Design Basis for CO_2 Recovery Plant

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1 General

1.1 Project Description

(1)	Name of Client	E-ON UK
(2)	Name of Project	Kingsnorth Carbon Capture & Storage Project
(3)	Plant Capacity	6,600 ton-CO_2/day from 47.3% of 819MWe coal fired boiler(Kingsnorth unit5)
(4)	Plant Location	Near the village of Hoo St Werburgh,UK

1.2 Symbol and Numbering System

(1)	Equipment Numbering System	( )	Client's practice
		(x)	Contractor's Practice
(2)	Line Numbering System	( )	Client's practice
		(x)	Contractor's Practice
(3)	Electric Equipment Numbering System	( )	Client's practice
		(x)	Contractor's Practice

1.3 Unit and Language

(1) Measurement Unit MKSA set *1)

(2) Language English

Note *1) Please refer to Attachment-1, 2 (Unit of Measurement , Prefixed for Multipliers)

1.4 Specification

Applicable UK design standards and codes such as BSI, EN, ASME, and ISA will be used throughout the design.

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2 Flue Gas / Recovered CO_2 Data

2.1 Flue Gas Composition and Properties

The composition and properties of the nominal flue gas condition is given in Table 2.1 below. And this condition is used for the material balance and for guarantee purpose.

Table 2.1 Flue Gas Composition and Properties(Full boiler Load)

Flue Gas Condition at FGD outlet		Design Gas Condition	Adaro/ Kuzbass coal bland	USA Gulf coal
Mass Flow Rate	[kg/h](wet,act.O_2)	3,157,654*2)	3,183,871	3,131,843
Flow Rate	[Nm^3/h](wet,act.O_2) *1)	2,416,424*2)	2,455,235*3)	2,419,734*3)
	[Nm^3/h](dry,act.O_2)	2,150,539*2)	2,150,773	2,110,770
Temperature *1)	[ºC]	48.1	50.5	51.1
Pressure	[mbar(a)]	1017.5	1017.5	1017.5
Composition				
CO_2	[%v](dry,act.O_2)	15.3	14.9	14.9
N_2 *1)	[%v](dry,act.O_2)	80.6	80.8	81.0
Ar	[%v](dry,act.O_2)	-	-	-
O_2	[%v](dry,act.O_2)	4.1	4.3	4.1
H_2O (Gas)	[kg/h]	213,702	244,708	248,326
H_2O (Liquid)	[kg/h]	32.3	32.3	31.7
HCl	[mg/m^3](dry 6%O_2)	0.3	0.3	3.5
SO_2	[mg/m^3](dry 6%O_2)	96.7	97.9	88.1
SO_3	[mg/m^3](dry 6%O_2)	5	2.7	18.8
NOx	[mg/m^3](dry 6%O_2)	≦100	≦100	≦100
Particulate	[mg/m^3](dry 6%O_2)	7	7	7

Note*1) Temperature and Flow Rate (Nm^3/h Wet) are calculated by MHI using the flue gas composition specified in Page 17 of KPC-EEN-CAP-SCP-0001 Rev.01.

Note*2) Flue gas flow rate at Carbon capture plant inlet is 47.3% of design gas condition (i.e. Kleinkopje at full boiler Load).
Flue gas flow rate at Carbon capture plant inlet
Flow Rate: 1,473,766 [kg/h](wet,act.O_2)
1,143,118 [Nm^3/h](wet,act.O_2)
1,017,338 [Nm^3/h](dry,act.O_2)

Note*3) A part of Flue Gas is drawn in Carbon Capture Plant.

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Table 2.2 Flue Gas Composition and Properties (Partial boiler Load)

Flue Gas Condition at FGD outlet		Kleinkopje 60% Load	Kleinkopje 25% Load
Mass Flow Rate	[kg/h](wet,act.O_2)	2,394,479	1,286,130
Flow Rate	[Nm^3/h](wet,act.O_2) *1)	1,843,228 *2)	992,892 *2)
	[Nm^3/h](dry,act.O_2)	1,655,272	906,171
Temperature*1)	[ºC]	46.6	42.8
Pressure	[mbar(a)]	1017.5	1017.5
Composition			
CO_2	[%v](dry,act.O_2)	12.8	10.3
N_2 *1)	[%v](dry,act.O_2)	80.46	80.1
Ar	[%v](dry,act.O_2)	-	-
O_2	[%v](dry,act.O_2)	6.68	9.6
H_2O (Gas)	[kg/h]	151,600	69,701
H_2O (Liquid)	[kg/h]	-	13.6
HCl	[mg/m^3](dry 6%O_2)	11.5	0.3
SO_2	[mg/m^3](dry 6%O_2)	96.7	93.5
SO_3	[mg/m^3](dry 6%O_2)	4.91	5
NOx	[mg/m^3](dry 6%O_2)	≦100	≦100
Particulate	[mg/m^3](dry 6%O_2)	7	7

Note*1) Temperature and Flow Rate (Nm^3/h Wet) are calculated by MHI using the flue gas composition specified in Page 17 of KPC-EEN-CAP-SCP-0001 Rev.01.

Note*2) A part of Flue Gas is drawn in Carbon Capture Plant.

2.2 Minimum PCC Plant Operating Point

The minimum PCC plant operating point will be at 25% of nominal flue gas flow (i.e. 47.3% flue gas of 25% boiler load of 819MWe coal fired boiler(Kleinkopje)) specified in Section 2.1.

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2.3 Liquid Effluents

Table 2.3 Waste water discharge quality limits

Component	Maximum concentration
Suspended solids (mg/l)	30
F (mg/l)	20
Cl (mg/l)	40,000
B (mg/l)	175
Cd (μg/l)	25
Hg (μg/l)	30
As (μg/l)	100
Cr (μg/l)	500
Cu (μg/l)	150
Pb (μg/l)	200
Ni (μg/l)	200
Zn (μg/l)	500
V (μg/l)	100
Fe (μg/l)	1,800
Se (μg/l)	150
Sb (μg/l)	80
Ag (μg/l)	50
Al (μg/l)	3,600
Mo (μg/l)	2,000

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3 Site Conditions

3.1 Site Location

Please refer to Fig.3.1 Proposed Site Locations

3.2 Climatic Data (based on years observation)

(1) Ambient Temperature

(a) Maximum Hourly Temperature 29.8 ºC (August)

(b) Minimum Hourly Temperature -5.5 ºC (February)

(e) Design Temperature for Equipment Sizing Max. 29.8 ºC Min. -5.5 ºC

(2) Barometric Pressure

(a) Average Pressure 1,013 mbar(a)

(b) Design Barometric Pressure 1,013 mbar(a)

(3) Relative Humidity

(a) Maximum Hourly Relative Humidity 100 %RH

(b) Minimum Hourly Relative Humidity 26 %RH(August)

(c) Average of Hourly Relative Humidity 77 %RH(August)

(d) Design Conditions: Max. 100 %RH, Min. 26 %RH

(4) Rainfall

(a) Average monthly Rainfall 55mm (May)

(b) Maximum Rainfall 148 mm/month (October)

(c) Design Rainfall _____ mm/d _____ mm/h

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(5) Snowfall

(a) Average Snowfall per Year _____days

(b) Maximum Snow Depth _____

(c) Snowy Season _____

(d) Design Snow Load _____

(6) Wind

(a) Wind Direction and Velocity

Wind	Limit
Prevailing Wind Direction	SW
Common Velocity	m/s

(7) Earthquake

(a) Frequency Frequent Infrequent None

(b) Seismic Design Req'd Not Req'd

(c) Dynamic Analysis Req'd Not Req'd

(d) Seismic Factor

(8) Dry and Wet Bulb Temperature (Outdoor Design Condition)

	Dry Summer / Winter	Wet Summer / Winter
Design Temperature	_____/_____ºC	_____/_____ºC

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3.3 Topographic Data

(1) Soil Conditions *1)

(a) Boring Data Available Data CJ Associate Report.2003

Time of Investigation 1987-1988

Investigator _____

(b) Soil Bearing Capacity

Long Term _____ kg/cm^2

Short Term _____ kg/cm^2

(c) Type of Soil

Depth (m)			
Specific Gravity (kg/m3)			
Bulk Density (kg/m3)			

Note*1) Please refer to Table 3.1 Summary of Land Contamination

(d) Groundwater Level _____ m

(e) Frost Penetration m for gravel, m for Coarse rock

(f) Soil Electrical Conductivity _____

(2) Site Elevations

(a) Benchmark Elevation _____ m

(b) Highest point Existing Grade _____ m

(c) Lowest Point Existing Grade _____ m

(d) Base Level Elevation _____ m

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(3) Water Level

Base Level
LB±0=DL+_____

Highest High Water Level
HHWL=DL+_____

Mean High Water Level
HHWL=DL+_____

Mean Water Level
MWL=DL+_____

Mean Low Water Level
MLWL=DL+_____

Chart Datum Line

Datum Line
DL±0

Lowest Low Water Level
LLWL=DL+_____

3.4 Special Consideration *1)

(1)	Provision for Winterization	(X)	Req'd	( )	Not Req'd
(2)	Provision for Tropicalization	( )	Req'd	(X)	Not Req'd
(3)	Provision for Sandstorms	( )	Req'd	(X)	Not Req'd
(4)	Provision for Flooding	( )	Req'd	(X)	Not Req'd
(5)	Provision for Lightning	( )	Req'd	(X)	Not Req'd
(6)	Provision for Termite	( )	Req'd	(X)	Not Req'd

Note*1) To be confirmed by E.ON-UK

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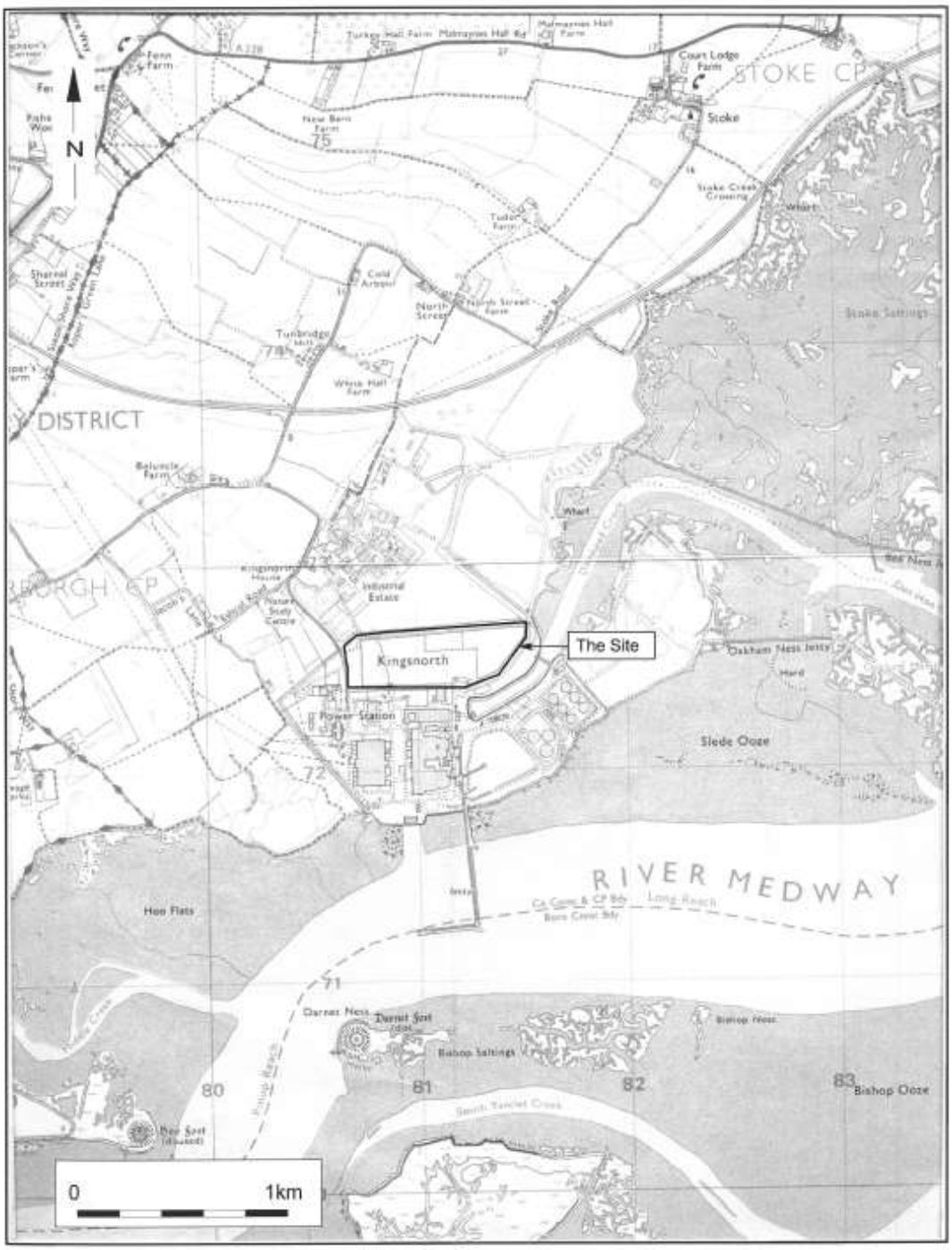

Figure 3.1 Proposed Site Locations

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4 Utilities

4.1 Steam

(1) Supply Steam

(a) Steam Source

(b) System Identification

			Reheat Steam	De-Aerator Steam	IP/LP Crossover	IP/LP Crossover with PCC Plant in Service
(c)	Pressure	Max.				
	(bar(a))	Nor.	56	13.35	5.83	3.55
		Min.	14.99	3.66	1.61	
(d)	Temperature	Max.		405.7	289	
	(ºC)	Nor.	619.3	393.2	283	222.1
		Min.	617.6			
(e)	Mass Flow Rate	Max.				
	(kg/s)	Nor.	538.2	393.2	455.6	451.66
		Min.	142.0	8.5	124.7	
(f)	Mechanical Design					
	Pressure (bar(g))					
	Temperature (ºC)					

(2) Steam Condensate

(a) Requirement of Condensate Return Req'd not Req'd

(b) Condensate from CO_2 recovery unit shall be discharged at 24 bar(a) Max. 137 ºC to the outside of battery limit.

(c) Steam Condensate Quality VGB-R 450 Le

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4.2 Process Water and Cooling Media

(1) Process Water and Cooling Media

(a)	Name		Demineralised Water	Sea Water
(b)	Composition			Refer to Table4.1
(c)	Source		To be supplied by E.ON-UK	From the outlet line of the unit 5 condenser
(d)	Supply Pressure (bar(g))	Max.		
		Nor.		
		Min.		
(e)	Return Pressure (bar(g))	Max.		
		Nor.		
		Min.		
(f)	Supply Temperature (ºC)	Max.		30
		Nor.		22
		Min.		
(g)	Return Temperature (ºC)	Max.		
		Nor.		
		Min.		
(h)	Available Capacity(t/h)	Max.		
(i)	Mechanical Design Press (bar(g))			
(j)	Mechanical Design Temperature(ºC)			

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Table4.1 Sea Water Specification

Parameter	Design Analysis
Calcium (ppm as Ca)	400
Magnesium (ppm as Mg)	1,272
Sodium (ppm as Na)	10,561
Potassium (ppm as K)	380
Bicarbonate (ppm as HCO_3)	142
Chloride (ppm as Cl)	18,980
Nitrate (ppm as NO_3)	2,649
Silica (ppm as SiO_2)	10

4.3 Electric Power

(1) Supply Power

(a)	Source		From E.ON-UK
(b)	Voltage	kV	415V / 11kV
(c)	Phase	φ	3
(d)	Frequency	Hz	50
(e)	Interrupting Capacity	MVA	150(11kV)
(f)	Supply Method		
(g)	Terminal Point of Supply		

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(2) Power Distribution

		Capacity	Voltage	Phase
(a) Motor				
Small		_____kW below	415 V,	3 ϕ
Large		_____kW above	11,000 V,	3 ϕ
(b) Control	DC	_____, AC	_____V,	_____ϕ
(c) Lighting	AC	_____kVA,	_____V,	_____ϕ
(d) Instrument		_____kVA,	_____V,	_____ϕ
		_____kVA,	_____V,	_____ϕ
(e) Maintenance		_____kVA,	_____V,	_____ϕ

(f) Distribution ( ) Under ground _____

( ) Over head _____

(3) Emergency Power Source

(a) Instrument _____

(b) Lights _____

(c) Communication System _____

(d) Fire Fighting System _____

(e) Instrument Air Compressor _____

(f) Cooling Media Pump _____

(g) Others _____

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4.4 Air（Generated in PCC Plant Island）

			Instrument Air	Plant Air
(a)	Name		Instrument Air	Plant Air
(b)	Supply Pressure (bar(g))	Max.		8.0
		Nor.	7.0	7.0
		Min.		
(c)	Supply Temperature (ºC)	Max.	Amb.	40
		Nor.		
		Min.		
(d)	Dew Point (ºC)		-30	
(e)	Available Capacity (Nm3/h)			
(f)	Source and Supply Method		New IA & PA System	
(g)	Contamination of Oil Mist		( )Yes, (x)No	( )Yes, (x)No
(h)	Retention Time at Emergency			
(i)	Mechanical Design			
	Pressure (bar(g))		9.8	9.8
	Temperature (ºC)		70	70

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4.5 Inert Gas（Generated in PCC Plant Island）

(a)	Name	Nitrogen		
(b)	Main Purpose			
(c)	Supply Press (bar(g)) Max.			
	Nor.			
	Min.			
(d)	Supply Temp (ºC) Max.			
	Nor.			
	Min.			
(e)	Dew Point (ºC) (@ ___ bar(g))	( )	( )	( )
(f)	Available Capacity (Nm3/h)			
(g)	Source and Supply Method	New PSA Nitrogen Generator		
(h)	Composition (%)			
(i)	Contamination of Oil Mist	( )Yes, (X)No	( )Yes, ( )No	( )Yes, ( )No
(j)	Retention Time at Emergency			
(k)	Mechanical Design			
	Pressure (bar(g))			
	Temperature (ºC)			

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5 Safety System

5.1 Hazardous area

No Hazardous area

5.2 Explosive protection

Not to be applied

5.3 Passive Fire Protection (PFP)

Not to be applied

6 Environmental consideration

6.1 Noise

Under normal steady operation the noise level at 1m from any item of plant dose not exceed 80dB(A).

7 Additional Design Parameter

7.1 PCC Plant life

25 years as minimum

7.2 Total design number of starts over life time*1)

Cold Starts (>50 hrs shutdown)	:	80	times
Warm starts (24 hrs shut down)	:	700	times
Hot starts (8 hrs shut down)	:	1,200	times
Load Changes (40% -100%)	:	40,000	times

Note *1): To be confirmed during detailed engineering.

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7.3 PCC Plant Availability (Expected)

Above 90% of PCC Plant Operational Duty(TBC)

7.4 Ramping Speed*1)

From 30-50% : 2-3% of MCR/minutes

From 50-90% : 4-6% of MCR/minutes

From 90-100% : 2-3% of MCR/minutes

The Maximum Continuous Rating (MCR) point corresponds to flow rate of design Gas Condition in Table 2.1.

Note *1): To be confirmed during detailed engineering.

8 Technical Schedules

8.1 Equipment Designation

Please refer to Table 8.1 Equipment Designation Letter

Table 8.1 Equipment Designation Letter

Letter/Symbol *1)	Equipment
C	Columns / Towers
DS	Desuperheater
E	Heat Exchangers and Coolers
BL	Blowers
K	Compressors
P	Pumps
PK	Vendor Packages
F	Filters
SL	Silencers
SU	Sumps
T	Tanks
V	Vessels

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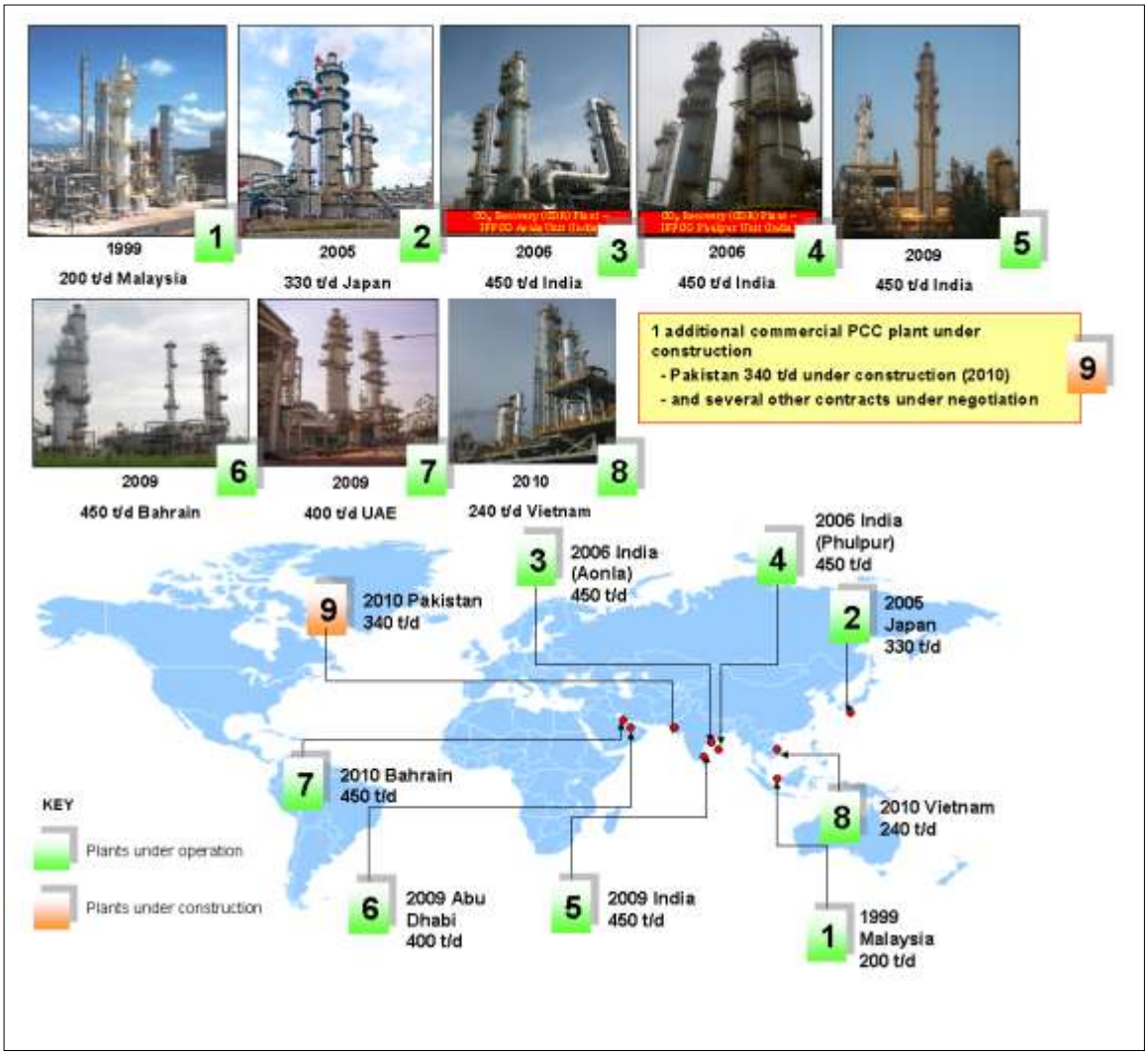
9 MHI's commercial CO_2 Capture Achievements

MHI has been involved in R&D relating to CO_2 capture from flue-gas streams of fossil fuel-fired power stations since 1990, undertaken jointly together with Kansai Electric Power CO. (KEPCO), the second largest electric utility in Japan. These efforts have led to the development of advanced PCC proprietary equipment and processes and the successful commercial deployment of (8) CO_2 capture plants. Accordingly MHI, as an independent licensor, now offers World leading LARGE-SCALE post combustion CO_2 capture technology as an independent licensor from a variety of natural gas sources, with commercially operating plants in Malaysia, Japan, multiple locations in India, Bahrain, UAE and Vietnum as highlighted in Figure 9.1. One (1) additional commercial PCC plant in Pakistan is currently under construction and will be commissioned in Q3 2010.

Figure 9.1 – MHI's Commercially Operating CO_2 Capture Plants



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10 R&D Experience and Activity

KEPCO & MHI's proprietary flue gas CO_2 capture technology has been the subject of an extensive R& D effort spanning more than 20 years. This has led to the development of the KM CDR Process ™, the advanced KS-1™ Solvent, proprietary energy efficient processes and large scale process unit designs. The advanced KS-1™ solvent has a number of intrinsic merits compared with conventional MEA solvent. The results below were obtained from internal testing for both the pilot and the commercial plants.

KS-1™ solvent has;

- High CO_2 Loading (1.5 times higher than MEA solvent)
- Negligible Corrosion (does not need corrosion inhibitor)
- Lower Dissociation Heat
  (68% of MEA solvent as regeneration heat including all process aspects)
- Negligible Solvent Degradation (10% of MEA solvent)

To maximize its ability in the overall CO_2 capture process, MHI continues the development and improvement of its process in parallel with the development of higher efficiency absorbents. In summary R&D activities have focused on the following 3 specialised fields aimed at progressing this technology to commercialization for coal fired boiler application.

R&D activity

A) Improvement of process and development of new absorbents utilizing Nanko Pilot Plant
B) Coal fired flue gas experience – understanding impact of coal fired flue gas impurities
C) Large scale up experience and confirmation

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Figure 10.1 Deployment of R&D facilities for specific PCC testing ~20 years of R&D Experience

a) 2.0 tpd Nanko Osaka pilot plant (operating since 1991)
Installed as a slip stream pilot plant of the Nanko Power station using an LNG fired boiler, the operation has continued since 1991 with mainly DSS operation and with more than 6 months per year operational experience on average. The main purpose of this plant has been to assist in various activities in relation to R&D activity A) above.

b) 1.0 tpd Hiroshima pilot plant (MHI's R&D Centre – operating since 2004)
The elementary test for the coal fired flue gas treatment has been successfully completed using a coal fired kettle boiler. The main purpose of this plant has been to assist in various activities in relation to R&D activity B) above.

c) 0.2 tpd mobile test unit
Screening and preliminary test was carried out prior to application of the Nanko Pilot Plant Test. The main purpose of this plant has been to assist in various activities in relation to R&D activity A) above. In addition this mobile test plant is available for project specific in-situ testing as per clients' request.

d) Absorber 1 by 1 scale test plant in Mihara (400 MW equivalent)
Original fluid dynamic data were obtained for FGD plant technology using synthetic flue gas at commercial scale (400MWe. This plant was the retrofitted for specific PCC plant testing replicating a commercial scale absorber (400MWe.). Liquid distribution tests, using commercial scale manufactured liquid distributor for PCC plant was carried out utilizing this facility. The main purpose of this plant has been to assist in various activities in relation to R&D activity C) above.

e) 10 tpd Matsushima pilot for testing coal fired flue gas
The main purpose of this plant has been to assist in various activities in relation to R&D activity A) above and the main details are explained later in section 11.Figure 10.2 shows the development cycle of these 3 respective activities.

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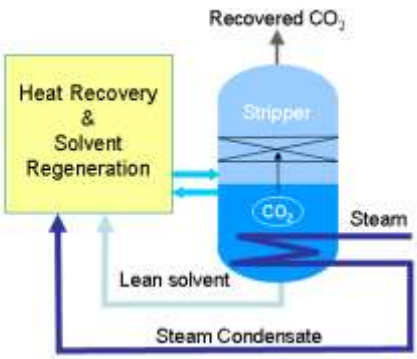
Figure 10.2 Development Schedule MHI's Evolution & Development of PCC Technology

10.1 Process Improvements

10.1.1 MHI's 'Improved Process'

In MHI's commercialized 'Improved Process', we utilize the semi lean solvent for the recovery of the lean solvent enthalpy as shown in Figure 10.3. Steam consumption is reduced by 15% compared to MHI's conventional process including the effect of the condensate heat utilization. We have officially presented the performance test results of the Nanko Pilot Plant at GHGT-8 conference and this process has since been applied commercially to the 400 tpd CO_2 capture plant operating in Abu Dhabi which is the highest performing MHI commercial CO_2 recovery plant.

Figure 10.3 MHI's Improved Process Concept



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10.1.2 MHI's 'Energy Saving Process'

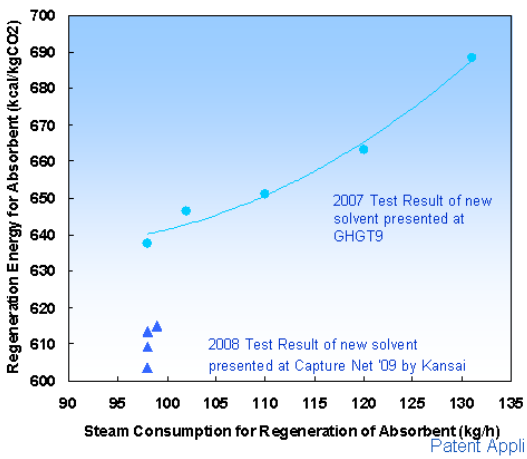
Furthermore MHI has continued the absorber heat balance optimization for further improvement of the overall process and we have subsequently confirmed a new process improvement at the Nanko Pilot Plant. Utilizing absorber heat optimization, the newly developed 'Energy Saving Process' can achieve approximately a further ~10% steam consumption reduction over MHI's 'Improved Process' utilizing absorber heat optimization. To realize the absorber heat optimization with the 'Energy Saving Process' under a wide range of commercial operating conditions, together with KS-1^{TM} solvent, MHI modified the CO_2 absorber process as part of our internal testing. The modification leads to improve absorption reaction efficiently. As a result, steam consumption reduces more than 10% compared with improved process during the testing at the Nanko Pilot plant.

10.2 Development of Absorbent

MHI has commercialized the KS-1^{TM} solvent but has continued the development of absorbents for almost 20 years. This extensive test campaign includes the laboratory testing of more than 200 solvents and pilot plant testing of more than 12. Recently we have developed a new increased efficiency absorbent as described below;

The new MHI solvent (yet to be named) has a reaction rate constant 1.4 times that of KS-1^{TM}. The thermal energy for CO_2 recovery was reduced by approximately 10% compared with KS-1^{TM}. Additionally we have continued the optimization of the pilot plant operating condition and further improvement of thermal energy to 2.5MJ/kg-CO_2 (604kcal/kg-CO2) has been achieved as shown in Figure 10.4.

Figure 10.4 New Absorbent Test Results (At Nanko Pilot Plant)



Patent Application submitted

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10.3 Scale up Application

MHI has already gained considerable commercial experience in CO_2 capture from natural gas-fired boilers. This experience, combined with extensive experiences from large scale commercial FGD deployment (eg 1,050MW single train) and the Controlled Flow Dynamic (CFD) data obtained from our large scale multi pollutant test plant ((d) of Fig 10.1), strongly positions MHI for the rapid commercialisation of PCC technology for coal fired boilers at large scale. MHI also has extensive long term commercial experience in providing large scale stripper vessels in the chemical plant industry. It must also be reinforced that MHI is NOW ready to provide large scale, single train commercial PCC plants for natural gas fired installations (with completed basic design for a 3,000tpd plant train) and intends to leverage this experience for application to large scale CO_2 capture for coal fired flue gas streams. MHI's combined experience in commercial CO_2 capture plants in the chemical industry, commercial FGD plant technology as well as CFD technology significantly mitigate the scale-up risk of PCC plant technology as shown in Figure 10.5.

To accommodate a higher gas flow, MHI adds a standardized module. A large module can be accommodated without sacrificing standardization as shown in Figure 10.6.

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Figure 10.5 Risk & Mitigation – Scale Up of MHI's PCC Technology

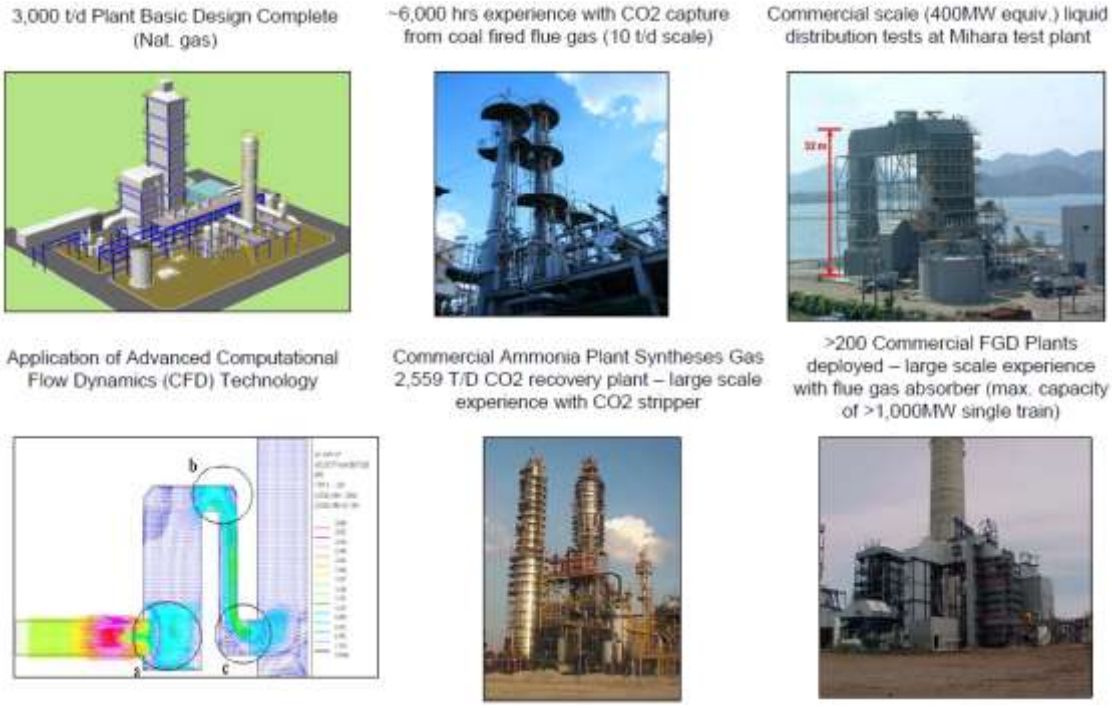
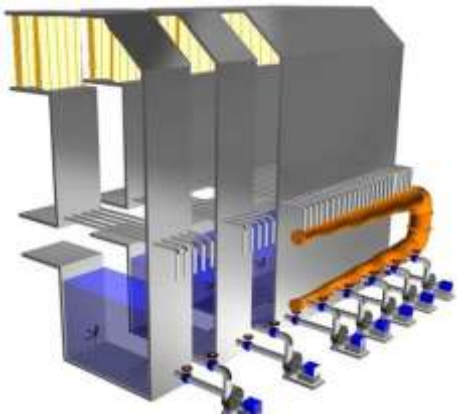


Figure 10.6 FGD Scale up Technology

- ✓ To accommodate a higher gas flow, MHI adds a standardized module
- ✓ A large module can be accommodated without sacrificing standardization



11 CO2 Capture from a Coal Fired Boiler

MHI has responded to the challenges of CO_2 capture from a Coal Fired Boiler by initially constructing and testing a CO_2 capture pilot plant in 2002, with a capacity of 1 tpd, using coal-fired flue gas at the Hiroshima R&D Center as shown in R&D facilities in Figure 10.2.

Based on the results of this successful testing, we deemed it important to gain larger scale experience with coal fired flue gas. Accordingly, as a next step, MHI built and operated a larger scale pilot plant at a commercial coal fired power station and

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successfully completed several test programs capturing 10 tpd CO_2 via a slip stream. The plant was located on a single unit attached to the 1,000MW unit, J-POWER coal fired power station in Matsushima, Japan, with grant funding (50% of project costs) from the Research Institute of Innovative Technology for Earth (RITE) and cooperation from J-POWER.

Long term operation of this plant (~6,000 hours) has enabled MHI to observe the influences of coal fired flue gas impurities on equipment and processes and develop respective countermeasures for these items. It is only through actual "in-situ" demonstration testing that some of these influences were identified and subsequently resolved through the deployment of specific countermeasures. MHI has ~6,000 hours of near-continuous operation of this facility and has gained significant know how with regards to the impact of explicit impurities and the countermeasures necessary to abate these impacts.

11.1 Demonstration Results

11.1.1 Outline of the demonstration plant

Table 11.1, Figure 11.1 and Figure 11.2 show the plant specifications and a flow diagram.

Table 11.1 Specifications of CO_2 Capture Demonstration Plant

Items	Parameters (planned values)
Installation location	Within Matsushima Thermal Power Station owned and operated by J-POWER
Flue gas source	Flue gas coal-fired boiler
Amount of flue gas to be treated	1 750 m^3_N/h
CO_2 recovery efficiency	90 %
CO_2 recovery capacity	Planned value: 9.5 ton/day (Max. 10 ton/day)
CO_2 concentration	14.1 v %
Other impurities	Dust, SOx, NOx, etc.
Solvent	KS-1 solvent

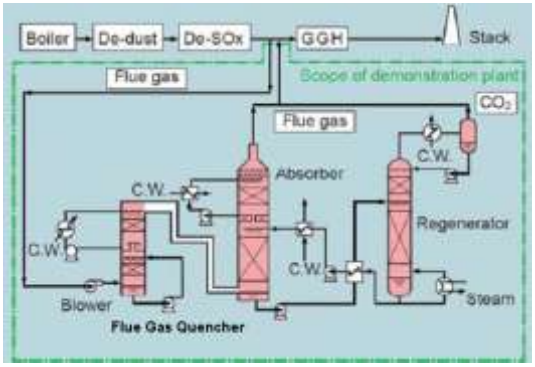

Figure 11.1 Flow Diagram of CO_2 Capture Demonstration Plant

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Figure 11.2 Matsushima Demonstration Plant Photograph

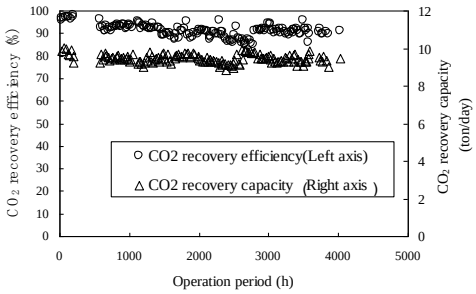

Figure 11.3 Stability of the CO_2 recovery efficiency and capacity

11.1.2 Demonstration Test Results

(1) Monitoring plant operations

Installing the pre-treatment equipment allowed the CO_2 capture plant to operate under stable conditions for a period of ~6,000 hours. The performance assessment is as follows:

a. CO_2 recovery efficiency and recovered CO_2 quantity

Figure 11.3 illustrates time-sequence data of CO_2 recovery efficiencies. Following ~6,000 hours of demonstration operation, both CO_2 recovery efficiency and recovered CO_2 quantities indicated equivalent or higher performance than our baseline prediction.

b. Heat consumption required for CO_2 recovery

Performance of heat consumption required for CO_2 recovery: 730 to 820kcal/kg-CO_2, which exceeded our original baseline forecast. If the energy saving process is applied, the heat consumption is expected to decrease by approximately an additional 15% to 630~700kcal/kg CO_2, which is higher performance than that recorded for natural gas fired flue gas due to the high CO_2 concentration in coal fired flue gas.

c. Purity of recovered CO_2

The results for CO_2 product purity shows that the KM CDR process ™ can achieve a CO_2 product purity of >99.9%, similar to our results for a natural gas-fired boiler.

(2) Identifying the influence of dust

The capture efficiency of dust in the flue gas ranges from 40 - 50% in the flue gas quencher, and 40 - 60% in the absorber. With a filter added to remove dust from the

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solvent, the dust concentration in the solvent does not increase and a dust concentration of approximately 10mg/kg can be maintained.

Our examination of the dust concentration in the solvent, and the foaming tendency of the solvent, indicated no interrelation with either the absorber pressure drop or the regenerator pressure drop. A dust concentration of 10mg/kg, or lower accumulated in the solvent, does not cause flooding.

Figures 11.4 and 11.5 illustrate trend data of the pressure drops recorded in the flue gas quencher and absorber. After 4,000 hours of near-continuous operation, no tendency was observed for increased pressure drop. The results revealed that the plugging of packing material and demisters can be prevented through dust removal utilising pre-treatment facilities and respective filter systems in the solvent line.

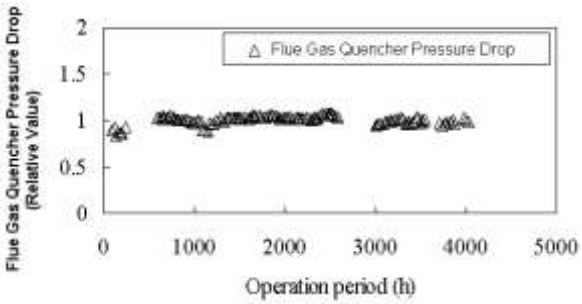

Figure 11.4 Stability of pressure drop of the flue gas quencher

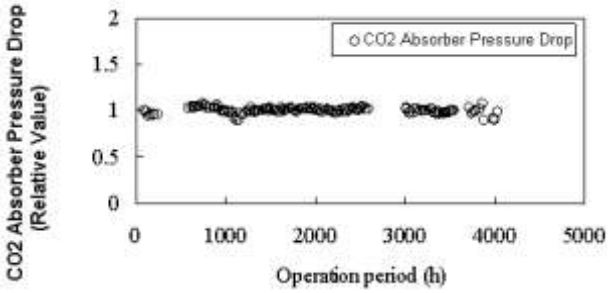

Figure 11.5 Stability of the pressure drop of absorber

Note* The heat transfer coefficient decreased in the heat exchanger using cooling water after the lapse of many hours of operation. This was explained by the adherence of material in the cooling water to the heat transfer surface. This problem can be solved by implementing appropriate water treatment. The heat transfer coefficient can not be reduced by using such treated water as cooling water for heat exchangers.

(3) Identifying the influence of SOx

The flue gas quencher provided with a desulfurization system using caustic soda, removed 98% or more of the SO_2 entering the system. This resulted in a SO_2 concentration at the CO_2 absorber inlet of less than 0.1 ppm as per our design and expectation. Almost all the SO_2 at the outlet of the flue gas quencher was absorbed by the solvent and generated heat-stable salts (HSS) which can be removed through a reclaiming process.

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(4) Identifying the influence of NOx

The flue gas quencher absorbed almost none of the NOx in the flue gas. The solvent in the CO_2 absorber absorbed approximately 1 to 3% of the inlet NOx. The HSS amounts produced were also recorded at very low levels, even after ~6,000 hours of demonstration operation, and did not cause any operational concerns.

(5) Identifying the influence of chlorine and fluorine

Chlorine or fluorine recorded impurities were below the detection limit in the flue gas or solvent during the entire demonstration testing period, and we assume these were completely removed upstream of the CO_2 capture plant.

(6) Confirming solvent loss

The solvent loss recorded was close to our expectation. In this test, we assessed the solvent loss quantitatively from the flue gas of the coal-fired boiler. We intend to apply the know how gained from these test results to specific projects.

12 Next Steps

(1) In recognition that MHI has completed extensive R&D programs, MHI's important engineering next scale up step is to test the Improved KM CDR Process ™ at medium to large scale for coal fired flue gas. MHI is working together with Southern Company, one of the largest US electric utilities and is building a 500 tpd coal; fired fully integrated Carbon Capture and Sequestration (CCS) demonstration plant at Alabama Power's Plant Barry power station. This plant aims to capture 500 tpd of CO_2 and to sequester this CO_2 into a Saline formation in a nearby oil field, thus demonstrating the full chain of CCS. The plant will commence operation in 2011 as shown below.

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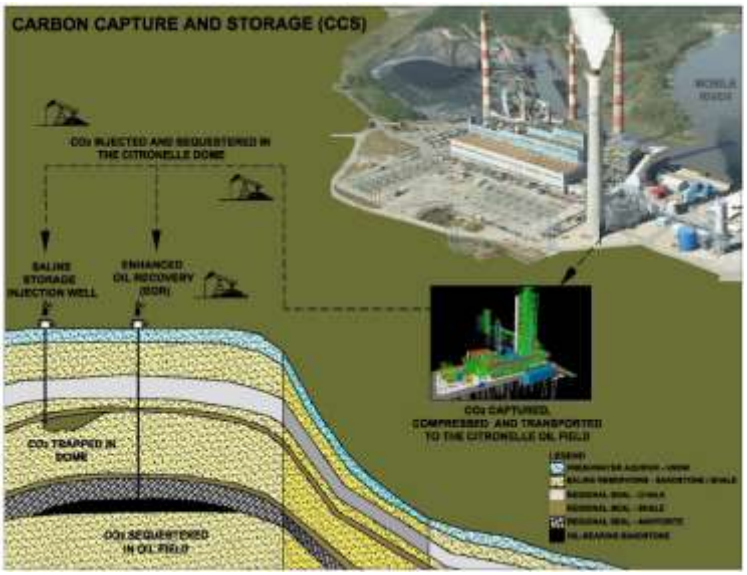
Figure 12.1 Outline of 500 tpd Demonstration Plant Project - Scope Schematic

- ✓ Solvent KS-1™
- ✓ Process Improved KM CDR Process ™
- ✓ Capacity 500 tpd
- ✓ Feed Gas Coal Fired Boiler (black/hard coal)
- ✓ Start-up Q2 2011 (expected)
- ✓ Location Plant Barry Power Station Alabama, US



(2) Construction of the large scale demonstration unit

The next step is to construct the large scale demonstration unit for commercialization for coal fired flue gas.

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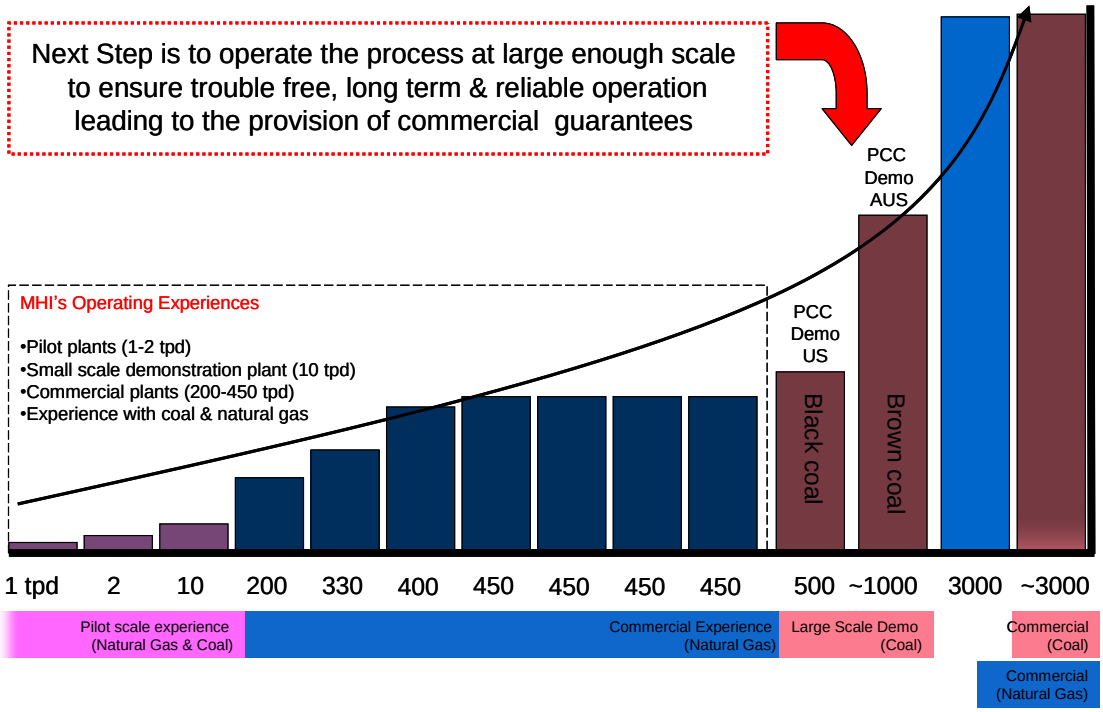
Figure 12.2 MHI's scale up & road map for commercialization of PCC for coal fired boilers



(3) Target of further development

For the further reduction of CAPEX and OPEX the following key activities are necessary.

- ✓ Reduction of the plot area by the enlargement of the equipment for the reduction of the train number and the integration of equipments to reduce the number of the separate equipment for simplification of the lay out.
- ✓ Reduction of the construction cost through the modular standardization, material selection through demonstration experience and the maturation of the technology.
- ✓ Reduction of the net energy loss by the addition of CO_2 capture plant through;
  - ➢ Application of the new energy efficient process (10% reduction in the LP steam consumption for CO_2 capture).
  - ➢ Commercialization of the new solvent (10% reduction in the LP steam consumption).
  - ➢ Further improvements with commercial sensitive technologies: (Reduction in LP steam consumption by 5%) the optimization of the system around the regenerator to utilize the input heat more efficiently for the recovery of CO_2.
  - ➢ Optimization of integration between the power plant and CO_2 capture plant.
  - ➢ Application of heat integration concepts with the power plant.

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13 General introduction of CO_2 Capture Process

The process uses a proprietary, advanced, hindered amine solution with specially designed equipment components. This is based on a proven and advanced technology for recovering CO_2 from the flue gases of various conditions. The deployment of this technology process shall lead to a number of advantages and benefits such as lower energy consumption, lower solution degradation and low corrosivity.

14 Integration of CO_2 Capture Plant

A plant design is stabilised for 3,000 metric tons/day of CO_2 capture plant. The larger size of CO_2 capture plant is designed to generate by setting some trains of CO_2 capture plant at parallel position for 6,600 metric tons/day of CO_2 @ 100%, dry basis. The CO_2 recovery rate will be 90% based on an 800MW coal fired supercritical boiler. A duct shall be connected to the outlet of FGD Absorber (before GGH). The flue gas shall be extracted from the outlet of FGD Absorber through the duct and delivered to the CO_2 capture plant via the flue gas blower located at the outlet of the flue gas quencher. CO_2 shall be recovered at the CO_2 capture plant from the flue gas.

15 CO_2 Capture Plant

The CO_2 capture plant consists of three (3) main sections; Flue gas quenching (water cooling) section, CO_2 recovery section, solvent regeneration section. The following block flow diagram demonstrates a typical plant configuration.

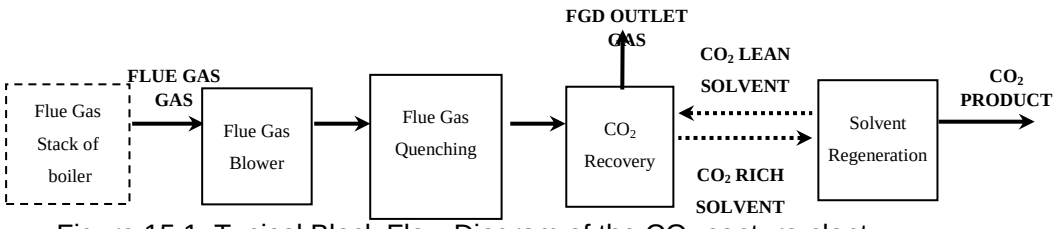

Figure 15.1: Typical Block Flow Diagram of the CO_2 capture plant

16 Flue Gas Duct

One (1) flue gas damper shall be installed in the sucking point of the duct from the FGD Absorber of the existing boiler. The flue gas shall be extracted from the FGD Absorber outlet and fed to the CO_2 capture plant through the duct by a flue gas blower and the treated gas is sent to the GGH treated side inlet through the outlet damper in one duct. The flue gas blower is required to draw the flue gas from the

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FGD Absorber outlet to overcome the pressure drop between the flue gas quencher, the CO_2 absorber and connecting duct including accessories such as the damper and the silencer. The flue gas blower will be installed downstream of the flue gas quencher.

In an emergency situation, in the event the flue gas blower is stopped suddenly with closing the inlet damper, flue gas shall by-pass the CO_2 capture plant so that operation of the Power Plant shall not be affected by a sudden failure of the CO_2 capture plant.

17 Flue Gas Quencher

A common characteristic relating to the composition of the flue gas from a coal-fired boiler is that it contains more NOx, SOx, particulate dust and other impurities, compared with a natural gas-fired boiler. Therefore, the pre-treatment system is designed to sufficiently minimize these components prior to entering the CO_2 absorber and to ultimately ensure smooth, efficient and reliable operation of the CO_2 capture plant. For this reason we have specially designed the flue gas quencher to include an integrated, NaOH, Deep FGD section (lower), Wet EP section (middle) and a flue gas washing section (upper).

The flue gas enters into the integrated NaOH Deep FGD wash section in the bottom part of the quencher, a process similar to that applied for other MHI Deep FGD processes, where the flue gas is made to contact directly with an alkaline, pH controlled solution re-circulated by the flue gas wash water pump for the specific absorption of SO_2. The Deep FGD consists of a rectangular column which incorporates packing. Caustic soda solution will be fed from the caustic storage supply. A Wet EP basically consists of the discharge electrode and the collecting electrode etc. The Wet EP unit is incorporated into the flue gas quencher in terms of minimizing the plot area for CO_2 capture plant for this project.

Following this section, the flue gas moves upward into the flue gas washing section, this also features a rectangular column and packing. The temperature of the flue gas from the Deep FGD is too high to feed directly into the CO_2 absorber, because a lower flue gas temperature is preferred for the exothermic reaction of CO_2 absorption and KS-1^{TM} solvent consumption. The hot flue gas, therefore, shall be cooled in the

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flue gas quencher by contact with circulation water supplied from the top of the flue gas quencher, prior to entering the CO_2 absorber. The water circulated by the flue gas cooling water pump is cooled by flue gas cooling water cooler and then enters into flue gas quencher. The flue gas quencher is comprised of a single train configuration.

18 CO_2 Recovery Section

The CO_2 absorber features a packed rectangular column.

The CO_2 absorber consists of two main sections; (1) the CO_2 absorption section in the lower part and (2) the treated flue gas washing section in the upper part.

18.1 CO_2 Absorption Section

The cooled flue gas is introduced into the bottom section of the CO_2 absorber. The flue gas moves upward through the packing material, while the CO_2 lean, KS-1™ solvent is introduced from the top of the absorption section onto the packing. The flue gas contacts with the solvent on the surface of the packing, where CO_2 in the flue gas is selectively absorbed by the solvent.

The rich solvent from the bottom of the CO_2 absorber is then directed to the regenerator via the solution heat exchange by the rich solution pump.

18.2 Water Wash Section

The flue gas from the CO_2 absorption section moves upward into the wash section, Wash water is circulated in the upper part of the CO_2 absorber to minimise emission. In addition, removing any vaporized solvent and is cooled down to maintain water balance within the system. The water wash section is split into tow sub-sections. A circulation pump circulates the water in each section, with an additional pump which circulates the water through the wash water cooler. The treated gas passes through the wash section and is cooled through direct contact with the wash water. The water wash section features a combination of packing. After that flue gas moves upward into Amine Deep Recovery System to minimise environmental emissions from CO_2 Absorber.

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19 Solvent Regeneration Section

Solvent regeneration shall take place in a cylindrical stripper column, whereby the rich solvent is steam-stripped, using low pressure steam, and CO_2 is removed from the rich solvent.

The rich solvent from the bottom of the CO_2 absorber shall be heated by the lean solvent from the bottom of the regenerator in the solution heat exchanger. The heated rich solvent shall be introduced into the upper section of the regenerator, where it contacts with the stripping steam.

The steam in the regenerator shall be produced by the regenerator reboiler, which uses LP steam to boil the lean solvent. LP steam will be provided by the turbine system and the condensate from the regenerator is collected at the steam condensate drum and then pumped by the steam condensate return pump.

The overhead vapour shall be cooled by the regenerator condenser system. The condensed water shall be returned from the regenerator condenser system to the top of the regenerator by the regenerator reflux pump. The product CO_2 gas is led to the following system.

The lean solvent shall then be cooled to the optimum reaction temperature by the solution heat exchanger and lean solution cooler prior to being sent to the CO_2 absorber by the lean solution pumps and the process starts again within a closed cycle.
A portion of lean solvent flows through an absorbent purification system to removes oil and other soluble impurities.

20 Solvent reclaiming (Intermittent Batch Operation)

Impurities reacts with the KS-1^{TM} solvent in the CO_2 absorber, and this reaction forms heat stable salts (HSS). The accumulation of HSS may lead to solution foaming. A reclaiming system shall be provided in order to remove the HSS accumulated in the KS-1^{TM} solvent. When the HSS content in the solvent reaches a pre-defined, maximum limit, the reclaiming system shall be operated to reduce HSS.

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After operating the reclaiming system, reclaimed waste shall remain in the system and KS-1™ solvent shall be recovered as vapour.

21 Solvent storage system

KS-1™ solvent is stored in a solution storage tank, on site, and the concentration is adjusted utilizing a solution sump tank and solution sump pump and fed to the process. A solution sump filter is utilized to clean the solvent and remove any particles. This system is also utilized during the periodical inspection when a drain out of the process is required.

22 Improved Process and Energy Saving System

Steam consumption is the most significant factor influencing operating cost of the CO_2 capture plant. Therefore, the most effective means for reducing operating costs is a reduction in the steam consumption required for solvent regeneration.

MHI has several process improvements (described in section 10.1 above) which can be incorporated into the CO_2 capture plant.

The Improved Process results in a reduced steam requirement of 30% over MHI's conventional KM CDR Process ™. If the energy saving system is applied, steam and cooling water requirement can be reduced by approximately 15 % and 5 % respectively compared with the conventional KM CDR Process ™.

The systems have been proven and applied at the Nanko pilot plant and at a commercial CO_2 recovery plant in Abu Dhabi. The long term operating cost savings are significant.

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Attachment-1 (Unit of Measurement)

Quantity	Unit	Abbreviation
Mass	Kilogram Tonne (metric)	kg t, Te
Molecular Mass	Kilogram-mole	kmol
Molecular Weight	Kilogram/kmol	-
Length	Metre	m
Area	Square metre Hectare	m^2 ha
Volume	Cubic metre	m^3
Volume Gas at NTP*1)	Normal cubic metre	N m^3
Density	Kilogram per cubic metre	kg/ m^3
Temperature	Celsius	°C
Pressure absolute	Bar absolute	bar(a)
Pressure gauge	Bar gauge	bar(g)
Velocity	Metre per second	m/s
Mass Flow	Kilogram per hour Tonne per hour	kg/h t/h
Volumetric Flow Liquid	Cubic metre per hour	m^3/h
Volumetric Flow Gas	Normal cubic metre per hour Actual cubic metre per hour	Nm^3/h am^3/h
Force	Newton	N
Moment of Force	Newton metre	Nm
Stress	Newton per square metre	N/ m^2
Energy	Joule	J
Power	Watt	W
Viscosity dynamic	Centipoise	cP
Viscosity kinematic	Centistokes	cSt
Heat Transfer Coefficient	Kilowatt per square metre per degree Celsius	kW/ m^2/ºC
Heat Capacity	Kilojoule per kilogram per degree Celsius	kJ/kg/ºC
Thermal Conductivity	Kilowatt per metre per degree Celsius	kW/m/°C
Surface Tension	Newton per metre	N/m
Latent Heat	Kilojoule per kilogram	kJ/kg
Current	Amps	A
Voltage	Volts	V
Frequency	Hertz	Hz

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Quantity	Unit	Abbreviation
Concentration	Parts per million by weight Parts per million by volume Micrograms per cubic metre Milligrams per cubic metre Milligrams per litre Weight percent Mole percent Volume percent	ppmw ppm $\mu g/m^3$ mg/m^3 mg/l wt % mol % vol %
Noise	Decibel ('A' - weighted)	dB(A)
Air Humidity	Percent relative humidity	% RH
Fouling Factor	Square metre, degree Celsius per Watt	m^2 ºC / W

Note*1) NTP : Normal Temperature Pressure Condition (Temp. :0 ºC (273.15^{o}K) Press : 1.01325 bar(a))

Attachment-2 (Prefixes for Multipliers)

10^3	K (kilo)	10^{-2}	c (centi)
10^6	M (mega)	10^{-3}	m (milli)
10^9	G (giga)	10^{-6}	µ(micro)

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