Carbon Capture and Storage Demonstration Test – Coal-fired Power Plant (in cooperation with Southern Company, a U.S. Electric Power Company)

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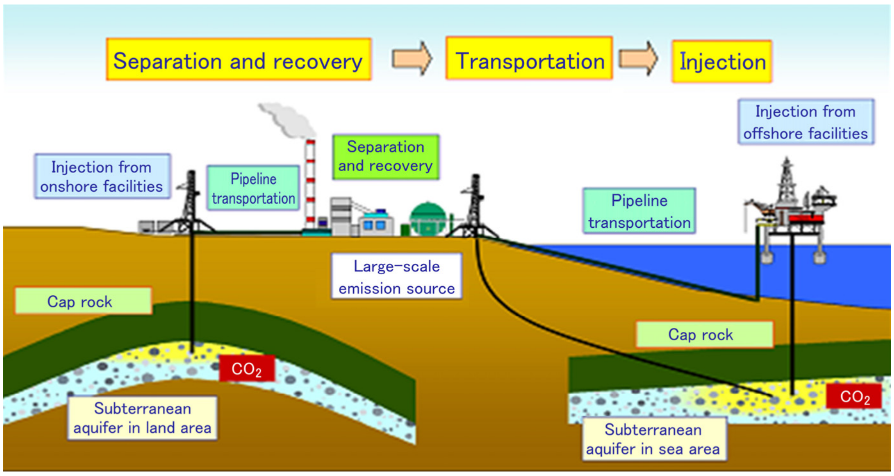
Carbon capture and storage (CCS) is a technology aimed at reducing CO_2 emissions from coal-fired power stations that have a high CO_2 output of per unit of generated power. In 2008, together with Southern Company (SoCo), Mitsubishi Heavy Industries, Ltd. (MHI) began a fully-integrated demonstration test for a 'source-to-storage' CCS project, capturing, transporting and storing CO_2 from the flue gas of a coal-fired power station. The CO_2 recovery portion of the test is located at the Barry Electric Generating Plant (Plant Barry) in Alabama, U.S. The 500 metric tons per day (MTD) recovery plant has been in operation for in excess 7,000 hours to date (25^{th} January 2013), recovering more than 127,000 metric tons of CO_2. The injection and sequestration of the recovered CO_2 started in August 2012, with more than 46,000 metric tons of CO_2 stored thus far. This report updates the results of CCS demonstration test and introduces future testing programs.

1. Introduction

Coal is widely used in the power-generation sector because of its abundance and economic advantage. Recently however, a reduction of CO_2 emissions from coal-fired power plants has been an important issue regarding climate change. Within Europe and U.S., newly-built coal-fired power plants will soon require the installation of CCS systems or be 'CCS ready', thus demanding the urgent verification of CCS technologies to treat coal-fired flue gas. **Figure 1** illustrates the concept of CCS.



Source: Ministry of Economy, Trade and Industry of Japan, CCS 2020

Figure 1 Conceptual illustration of carbon capture and storage (CCS)

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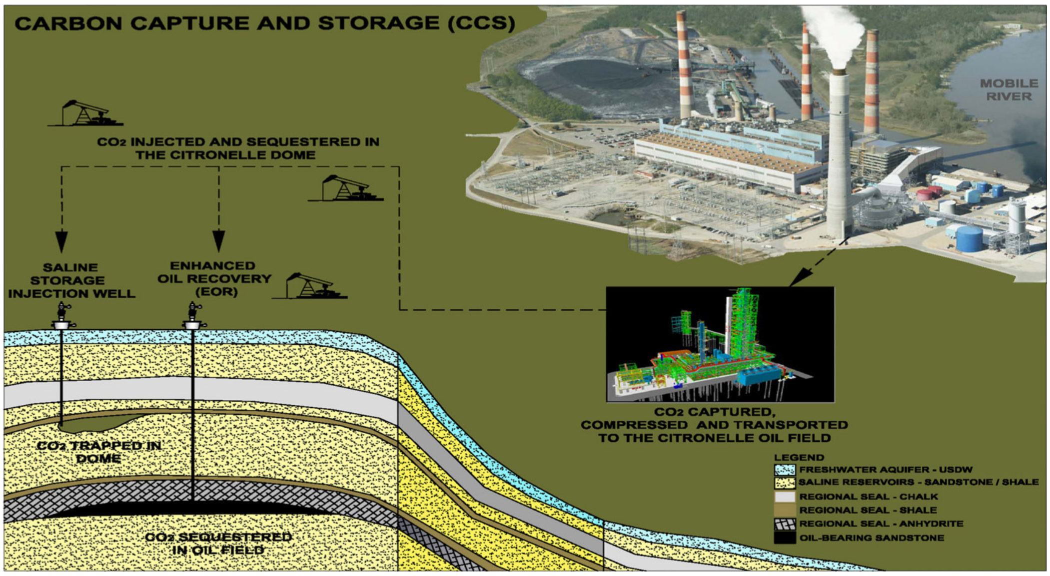
CCS denotes the process of separating/capturing CO_2 from large-scale emission sources such as power stations, transporting it to an injection site, and injecting it into deep onshore or offshore saline aquifers for permanent storage. Depleted oil and gas fields are also attractive sites for CO_2 storage. In cooperation with a major U.S. electric power company, SoCo, and Electric Power Research Institute (EPRI), MHI constructed a large demonstration plant with a CO_2 recovery capacity of 500 MTD for the treatment of coal-fired flue gas in Alabama, U.S. The CO_2 recovery operation began in June 2011, with the recovered CO_2 first injected and safely stored during August 2012.

2. Outline of the joint project for CCS demonstration

Figure 2 shows the outline of the CCS demonstration project. The recovered CO_2 is compressed and transported approximately 12 km via pipeline to the Citronelle Dome, where it is injected and sequestered in the saline aquifer approximately 3,000m below the ground surface. The aim of the project is to store between 100,000 to 150,000 metric tons of CO_2 per year, for four (4) years. The CO_2 transportation and sequestration aspect of the project is being conducted as Phase III of the Regional Carbon Sequestration Partnership Program of the U.S. Department of Energy (DOE) and is managed by the Southeast Regional Carbon Sequestration Partnership (SECARB). An overview of the CO_2 recovery demonstration plant is given in **Table 1**.



Source: Project Update of 500 MTPD Demonstration Plant for Coal-fired Power Plant and MHI Amine Emission Reduction Technology, MEGA Symposium 2012.

Figure 2 Outline of the CCS demonstration joint project

Table 1 Overview of the CO_2 recovery demonstration plant

Items	Conditions
Location	Bucks, Alabama
Ownership	Southern Company (Alabama Power)
Process	KM CDR Process®
Solvent	KS-1™ solvent
Capacity	25MW equivalent
Flue gas flow rate	116800 Nm^3/h
CO_2 removal efficiency	90%
CO_2 capture rate	500 t/d (150000 t/y)
CO_2 concentration	10.1 mol.%-wet

MHI has consolidated a partnership with SoCo since the delivering a desulfurization unit to the Gorgas Electric Generating Plant in 2007. Both companies see the need to develop eco-friendly equipment for coal-fired power plants if they are to be viable power generation options in the future. For this project, American engineers were appointed for key tasks and after constructive discussions with SoCo, most of the design work was completed in the U.S. On-site construction time and construction costs was greatly reduced by utilizing “modular construction”, in which the facility was pre-assembled in modules at an off-site factory, transported to site and ‘hooked-up’ (**Figure 3**). The demonstration plant was completed on time, with operation also commencing as scheduled.

Figure 3 Modular construction

The demonstration plant utilizes the KM CDR Process® (see Section 3 for details), which was jointly developed by MHI and Kansai Electric Power Co. Inc. (KEPCO). The plant has the following specifications: CO_2 capture rate of 500 MTD, CO_2 removal efficiency of 90%, and capacity to process the equivalent of 25 MW worth of flue gas from the power plant.

In order to ensure the realization of commercial CCS plants in the future, the goals for the demonstration test are:

- Process modification from an energy-saving point of view;
- Establishment of the operational control for CO_2 capture, compression and storage in accordance with the power plant load;
- Understanding the effects of impurities contained in coal-fired flue gas on the CO_2 recovery facility and its absorption solvent (KS-1); and
- Establishment of valid countermeasures against such effects.

3. CO_2 capturing and compressing process from coal-fired flue gas

(a) Process flow of the demonstration plant

Figure 4 shows a flow diagram of the CO_2 recovery facility.

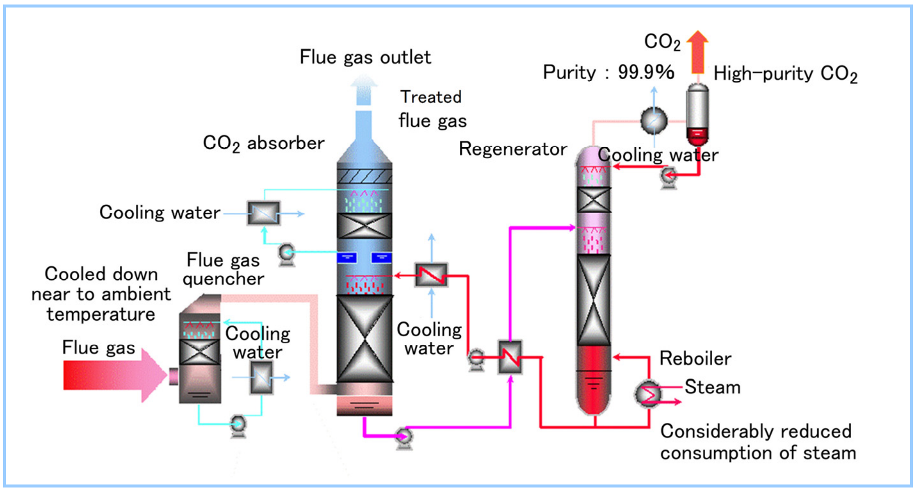


Figure 4 Flow diagram of MHI's CO_2 recovery process (KM-CDR Process®)

The flue gas, containing CO_2, is introduced into the flue gas quencher, cooled then pressurized by the blower installed downstream of the quencher, and delivered into the CO_2 absorber that is filled with packing. The flue gas enters the bottom section of the absorber and reacts with the alkaline absorption solvent, KS-1™, on the surface of the packing. The KS-1™ absorbs the CO_2 with the remaining flue gas is exhausted to atmosphere. The KS-1™ solvent however, now rich in CO_2, is transferred to the regenerator where the CO_2 is separated from the

KS-1™ via steam stripping, resulting in regeneration of the KS-1™ (ready for re-use). Use of our latest energy-saving process for the regeneration can considerably reduce the amount of steam required for this process, reducing operational expenditure (OPEX).

(b) Past milestones in the development of CO_2 recovery process for coal-fired flue gas

The first commercial plant was delivered to Malaysia in 1999 and had a CO_2 capture rate of 200MTD. The plant has been in operation for more than 13 years, using the recovered CO_2 for increased production of urea.

When capturing CO_2 from flue gas of coal-fired power plants, large quantities of impurities such as sulfur oxides, nitrogen oxides and particle matter, need to be treated and their effect on the process and solvent studied. Prior to the implementation of the large-scale demonstration project in the U.S., MHI also conducted demonstration tests using the small pilot plants listed in **Table 2**. In our research center, a pilot plant on a scale of one (1) MTD was fabricated to conduct a demonstration test for CO_2 recovery from coal-fired flue gas. Subsequently, with the support of the Research Institute of Innovative Technology for the Earth (RITE) and the cooperation of the Electric Power Development Co., Ltd. (J-Power), a pilot plant on a scale of 10MTD was constructed at an existing coal-fired power plant in Matsushima, Nagasaki, Japan. The successful demonstration project ran from 2006 to 2008. Through the long run of this test operation in Matsushima, 5,000 hours of continuous operation was achieved, operational expertise and knowhow was gained, the effects of impurities in flue gas were examined to find the effective countermeasures, and data was collected for medium-scale coal-fired flue gas CO_2 recovery.

Table 2 Demonstration plants for CO_2 recovery from coal-fired flue gas

Location	Capacity	Client/Host	Flue gas source	Start up
Japan MHI R&D Center	1 ton/day	-	Coal fired boiler flue gas	Apr. 1999
Japan Matsushima Power Station	10 ton/day	-	Coal fired boiler flue gas	Jul. 2006
U.S.A SoCo Barry Power Station	500 ton/day	Southern Company	Coal fired boiler flue gas	Jun. 2011

(c) MHI's CCS-related technologies

Figure 5 shows the CCS-related technologies which are applicable to coal-fired power plants. MHI is one of the few manufacturers that can offer a whole range of technologies necessary for the implementation of CCS system at a coal-fired power plant, even including the boilers. The U.S. demonstration plant utilizes both MHI CO_2 compressors and FGD (Flue gas desulphurization unit) technology.

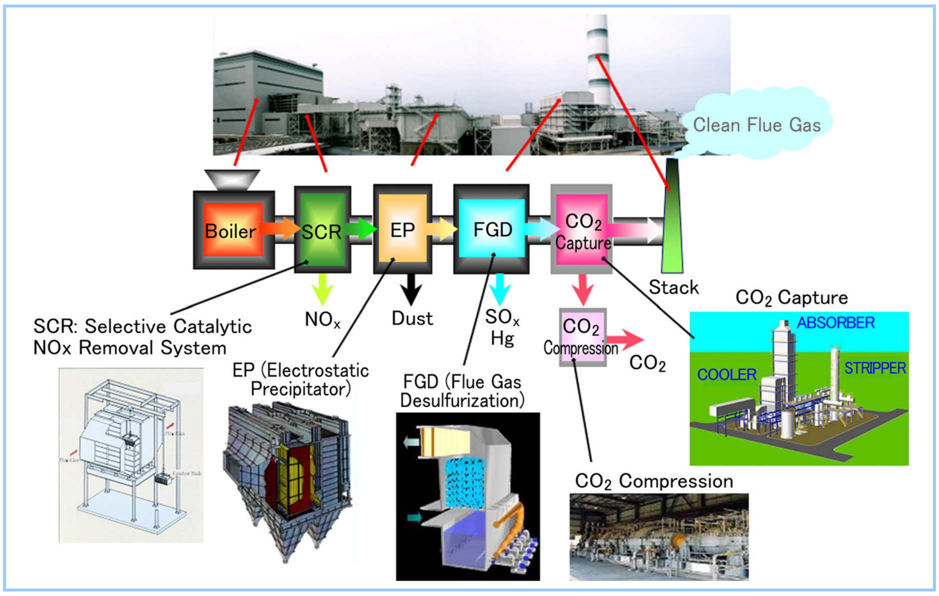


Figure 5 MHI's CCS-related technologies

4. Demonstration test results

(a) Operational status

The demonstration plant began receiving feed gas during June 2011; as of January 2013, total operation time exceeded 7,000 hours. Total CO_2 recovery for this period was approximately 127,000 metric tons.

Figure 6 shows the test operation results of the CO_2 pipeline. With the start of recovered/compressed CO_2 flowing into the pipeline, the pressure in the pipeline increases. When it approaches 1,000 psig, gaseous CO_2 in the pipeline changes its phase and becomes a supercritical fluid, keeping the pressure constant for a while before allowing the pressure to increase again. The underground injection and sequestration of CO_2 started in August 2012; total CO_2 stored now exceeds 46,000 metric tons (January 2013).

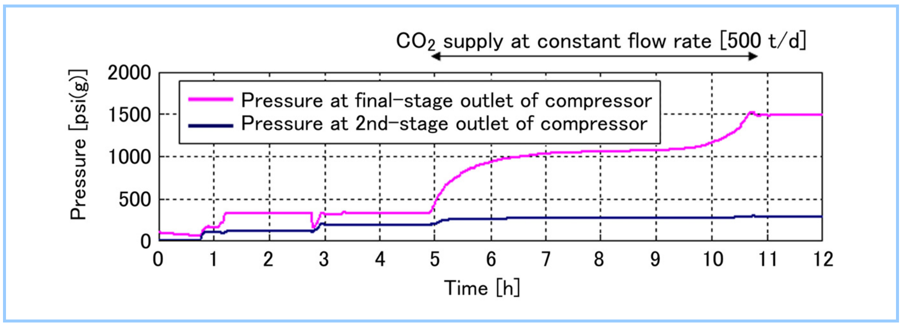


Figure 6 Results of the CO_2 pipeline test operation

(b) Parameter test

The test was conducted under the following three conditions:

- Normal operation. Major operational parameters, such as flue gas volume, were determined to achieve the intended CO_2 capture rate and CO_2 removal efficiency;
- Energy-saving operation. The circulation volume of absorption solvent was optimized; and
- High CO_2-recovery load operation. Intended volume of flue gas was treated, however the flue gas contained higher CO_2 levels than designed.

The results are given in **Table 3**. Under all conditions, CO_2 capture rate of 500 metric tons per day and the CO_2 removal efficiency of 90% were achieved, demonstrating stable performance despite varying operation conditions.

Table 3 Parameter test results

		Normal operation	Energy-saving operation	High CO_2-recovery load operation
Flue Gas Condition	Flue Gas Flow Rate [Nm^3/hr]	109,000	112,000	116,000
	CO_2 Concentration at the Quencher Inlet [vol.% (w)]	10.8	10.5	10.8
Operation Results	CO_2 Capture Rate [TPD]	505	509	543
	CO_2 Removed Efficiency [%]	91	91	91
	Steam Consumption [tonne-steam/tonne-CO_2]	0.98	0.95	1.02

(c) Load following test

Figure 7 shows the results of load following test. The CO_2 recovery and flue gas loads were increased by 5% per minute, from 60% up to 100%. The results indicate that the operation control system plant responded correctly to the load changes, as predicted by the MHI dynamic simulation. Similarly, the system performed as expected when the load was decreased by 5% per minute, 100% to 60% load.

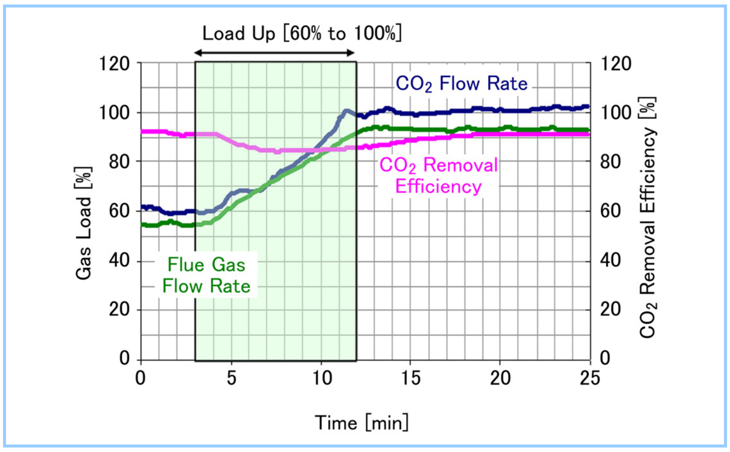


Figure 7 Load following test results

(d) Reclaiming operation

During post combustion CO_2 recovery from coal-fired flue gas, some impurities accumulate in the circulating absorption solvent. It, therefore, is important to perform timely and effective reclaiming operations to remove these impurities. In this demonstration test, it was verified that the impurities of concern can be effectively removed from the absorption solvent through reclaiming operations.

(e) Online amine analyzer

Figure 8 is a photograph of the online amine analyzer. The analyzer automatically takes a sample of the solvent in the demonstration plant on a regular basis, and automatically analyzes both KS-1^{TM} and CO_2 concentrations in the circulating absorption solvent. Use of the analyzer has considerably reduced the analytical workload, and frequently-updated solvent and CO_2 concentrations have allowed operational optimization to be conducted in ‘real time’. As the gas released from the CO_2 absorber can also be sampled by the analyzer, amine emissions in the exhausted gas can also be monitored.

Through small scale R&D and large scale demonstration, MHI have verified that the KM CDR Process® is ready for coal-fired flue gas commercialization. The facility and the advanced CCS operation control system are commercially viable, giving generators the flexibility they require to maintain profits and reduce their impact on the environment.

Figure 8 Photograph of the online measurement device for absorption solvent

5. Future testing programs

Future testing programs are summarized below.

(a) OPEX & CAPEX reductions

Under a wider range of operational parameter conditions, the consumption of steam, power, etc. will be evaluated to further reduce OPEX. Options for further reducing CAPEX (facility cost) will also be assessed and verified.

(b) Verification of long-term reliability of the facility

Throughout the long-term operation of the demonstration plant inspections will be routinely made, checking for the effects that flue gas impurities, fluid flow and general operation has on equipment. The current flue gas impurity countermeasures will also be assessed.

(c) Environmental measures

When a commercial plants with CO_2 capture rates of >2000MTD are installed, an extremely large volume of flue gas, as much as a few millions m^3 per hour, will be treated by the plant. The production of waste (e.g., through reclaiming operations) also increases with facility scale-up. For further reduction of environmental impact, environmentally hazardous substances in the treated flue gas or waste will be quantified and their relationship with operational parameters will be examined.

6. Conclusion

In June 2011, MHI and SoCo started the operation of a 500MTD CCS demonstration facility (the world's largest), constructed at Plant Barry in Alabama, U.S.; injection and sequestration of the recovered CO_2 began during August 2012. The demonstration test results indicate that not only that the KM CDR Process® is ready for coal-fired flue gas commercial application, but also that the facility and its control system for advanced CCS operation is commercially viable. In addition to the verification of long-term reliability of the facility, we will continue to investigate other possible environmental measures and OPEX & CAPEX reductions. MHI are now ready to efficiently, safely and confidently construct commercial CO_2 recovery plants >2000MTD.

(Note) The KM CDR Process® is an MHI trademark registered in Japan, U.S., European Union (CTM), Norway, Australia, and China.

References

1. Nick Irvin. et al., Project Update of 500TPD Demonstration Plant for Coal-fired Power Plant, GHGT-11
2. Nick Irvin. et al., Project Update of 500TPD Demonstration Plant for Coal-fired Power Plant and MHI Amine Emission Reduction Technology, MEGA Symposium 2012