MHI's Energy Efficient Flue Gas CO_2 Capture Technology and Large Scale CCS Demonstration Test at Coal-fired Power Plants in USA

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The long-term use of fossil fuels as a primary energy source is unavoidable. Among other fossil fuels, coal, which is inexpensive and can be supplied stably on a long-term basis, will continue to be used. However, coal-fired power plants emit a large amount of CO_2. We believe that the commercialization of carbon capture and storage (CCS) systems will be indispensible as a counter measure against global climate change. This report describes the technology development efforts of Mitsubishi Heavy Industries, Ltd. (MHI) and verification tests for the capture of large amounts of CO_2 from coal-fired power plants, with a focus on improving the energy-saving performance of the CO_2 recovery technology. The paper will also review the range of commercial MHI CO_2 capture plants operating in the chemical and fertilizer industries overseas.

1. Introduction

Carbon capture and storage (CCS) technologies, in which CO_2 in power station exhaust gas is recovered and stored in various geological formations, are thought to represent a key technology for preventing climate change. According to the World Energy Outlook (2009) released by the International Energy Agency, the global demand for energy in 2030 is expected to increase by approximately 1.4-fold relative to the demand in 2007 [1] **(Figure 1)**.

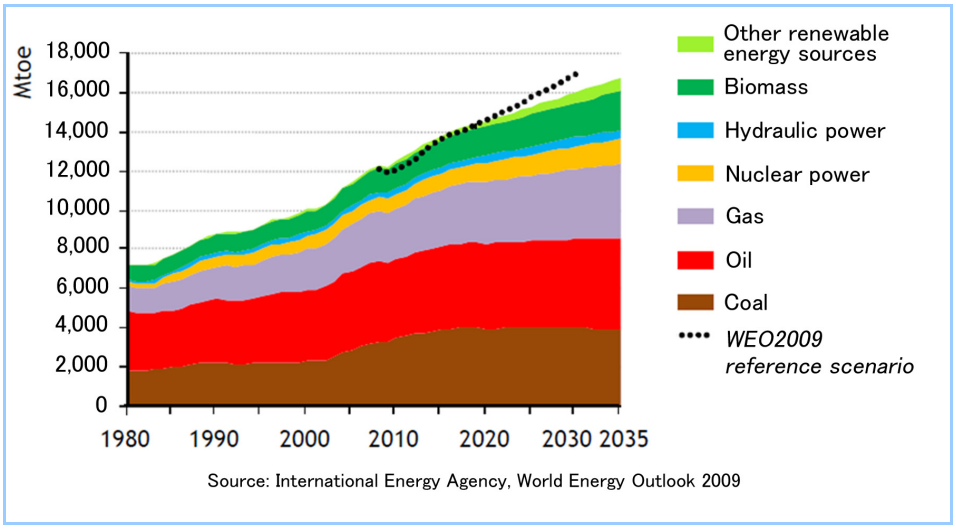

Figure 1 World energy demand
Fossil fuels will continue to play an important role as a primary energy source. It is essential to make continued efforts to reduce climate change caused by the use of fossil fuels such as coal, which generate higher CO_2 emissions compared to other fuels per output unit.

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Under this situation, the need for fossil fuels for use as a major primary energy source is anticipated to increase. If we continue to use fossil fuels, however, the CO_2 concentration in the atmosphere will certainly continue to increase. Under these circumstances, CCS is positioned as an important CO_2 emissions reduction method. However, in order to overcome the technological and financial barriers for the commercialization of CCS, it is necessary to solve the anticipated issues using large-scale CCS verification tests, which are planned by several international governments and to create legal, regulatory and financial frameworks for the promotion of CCS technology.

2. World trend toward the commercialization of CCS

Large-scale CCS verification projects targeting coal-fired thermal power plants and led by governments are expected to soon commence in Europe and North America. Currently, there are 12 projects planned in Europe; these plants are expected to start up around 2015. Commercial-based activities for CCS as a measure against climate change are being accelerated, as outlined below.

Major projects include one planned for Rotterdam in the Netherlands, in which the recovery and storage of CO_2 from exhaust gas emitted from a 1,100-MW coal-fired thermal power plant will be verified.[2] At this site, approximately 4,000 tons per day (approx. 250 MW) of CO_2 will be recovered by a post-combustion CO_2 recovery method. The recovered CO_2 will be stored in a depleted offshore gas field located 25 km from the power plant. Through this project, CO_2 emissions are expected to be reduced by 1.1 million metric tons per year.

In parallel, a post-combustion CO_2 recovery project and an oxygen combustion project are planned for verification at the Jänschwalde lignite-fired power plant in Germany. To verify the oxygen combustion method, an existing coal-fired boiler will be replaced with a newly installed oxygen combustion boiler. To verify the post-combustion CO_2 recovery method, a post-combustion CO_2 recovery plant will be installed at the existing boiler to recover 1,200 tons of CO_2 per day. The CO_2 recovery rate is expected to be 90% or higher for both methods. The recovered CO_2 is to be stored in depleted natural gas formations or alternatively in an aquifer. [2]

In Porto Tolle, Italy, a 660-MW coal-fired thermal power plant will be constructed to replace an existing oil-fired thermal power plant for a large-scale CCS verification project of post-combustion CO_2 recovery. The recovered CO_2 will be stored in an offshore aquifer. The amount of CO_2 recovered and stored per year is expected to reach approximately 1.5 million tons.[2]

In addition, the European Union (EU) has decided to implement the "Carbon Capture-ready Obligation," which requires newly-built power plants with a capacity of 300 MW or greater to allocate space for CO_2 recovery facilities and to propose a storage site capable of storing the CO_2 from the site.

Meanwhile, in the United States (U.S.), the construction of a medium scale verification plant with a capacity of 500 tons of CO_2 per day has begun as part of a joint CCS demonstration project by a major electric power company (Southern Company), the Electric Power Research Institute (EPRI) and MHI. The plant is intended to verify CO_2 recovery from the emissions of a coal-fired power plant. The operation of this plant is scheduled to commence in June 2011.

3. MHI's commercial scale CO_2 capture plant deployment strategy

3.1 MHI's CO_2 recovery technology

MHI has been developing the KM-CDR Process® (see Note), a CO_2 recovery process, jointly developed together with Kansai Electric Power Co., Inc., since 1990. A flow chart of the CO_2 recovery pilot plant is illustrated in **Figure 2**. Exhaust gas containing CO_2 is first cooled in a flue gas quencher; it then contacts an alkaline absorption solvent, KS-1TM (which was developed jointly by MHI and Kansai Electric Power Co., Inc.), in a CO_2 absorber, where the CO_2 is absorbed. The KS-1™ solvent, containing a large amount of CO_2, is then delivered to a regenerator vessel and heated by steam for CO_2 release and solvent regeneration. The regenerated absorption solvent is returned to the CO_2 absorber and the process continues within a closed loop.

3.2 Commercialized MHI CO_2 Capture Plants

MHI has already commercialized CO_2 recovery technology targeting exhaust gas from natural gas-fired boilers and gas turbines and to date, eight units have been delivered for commercial application and are currently under operation (with an additional two units under

construction). The first unit, which was delivered in Malaysia in 1999, has a maximum CO_2 capture capacity of 200 tons per day. The recovered CO_2 has been used to effectively increase the production of urea for more than 10 years. Following the delivery of this initial unit, MHI subsequently delivered additional units to several countries throughout the world for chemical and general use applications, under international competitive bid tendering processes. MHI's energy-saving regeneration system (explained in more detail in section 4.1), further reduces the heat source required for CO_2 recovery (**Figure 3**) and was first introduced to the commercial CO_2 recovery plant (with a capacity of 400 tons/day) delivered to Abu Dhabi in 2009.

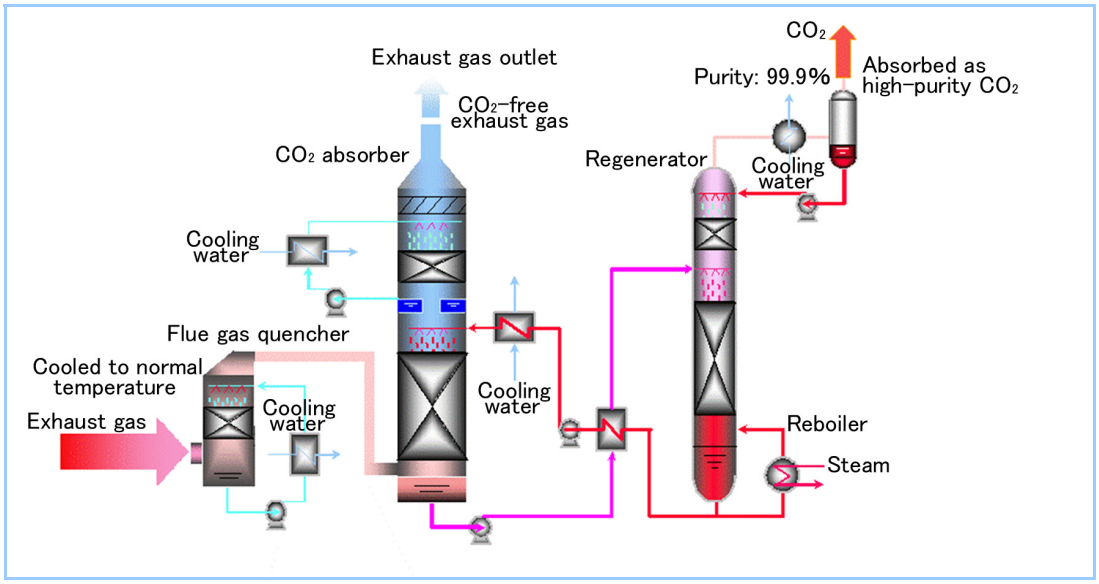

Figure 2 Process flow for CO_2 recovery from exhaust gas
KM-CDR Process®: The exhaust gas is sent to the flue gas quencher, where it is cooled down to a temperature appropriate for CO_2 recovery and supplied to the CO_2 absorber. The exhaust gas contacts the absorption solvent in the CO_2 absorber and the CO_2 is absorbed in the solvent. The scrubbed exhaust gas is then released in the atmosphere from the top of the CO_2 absorber in the form of clean exhaust gas.

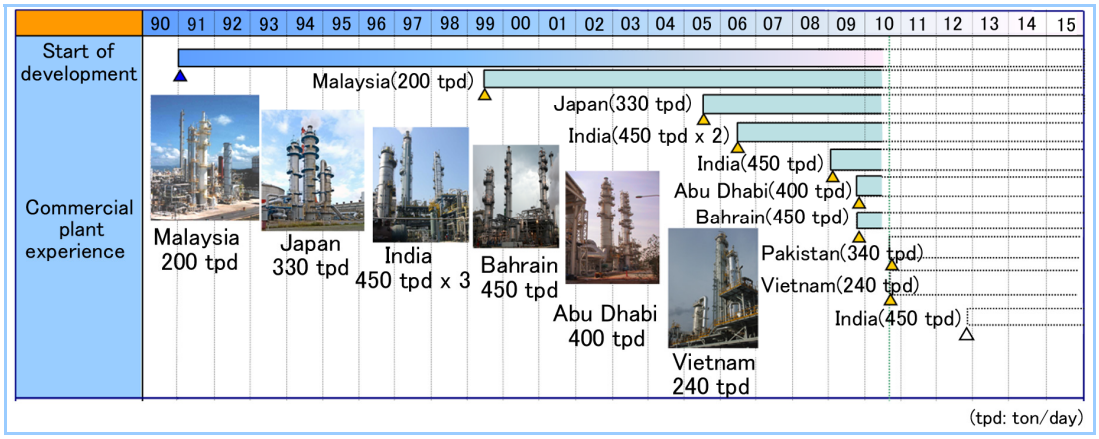

Figure 3 MHI's performance in commercial plants
The chart shows MHI's performance in commercial CO_2 recovery plants (tpd: tons per day). Currently, eight commercial plants are in operation at natural gas-fired facilities (with two additional plants under construction). MHI's CO_2 recovery plants have enjoyed the largest share in the global chemical CO_2 recovery market since 1999. MHI CO_2 recovery plants have been delivered to many countries, including Malaysia, Japan, India, Bahrain, Abu Dhabi and Vietnam.

4. Technology development for CO_2 recovery plants

4.1 Energy Saving Process

The cost of the steam used to regenerate the absorption solvent comprises the greatest portion of the operations costs of CO_2 recovery plants. MHI and Kansai Electric Power Co., Inc. constructed a pilot test plant with a capacity of 2 tons of CO_2 per day (**Figure 4**) at the Nanko Power Plant of Kansai Electric Power Co., Inc. near Osaka, with testing commencing in 1991. This testing focused on the development of a new absorption solution and enhancing the CO_2 capture process in terms of energy saving and integration. These activities led to the development and

commercialization of the KS-1™ absorption solvent and MHI's proprietary Energy Saving Process (patent pending). MHI has been working to further develop new absorption solvents and the Energy Saving Process as outlined below, with the aim of further improving the process through reduced energy consumption.

Source of exhaust gas	Exhaust gas from a natural gas-fired facility
Amount of exhaust gas	600 m^3N/h (planned)
CO_2 capacity	2 (tons per day)
CO_2 recovery ratio	90% (planned)
Purity of recovered CO_2	99.9%

Figure 4 Pilot test plant at the Nanko Power Plant

The conventional monoethanolamine (MEA) absorption solvent, which has been used for several decades, has the following shortcomings: (1) it requires a high amount of energy for regeneration, (2) the amount of absorption solvent loss is significant and (3) it generates a large amount of degraded product (such as heat stable salts or HSS), requiring frequent reclaiming to remove the degraded product and HSS from the absorption solvent. In order to overcome these issues, MHI investigated the molecular structure of the absorption solvent and tested a number of available amine compounds and alkali substances. Consequently, MHI developed the KS-1™ absorption solvent, which features low energy consumption, minimal solvent loss and low corrosivity. Currently, MHI is engaged in developing a new absorption solvent that requires even less recovery energy than KS-1™, aiming to further improve the overall economics of the CO_2 capture process.

In addition, MHI has developed further energy-saving measures for the process. To further reduce the amount of steam consumed, an energy-saving process (**Figure 5**) that utilizes the heat of the lean solvent and steam condensate repeatedly to regenerate the absorption solvent has been developed and employed in commercial plants delivered to Abu Dhabi (under operation) and India (under construction). These commercial plants are used for urea production and have a capacity of 400 and 450 tons of CO_2 per day respectively. The energy consumption for the Abu Dhabi plant, per unit at a guarantee test run, was 680–690 kcal/kg CO_2 which is the lowest CO_2 recovery energy observed among MHI's commercial plants currently in service.

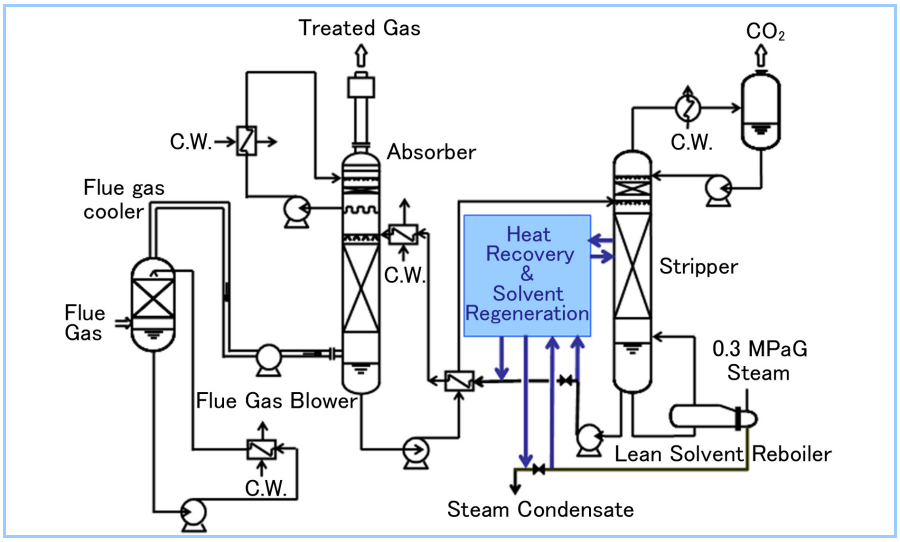

Figure 5 Process flow chart of the energy-saving regeneration system
This energy-saving process was developed to further reduce the heat required for CO_2 recovery. Exhaust heat from the lean solvent and steam condensate in the regenerator

Further energy savings are expected from the improvement of various CO_2 recovery plant operating conditions including (1) increased CO_2 loading of the CO_2-rich solvent by reducing the temperature of the CO_2 absorption section, (2) reduced quantity of heat needed to regenerate the absorption solvent by reducing the circulation volume of the solvent and (3) controlled heat loss from the emission of steam by lowering the temperature at the top of the regenerator.

In order to demonstrate these energy-saving processes, tests were carried out by modifying the pilot test plant at the Nanko Power Plant. The test results indicated that the energy consumption for CO_2 recovery per unit was 603 kcal/kg CO_2 (2.53 MJ/kg CO_2) for the KS-1™ absorption solvent. For the newly developed absorption solvent (currently unnamed), the energy consumption per unit recovery was 583 kcal/kg CO_2 (or 2.44 MJ/kg CO_2) (**Table 1**).[3]

Table 1 Test results from the pilot plant at the Nanko Power Plant

	Test conditions		Test results	
Absorption solvent	CO_2 concentration at inlet (%)	Cooling of CO_2 absorption section	CO_2 recovery ratio (%)	Energy consumption for CO_2 recovery per unit (kcal/kg CO_2)
KS-1™	10.2	Not cooled	90.3	669
	10.2	Cooled	82.5	**603**
New absorption solvent (1)	10.3	Not cooled	85.0	694
	10.4	Cooled	87.3	601
New absorption solvent (2)	10.1	Not cooled	84.7	657
	10.3	Cooled	77.8	**583**

4.2 MHI activities relating to CO_2 from coal-fired thermal power plants

MHI has Achieved exemplary results from its commercial CO_2 recovery plants from natural gas-fired facilities. Large-scale verification projects are being considered throughout the world, with a clear focus on coal fired power generation units, which emit the highest amount of CO_2.

To recover CO_2 from the exhaust gas generated by coal-fired thermal power plants, it is necessary to assess the influences of impurities and minor components in the flue gas to ensure the performance of the CO_2 capture technology and guarantee long-term, stable and trouble-free operation. MHI has conducted long-term CO_2 recovery verification tests at J-POWER's Matsushima Thermal Power Plant, in which CO_2 was recovered from the exhaust gas generated by a commercial coal-fired boiler at a capacity of 10 tons per day (**Figure 6**) using the slip stream of the flue gas. MHI examined the accumulation of impurities in the CO_2 capture plant and evaluated the influence of minor components on the absorption solvent by operating the system continuously for 4,000 hours. Through these tests, MHI has confirmed that is it technically possible to apply the MHI CO_2 capture technology process to medium to large scale plants (several hundreds to several thousands of tons of CO_2/day), which has been considered as the next step in the evolution of the technology.

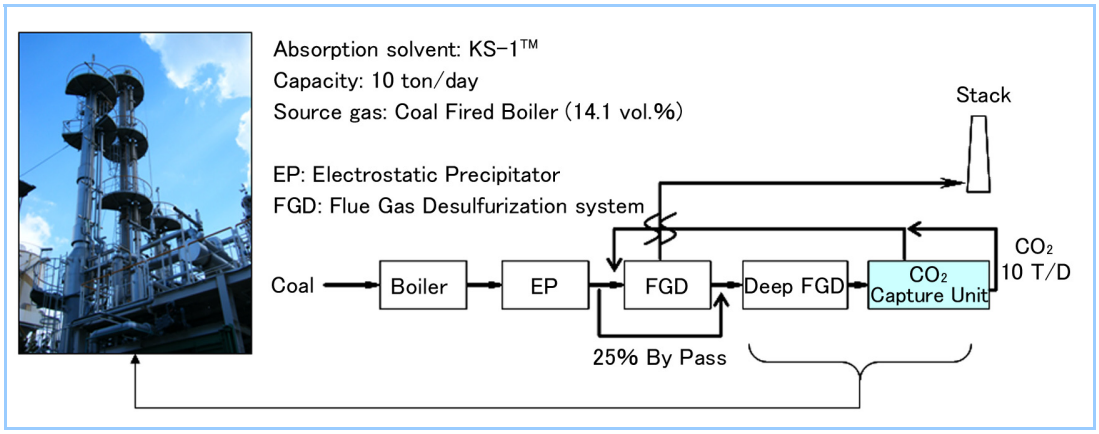

Figure 6 Verification test plant at the Matsushima Thermal Power Plant
The absorption solvent used is KS-1™, the capacity is 10 tons/day and the source gas is a coal-fired boiler (14.1vol%).

MHI is jointly developing a CCS verification plant with a capacity of 500 tons/day together with Southern Company and EPRI in Alabama, US. This plant is designed on the basis of the results obtained from the Matsushima Thermal Power Plant.

Part of the exhaust gas from the Barry coal-fired thermal power plant in Alabama will be supplied to a CO_2 recovery plant to recover the CO_2. The recovered CO_2 will be compressed, dehydrated and transported via a pipeline for storage in an underground aquifer (**Figures 7, 8**). In this project, MHI will handle the cleaning of the exhaust gas, the CO_2 recovery, the compression and the dehydration of the recovered CO_2, while the Southeast Regional Carbon Sequestration Partnership (SECARB) will handle the CO_2 storage scope. Southern Company is involved in both the CO_2 recovery and the storage scope together with other partners.[4]

By utilizing the findings from the CO_2 recovery verification tests at the Barry coal-fired verification CCS plant, MHI plans to verify the performance of a large-scale CCS plant with a capacity of 3,000 to 5,000 tons of CO_2 per day together with partners in the electric utility sector.

Figure 7 Location of the Barry coal-fired thermal power plant in Alabama
Southern Company will construct a verification plant for the separation, recovery and injection of CO_2 contained in exhaust gas, with financial support from the U.S. Government and other partners. The recovered CO_2 will be stored in a geological formation deep underground. Verification tests are expected to commence in June 2011.

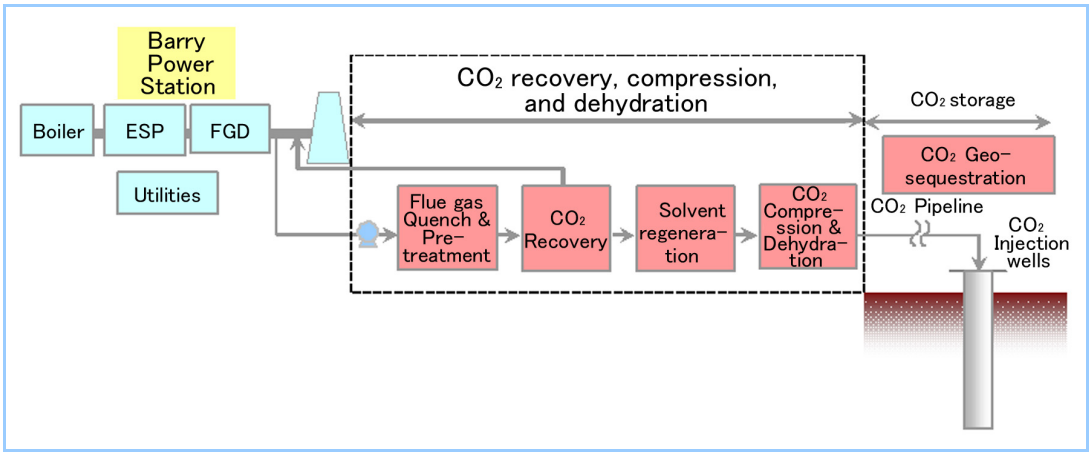

Figure 8 Flow chart of the verification plant at the Barry coal-fired thermal power plant
Verification tests covering the entire CCS process from gas cleanup, CO_2 recovery and compression to underground storage will be conducted at the plant. MHI will handle the CO_2 recovery, compression and dehydration. The storage process will be handled by Southern Company and SECARB.

5. Conclusion

CCS has attracted attention as a potential measure against climate change through the ability of this technology to significantly reduce CO_2 emissions from power generation facilities. CCS verification tests led by international governments are being pursued in Europe and North America.

MHI is undertaking significant efforts to reduce the costs associated with CO_2 recovery by reducing the energy consumed in the KM-CDR Process® and by developing new absorption solvents, with a focus on the most efficient and economical CO_2 recovery process. Currently, the MHI energy consumption for CO_2 recovery per unit is 583 kcal/kg CO_2 (or 2.44 MJ/kg CO_2). MHI continues with extensive technology development activities to achieve even further reductions in

the energy consumption per unit of CO_2 recovery.

With respect to CO_2 recovery from coal fired exhaust flue gas that contains substantial levels of impurities, MHI has completed verification tests at a 10 tons of CO_2/day Japan based demonstration plant and will commence medium-scale verification tests at a 500 tons of CO_2/day demonstration plant in the U.S. from June 2011. Based on the findings from these verification tests, MHI aims to work on commercializing large-scale single train CO2 capture plants with a capacity of 3,000 to 5,000 tons of CO_2 per day intended for coal-fired thermal power plant applications.

Note : The KM-CDR Process® is a trademark of Mitsubishi Heavy Industries, Ltd., registered in Japan, the U.S., the EU (CTM), Norway, Australia and China.

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