

# OPTIMUM DESIGN OF TURBO EXPANDER PROCESS

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## ABSTRACT

This paper presents a new methodology called “Constrained Maximum Recovery” (C-MAR)\*, to determine the optimum design of turbo-expander C<sub>2</sub> recovery processes. This approach utilizes a set of curves developed to benchmark C<sub>2</sub> recovery applications based on the popular GSP process and external propane refrigeration (-35°C). Utilizing the C-MAR curves one can quickly determine the optimum design and estimate the performance and cost of various C<sub>2</sub> recovery opportunities without performing time-consuming simulations. Moreover, they allow one to compare alternative process configurations to the GSP performance.

\* C-MAR is successor to the SIMAR methodology presented last year.<sup>(3)</sup>

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## INTRODUCTION

Since its acceptance by the industry in the 1970s, the expander-based process has become the mainstay technology in ethane recovery applications [1]. Despite the great technical and commercial success, a systematic methodology leading to the optimum design system remained missing until recently. Typically a new process engineer would spend several years in mastering this art. This steep learning curve is frustrating and would not help the spreading of this art to general engineers.

Recently, a methodology called SIMAR, which stands for System Intrinsic Maximum Recovery, has been published [2, 3]. These works and subsequent follow-up works [4, 5] presented a systematic approach in search of the optimum design for a given feed stream. Although SIMAR greatly facilitates the design procedures by reducing a two-dimensional (2-D) search to one-dimensional (1-D), its reference case is a hypothetical scenario, in which infinite amounts of refrigeration are available to the system. In many real cases, the refrigeration supply is limited and costly. Therefore, it would be necessary to go to sub-SIMAR operations and additional steps would be required.

This paper presents a new approach to eliminate the aforementioned shortcomings of SIMAR. The new method is called C-MAR, which stands for Constrained Maximum Recovery. C-MAR redefines the reference case by adopting the GSP, a well-known industrial design [6], as the benchmark case and by incorporating a fixed refrigeration temperature of  $-35\text{ }^{\circ}\text{C}$ , the practical lower bound of propane refrigeration circuits. Since this new reference case is a realistic industrial design, its results are more readily available for industrial applications, for example, cost estimates.

This paper will first present some technical background required for the development of C-MAR. After detailed descriptions of its development, its usefulness and applications are demonstrated in real cases using the process called Enhanced NGL Recovery Process (ENRP) [7, 8, and 9] or stripping gas refrigeration process and the Lean Reflux Process (LRP) [10].

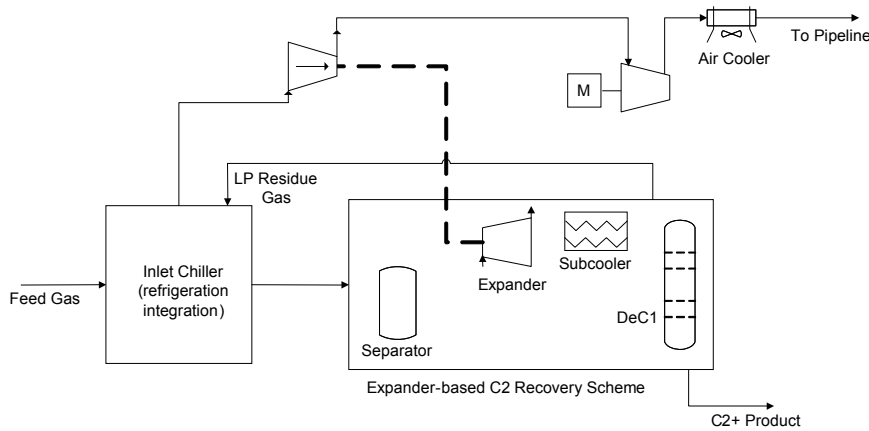
## TECHNICAL BACKGROUND

The background is presented in three subsections here. The first one gives a general categorization of expander-based C<sub>2</sub> recovery processes. The second subsection gives a brief description of SIMAR methodology. The illustration uses liquefied natural gas (LNG) as feed. Since LNG contains abundant refrigeration, the SIMAR reference case can be approximated well. The third subsection describes the impact by replacing LNG with regular natural gas.

### **C<sub>2</sub> Recovery Processes**

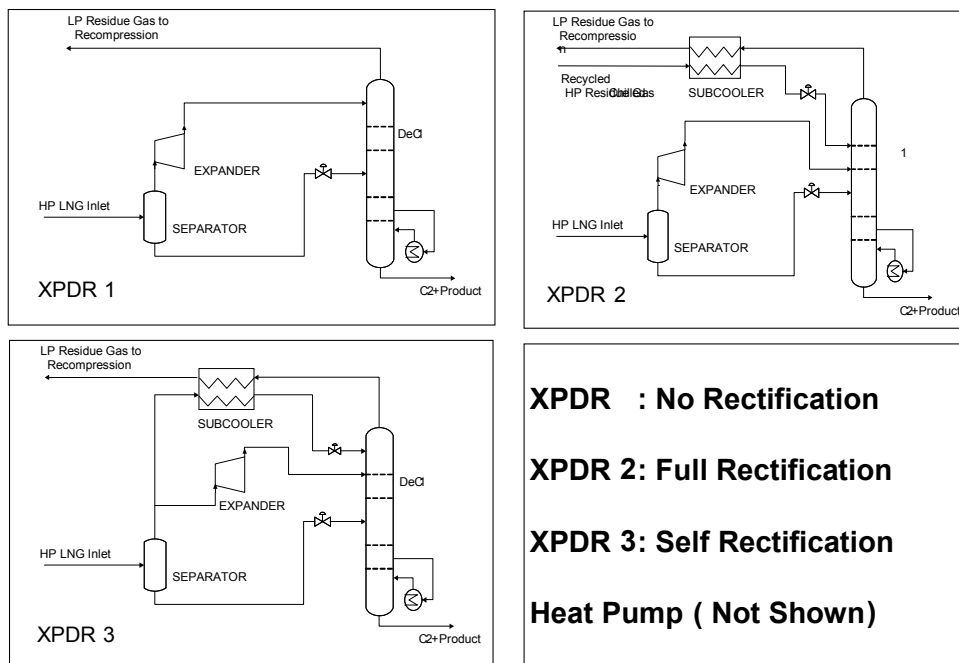
Figure 1 shows a generalized scheme for C<sub>2</sub> recovery based on expander-technology. The process is intended to strip the inlet natural gas (NG) of its heavier components. The residue gas is recompressed and returned to the pipeline. Sweet, dry NG inlet goes through an inlet chilling section, where the gas is chilled to a suitable level before entering the heart of the plant: an expander-based C<sub>2</sub> recovery scheme. The refrigeration of the inlet chilling section is mainly provided by the returning residue gas and supplemented by side-draws from the demethanizer (DeC1, side-draws not shown). Depending on actual requirements, external refrigeration may be required (not shown).

The main components of the expander section include a separator, expander, and DeC1. A subcooler is usually provided for improved refrigeration integration in the low temperature regions. The exact design of this section is an art.



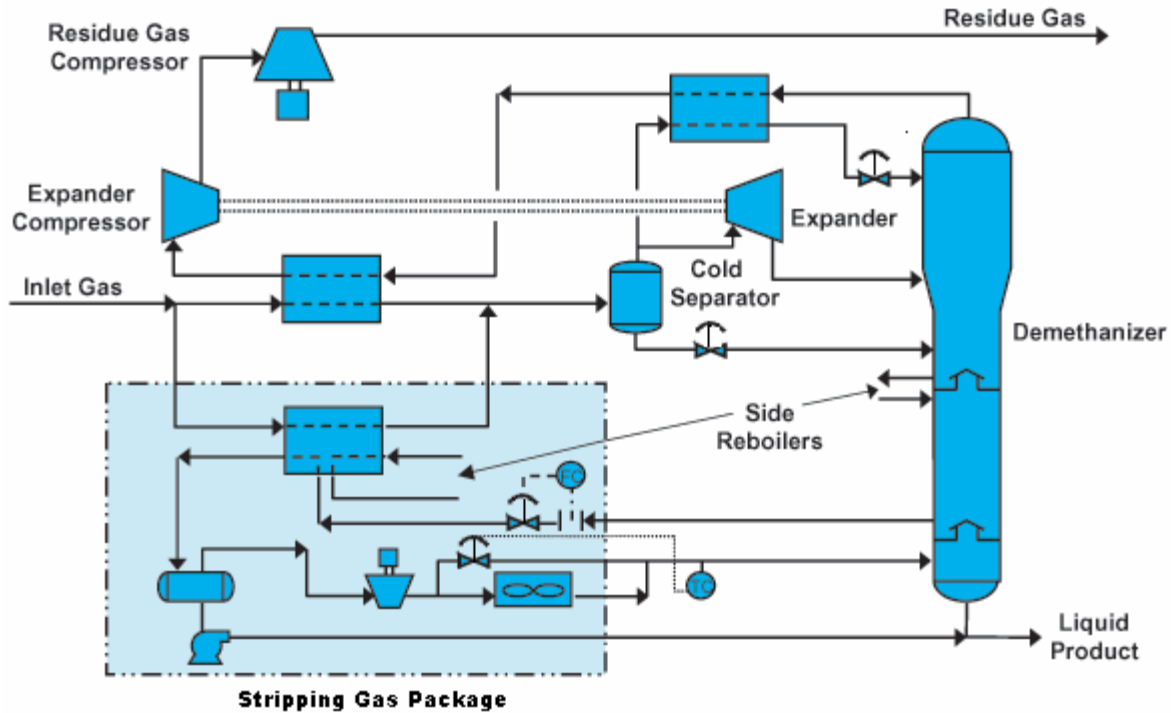
**Figure 1 Generalized gas processing scheme for C2 recovery**

Figure 2 provides further details of the expander section. Following previous works, the expander schemes are grouped into three types: separator top not rectified (XPDR 1), separator top fully rectified (XPDR 2), and separator top self-rectified (XPDR 3). A fourth category of heat pumps is not shown but will be elaborated shortly. The XPDR 3 is the well-known GSP (gas sub-cooled process) in the industry, which uses a small portion of the non-condensed vapor as the top reflux to the demethanizer, after substantial condensation and sub-cooling. The main portion, typically in a range of 65-70%, is subjected to turbo expansion as usual.



**Figure 2 Categorizing expander-based schemes**

Configurations with heat pumps must be discussed separately because: (1) a heat pump can be an enhancement to any of the aforementioned three categories, and (2) a heat pump moves heat from low to high temperature and changes the temperature distribution in its base configuration. Its working principle is different from the three categories. A heat pump design can be recognized by the use of a compressor, a cooler for rejecting heat to a high-temperature sink, a Joule-Thompson (JT) valve or a second expander and, optionally, a second exchanger to take heat from the low-temperature source. Figure 3 uses the ENRP process as an example.



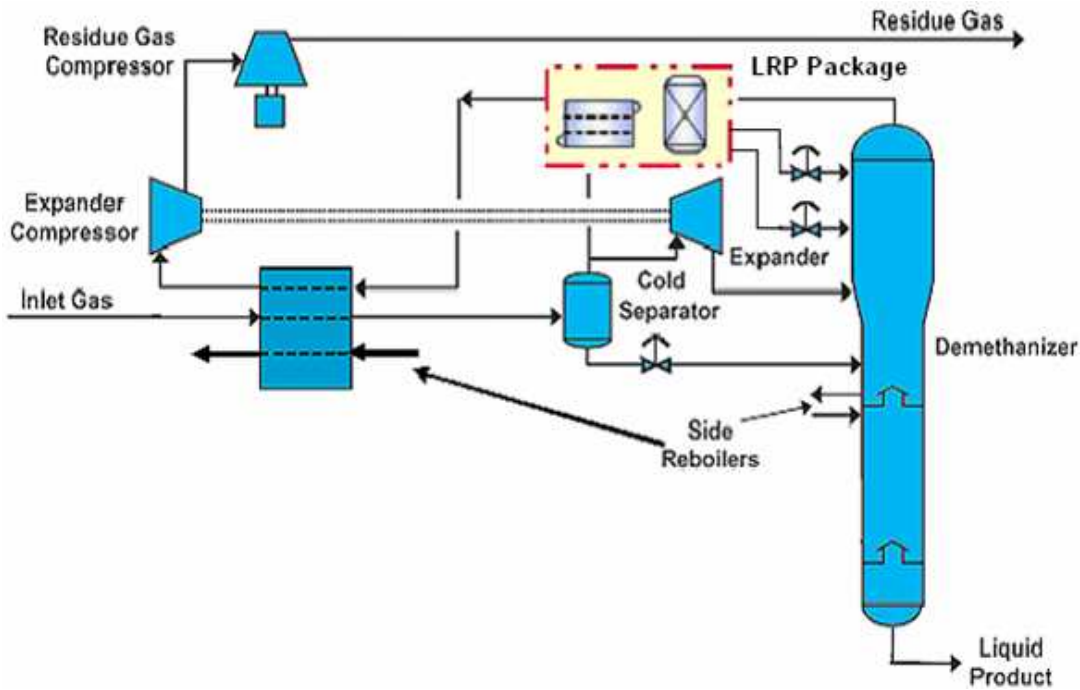
**Figure 3 Enhanced NGL Recovery Process (ENRP)**

In the Figure 3 configuration, a side draw liquid stream from the bottom of the demethanizer is expanded to generate refrigeration. This stream is then heated by indirect heat exchange with inlet gas to generate a two-phase stream. The two-phase stream is flashed in a separator. The flashed vapor is compressed and recycled to the demethanizer as a stripping gas. The flashed liquid stream can be mixed with other NGL product streams or returned to the column. This heat pump effectively moves heat from the inlet stream to the bottom of column.

The main features of this novel design are: (1) stripping gas enhancing relative volatility ratios and NGL recovery levels, and (2) stripping gas lowering column temperature profile and making heat integration easier.

Lean reflux process (LRP), which belongs to XPDR3, was developed to achieve high recovery levels of ethane in a natural gas feed without the addition of substantial amounts of recompression and/or external refrigeration power. This process utilizes a slipstream from the cold separator or feed gas to generate an essentially ethane-free stream as a lean reflux to the demethanizer. The introduction of a lean reflux considerably reduces equilibrium loss, thereby leading to high ethane recovery while maintaining the demethanizer at a relatively high operating pressure. The process overcomes deficiencies in the commonly-used gas subcooled reflux process in which ethane recovery levels are

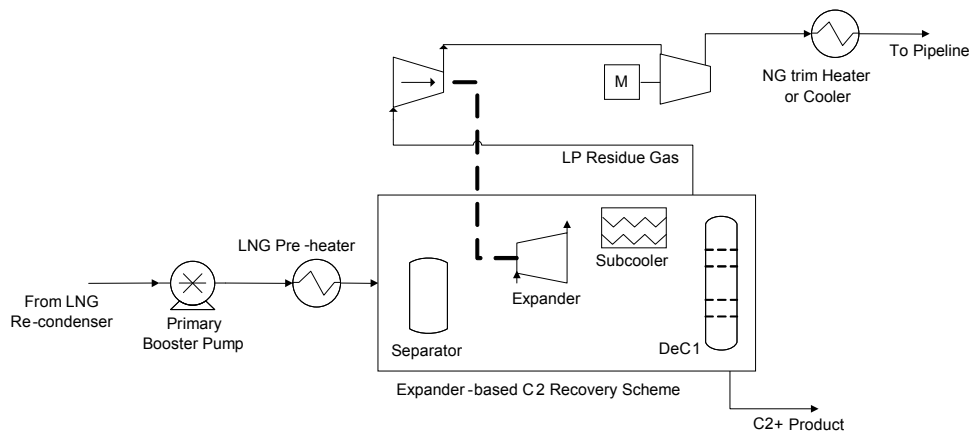
ultimately restricted to approximately 90 percent due to equilibrium loss, or otherwise demand a lower demethanizer pressure and a higher recompression and/or refrigeration HP.



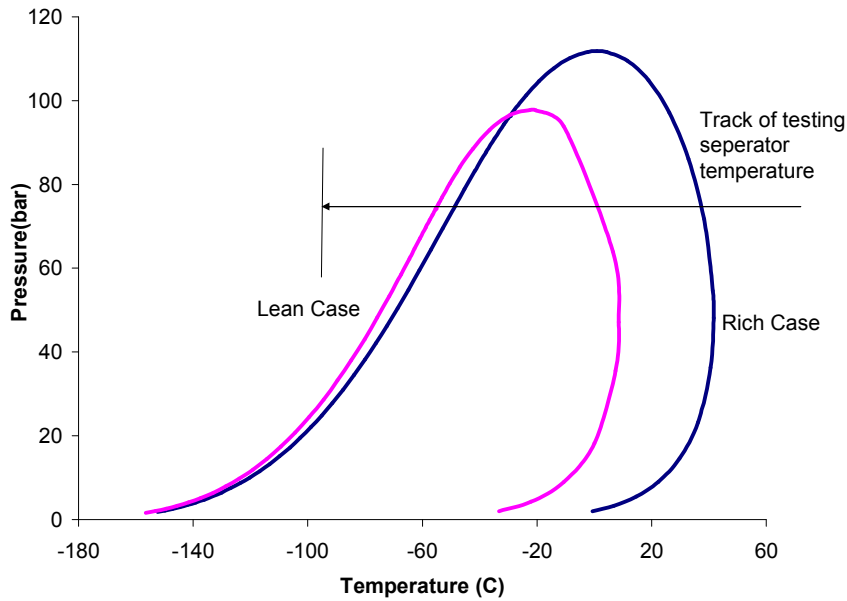
**Figure 4 Lean Reflux process (LRP)**

### SIMAR Methodology

For the sake of easy visualization, Figure 5 presents the scenario when the natural gas feed in Figure 1 is replaced by LNG. The major difference resulted from this change is the inlet pre-chilling section. When LNG is used as the feed, the entire pre-chiller can be eliminated. The refrigeration in the residue gas can be retained, thus dramatically reducing the recompression power.

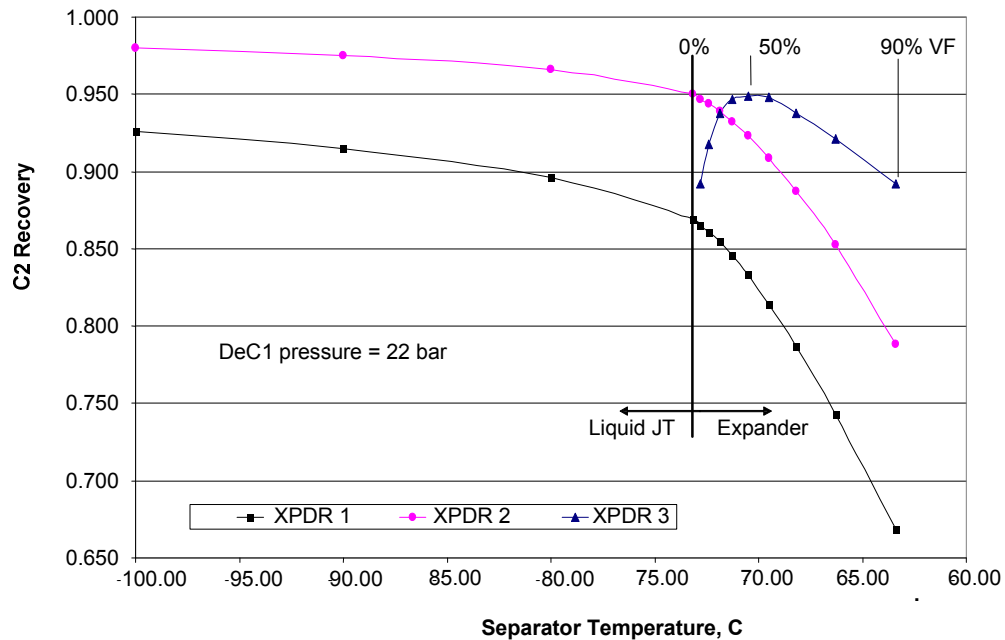


**Figure 5 Generalized processing scheme for C2 recovery with LNG as feed**



**Figure 6 Phase envelope of inlet gas**

SIMAR curve can be constructed following a few simple steps. The procedure starts from a relatively high temperature at a reasonable pressure level, also shown in Figure 6. The track of testing temperatures penetrates through the two phase region and ends at an arbitrarily chosen level of -100°C. The fluid would remain liquid at and below this temperature level. Once the temperature reaches a certain point the column's operating limits will be exceeded and the column will no longer converge.



**Figure 7 Two types of behavior for different categories, VF stands for Vapor Fraction**

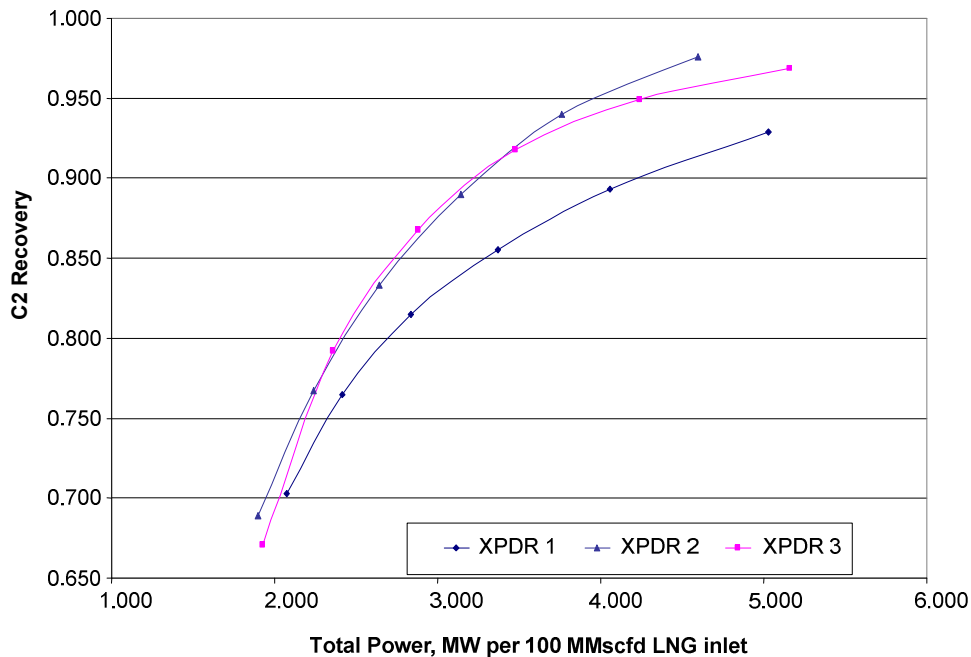
Figure 7 plots the C2 recovery level against the test separator temperature for the three categories of process configurations. The DeC1 operating pressure is 22 bars. Both XPDR 1 and XPDR 2 show monotonic trends of improvement as the temperature decreases. This trend continues even after the inlet gas is totally liquefied, when the expander is replaced by a Joule-Thompson (JT) valve and no expansion work is recovered. XPDR 3 shows a different trend though. As the separator temperature decreases, the C2 recovery goes through a maximum point. In other words, too much refrigeration at the separator may hurt the C2 recovery.

For XPDR 3, the SIMAR is defined as the maximum of the curve. For XPDR 1 and XPDR 2, the SIMAR is defined at the temperature level where the separator fluid has 30% vapor fraction (VF). The choice of 30% is based on a practical consideration that no expanders would be installed if the gas flow is below this level.

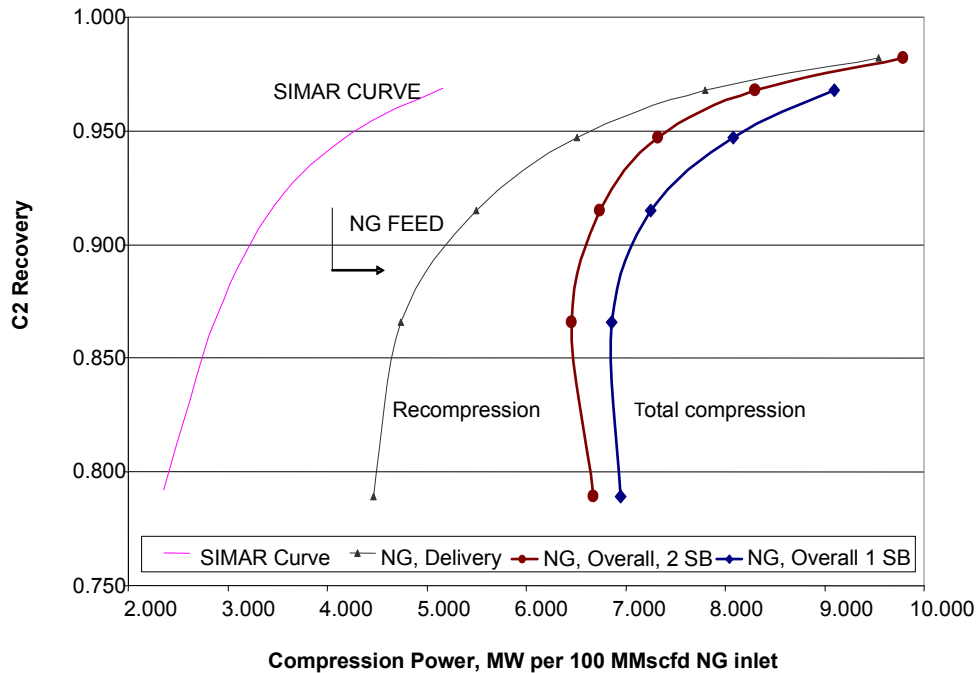
A SIMAR curve is the collection of all the SIMAR conditions which cover the entire range of DeC1 operations of interest. Figure 8 depicts typical SIMAR curves corresponding to the aforementioned three categories. The characteristics of the three categories are observed. (1) The reflux stream makes XPDR 2 more efficient than XPDR 1 throughout the entire range, which corresponds to the operating pressures of DeC1 from 17 to 42 bars. (2) The efficiencies of XPDR 2 and XPDR 3 are comparable, while each has its advantages over a certain span.

### SIMAR Methodology with Natural Gas as Feed

Figure 9 shows typical results when the feed is shifted from LNG to NG. The results were based on the XPDR 3 category. Since the refrigeration in the residue gas must be recovered to cool the inlet gas, the recompression power increases significantly by this shift in feed. As indicated by the two thin curves on the left, there is a big gap between them.



**Figure 8 Comparing SIMAR curves for three XPDR categories**



**Figure 9 Comparing compression duties and impact of side-reboilers (SB) based on XPDR3**

In addition to the recovered refrigeration in the residue gas, external refrigeration may also be needed. When this is true, the compression power required in the external refrigeration power should be added to the aforementioned recompression power to form the total compression power. The two thick curves on the right represent the recompression duties by using one or two side-reboilers (SB). The gap between the curves of total compression and the recompression curves on the left in Figure 9 represents the external refrigeration. Using two SB reduces the external refrigeration because of improved refrigeration integration in the pre-chilling section.

The gap narrows when the DeC1 operating pressure decreases. This indicates the decreased demands for external refrigeration. Also observed in Figure 8 is that when the DeC1 operating pressure decreases, or C2 recovery level increases, the need for external refrigeration also decreases. The expander provides more refrigeration for process needs at lower DeC1 operating pressures.

## STUDY BASIS

Table 1 lists two gas compositions used in this work, lean case and rich case. They represent different richness in C2+ components. The richness of a gas sample is reflected in its C2+ or C3+ components, which are indicated in gallons per thousand SCF (GPM). The GPM value for rich case is 5.71 and that for lean case is 2.87. The phase envelopes corresponding to the two compositions are shown in Figure 6. The richer the gas, the wider its envelope becomes. The raw gas supply is 300 MMSCFD (Dry basis).

**Table 1 – Feed gas compositions**

Components	Rich Case (mole %)	Lean Case (mole %)
Nitrogen	0.315	0.750
CO <sub>2</sub>	0.020	0.217
Methane	79.550	88.910
Ethane	10.600	4.950
Propane	5.470	3.090
i-Butane	0.926	0.442
n-Butane	1.690	0.894
i-Pentane	0.468	0.224
n-Pentane	0.478	0.221
n-Hexane	0.295	0.300
n-Heptane	0.132	0.000
n-Octane	0.060	0.000
n-Nonane	0.020	0.000
GPM for C2+	5.710	2.870

All simulations in this work are performed using HYSYS 3.2. Table 2 lists pertinent parameters. The delivery pressure to pipeline is equal to the inlet pressure. Two temperature levels of heat sinks are defined. The high-temperature (HT) sink represents air coolers. The low temperature (LT) level represents the external refrigeration temperature supplied by two-stage propane compressor loops.

**Table 2 - Simulation parameters used in this work**

	Unit	Value
Inlet temperature	C	27
Inlet pressure	Bar	69 or 55
Send-out residual gas temperature	C	38
Send-out residual gas pressure	Bar	69 or 55
Number of trays in DeC1 column		16
DeC1 operating pressure	Bar	17 to 37
Composition ratio of methane to ethane in DeC1 Bottom product		0.015
High-temperature sink	C	38
Low-temperature sink	C	-35

## APPROACHES

C-MAR methodology includes two major elements:

1. XPDR 3 process configuration as the benchmark model. This process is the GSP process which is well-known in the industry.

## 2. Fixed refrigeration temperature of $-35^{\circ}\text{C}$ .

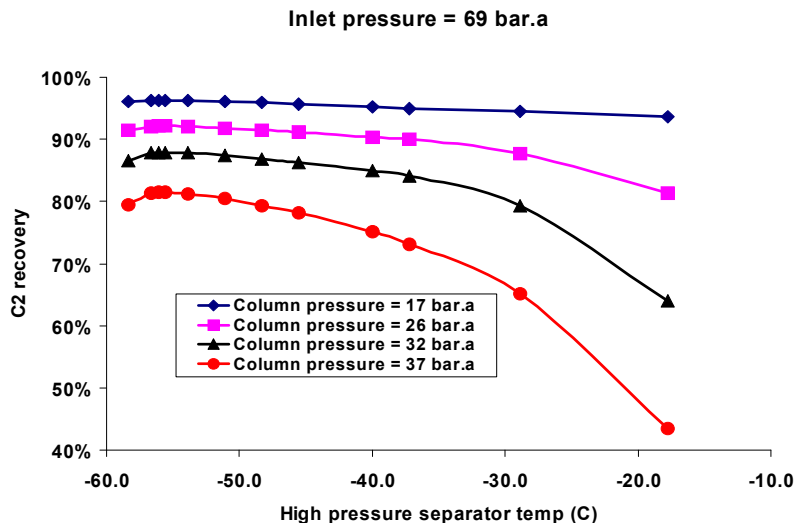
For purposes of conceptual discussions, the pre-chiller is simulated using one integrated exchanger, which handles all streams including inlet gas, returning residue, side-reboiler(s), and external refrigeration. Only the minimum amount of refrigeration is added to satisfy the refrigeration balances. The intention is to minimize the additional compression work. Unless specified otherwise, two side-reboilers in an integrated exchanger will be assumed. External refrigeration implies closed-loop designs of propane circuits.

## RESULTS

Results are presented in the following two subsections. The first one presents the results of C-MAR Methodology. The characteristics of resultant curves and their relations to SIMAR are discussed. The second subsection shows the comparisons of C-MAR predictions with ENRP and LRP.

### C-MAR Methodology

Figure 10 shows the C2 recovery vs. separator temperature for the lean case. As the separator temperature decreases, the C2 recovery shows a maximum at about  $-57^{\circ}\text{C}$  for all curves. This pattern bears similarities to the XPDR 3 curve in Figure 7, indicating the existence of the maximum behavior for the GSP configuration under different constraints, e.g. DeC1 pressure and refrigeration availability. Physically, separator temperatures that are too cold result in C1 condensation. The DeC1 reboiler would input extra heat to prevent excessive C1 loss from the bottom. The net result is the increased C2 loss in the residue gas. To calculate the power requirement for the external refrigeration, we assume the external refrigeration is from two-stage propane compressor circuits with evaporator temperature at  $-41^{\circ}\text{C}$  and refrigerant condensing temperature at  $49.5^{\circ}\text{C}$ . From GPA data book [10], the value for the power can be obtained.

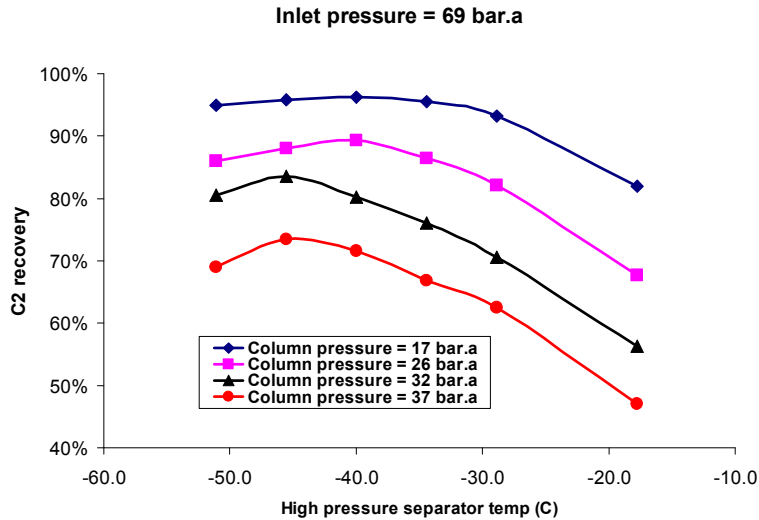


**Figure 10 Determining maximum C2 recovery using C-MAR methodology (Lean Case)**

It should be noted that the maximum C2 recovery using C-MAR occurs at a higher temperature ( $-57^{\circ}\text{C}$ ) than that of SIMAR (about  $-70^{\circ}\text{C}$ ). Using C-MAR, the constraint in refrigeration prevents the

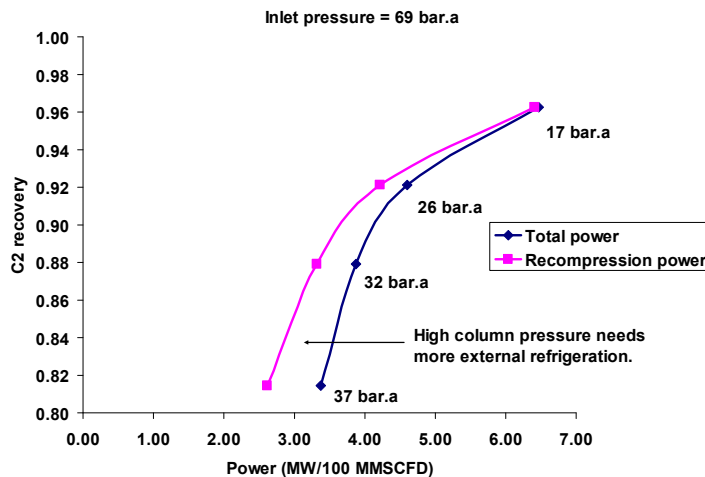
separator temperature from further decreasing. Using SIMAR, the constraint is imposed last by forcing the selection into the sub-SIMAR region. Either approach would lead to similar results.

Figure 11 shows similar trends as described above for the rich case. With the separator temperature further decreasing below some point, the C2 recovery decreases due to methane condensation.

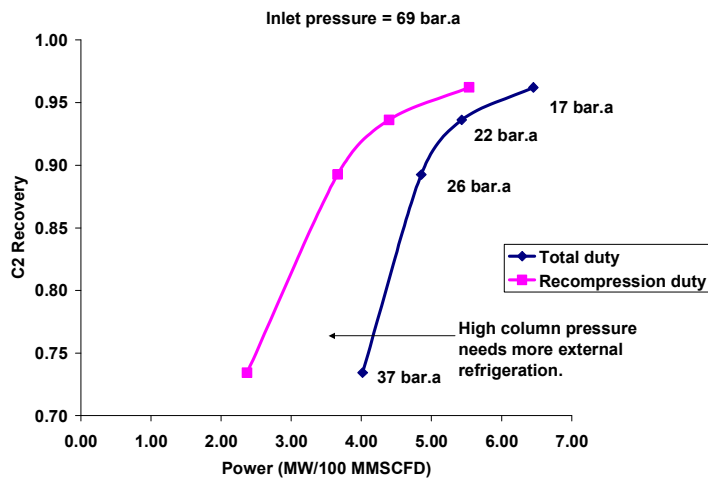


**Figure 11 Determining maximum C2 recovery using C-MAR methodology (Rich Case)**

Figures 12 & 13 show operation curves determined by C-MAR methodologies for lean and rich cases. As anticipated, the trends are similar to those shown in Figure 9 of SIMAR. The gap between recompression and total power represents the external refrigeration. As anticipated, the rich case demands more refrigeration duties than the lean case at the same inlet pressure. And with the decrease of demethanizer column (DeC1) pressure, C2 recovery increases and less external refrigeration is needed because the relative volatility is larger at lower column pressure.



**Figure 12 Operation curves by C-MAR methodology (Lean case)**

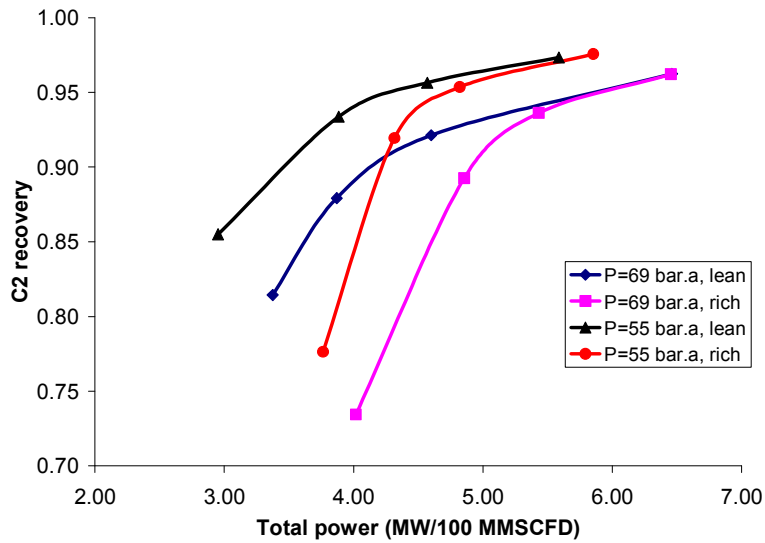


**Figure 13 Operation curves by C-MAR methodology (Rich case)**

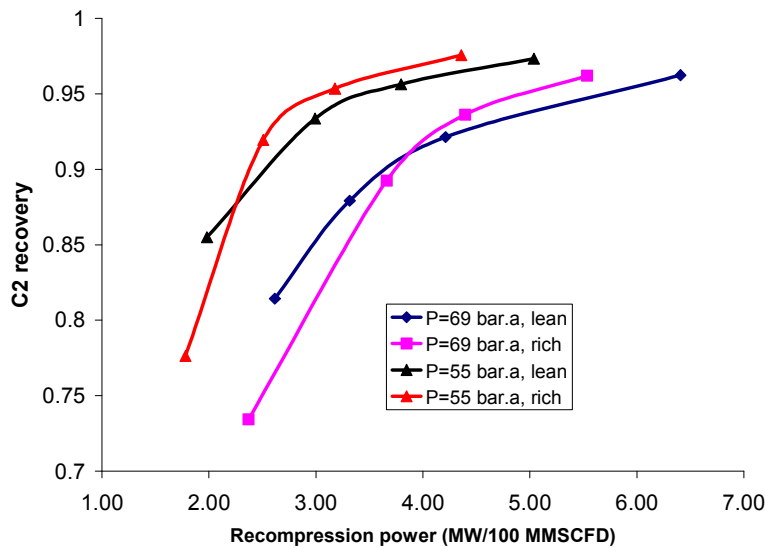
Figures 14 & 15 show C-MAR curves at two different inlet pressure levels and two different inlet gas GPM. Figure 14 is for total power and Figure 15 is for the recompression power only. In Figure 14, rich feed gas needs more total power than lean feed gas because more external refrigeration is needed to condense heavy components in rich feed in DeC1 into the liquid product. But the total power of lean and rich feed gas will meet together or lean case can be even over rich case at high C2 recovery. The reason is that more recompression power is needed for lean feed gas to get compression of the larger residual gas flow. From Figure 15, for both 69 bar.a and 55 bar.a inlet pressure cases, rich feed gas needs more recompression power at low C2 recovery level than lean feed gas. But at high C2 recovery level, lean feed gas needs more recompression power than rich feed gas. At low C2 recovery level or high DeC1 pressure, to get the same C2 recovery, rich feed gas needs lower DeC1 pressure to get higher relative volatility which leads to higher recompression power requirement. But at high C2 recovery or low DeC1 pressure, either lean or rich feed gas has high relative volatility while lean feed gas needs to get larger flow rate for the same C2 recovery. This explains the larger recompression power requirement by lean case at high C2 recovery. It is easy to understand high pressure feed gas (69 bar.a) needs more recompression power than low pressure feed gas (55 bar.a) because we assume the inlet pressure is the same as delivery pressure. As mentioned before, the external refrigeration requirement can be deduced from the curves in Figures 14 & 15 because it is just the difference between the total power and the recompression power.

Examining the regularities between the rich and lean cases in Figure 14 leads to an important conclusion. At a given feed gas pressure and a given richness of inlet gas (e.g. GPM), it is possible to develop general correlations to interpolate required duties for different feed gases. Since the curves in Figure 14 represent the maximum C2 recoveries achievable by GSP with realistic refrigeration supplies, the interpolated results provide expedient estimations in feasibility investigations.

Additionally, since GSP practically has become a benchmark configuration in this field, the curves in Figures 14 acquired by C-MAR methodology can be used to evaluate different process configurations. The following subsection provides an illustration using ENRP process and Lean reflux process as examples.



**Figure 14 Impact of inlet pressure and richness of feed gas on C-MAR curves (Total power)**

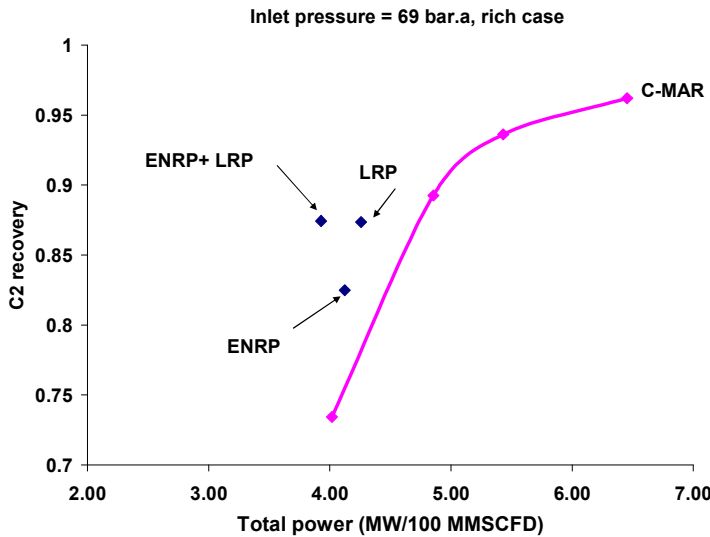


**Figure 15 Impact of inlet pressure and richness of feed gas on C-MAR curves (Recompression power)**

### Applications of C-MAR

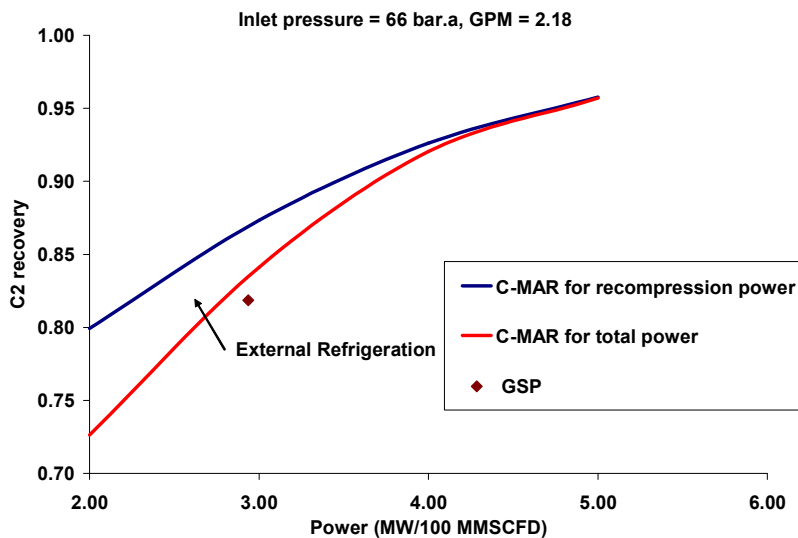
Figure 16 shows the comparison of ENRP and LRP with C-MAR curve. Either of the two processes or the combination of them can achieve higher C2 recovery at lower power than C-MAR curve or the highest potential recovery by GSP process. Improvement can be expected from the two processes. Obviously, ENRP process can spend less power to get higher C2 recovery than GSP

process. The lean reflux process (LRP) can achieve high C2 recovery with less power than GSP process. The combination of ENRP and LRP is better because it can achieve high C2 recovery with less power.



**Figure 16 Comparing Lean reflux and ENRP with C-MAR**

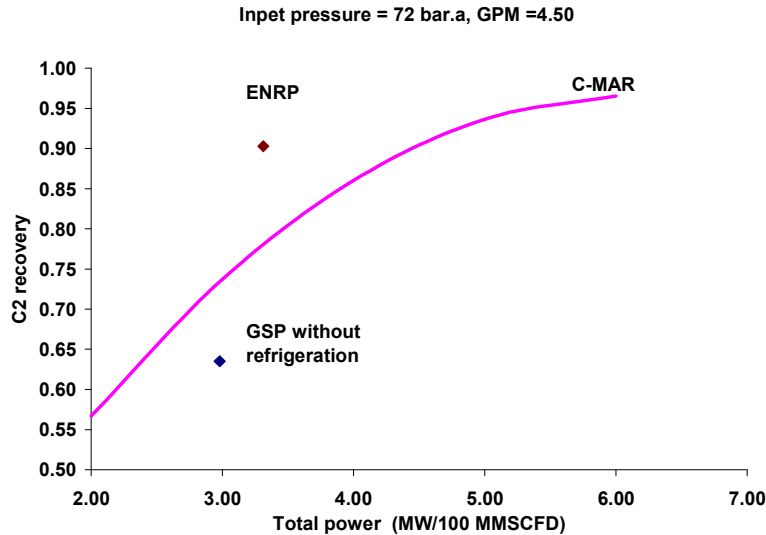
Figure 17 shows the comparison of C-MAR curve with recovery and power for a real NGL plant which uses GSP process. The point of real plant GSP falls on the right side of C-MAR curve. This shows the design of this plant didn't achieve the highest potential C2 recovery. The reason is that in real design the external refrigeration for this plant is limited to  $-30^{\circ}\text{C}$ .



**Figure 17 C-MAR with Pascagoula GSP**

Also from Figure 17, we can find the application of C-MAR in project scoping. If there is a new project with given inlet pressure and feed gas composition, the new C-MAR curve can be obtained by interpolation or extrapolation from existing C-MAR curves. C-MAR curves represent the highest potential C2 recovery at different power by GSP process. If the power is limited to a certain

value, the maximum C2 recovery can be found. And if the C2 recovery is given, the total power and the recompression power can be obtained. The refrigeration power is just the difference between them. Then we can get the turbine-compressor size accordingly. Further, the budget for the new NGL plant can be estimated. By comparing different C2 recovery and power requirement along the C-MAR curve, the optimum design shall be found.



**Figure 18 C-MAR with Neptune II**

Another example shown in Figure 18 is the Neptune II NGL plant which uses ENRP process in design. For comparison, the point for GSP without refrigeration process is also marked up. The point of ENRP process is on the left side of C-MAR curve. It shows there is improvement from ENRP over GSP. GSP without refrigeration is some distance away from C-MAR curve on the right side for the C2 recovery is limited because no external refrigeration is supplied.

## CONCLUSIONS

The conclusions of this work are summarized as follows:

1. Based on the GSP process, C-MAR represents a methodology in determining the maximum C2+ recovery at a given compression power.
2. The results of two inlet gas pressures and two levels of gas richness are presented. The data can be used for project scoping without rigorous simulations.
3. The results can be used to analyze the benefits of new processes.
4. Used separately or in combinations with, the Stripping Gas refrigeration process (ENRP) and Lean Reflux process (LRP) improve system performance.

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