the gas permeability necessary for the reduction reaction of iron ore under reduced coke feeding rates in blast furnaces. In addition, higher reactivity is needed for the iron ore reduction.

(4) CO₂ separation and Capture Technology

To reduce the costs associated with separating and capturing the CO₂ that is emitted from blast furnaces, efforts will center on improvements in the physical and chemical absorption methods, separation/capture technology and effective utilization of unused energy.

(5) Unused Exhaust Heat Utilization Technology

Efforts in the area of unused exhaust heat utilization will focus on the development of heat recovery technologies that effectively utilize the sensible heat in steelmaking slag and the unused low-temperature exhaust heat produced within the steel mill.

(6) Process Evaluation Technologies Based on Experimental Blast Furnaces

Process evaluation technologies will be developed to maximize the effect of hydrogen reduction that incorporates the component technologies developed in Phase I / Step 1 shown in Figure 1.

(7) Evaluation and Study of the Overall Process

Optimization of the entire steelmaking process will be studied, and comprehensive evaluation and research will be conducted to make it possible to achieve a 30% reduction in CO₂ emissions from steelmaking plants.
4. Current status and development timeline

Figure 1 shows the development timeline for the COURSE-50 project. In Phase I / Step 2, in addition to refining the component technologies, a 10-m³ scale test blast furnace with a tapping capacity of 35 t/d will be constructed. Integrating the component technologies through plant operations will lead the way to Phase II, in which a verification-scale test will be performed.

<table>
<thead>
<tr>
<th>Year</th>
<th>2008</th>
<th>2012</th>
<th>2013</th>
<th>2017</th>
<th>2020</th>
<th>2030</th>
<th>2040</th>
<th>2050</th>
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<tbody>
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<td>Implementation and dissemination</td>
<td>Development of component technologies conducting iron ore reduction using hydrogen and capturing carbon from blast furnaces</td>
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</table>

5. Technical issues

(1) Hydrogen utilization technologies for iron ore reduction
   - Quantitative analysis of various gas blowing in blast furnace

(2) Coke oven gas reforming technology
   - Development of countermeasures to catalyst deactivation
   - Development of reforming technologies used in partial oxidation of the methane contained gas
   - Development of long term continuous operation technologies for reforming coke oven gas

(3) Coke improvement technology
   - Development of coke production technology that controls the strength and the reactivity of the coke by employing high-performance caking materials
   - Coke manufacture for use with the test blast furnace

(4) CO₂ separation and capture technology
   - Development of a high-performance absorbing solution that reduces the energy used for CO₂ separation and recovery
   - Efficiency enhancements to the system for physical adsorption using an adsorption bed height that is suitable for equipment

(5) Technology to utilize unused discharged heat
   - Development of technologies for recovering heat from low-temperature gas and high-temperature slag
   - Construction of a heat recovery network from various heat sources in the plant

(6) Process evaluation technologies based on the test blast furnace
   - Ascertainment of the operating conditions for minimizing coal consumption and verifying effectiveness through integration of items (1) - (5)
   - Acquisition of scale-up data aimed at the construction of a 100m³ blast furnace for Phase II

(7) Evaluation and study of the overall process
   - Optimization study of the overall steelmaking process with the goal of making it possible to achieve a 30% reduction in CO₂ emissions from steelmaking plants
B. Technologies for High-Efficiency Applications

B-07-09. Ferro Coke

This project has two primary objectives. The first is to develop technologies for an innovative steelmaking process that works under a rapid and low-temperature reduction reaction inside the blast furnace. This technology would employ a reducing agent produced by mixed forming and carbonization of low-quality iron ore and low rank carbon (ferro-coke) and develop an operational process. The second objective is to develop innovative technologies that can expand utilization of low-quality raw materials and can reduce energy consumption during the steelmaking process. By applying these technologies, a maximum energy savings of 10% and a 20% reduction in high-rank coal usage compared to current blast furnace operations can be realized.

In Japan’s steel industry, attaining long-term and stable raw material procurement is a major issue, and there is a need to achieve significant reductions in CO₂ emissions over the medium to long term. This technology can help resolve these issues. Ferro-coke is a raw material for blast furnaces wherein the metallic iron in the coke is dispersed by means of forming and carbonization. Because it is possible to utilize low-quality coal and iron ore, it can contribute to stabilizing resource supply. In addition, because it is possible to increase the iron ore reduction rate through the effects of metallic iron, it is possible to reduce amount of coke required, while achieving energy savings and a major reduction in CO₂ emissions.

A. New Binder
This project produces a new binder which differs from the conventional binder (petroleum-based ASP). The new binder is produced from solvent extract matter of coal that is inexpensive and widely available. By using this binder, the adhesiveness of the coal particles is increased and the overall resulting strength is improved.

B. Blast furnace operation process
Through the construction of a blast furnace and reaction model that can express the gasification behavior of ferro-coke with high precision, optimizations for intra-furnace placement and ferro-coke usage can be achieved.
4. Current status and development timing

Figure 2 shows the research and development timeline. From 2009 - 2010, a search for the composition and structure conditions of ferro-coke and a small-scale carbonization experiment were conducted using lab testing. Based on laboratory-scale data, pilot-test facilities were constructed from 2010 – 2011, and an experiment on the optimal forming conditions for ferro-coke and the adaptability test of the new binder was conducted from 2011 - 2012. Through this long manufacturing experiment, the reduction in the amount of high-quality coal used and the strengthening of the ferro-coke was verified. Based on the verification results on the operating conditions when employing ferro-coke, the rates of energy savings and coke usage reduction when actually employed in a blast furnace were confirmed. Looking forward, research and development on implementation will be conducted. The current technological issues are as follows:

(1) Ferro-coke production technology
- Improvements to kneading and forming equipment, and scaling up of the carbonization oven
- Determination of optimal production conditions for the new binder and design of industrial size equipment

(2) Blast furnace operation technology
- Establishment of optimal charging method in accordance with the particle diameter of the ferro-coke
- Maintain the optimal pressure drop of in the blast furnace when increasing the amount of ferro-coke used and establish measures to prevent a lowering of the upper furnace temperature

C-06-01. Hydrogen Production by a Reaction Integrated Novel Gasification Process (HyPr-RING)

(Coal Energy Center, National Institute of Advanced Industrial Science and Technology, IHI Ltd., Babcock-Hitachi K.K., Mitsubishi Materials Corporation, and JGC Corporation

Project Type
METI-subsidized project

Development Periods
FY2000 – FY2007 (8 years)

Technology Overview

1. Development objective
Coal is the most abundant energy resource in the world, and is also an important primary energy source because it is economical. As economies grow and populations increase, coal usage is expected to increase. However, the human race must find ways to resolve global climate issues, especially the issue of global warming caused by carbon dioxide. As such, the world sorely needs technologies for utilizing coal cleanly and efficiently as well as technologies that contribute to a reduction in CO2 emissions.

Hydrogen production using a reaction integrated novel coal gasification process (HyPr-RING) technology was developed in response to these needs. Efforts were made to produce and supply hydrogen while implementing carbon capture technology.

2. Principles
The HyPr-RING method employs a process wherein CaO, a CO2-sorbent, is added directly into a coal gasifier. Hydrogen is directly produced in the gasifier and generated CO2 is secured in the form of CaCO3. Heat is produced by the reaction of CaO and H2O, and because this heat can be retained within the furnace and applied to the hydrogen producing reaction, this process has significant merits from a thermal energy standpoint.

The HyPr-RING method utilizes a dry CaO (decarboxylation agent) and absorbs CO2 within the high-temperature (pressurized) furnace. The heat generated from absorption of CO2 is released as thermal energy at a temperature of 700°-800°C, and is provided to the hydrogen producing reaction.

3. HyPr-RING process

1) Cold gas efficiency
In the HyPr-RING method, the portion of fuel coal that is easily gasified under low-temperature conditions of 600°-700°C is gasified and converted to hydrogen, while the remaining, difficult-to-react char is used as fuel for the CaCO3 calcination. In order to recover pure CO2, combustion must be performed using oxygen. Figure 2 shows an example of a process that is configured with a fluidized-bed gasifier and an international combustion calcination furnace. For a product composition of 95% H2 and 5% CH4, the cold gas efficiency was about 76%.

2) Temperature distribution inside the gas furnace
Because the CO2 concentration is low at the reactor inlet (1), CaO first reacts with H2O to form Ca(OH)2, and provides heat for the thermal decomposition of coal. In regions where the partial pressure of CO2 is high, the Ca(OH)2 absorbs CO2 to become CaCO3 while releasing heat. This heat is used for the char gasification reaction.

3) Problems with using CaO absorbent and solutions
As a result, there is no need for external heat or coal combustion heat to achieve the required furnace temperatures. In addition, the CaCO3 obtained following the absorption of CO2 may be returned to CaO by calcination (regeneration). In that case, 50% - 80% of the thermal energy required is converted into chemical energy for the CaO, and is reused in the gasifier (see Figure 1 and Table 1).

Table 1 CO2 separation energy and temperature level

<table>
<thead>
<tr>
<th>Process</th>
<th>Heating value of carbon (C→CO2)</th>
<th>CO2 absorption energy</th>
<th>CO2/H2 generation ratio</th>
<th>CO2 separation energy per mole of H2 generated</th>
<th>Temperature level</th>
</tr>
</thead>
<tbody>
<tr>
<td>HyPr-RING</td>
<td>393 kJ/mol</td>
<td>178 kJ/mol</td>
<td>0.5 mol/mol</td>
<td>89 kJ/mol</td>
<td>973-1073 K</td>
</tr>
<tr>
<td>Partial combustion</td>
<td>393 kJ/mol</td>
<td>84.5 kJ/mol</td>
<td>1 mol/mol</td>
<td>84.5 kJ/mol</td>
<td>about 323 K</td>
</tr>
</tbody>
</table>

4. Project overview
This project was started in 2000. Based on tests using batch and semi-continuous devices, the process configuration was confirmed, and a feasibility study was undertaken. Various element tests were also conducted. Starting in 2003, continuous tests were implemented by producing a continuous test device processing 50 kg/d on a coal basis. Taking into consideration the hydrogen utilization technology and the development status of carbon gasification furnaces at that time, the project was terminated at the 5-t/d concept design scale in 2007.

Table 2 Development schedule

<table>
<thead>
<tr>
<th>Component testing</th>
<th>Acquirement of design data</th>
<th>Field trial in the same process</th>
<th>Feasibility study</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>2001</td>
<td>2002</td>
<td>2003</td>
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<tr>
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<td>2006</td>
<td>2007</td>
</tr>
<tr>
<td>2008</td>
<td>2009</td>
<td>2010</td>
<td>2011</td>
</tr>
</tbody>
</table>

References
1) Shiying Lin, Yoshizo Suzuki, and Hiroyuki Hatano, Patent No. 29791-49, 1999

Figure 1 Hydrogen production using HyPr-RING process

Figure 2 HyPr-RING process
Clean Coal Technologies in Japan

C-06-02. CO₂ Recovery Technologies from Combustion Gas (Post-Combustion)

<table>
<thead>
<tr>
<th>Research and Development</th>
<th>Major Manufacturers and Power Companies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Type</td>
<td>Voluntary project</td>
</tr>
<tr>
<td>Development Periods</td>
<td>1990 –</td>
</tr>
</tbody>
</table>

**Technology Overview**

1. **Overview**

The most realistic technologies presently under development for capturing CO₂ that is discharged from steelmaking plants and coal-fired power generation plants are the amine absorption process and chilled ammonia process. Energy consumption and costs are both high for these technologies. Methods based on a membrane separation method and solid absorbents have also been developed, but there remains a need for a technology with still lower energy consumption and costs to make CO₂ capture viable.

2. **Needs for the technology**

Technologies for capturing and storing CO₂ discharged from power generation systems are needed to address global warming concerns. As a method for separating and capturing CO₂ on a large scale at commercial plants, amine absorption and membrane separation technologies have been developed in countries throughout the world.

By pursuing the development targets of significant cost reductions, system optimization, and optimization of amine used, the hope is to greatly reduce the auxiliary power consumption of the power plant (to 10% or less). By implementing this technology, the hope is to reduce CO₂ emissions a by up to 90%.

3. **Project status to date**

Mitsubishi Heavy Industries, Ltd., Toshiba, Hitachi, Ltd., and Nippon Steel Sumitomo Metals Engineering etc. have conducted tests up to the pilot scale (10 - 30 t/d). Additionally, Mitsubishi Heavy Industries and Southern Company of the U.S. will jointly implement a CO₂ separation and capture verification test (500 t/d) using an amine absorption method from a coal-fired power plant.

4. **Project of introduction to the market**

Carbon capture and storage (CCS) technology, where CO₂ is separated and recovered from coal-fired thermal power plants and stored in aquifers, will be implemented on a large-scale verification test (1,000–3,000 t/d) around 2020. After verifying significant reductions in cost and energy consumption, it is expected that it will be introduced to the market on a full scale by around 2030.

In 2014, Mitsubishi Heavy Industries received an order for carbon capture facilities to be applied on an enhanced oil recovery (EOR) project in Texas, United States. The EOR project captures CO₂ from the combustion exhaust gas of an existing coal-fired power generation plant, and infuses the captured CO₂ into an aging oil field. The carbon capture capacity was approximately 5,000 t/d, with a CO₂ recovery rate of 90%. An image of the plant is shown in Figure 1. This is the world's first project to utilize CO₂ derived from coal-fired power.

This is an example of a project that was commercialized under a business model that incorporates recovered oil revenues from EOR into a portion of project profits. In CCS-oriented projects where the cost of captured CO₂ is unknown, further cost reductions will be needed.

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**Figure 1 Overview of a CO₂ capture plant targeting coal combustion exhaust gases**

(Source: Mitsubishi Heavy Industries HP)

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**References**

1) Baden Firth, MHI PCC Progress and challenges, 2014 National CCS Conference
C. Carbon Countermeasure Technologies

The EAGLE project is a project undertaken by the Electric Power Development Co., Ltd. in cooperation with NEDO to conduct testing which started in 1998. In addition to performing gasification using a 150 t/d gasifier, the project also deployed carbon capture equipment. Figure 1 shows the system configuration of the EAGLE facilities. In Step 1 of the EAGLE development timeline, development of an oxygen-blown gasification technology was successfully completed. Next, in Steps 2 and 3, a test was conducted to efficiently separate and capture CO₂ from a power generation system. The EAGLE carbon capture project is the world’s first to be equipped with both chemical absorption and physical absorption facilities. This section will give an overview of the carbon capture test that was performed in Steps 2 and 3.

1. Necessities of Technological Development

The establishment of a technology for separating and recovering CO₂ generated from coal gasification processes will be an important element in contributing to reducing the burden on the global environment and maintaining energy security during the expected expansion of coal utilization in the medium to long term. In “Energy Supply and Demand Outlook for 2030” by the Advisory Committee for Natural Resources and Energy Supply and Demand Subcommittee (March 2005), it is noted that, “It is expected that fossil fuels will continue to occupy a relatively large share of the total supply of primary energy for Japan.” The document also states that: “Carbon sequestration will be one of the ways to overcome environmental concerns surrounding the use of carbon, and will be an important technology for expanding energy choices. On the energy supply side, as well, measures based on such technology must be advanced in earnest.”

Coal gasification—especially synthesis gas (syngas) that is produced from an oxygen-blown coal gasification process—produces a high-pressure gas whose main components are CO and H₂. If a CO shift reaction is incorporated, high concentrations of carbon dioxide can be produced. CO₂ is relatively easy to separate from synthesis gas. This technology incorporates monitoring technologies into CO₂ storage, and an important issue will be to broadly establish these technologies.

2. Objectives and achievements to-date

The EAGLE project is a project undertaken by the Electric Power Development Co., Ltd. in cooperation with NEDO to conduct testing which started in 1998. In addition to performing gasification using a 150 t/d gasifier, the project also deployed carbon capture equipment. Figure 1 shows the system configuration of the EAGLE facilities. In addition, Photo 1 shows the external appearance of EAGLE facilities. In Step 1 of the EAGLE development timeline, an object of Step 2 of the EAGLE project was to establish a carbon separation and recovery technology (that is, a “carbon capture” technology) for carbon dioxide emitted from coal gasification gas. In the second half of 2008, a carbon capture test began. Figure 2 shows the system configuration of the carbon capture equipment that was used. For the absorbing solution, a methyl diethanolamine (MDEA) based absorbing solution was selected. Carbon dioxide contained in the gas sent to the carbon capture system is absorbed by the amine solution in the absorption tower, and hydrogen-rich gas is extracted as a purification gas. The amine solution that has absorbed CO₂ is then sent to the regeneration system, and is recovered in the form of a gas that will ideally have a purity of 99%. Two modes for the process used to regenerate the absorption solution were tested: heated flash regeneration, and regeneration using a regeneration tower.

Figure 1 System configuration of the EAGLE project facilities

Photo 1 Appearance of the EAGLE facilities

An object of Step 2 of the EAGLE project was to establish a carbon separation and recovery technology (that is, a “carbon capture” technology) for carbon dioxide emitted from coal gasification gas. In the second half of 2008, a carbon capture test began. Figure 2 shows the system configuration of the carbon capture equipment that was used. For the absorbing solution, a methyl diethanolamine (MDEA) based absorbing solution was selected. Carbon dioxide contained in the gas sent to the carbon capture equipment is absorbed by the amine solution in the absorption tower, and hydrogen-rich gas is extracted as a purification gas. The amine solution that has absorbed CO₂ is then sent to the regeneration system, and is recovered in the form of a gas that will ideally have a purity of 99%. Two modes for the process used to regenerate the absorption solution were tested: heated flash regeneration, and regeneration using a regeneration tower.
Clean Coal Technologies in Japan

3. Future plans

These test results are reflected in the Osaki CoolGen Project, which will implement a demonstration operation of an IGCC/IGFC system incorporating oxygen-blown gasification technology.

References
Part 2 CCT Overview

C. Carbon Countermeasure Technologies

C-06-04. Chemical Looping Combustion as a Coal Utilization Technology with CO₂ Separation

- **Research and Development**: Mitsubishi Hitachi Power Systems Co., Ltd., Coal Energy Center, IAE
- **Project Type**: NEDO-commissioned project
- **Development Periods**: FY 2007- FY 2011 (5 years), FY 2012- FY 2014 (3 years)

**Technology Overview**

1. **Objectives of technological development**

Chemical looping combustion (CLC) technology is a method for converting fuel to heat or fuel gas via chemical reactions with metals. The fuel does not burn with oxygen (air), and CO₂ can be separated easily. CLC does not require an air separation process, and even if CO₂ is recovered, plant efficiency (net thermal efficiency) is not degraded. This makes it possible to create high-efficiency coal-fired power generation. As shown in Figure 1, 1 - 3 MWth-scale pilot plants are being constructed as a CO₂ reduction technology options from 2020 onward in the EU and United States, and practical technological development is underway.

![Figure 1](image1.png)

**'96 '98 '00 '02 '04 '06 '08 '10 '12 '14 '16**

- **Japan**
  - NG Combustion / NEDO etc. Internal Circulation Device, Tokyo Institute of Technology
- **United States**
  - DOE_1: 65-kWth device, NETL, $6.5M
  - DOE_2: 3-MWth device, ALSTOM, $6.2M
  - DOE_3: 25-kWth device, Ohio University, $3.9M
- **Europe**
  - Coal combustion
    - 10-kWth device, IFP, a portion of €22M
    - 1-MWth device, Darmstadt University of Technology and Alstom, €6.4M
  - Pilot device, Chalmers University, €2.5M

2. **Need for technological development and effects**

In the Basic Energy Plan (resolved by the Cabinet in April 2014), coal-fired power generation was highlighted as an important base-load power resource. However, to further suppress the release of gases that contribute to global warming into the atmosphere, coal-fired power generation systems that reduce their environmental footprint are being further promoted.

In addition to the expectation that coal will be used moving forward, there are also hopes that zero-emissions can be attained by recovering carbon dioxide and then storing it stably underground. However, in cases where CO₂ from syngas in a gasification plant or from coal combustion exhaust gas are recovered by an absorbing solution, a large amount of gas must be processed. When desorbing the CO₂, a massive energy loss is produced compared to the energy required for dust removal, desulfurization, and denitrification.

As shown in Figure 2, chemical looping combustion has the advantage of maintaining good net thermal efficiencies even when CO₂ is recovered. However, as shown in Figure 3, plant scale and cost concerns, which accompany the use of an oxygen carrier, remain as significant issues. For this reason, basic research and development for a low-cost coal utilization technology with chemical combustion (chemical looping combustion or CLC), pilot plant tests, and demonstration plant tests must be undertaken sequentially with the aim of realizing this technology in the 2030s. Utilization of low-rank coal and/or biomass will be possible with this technology because a fluidized bed boiler is used.
Clean Coal Technologies in Japan

3. Component technologies

(1) Oxygen Carrier
A low-cost, highly reactive, highly durable carrier is indispensable for this technology. Consequently, natural and artificial carriers must be evaluated, and a practical carrier must be identified. In addition, the effects of coal utilization must be assessed and countermeasures determined.

(2) CLC Reaction Unit
A circulating fluidized bed reactor that can maximize the performance of the target carrier while being both efficient and economical is needed.

(3) Efficient CLC Power Generation System
A CLC power generation system that can recover CO₂ at low costs while achieving high power generation efficiency is needed. The system must also optimize the auxiliary device configuration and heat exchange method.

4. Current status
During a NEDO research project conducted in 2012 and 2013 entitled “Study on Coal Utilization Technology Employing Chemical Combustion and CO₂ Capture,” an investigation was done on technological development trends within and outside of Japan, as well as on specific technological development items in Japan.

Additionally, during a NEDO research product conducted in 2014 entitled “Study on Carbon Utilization Technology Employing Chemical Combustion and Carbon Capture,” a study was done on the goal of minimizing plant costs and carrier costs to achieve a carbon capture cost of ¥2,500 / t-CO₂ or less.
C-06-05. Combustion Technology of Pulverized Coal (Oxyfuel)

Electric Power Development Co., Ltd., IHI, and Mitsui & Co., Ltd.
NEDO-commissioned project, METI-subsidized project
1990s, FY2006 – FY2015 (10 years)

Technology Overview

1. Background on technological development

Among the ways for reducing the emissions of carbon dioxide produced by burning coal, capturing and storing carbon dioxide is one of the most efficient methods. Pulverized coal oxygen combustion technology, known as Oxyfuel, is one such CO₂ recovery technology. A demonstration plant is operating in Australia. This technology is being assessed to have a strong and realistic future.

In the Oxyfuel system, oxygen is first separated from air to be used as a combustion medium. Next, coal is burned using that oxygen. This combustion increases the concentration of CO₂ in the exhaust gas to 90% or greater, making it easy to separate and recover. Figure 1 shows a concept diagram of a CO₂ Recovery Process employing Oxyfuel technology. At the Australia Callide power plant, 30-MWe-scale verification operations have been implemented (Figure 2). With this oxygen combustion process, not only is it possible to recover CO₂, but a large quantity of N₂ is also discharged. This gas can be effectively utilized in various applications, which provides economic benefits. Accordingly, coal utilization, CO₂ storage (or use), and N₂ use will be key to the results and determination of commercial implementation.

Figure 1 Concept diagram of the CO₂ recovery process using oxygen combustion

Figure 2 Australia Callide power station A (provided by IHI)
2. Status of technological development and results to-date

In the oxygen combustion project, research and development of an oxygen combustion boiler began in 1989, with basic research and a feasibility study conducted during the 1990s. Starting in 2004, in partnership with Australia, a feasibility study was conducted targeting application of the technology to an existing power plant, and in 2008, a demonstration project began. Oxyfuel operations commenced in June 2012, and as of February 2015, over 10,000 operational hours have been logged, with total operation time for the CO₂ recovery equipment reaching 5,500 hours. This plant is the world’s only operating Oxyfuel power plant with CO₂ recovery capabilities. The plant is being used to gather operating data and conduct various tests. The main results outlined from the project include:

• Target CO₂ concentration: 55 wet-% (70 dry-%) or greater
• Conducted an inlet-O₂ concentration change test, implemented a coal test, confirmed the characteristics of Oxyfuel boilers, and confirmed the behavior of the trace elements in coal
• In line with the pilot test results, reduced the NO exhaust amount (one half or less), and confirmed 50% reduction in unburned carbon in ash
• With respect to CO₂ recovery facilities, ascertained the behavior of the in-process minor components, and confirmed that the purity of the produced CO₂ was 99.9% or greater

3. Future issues and commercialization outlook

Oxygen production costs are a major issue weighing on the realism of the dissemination of oxygen combustion technologies, and an oxygen production method that is as efficient and cost-effective will be needed. As for CO₂ recovery devices, the ability to optimize processes to match the application and achieving cost reductions are both major issues. The target value of CO₂ recovery efficiency for the process as a whole is 90% or greater.

In addition, commercial-scale projects need to be created in locations where it is possible to effectively utilize the N₂ discharged from an oxygen production device while also making use of the CO₂ that is recovered.

The timeline for project planning and market introduction is as follows.

2014   Implementation of injection test for Oxyfuel CO₂ to storage site
2014-2015  Summary of Callide project results
2014-2017  Digging of commercial-scale plant project / implementation of feasibility study and FEED
2020   Realization of a commercial-scale oxygen combustion plant

References

Chris Spero, “Callide Oxyfuel Project Update.” 2014 Nation CCS Conference
C-10-01. CO₂ Conversion Technology

Universities, Panasonic Corporation, Toyota Motor Corporation, Asahi Kasei Co., Ltd.
Independent project, MEXT Grant-in-Aid for Scientific Research

Technology Overview

1. Background on technological development

Among the chemicals that are currently produced worldwide each year from CO₂ are 100 million tons of urea, 1 million tons of methanol, and 3 - 4 million tons of poly-carbonate (including that produced using the phosgene method). In addition, there is DME production using methanol and hydrocarbon production through artificial photosynthesis. However, in Japan the economic benefits of most of these processes still do not meet production costs, and therefore have yet to be commercialized. Only Asahi Kasei Chemical has managed to bring aromatic polycarbonate production to the commercialization phase. Manufacturers that have the technology are generally oriented toward enterprises operating overseas where manufacturing costs are low. One example of an approach that could contribute to reductions in CO₂ based on its immobilization in a chemical project is the manufacture of polycarbonate without passing through phosgene.

Taiwan, Korea, Russia, and Saudi Arabia are operating actual plants. Additionally, as shown in Figure 1, methanol is being studied as a CO₂ fixation technology and as a fossil fuel alternative for the future. Although it is not being commercialized in Japan, if a stable and pure CO₂ supply source were secured and an inexpensive and high-performance catalyst were developed, implementation would be a real possibility. That said, the following issues remain:

- Cost reduction (it costs 2 - 3 times as much as producing methanol from natural gas)
- Introduction of a CO₂ emissions trading scheme
- Securing of a very pure CO₂ supply source
- Development of an inexpensive and highly active (artificial photosynthesis) catalyst and support for a long-term development
- Development of a new market

2. Component technologies

In chemical plant technology in general and particularly for artificial photosynthesis, catalyst technology is critical.

3. Current status

Technologies for the manufacture of polycarbonate from CO₂ by Asahi Kasei, shown in Figure 2, were commercialized in Taiwan in 2002 following approximately 20 years of R&D efforts.

Development is advancing in Japan, but implementation has not been reached due to cost factors. In artificial photosynthesis, much emphasis is placed on the research of hydrogen production, but it remains in the university research phase.

An example of artificial photosynthesis research is a grant-aided project entitled "Material Conversion of Solar Energy Based on Artificial Photosynthesis."

Source: State-of-the-Art Technologies for the Direct Utilization of Carbon Dioxide. Published by NTS, April 2013.
D-08-01. SOx Reduction Technology

Mitsubishi Heavy Industries, Ltd.; Babcock Hitachi K.K.; Ishikawaji-ma-Harima Heavy Industries Co., Ltd.; Chiyoda Corporation; Kawasaki Heavy Industries, Ltd.; others

Technology Overview

1. Background

Sulfur oxides (SOx, mainly SO2) are regulated by two rules. "K-value control" is defined according to exhaust heights and regional coefficients, and "Total amount control" is defined from the total emissions of a region. To comply with these regulations, flue gas desulfurizers were commercialized in 1973. Efforts to improve desulfurizer performance and lower costs have been ongoing. Most pulverized coal-fired thermal power plants are currently equipped with wet limestone and gypsum-based desulfurization systems. A wet desulfurization process requiring no wastewater treatment is under development.

2. Technology

Wet limestone-gypsum process overview:

There are two processes in use. The first is a soot-separation process, in which a dust (cooling) tower is installed upstream for dust collection, HCl/HF removal and cooling. The second is a soot-mixed process without a dust (cooling) tower. The soot-separation process is used when high-purity gypsum containing no soot or dust is desired. At present, however, more and more systems are being installed that employ the soot-mixed process due to lower installation costs. The development of high-performance dust collection devices, such as an advanced low-temperature electrostatic precipitator, which lowers soot/dust concentrations have also contributed to the increased use of the soot-mixed process.

In the absorption tower, a water-limestone slurry is reacted with the SO2 in the exhaust gas for the recovery of sulfur as gypsum (CaSO4·2H2O). The overall reaction is as follows:

\[
\text{CaCO}_3 + \text{SO}_2 + 0.5 \text{H}_2\text{O} \rightarrow \text{CaSO}_3 \cdot 0.5\text{H}_2\text{O} + \text{CO}_2
\]

\[
\text{CaSO}_3 \cdot 0.5\text{H}_2\text{O} + 0.5\text{O}_2 + 1.5\text{H}_2\text{O} \rightarrow \text{CaSO}_4 \cdot 2\text{H}_2\text{O}
\]

There are two types of absorption towers, as shown in Figure 1: one where oxidation (CaSO3·0.5H2O formation) occurs in a separate tower and one where oxidation occurs in the absorber itself (single tower). Single tower oxidation systems are currently less expensive to install and operate, and their use is increasing annually. There are several methods to facilitate contact between SO2 and the recycling absorption liquid in the absorption tower. The "spray method" sprays the absorption liquid, the "grid method" spreads the absorption liquid on the surface of a grid-like pad, the "jet-bubbling method" blows exhaust gas into the absorption liquid, and the in the "spouting liquid method" absorption liquid flows like a fountain in the absorption tower. There are three of these methods in use: the "spray method", the "jet-bubbling method", and the "spouting liquid method". The separate-tower oxidation system is not currently in use. A simple desulfurizer has also been commercialized for use in developing countries that can be installed in the flue gas duct or at the lower part of a stack.

Figure 1 Limestone-gypsum process-based desulfurizers
Part 2 CCT Overview
D. Flue Gas Treatment and Gas Cleaning Technologies

D-08-02. NOx Reduction Technology

Technology Overview

1. Background
Nitrogen oxide emissions are regulated, with acceptable concentration levels being set according to the type of fuel and the size of the boiler. Due to the recent stiffening of regulations, however, some regions are subject to a "total amount control." This type of regulation sets a region-wide overall emissions level, similar to sulfur oxide emission regulations. To comply with these regulations, flue gas denitration equipment was commercialized in 1977, and ongoing efforts have been made to improve the durability of DeNOx catalysts as well as to reduce costs. The Selective Catalytic Reduction (SCR) process is used to decompose nitrogen oxides, mainly through the use of ammonia.

2. Technology

(1) Selective Catalytic Reduction Process
Research and development: Mitsubishi Hitachi Power Systems; IHI Corporation; others
Overview
In this process, ammonia (NH₃) is blown into exhaust gas, allowing it to selectively react with nitrogen oxides NOx (NO, NO₂). Through the reaction with ammonia, the nitrogen oxides are decomposed into water (H₂O) and Nitrogen (N₂). Since soot and dust are present in the exhaust gas, a grid- or plate-like catalyst is used in the DeNOx reactor as shown in Photo 1 and 2. The catalysts, installed in the reactor as shown in Figure 1, react with the NH₃ blown into the catalyst layer from its inlet. This allows NOx (NO, NO₂) to decompose into water vapor (H₂O) and Nitrogen (N₂). The catalyst is mainly composed of TiO₂, to which active ingredients such as vanadium (V) or tungsten (W) are added. The ammonia-NOx reaction is shown below.

\[
4\text{NO} + 4\text{NH}_3 + \text{O}_2 \rightarrow 4\text{N}_2 + 6\text{H}_2\text{O}
\]

The temperature at which the catalyst attains optimal performance is 350°C. At a temperature lower than this, SO₃ in the exhaust gas reacts with NH₃ to produce ammonium hydrogen sulfate (NH₄HSO₄) which covers the surface of the catalyst and reduces its ability to remove NOx. At a temperature higher than 350°C, the NH₄HSO₄ formation reaction does not take place significantly. At a temperature above 400°C, NH₃ is oxidized and its volume decreases, which reduces its ability to remove NOx. The process is also designed to limit NH₃ leaks from the reactor to 5ppm or less. If a significant quantity should leak, it will react with the SO₃ in the exhaust gas. This would form NH₄HSO₄ at the air heater and plug the piping.

The NOx removal efficiency is around 80-90% for pulverized coal-fired thermal power plants. In recent years, there has been a trend towards fuel diversification resulting from power plants’ need to economize, take measures against global warming, and keep up with the strengthening of various environmental regulations. The diversification has led to the increase in co-combustion of coal and biomass, and has created a need for DeNOx reactors at gas turbine power generation facilities. A durability verification of the catalyst is required in cases of co-combustion with bio-mass. For gas turbine applications, the performance of the catalyst in start up and low-load operations is examined and verification of high-temperature catalysts for simple cycle gas turbines is also performed. In response to larger boiler size and more efficient DeNOx processes, the uniform dispersing and mixing of the NH₃ with flue gas have been developed. These improvements include a "guide vane" at the gas inlet and the multiple NH₃ injection nozzle arrangement.
(2) Selective Non-Catalytic Reduction (SNCR) Process  
Research and Development: Chubu Electric Power Co., Inc.; Mitsubishi Heavy Industries, Ltd.  
Project Type: Independent Project  
Overview  
SNCR is a process which blows NH₃ into the boiler section where the exhaust gas temperature is 850-950°C to decompose NOₓ into N₂ and H₂O without the use of a catalyst. This process is shown in Figure 2. Despite the advantages of not requiring a catalyst and lower initial costs, the NOₓ removal efficiency is as low as 40% at an NH₃/NOₓ molar ratio of 1.5. Because of this, it is used in regions or with equipment where there is no need for a high NOₓ removal efficiency. More NH₃ is also leaked than with the selective catalytic reduction method, requiring measures to cope with NH₄HSO₄ formation in the high SOₓ concentration. This technology is mainly used at small commercial boilers and refuse incinerators. With respect to thermal power plant applications, this technology was only installed at Chubu Electric Power’s Chita thermal power plant No. 2 unit (375kw) in 1977.

(3) Radical injection method  
Research and Development: Japan Coal Energy Center, Gifu University, Ushio Inc., ACTREE Corporation  
Project Type: METI-subsidized project  
Overview  
In the radical injection method, as shown in Figure 3, argon plasma is radiated to NH₃. This generates NH₂ and NH plasma, which are then injected into the boiler to decompose NOₓ into N₂ and H₂O. The target for this technology is to attain a NOₓ concentration of 10ppm or less. Gifu University, Ushio Inc., and ACTREE Corporation are continuing the development of this technology. It is expected to be an effective exhaust gas management strategy for small and medium-sized incinerators and industrial boilers that were operated under loose regulations and had insufficient flue gas treatment technology. Research of this technology research has continued through the Innovative Japan Science and Technology Agency’s Seeds Development Project of 2005.

References  
In October of 2013, Japan concluded the Minamata Convention on Mercury. Coal-fired power plants and industrial boilers were listed as mercury sources, and air emission reduction became an issue to be addressed. Prior to this change, the proposed Mercury and Air Toxics Standards (MATS) in North America were revised and required coal-fired power plants to regulate mercury emission per amount of power generated by 2016 to a standard of 0.013 lb/ GWh(1.2 lb/TBtu). In places like North America where regulation predated the Minamata Convention on Mercury, mercury removal technology (e.g., activated charcoal spray) is already in use.

While this technology is easy to install, the operational cost is exceedingly high. Also, there is still the problem of disposing the activated charcoal that has adsorbed mercury.

The equipment already installed as environmental measures at coal-fired power plants (NOx, soot and dust, and SOx) is known to remove mercury contained in flue gas to a certain degree. To improve the efficiency of mercury removal capacity in flue gas, mercury oxidation performance was improved while maintaining the De-NOx catalyst performance. This in turn improved the removal efficiency of the desulfurization unit.

In Japan, thermal power plants are already equipped with De-NOx, De-SOx, and dust collection units. These facilities meet current emissions regulations and the technical advantages of these units are being actively explained to power plants abroad, where this technology is required in order to be in compliance with regulations. The mercury removal technology using halogen injection, such as ammonium chloride, was developed with the goal of improving mercury oxidation by a catalyst.

It has a low equipment modification cost, would significantly reduce operational cost, and does not produce waste. Also, since ammonium chloride is a stable solid matter, handling it is easy. Ammonia, which is explosive, can be replaced with ammonium chloride, which can act as a reducing agent in the De-NOx process and an oxidizing agent in the mercury removal process, thus improving the safety of environmental units at power plants.

(1) High Mercury Oxidation Denitration Catalyst (Photo 1): This is a technology that improves the mercury oxidation capacity while maintaining the DeNOx capacity. This is done by replacing the existing DeNOx catalysts with the high mercury oxidation catalysts.

(2) Mercury Removal Technology through Halogen Injection, such as Ammonium Chloride (Figure 1): this improves the mercury oxidation capacity by injecting halogens, such as ammonium chloride, upstream of the DeNOx catalyst. It also manages the oxidation-reduction potential in the desulfurization equipment, providing additional benefit as a mercury-scattering prevention method.
In Japan, there are air quality standards for mercury, but no emission regulations specifically for power plants and industries. For the purpose of overseas sales, this technology would allow plants to meet the MATS regulation standards. Through its application, 80-90% of mercury would be removed from existing plants. This high mercury oxidation catalytic De-NOx technology was introduced in 2007 and has been used for over five years.

![Diagram of mercury behavior in flue gas at coal thermal power plants](image)

**Figure 1 Behavior of mercury contained in flue gas at coal thermal power plants (sponsor: Mitsubishi Hitachi Power Systems)**
### D-08-04. Simultaneous De-SOx and De-NOx Technology

<table>
<thead>
<tr>
<th>Research and Development</th>
<th>J-Power EnTech, Inc.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Type</td>
<td>Independent project</td>
</tr>
<tr>
<td>Development Periods</td>
<td>Second half of 1970s to 1990s</td>
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#### Technology Overview

**1. Background**

The technology behind the wet desulfurization process has matured but still requires a significant amount of service water as well as advanced wastewater treatment measures. Similarly, an already commercialized ammonia-based selective catalytic reduction (SCR) process requires not only long-term control of expensive De-NOx catalysts but also measures to prevent ammonia leaks.

In order to replace these processes, the dry combined De-SOx and De-NOx method was developed. Since this technology allows for simultaneous De-SOx and De-NOx, it is expected to be useful in places with limited space, such as urban power plants, as a total flue gas treatment process.

**2. Core technologies**

The dry flue gas treatment process utilizes activated coke (AC) and can remove trace elements, such as mercury, as well as SOx, NOx, dust, and dioxins. The processes that make up this technology, known by the trade name “ReACT,” are composed of activated coke manufacturing technology and dry desulfurization technology (Figure 1).

**1) Adsorption**

The adsorption tower is filled with AC and removes SOx, NOx, and dust. The SOx is converted into sulfuric acid, or it reacts with ammonia injected before reaching the adsorption tower to become ammonium chloride, which is then adsorbed by the AC. The NOx is reduced into nitrogen through catalytic reactions with ammonia and AC. The dust in the flue gas is collected and separated at the absorption tower. AC then goes through the regeneration stage. The reactions involved in this process are:

- a) De-SOx Reaction: \( \text{SO}_2 + \frac{1}{2}\text{O}_2 + \text{H}_2\text{O} \rightarrow \text{H}_2\text{SO}_4 \)
  
  \(<\text{with simultaneous presence of ammonia} >\)
  
  \(\text{SO}_2 + \frac{1}{2}\text{O}_2 + \text{H}_2\text{O} + \text{NH}_3 \rightarrow \text{NH}_4\text{HSO}_4\)
  
  \(\text{SO}_2 + \frac{1}{2}\text{O}_2 + \text{H}_2\text{O} + 2\text{NH}_3 \rightarrow (\text{NH}_4)_2\text{SO}_4\)

- b) De-NOx Reaction: \(\text{NO} + \text{NH}_x\cdot\text{AC} \rightarrow \text{N}_2 + \text{H}_2\text{O} + \text{OH}\cdot\text{AC} \)
  
  (De-NOx through AC’s surface functional groups)

![Figure 1 Overview of the dry desulfurization process (ReACT)](Source: J-PowerEnTechHP)
(2) Regeneration

The AC that adsorbed sulfur oxides at the adsorption tower will be sent to the regenerator where it is heated up to 400-500°C and thermally regenerated. Then, it is sent back to the adsorption tower again and reused. The regeneration reactions are:

\[
\begin{align*}
H_2SO_4 & \rightarrow H_2O + SO_3 \\
NH_4HSO_4 & \rightarrow H_2O + SO_3 + NH_3 \\
(NH_4)_2SO_4 & \rightarrow H_2O + SO_3 + 2NH_3 \\
SO_3 + C(AC) & \rightarrow SO_2 + 1/2CO_2 (AC activation) \\
3SO_3 + 2NH_3 & \rightarrow N_2 + 3SO_2 + 3H_2O \\
& \text{(ammonia decomposition)}
\end{align*}
\]

3. Field applications

- 1987: Delivered to Unit No.1 as an exhaust gas removal unit for a heavy oil catalytic cracking unit
- 1995: J-Power’s Takehara thermal power plant Unit No. 2 (FBC boiler, 350MW) adopted the technology in their first unit for a large-scale coal-fired power plant.
- 2002, 2009: Isogo thermal power plant Unit No. 1 (600 MW) and Unit No. 2 (600MW)
- 2013: Wisconsin Public Service (WPS) decided to adopt this technology for its Unit No. 3 at the Weston power plant (365MW).

4. Topics for future development

1. Further reduction of cost

This technology excels in environmental aspects because it hardly requires any water. However, in order to popularize this technology, economic feasibility needs to be considered. Since the market for AC is small, it is especially necessary to find ways to reduce its price through improved procurement methods and performance.

2. Proposal to add to existing plants

Since this technology allows for total processing of SOx, NOx, and trace elements, it would be effective to install to existing plants, which have limited space and would undergo tightening of regulations. Therefore, it is important to promote this technology to plants overseas.
1. Background
Like NOx, emissions of particulate matter are regulated, with acceptable concentration levels set according to the type of fuel and size of boiler. At present, however, some regions are subject to a “total amount control,” which pro-vides for a region-wide overall emissions level as is the case with sulfur and nitrogen oxides. To comply with the regulations, the world’s first electrostatic precipitator was employed in a Yokosuka thermal power plant (oil-fired) in 1966 and many other thermal power plants have followed suit. To improve power generation efficiency, the development of pressurized fluidised-bed combustion and coal gasification combined-cycle technologies that use cyclones and ceramic/metal filters is underway. Trace element control is also now being intensified, such as through the addition of boron (B) and selenium (Se) to the regulated wastewater materials, and through the application of U.S. regulations for mercury (Hg).

2. Technology
(1) Electrostatic precipitator
Research and Development: Mitsubishi Hitachi Power Systems; Hitachi Plant Construction; Sumitomo Heavy Industries, Ltd., others

Technology overview
Electrostatic precipitators remove particulate matter in exhaust gas (Figure 1) in accordance with the theory that dust charged by a negative corona at a discharge electrode adheres to a positive dust-collecting electrode. The particulate matter that adheres to the electrode is removed and falls when the collecting electrode is tapped with a hammering device. The dust removal efficiency depends upon the electric specific resistance of dust, and is most effective in a range of $10^4$-$10^{10}$ Ω/cm. In a coal-fired power plant, current resistance of the dust is high which requires various countermeasures be taken against such dust.

One such measure involves adjusting the temperature conditions for dust collection as electric resistance varies with temperature as shown in Figure 2. In response to these characteristics, a high-temperature electrostatic precipitator (EP) was developed. The operating temperature is 350°C, higher than that of conventional low-temperature electrostatic precipitators (130-150°C). This EP is operated under low electric resistance. Another application is an advanced low-temperature electrostatic precipitator, where the collecting electrode surface dust layer always remains, and when hammered, part of the dust flows out through the gas flow. In the moving electrode system, the brush scrapes off the collected dust, so dust doesn’t remain on the collecting electrode. Since the collecting electrode surface is clean, there is no back corona that affects a high efficiency for removing high-resistance fine dust.

![Figure 1 Theory behind electrostatic precipitator](image1)

Figure 1 Theory behind electrostatic precipitator

![Figure 3 Moving-electrode type electrostatic precipitator](image3)

Figure 3 Moving-electrode type electrostatic precipitator

Source: Hitachi plant construction
(2) Trace element removal method
Research and Development: Japan Coal Energy Center Project
Type: METI-subsidized project

Overview
Among the trace elements of coal, mercury is cited as the material released into the atmosphere at the highest rate. Approximately 30% of the mercury not removed by the precipitators/desulfurizers is estimated to be released. However, nearly all bivalent mercury (Hg2+) is removed, leaving behind nonvalent mercury (Hg) as the discharge matter.

(3) High accurate analytical method of trace elements
Research and Development: Idemitsu Kosan, Co., Ltd., Central Research Institute of Electric Power Industry
Project Type: NEDO-commissioned project
Development Period: FY2005 - FY2013 (9 years)

Background and objectives
Along with halogen and mercury, boron (B) and selenium (Se) are volatile gaseous trace elements contained in coal combustion exhaust gas. Their environmental impact is of concern. JIS and ISO are currently working on standardizing the measuring techniques of these elements contained in the combustion exhaust gas. In accordance with the Water Pollution Prevention Law, several trace substances contained in the waste water from coal-fired power plants are regulated. Although gaseous trace substances contained in exhaust gas are collected at wet desulfurization units, they get transferred to desulfurization waste water. This poses an additional issue for wastewater disposal, especially regarding boron and selenium, which are difficult to manage.

To reduce environmental impact, analytical methods were established for boron and selenium, which underwent JIS/ISO standardization, and the behaviors of these elements in coal-combustion plants were examined.

A method to remove this nonvalent mercury is being actively reviewed. The Japan Coal Energy Center, though still in the process of basic research, selected active carbon, natural inorganic minerals, and limestone as materials that can absorb mercury. Their absorption characteristics are now being evaluated. The research results prove that the injection of active carbon or an FCC ash catalyst into the flue gas is effective, and 90% or more of the mercury can be easily removed by using this method and the flue gas desulfurizer together.

Project overview
Analytical methods were developed between 2005 and 2013 through a NEDO project titled, “Zero-emission coal-fired power plant project; method development to reduce environmental impact of trace elements as a result of coal utilization; data collection for standardization of high accurate analytical method of trace elements and trace element behavior analysis inside plants upon combustion.” These analytical methods, using a sampling technique shown in Figure 4, measure trace elements absorbed in a nitric acid hydrogen peroxide solution (HNO3(5wt%)/H2O2(10wt%)) through atomic absorption spectrometry or mass spectrometry.

Establishment of boron and selenium measurement methods by JIS/ISO:
JIS: JISK0083-2006 revision(Selenium compound)
ISO: ISO17211(Selenium)scheduled for DIS standardization through TC146(2014)

Current Situation
Upon completion of the developing boron and selenium measurement methods, the project will continue towards their JIS/ISO standardization, as shown in Table 1.

Table 1 Schedule for field application

<table>
<thead>
<tr>
<th>Year</th>
<th>Development, standardization, and behavioral study of high-accurate analytical methods of gaseous boron and selenium</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>JIS standardization (Completion planned btw 2014-2015)</td>
</tr>
<tr>
<td>2008</td>
<td>JIS standardization (Completion planned btw 2014-2015)</td>
</tr>
<tr>
<td>2009</td>
<td>JIS standardization (Completion planned btw 2014-2015)</td>
</tr>
<tr>
<td>2010</td>
<td>JIS standardization (Completion planned btw 2014-2015)</td>
</tr>
<tr>
<td>2011</td>
<td>JIS standardization (Completion planned btw 2014-2015)</td>
</tr>
<tr>
<td>2012</td>
<td>ISO proposal, JIS revision (Request for review in drafting organization)</td>
</tr>
<tr>
<td>2013</td>
<td>ISO proposal, JIS revision (Request for review in drafting organization)</td>
</tr>
<tr>
<td>2014</td>
<td>ISO revision, JIS standardization (Completion planned btw 2014-2015)</td>
</tr>
</tbody>
</table>

(Source: NEDO post evaluation subcommittee meeting data)

References
D. Flue Gas Treatment and Gas Cleaning Technologies

Part 2 CCT Overview

D-08-06. Gas Cleaning Technology

Technology Overview

1. Background
For the development of coal gasification combined cycle power generation and fuel synthesis technologies, it is necessary to remove sulfur compounds (H₂S, COS), halides (HCl, HF), and other gas contaminants. As shown in Figure 1, a key application of this technology is found in the wet gas purification process that, after removing water-soluble halides and other contaminants with a water scrubber, desulfurizes the gas with a methyl diethylamine (MDEA) or other amine-based liquid absorbent for gas purification. This method, however, requires the gas to be cooled to around room temperature, thus incurring high heat loss. Furthermore, the process becomes complex since it requires not only a heat exchanger but also a catalyst that converts COS (hard-to-remove) into H₂S. It is also difficult to precisely reduce sulfur compounds to a 1ppm level. To solve problems relating to the wet gas purification process, efforts are now underway to develop dry gas purification technology that purifies hot coal gasification gas as it is.

2. Technologies
(1) Dry Desulfurization Method

Research and Development: Japan Coal Energy Center; IGCC Research Association; Central Research Institute of Electric Power Industry; Kawasaki Heavy Industries, Ltd.; IHI Ltd.; Mitsubishi Heavy Industries, Ltd.
Project Type: NEDO-subsidized project, voluntary
Development Period: FY1991 - FY1995 (5 years)

Overview
In the dry desulfurization process, metal oxides are reduced by coal gasification gas, and the reduced metal oxides remove sulfur compounds from the gas, which are then converted to sulfides. As shown in Figure 2, this method can be used more than once by letting the sulfides react with oxygen to release the sulfur contents as SO₂ to return them to metal oxides. The development of this process was promoted as a technology for integrated gasification combined-cycle power generation (IGCC) with a target of reducing sulfur oxides to 100ppm or less in a temperature range of 400-500°C, where economical carbon steel can be used for piping. Iron oxide was selected as the metal oxide to be used and Ishikawajima-Harima Heavy Industries Co., Ltd. built a fluidized-bed desulfurization pilot plant (Fig. 3) that can treat all of the coal gas, using 100-200 µm iron ore particles. It was verified in the 200 ton/day Nakoso IGCC pilot plant project (for coal gas production of 43,600 Nm³/h), a pilot plant that can treat one-tenth of the amount of coal gas produced. The performance of the honeycomb desulfurization agent is being verified. Meanwhile, Kawasaki Heavy Industries, Ltd. has developed an iron oxide-based, highly wear-resistant granular desulfurization agent for use in a moving-bed combined-desulfurization/dust collection system (Fig. 5) and evaluated its performance in a pilot plant capable of treating one-fourtieth of the coal gas produced by the 200-ton/day Nakoso pilot plant.
At present, a desulfurization agent that can reduce sulfur compounds to a level of 1ppm is under development for use in such applications as molten carbonate fuel cells, solid oxide fuel...
cells, and fuel synthesis. At the Central Research Institute of Electric Power Industry (CRIEPI), a desulfurization agent using zinc ferrite (ZnFe₂O₄), a double oxide of iron and zinc, has been developed and found capable of reducing sulfur compounds to 1ppm or less. It is now at the stage of real-gas validation. In addition, efforts to introduce the desulfurization agent into air-blown entrained-bed gasification systems have been made. Another important subject is the application of the agent to oxygen-blown gasification gas with a high carbon-monoxide concentration, which degrades the desulfurization agent by allowing carbon to be separated out of it.

(2) Dry Dehalogenation Method
Research and Development: Central Research Institute of Electric Power Industry
Project Type: Voluntary, NEDO joint research
Development Period: FY2005-FY2007 (3 years)

Overview
To use coal gasification gas in molten carbonate/solid oxide fuel cells and for fuel synthesis, it is necessary to remove not only soot, dust, and sulfur compounds but also halogen compounds. For these applications, efforts are underway to develop a halide absorption agent capable of reducing halogen to 1ppm or less. A method to remove HCl/HF from gas as NaCl/NaF using a sodic compound is under development. CRIEPI produced and tested a sodium aluminate (NaAlO₂)-based absorbent, confirming a possible reduction to 1ppm or less, and completed the development of the absorbent in a joint NEDO research project titled, “The development of a dry gas purification system for multiple fuel and various impurities.” Although performance and system improvements continue, there is already an example of partial use of the technology.
E-09-01. Coal Ash Generation Process and Application Fields

Technology Overview

1. Background and general status of generation process

Coal ash has, since it was commercialized as a cement admixture in the first half of the 1950s, been widely used in commercial applications. These applications include uses as a raw material for cement, cement mixtures, roadbed material, back-filling material, and embankment material. Coal ash has been particularly applicable in the cement sector, notably as a clay-alternative raw material for cement.

2. Generation rate

According to a survey report by the Japan Coal Energy Center (JCOAL) in March 2014, the coal ash generation rate in Japan in 2012 was 12.66 million tons, up 9.4%, or 1.09 million tons, from the preceding year. Most coal-fired boilers for the electric utility industry are combusting pulverized coal. In general industrial applications, 1,000MW or larger coal-fired boilers are in operation, of which a majority combust pulverized coal. In terms of boiler capacity (steam generation rate), 50-ton/hr or smaller boilers are mostly of a stoker combustion type while many of the 100-ton/hr or larger boilers combust pulsed coal. Figure 2 shows changes in the rate of coal ash utilization and generation from electric power utilities and industries (1,000MW or larger) from 1993 through 2003.

3. Composition of coal ash

In Japan, 90% or more of the coal ash generated is from pulverized coal combustion, dwarfing the 7% or so from fluidized-bed and 1-2% from stoker combustion. The generation ratio of fly ash to clinker ash (bottom ash) is 9:1.

As for the shape of coal ash particles, low-melting point ash is often spherical while much of high-melting-point ash is indeterminate in shape. The average grain size of fly ash from pulverized coal combustion is approximately 25µm, similar to silt in fineness, and falling between finer clay and coarser fine-grained sand for use as a soil material. The chemical composition resembles mountain soil, with two inorganic components, silica (SiO₂) and alumina (Al₂O₃), accounting for 70-80% of the total composition. Ferric oxide (Fe₂O₃), magnesium oxide (MgO), and calcium oxide (CaO) are also contained in small amounts. In Japan, the composition of coal varies widely since 100 or more varieties of coal are imported from all over the world.
4. Application fields

Table 1 shows the effective utilization of coal ash in FY2012 by field. Usage in the cement industry is increasing annually. Of the 12.36 million tons used, the cement industry accounted for 8.39 million tons, or 67.9%. Recently, however, cement production has been declining and the prospects for substantial future increases are not bright. To cope with a likely increase in coal ash in the future, expanding utilization in other sectors will be important. In particular, the civil engineering field is expected to use more coal ash because of its high potential for consuming large quantities.

Table 1 Breakdown by fields for the effective use of coal ash (FY 2012) (Unit: thousand tons)

<table>
<thead>
<tr>
<th>Field</th>
<th>Application</th>
<th>Total</th>
<th>Electric utilities</th>
<th>General industry</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rate of utilization</td>
<td>Composition ratio(%)</td>
<td>Rate of utilization</td>
<td>Composition ratio(%)</td>
<td>Rate of utilization</td>
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<td>Cement</td>
<td>Cement raw material</td>
<td>5,529</td>
<td>62.72</td>
<td>2,663</td>
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<td>Cement mixture</td>
<td>95</td>
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<td>Cement admixture</td>
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<td>0.79</td>
<td>64</td>
<td>1.81</td>
</tr>
<tr>
<td>Others</td>
<td>Sewage treatment agent</td>
<td>2</td>
<td>0.02</td>
<td>0</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>Steel making</td>
<td>1</td>
<td>0.01</td>
<td>5</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>Others</td>
<td>1,572</td>
<td>17.83</td>
<td>88</td>
<td>2.48</td>
</tr>
<tr>
<td></td>
<td>Sub-total</td>
<td>1,575</td>
<td>17.87</td>
<td>93</td>
<td>2.64</td>
</tr>
<tr>
<td></td>
<td>Total</td>
<td>8,816</td>
<td>100.00</td>
<td>3,541</td>
<td>100.00</td>
</tr>
</tbody>
</table>

References
4) Natural Resources and Fuel Department, the Agency for Natural Resources and Energy: Coal Note (2003 edition), 2003.
Part 2 CCT Overview

E. Technologies to Effectively Use Coal Ash

E-09-02. Effective Use of Ash in Cement / Concrete

Technology Overview

1. Technology overview
Research has been conducted on utilizing fly ash in the cement sector as an alternative for pozzolana. Enhanced research on the use of fly ash as a good-quality alternative to pozzolana led to its first application as a concrete admixture in the late 1940s, when it was used for structures such as dams in the United States. This process was subsequently disseminated to other countries. In Japan, following its commercialization as a cement admixture early in the 1950s, standards were established for fly ash in 1958 and then for fly ash cement in 1960. This encouraged its widespread application in general concrete structures. Fly ash came to be used as a clay-alternative raw material in cement in 1978, and by 2003, 70.1% of utilized fly ash was used in this manner.

2. Utilization in the cement sector
1) Utilization as a clay-alternative raw material in cement
The raw materials for cement are limestone, clay, silica, and ferric oxide. Clay accounts for 15% of the total composition. Coal ash containing silica (SiO₂) and alumina (Al₂O₃) is also used as an alternative to clay. However, coal ash contains less SiO₂ and more Al₂O₃ than clay, which requires that more silica be used to offset the shortage of SiO₂. This deficiency limits the substitutability of coal ash for clay.
At present, coal ash can constitute approximately 5% of the raw materials for cement but theoretically its use could be as high as around 10%.

2) Utilization as cement mixture
Japanese Industrial Standards (JIS) specify standards for fly ash cement, allowing the mixture to range from 5-30%. In general, fly ash can also be used as a Portland cement mixture, blended at 5% or less.

3. Utilization in the concrete sector
1) Utilization as a concrete admixture
[1] Dam concrete
In Japan, research on fly ash as a concrete admixture started around 1950, with favorable results and economics through the first commercial use at a dam site in 1953. Roller compacted dam-concrete (RCD) is a concrete product finished by compacting concrete of ultra-thick consistency with a vibration roller. The Ministry of Construction led independent technology development for utilization in a concrete dam, successfully systematizing the trial into the RCD construction method, which was commercialized for dam construction in 1978. In order to prevent cracks, dam concrete is generally not allowed to reach high temperatures. Due to this restriction, in RCD only a portion of the cement can be replaced by fly ash to limit temperature increases. Generally, the replacement ratio is 20-30%.
As many as some 30 dams have thus far been built employing this construction method, making it a well-established engineering method and justifying the development efforts.

[2] Pre-packed concrete
Pre-packed concrete is a concrete product fabricated by casting coarse aggregate of a designated grain size into a mold or place of application beforehand and injecting mortar into voids at an appropriate pressure. The mortar used must be one of high fluidity, with little material separation, and of moderate expansibility. For this purpose, fly ash is generally mixed at a rate of 25-50%. Applications include underwater concrete, mass concrete, and the repair/reinforcement of existing concrete work. The substructure work for the Honshu-Shikoku Bridge also employed this construction method.

Fly ash enriched concrete (FEC) is a two component-type, high-fluidity concrete product using cement and fly ash as powder materials. It can contain 40% or more fly ash. This provides such characteristics as excellent self-filling capability requiring no compaction after casting, minimal cracking due to heat of hydration to increase its long-term strength, as well as higher durability against alkali aggregate reactions and salt/acid damage.
Fly ash and slag concrete (FS), using steel slag and coal ash as aggregates, is a plain concrete product developed for wave-breaker superstructure works and fixation blocks/ tetrapod that do not require great strength.
Industrial standards for concrete-purpose fly ash

After evaluating fly ash as a concrete admixture it was determined that it performed well due to its ultra-fineness and the limited quantity of unburned carbon. Subsequently, ultra-fine items produced by an advanced analyzer (sieving machine) were commercialized. In addition, items with higher-performance qualities, or qualities likely to prove effective as admixture despite their substandard state, were added to the JIS standards and classified as grade 4 materials. This designated them with a quality suitable for utilization. Fine fly ash is used as an admixture for concrete products used as water/moisture barriers. It must be durable, among other characteristics. Uses include ocean concrete and specially-reinforced shielding material used for long-distanced pumping.

### Table 1 Quality of fly ash (JIS-A 6201)

<table>
<thead>
<tr>
<th>Class</th>
<th>Class I fly ash</th>
<th>Class II fly ash</th>
<th>Class III fly ash</th>
<th>Class IV fly ash</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica dioxide (%)</td>
<td>45.0 or higher</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moisture content (%)</td>
<td>1.0 or less</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ignition loss1 (%)</td>
<td>3.0 or less</td>
<td>5.0 or less</td>
<td>8.0 or less</td>
<td>5.0 or less</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>1.95 or higher</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fineness2</td>
<td>Residence on 45 m sieve (screen sieve method)3 (%)</td>
<td>10 or less</td>
<td>40 or less</td>
<td>40 or less</td>
</tr>
<tr>
<td>Specific surface area (Blaine method) (cm²/g)</td>
<td>5000 or higher</td>
<td>2500 or higher</td>
<td>2500 or higher</td>
<td>1500 or higher</td>
</tr>
<tr>
<td>Flow value ratio (%)</td>
<td>105 or higher</td>
<td>95 or higher</td>
<td>85 or higher</td>
<td>75 or higher</td>
</tr>
<tr>
<td>Activity index (%) Material age: 28 days</td>
<td>90 or higher</td>
<td>80 or higher</td>
<td>80 or higher</td>
<td>60 or higher</td>
</tr>
<tr>
<td>Material age: 91 days</td>
<td>100 or higher</td>
<td>90 or higher</td>
<td>90 or higher</td>
<td>70 or higher</td>
</tr>
</tbody>
</table>

1. In place of ignition loss, the unburned carbon content ratio may be measured by the method specified in JIS M 8819 or JIS R 1603 to apply to the result a stipulated value of ignition loss.
2. Fineness based on the screen sieve method or the Blaine method.
3. Regarding fineness, the results of the Blaine method are provided as a reference value for the screen sieve method.

---

References
E-09-03. Effective Use of Ash in Civil Engineering / Construction and Other Applications

Technology Overview

1. Technology overview

Besides its application in concrete, coal ash is also widely used in the civil engineering sector for road construction, foundation improvements, back-filling or use in other earthwork uses, and in the construction sector as an artificial light-weight aggregate. In the agriculture/forestry/fisheries sector, it is used as a fertilizer or soil conditioner.

To cope with the anticipated increase in the generation of coal ash in the future due to such factors as the construction of new coal-fired power plants, utilization technologies are now under active development to expand the utilization of coal ash in the above-mentioned sectors. In order to accomplish this, several challenges, including the diffusion of technology, the exploitation of demand, and the improvement of the distribution system, must be addressed.

2. Utilization for civil engineering

1) Road construction material

The “Outline of Asphalt Pavement” allows fly ash to be used as an asphalt filler material, and for clinker ash to be used as a lower subbase material, frost heave depressant, or barrier material. Fly ash can be used for the upper/lower subbase and subgrade. A cement stabilization treatment construction method adds fly ash to cement to be treated under moderate moisture content for application. This construction method strengthens quickly and is stable over the long-term. Other technologies have also been developed to process coal ash for use as a road construction material. Clinker ash can be used as roadbed material due to its high bearing capacity. It is also used as mid-layer material for ground construction due to its water retention and permeability properties.

2) Earthwork material

Fly ash can be effectively used for an embankment or reinforcement material since it is lighter than common earthwork materials. In recent years, various technology development efforts have been made, resulting in a number of applications. Among these is an application using fly ash in its original powder state with cement added as a solidifier to coal ash, as well as fly ash’s utilization as a stabilizing material. It is also granulated or processed in other ways for different applications. Review is also underway for the intended commercialization of fly ash as a soil stabilizer or a construction sludge conditioner due to its pozzolanic activation and self-hardening properties.

Basic research of the elution of coal ash’s trace elements is continuing since fly ash’s use in earthwork must be environmentally sound.

Photo 1 Application for road construction
3. Utilization in the construction sector

1) Artificial light-weight aggregate

Development efforts\textsuperscript{11,12} have successfully produced technology to pelletize/calcine coal ash and cement into artificial, lightweight aggregate. Demand, driven by urban development and high-rises, is expected to grow, making it important to further the technological development of artificial lightweight aggregate as well as to reduce production costs.

2) Others

The resemblance of coal ash’s elements to the chemical composition of existing construction materials also allows it to be used as a clay-alternative raw material for ceramic products, such as clay roofing tile, bricks, and tiles, or as a cement mixture for boards (interior/interior wall material for construction).

1) Fertilizer

Fly ash from pulverized coal-combustion was designated as a special fertilizer in 1960, as was clinker ash in 1992. Several thousands of tons a year of potassium silicate fertilizer, containing hard-to-dissolve silicic acid from coal ash, is also produced.

2) Soil conditioner

Clinker ash, whose main components, SiO$_2$ and Al$_2$O$_3$, are almost the same as those of ordinary soil, is suitable for the growth of vegetables. Moreover, it is used to grow sod for golf courses or to improve the soil of poor-drainage areas or arable land since its countless spores retain water well. This enables fertilizers to be effective for a longer duration and, its similarity in shape to sand provides comparable water permeability.

3) Utilization in the fisheries sector

There are long-established cases where coal ash has been used for fish breeding reefs and seaweed beds. A recent effort aims to use coal ash as a mounding material for a man-made underwater mountain range to cause artificial upwelling currents\textsuperscript{13}.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig2.png}
\caption{Photo 2 Artificial aggregate fabricated from coal ash (Toughlite)}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig3.png}
\caption{Photo 3 Application as fertilizer}
\end{figure}

\begin{itemize}
\item References
\end{itemize}

12) Ozasa et al., CCUJ, 10th Annual Conference on Clean Coal Technology lecture collection, 2000.
Due to global warming concerns, there is a demand to reduce the amount of CO₂ emissions from coal utilization. IGCC, a highly efficient power generation technology, will likely come be put into practical application. In Japan, a 250 MW IGCC plant is already in commercial operation and a 170MW IGCC (OCG project) will start in 2016. They discharge ash as a slag state, which is not powdery but glassy (Photo1). Due to the decrease in cement manufacturing in recent years, it is difficult to expand the use of coal ash as materials for cement production. Therefore, there is a need to establish other ways to utilize coal ash. The slag from IGCC plant also requires effective uses. Thus the technological development and industrial standardization of slag utilization is of great importance. The establishment of a new way to utilize slag would lead to cost reduction of IGCC power generation and contribute to the spread and expansion of IGCC technology.
In order to use coal gasification slag as alternate materials to sand and crushed stone, which are demanded in mass quantities, there is a need to determine its properties and qualities, develop technology that improves its function as an alternate material, ensure compliance with various laws and regulations, and standardize it. A molten slag standardization committee is to be launched in the coming year. The market introduction schedule is as follows:

- 2013: Begin commercial use at Joban Joint Power Co., Ltd. (250MW)
- 2017: Begin operations at Osaki CoolGen (170MW)
- Early 2020s: Fukushima IGCC operation begins (500MW x 2: under planning)

2. Tasks and current situation

In order to use coal gasification slag as alternate materials to sand and crushed stone, which are demanded in mass quantities, there is a need to determine its properties and qualities, develop technology that improves its function as an alternate material, ensure compliance with various laws and regulations, and standardize it. A molten slag standardization committee is to be launched in the coming year. The market introduction schedule is as follows:
In order to achieve the goal proposed by Cool Earth 50 – reduce the amount of global greenhouse gas emission by 50 percent from the present state (2007) by 2050 – an innovative technology development is required that involves CO₂ separation, collection, and storage (CCS – Carbon Capture Storage). For this reason and to gauge the feasibility of CCS implementation by Japan, a feasibility study (FS) was conducted regarding the whole system, from power generation to CO₂ storage.

2. Case study overview

2.1 Case study review

Using various references such as storage reservoir selection guidelines, expert hearings, and past study data, storage sites and emission sources were selected. Table 1 shows the six case study subjects.

Table 1 Study subjects

<table>
<thead>
<tr>
<th>Emission source</th>
<th>Storage site</th>
<th>Form of transport</th>
<th>Demonstration project plant</th>
<th>Commercial Plant</th>
<th>Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site A</td>
<td>Site A offshore</td>
<td>No transport (ex: ERD¹)</td>
<td>O</td>
<td>O</td>
<td>(1)</td>
</tr>
<tr>
<td>Osaka</td>
<td>Site A Land base</td>
<td>Shipping (Liquefied CO₂)</td>
<td>O</td>
<td>O</td>
<td>(2)</td>
</tr>
<tr>
<td></td>
<td>Site B Submerged base</td>
<td></td>
<td>O</td>
<td>O</td>
<td>(3)</td>
</tr>
<tr>
<td></td>
<td>Site C Floating base</td>
<td></td>
<td>O</td>
<td>O</td>
<td>(4)</td>
</tr>
<tr>
<td>Matsuura</td>
<td>Site C Pipeline transport (liquid)</td>
<td></td>
<td>O</td>
<td>O</td>
<td>(5)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pipeline transport (gas)</td>
<td></td>
<td>O</td>
<td>(6)</td>
</tr>
</tbody>
</table>

¹ERD: Extended reach drilling

2.2 Separation and collection systems study

For the CO₂ collection process, we selected the sweet water gas shift process, which has a low utility consumption, and chemical absorption process. Figure 1 shows the system construction and plant specifications, which assumes a commercial scale of 2,000t-coal/day.

Table: Power generation and transport efficiency

<table>
<thead>
<tr>
<th></th>
<th>Coal removal</th>
<th>CO₂ collection</th>
<th>Power generation output</th>
<th>Gross power generation efficiency</th>
<th>Power transport output</th>
<th>Net transport efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unit</td>
<td>t/d</td>
<td>t/d</td>
<td>MW</td>
<td>%</td>
<td>MW</td>
<td>%</td>
</tr>
<tr>
<td>0% collection</td>
<td>2,178</td>
<td>0</td>
<td>364.1</td>
<td>55.0</td>
<td>315.2</td>
<td>47.6</td>
</tr>
<tr>
<td>90% collection</td>
<td>2,380</td>
<td>* 5,280</td>
<td>341.7</td>
<td>47.3</td>
<td>282.5</td>
<td>39.1</td>
</tr>
</tbody>
</table>

*1.5 million t/y assuming 80% capacity utilization, 30.8million t/20y assuming a twenty-year storage period

Figure 1 IGCC power generation system
2.3 Transport system study

2.3.1 Liquefied CO\textsubscript{2} shipping system conceptual design

As Figure 2 shows, the collected CO\textsubscript{2} is liquefied (-46 °C, 0.7MPaG), shipped from land storage base via a CO\textsubscript{2} transport craft, unloaded at either an offshore submerged station (point B), a floating base (point C), or a land base (point A), and is sequestered into a reservoir. Below are plans for the major facilities:

(1) Liquefied CO\textsubscript{2} Transport Craft (for Domestic Transport)

Transport capacity: 21,000ton; tank design temperature and pressure: -50°C, 1.0MPaG; hull structure: double hull bulkers (Figure 3)

(2) Land Base

The storage capacity of both the loading tank and unloading tank is 24,000ton. To ensure safety and to reduce costs, a two-tank system was selected (to avoid having to load and un-load liquefied CO\textsubscript{2} at the same time at one tank).

(3) Offshore Submerged Storage

Tank capacity: 3,000ton x 8 units; dimensions (length x width x height): 250m x 42m x 25m.

A pier docking is prepared with a load capacity of 21,000ton, a length of 161m and a draft of 9.4m.

The concrete structure is built using a dry dock. It was decided to load equipment such as tanks and booster machines off shore (in a wharf), tow to the storage location, and install the equipment at the site.

(4) Offshore Floating Platforms

A mono-column type was selected (length and width: 86m) that performs well under wave motions, and the eight 3,000t-grade CO\textsubscript{2} tanks are vertically placed in the column with the pressing equipment positioned on the deck.

2.4 Sequestration study

2.4.1 Investigation of possible reservoir site and reservoir potential in Japan

Sedimentary layers, which indicate potential CO\textsubscript{2} storage sites, are present in areas near Japan and shown in Figure 5. A study was conducted on the distribution of these sedimentary layers and the possible CO\textsubscript{2} storage amount at these sites.

The reservoir potential was calculated based on two references; “CO\textsubscript{2} underground storage project-National reservoir endowment survey”, and “The new edition of Japanese active faults (one-millionth).”

In this calculation, the CO\textsubscript{2} reservoir sites located within certain distances from the active faults were excluded from being considered potential reservoir sites.

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Distance from active faults</th>
<th>Without regard</th>
<th>2km</th>
<th>5km</th>
</tr>
</thead>
<tbody>
<tr>
<td>A2</td>
<td>52</td>
<td>43</td>
<td>34</td>
<td></td>
</tr>
<tr>
<td>A3</td>
<td>214</td>
<td>169</td>
<td>135</td>
<td></td>
</tr>
<tr>
<td>B1</td>
<td>275</td>
<td>261</td>
<td>231</td>
<td></td>
</tr>
<tr>
<td>B2</td>
<td>885</td>
<td>813</td>
<td>694</td>
<td></td>
</tr>
<tr>
<td>B2*</td>
<td>98</td>
<td>85</td>
<td>62</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>1524</td>
<td>1372</td>
<td>1156</td>
<td></td>
</tr>
</tbody>
</table>

B2*: Reservoir potential survey from the CO\textsubscript{2} underground storage project
2.4.2 The selection of prospective reservoir sites and the calculation of reservoir potential
A total of three locations (point A through C) were selected as prospective CO₂ reservoir sites from the Japan Sea side of Tohoku Region, the Pacific side of East Japan, and the continental shelf of West Japan. Table 2 shows the initial calculation results on the reservoir potential at each site. The storage capacity far exceed the projected 20-year commercial CO₂ emission of about 30 million tons. Table 2 Investigated CO₂ storage sites

<table>
<thead>
<tr>
<th>Regions</th>
<th>Tohoku region</th>
<th>Japan Sea side</th>
<th>East Japan Pacific side</th>
<th>West Japan continental shelf</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sites</td>
<td>Site A</td>
<td>Site B</td>
<td>Site C</td>
<td></td>
</tr>
<tr>
<td>Reservoirs</td>
<td>Layer G (Pliocene)</td>
<td>Layer C (Pliocene bottom layer)</td>
<td>Layer D predominantly sandstone (Pliocene)</td>
<td></td>
</tr>
<tr>
<td>Depth (m)</td>
<td>800-1200</td>
<td>800-2000</td>
<td>1200-1610</td>
<td></td>
</tr>
<tr>
<td>Depth representative value (m)</td>
<td>1100</td>
<td>1650</td>
<td>1200</td>
<td></td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>40</td>
<td>50</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Hydrostatic pressure (MPa)</td>
<td>12</td>
<td>17</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>Storage ratio (Sf)</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
<td></td>
</tr>
<tr>
<td>Target area A (km²)</td>
<td>60</td>
<td>1300</td>
<td>528</td>
<td></td>
</tr>
<tr>
<td>Effective layer thickness h (m)</td>
<td>87</td>
<td>20</td>
<td>251</td>
<td></td>
</tr>
<tr>
<td>Porosity ψ</td>
<td>0.40</td>
<td>0.40</td>
<td>0.37</td>
<td></td>
</tr>
<tr>
<td>Supercritical CO₂ saturation ratio Sg</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>CO₂ density (t/m³)</td>
<td>0.001976</td>
<td>0.001976</td>
<td>0.001976</td>
<td></td>
</tr>
<tr>
<td>CO₂ volume coefficient</td>
<td>0.00276</td>
<td>0.00274</td>
<td>0.00455</td>
<td></td>
</tr>
<tr>
<td>Storage capacity (hundred million t CO₂)</td>
<td>2</td>
<td>9</td>
<td>26.6</td>
<td></td>
</tr>
</tbody>
</table>

2.4.3 Conceptual design of the storage unit
A CO₂ sequestration simulation was conducted at these three sites. The storage potential on a demonstration level (1.54 million tons CO₂/year) and a commercial level (10 million tons CO₂/year) were studied, and sequestration conditions were examined. The necessary equipment at each of these sites was conceptually designed. Additionally a new “Site D” was projected in case a large-scale facility that collect CO₂ from many large emission sources was developed. Its conceptual design and costs were examined (Table 3).

<table>
<thead>
<tr>
<th>Approximate cost</th>
<th>1 Preliminary survey (including exploration)</th>
<th>2 Construction (storage facility)*</th>
<th>3 Operation (20 years)</th>
<th>4 Monitoring (20 years)</th>
<th>5 Abandoned mine</th>
<th>6 Monitoring (50 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Site D 2011 (1.54 million)</td>
<td>316</td>
<td>203</td>
<td>148</td>
<td>30</td>
<td>49</td>
<td>49</td>
</tr>
<tr>
<td>B: Site D 2011 (10 million)</td>
<td>894</td>
<td>705</td>
<td>75</td>
<td>577</td>
<td>62</td>
<td>62</td>
</tr>
<tr>
<td>Ratio = Sequestered amount B/A</td>
<td>6.5</td>
<td>2.8</td>
<td>3.5</td>
<td>2.5</td>
<td>3.9</td>
<td>3.9</td>
</tr>
</tbody>
</table>

2.5 Total system assessment

2.5.1. Power generation cost analysis
Figure 6 shows the costs of power generation. The IGCC construction cost was corrected based on market price recorded for IGCC at Edwardsport power station (U.S.A.). Since many of the sequestration sites for Japan are in marine areas and are not of large capacities, shipping transport is more suitable than pipeline transport. However, because the shipping cost accounts for a lot of the power generation cost, a cost reduction plan case was outlined. The cost reduction study of 2011 showed that the power generation cost can be reduced by about 7% through barge shipping and the cryogenic separation liquefaction method (developed by ENAA). The cost reduction study of 2012 demonstrated a total of 13% cost reduction potential by scaling up sequestration facility (developed by ENAA and RITE)

2.5.2 Energy consumption assessment
Figure 7 shows the energy consumption of each stage: 90% CO₂ separation and collection, transport, and storage. The liquefaction compression accounts for a relatively large portion of the energy consumption. CO₂ liquefaction through the cryogenic method stated in the previous section was reviewed as an energy-saving measure.
2.5.3 CO₂ processing cost and CO₂ balance assessment

Figure 8 shows the CO₂ processing cost. The bar graph represents the “Captured Cost” and the line graph represents the “Avoided Cost”. Figure 9 shows the CO₂ balance. In the case of shipping transport, about 28% of the CO₂ collected is generated in the process. This is mainly caused because CO₂ liquefaction accounts for 50% of the energy use. The cryogenic liquefaction separation method identified in Section 2.5.1, was reviewed as an energy-conserving measure.

![Figure 8 Estimated processing cost](image)

![Figure 9 CO₂ balance assessment](image)

3. Construction of the economic evaluation model

A business assessment analysis tool for CCS economic analysis was developed by creating a geographical information system (GIS) based on parameters such as power generation system, separation and collection technology, transport, storage, monitoring, generation source, and storage site position conditions.

4. Structure and evaluation of the energy supply and demand impact assessment model

The introduction of the zero-emission coal-fired electric power generation system established the following in Japan: 1) long-term electricity demand structure, 2) long-term energy supply-demand structure, and 3) models to analyze CO₂ emission reduction. The analysis results of a long-term electricity supply-demand scenario made it evident that, in order to achieve the government’s goal to reduce CO₂ emission to 80% of the current use by 2050, it is necessary to use CCS for not only coal-fired thermal power, but also natural gas thermal power. The results also showed that in the case that CO₂ reduction is not possible through the use of nuclear power, the necessary CO₂ collection and storage amounts would be 20-50 million tons by 2030, and 200 million by 2050.

5. Others

In order to advance the practical use of innovative zero-emission coal-fired electric power generation systems, research topics were selected that would be useful for international standardization. Topics that were deemed important to allow Japan to take global leadership in the field were especially considered. Additionally, knowledge was updated on domestic and foreign policy trends and investigations were conducted to strategize the introduction of zero-emission thermal power that would be economically efficient and effectively feasible in Japan. These topics included:

1) examination on retrofitting existing thermal power plants with CO₂ equipment, 2) cost assessment of CCS with shuttle tankers and off-shore sequestration, 3) study on the floating-type CO₂ separation and collection equipment, 4) assessment on the potential of a seabed reservoir deeper than 200m, and 5) investigation into the institutions that would promote practical application of CCS.

6. Issues and feasibility of practical application

An assessment on the possibility of CCS and the projected power generation cost of IGCC electricity generation with CCS near Japanese coastal waters demonstrated that CCS is possible with an average power generation cost of 20 yen/kWh, the same as renewable energy. Technology development hereafter is expected to reduce the cost even further by improving efficiency and plant cost. The hope is to use the study results towards further economic impact study and the estimation of the amount of CO₂ reduction achievable in Japan upon CCS implementation to ultimately make CCS zero-emission coal thermal power generation a reality.
F-01-02. Hydrogen Production and Transport Technology

F. Energy Chain System

Kawasaki Heavy Industries, Ltd.
Voluntary project, NEDO-commissioned project
FY2010 – FY2011 (2 years), FY2011 (1 year), FY2012 (1 year), FY2014 (1 year)

Technology Overview

1. Technology development necessity and impact
In the basic energy plan decided by the cabinet in April 2014, hydrogen was identified as a secondary energy source. In the hydrogen fuel cell strategy road map developed in June by the Ministry of Economy, Trade, and Industry (METI), a goal to practically apply hydrogen power generation by 2030 was established. The road map shows the necessity of importing hydrogen from overseas for practical application to hydrogen power generation, and it specifies lignite as an un-tapped fossil fuel reservoir for obtaining hydrogen.

Lignite exists worldwide, amounting to 23% of the nine billion tons of recoverable coal reserves (Reference: WEC2013). It has high moisture content (over 30-60%), and spontaneously combusts upon drying, making long-distance transport impossible. Therefore, its usage is limited and it is mainly used near coal mines as low-efficiency thermal power fuel. Furthermore, although lignite that has a relatively low moisture content is starting to have market value due to the recent increase in coal utilization and is traded at a fixed price, high-moisture-content lignite (over 60%) has no market value. Therefore, the use of such lignite as hydrogen source would be cheaper than manufacturing hydrogen from other fossil fuels. This technology can lead to supplying a large amount of hydrogen to Japan cheaply. It allows for the conversion of lignite which exists worldwide into a massive quantity of hydrogen, a secondary energy source, which would be liquefied in the producing country and transported to Japan. There are many other benefits to this technology for Japan such as energy security through independent, low CO2-emission energy development, ensuring abundant and stable energy supply. Environmental benefits are achieved as the technology dramatically reduces CO2 emission and economic benefits result from the small outflow of national resources. At the same time, the producing countries benefit from the creation of a new export industry in converting formerly unused lignite into hydrogen. It also revitalizes related industries and creates jobs, resulting in a win-win situation for both Japan and the producing countries.

2. Objective
Producing hydrogen from unused, cheap lignite abroad and importing liquefied hydrogen for mass transport to Japan, will create a large-scale hydrogen import chain. The following are technologies to be developed: a high-efficiency gasification hydrogen production technology from high-moisture lignite, a high-efficiency hydrogen liquefaction technology, a large-capacity liquefied hydrogen storage technology, and a high-efficiency hydrogen power generation technology.

3. Core technologies
There are five core technologies involved in this technology:
[1] A total lignite gasification technology, from drying the high-moisture lignite to gasification
[2] Hydrogen liquefaction technology
[3] Liquefied hydrogen storage tank technology
[4] Liquefied hydrogen transport tanker technology
[5] Large-quantity hydrogen usage technology (power generation)

4. The current situation and development schedule
Currently, there are plans to design and construct the pilot chain between 2015 and 2019 in order to demonstrate the viability of this unused, overseas energy utilization chain by 2020. Additionally, commercial chain for post-2025 will be built based on the knowledge obtained from the pilot demonstration in 2020. Figure 1 shows the chain overview, and Figure 2 shows the hydrogen production technology. Regarding the post-2025 commercial chain, cost of hydrogen is estimated to be 29.3 yen/Nm$^3$ (Figure 3).
Clean Coal Technologies in Japan

(1) A total lignite gasification technology, from drying lignite to gasification
In order to gasify high-moisture content lignite, it needs to be dried in preprocessing. However, since heat is required for this process, a gasifier that can minimize the drying process would be desirable. For this, a total gasification technology will be developed. Figure 2 shows the technology to produce hydrogen from lignite.

(2) Hydrogen liquefaction technology
Similar to natural gas, a massive amount of energy is required to liquefy hydrogen gas. A technology to improve the efficiency of the liquefaction process will be developed, which will improve the efficiency of the entire chain.

(3) Liquefied hydrogen storage tank technology
The liquefying temperature of hydrogen is -253°C. In order to suppress the evaporation loss of liquefied hydrogen and store it at this extremely low temperature, a technology to improve the tank’s thermal insulation will be developed.

(4) Liquefied hydrogen transport vessel technology
The transportation tank design and material will be developed for the marine transport of the volatile liquefied hydrogen taking the sloshing from wave motions into consideration. Data from voyages will also be confirmed.

(5) Mass-quantity hydrogen usage technology (power generation)
Hydrogen power generation would be effective in creating a massive utilization for hydrogen, which would lead to promoting a low-cost, CO2-free hydrogen distribution. In particular, hydrogen-fired gas turbine technology will be developed due to its potential to generate power more efficiently.

When hydrogen is used in Fuel Cell Vehicles (FCV), the price is competitive to current gasoline prices (Figure 4). For the case of hydrogen use in power generation, although more expensive than present fossil fuel power generation, among the CO2-free energy options, it is cheaper than renewable energy and has the potential for stable and large-quantity usage (according to the 2010-2011 International Partnership Clean Coal Technology Development Project).

Figure 1 An overview of the CO2-free hydrogen chain (pilot chain and demonstration chain)

Figure 2 Production technology of hydrogen from lignite

Figure 3 Cost of hydrogen from lignite

Figure 4 Comparison of fuel consumption by current vehicles and FCV

Figure 5 Comparison of power generation cost

Source: Energy and Environment meeting; verification committee report 230 model plant

5. Tasks for further development

(1) A total lignite gasification technology, from drying lignite to gasification

(2) Hydrogen liquefaction technology

(3) Liquefied hydrogen storage tank technology

(4) Liquefied hydrogen transport vessel technology

(5) Mass-quantity hydrogen usage technology (power generation)
F. Energy Chain System

Part 2 CCT Overview

F-01-03. Manufacturing of Lignite Gasification Substitute Natural Gas (SNG) (South Sumatra SNG Project and CO₂ Enhanced Oil Recovery (EOR) Demonstration Project)

<table>
<thead>
<tr>
<th>Research and Development</th>
<th>Mitsubishi Heavy Industries, Ltd.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Type</td>
<td>Voluntary project, NEDO-commissioned project</td>
</tr>
<tr>
<td>Development Period</td>
<td>FY2012 – FY2014 (3 years)</td>
</tr>
</tbody>
</table>

**Technology Overview**

1. **Technology development necessity and impact**

   This technology can produce substitute natural gas (SNG), from low-rank and low-quality coals, which are unutilized in coal countries. This would contribute to energy supply/demand relief and improved environmental impacts in the coal producing country while allowing Japan to secure a stable energy supply. By collecting and storing CO₂ in SNG production process, CO₂ emission is reduced in the use of SNG.

2. **Objective**

   The objective is to introduce Japan’s gasification technology to Indonesia, and to produce and supply SNG for their domestic use. Japan’s technology can gasify a low-rank coal at a very high efficiency. The SNG plant construction is planned at a mine mouth in South Sumatra, and the CO₂ is will be used in Enhanced Oil Recovery (EOR) and underground immobilization.

3. **Core technology**

   This is a compound plant that combines CCS/EOR with an SNG plant using the entrained gasification technology.

4. **Current situation and development schedule**

   Between 2012 and 2014, an Indonesian low-rank coal gasification test and a feasibility study were conducted. The feasibility study regarding the end-product (power, SNG, fertilizer) also determined that SNG is the most economically advantageous option (SNG price can be cheaper than LNG), and that the project is feasible. A project scheme study was also conducted with the cooperation of the local government. Coal-supplying companies, the potential stakeholders, are showing interest in supplying low-rank coal over a long term, and end users are also showing interest in long-term receiving contracts. On October 16, 2014, a MOU was established with the national oil company for a joint study on the use of CO₂ for EOR.

5. **Tasks for further development**

   Although this is an application of existing technology (e.g., gasification technology), several areas for further development should be considered in working towards commercial plant construction such as gasifier cost reduction and the optimization of systems for utilizing varying coal types.

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**Figure 1** Overview of Sumatra SNG project

**Figure 2** Example of a potential site for a SNG synthesis plant in Indonesia’s south Sumatra Islands
F-01-04. Substituted Natural Gas (SNG) from Fossil Fuels such as Coal and Heavy Oil


New Sunshine Project – Development of Coal Hydrogenation Gasification Technology

FY1990 – FY2000 (11 years)

Technology Overview

1. Background and objectives

The subject matter of energy security measures is becoming important, such as is discussed in the “New National Energy Strategy.” Regarding measures to secure natural gas, which is difficult to store, purchase-source diversification is occurring at the nongovernmental level. However, there is a need for management at the national level to further expand choices.

At the time of this study, the crude oil price was very high and the importance of developing a technology to substitute conventional fossil fuel was increasing. Furthermore, production of unconventional crude oil obtained from reserves with an abundance of low-grade coal and heavy oil is expected to increase in the future. Utilizing this unconventional crude oil is important to improving energy security.

Under the circumstances of seeking a countermeasure to the price increases of crude oil and LNG and the tightening of their supply and demand, one of the steps taken was to develop SNG production technology from coal and heavy oil. Specifically, the use of low-rank from Australia and Indonesia was most desirable.

A national project to research and develop the core technology was conducted for this SNG technology between 1990 and 2000. Afterwards, in 2008 and 2009, a pre-feasibility study was conducted that was based on existing gasification technology. There is a need to continuously explore this technology as related gasification technologies advance and changes in crude oil/LNG prices and CO2 emission regulations occur.

2. Core technology

To deal with recent energy conditions and in an effort to ensure natural gas security, this technology will manufacture SNG from fossil fuel resources, such as low-rank coal and heavy oil. Additionally, a high-calorie gas manufacturing technology that is suitable towards achieving household gas standards will be developed.

[1] Gasification process technology, methanation technology (including C2, C3 components in the production gas)
[2] CO2 separation, collection, and fixation technology

3. Tasks for further development and the current status

(1) The long-term energy supply and demand outlook and a feasibility study on the trend of SNG technology development
(2) Large-scale gasifier that is highly efficient and low-cost
(3) Separation, collection, and fixation of CO2 to prevent an increase in CO2 emissions from the increased use of coal and heavy oil
(4) High-calorie manufacturing technology of gas that contains C2, C3 during methanation technology which utilizes a coal gasification gas containing C2, C3 components

According to the pre-feasibility study and depending on the natural gas price trend, if the SNG plant is built in a coal-producing country that also is a gas-producing country, there is a possibility of trading LNG.

Cheap fuel such as lignite and heavy oil, which are difficult to transport, could be utilized by establishing this technology abroad. Additionally, when the natural gas resource is depleted in the producing country, this technology could possibly allow for the effective utilization of the existent liquefying facility. In these ways, this technology from Japan has the potential to be a tool to strengthen relationships with resource-rich countries.

This technology has the potential to produce a substantial amount of high-value BTX (benzene, toluene, xylene) and LPG as by-products through the use of resources like abundant, low-rank coal and unconventional crude oil, such as heavy oil.
F-01-05. High Efficiency Coal Washing Technology (Demonstration of Vari-Wave Jig)

Nagata Engineering (former Nagata Seisakusyo Co., Ltd.), Coal Technology Research (one of the predecessors of JCOAL), Kyushu Institute of Technology

METI-subsidized project, NEDO-model demonstration project
FY 1997 (1 year), FY2009 – FY2014 (6 years)

Technology Overview

1. Background
Coal washing machines that separate raw coal with sizes between 0.5mm-0.50mm can be globally classified into dense liquid cyclone & bath machines and jig machines. In general, the coal separation accuracy is better using the dense liquid cyclone & bath option, but the operational costs are high. Jig machines have inferior separation accuracy, but their operational costs are comparatively low. Variable-wave air-pulsated jigs, or vari-wave jigs, are coal separation units that stratify the coal by different specific gravity through the up-and-down movement of water. Kyushu Institute of Technology’s pilot plant demonstrated that the trapezoidal waveform was the best among several waveforms for separation accuracy. The technology was completed when the former Nagata Seisakusyo Co., Ltd., adapted this waveform in its conventional jig and used it in conjunction with the automatic refuse ejector.

2. Objective
The objective is to improve separation accuracy by forming trapezoidal waves with the vari-wave jig, which can adjust waveforms. Another goal is to increase the coal discharge efficiency by controlling the amount of post-sorting product with the automatic refuse ejector.

3. Core technology

[1] Equipment configuration and programming of trapezoidal wave formation
High and low pressure air is blown by controlling valve opening/closing timing electronically, which results in the formation of trapezoidal waves. The wave height and the up-and-down cycle vary according to the raw coal properties. This leads to easier operations. Other core technologies involved are air valve construction, a sheet gasket that can withstand long-period operation, and exhaust noise reduction measures.

The automatic refuse ejector ensures the accurate discharging of lighter and heavier products from coal particle layer, which is stratified to the order of specific gravity by the trapezoidal waveform. This technology involves a measuring device for...
the set specific gravity and a program that sets the relationship between the signal from the measuring device and the discharge amount based on empirical value. This program is equipped with a function that is able to deal with changes in raw coal properties. Additionally, the ejector is a star wheel type, which not only controls the discharge amount through rotation, but also increases the product's particle size acceptance range and prevents blockage during discharge.

4. Achievements
The vari-wave jig has better separation accuracy compared to the existing jig, with the vari-wave jig yielding about 3% more than the existing jig. The results of a test on the vari-wave jig performance on Indian coal, which is especially difficult to sort, verified that the vari-wave jig performed better than the existing one.

Through the 1997 METI subsidized project, the Coal Institute of Technology conducted a verification test of the vari-wave jig in partnership with the Ikeshima coal mine.

In 2000, the technology was introduced to the Pacific Coal Mine.

Through the NEDO model project, a new private coal preparation plant in India adopted the technology in 2014 and conducted a demonstration. Existing jig coal preparation machines can be remodeled into vari-wave jigs by merely changing the blower, valve, and controller.

5. Issues
At coal washing plants nowadays, there is a trend towards increasing the processing amount. Since jig processing capacity of 800t/hr – 1,000t/hr is desired, there is a need for technological and economic study to upsize these plants.
The technology to drill a borehole from the earth’s surface and collect coal-bed methane, or CBM, has not been demonstrated in Japan. However, the technology to collect methane from closed mines has been established. This methane gas is called abandoned mine methane, or AMM. Its collection was conducted at the Sumitomo Akabira Coal Mine, where it was used for micro gas turbine power generation.

Coal Mine Methane, or CMM, has been proactively used in Hokkaido, where there are high gas-content coal mines. In order to prevent serious accidents such as gas explosions at these coal mines, gas-releasing boring from coal layers was performed prior to coal development. The collected gas was used as fuel for power generation. Technologies like this already exist for CMM collection and utilization at gas power plants. Currently, the Kushiro Coal Mine is effectively collecting and utilizing CMM.
Image of IGCC commercial plant
Source: Mitsubishi Hitachi Power Systems, Ltd.
There are three very diverse technological trends that are crucial when examining the future of clean coal technology from the viewpoint of technical innovation in the coal industry.

The first trend is that many different technologies or systems that utilize coal gasification as a core component are now under development. For example, R&D on high-efficiency power generation systems, which include integrated coal gasification combined cycle (IGCC) and integrated coal gasification fuel cell combined cycle (IGFC) systems, has steadily progressed toward commercialization (Figure 1). Another example is the conversion of coal gas into liquid fuel or chemical raw materials that are clean and contain no impurities, such as methanol, DME and GTL (Figure 2). Once these technologies are attained, co-production system that produce electricity and chemicals simultaneously will be possible.

The second trend is the movement towards “a hydrogen energy society.” According to the International Institute for Applied Systems Analysis 2000 (IIASA 2000), the “H/C (hydrogen/carbon)” ratio of primary fuel use increased at an almost constant rate from the mid-1800’s to around 1980. Since 1980, the H/C ratio has remained almost unchanged at around two due to an increase in oil consumption. However, the pre-1980 trend is expected to resume, leading an increase in the H/C ratio to four by approximately 2030. In a society where the primary energy source is shifting from natural gas to hydrogen, energy consumption derived from carbon combustion will finally be discouraged. It is even predicted that coal energy utilization will owed necessarily to CO₂ separation, capture and fixation.
There are essentially two important clean coal technologies. One is a series of technologies to separate, recover, sequester and store CO₂ generated from the direct combustion of coal. The other is comprised of high-efficiency coal utilization technologies. These include coal gasification, coal upgrading, and material conversions to use carbon from coal as fuel or as a feedstock for the chemical production.

The third trend is that coal technology has progressed with the parallel progression of environmental/energy technology, biotechnology, nanotechnology, and information technology either directly or interactively. Those technologies have all been categorized as priority R&D targets in Japan. Environmental/energy technology is focused on achieving a zero-emission society (Figure 5), mainly through utilization of cheap fossil fuels while controlling CO₂ generation. The co-production system shown in Figure 6 is regarded as a necessary technology to implement for society’s benefit.

Advances in biotechnology could also unlock methods for the fixation and effective utilization of CO₂. Furthermore, there are techniques that allow for advanced utilization of coal as a carbon source, not solely as fuel. Developments in nanotechnology, such as nanocarbon fibers, provide potential technical innovation options for coal.

Information technology progress has provided innovative developments in computational capabilities for modeling and simulating coal technologies, which will only continue to improve.
CCT plays an important role in steelmaking as well as in power generation. Coal is used in the steelmaking industry not only as an energy resource but also as a high-quality reducing agent, and as a raw material. A potential application to well-established steelmaking processes, such as the blast-furnace process, is to achieve an innovative level of total coal utilization efficiency by using a co-production system, like DIOS (Direct Iron Ore Smelting reduction process). This process would simultaneously produce iron and synthetic gas, electric power, hydrogen/thermal energy, and chemical feedstocks from steam coal supporting the steady implementation of improved environmental measures aimed at zero emissions.

As the world’s largest coal importer and as the leader in CCT, Japan should remain active in international cooperation. This should include technology transfers and human resource development with developing countries, mainly in Asia. Such international activities will not only benefit countries that are trying to improve their economic growth by relying on coal energy, but also help Japan ensure a stable energy supply. These activities would also help support efforts to utilize the Kyoto Mechanisms, including the Clean Development Mechanism (CDM), which address global environmental problems.

Economic growth can only be achieved with a stable supply of energy, while environmental conservation is a challenge to be addressed by the whole world. The former is a limiting factor for the latter and vice versa. Explosive population growth has been a common fundamental problem for both economic growth and environmental conservation throughout history. Efforts for environmental conservation, including eliminating emissions to control global warming are the top priority in the development of CCT in Japan. However, the concerns of maintaining energy security to stimulate economic growth cannot be ignored. It is therefore essential to build an efficient advanced coal energy utilization system with minimum impact on the global environment. The coal sector must solve the highest priority challenges within the energy sector, and being in a strong position to develop technologies it needs to work towards innovative clean coal technology (Figure 7) to create a comfortable and clean society that establishes harmony between economics and the environment.

With an aim to positioning coal as a source of CO₂-free energy by 2030, innovative CCT development will be promoted, including CO₂ fixation technology and next-generation high-efficiency gasification technology, toward the goal of eliminating emissions, while identifying the role of individual technologies in the overall scheme.
### (1) Main SI units

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<th>Quantity</th>
<th>SI unit</th>
<th>Unit applicable with SI unit</th>
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<tr>
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</tr>
<tr>
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<td>Volume</td>
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<tr>
<td>Time</td>
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<td>Frequency of vibration</td>
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<tr>
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<tr>
<td>Quantity of heat</td>
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### (2) Prefix of SI system

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</tbody>
</table>

### (3) Typical conversion factors

1. **Basic Energy Units**
   - 1J (joule) = 0.2388cal
   - 1kJ (kilocalorie) = 4.1868J
   - 1BtU (British thermal unit) = 1.055kJ = 0.252kcal

2. **Standard Energy Units**
   - 1tonne of oil equivalent = 42 GJ = 10.034 Mcal
   - 1tonne of coal equivalent = 7000 Mcal = 29.3 GJ
   - 1 barrel = 42 US gallons = 159 l
   - 1 m³ = 35.315 cubic feet = 6.2898 barrels
   - 1 KWh = 3.6 MJ = 3600 kJ
   - 1,000scm (standard cubic meter) of natural gas = 36 GJ (Net Heat Value)
   - 1 tonne of uranium = 10,000-16,000toe (Light water reactor, open cycle)
   - 1 tonne of peat = 0.2275toe
   - 1 tonne of fuelwood = 0.3215toe

### (4) Coal gasification reactions

**Coal Pyrolysis**

- Coal $\rightarrow$ C + (char/coke) + (Generated heat) (1)

**Chemical reaction with oxygen**

- $C + O_2 \rightarrow CO_2$ + 97.0 kcal/mol (2)
- $C + O_2 \rightarrow CO$ + 29.4 kcal/mol (3)

**Chemical reaction with carbon dioxide**

- $C + CO_2 \rightarrow 2CO$ + 38.2 kcal/mol (4)

**Chemical reaction with steam**

- $C + H_2O \rightarrow CO + H_2$ + 31.4 kcal/mol (5)
- $C + 2H_2O \rightarrow CO_2 + 2H_2$ + 18.2 kcal/mol (6)
- $CO + H_2O \rightarrow CO_2 + H_2$ + 10.0 kcal/mol (7)

**Chemical reaction with hydrogen**

- $C + 2H_2 \rightarrow CH_4$ + 17.9 kcal/mol (8)
- $CO + 3H_2 \rightarrow CH_4 + H_2$ + 49.3 kcal/mol (9)

### (5) Standard heating value for each energy source

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<tr>
<th>Energy source</th>
<th>Unit</th>
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<tr>
<td>Coal</td>
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<tr>
<td>Imported coking coal</td>
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<td>Imported anthracite</td>
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<td></td>
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<tr>
<td>Coal product</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coke</td>
<td>kg</td>
<td>30.1 MJ</td>
<td>7191 kcal</td>
<td>7200 kcal</td>
<td></td>
</tr>
<tr>
<td>Coke oven gas</td>
<td>Nm³</td>
<td>21.1 MJ</td>
<td>5041 kcal</td>
<td>4800 kcal</td>
<td></td>
</tr>
<tr>
<td>Blast furnace gas</td>
<td>Nm³</td>
<td>3.41 MJ</td>
<td>815 kcal</td>
<td>800 kcal</td>
<td></td>
</tr>
<tr>
<td>Converter gas</td>
<td>Nm³</td>
<td>8.41 MJ</td>
<td>2009 kcal</td>
<td>2000 kcal</td>
<td></td>
</tr>
<tr>
<td>Oil</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crude oil</td>
<td></td>
<td>38.2 MJ</td>
<td>9126 kcal</td>
<td>9250 kcal</td>
<td></td>
</tr>
<tr>
<td>NGL, Condensate</td>
<td></td>
<td>35.3 MJ</td>
<td>8433 kcal</td>
<td>8100 kcal</td>
<td>Formerly NGL</td>
</tr>
<tr>
<td>Oil product</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LPG</td>
<td>kg</td>
<td>50.2 MJ</td>
<td>11992 kcal</td>
<td>12000 kcal</td>
<td></td>
</tr>
<tr>
<td>Naphtha</td>
<td></td>
<td>34.1 MJ</td>
<td>8146 kcal</td>
<td>8200 kcal</td>
<td></td>
</tr>
<tr>
<td>Gasoline</td>
<td></td>
<td>34.6 MJ</td>
<td>8266 kcal</td>
<td>8400 kcal</td>
<td></td>
</tr>
<tr>
<td>Jet fuel</td>
<td></td>
<td>36.7 MJ</td>
<td>8767 kcal</td>
<td>8700 kcal</td>
<td></td>
</tr>
<tr>
<td>Kerosene</td>
<td></td>
<td>36.7 MJ</td>
<td>8767 kcal</td>
<td>8700 kcal</td>
<td></td>
</tr>
<tr>
<td>Gas oil</td>
<td></td>
<td>38.2 MJ</td>
<td>9126 kcal</td>
<td>9200 kcal</td>
<td></td>
</tr>
<tr>
<td>Heavy oil</td>
<td></td>
<td>39.1 MJ</td>
<td>9341 kcal</td>
<td>9300 kcal</td>
<td></td>
</tr>
<tr>
<td>C-heavy oil</td>
<td></td>
<td>41.7 MJ</td>
<td>9962 kcal</td>
<td>9800 kcal</td>
<td></td>
</tr>
<tr>
<td>Lubrication oil</td>
<td></td>
<td>40.2 MJ</td>
<td>9603 kcal</td>
<td>9600 kcal</td>
<td></td>
</tr>
<tr>
<td>Other heavy oil product</td>
<td>kg</td>
<td>42.3 MJ</td>
<td>10105 kcal</td>
<td>10100 kcal</td>
<td>Formerly other oil products</td>
</tr>
<tr>
<td>Kerosene</td>
<td></td>
<td>36.7 MJ</td>
<td>8767 kcal</td>
<td>8700 kcal</td>
<td></td>
</tr>
<tr>
<td>Oil coke</td>
<td></td>
<td>35.6 MJ</td>
<td>8504 kcal</td>
<td>8500 kcal</td>
<td></td>
</tr>
<tr>
<td>Refinery gas</td>
<td>Nm³</td>
<td>44.9 MJ</td>
<td>10726 kcal</td>
<td>9400 kcal</td>
<td></td>
</tr>
<tr>
<td>Gas</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flammable natural gas</td>
<td>kg</td>
<td>54.5 MJ</td>
<td>13019 kcal</td>
<td>13000 kcal</td>
<td>Formerly LNG</td>
</tr>
<tr>
<td>Imported natural gas (LNG)</td>
<td>Nm³</td>
<td>40.9 MJ</td>
<td>9771 kcal</td>
<td>9800 kcal</td>
<td>Formerly natural gas</td>
</tr>
<tr>
<td>Domestic natural gas</td>
<td>Nm³</td>
<td>41.1 MJ</td>
<td>9818 kcal</td>
<td>10000 kcal</td>
<td></td>
</tr>
<tr>
<td>City gas</td>
<td>Nm³</td>
<td>41.1 MJ</td>
<td>9818 kcal</td>
<td>10000 kcal</td>
<td></td>
</tr>
<tr>
<td>Electric power</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Generation side</td>
<td></td>
<td>9.00 MJ</td>
<td>2150 kcal</td>
<td>2250 kcal</td>
<td>Efficiency 39.98%</td>
</tr>
<tr>
<td>Heat supplied to power generator</td>
<td></td>
<td>3.60 MJ</td>
<td>860 kcal</td>
<td>860 kcal</td>
<td></td>
</tr>
<tr>
<td>Consumption side</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heat produced from electric power</td>
<td></td>
<td>2.68 MJ</td>
<td>641 kcal</td>
<td>—</td>
<td>100°C, 1 atm Saturated steam</td>
</tr>
</tbody>
</table>

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**Clean Coal Technologies in Japan**

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New Energy and Industrial Technology Development Organization (NEDO)
MUZA Kawasaki Central Tower, 1310 Omiya-cho, Saiwai-ku, Kawasaki City, Kanagawa, 212-8554 Japan
Tel. +81-44-520-5250
Fax. +81-44-520-5253
URL: http://www.nedo.go.jp/english/

Japan Coal Energy Center (JCOAL)
3F, Daito Nishishimbashi Building, 3-2-1 Nihonbashii, Minatoku, Tokyo, 105-0003 Japan
Tel. +813-6402-6100
Fax. +813-6402-6110

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