Crude unit revamp increases diesel yield

An account of a crude vacuum unit revamp in which detailed calculation of the true performance of existing equipment, plus a realistic calculation of the benefits a revamp would bring, raised diesel production by 14.5 vol% on crude

Tony Barletta *Process Consulting Services Inc.*
Matthew Smith and Catherine Macfarlane *Caltex Refineries NSW*

Captial is scarce in today's low margin, highly competitive refining industry. This is a fact of life. For revamps to be approved they must fit into constrained capital budgets. Revamp costs must match financial objectives. Revamps must be minimum cost. A minimum cost revamp improves existing equipment utilisation and pushes equipment to its ultimate capacity. There is no room for large design tolerances or "design fat".

Although the revamp approval process varies from company to company, most revamps are funded based on cost/benefit analysis. Cost/benefit methodologies vary and are not important in this discussion. What is important, however, is that the benefits are estimated accurately, and they are realised.

Under- or over-predicting revamp benefits can lead to undesirable outcomes. Under-predicting revamp benefits, for instance, can result in a revamp that will not be funded from a perceived lack of benefits. This represents a lost business opportunity. On the other hand, over-predicting can result in a revamp that will not meet financial expectations. Figure 1 shows the product yields before the revamp. A large quantity of diesel was lost to atmospheric residue. Atmospheric residue was used as FCC feedstock.

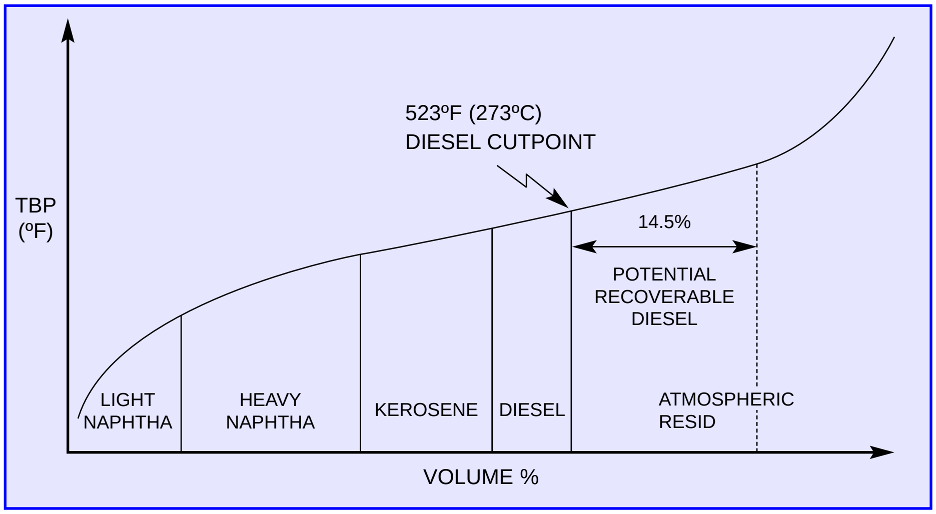

Figure 1 Pre-revamp product yields, crude TBP curve

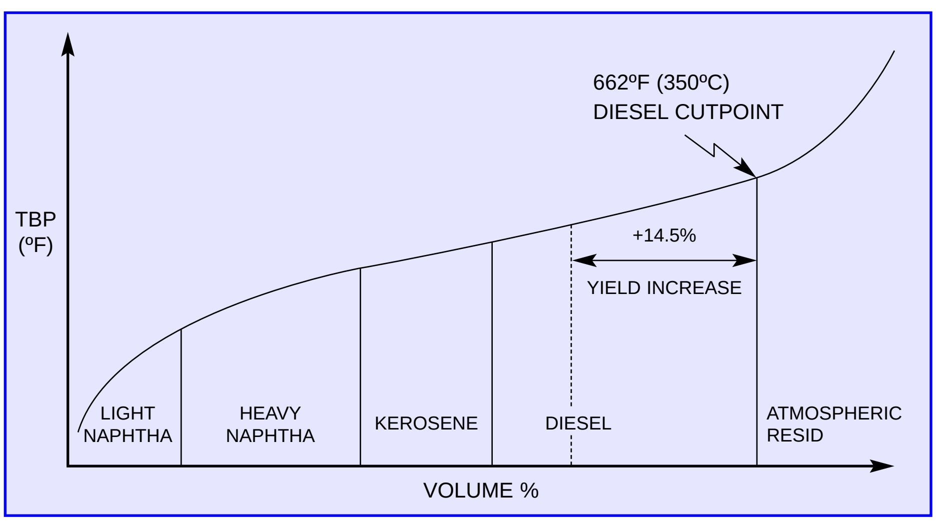

Figure 2 Revamp product yields, crude TBP curve

In this article, we examine a crude vacuum unit revamp to illustrate two important revamp considerations: prediction of revamp benefits and minimising capital expenditure. This crude unit revamp increased diesel production by 14.5 vol% on crude oil (Figure 2). Crude characterisation and diesel cloud point prediction methods enabled accurate estimation of diesel yield. Also, by changing the process flow scheme, crude preheat was increased by 108°F (60°C) and costly fired heater modifications were avoided.

Unit description

The distinguishing characteristic of this crude unit is the requirement to operate in two modes of operation. Conventionally, the vacuum unit is operated in series with the crude unit. In this case, however, the vacuum unit is operated in series *and* in parallel with the crude unit. The crude unit and vacuum unit modes of operation are:

1. Crude oil is processed through the crude unit and atmospheric resid is fed directly to the vacuum unit. This is referred as series operations, and is illus-

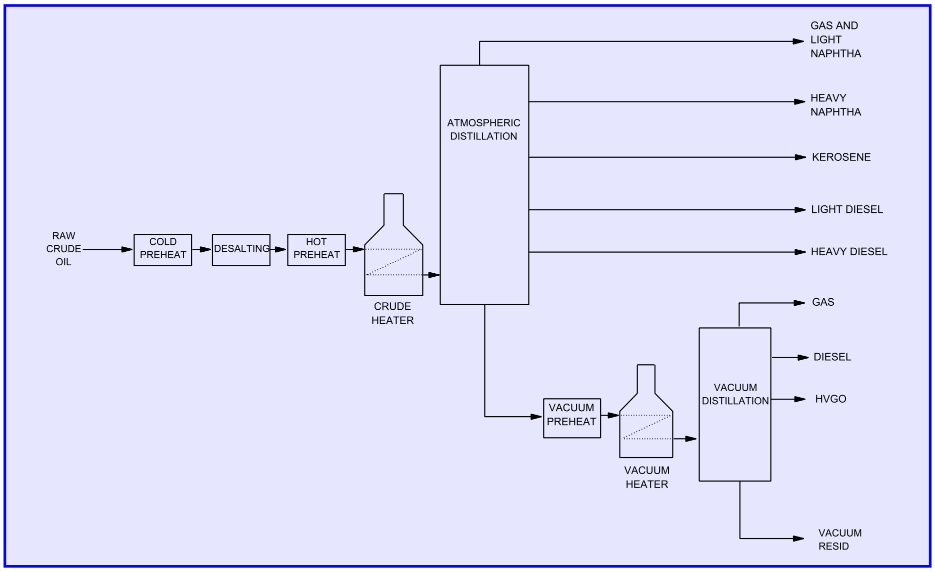

Figure 3 Series operation for processing crude oil

trated in Figure 3.

2. Crude oil is processed in the crude unit and atmospheric resid is routed directly to the FCC unit. The vacuum unit operates independently of the crude unit and processes a special feedstock to produce lube oil refinery feedstock and bitumen. This is referred to as parallel operation (Figure 4).

The crude column has light and heavy diesel side products. The heavy diesel product is the lowest side product. When the unit is operated in parallel mode, atmospheric resid is sent to the FCC unit as feedstock. The unit is operated in the parallel mode 60% of the time.

During parallel operation, diesel boiling range material in the atmospheric resid is lost to FCC unit feed, which results in loss of revenue based on overall refinery economics.

The primary revamp objectives were to increase crude unit diesel yield and keep revamp costs to a minimum. Secondary objectives were to increase crude throughput by 10 percent, process a range of "light and heavy" crudes, and improve energy efficiency. To accomplish these objectives, a performance test was conducted to uncover unit constraints and identify opportunities.

Constraints and opportunities

Revamp design is inherently more difficult than grassroots design. By definition, revamps start with an existing plant, and most of the existing equipment is reused. Therefore, existing equipment performance is critical. If a specific piece of existing equipment is under-performing and goes unnoticed, then a revamp can fail to meet its objectives.

Office-based assumptions about existing equipment performance are often wrong, so it is therefore better to conduct actual performance tests. These make no assumptions and minimise unwanted surprises. Properly executed, performance tests identify unit constraints, unit capabilities, and under-performing equipment.

In terms of an analogy, if a revamp is a house, then a performance test is its foundation. A performance test can make the difference between a failed revamp and a successful one, or a minimum cost revamp and one that wastes capital. To many people, "performance test" implies a single event but, in fact, it involves preparation, execution, and flow sheet modeling.

Preparation is key to a performance test. A significant amount of planning and preparation is required to execute a successful performance test. For example, flow meters must be calibrated, material balance checked, sample schedule prepared, and P&IDs walked out. Only after the necessary preparation is complete can the actual field work take place.

Performance test execution can begin after all necessary preparation is complete. It takes place in the field, not in the control room. Field measurements supplement and confirm process computer data. Temperature and pressure measurements are used to develop a complete temperature and pressure profile of the unit.

Field observations often give clues to problems that may be otherwise difficult to detect, like a cavitating pump or a thermocouple that is located in the wrong place and is supplying misleading information.

Then, rigorous flow sheet modeling establishes a baseline process model. The flow sheet model is adjusted to match performance test data. All pertinent equipment is rigorously modeled. This includes distillation columns, fired heaters, and heat exchangers. Here, actual equipment performance is determined. No assumptions are made. For example, actual heat exchanger fouling factors are calculated, measured exchanger pressure drops are compared to calculated clean pressure drops, and distillation tray efficiencies are determined. The calibrated process model is used as the basis for subsequent revamp simulation.

Successful performance tests identify

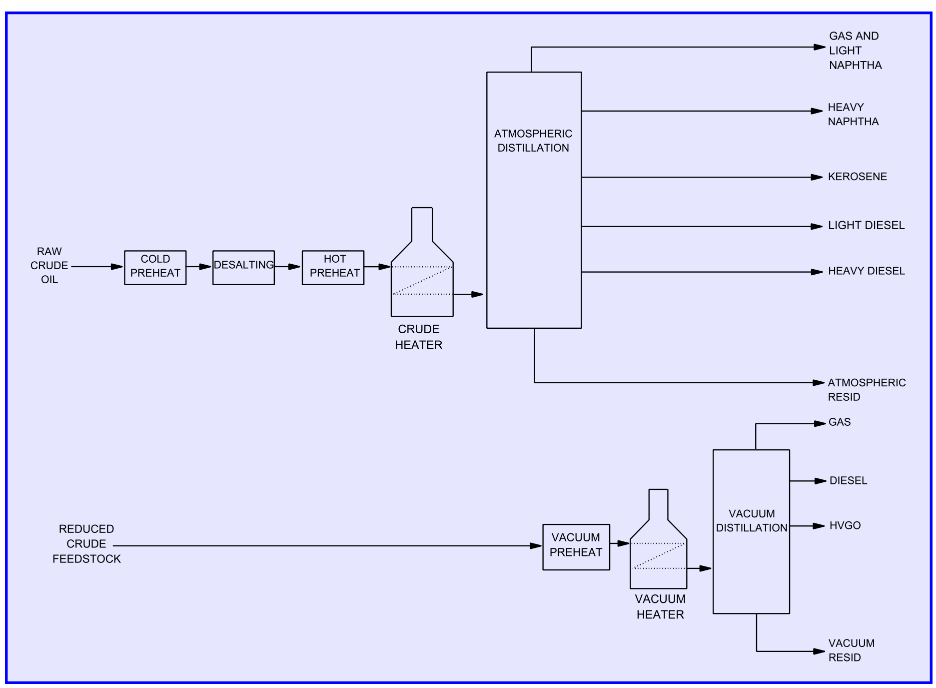

Figure 4 Parallel operation for processing crude oil

unit constraints and opportunities. It is the identification of detailed constraints and potential opportunities that starts the revamp process design in the right direction. Early identification of unit constraints and opportunities leads the way for investigation of low cost methods to circumvent or remove constraints while exploiting any under-utilised equipment.

This crude unit's performance test showed that a significant amount of diesel boiling range material was being sent to the FCC (in the atmospheric resid) during parallel operation. As a result, the diesel product TBP cutpoint was only 523°F (273°C), and the atmospheric resid contained 42 vol% diesel boiling range material.

However, crude column heat input, crude column heat removal, and crude column fractionation limited any increase in diesel production. Determining how much diesel boiling range material could be moved (cost-effectively) from atmospheric resid to diesel product required additional work.

Product yield predicting

Diesel specification

The amount of diesel in a crude blend is a function of crude type. Crude oil contains a certain amount of diesel boiling range material. An accurate crude oil assay, or a crude oil high temperature simulated distillation (HTSD), will show how much diesel boiling range material is present.

The amount of recoverable diesel in a specific crude oil or crude oil blend, however, is not always equal to the amount of diesel boiling range material in the crude oil. Often, the amount of recoverable diesel is less than the amount in the crude oil. Finished product specifications, crude unit equipment design and operation, and refinery distillate blend pool components ultimately determine how much diesel is recoverable.

LP models and other blending programs often set crude unit diesel specification based on finished product specifications and consideration of other refinery diesel pool blend components. Often, cold flow properties limit how much diesel can be recovered from a given crude oil or crude oil blend, not the boiling range specification.

Even though there may be more diesel boiling range material in a specific crude oil or crude oil blend, cold flow properties can limit the amount that can be recovered. In this unit, cloud point specifications limited crude unit diesel production.

Cloud point

Cold flow properties describe a fuel's suitability in low-temperature operation. Cloud point is a cold flow property and is the temperature at which a clear liquid becomes hazy or cloudy due to the formation of wax crystals.

As diesel is chilled below its cloud point, the formation of wax crystals accelerates. This can clog fuel lines and filters, which can lead to stalled engines. Since diesel fuel is used in cold temperatures, cloud point specifications are typically set below the minimum ambient temperature for the area in which it is used.

Summer and winter specifications can vary. The test method for diesel cloud point is ASTM D2500. This is a visual test method. A sample is cooled at a specified rate, and the temperature at which a cloud of wax crystals first appears is the cloud point [ASTM D2500 Standard Test Method for Cloud Point of Petroleum Oils, *Annual Book of ASTM Standards*, American Society for Testing and Materials]. Cloud point is directly related to the hydrocarbon composition and boiling range. For instance, normal paraffins have higher cloud points than molecules with side chains - the more paraffinic the molecule, the higher the cloud point. Diesel cloud points are specific to each crude oil or crude oil blend. When diesel production is limited by cloud point as opposed to boiling range specifications, a process flow sheet model will not accurately predict diesel yield with standard crude oil characterisation methods.

To accurately predict diesel yields, process flow sheet models must include:
- Cloud points for the diesel boiling range pseudo-components.
- Mixing rule constant for pseudo-component cloud point blending.

Crude characterisation

Process flow sheet simulations are important tools that are used to determine revamp product yields and evaluate equipment limits and requirements. For process simulations to be useful revamp tools, crude oils must be characterised properly. Standard crude oil characterisation includes an accurate true boiling point (TBP) curve, gravity data, and light-ends analysis.

This is effective in most cases. However, standard crude characterisation methods alone are not adequate for diesel cloud point prediction. Before cloud point characterisation methods can be reviewed, a basic understanding of how the process flow sheet model uses standard characterisation data is needed.

In any given crude oil, thousands of molecules are present in varying quantities. It is unrealistic to characterise crude oil by each molecule. For standard characterisation methods, process simulations use the crude TBP curve, gravity curve, and lightends analysis to assign pseudo-components that represent many undefined molecules in the crude oil.

Every pseudo-component is represented by a volumetric portion of the crude oil and is characterised by a normal boiling point, gravity, molecular weight, critical temperature and pressure, and acentric factor. These characterisation properties are then used to predict vapour/liquid phase equilibrium in equation of state or generalised correlation models.

When crude unit diesel cloud point prediction is necessary, additional crude characterisation is needed to accurately predict diesel yield for revamp crude blends and modified unit configurations. Most commercial simulation packages contain methods to compute special refinery properties like cloud point. However, for accurate prediction of diesel cloud point, cloud points must be assigned to the diesel boiling range pseudo-components.

When the revamp crude blend is the same as the performance test crude oil blend, the diesel boiling range pseudo-component cloud points can be derived directly from performance test data. If the revamp crude blend is vastly different from the performance test crude blend,

Middle distillate narrow fraction data from ASTM D2892 tests

Narrow fraction				Cloud point, ºF				
No.	IBP, ºF	EP, ºF	Mid-BP, ºF	Light diesel	Heavy diesel	Vacuum diesel	HVGO	Average
1	356	392	374	-75.28				-75.28
2	392	428	410	-45.22	-46.30	-46.12		-45.88
3	428	464	446	-36.40	-37.66	-38.92		-37.66
4	464	500	482	-11.20	-10.30	-16.78		-12.76
5	500	536	518	4.64	-00.04	00.86		1.82
6	536	572	554	25.34	21.20	22.46	16.34	21.34
7	572	608	590	44.60	42.44	43.52	43.88	43.61
8	608	644	626			61.34	61.34	61.34
9	644	680	662				77.00	77.00
10	680	716	698				91.40	91.40
11	716	752	734				109.40	109.40

Table 1 Narrow fraction cloud points

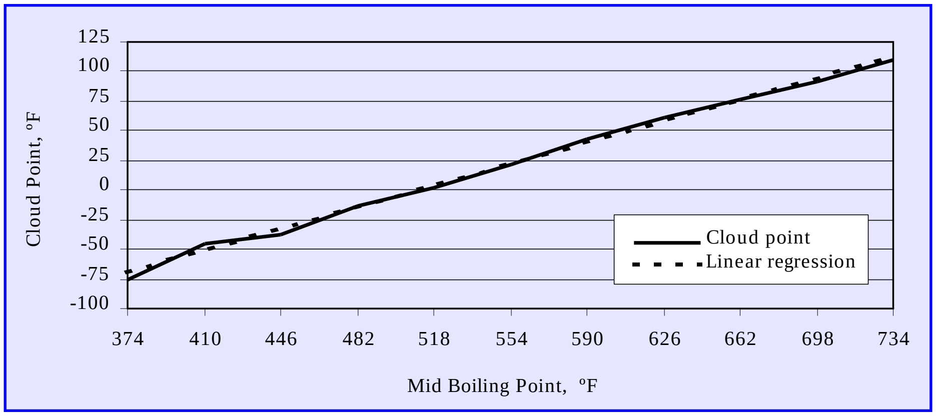

Figure 5 Relationship of cloud-point and mid-boiling point of diesel

then crude samples must be obtained or crude assay cloud point data must be used, when available.

In this revamp, performance test data was used to determine pseudo-component cloud points. Crude unit middle distillate product samples were distilled into 36°F (20°C) fractions with the ASTM D2892 test. ASTM D2892 uses a fractionating column with an efficiency equivalent to approximately 15 theoretical plates operated at a reflux ratio of 5:1.

This method provides a high level of fractionation between narrow fractions. The apparatus permits recovery of the narrow fractions for subsequent cloud point, weight, and density analysis. Table 1 shows middle distillate narrow fraction data obtained from the ASTM D2892 tests.

Since crude column product fractionation is not perfect, some narrow fractions will be present in more than one product. Narrow fraction No. 4, for example, is present in the light, heavy, and vacuum diesel products. Cloud points are averaged for the narrow fractions that are present in more than one sample product. Then, cloud points are plotted versus mid-boiling point for each narrow fraction.

Figure 5 shows that the cloud point increases as the mid-boiling point increases. This is why a crude unit operator will correctly decrease diesel yield if diesel product cloud point is above product specification. This is also why improving crude unit fractionation between the diesel product and the next lowest sidecut can sometimes permit higher diesel yield for a fixed cloud point specification. Better fractionation reduces the “tail” on the end of the diesel product, and this is where the high cloud point molecules exist.

A linear regression of the cloud point versus mid-boiling point curve generates an equation that defines cloud point as a function of mid-boiling point. This equation is used to calculate diesel boiling range pseudo-component cloud points. These cloud points are assigned to diesel boiling range pseudo-components in the process flow sheet model.

The equation for this example is:

$$T_S = (0.5067 \text{ x } T_{Mbp}) - 259.4$$

where:

T_S = pseudo-component cloud point, °F

T_{Mbp} = pseudo-component mid-boiling point, °F

Mixing rule

In the process model, the diesel product is represented by a series of pseudo-components. Each pseudo-component has its own normal boiling point and cloud point. Special mixing rules, which are available in most commercial simulators, calculate cloud point from a blend of pseudo-components. The Hu-Burns mixing method works well. It predicts cloud points of pseudo-component blends by the following equation.

$$(T_b)^{1/x} = \Sigma V_i (T_i)^{1/x}$$

where:

T_b = cloud point of the blend, °R

T_i - cloud point of the pseudo-component i, °R

V_i = volume fraction of component i

x = constant.

For this method to accurately predict the *blend* cloud point, the mixing constant, x, must be determined from performance test data. The optimum value of x is determined by trial and error to fit the performance test narrow fraction data.

Once the process model is “calibrated” with pseudo-component cloud points and a cloud point mixing constant has been determined from plant data, the model can be used to accurately predict diesel cloud point & evaluate the impact of flow scheme changes on diesel yield.

Unit modifications

Crude unit diesel yield is a function of the following variables:

- Crude heater outlet temperature
- Column heat removal
- Residue stripping
- Column fractionation
- Tower pressure.

Some of these variables are related to column fractionation while others are not. When diesel is the lowest crude column side product, improving residue stripping and fractionation between diesel and atmospheric resid will increase diesel production for a fixed heater outlet temperature. In this refinery, two crude column diesel products were no longer required. Therefore, the light and heavy diesel draws were combined into a single diesel product. This permitted better utilisation of the space in the bottom section of the crude column for modifications to the column internals that would improve diesel fractionation. Figure 6 shows these modifications.

The column simulation model showed that improving fractionation in the bottom of the column could increase diesel yield by 2-3 vol% on crude oil. Although these

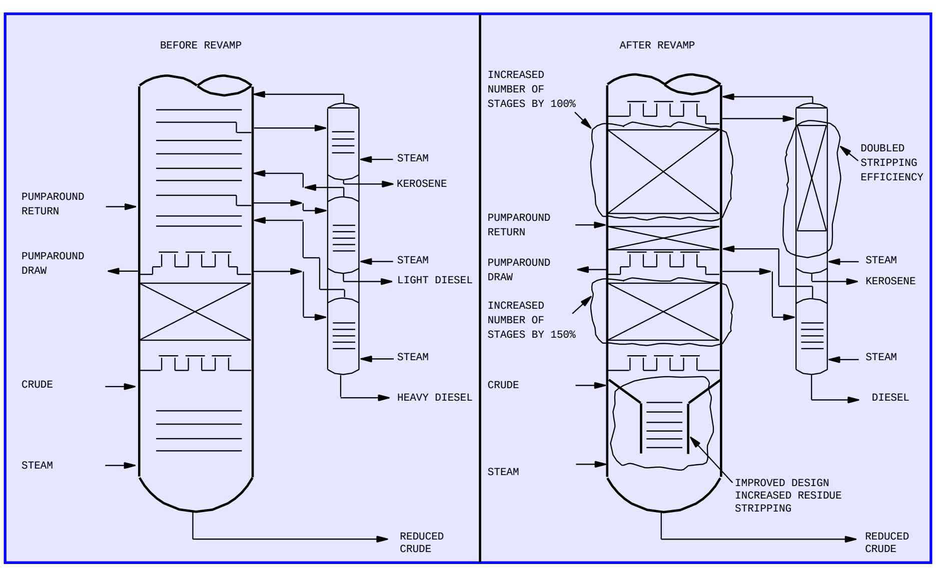

Figure 6 Detail of modifications to the column internals

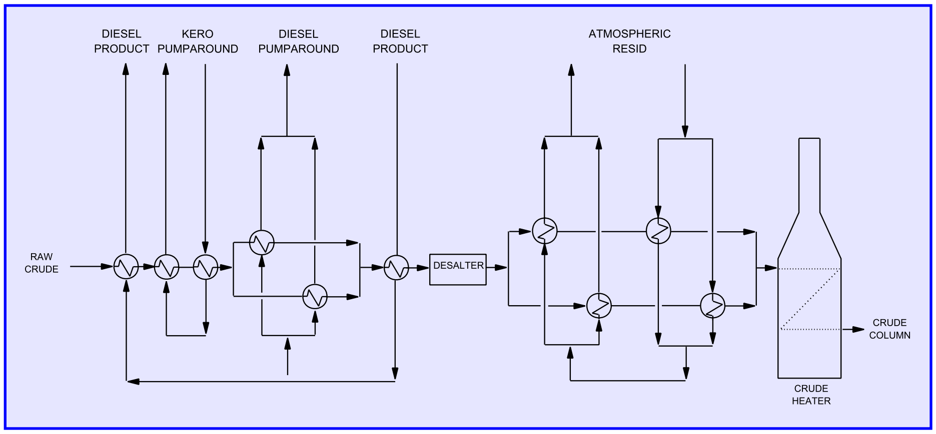

Figure 7 Preheat train configuration before revamp

modifications would increase diesel production, the model showed that a higher heater outlet temperature would be required to maximise diesel production.

The calibrated simulation model showed that the diesel yield could be increased by an additional 11.5-12.5 vol% (on crude feed) if the crude heater outlet temperature was increased by 65°F (36°C). It also indicated that the crude column heat removal requirements (in the overhead and pumparound exchangers) would increase by 39 percent.

Accurate prediction of maximum diesel yield is relatively straight-forward with a properly calibrated performance test model and accurate crude oil characterisation. The process model generates a unit heat and material balance (H&MB) for the revamp design. However, figuring out how to achieve the new H&MB with minimum capital investment is not so easy.

There is no standard crude unit process flow scheme. Every crude unit is different. In this crude unit, the "knobs that needed to be turned" to achieve maximum diesel yield were unit constraints. For instance, the crude heater duty was at maximum capacity, but a higher outlet temperature was needed. Heat removal in the pumparounds and overhead system were limited, and the crude column internals were flooding during the performance test. Crude preheat train hydraulics were limited at the higher throughput.

To increase diesel yield, all of these constraints must be circumvented or removed with new equipment or flow scheme changes.

Minimum cost revamps are more difficult to implement with conventional design methods. The complex interactions among crude unit equipment demands a more practical, hands-on approach. A practical approach that alters the process flow scheme will better utilise existing equipment. This evolves from accurate determination of unit constraints [Martin and Cheatham, Keeping down the cost of revamp investment, *Petroleum Technology Quarterly*, Summer 1999].

All real unit constraints must be understood before the conceptual design stage. This way, all process implications and their associated costs are clearly understood when evaluating unit modifications. Maximising crude column diesel yield almost always requires increasing crude heater outlet temperature, especially when diesel is the lowest side product.

An increase in the crude heater outlet temperature increases feed vaporisation. Higher vaporisation increases the crude heater pressure drop. When crude column feed vaporisation increases, crude column heat removal must also increase. Thus, overhead condensers and pumparounds must remove the incremental heat from the column flash zone vapour.

Increasing the crude heater outlet temperature increases the heat input to the crude oil. There are three ways of increasing crude column heat input.

Option 1. Increase the crude heater capacity (duty).
Option 2. Increase the crude heater and preheat train capacity (increase heater inlet temperature).
Option 3. Increase the preheat train capacity enough to stay within the heater limits.

If the crude heater capacity can be increased easily and with minimum capital, then Option 1 is attractive. It focuses on one piece of equipment and does not involve the complex interactions of the other equipment. However, this is rarely the case. Often, crude column heat removal is also a unit limit. Additional capital must be spent to increase heat removal. Crude column heat can be recovered to crude oil or discarded to air and cooling water.

Adding a pumparound air cooler may be a simple method of increasing crude column heat removal, but it does not improve energy efficiency. Improving preheat train heat recovery, on the other hand, reduces the fired heater duty and reduces heater stack emissions. Ultimately, preheat train improvements can prevent costly modifications to the crude heater while saving energy.

The preheat train configuration, before the revamp, is shown in Figure 7.

The before revamp preheat train limitations and opportunities are summarised below:

Limit: Pumparound heat removal.
Opportunity: Increase pumparound circulation flow rates to increase exchanger LMTD.

Limit: Heavy naphtha and kerosene product rundown cooling.
Opportunity: Heat is discarded to water - cool products with crude oil heat exchange.

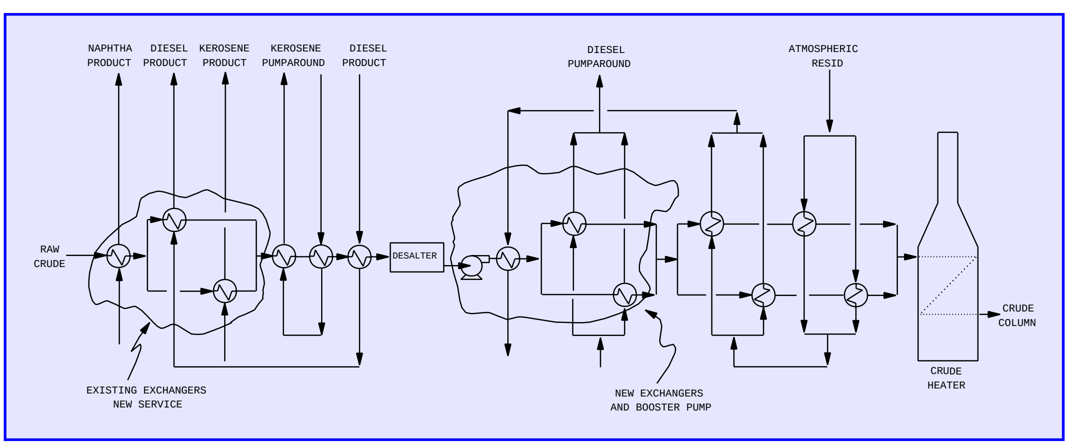

Figure 8 Revamp preheat train configuration

Limit: Preheat train exchanger surface area.

Opportunity: Minimal incremental surface area would result in a significant increase inlet temperature.

Various techniques can be used to increase preheat train recovery. New exchangers can be added to the train, exchanger sizes can be increased, or the order of the exchangers can be changed, to name a few. The techniques that are used must be weighed against the cost effectiveness and ease of construction. A total re-configuration of the preheat train, for example, may achieve the desired objectives, but will require a large number of piping modifications.

A more cost-effective solution may be to buy additional surface area to minimise piping changes. In this example the preheat train performance was improved with minimum cost by balancing the following variables:

- Change exchanger order
- Increase pumparound flow rate
- Change heat exchanger service
- Add surface area.

The revamp preheat train configuration is shown in Figure 8. The new configuration exploits the opportunities and circumvents constraints of the existing preheat train. These modifications increased the crude heater inlet temperature by 108°F (60°C).

The additional preheat was enough to offset the additional heater duty required to increase the outlet temperature by 65°F (36°C). The end result is increased diesel yield at constant crude heater duty. No heater modifications were required. Taking advantage of preheat train opportunities to circumvent constraints reduces capital expenditure.

Crude heater modifications were not required to achieve the desired outlet temperature. However, the additional vaporisation increased the crude heater pressure drop, which hydraulically limited the raw crude charge pumps at the higher unit throughput. Increasing the heater tube sizes would reduce the heater pressure drop, but this would be costly. Instead, a desalted crude booster pump was installed to debottleneck the crude charge hydraulics.

Figure 9 Minimal capital-cost revamp, maximum equipment reuse

Final thoughts

This unit revamp has increased diesel yield by 14.5 vol% on whole crude oil. The increase in diesel yield corresponds to an increase in crude column diesel TBP cutpoint from 523°F to 662°F (273°C-350°C). Actual diesel yield is marginally higher than predicted yield and is limited by cold flow property specifications. Appropriate crude oil characterisation made it possible to accurately predict yields and deliver realistic revamp benefits.

All too often, successful revamps are not minimum cost. Needless funds are wasted to achieve design objectives because existing process flow scheme opportunities are neither identified nor understood. In our example, all revamp objectives were achieved while staying within an assigned capital budget. This was accomplished by understanding unit constraints and opportunities, altering the process flow scheme, and reusing existing equipment. In this case, preheat train modifications circumvented heat input, heat removal, and product cooling limitations.

The net result was an increase in heater inlet temperature of 108°F (60°C). This permitted a 65°F (36°C) increase in crude heater outlet temperature with no net increase in crude heater firing rate. As a result, costly crude heater modifications were not necessary and revamp capital cost was held to a minimum (Figure 9).

Tony Barletta is a chemical engineer with Process Consulting Services, Inc., Houston, Texas, USA. The company provides revamp and field troubleshooting to the refining industry worldwide.

Matthew Smith is a senior process engineer with Caltex Refineries NSW, in Sydney, Australia.

Catherine Macfarlane is a process engineer with Caltex Refineries NSW and is involved in crude oil distillation troubleshooting, optimisation and design.

PROCESS CONSULTING SERVICES, INC.

Process Consulting Services, Inc.
3400 Bissonnet
Suite 130
Houston, Texas 77005
U.S.A.

[1]-(713)-665-7046
[1]-(713)-665-7246
info@revamps.com
www.revamps.com

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