To develop a minimum cost revamp of a fluid catalytic cracking (FCC) unit requires a detailed and rigorous analysis analysing alternate flow schemes and changes in operation to overcome existing equipment limitations by taking advantage of under-utilised equipment. A common mistake is assuming a revamp project can be broken down into evaluating individual pieces of equipment or circuits to develop the modifications necessary in meeting revamp objectives without considering solutions to the limitations from a ‘big picture’ perspective. While this would determine the equipment that is limiting in meeting the design objectives it does not provide the process evaluation necessary to develop the minimum cost modifications. It leads to replacing the limiting equipment with larger equipment instead of employing other under-utilised equipment to circumvent equipment limitations, or modifying other lower cost equipment to overcome the high cost equipment limitation.

The lead process engineer must not only have a very good understanding of the process but also of the equipment. The lead process engineer needs to be able to see the big picture. Knowing the interaction of the process with good knowledge of the individual pieces of equipment enables one to develop changes to the process flow configuration or implement changes to lower cost equipment to debottleneck other high capital cost equipment. This approach to revamp design is required to develop a process design solu-

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**Selective modifications for FCC unit revamps can deliver the best return on investment**

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**Figure 1** Base pressure profile at 33 500 b/d fresh feed
tion that provides the best return on investment (ROI). Examples provided illustrate how this methodology is implemented in the revamping of FCC units.

**Air blower through wet gas compressor**

The regenerator air blower and the main fractionator overhead wet gas compressor are linked as shown in Figure 1. In comparison to designing a new unit, understanding the ultimate limitations and operation of the integrated equipment is more important in the revamp of an existing unit. To minimise investment, existing equipment performance must be pushed to maximum realistic capacities. To determine maximum realistic capacities requires that the existing equipment performance be thoroughly understood.

The reactor, regenerator, and main fractionator vessels, as well as the air blower and wet gas compressor, are major cost items to replace. A revamp design based on replacing any of these items will be expensive and will often prove not financially viable. Understanding how to change the unit operation and selectively modify existing equipment, instead of replacement, yields a minimum cost revamp.

**Example 1**

The first example considers the revamp of an FCC unit to expand the capacity from 33 500 b/d to 40 000 b/d (5.33 m³/h to 6.36 m³/h) and increase the conversion from 78.5 vol% to 81.8 vol%. The regenerator operating pressure currently limits the charge rate to the FCC unit. The regenerator’s maximum allowable working pressure is 30 psig (2.07 bar). The critical operating limit is set at 90% of the PRV set point, which is 27 psig (1.86 bar). Operations must reduce the charge rate when the regenerator pressure reaches this pressure. The current operating pressure profile is shown in Figure 1.

The current and revamp design reactor yields are shown in Table 1. It should be noted that the dry gas yields are increasing from 2.25 wt% to 2.71 wt% in addition to the 19.4% increase in unit throughput; this has a significant effect on the wet gas compressor load. The wet gas compressor is already driver limited.

Prorating the system pressure drop based on the increase in throughput determines a system pressure drop increase from 4.9 psi to 7.0 psi (0.34 bar to 0.48 bar) between the reactor and the wet gas compressor suction. This yields a corresponding regenerator operating pressure that exceeds the critical operating pressure of the regenerator. This operation is not feasible without replacing the regenerator vessel.

Major equipment constraints at current throughput and conversion include:

- The operating pressure of the regenerator is at the vessel’s critical operating pressure limit.
- The wet gas compressor motor is at current limitation.

Replacing the regenerator vessel is not economically feasible and requires a solution that involves modifications to other equipment to resolve the problem with the regenerator’s critical pressure limitation. The solution requires either lowering the system pressure drop between the regenerator and the wet gas compressor inlet, lowering the compressor suction pressure, or some combination of the two.

**Wet gas compressor**

Two-stage centrifugal machines...
are normally selected for wet gas compressors. However, there are older FCC units with reciprocating wet gas compressors still in use. These reciprocating wet gas compressors are less reliable. The characteristics of a centrifugal compressor are determined by the impeller, diffuser, and return channel (see Figure 2). A typical centrifugal compressor designed for FCC wet gas compressor service is designed with backward-leaning bladed impellers due to its higher overall stage efficiency. The designer can select a tip width and blade angle that best fits the desired head and efficiency for the application.

The general shape of the performance curves, as a function of compressor speed, for a centrifugal wet gas compressor is shown in Figure 3. Parameters such as diffusor width, blade angle, gas density, compressor speed, and Mach number play a role in the development of the compressor’s characteristic curve shape. For a typical backward-leaning bladed impeller, as the flow decreases at constant speed, the gas velocity relative to the blade decreases. This makes the tangential velocity increase, which increases the head output. This head increase with decreasing flow is what causes the basic slope of the performance curve. For a given compressor speed, as the flow rate is increased at some point the increase in flow rate results in an excessive decrease in head, which is known as stone-wall or choke. This occurs because the Mach number is approaching 1.0. This is why the right hand side of the performance curve rapidly drops off. As the compressor flow rate is decreased at a given speed there is a point where the head decreases with a decrease in flow. At this point of peak head surge flow occurs. Surge flow should be avoided because it can be damaging to a compressor. Flow reversal occurs, resulting in reverse bending of nearly all compressor components.

For this revamp case it is desired to decrease the compressor suction pressure while achieving an increase in throughput. A centrifugal compressor develops a certain head for any given inlet flow rate. The operation of the compressor can be changed to provide a lower suction pressure. However, for a given inlet volumetric flow rate the compressor will produce a head according to its polytropic head performance curve. For this revamp case the polytropic head is:

\[ H_{poly} = (Z)(1545/MW)(T_1)\left[(P_2/P_1)^{(n-1)/n}-1\right] \]  

and the equation for inlet volumetric flow rate is:

\[ ICFM = (M) \left[ (Z)(1545)/(MW)\left(T_1\right) \right] \]  

where:
- ICFM = inlet air capacity
- Z = compressibility factor
- MW = molecular weight
- T = inlet temperature
- n = polytropic exponent
- P = inlet pressure
- P = outlet pressure
- M = mass flow rate

For a given reactor yield, as the wet gas compressor suction pressure is reduced more material is not condensed by the main fractionator overhead condensers, leading to an increase in the mass rate to the compressor; the MW increases slightly; and the inlet temperature in this case essentially remains the same, with all of this dependent on the operation and design of the overhead condenser exchangers. Normally, as the inlet pressure is reduced, the overriding factor in the change of the compressor’s inlet capacity is from the change in inlet

![Figure 3 Typical centrifugal compressor performance curves](image-url)
pressure and mass flow rate. The following discussion is based on the compressor at constant speed. This will show how a small change in the inlet pressure to a compressor has a large influence on operation even when only considering the effect of the pressure change; considering the increase in mass further compounds this problem.

From the equation above, if the inlet pressure is reduced from 32.6 psia to 30.6 psia (2.25 bar to 2.11 bar) the compressor’s inlet capacity will increase by 6.5% based on the pressure change alone. As the compressor moves out on its curve it produces a lower polytropic head. And as can be shown from the equation for polytropic head, the discharge pressure must decrease to achieve this volumetric capacity and suction pressure. Assume the compressor operating at 32.6 psia (2.25 bar) suction pressure has a discharge pressure of 234.7 psia (16.18 bar) with a 7.2 compression ratio. Without going through the detailed calculations, if the suction pressure is changed from 32.6 psia to 30.6 psia (2.25 bar to 2.11 bar) and we assume the compression ratio is the same then the discharge pressure will decrease from 234.7 psia to 220.3 psia (16.18 bar to 15.19 bar), which is a reduction of 14.4 psi (0.99 bar). In reality, the change in suction pressure is more significant on the lowering of the discharge pressure than shown in this simple approximation. In addition, this does not include the effect of increasing the FCC unit’s feed rate and conversion. More important is an understanding of the influence in lowering the wet gas compressor suction pressure on the overall unit performance. Changing the operation of the compressor must consider the dynamics with the vapour recovery unit (VRU). The VRU operating pressure has a significant effect on the recovery of C3 molecules from the fuel gas. Operating at a lower compressor suction pressure results in a lower achievable discharge pressure, which has a significant influence on C3 recovery. As a rough estimate, propylene recovery in the VRU increases by about 0.9 mole% for every 10 psi (0.69 bar) increase in operating pressure with all other factors constant. This loss in propylene recovery is usually deemed unacceptable. Thus, lowering compressor suction pressure at the expense of propylene recovery is not a partial solution to fix the regenerator’s critical pressure limitation.

The existing packed main fractionator already has low pressure drop (see Figure 1) and there is no practical advantage in modifying the main fractionator to reduce pressure drop. The overhead exchangers also have low pressure drop and there are no practical exchanger modifications that can be made to overcome the regenerator pressure limitation while meeting the capacity of the future operating case. The existing compressor, a two stage design with inter-stage condenser system and knock-out drum, is already limited at the current operation. A new stand-alone compressor or a new parallel compressor could be installed to provide an adequate regenerator pressure at the future operating loads, but this is an expensive solution with a poor ROI.

A rerate of an existing compressor can provide a means to meet the new operating conditions at significantly less cost since much of the existing equipment can be reused. A rerate does have limitations since the casing size and bearing span are fixed. The rerate feasibility must consider capacity, horsepower, pressure, and speed limitations limited by the portion of the equipment being reused. As shown in Table 2, the inlet flow rate to the compressor at the current operation is 8664 acfm (245.3 actual m³/min) and the design value for the rerate is 12,100 acfm (342.6 actual m³/min), which is an increase of 39.7%. This loading includes adding additional surface area to the main fractionator overhead condensers, which includes converting an adjacent fin fan bay to main fractionator condenser service and relocating...
ing the existing exchanger, which was not sensitive to system hydraulics. The additional surface area at the higher duty requirements of the future operation maintains a low overhead system pressure drop (see Figure 4). Without these modifications the existing compressor frame size is inadequate. The addition of the main fractionator condenser surface area maintains low system pressure loss and outlet temperature, which enables reuse of the existing compressor frame with some margin.

Rerating the compressor to operate at higher speed is useful when a greater compressor compression ratio is desired to either increase the discharge pressure or to operate at a lower suction pressure. A change in compressor speed will provide an increase in head determined by the following equation:

$$H_{\text{rate}} = (H_{\text{original}})(N_{\text{rate}}/N_{\text{original}})^2$$  \hspace{1cm} (3)

Centrifugal compressors run at high revolutions per minute, and as a result speed is a serious consideration. The higher speed must not cause high stress on the impellers. Also, the critical speeds of the rotor must be avoided. A critical speed occurs when the rotor speed corresponds to a resonant frequency of the rotor-bearing support system. The critical speeds are somewhat fixed by the bearing span and shaft diameter, however new bearings and other factors may provide extra margin to a critical speed. The rotor must be stable at the higher operating speed. Vibration excursions can lead to serious damage of the compressor or result in poor compressor efficiency due to damaging of interstage seals and balance piston damage. The rerate must verify that the new speed will provide a satisfactory mechanical tip speed as well as an adequate differential between the new higher operating speed and the compressor’s critical speed.

Increasing the compressor speed also provides a capacity increase as determined from the fan laws:

$$Q_{\text{rate}} = (Q_{\text{original}})(N_{\text{rate}}/N_{\text{original}})$$  \hspace{1cm} (4)

The higher flow rate can be limited by sonic velocity anywhere in the compressor, however the ultimate compressor capacity is limited by the frame size.

To maintain the VRU operating pressure and provide a lower wet gas compressor suction pressure at the higher throughput, the compressor rerate requires an increase in the compressor speed from 8010 rev/min to 8420 rev/min. The higher mass flow rate and compressor polytropic head requirements requires an increase in the driver horsepower (see Table 3).

Modifying the wet gas compressor and replacing the motor enabled dropping the system pressure. This enabled operation of the regenerator to be within its operable limit and fixed the wet gas compressor limitation while meeting the higher throughput and conversion. The high cost to replace the major equipment that was limiting could not be justified, but understanding the interac-
tion of the equipment in the entire processing unit enables one to selectively determine processing flow configuration changes or equipment to be modified that will produce the lowest cost solution. These relative lower cost modifications to the wet gas compressor provide a good return on investment in meeting the new operating conditions.

**System pressure drop**

Often the regenerator air blower or the main fractionator overhead wet gas compressor limits the capacity and conversion of FCC units. Replacing these machines is expensive. Modifications to these machines may or may not be possible to meet the new operating conditions. It is important to determine if unnecessary pressure loss is occurring between the air blower and the wet gas compressor. Items that could be causing high pressure drop between the air blower and wet gas compressor are:

- Main fractionator designed with trays
- Reactor transfer line undersized
- Main fractionator overhead line undersized
- Insufficient main fractionator overhead exchanger surface area
- Submerged main fractionator overhead exchangers (cooling water exchangers at grade)
- Inadequate design of reactor and regenerator internals.

Most FCC units have already been modified from their original design. In doing so, some equipment has been modified to meet new operating conditions and other equipment has not. This sometimes leads to high pressure drop in areas that were not modified such as the reactor transfer line and the main fractionator overhead line. In addition, technical advances over the years in equipment design have led to improvements in low pressure drop designs. A case in point is that of Example 2.

**Example 2**

The FCC unit of this refinery was capacity limited at 80 000 b/d (530 m³/h) and the refiner wanted to revamp the unit to process 95 000 b/d (629.3 m³/h) of feed. A test run and its subsequent evaluation developed the following major equipment constraints at the higher throughput:

- Throughput exceeds capacity of main fractionator column internals
- New loadings exceed capacity of wet gas compressor.

At the current throughput the wet gas compressor is capacity limited. It is not possible to process additional feed without rectifying this problem. The main fractionator is designed with valve trays throughout the column, except shed deck trays are used in the slurry pumparound zone. The pressure drop across the column was measured at 5.7 psi (0.393 bar). Hydraulic calculations of the column internals showed that the existing column internals were near their capacity limit at the current throughput and would not meet the future operating conditions.

The main fractionator vessel, as well as the wet gas compressor, are major cost items to replace. A revamp design based on replacing any of these items will often prove not financially viable. Selectively modifying existing equipment to overcome its capacity limitation, while at the same time circumventing the capacity limitation of another piece of equipment, is another means of yielding a minimum cost revamp that will yield the best ROI.

The wet gas compressor is capacity limited by the frame size. The only method to increase throughput using the existing compressor system is to make process changes that allow for increasing the mass through the wet gas compressor while maintaining the same or lower volumetric flow rate to the compressor. This can be done by increasing the suction pressure. However, doing this requires an increase in the system pressure back to the regenerator air blower, if no other changes are implemented. The higher regenerator operating pressure must not exceed the regenerator’s maximum allowable working pressure or result in an air blower limitation. In this case the operational change only moves the process throughput limitation to other high cost equipment.

The main fractionator is capacity limited and modifications are necessary to meet the increase in throughput. High capacity trays or packing could meet the design loadings. High capacity trays on an installed basis are cheaper in most cases than revamping the column to a packed design. A packed design does have an advantage in providing a lower pressure drop design, whereas modifying to high capacity trays can
only provide for a minimal reduction in column overall pressure drop.

Trays are designed to produce spray or froth above the tray. Whether the tray is designed using sieves, standard valves, or specialty valves, the basic concept is to use the pressure energy of the incoming vapour fluid converted to velocity energy through the restricted vapour passage of the sieves or valves to promote aggressive interaction between the liquid flowing across the tray and the vapour erupting out of the orifices. The velocity energy of the vapour lifts the liquid off the tray creating a somewhat violent spray from the tray active area. This intimate contacting between the vapour and liquid enables mass transfer to occur between the vapour and liquid phases. How efficient mass transfer occurs is dictated by the trays’ ability to ensure uniform and good exchange of energy between the heavier and lighter molecules in the vapour and liquid phases such that a temperature gradient is established across consecutive trays. It is important to note that trays require pressure drop to perform properly. Designing the trays with excessive open area to reduce the pressure drop will lead to poor vapour/liquid contacting, resulting in poor product separation. The type of orifice has an influence on the pressure drop, as do other features such as the weir height, but they provide minimal benefit in pressure drop reduction.

A packed column design can provide for a more significant improvement in column pressure drop. Refiners’ past experience has shown that experienced engineers are needed to provide successful revamping of the main fractionator with packing. Efficiency of structured packing in FCC main fractionators is very good if properly designed. Packing type is selected based on the service, capacity, efficiency, and pressure drop requirements. Packing has a very high open area compared to the orifice active area found with a tray’s active area. This provides for low pressure drop. The packing capacity is determined by the packings’ geometry, including the minimum open area at any given horizontal plane in the packed bed. If we consider a common high efficiency structured packing with a 1 inch (25.4 mm) crimp height, a 45 degree crimp angle, and using lancing surface treatment, the packing surface area is about 35 ft²/ft³. The capacity of this packing is about 60% greater than a standard tray on 24 inch (610 mm) tray spacing. The fractionating efficiency is roughly 15% greater on a per foot basis of column vertical height than a tray design. However, vertical column height is consumed by items such as distributors and collectors needed for a packed tower design.

Modifying this FCC unit main fractionator to a packed tower design provides the benefit of meeting the capacity and efficiency requirements and also provides for lower pressure drop. As Figure 5 shows, the column pressure drop at current operation is 5.7 psi (0.393 bar). Figure 6 shows the pressure profile with a packed tower design. The packed tower column pressure drop is 1.4 psi.
Modification of the column to a packed column design will provide a reduction in pressure drop of 4.3 psi (0.296 bar) at the higher throughput, which can be utilised to overcome the wet gas compressor limitation.

The wet gas compressor system uses two parallel compressors each with two stages that use a common intercooler exchanger and knockout drum. At the current operation the compressor system is limited to a volume capacity of 19,262 acfm (545.4 actual m$^3$/min) to the first stage at an overall compressor polytropic head for both stages of 49,732 ft (15,158 m). The increase in compressor inlet pressure from the reduction in main fractionator pressure drop increases the compressor suction pressure to 31.3 psia (2.16 bar abs.) while maintaining essentially the same regenerator pressure. The higher pressure increases the vapour density to the compressor, which enables a higher mass flow rate through the compressor while maintaining the same inlet volumetric flow rate, as shown in Table 4. This enables an increase in the mass flow rate to the compressor of 18.4% without requiring compressor modifications. The increase in mass flow rate increases the compressor horsepower requirements but is partially offset by the reduction in head (see Table 5).

Modifying the main fractionator column internals from trays to packing fixed the hydraulic limitation of the tower internals for the higher throughput. In addition, the packed tower’s low pressure drop has a significant benefit for the wet gas compressor. The higher compressor suction pressure enabled reuse of the existing wet gas compressor without any modifications. This provides a significant capital cost reduction, improving the revamp’s return on investment. A number of FCC units that were limited in capacity and/or conversion due to the limits of the wet gas compressor or air blower have

### Table 4

<table>
<thead>
<tr>
<th></th>
<th>Base 80 000 b/d charge</th>
<th>Rerate 95 000 b/d charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined WGC inlet flow, acfm</td>
<td>19,262</td>
<td>19,232</td>
</tr>
<tr>
<td>Combined WGC inlet flow, lb/hr</td>
<td>236,856</td>
<td>280,500</td>
</tr>
<tr>
<td>Inlet pressure, psia</td>
<td>26.6</td>
<td>31.3</td>
</tr>
<tr>
<td>Discharge pressure, psia</td>
<td>237.7</td>
<td>237.7</td>
</tr>
</tbody>
</table>

**Table 5**

<table>
<thead>
<tr>
<th></th>
<th>Base 80 000 b/d charge</th>
<th>Rerate 95 000 b/d charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polytropic head, ft-lbf/lbm</td>
<td>49,732</td>
<td>46,079</td>
</tr>
<tr>
<td>Compressor #1 speed, rev/min</td>
<td>8700</td>
<td>8700</td>
</tr>
<tr>
<td>Compressor #1 driver, HP</td>
<td>4477</td>
<td>4974</td>
</tr>
<tr>
<td>Polytropic Head, ft-lbf/lbm</td>
<td>49,791</td>
<td>46,131</td>
</tr>
<tr>
<td>Compressor #2 speed, rpm</td>
<td>10,100</td>
<td>10,100</td>
</tr>
<tr>
<td>Compressor #2 driver, HP</td>
<td>3114</td>
<td>3455</td>
</tr>
</tbody>
</table>

Polytropic head is the combined head of the 1st and 2nd stages.

![Figure 6 FCC unit pressure profile at 95 000 b/d fresh feed after modifying main fractionator internals](image)

(0.097 bar). Modification of the column to a packed column design will provide a reduction in pressure drop of 4.3 psi (0.296 bar) at the higher throughput, which can be utilised to overcome the wet gas compressor limitation.
used packing the main fractionator as a means to provide a minimum cost solution to meet the higher capacity and conversion.

**Conclusion**
Developing solutions to limitations from a big picture perspective is necessary to develop minimum cost modifications. Replacement of capacity limiting equipment with larger equipment instead of employing other under-utilised equipment leads to expensive revamps with poor ROI. Knowing the interaction of the process with good knowledge of the design and operation of individual pieces of equipment enables one to develop changes to the process flow configuration or implement changes to lower cost equipment to debottleneck other high capital cost equipment. Reducing capital investment required for a revamp by modifying lower cost equipment to circumvent limitations in higher cost equipment should not just consider the major equipment cost items noted. This methodology in revamp design should be exercised throughout the process design. The revamp methodology presented is necessary to develop minimum cost modifications that provide the best ROI.

**Reference**

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