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Advanced KM CDR Process using New Solvent

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Abstract

Upon completion of the world largest post combustion CO_2 capture plant – Petra Nova Project – MHIEng has demonstrated that commercial-scale CO_2 capture plant is technically feasible. With the updated technology and lessons learned, the Advanced KM CDR Process has been developed, providing superior performance as usual but with a significantly lower capital cost. The cost reduction is contributed by the reduced size of the flue gas quencher and CO_2 absorber, reduced design redundancy, and the modular design. The total project cost of the CO_2 capture and compression is expected to be reduced by nearly 30% for the next large-scale plant. The Advanced KM CDR Process together with new solvent (KS-21) that targets at improving overall plant economics is as well under development. Also, KS-21 solvent is expected to have higher technical advantage comparing with existing KS-1™ solvent, such as higher stability and lower volatility. The preliminary pilot plant test showed that the KS-21 has 50% lower amine emission than KS-1™ while giving comparable energy performance. MHIEng will offer the Advanced KM CDR Process using KS-21 with attractive properties facilitating solvent management in early 2019.
Keywords: MHIEng; amine scrubbing; CO_2 capture; Petra Nova

1. Introduction

Amine scrubbing is considered the most mature technology to mitigate the anthropogenic CO_2 emissions from fossil fuel-burned power plants [1]. Coal-fired power plant and natural gas combined cycle (NGCC) with CO_2 capture can be regarded as clean power generation if the cost is competitive compared to other low-carbon alternatives such as renewable energy. The impurities in the flue gas and the unprecedented scale are the major obstacles to deploying CO_2 capture for fossil fuel-fired power plants.

The coal-fired flue gas has various impurities than other applications. The SO_x, NO_x, and particulate matters (PM) will increase the amine consumption rate by degradation and emissions. Higher amine makeup rate and additional equipment for solvent management result in additional cost. The heat stable salts formed from the reactions between amine and impurities need to be removed by solvent reclaiming otherwise the CO_2 capture performance become degraded [2]. The solvent reclaiming increases both operating and capital cost and add operation complexity [3]. The SO_3 containing in the flue gas can serve as aerosol nuclei and increases the amine carryover from the CO_2 absorber that cannot be mitigated by conventional water wash [4]–[6]. Additional equipment is required to reduce the amine emissions from the treated flue gas. The accumulated PM in the solvent

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can cause foaming and needs to be removed by filters. The CO_2 capture plant at Boundary Dam had experienced issues that the amine was degraded at a significantly faster rate than expectation and had to spend more than 3 times original budget on in cleaning solvent and supplying fresh amine [7]. The owner of the capture plant, SaskPower, was planning to expand the capacity of the thermal reclaimer in order to reduce the prohibitive cost on amine maintenance [8]. This suggests that the impact of the contaminants in the coal-fired flue gas is significant not only rising the amine makeup cost but also affecting the system performance and operation.

Scaling up by 10-fold from demonstration plants at 10 to 25 MW equivalent size to full-scale plants was another challenge. Due to the unprecedented scale, redundancy and relatively conservative design are inevitable in order to reduce the technology risks.

In December 2016, Mitsubishi Heavy Industries America Inc. (MHIA), a wholly-owned subsidiary of Mitsubishi Heavy Industries, Ltd. (MHI) and together with its consortium partner, TIC (The Industrial Company), delivered the world's largest CO_2 capture plant in Petra Nova project (240 MW equivalent) using the proprietary KM CDR Process^{TM} and KS-1^{TM} solvent jointly developed by Mitsubishi Heavy Industries Engineering, Ltd. (MHIEng) and Kansai Electric Power Co., Inc. (Kansai EPCO). The plant has been under stable operation since startup at guaranteed capture efficiency and energy performance. MHIEng's KM CDR Process^{TM} using KS-1^{TM} has demonstrated that clean coal power generation is technically feasible at commercial scale. The success largely relies on the superior performance of the MHIEng's technology and the extensive experiences MHIEng had learned from the past 14 commercial and demonstration plants. MHIEng has been continuously dedicating to improving the technology and offering a cost-effective process.

This paper will present the recent effort MHIEng has made in achieving the improvement of overall economics for CO_2 capture plant from capital and operation cost point of view. The Advanced KM CDR Process is MHIEng's new product and is expected to reduce the total EPC cost by approximately 30% compared to last generation. A new solvent, KS-21, is as well under testing, aiming to reduce the amine degradation and emissions by approximately 30% so that the cost related to solvent management can be reduced. MHIEng expect to offer the Advanced KM CDR Process with KS-21 solvent for new commercial projects in early 2019 after further evaluations and tests.

2. Advanced KM CDR Process

The Advanced KM CDR Process is considered MHIEng's next-generation process that significantly reduces the capital cost while maintaining the superior capture and energy efficiency. When the conventional process was designed for the first full-scale capture plant for coal-fired flue gas, design redundancies were inevitably included to reduce the risk of underperformance. However, with lessons learned from recent projects and the updated technology, MHIEng has developed the Advanced KM CDR Process with a significantly lower cost. This section will show the result of the study conducted by MHIEng to compare the Advanced KM CDR Process and the conventional process within the scope shown in Figure 1 including the flue gas quencher, the CO_2 absorption section, the solvent regeneration section, and the CO_2 compression and dehydration section. CO_2 pipeline and auxiliary systems that supply utilities are not in the scope. Typical coal-fired flue gas and CO_2 product conditions specified in this study are shown in Table 1.

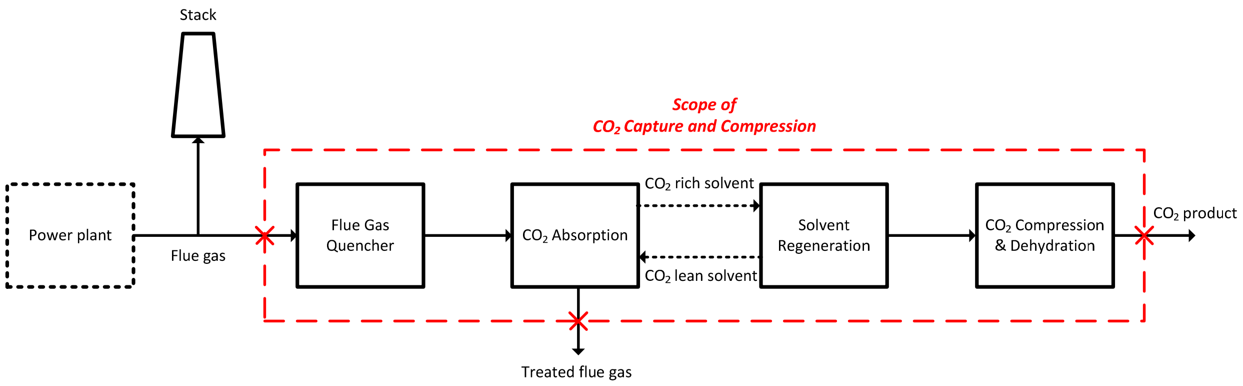

Figure 1: Scope of CO_2 capture and compression in this study.

Table 1: Flue gas and CO_2 product specifications of this study.

Specification	Value
CO_2 capture ratio (%)	90
Flue gas T (C)	75
CO_2 concentration in flue gas (mol%)	11
CO_2 product P (bar)	130

2.1. Flue gas quencher and CO_2 absorber

The flue gas quencher (i.e., direct contact cooler) and the CO_2 absorber are the largest pieces of equipment in the capture plant due to the large gas volumetric flow rate. The towers have been indicated as the major cost center accounting for up to 30% of total capital cost [9], [10]. Reducing the cost of the large towers can significantly improve the overall economics. Gas-liquid maldistribution is often one of the reasons that large columns suffer from poor performance when scaling up. MHIEng conducted several R&D projects to ensure the performance of large columns. Commercial liquid distributors were tested in MHIEng's facility in Mihara, Japan, making sure the water or solvent have good initial distribution before flowing down to the packing sections. The rectangular towers are designed with validated CFD simulations and MHIEng's past experiences in large FGD systems. All these efforts contributed to the success of the USA's full scale project. In the Advanced KM CDR Process the flue gas quencher and the CO_2 absorber are optimized and can be fabricated in modules to provide a lower manufacture cost.

2.1.1. Reduced size with validated performance

In the recent projects, the performances of the flue gas quencher and the CO_2 absorber have been validated and re-optimized in the Advanced KM CDR Process. Table 2 shows the size reductions compared to the conventional process. The new flue gas quencher integrates the SO_2 removal section and the cooling sections using less packing while still being able to achieve the target performance. The CO_2 absorber consists of the absorption section and the water wash section. The height of the absorption section is reduced by 29% without losing the capture efficiency. MHIEng's proprietary water wash system and demisters can effectively reduce the aerosol emissions caused by the SO_3 from the coal-fired flue gas. Even though the water wash section is reduced by 39%, the KS-1^{TM} concentration at the absorber outlet can be controlled much lower than ppm level including volatile and aerosol losses.

Table 2: Optimized flue gas quencher and CO_2 absorber. (Scale against base value: 100)

Parameters Relative to conventional	Conventional	Advanced KM CDR Process
Flue gas quencher tower height (% in m)	100	61
CO_2 absorber tower height: absorption section (% in m)	100	71
CO_2 absorber tower height: water wash section (% in m)	100	61

2.1.2. Modularized towers

In the conventional process, the rectangular flue gas quencher and CO_2 absorber were fabricated in the nearby temporary working area, transported to the site, and stacked up. The onsite fabrication and welding of the large towers was intensive and costly. To minimize the onsite fabrication, the Advanced KM CDR Process can include rectangular towers supplied in modules, which could be used as standard for large-scale towers in future projects. The towers are shop fabricated in sub-modules as transportable size and shipped to the site. The onsite construction work is therefore largely reduced with only module assembly remained. The temporary facility and consumables associated to onsite fabrication can also be avoided. The modular design not only reduces the cost, but also improves the fabrication quality and productivity. In this study, the onsite labor hours for the flue gas quencher and the CO_2 absorber were reduced by 71% by applying modularized towers in the Advanced KM CDR Process compared to conventional design. Reduction for actual projects will depend on site logistics and other factors.

2.2. Reduced redundancy

The design redundancy has been examined using the performance data obtained in recent projects. Supported by actual performance data, MHIEng is confident of minimizing the design redundancy in the Advanced KM CDR Process. Table 3 shows the reduced equipment cost resulted from reduced redundancy. MHIEng's proprietary filtration system is installed to remove the accumulated PM in the KS-1^{TM} solvent. The accumulation rate and filtration efficiency relies on the size distribution and the PM capture efficiencies in the flue gas quencher and the CO_2 absorber, which are difficult to predict until actual operation using real flue gas. Using the performance data, the filtration system has been optimized to a significantly smaller size, 57% reduction compared to conventional design in the study. Reduced equipment size also results in less solvent holdup in the system, which not only reduces the cost of the initial solvent fill but also lowers the solvent degradation rate.

Table 3: The cost reduction from reduced redundancy (Scale against base value: 100)

Parameters Relative to conventional	Conventional	Advanced KM CDR Process
Pumps (% in $)	100	49
Heat exchangers (% in $)	100	80
Tower internals (% in $)	100	74
Filtration system (% in $)	100	43
Tanks (% in $)	100	74

2.3. Modularization and compact design

2.3.1. Modularization

Modularization can remarkably improve the construction cost for large-scale capture plants. Not only the rectangular towers mentioned in Section 2.1.2, the pipe rack, heat exchangers/pipe and pump/pipe can also be fabricated as skids in shop to reduce the field fabrication and onsite welding. The pre-fabricated skids can be shipped to the site and assembled. Field fabrication is more expensive and has risks that the production could be affected by the site conditions and weather. The shop fabrication can improve safety, quality and productivity performance and consequently facilitates schedule and budget control. In this study of the Advanced KM CDR Process the total onsite construction labor hours (excluding quencher and absorber) is reduced by 60% by applying modularization compared to conventional design in the study. In practice the benefits of modularization may be site-specific.

2.3.2. Optimized plot plan and minimized footprint

For the Advanced KM CDR Process the plot plan of the CO_2 capture and compression facility has been re-arranged to minimize the footprint. Smaller footprint requires less concrete, structural steel and piping material, leading to a lower construction cost. The compact design and modularized pipe rack reduce the foot print by 25% as well as the piping and structural steel work volume (Table 4).

Table 4: Reduced footprint and construction work volume. (Scale against base value: 100)

Parameters Relative to conventional	**Conventional**	**Advanced KM CDR Process**
Footprint (% in m^2)	100	75
Structural steel (% in tonne)	100	76
Piping (% in tonne)	100	79

2.4. Overall capital cost reduction

Figure 2 compares the overall project cost including engineering, procurement, and construction (EPC). The Advanced KM CDR Process reduces the total EPC cost by nearly 30% compared to the conventional process in the study. The cost reductions can be attributed to reduced size and modular construction of quencher & absorber, reduced redundancy, modular construction of pipe rack, heat exchangers/pipe, and pumps/pipe, and compact layout as described in Section 2.1-2.3. Since the flue gas quencher and the absorber are the most expensive equipment in the capture plant, the reduced size and improved manufacture method make the largest contribution, accounting for 48% of overall reduction. Reduced redundancy and modular & compact design contribute to 10% and 42%, respectively.

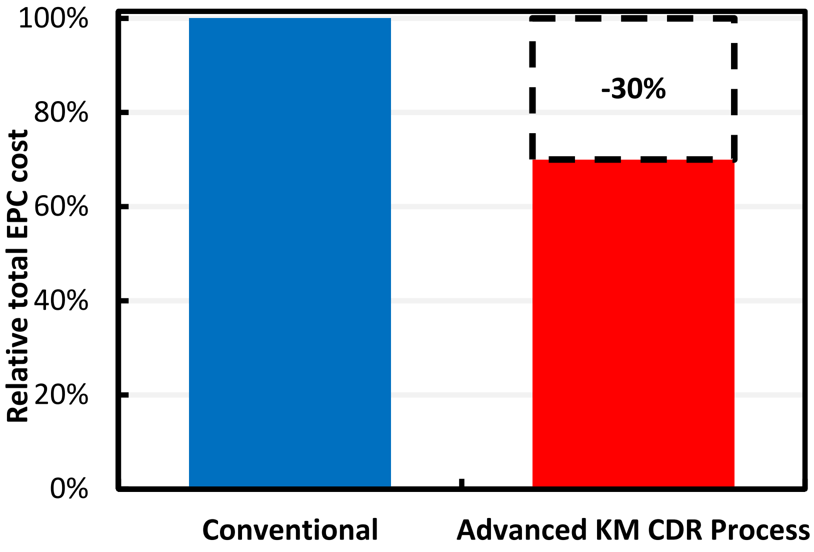

Figure 2: The expected reduction of total EPC cost.

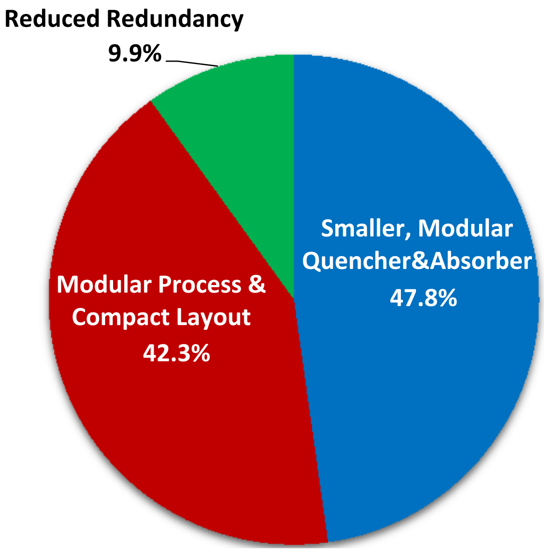

Figure 3: Contribution of cost reduction.

2.5. Automatic operation system

An Auto Load Adjustment Control (ALAC) system developed by MHIEng has been applied in the conventional process. The system can control and maintain the CO_2 capacity as disturbances such as the variations of flue gas rate and CO_2 compositions can be observed in the capture plant. Stable CO_2 delivery is particularly essential for a CO_2 capture plant that supplies CO_2 for enhanced oil recovery or CCU purpose. This system is further improved in the Advanced KM CDR Process by automating the startup operation. It can greatly reduce the workload of the operators, and lead to less human errors.

3. New solvent development

3.1. Motivation

KS-1^{TM} is renowned for its great absorption capacity, low steam consumption, and resistance to oxidation compared to conventional solvents. It is a fully proven absorbent that has been demonstrated in over a dozen of commercial plants capturing CO_2 from various sources. When dealing with coal-fired flue gas that contains a variety of impurities, amine consumption and capital expenditures for solvent management inevitably increase. Amine consumption is also a concern for NGCC application as it shows a growing interest in recent years. The consumption from volatile loss and oxidation will increase due to higher flue gas rate relative to the solvent rate and the higher oxygen concentration in the flue gas.

Therefore, recent activity in solvent development has focused on reducing the amine consumptions and improving solvent management. The selection considerations are listed in the following section.

3.2. Selection considerations for solvent management

3.2.1. Thermal stability

Amine can be thermally degraded in the regenerator and reboiler as the solvent is heated up to high temperature for regeneration. Thermal degradation also happens during the reclaiming operation that is typically operated at an even higher temperature than reboiler.

Higher regeneration temperature lowers the reboiler steam requirement as well as elevates the regenerator pressure, reducing the CO_2 compression work. A thermally stable solvent allows higher regeneration temperature without excessively losing amine from thermal degradation.

3.2.2. Oxidative stability

Amine can be oxidized by the oxygen contained in the flue gas and results in accumulation of heat stable salts (HSS), which would reduce the CO_2 capture performance and cause foaming of solvent or corrosion in the plant equipment. The resistance to oxidation is even important to NGCC application that has twice oxygen concentration in the flue gas compared to coal-fired flue gas.

3.2.3. Volatility

The amine volatility determines the amine emissions from the absorber and affects the water wash design. Amine with higher volatility requires additional water wash packing height and circulation water in order to meet the emission regulations.

3.2.4. Cost

Complex synthesis process and pricey raw materials for amine manufacture should be avoided to make amine affordable. The cost of KS-21 solvent is competitive regardless of the above superior features.

3.3. Expected amine consumptions

MHIEng and Kansai EPCO have screened several solvents with the criteria mentioned above and conclude a promising candidate, KS-21. From the preliminary analysis, KS-21 has shown better stability and volatility compared to KS-1^{TM}.

Table 5: Comparison of KS-21 and KS-1^{TM}.

Parameters Relative to conventional	KS-1™	KS-21
Volatility	100	50-60
Thermal degradation rate	100	30-50
Oxidation rate	100	70
Heat of absorption	100	85

Remarks) The above comparison is based on MHIEng's analysis of the results in the pilot plant tests. Please be noted that it does not necessarily indicate the difference in the physical properties of each solvent.

3.4. Preliminary pilot test results

3.4.1. Pilot test unit

A pilot test has been conducted to test KS-21 at the Nanko Pilot Plant of Kansai EPCO in Osaka with CO_2 capacity at 2 metric tonnes/day. A slip stream of flue gas from a natural gas-fired boiler is fed to the pilot plant. The CO_2 concentration is adjustable in a wide range of 4-20% by recycling captured CO_2 or diluting with air. The pilot plant mainly includes flue gas quencher, CO_2 absorber, water wash, regenerator and proprietary process features that commercial plants are equipped with such as the energy-saving system. KS-1™ was tested in the same campaign for comparison at similar conditions.

Table 6: Pilot plant test condition

Location	Osaka, Japan
Flue gas source	Natural-gas fired boiler
CO_2 capacity (tonne/day)	2
Design capture ratio (%)	90
CO_2 concentration testing range (mol%)	4-20

3.4.2. Preliminary results

Figure 4 shows comparison of the gas-phase amine concentration at the water wash outlet between KS-1™ and KS-21 at various operating conditions. The KS-21 clearly has lower volatility than KS-1™ and amine emission is reduced by 50% in average. It can be expected that in commercial design the water wash section can be reduced using KS-21. During the preliminary testing, KS-21 requires higher solvent rate than KS-1™ to achieve 90% CO_2 removal. However, the reboiler duty is almost same or only increases by around 1% in average, suggesting that KS-21 has less heat of absorption or/and needs less heat for water vaporization. The operating conditions will be optimized in the future to reduce the required solvent rate while minimizing the reboiler duty. In the Advanced KM CDR process, the regenerator can be operated at higher pressure than KM CDR process™ using KS-1™ solvent by utilizing high stability of KS-21. This contributes to not only reduction of the size of Regenerator but also the reduction of the power of the CO_2 compressor.

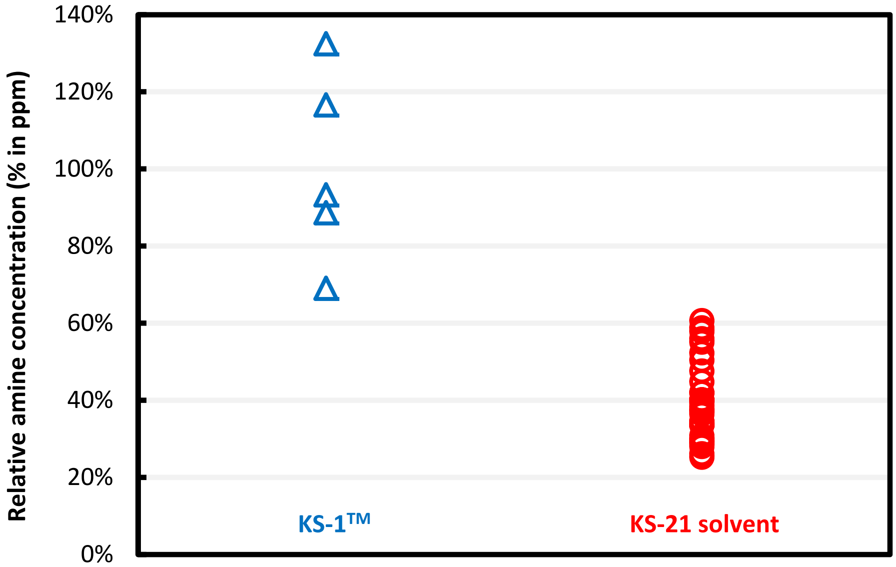

Figure 4: Relative amine concentration at water wash outlet in pilot test.

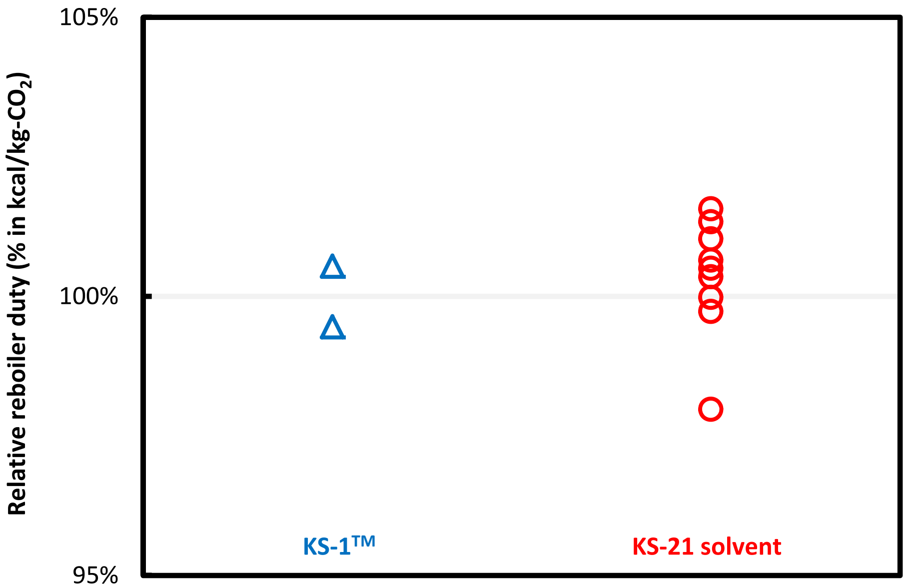

Figure 5: Relative reboiler duty in pilot test

4. Conclusions

- The Advanced KM CDR Process has been developed using updated technology and lessons learned in recent projects.
- The capital cost could be reduced by nearly 30% compared to MHIEng's conventional process while maintaining the same capture efficiency and energy performance based on the study result.
- The reduced size and modular design of the flue gas quencher and CO_2 absorber contribute to the major cost reduction, accounting for 48% of total cost reduction.
- The design redundancy has been reduced reflecting the actual performance in recent projects.
- Modular design has been applied to minimize the footprint and the construction cost.
- A new solvent, KS-21 has been developed and provides higher stability and lower volatility.
- The preliminary pilot plant test showed that the new solvent has 50% lower amine emission than KS-1™ while giving comparable energy performance.
- The Advanced KM CDR Process using KS-21 with attractive properties facilitating solvent management is expected to be offered in early 2019.

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