APC in a mild hydrocracker fractionator

Advanced process control of a mild hydrocracker can save millions of dollars annually by maximising kerosene and/or diesel

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Bayernoil Neustadt refinery is built for a high yield of diesel and jet fuel, equipped with a mild hydrocracker (MHC), hydrogen plant, plus sulphur removal and recovery units (see **Figure 1**). Among many units, the ones directly associated with the MHC are:
- Three crude distillation units (CDU)
- Two vacuum distillation units (VDU) taking feed from the CDUs
- An MHC taking feed from the VDUs
- Two fluid catalytic crackers (FCC) taking unconverted oil (UCO) from the MHC.

Figure 2 shows the MHC configuration with reaction and separation sections. Reactor effluent is a wide boiling range material that must be separated into narrow cut products. First, light naphtha is separated out in a stripper. Stripper bottoms are taken into the fractionator, which separates naphtha at the top, kerosene and diesel as side draws, and heavy UCO at the bottom. Naphtha is further separated into light and heavy naphtha. Product values differ significantly and specifications vary by season and type of operation. Kerosene is sometimes produced as jet fuel and at other times blended into diesel.

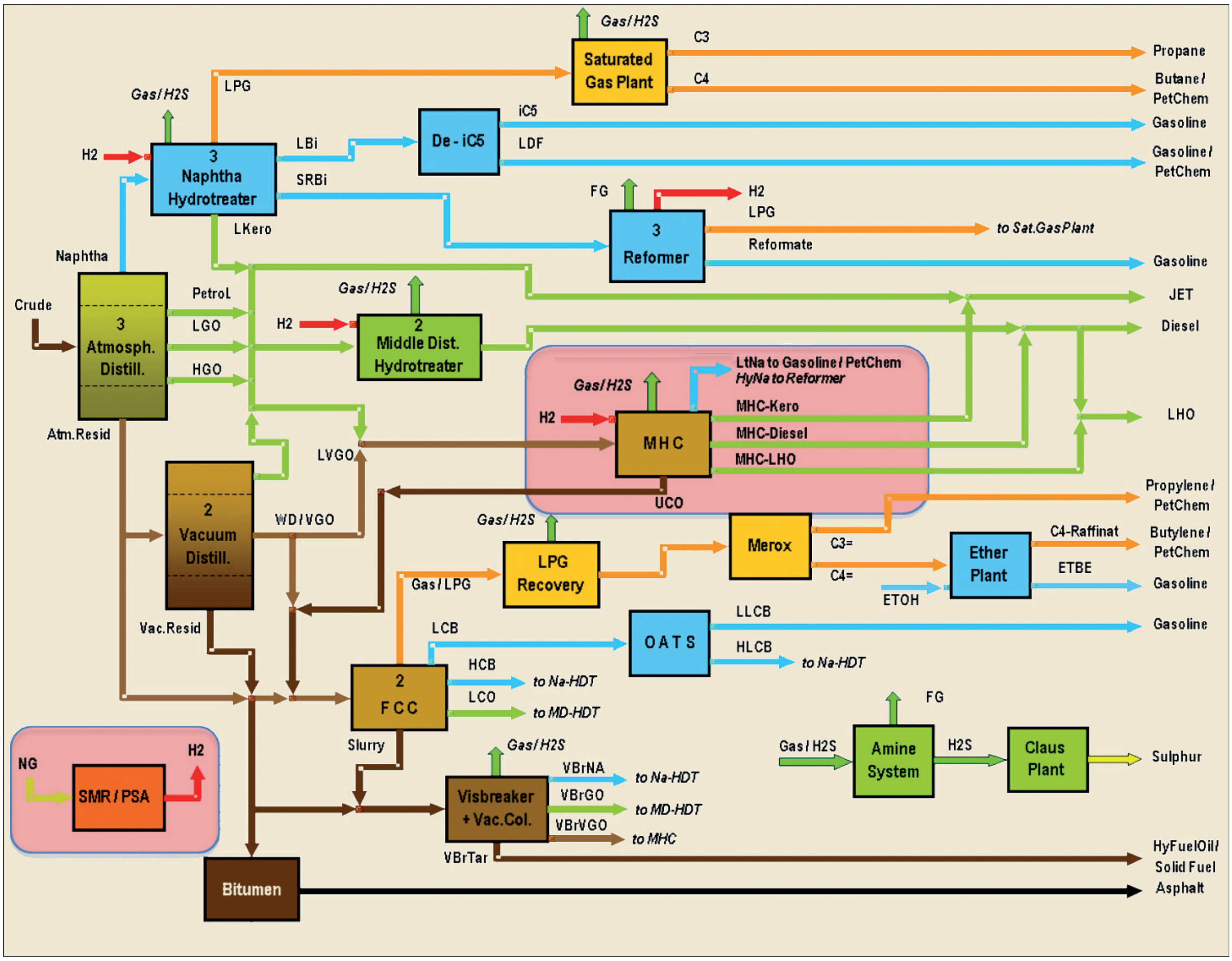

Figure 1 Refinery flow diagram

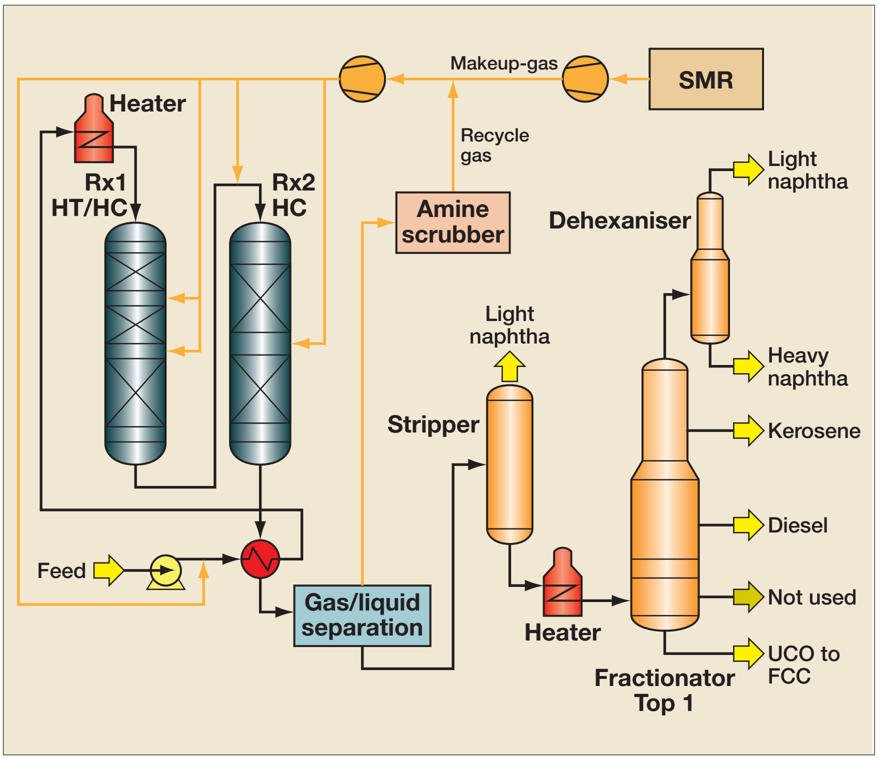

Figure 2 MHC process flow diagram

Advanced process control (APC) of a typical MHC process can potentially recover benefits in the order of millions of dollars per annum by maximising kerosene and/or diesel. The capture of these benefits is contingent on reliable control of product qualities at targets while nudging the unit against physical constraints.

Product qualities are typically not measured but inferred, whereas such inferences are the 'Achilles heel' of our industry. It takes knowledge and skill to obtain reliable product quality inferences. Neustadt is actually blessed with the ability to maintain on-stream analysers, an art that by and large has been abandoned by our industry. Even so, when compared against inference models, analyser dead time in the order of 90 minutes would negatively affect APC control performance. Furthermore, even high reliability analysers occasionally give erroneous readings, which may cause the multivariable predictive control (MVPC) to drive products off specification.

Desiring to control product qualities precisely, Neustadt has chosen the Petrocontrol/AMT generalised cutpoint calculation (GCC) inferential package. GCC employs first principles calculation methods to estimate a fractionator feed true boiling point (TBP) curve, before inferring cutpoints and other product properties. GCC was originally invented to deal with crude fractionators, and the theory and performance have been documented in several papers.[6,8,10,11,12,13,14] Adaptation of GCC to other types of refinery hydrocarbon fractionators has also been addressed in the literature.[1, 2, 3, 4, 5, 7, 9, 10] This is the first article detailing the application of GCC to MHC fractionators.

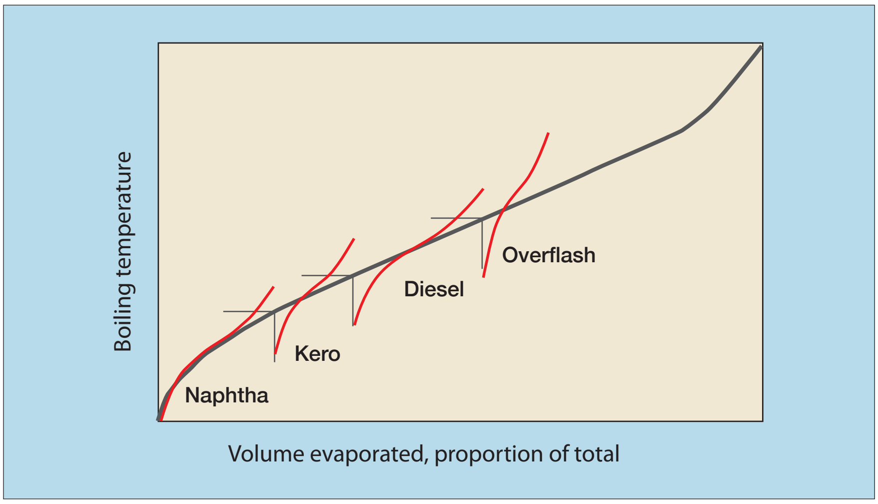

Figure 3 Reactor effluent TBP curve

GCC features

GCC theory has been documented in many publications and hence this article only describes the main concepts. Fractionator temperature measurements reflect tray composition at vapour/liquid equilibrium at a given hydrocarbon partial pressure. The opposite is also possible: estimate tray compositions from column conditions. GCC begins with estimating partial pressure. That is a function of total pressure (measured), steam flows (measured), and vapour traffic (calculated from measurements and heat balances). Once partial pressures are estimated, GCC corrects temperature readings from actual conditions to atmospheric pressure. Pressure corrected temperature (PCT) formulae are well known. These PCT temperatures, corrected to atmospheric pressure, now reflect the bubble points or dew points of products, sometimes a mix of products, whereas dew points and bubble points are functions of product cutpoint temperatures. Calculation of those cutpoints becomes a simple arithmetic GCC procedure.

From cutpoints and yields, GCC next constructs the TBP curve of fractionator feed material. A TBP curve is convenient because it describes ideal fractionation of the feed. An example of a TBP curve is illustrated in **Figure 3**. The heavy continuous line is column feed boiling curve, and the cutpoints define ideal product yields. Three products are shown: naphtha, kerosene and diesel. The fourth cut is called overflash and is not a real product, but material to be evaporated in the flash zone, then refluxed back down to the bottoms. Overflash is an important operating parameter in that it determines the separation between diesel and UCO. Many fractionators are designed with special flow meters attempting to measure the overflash. However by and large those measurements are not successful and the ability of GCC to infer overflash is an asset in itself.

The red lines of **Figure 3** show typical product TBP curves. Had we experienced ideal fractionation, product TBP curves would coincide with the feed curve. The heavy and light 'tails' on product curves are due to imperfect fractionation causing boiling range inter-mixing.

Cutpoint is a theoretical concept used to estimate product properties, for example product 90% point. GCC must be validated against lab tests, which use an ASTM D86 apparatus, a simple distillation machine, but not remotely a TBP machine. The GCC D86 prediction is a function of both front and back cutpoints, as well as internal reflux. Internal reflux is typically of secondary importance in the GCC D86 boiling point estimation. The following example shows the form of GCC diesel 90% point calculation based on cutpoints and internal reflux:

Diesel 90% point = K1 * KCP + K2 * DCP + K3 * [FDSL / (FDSL + FDSLIR)]

K1, K2 = known coefficients
KCP = kerosene cutpoint
DCP = diesel cutpoint
FDSL = volume flow of diesel
FDSLIR = internal reflux below the diesel draw tray

Shown in **Figure 4**, the term [FDSL / (FDSL + FDSLIR)] is a number between 0 and 1, 1 when there is no reflux. K3 can be viewed as the heavy tail penalty for no reflux. The penalty function decays quickly as internal reflux increases, and beyond an internal reflux ratio of 1:1 further improvement in separation is small. Well designed fractionators operate at about 1:1.

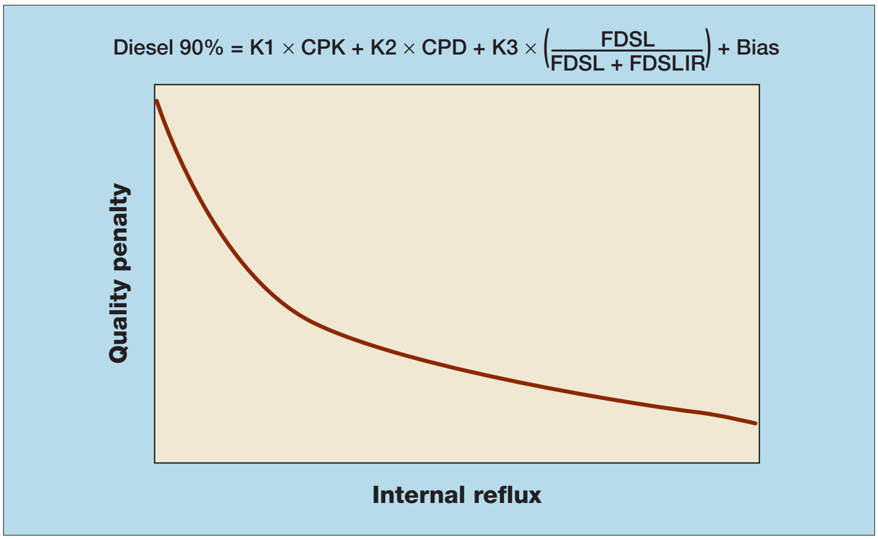

Figure 4 Quality is a function of cutpoints

Following D86 90% inferences, the model most in demand is kerosene flash point, an important jet fuel specification. Flash point is the temperature at which vapour in equilibrium above kerosene forms an explosive mixture with air. The partial pressure of kerosene vapour at flash point is theoretically known. To estimate flash point, GCC first estimates kerosene bubble point, and from that finds the partial pressure of kerosene vapour in air and the temperature at which explosion could take place. When kerosene is stripped by steam, the flash inference is corrected for steam ratio.

Cold properties such as freeze and cloud are a function not only of cutpoints but also of aromatic content. Given that aromatics have high density relative to their boiling point, a density meter is often used to estimate the aromatic content of a product, and related cold property shift. This is the preferred method in situations where the aromatics content is routinely changing, for example on a crude fractionator where the quality of the different crude processed varies significantly. Having said that, aromatic components in hydrocracker feed become saturated in the reactor and cold properties can be predicted with acceptable accuracy just from product cutpoints, without density correction.

GCC inferential performance

Figures 5, **6**, **7** and **8** illustrate the GCC inferential precision for kerosene 90% point, diesel 90% point,

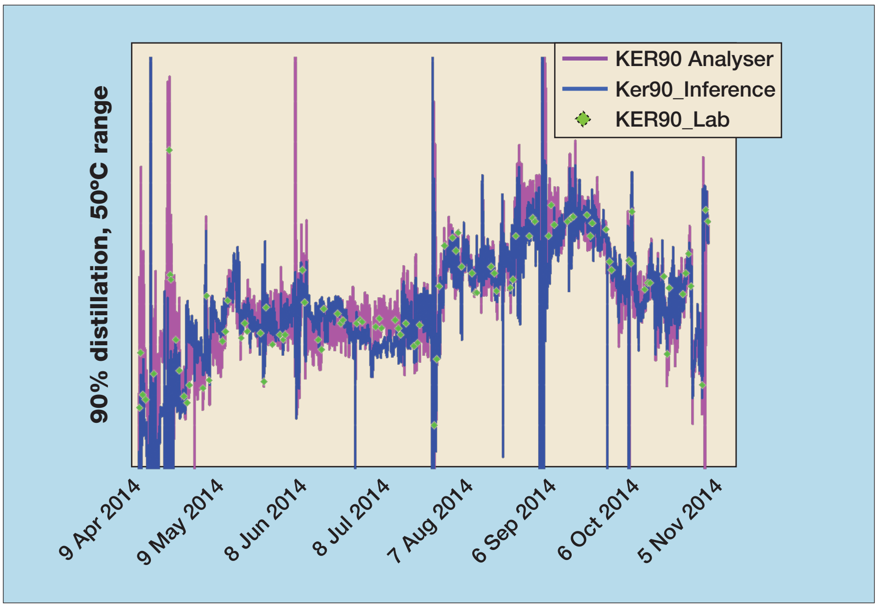

Figure 5 Kerosene 90% point inference seven months trend

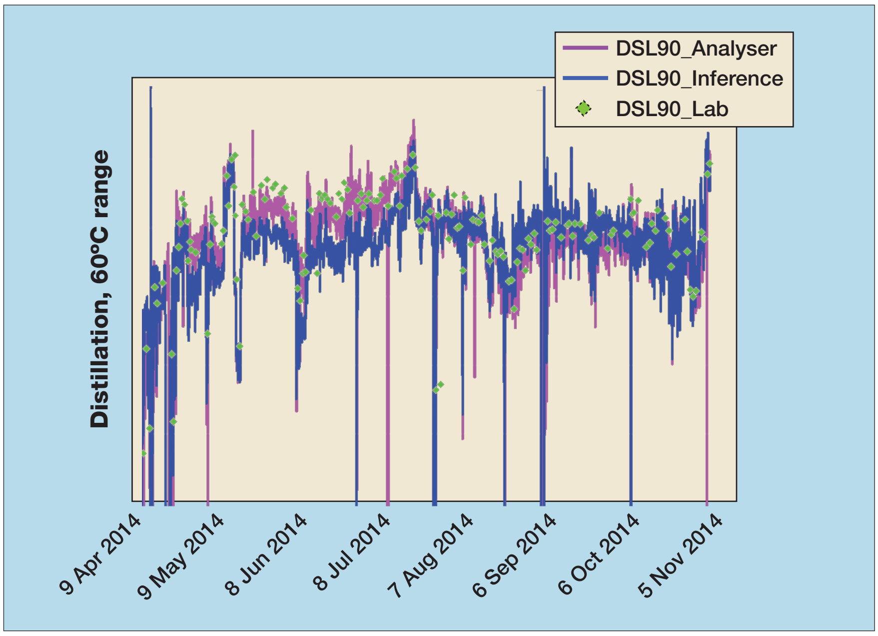

Figure 6 Diesel 90% point inference seven months trend

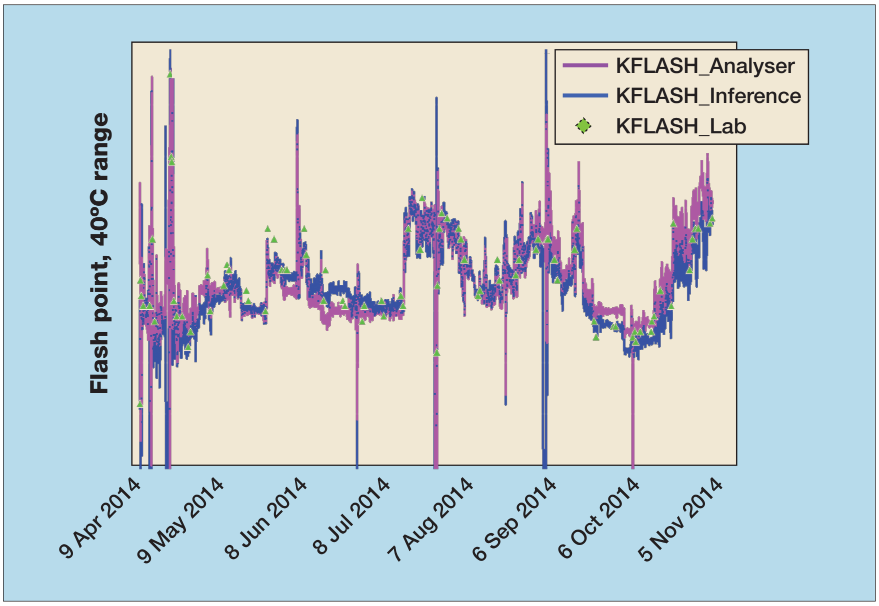

Figure 7 Kerosene flash point inference seven months trend

kerosene flash point and diesel cloud point respectively over a period of seven months. Inferential models are compared against lab results, as well as analyser readings. All four models trend quite well against lab values. In the case of diesel 90% point, the model shifted by 5°C and held there for several months. That is typically the result of a drift in one of the inputs, and the bias has reset itself upon instrument recalibration. Such a slow long-term shift is not an impediment to APC control precision. **Figure 6** trends an unbiased result, the raw GCC calculation, whereas the inference used as the controlled variable would be biased to correct for the drift.

The four analysers also exhibit near perfect reliability, to the point that with some dynamic correction we are able to use analyser readings to reset inferential biases. Still, because of analyser dead times in the order of one to two hours we are better off using inferences as control variables.

Conversion calculation

Economics call for 70% conversion, where 'converted material' is defined as the part of reactor effluent boiling below 363°C. Neustadt has a DCS calculation tag assuming that diesel is drawn precisely to a cutpoint of 363°C:

Conversion = 100 – yield of UCO

That creates two control difficulties. First, the yield of UCO is a noisy measurement because UCO is on level control. We do not wish to change reactor severity up and down in response to level control oscillations. Second, as **Figure 6** shows, diesel is not always drawn precisely to a cutpoint of 363°C. Even when the target is indeed 363°C, process variations around the target last hours. We do not wish to change reactor conditions in response to temporary dynamic changes of diesel cutpoint.

For conversion control we use a GCC inferential model, which calculates conversion inputting not only the yield of UCO but also all other products in a way that eliminates dynamic UCO level disturbances from affecting the conversion inference. And further, the yields of diesel and UCO are modified to reflect a cutpoint of 363°C. **Figure 9** illustrates the stability of GCC versus DCS conversion calculation. Before starting APC, the calculation varied widely though that was in open loop, not directly affecting the reactor. Starting January 2015, conversion was under APC control, being held stable at target. Conversion changes became deterministic, in response to the planners' desire, and this control handle was being used to balance between MHC versus FCC operation. This newly available ability to control conversion at target while keeping reactor conditions steady has much value in itself, before even considering the benefits of product quality control.

DMC performance

Figure 10 shows the 'big picture' of fractionator control. Once the APC application was commissioned, product qualities went from random giveaways to tight control at the planner's targets. And planners quickly became aware of the opportunity to specify targets that are consistent with the economics of the day. For simplicity, **Figure 10** shows only the analyser values. **Figures 11**

Summary of APC benefits

Product	Mass balance shifts m³/h	Mass balance shifts t/h
Bottoms UKO	0.4	0.3
Kerosene	4.8	3.9
Diesel	-2.2	-1.9
Overhead naphtha	-3.1	-2.3
Benefits realised		
Hourly yield benefit, €/h	527	
Annual yield benefit, €/a	>4.200.000	

Table 1

and **12** illustrate how the controller follows targets with fidelity, and the close agreement between inferences and lab values. Of interest, **Figure 11** shows the DMC response to some mistaken diesel 90% target moves that were reversed several hours later. Even more detailed APC opportunity capturing mechanisms are shown in **Figures 13** and **14**. These charts are standard DMC dynamic trends showing the process variable in blue, as measured up to current time and predicted into the future. The green lines are DMC predictions of the process variable, and the red lines are operating limits. The trends illustrate how pushing against kerosene and diesel specifications and minimising naphtha cutpoint brings about a substantial increase in kerosene yield.

To no-one's surprise, the service factor is consistently above 90%. The existence of on-stream analysers has actually contributed to a high service factor because, as operators observe the agreement between inferences and analysers, they are more confident about pushing the unit to operate near constraints.

APC benefits

A project post audit was performed several months after commissioning of the application. **Table 1** is a summary of the audit in terms of financial benefits, calculated from observed product yield shifts. It is of interest to note the positive shift in UCO make. The overall economic objective is not to maximise conversion but to produce UCO to a planner's target, thus balancing between hydrocracking and FCC charges. For middle distillates the objective is to maximise the yield of kero-

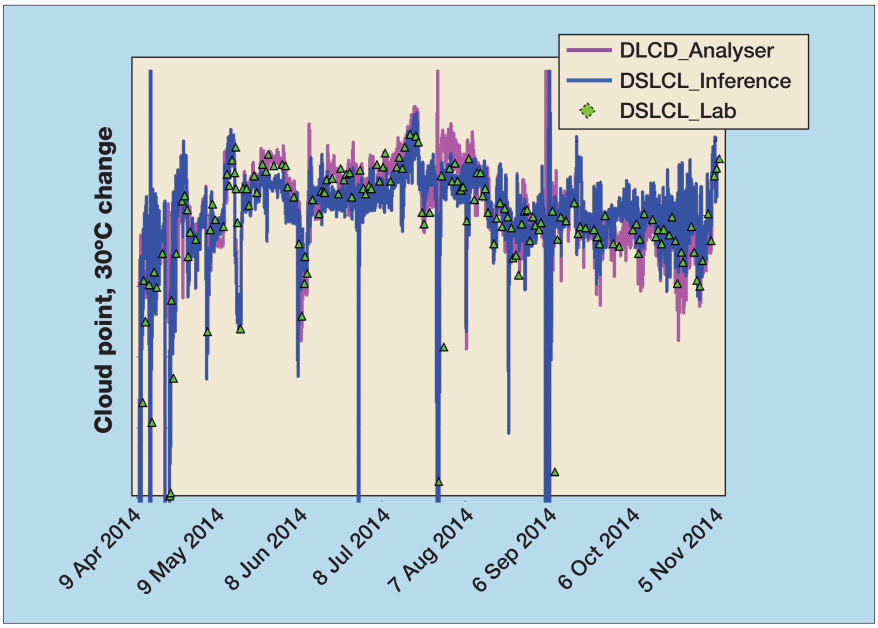

Figure 8 Diesel cloud point inference seven months trend

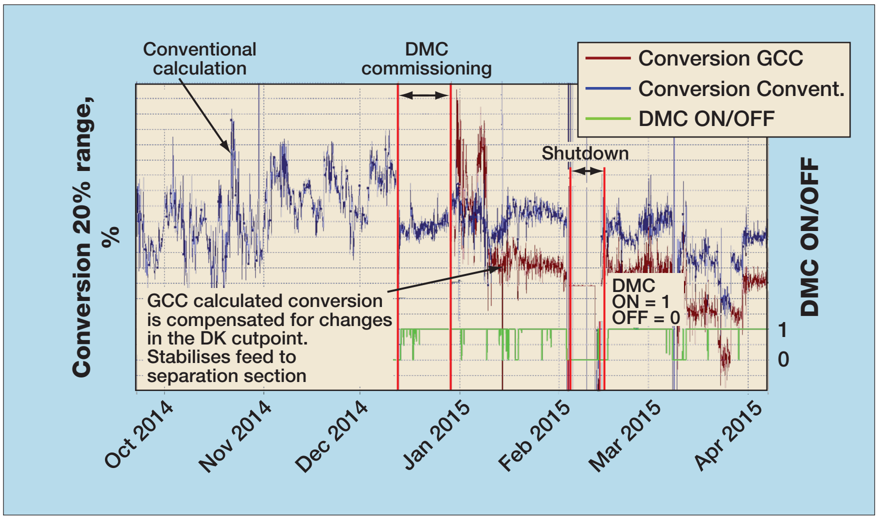

Figure 9 DSC and GCC conversion trend

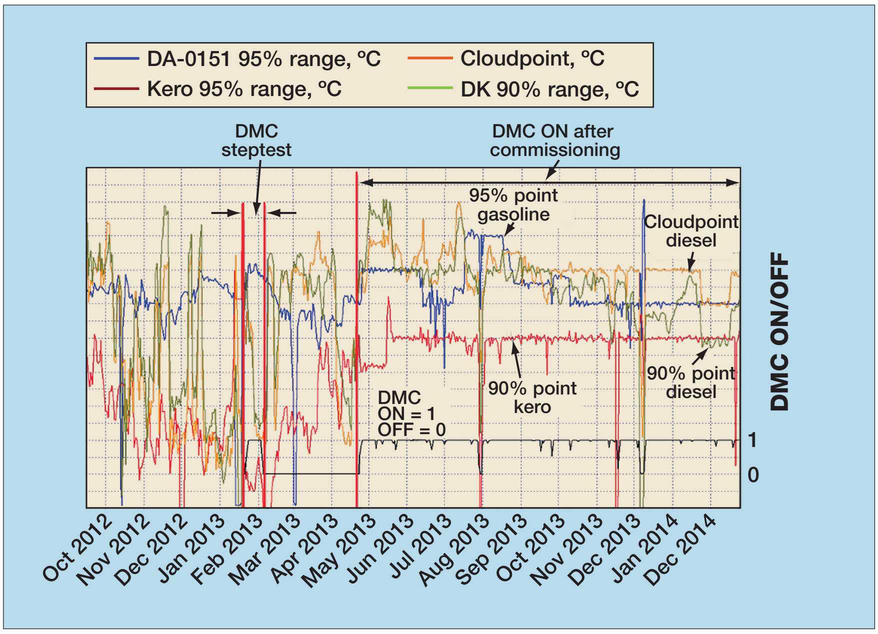

Figure 10 APC quality control trend

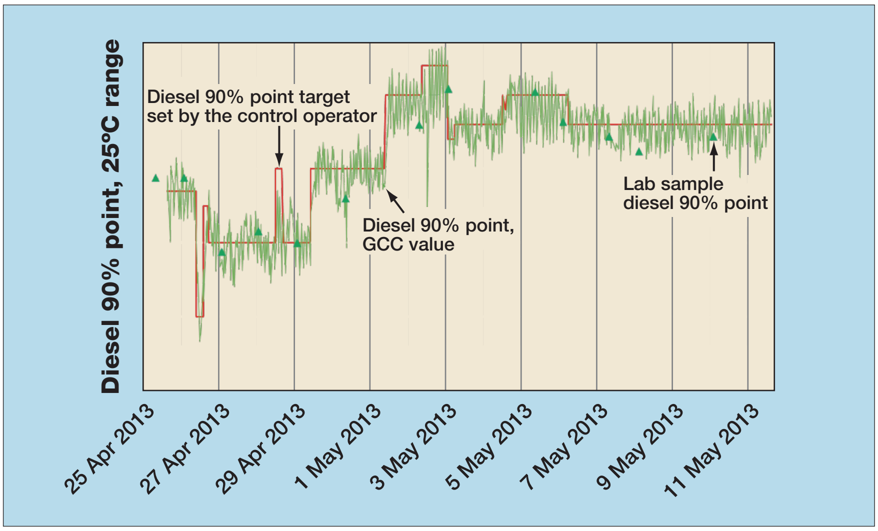

Figure 11 APC control of diesel 90% point

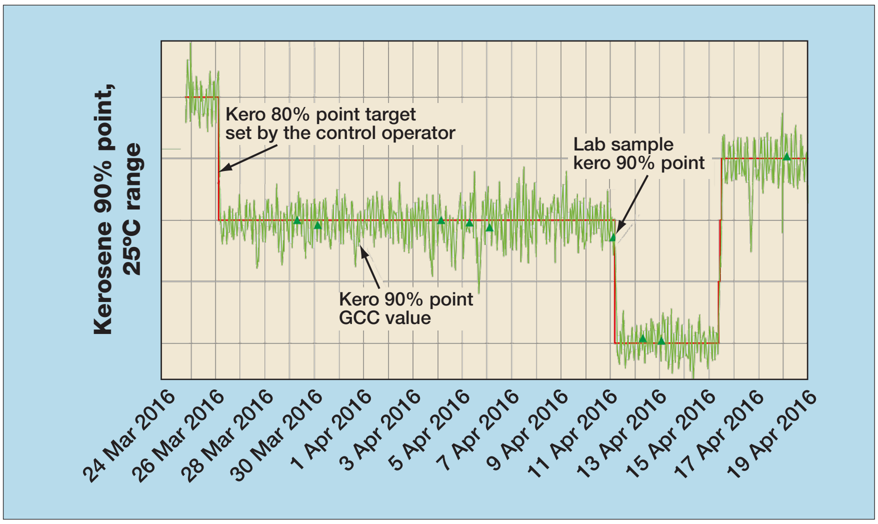

Figure 12 APC control of kerosene 90% point

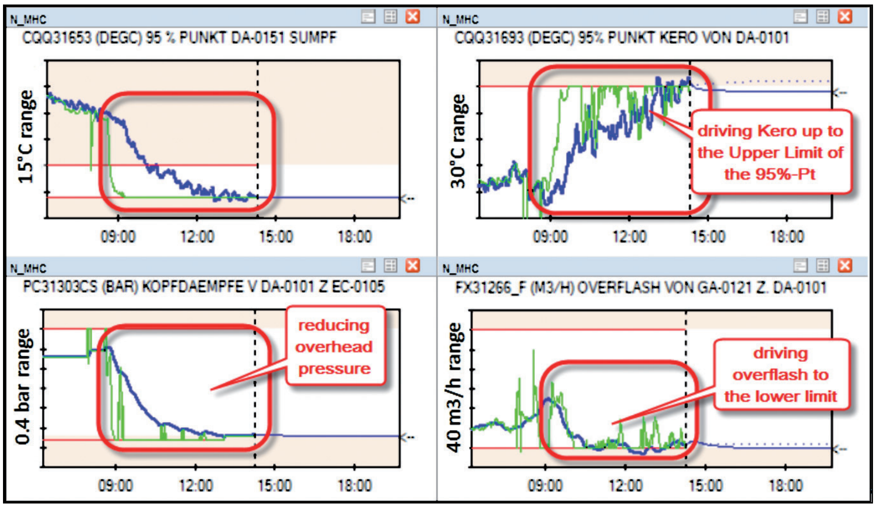

Figure 13 Increasing kerosene at the expense of naphtha following start-up

sene at the expense of first naphtha, and second diesel. Kerosene is sold as jet fuel, the most profitable refinery product, while naphtha is low octane, low value mogas material that must be upgraded by reforming. Diesel is a valuable product though not as valuable as kerosene. For the period of observation, APC benefits were €527/hour, or €4.2 million/y, representing a payback period shorter than six months.

That analysis does not take into account the benefits of stabilising conversion and reactor conditions, which contribute substantially by affecting run length.

Conclusions

What are the key ingredients for a successful APC application?

- Good design, selection of control and manipulated variables to create a well-conditioned control matrix; control variables must include both unit hard constraints and soft product quality constraints.
- Inferential models should be of top quality to produce products at quality targets, deliver the high benefits associated with those targets and capture the operator's confidence.
- Good implementation, identify correct DMC dynamic control models; that is not difficult to achieve when the control matrix is well behaved.
- Train operators extensively, going through formal class training plus one-on-one informal sessions.
- Address every operator request quickly.

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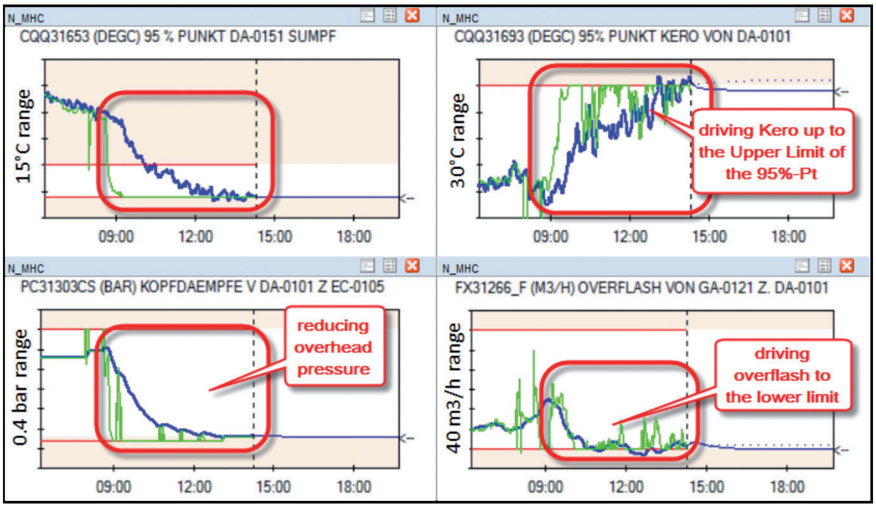

Figure 14 Increasing kerosene at the expense of diesel following start-up

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Y Zak Friedman is a Principal Consultant with Petrocontrol and has practised advanced process control for most of his career, specialising in the use of first principle models for inferential process control, and has developed inferential models to fit many hydrocarbon processes. His experience spans over 40 years, working with Exxon Research and Engineering, KBC Advanced Technology and Petrocontrol. He holds a PhD degree from Purdue University.