

Fluor's Econamine FG PlusSM Technology For CO₂ Capture at Coal-fired Power Plants



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Presented At:
Power Plant Air Pollutant Control "Mega" Symposium
August 25-28, 2008
Baltimore

The Econamine FGSM and Econamine FG PlusSM technologies are Fluor proprietary amine-based carbon dioxide removal processes. All of the Econamine FGSM and Econamine FG PlusSM technology described in this paper is protected by existing or pending patents owned by Fluor.

Econamine FGSM Process Technology Background

Econamine FGSM (EFG) is a Fluor proprietary amine-based technology for large scale post-combustion CO₂ capture. The EFG technology is the first and the most widely applied process that has extensive proven operating experience in the removal of carbon dioxide from high oxygen content flue gases (up to 15 vol.%).

Carbon dioxide capture can be used for the following applications:

- CO₂ sequestration
- Enhanced oil recovery (EOR)
- Merchant CO₂ sales
- Chemical feedstock production

Monoethanolamine (MEA) is the basic ingredient of the EFG solvent. However, the solvent formulation is specially designed to recover CO₂ from low pressure, oxygen-containing streams, such as boiler and reformer stack gas and gas turbine flue gas streams. Most amine systems cannot operate in such an environment, because the amine will rapidly degrade in the presence of oxygen.

The EFG+ flowsheet is similar to a generic gas treating process, which has been practiced for many years. Simple, reliable equipment that is well-known to gas treating operating personnel is used. A typical flowsheet is presented in Figure 1, for reference.

Fluor has experience putting the EFG process on a pressure sensitive source, such as a gas turbine exhaust, boilers or steam-methane reformer (SMR) flue gas line without any adverse effects. At one facility located in the United States, the EFG plant is located on the exhaust duct of a gas turbine in a power plant, where neither a backpressure nor pressure fluctuation can be tolerated. The technology is also located on steam-methane reformer flue gas lines in Brazil and Singapore. These plants consistently remove the carbon dioxide from the flue gas without disturbing the upstream pressure.

The EFG+ technology has also been demonstrated on a plant that receives flue gas from a heavy fuel oil fired power plant boiler. The flue gas from this source is much dirtier than flue gases from coal-fired power stations that are fitted with FGD units and contained high levels of NO_x, SO_x, ash and metals including vanadium. In order to make the source of the flue gas a non-issue for the solvent, the pollutants and ash/metals were scrubbed to an insignificant level in a pretreatment unit located upstream of the EFG+ unit.

Benefits of the EFG+ technology include the following:

- The process is specially designed for removing carbon dioxide from low-pressure, oxygen-containing flue gas streams.

- EFG technology does not require a custom-manufactured or expensive solvent. The main ingredient of the solvent is MEA, which is readily available and inexpensive. MEA is produced by solvent manufacturers worldwide.
- The technology has been successfully demonstrated in 25 commercial installations that were licensed over the past 20 years.

A typical EFG process flowsheet is given in Figure 1

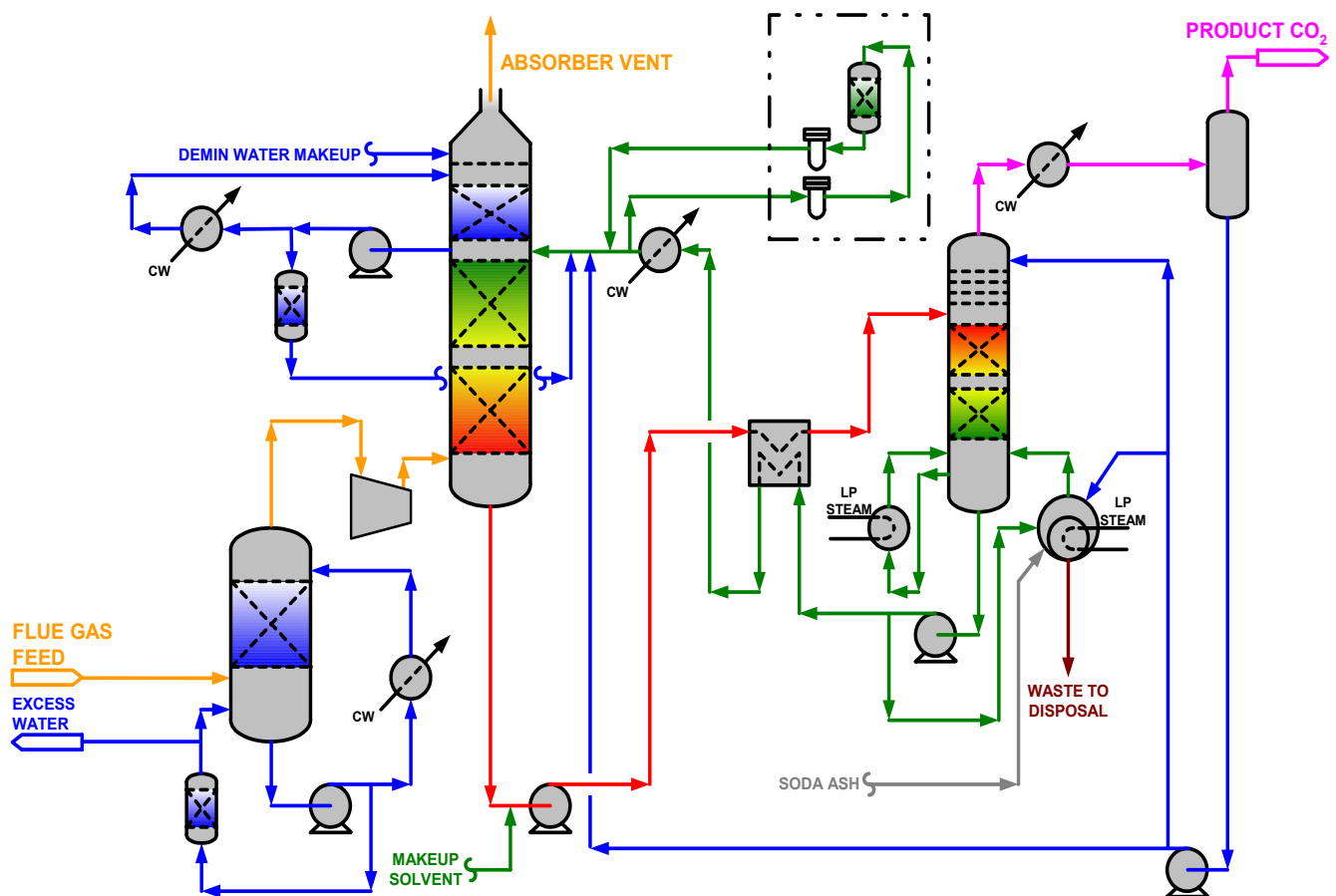


Figure 1: Typical Econamine FGSM Flowsheet

Commercial Plant Experience

Fluor has mastered the art of removing carbon dioxide from dilute sources. In one of the 25 licensed plants, owned by Florida Power and Light, 365 short tons per day of CO₂ is recovered from the exhaust of a natural gas fired power plant located in Bellingham, MA,

USA. This Econamine FGSM plant was designed and constructed by Fluor, and maintained continuous operation from 1991-2005. Due to increased natural gas prices in 2004/2005, the power plant began operating during peak hours only, rendering the Econamine FGSM plant uneconomical.

This facility is the only commercial-scale CO₂ recovery unit in the world that has operated on gas turbine flue gas. This is notable for three reasons:

- 1) Low CO₂ concentration in flue gas – 3.1 vol%
- 2) High oxygen concentration in the flue gas – 13 vol%
- 3) Pressure sensitive source where neither backpressure nor a pressure fluctuation in the flue gas line can be tolerated

Bellingham is also an air-cooled plant, demonstrating the option of using air coolers with this technology. Figure 2 shows an aerial view of the Bellingham Econamine FGSM plant. The area shown in the picture also includes the CO₂ liquefaction, storage, and truck loading facilities. Figure 3 shows a ground level view of the absorber and stripper at the Bellingham facility.

The experience gained from the design, construction and 14 years of operation at the Bellingham facility is continually being used to further advance the Econamine FGSM technology. Fluor has developed innovative strategies to prevent amine degradation and corrosion. No other vendor can match the long term commercial operating experience with CO₂ recovery from flue gas with a very high oxygen concentration. This translates into a more reliable and cost effective design and operation of future Econamine FGSM plants.

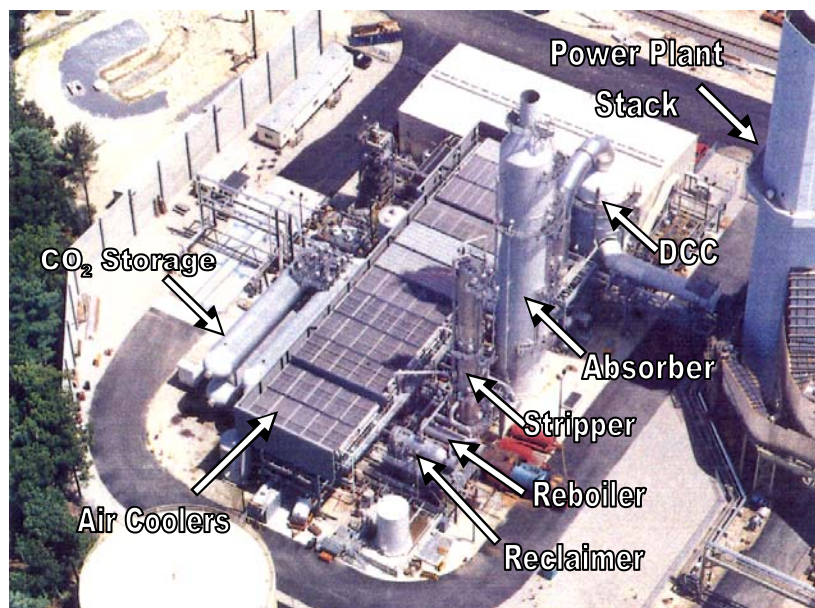


Figure 2: Bellingham Plant Aerial View



Figure 3: Bellingham Econamine FGSM Plant Ground View

Fluor has developed an advanced simulator to account for mass transfer, heat transfer and reaction kinetics. The simulator has been calibrated to performance test data from the Bellingham facility. This allows Fluor to test new flowsheet configurations in order to further improve the EFG process.

Application to Coal fired Power Plants

As concern for environment has grown over the last four decades, a greater control of pollutants in the flue gas from fossil fuel fired power plants has been mandated. Greenhouse gas emissions (carbon dioxide, nitrous oxide, methane, HCF, hydrogen sulfide, and PFC) are also the subject of intense political discussion.

Today, technologies are available for the capture of most pollutants released from coal-based power plants. Proven processes are routinely used today to remove sulfur dioxide (SO₂), nitrogen oxides (NO_x), Hydrogen Chloride (HCl), Hydrogen Fluoride (HF), particulates and mercury.

For the removal of SO₂, HCl and HF from flue gas, two commonly systems used are dry lime scrubbing (commonly referred to as “Dry Scrubbing”) and wet lime or limestone scrubbing (commonly referred to as Wet Flue Gas Desulfurization or WFGD). The design for the WFGD systems, even for high sulfur fuels, is approaching or exceeding 99% SO₂ removal efficiency without the use of additives. The use of various additives can enhance the removal process for limestone.

Even with the deployment of high efficiency pollutant removal technologies, there are still residual quantities of SO₂ and H₂SO₄, ammonia, particulates, and other trace constituents that remain in the flue gas entering the carbon capture system. However, the CO₂ absorption solvent will remove the majority of these pollutants. Although there is a significant reduction in power plant emissions, the pollutants in the flue gas increases the complexity and operating cost of the CO₂ capture process regardless of the technology.

Impurities in the flue gas, particularly SO_x, NO_x, HCl and HF will lead to the formation of Heat Stable Salts (HSS) in any amine system. HSS are the product of acid-base reactions between amines and different acidic species in the flue gas. The HSS must be converted back into amine through a reclaiming process. In order to avoid excessive HSS build-up rates, the flue gas impurities must be reduced to a very low level upstream of the EFG+ absorber. Fluor has assessed that it is more cost-effective to remove HSS precursors before the flue gas encounters the solvent. The pre-treatment step to remove HSS forming precursors is a part Fluor's process design strategy for coal-fired power plants. Figure 4, below, shows a schematic of a modern power plant.

In this example, an SCR is used to control NO_x. First ammonia is vaporized, mixed with air, and injected upstream of the SCR where NO_x, primarily in the form of NO is converted to nitrogen gas. The next step might be sorbent injection for control of SO₃ gas. The sorbent can be injected in any of a number of locations, such as just before the air preheater (APH), but almost always upstream of the particulate control device. Activated Carbon Injection (ACI) is one method of removing mercury from gas streams. This will also occur upstream of the particulate control device which will usually consist of a dry electrostatic precipitator (DESP) and/or a fabric filter (FF).

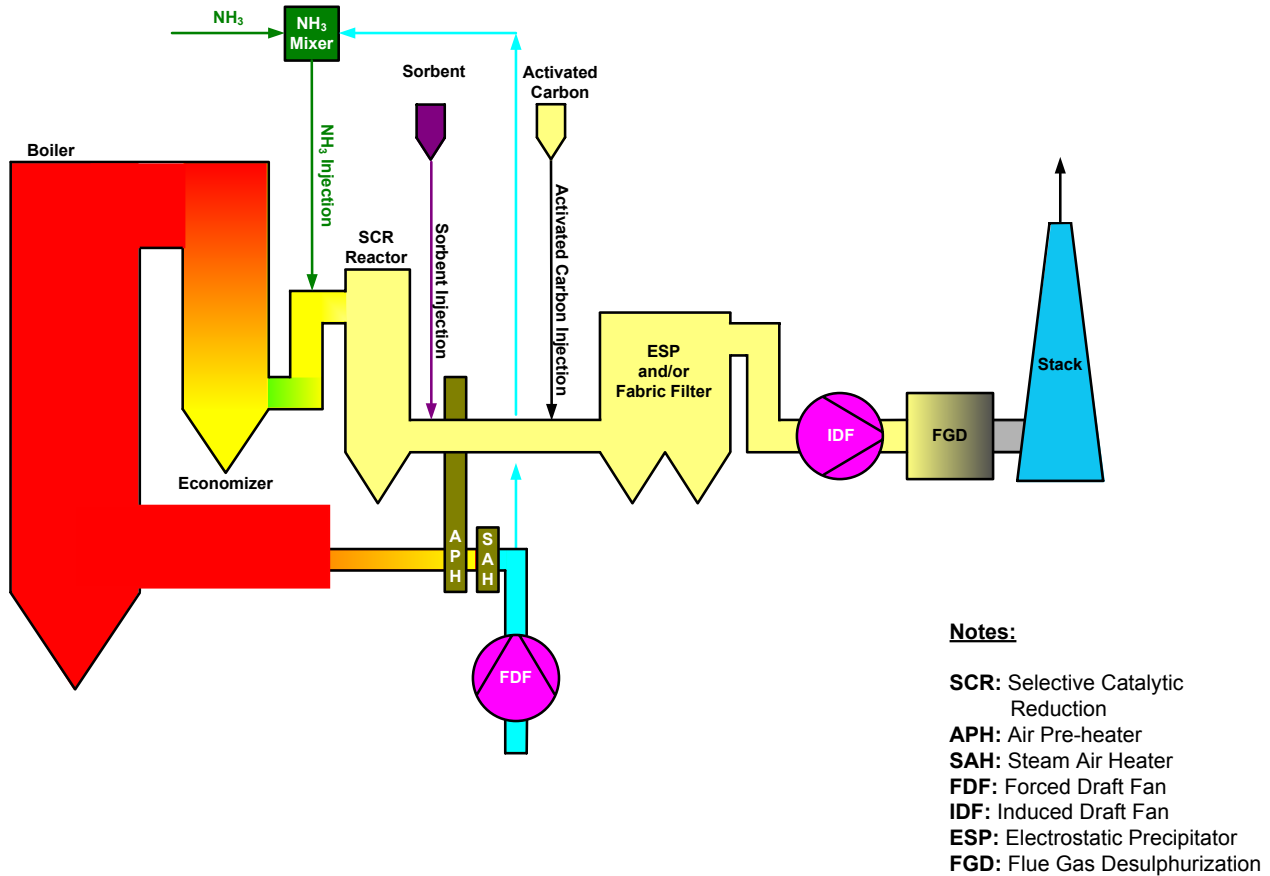


Figure 4: Power Plant without CO₂ Capture

Figure 4 also shows the path to a wet flue gas desulfurization (FGD) unit. However, many plants use dry FGDs, especially those with low sulfur fuel such as PRB. The dry FGD would be located upstream of the particulate control device. Regardless of whether SO₂ is removed by wet or dry FGD, the carbon dioxide capture plant will be located downstream of the air quality control system. The flue gas will still have small quantities of particulate, SO₂, ammonia, and other pollutant species that will need to be identified, quantified and considered in the design of the CO₂ Capture unit. Ammonia based SO₂ capture processes will also require a wet ESP to remove aerosols produced by ammonia the ammonia scrubbing process.

Figure 5, below shows a modern power plant that is retrofitted with a CO₂ Capture Unit.

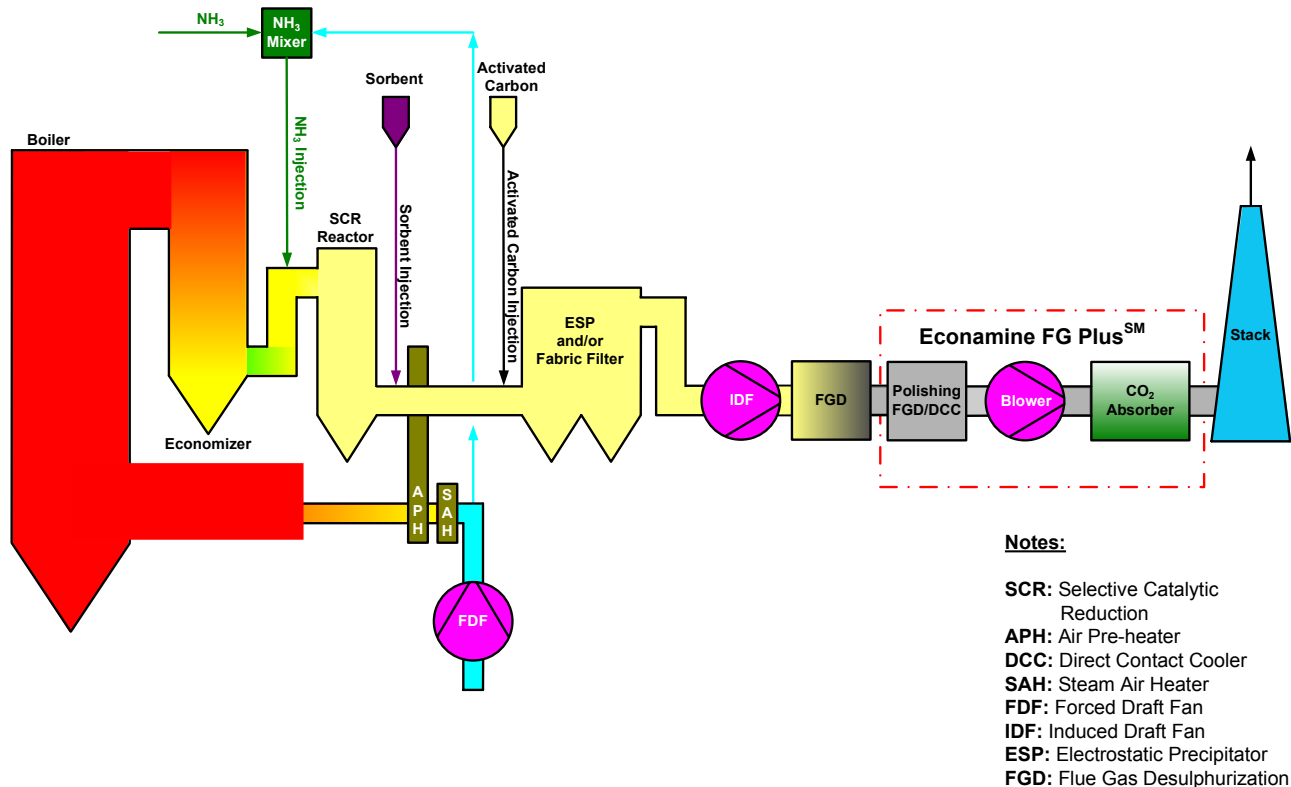


Figure 5: Power Plant with CO₂ Capture

The new equipment added in the flue gas path for carbon capture include a polishing FGD or Direct Contact Cooler (DCC) with a scrubbing capability, a blower and a CO₂ absorber. There are three polishing FGD concepts:

- Adding a polishing section within an existing FGD: For this alternate, some of the FGD internals can be removed and replaced with new internals required to implement a polishing reagent circuit. These modifications would probably be less expensive than adding a new polishing scrubber. However, the FGD modifications would normally require a longer outage than is required for routine maintenance for a FGD system. Any work of this nature would require careful construction planning and coordination. In many cases, there might not be sufficient room to install the new internals that are required for polishing scrubbing.
- Adding a new (secondary) polishing scrubber: This option could have a higher capital cost but does not require a lengthy shutdown of the power plant.
- Adding scrubbing capability into the DCC: As the temperature of the flue gas entering the absorber is decreased, the efficiency of the EFG+ process increases. The DCC is included in the EFG+ flowsheet to sub-cool the flue gas to a temperature below the adiabatic saturation temperature. The DCC can be designed

to achieve SO_x removal in addition to flue gas cooling. A polishing scrubber can be added to the DCC to further reduce SO_x to very low levels.

For power plants in countries or locations where the pollution control legislation is weak or non-existent, the following capital intensive items need to be considered for retrofitting of a CO₂ capture unit:

- Adding a SCR which requires major construction downstream of the boiler
- Adding an ESP
- ID fan replacement or revamp
- Adding a wet FGD
- Installing facilities for reagents storage and spent reagent product handling
- Adding new chimneys to handle wet flue gas conditions

Enhancements to Econamine FGSM Technology

Fluor has been continuously improving its EFG process through solvent and flowsheet enhancements to lower both the energy consumption and solvent loss. Since the design of the Bellingham Plant, Fluor has developed an improved EFG process to incorporate the process enhancements. The enhanced process, called Econamine FG PlusSM (EFG+) is now being commercially offered.

Advanced features of the EFG+ technology include the following:

- Improved solvent formulation
- Absorber intercooling
- Lean vapor compression configuration
- Advanced reclaiming technologies
- Heat integration with the power plant

The above list serves as a menu of options from which a customized plant design can be developed. Each CO₂ removal application has unique site requirements, flue gas conditions and operating parameters. Based on the given CO₂ removal application, it may be beneficial to implement only some of the enhancement features listed above. In this way, every plant will be optimized for its specific CO₂ removal application.

Improved Solvent Formulation

Generic MEA based plants operate at low concentrations of approximately 18-20 wt%. Fluor's standard Econamine FGSM plants are based on an MEA concentration of 30 wt%. The latest EFG+ plants are designed with MEA concentrations greater than 30 wt%.

The improved solvent formulation results in increased reaction rates, which decreases the required packing volume in the absorber, thereby lowering capital cost. The improved solvent also has higher solvent carrying capacity for carbon dioxide, thus decreasing the solvent circulation rate; this reduces the plant steam requirement and decreases the capital cost for solvent circulation equipment.

Absorber Intercooling

The absorber operating temperature plays a significant role in the overall performance of any EFG+ plant. Heat is released in the absorber due to the heat of reaction from the absorption of CO₂ in MEA. Higher flue gas CO₂ concentrations lead to more heat release in the absorber, and therefore higher operating temperatures. Higher operating temperatures lead to faster reaction kinetics, but reduce the solvent's carrying capacity. This means there is an optimum temperature profile for each CO₂ capture application.

For a standard EFG plant, the Absorber operating temperature can only be controlled by manipulating the flue gas inlet temperature and/or the lean solvent inlet temperature. The flue gas is heated as it travels upward through the column due to the heat of reaction. As the flue gas nears the top of the column, it is cooled by the lean solvent entering the absorber, resulting in a temperature bulge towards the middle of the column. Figure 6 illustrates how the magnitude of the temperature bulge increases as flue gas CO₂ concentration increases.

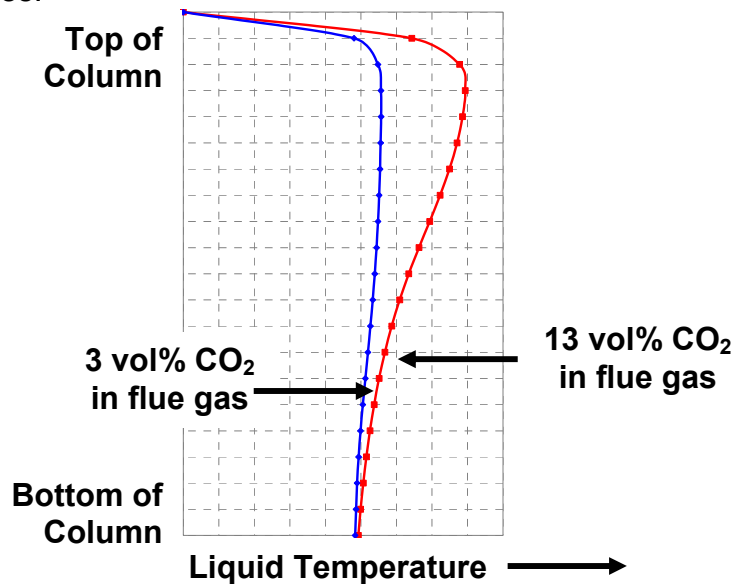


Figure 6: Absorber Temperature Profile

For higher flue gas CO₂ concentrations, as encountered in coal fired power plants, it is beneficial to remove a portion of the reaction heat towards the bottom of the absorber in order to reduce the liquid temperature. This can be achieved with absorber intercooling, as

shown in Figure 7. Absorber intercooling is achieved by extracting the semi-rich solvent between two of the absorption beds, cooling this solvent, and returning it just below the extraction point.

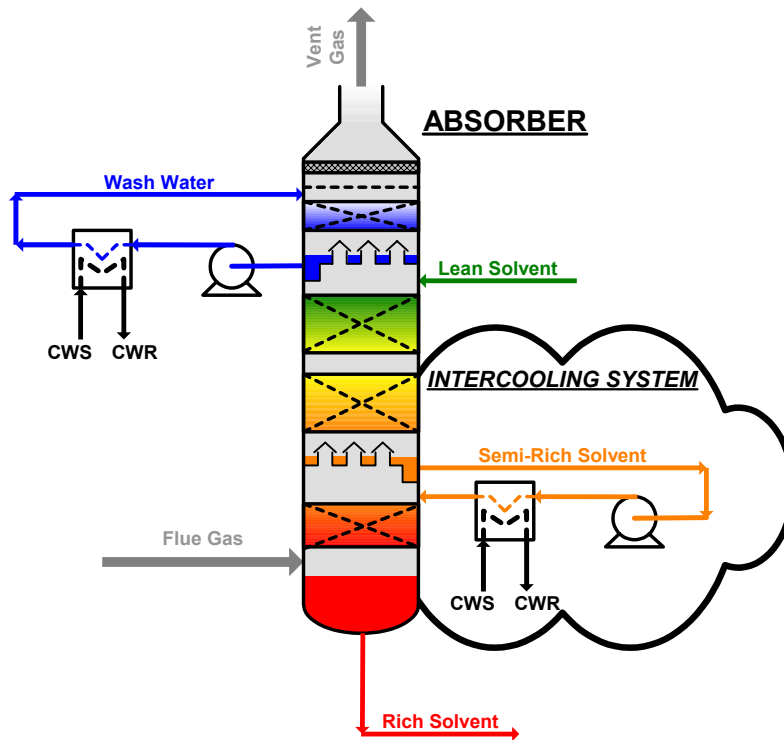


Figure 7: Absorber Intercooling Configuration

Reducing the liquid temperature increases the solvent carrying capacity, which reduces the solvent circulation rate, thereby reducing both the plant steam requirements and the capital cost of the solvent circulation equipment. In addition, the lower operating temperature results in a lower volumetric gas flow through the column, and therefore a smaller diameter. Figure 8 compares the absorber temperature profile for both an intercooled configuration against the temperature profile for a standard configuration based on the same 13 vol% flue gas shown in Figure 6 above.

Figure 8 shows that by locating the intercooler in lower section of the absorber, the bottom portion of the column operates significantly cooler, while the top portion of the column operates only slightly cooler. This is advantageous since the reaction kinetics is only slightly hindered at the top of the column, while the solvent carrying capacity is maximized near the rich outlet at the bottom of the column.

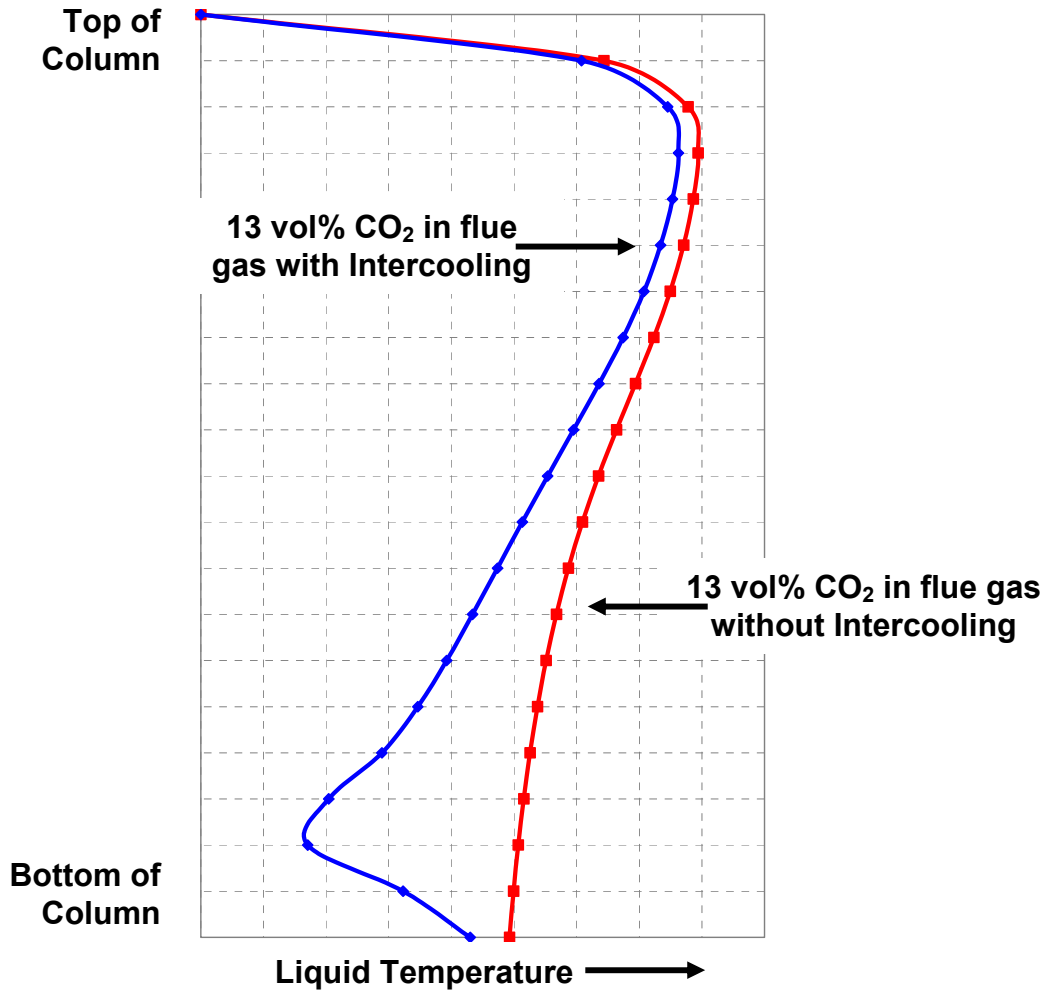


Figure 8: Effect of Intercooling on Absorber Temperature Profile

Since the amount of heat released in the absorber is smaller for flue gases with low CO₂ concentrations, the magnitude of the temperature bulge is reduced and the column will operate at a lower overall temperature. The lower operating temperature hinders the reaction kinetics and the benefits of intercooling are not realized.

Lean Vapor Compression Configuration

In a standard Econamine FGSM plant, the lean solvent from the Stripper, containing a low loading of carbon dioxide, is cooled and routed to the Absorber. Fluor now offers a lean vapor flash configuration (patent pending) in which the hot lean solvent from the Stripper is flashed at low-pressure in a flash drum. The resulting flashed vapor consists mostly of steam with small amounts of carbon dioxide and solvent. The flashed vapor is compressed

in a thermo-compressor and returned to the bottom of the Stripper where it flows upward through the column while stripping CO₂ from the rich solvent. Figure 9 illustrates the lean vapor compression configuration.

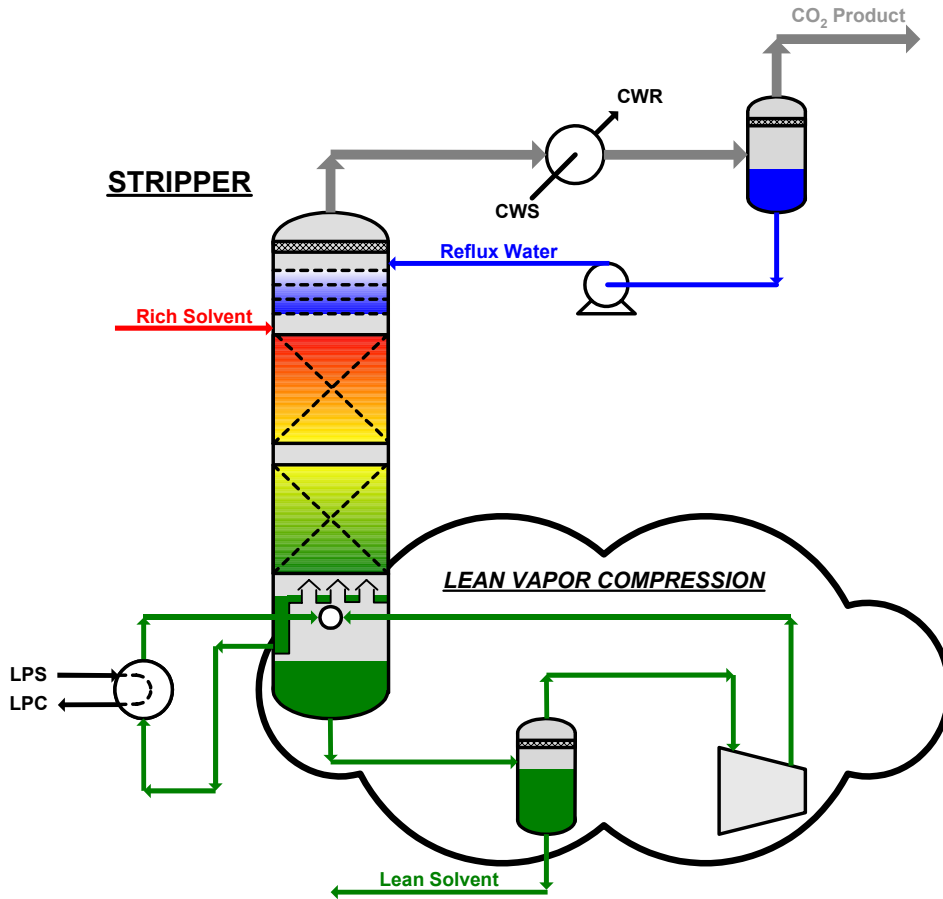


Figure 9: Lean Vapor Compression Configuration

With a portion of the stripping steam requirement being supplied by the flashed vapor, the reboiler steam requirement is reduced. Since the temperature of the lean solvent is reduced in the flash drum, the temperature of the rich solvent leaving the cross exchanger is also reduced, thereby lowering the temperature at the top of the Stripper. This results in a lower cooling load in the condenser and therefore, a lower overall plant cooling water requirement.

Both the capital cost and power requirements of the plant increase with the lean vapor compression configuration. The benefits of this configuration are highly dependent upon the local utility costs. Fluor has encountered several cases for large-scale plants where this configuration pays out in a relatively short period of time.

Advanced Reclaiming Technologies

In the past, Econamine FGSM plants were designed with thermal reclaimers. At the operating temperature and residence time of the thermal reclaimer, a considerable amount of degradation products were created during the reclaiming campaign. Recently, Fluor has developed new processes for low temperature MEA reclaiming that dramatically reduce solvent losses.

One of these technologies is based on ion-exchange reclaiming. Ion-exchange reclaiming efficiently regenerates the solvent from heat stable salts with a very low solvent losses. However, there is a small amount of degradation product generated in the Econamine FG PlusSM process that cannot be removed with the ion-exchange process. Fluor has also developed a new atmospheric reclaiming process to remove these degradation products. Depending on the CO₂ capture application, an Econamine FG PlusSM plant can be configured to incorporate both of these reclaiming processes to minimize solvent losses and significantly improve the environmental signature of the facility.

Environmental Signature

The Econamine FG PlusSM process produces the following emissions/effluents:

- Absorber stack emissions
- Reclaimer wastewater
- Excess water from flue gas cooling

Absorber stack emissions

Typically, the absorber stack emission is essentially the same as the source stack except for the absorbed CO₂, SO_x and a portion on the NO_x. In addition, due to vapor pressure loss and mechanical carryover, a trace quantity of MEA is emitted from the absorber. In addition, a small amount of ammonia is formed by the oxidation of MEA due to the oxygen present in the flue gas. The ammonia is stripped from the liquid phase by the flue gas as it flows through the absorber and is vented to the atmosphere. Fluor has aggressively pursued strategies for minimizing ammonia formation and reducing the loss of MEA in the vent by washing the treated flue gas in advanced column internals.

Reclaimer waste/wastewater

Fluor has developed an advanced low-temperature reclaiming technology that has significantly reduced the quantity of reclaimer waste.

Excess water from flue gas cooling

As the Econamine FG PlusSM absorption process is carried out at near ambient temperature, flue gas cooling is frequently required upstream of the absorber. Water vapor that is condensed out by cooling the flue gas is removed from the system. The condensed water is of good quality and can be used as a feed stream to demineralization plant or within the process itself after minimal treatment.

Plot Space Minimization

Large-scale CO₂ sequestration projects that are currently in development require multiple CO₂ absorption trains that result in large plot areas. Even for smaller CO₂ capture retrofit applications, plot availability can play a vital role in the feasibility of the project. As a result, Fluor has focused on strategies to minimize the footprints of Econamine FG PlusSM plants. These strategies include:

- Large diameter absorber design
- Plate and frame exchanger train minimization
- Reboiler shell count minimization

Large diameter absorber design

For large-scale CO₂ capture applications, Fluor has been designing absorbers with diameters up to 60 feet in order to minimize the number of absorption trains. Fluor has experience with the design and construction of absorbers with diameters of 40 to 50 feet. An example of a large diameter column designed and built by Fluor is given in Figure 10 below:



Figure 10: Fluor's DGA Plant in Uthamaniyah, Saudi Arabia has absorber (center-right) with a large diameter

There are four major issues in the design of large diameter columns:

- Gas distribution
- Liquid distribution
- Support structure
- Materials of construction

Gas distribution

Vapor distribution in a column is most critical above vapor inlet ducts. Two primary considerations must be taken into account in the absorber design with regards to vapor distribution: the kinetic energy of the incoming gas and the vertical clearance between the vapor inlet and the bottom packed bed.

Over the years, Fluor has developed design rules to ensure proper vapor distribution in column. These design rules have been validated through computational fluid dynamic (CFD) modeling of the column and the successful operation of the Bellingham plant. The CFD model's domain comprised of the Blower discharge (rotational effects), the flue gas duct from the blower to the column, the vapor space below the bottom bed and the bed itself.

Liquid distribution

Packed columns are sensitive to proper liquid distribution throughout each bed. Mal-distribution results in loss of efficiency and therefore loss of performance. As such, the design of the liquid distributors and redistributors above each packed bed are critical to the successful operation of the column. The successful experience in selecting and designing column internals for the Bellingham plant is the basis of designing future large absorbers.

Support structure for column internals

A major challenge in design large diameter columns is simply handling the overall sheer size and weight. The internal infrastructure must be design to support the massive static loads of the column internals from both a mechanical and structural point of view.

Fluor is implementing a novel design concept which consists of a hub ring type structure to support the column internals. Fluor has successfully implemented this support system in refinery columns of 45 to 55 feet diameter.

Plate and frame exchanger train minimization

Fluor has selected plate exchangers for thermal efficiency and plot size minimization. However, for large CO₂ capture units, plate exchangers are usually applied in multiple trains and require a considerable plot space.

Fluor has been working with plate exchanger vendors to minimize the number of parallel exchanger trains. The number of parallel trains for a service can be reduced by increasing the plate size and/or improving the plate efficiency.

By design, exchanger plates are very thin. As the plate size increases, the plate becomes more flexible making it more difficult for plate-pack re-assemble after routine cleaning. Vendors are making their best efforts to supply the largest plates possible.

Reboiler shell count minimization

For large-scale applications, Fluor has developed a unique reboiler design to minimize the number of shells. Not only does minimizing the number of shells reduce the plot space requirements, but it also simplifies the complexity of the system from both a design and operating point of view. The number of reboiler feed lines, return lines, nozzles and associated piping, instrumentation, and controls increase proportionally with the number of shells. The draw tray design becomes more complex, requiring balanced solvent flow to more shells. Balancing the steam flow to each shell of the reboiler becomes more complicated as well.

Fluor has built and commissioned reboilers (in refinery service) similar in size to those required for CO₂ capture in 1000 MW coal fired power plants.

Summary

Fluor's proprietary Econamine FGSM technology is a proven, cost-effective process for the removal of CO₂ from low-pressure, oxygen containing flue gas streams. The performance of the process has been successfully demonstrated on a commercial scale over the past 20 years.

Through rigorous laboratory and field tests, Fluor has made added several enhancement features to further reduce the process energy consumption. In conjunction with the Econamine FGSM technology, these enhancement features are now available at the improved Econamine FG PlusSM technology. Any combination of these enhancement features can be assembled in a custom-fit solution to optimize each and every CO₂ capture application. Furthermore, the Econamine FG PlusSM process offers an improved environmental signature and can be configured around tight area requirements.

Fluor has developed a pre-treatment process for applying EFG+ technology to coal fired power plants. The strategy consists of three options for polishing scrubbing and incorporates Fluor's experience in large FGD projects.