

# Performance testing of naphtha reforming catalysts

## High throughput screening of naphtha reforming catalysts under commercially relevant conditions

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Catalytic naphtha reforming, in which low octane naphtha feedstock is converted into high octane reformat, is one of the core processes in modern refineries.<sup>1,2</sup> The reformat produced includes high-value aromatics for the petrochemical industry such as benzene, toluene, and xylenes (BTX). Hydrogen as a main byproduct is highly valued for its use in hydro-treating, hydrocracking, and other hydrogen consuming processes in the refinery.

There has been ongoing research in the last decades with the aim of optimising activity, selectivity and stability in order to increase high octane C<sub>5</sub>+, aromatics and hydrogen yield. More recently, additional challenges have emerged due to environmental regulations, requiring a reduction of aromatics content (especially benzene) in gasoline and an increase in hydrogen for the production of clean fuels.

On the other hand, market trends show increasing global demand for aromatics in the petrochemical industry. In regions of developing markets such as Asia, strong growth in gasoline demand is expected, while demand is declining in developed regions such as North America, Europe and Japan.<sup>3</sup>

Refiners need to decide whether to meet gasoline or aromatics demand by changing the catalyst, changing the mode of operation, revamping existing reformers from fixed bed to continuous catalyst regeneration (CCR) reformers, or installing new reforming capacity in regions close to developing and growing economies. At the latest when a catalyst reaches the end of

its service life, the difficult question comes up of whether to reduce risk and stick to the same catalyst, or to select a new, potentially better performing catalyst for the change-out. Besides risk minimisation, catalyst costs have to be taken into account versus increase in profitability, operability, stability and the capability to deal with different feed compositions. This is made more difficult by the fact that commercial naphtha reforming catalysts on the market have been optimised for decades and differences in performance can be very

### High throughput experimentation technology can increase efficiency by testing many reactors in parallel

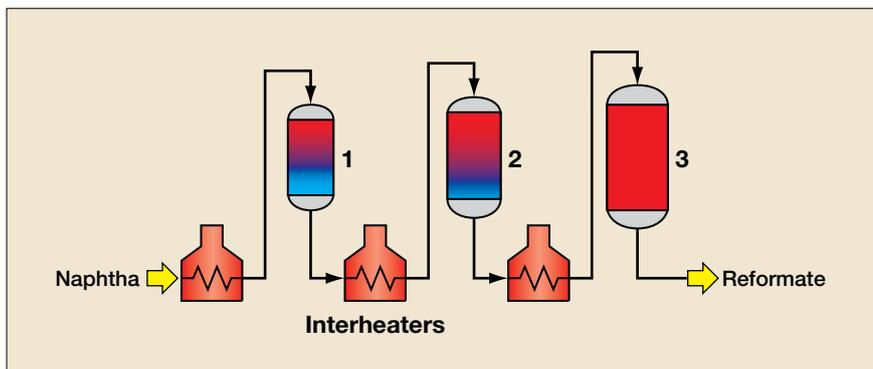
small. Notwithstanding this, even small differences in performance have a great impact on process profitability due to the large capacity of reformers. Therefore, an independent catalyst test to benchmark catalysts on the market and compare their performance to the catalyst currently in service should be considered to minimise risks, increase economic return and help to make the right decision.

Detecting these small differences in performance, however, takes conventional sequential catalyst testing in single-fold pilot plants to the limit and even minor deviations

in process variables and the calibration of technical equipment (temperatures, pressures, flows, and analytics), feed composition or catalyst ageing between runs can easily compromise the results. Multiple runs have to be performed in order to obtain adequate statistical significance for reliable results, in the worst case not yielding sufficiently small error limits or reproducibility to differentiate between catalysts. In addition, running these tests for multiple catalysts or process conditions consumes time that is often not available and is expensive.

High throughput experimentation (HTE) technology can increase efficiency by testing many reactors in parallel, which allows several catalysts and process conditions to be tested simultaneously and saves time and costs. The option of installing the same catalyst in multiple positions immediately generates results with meaningful statistical significance. Nevertheless, differentiation of catalysts is only achieved if performance differences are higher than the statistical error of measurements, thus rendering catalytic naphtha reforming a challenging application for parallel testing of catalysts. Reproducible reactor loading, constant process conditions in each reactor (temperatures, pressures, flow distribution) and high analytical precision are of great importance.

Catalytic naphtha reforming is predominantly carried out in fixed bed reformers comprising both cyclic and semi-regenerative operations, though newer and more effective CCR reformers have high



**Figure 1** Schematic view of an industrial fixed-bed reactor set-up. Endothermic temperature drops are indicated in blue

penetration nowadays and are continuing to gain ground. Process conditions and catalysts for these processes differ significantly from each other and require a highly flexible parallel test unit to realise both protocols. The long cycle length and slow deactivation of fixed bed reforming catalysts (up to a year or more) requires a fast testing approach employing accelerated decay conditions in order to gather results in a reasonable time frame. On the other hand, short deactivation of CCR reforming catalysts demands a fast approach in order to collect enough data before the catalyst deactivates, by reducing analysis time to increase sampling frequency, increasing the parallelisation degree of the analytics, reducing the number of reactors that are on stream in parallel, or sequentially starting up single reactors.

In earlier stages of catalyst development with only small amounts of catalyst available as powder, testing under isothermal conditions can deliver initial qualitative results, identify leads, and provide a tool for fast performance checks after regenerations or to monitor production. Commercial naphtha reformers, however, operate adiabatically with multiple sequential reaction zones and inter-heaters in between (see **Figure 1**). Many types of reactions interact with each other, including desired reactions such as dehydrogenation, dehydrocyclisation or isomerisation and undesired reactions such as hydrocracking and hydrogenolysis. Especially in the first reactor of a commercial set-up, fast and endothermic reac-

tions such as dehydrogenation and dehydrocyclisation prevail over exothermic reactions, leading to a significant temperature drop. If a catalyst is very active, it will cause a higher endothermic temperature decrease than less active catalysts. When benchmarking these catalysts under isothermal conditions, the relative rates and contributions of the reactions involved will be different, leading to different selectivities and in the worst case an incorrect ranking of catalysts. On the other hand, testing catalysts adiabatically in multiple sequential reactors requires an extensive set-up and high amounts of catalyst and feed even in a single-fold unit. In a 16-fold parallel test rig, a good compromise between complexity and closeness to industrial practice was found by multiple reaction zones that allow the development of semi-adiabatic temperature profiles with same weighted average inlet temperatures (WAITs). Finally, usage of full extrudates improves reproduction of transport phenomena such as heat and mass transfer and is closer to practical conditions.

In naphtha reforming, low octane paraffins and naphthenes in naphtha are converted to high octane iso-paraffins and aromatics in reformate. Along the cycle time, catalyst deactivation occurs predominantly through carbonaceous deposits and leads to a gradual decrease of the research octane number (RON). However, refineries rely on a constant reformer output for gasoline blending purposes, aromatics downstream processes or hydrogen supply. In order to compensate the

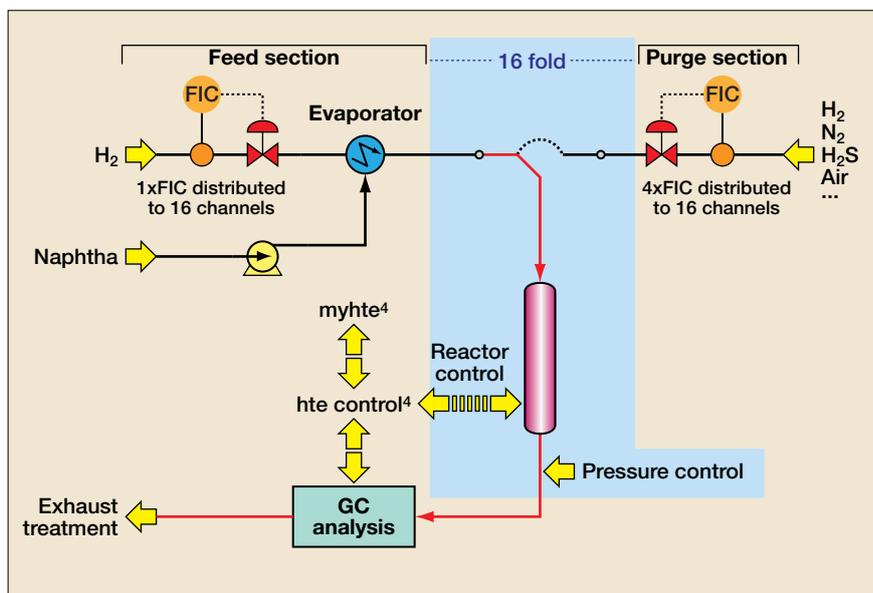
RON decrease, the temperature can be increased or pressure and weight hourly space velocity (WHSV) decreased. While lowering pressure increases coking and shortens catalyst lifetime significantly (which makes it a good measure to accelerate decay in laboratory testing), decreasing WHSV limits capacity and increases hydrocracking to lights. Therefore, temperature remains as a sensible variable and operation at constant RON in fixed bed reformers is achieved by gradually increasing the temperature until heater capacity is reached or process economics become unfavourable due to increased hydrocracking and strongly reduced  $C_5+$  yields. In a parallel test rig, this constant or iso-RON operation requires a fast and reliable analytical method to determine RON in each reactor combined with individual temperature control for each reactor. In summary, the combination of multiple reaction zones with semi-adiabatic temperature profiles, usage of full extrudates, and operation under iso-RON conditions brings parallel testing very close to commercial practice.

In this article, we present the latest developments in high throughput technology as a case study, in which different catalysts for naphtha reforming were tested in 16 parallel reactors under industrially relevant conditions. The study was carried out in our research facilities at hte GmbH, Heidelberg, Germany. All relevant aspects of a typical HTE program such as reactor loading, test set-up, analytics, precision and data evaluation are covered including special requirements for naphtha reforming such as appropriate test protocols to handle different deactivation time scales for fixed bed reforming and CCR reforming catalysts. Emphasis will be placed on iso-RON operation for producing reformate with a constant RON for each catalyst, at the same time demonstrating the importance of integrated software solutions for process control, analytics and data evaluation. This results in a precise, fast and statistically significant differentiation of catalysts by activ-

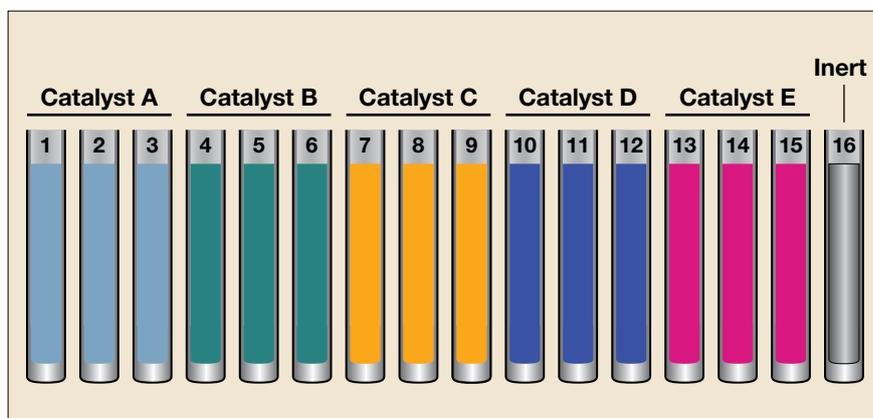
ity, selectivity and stability close to commercial practice.

### Set-up

The high throughput system used in this case study is shown in **Figure 2** with 16 reactors in parallel. This unit has a modular design and the feed section pictured on the upper left provides consistent dosage of naphtha and evaporates it pulse-free under inert conditions in a stream of dry hydrogen. On the upper right, the purge section with multiple mass flow controllers can supply additional gases such as  $H_2$ ,  $N_2$ , air, and  $H_2S$ . Both gas flows are distributed into 16 single gas streams and the operator can select between feed or purge flow for each individual reactor. This offers flexibility for activation and regeneration procedures or for keeping reactors under inert conditions. Especially for CCR reforming catalyst testing, reactors can be started up sequentially with the same time on-stream (TOS), or the degree of parallelisation can be reduced to increase sampling frequency and collect more data points for each reactor. These selected gas streams from the feed or purge section enter the reactors placed in individually controllable heaters. Reactors with smaller or larger inner diameters are available to test either powder or extrudates respectively. Information on temperature profile, weighted average inlet and bed temperatures (WAITs, WABTs) for each reactor are provided by movable inner thermocouples. In the downstream section below the reactors, reformat products are diluted by a pressure control system that also keeps the pressure in each reactor exactly the same. High upstream and downstream temperatures are applied to keep all compounds of naphtha feed and reformat products in the gas phase. The effluent of one selected channel is directed to online GC analysis for measurement of permanent gas and hydrocarbon composition. Further evaluation of the hydrocarbon composition yields the RON, which can, in turn, be used to control the heaters for iso-RON operation. When handling



**Figure 2** Simplified process diagram of high throughput unit for naphtha reforming



**Figure 3** Schematic design of screening plate (16 positions) for this case study, charged with five different catalysts in three redundant positions and one inert position

naphtha, hydrogen, and high aromatics reformat, the safety of the unit is ensured by operating the whole unit in a closed ventilated hood equipped with several detectors for hydrogen, smoke and lower explosion limits, which trigger immediate safety shutdown procedures in case of any unusual event. All exhausts are incinerated to comply with air quality regulations.

In order to obtain meaningful and reproducible results, loading the reactors is one of the crucial steps when testing catalysts in parallel. Variations in the length or diameter of catalyst particles, inhomogeneous flow around the particles, or deviations from ideal plug flow can cause differences in mass or heat transfer, different catalyst performance and non-reproducible results.

In order to resemble the commer-

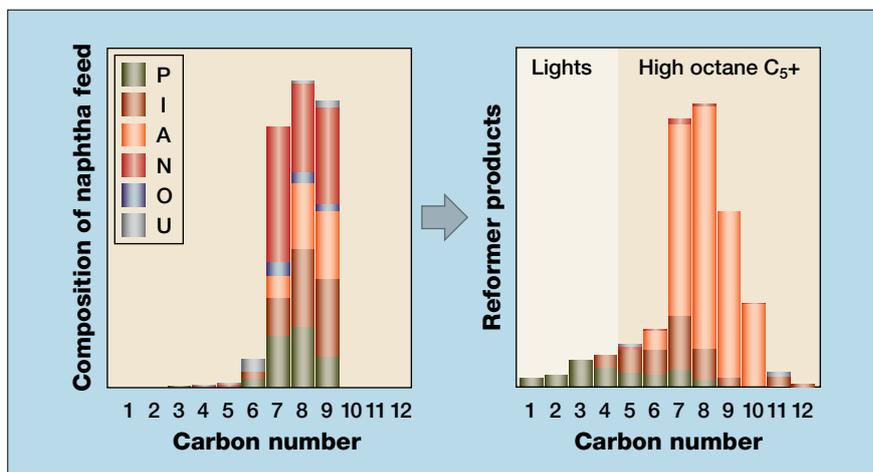
cial set-up of multiple sequential reaction zones (see **Figure 1**), the extrudates were loaded in several catalyst zones close to the mass distribution in commercial units. As mentioned before, prevailing strong endothermic reactions in the first, and to a lesser extent in the following reaction zones, lead to a temperature drop, making it necessary to reheat the feed in order to ensure that the feed enters each catalyst zone with the same WAIT. Measurement of temperature profiles inside the reactor indicates that the feed is reheated to the same WAIT and that semi-adiabatic temperature profiles exist.

In this case study, five different fixed bed reforming catalysts were tested in three redundant positions to check reproducibility and provide statistically significant

results. A total amount of 10 ml was loaded as full extrudates into 15 positions, leaving space for one position filled with inert material for measurement of any blind activity (see **Figure 3**). Regular feed analysis is possible via a by-pass channel and inner thermocouples for temperature measurement were placed in each reaction zone.

### Feed

Hydrotreated, full-range heavy naphtha with an average molecular weight of 110 g/mol and 66-204°C IBP-FBP range was dried to <10 ppm water content to minimise chloride leaching and transferred into the unit under inert conditions. The drying workflow was optimised to consistently process barrels of naphtha feedstock when testing larger catalyst amounts in a 16-fold reactor system. In case of an exemplary WHSV of 2 and 10 ml of catalyst per reactor, around 6 l of naphtha per day are required. The feed composition measured by online GC in the inert channel and the corresponding high octane reformat for one of the catalysts is shown in **Figure 4**, split by carbon number and PIANOU lumps (paraffins, iso-paraffins, aromatics, naphthenes, olefins, unknowns). The amount of unknowns or unidentified compounds in the



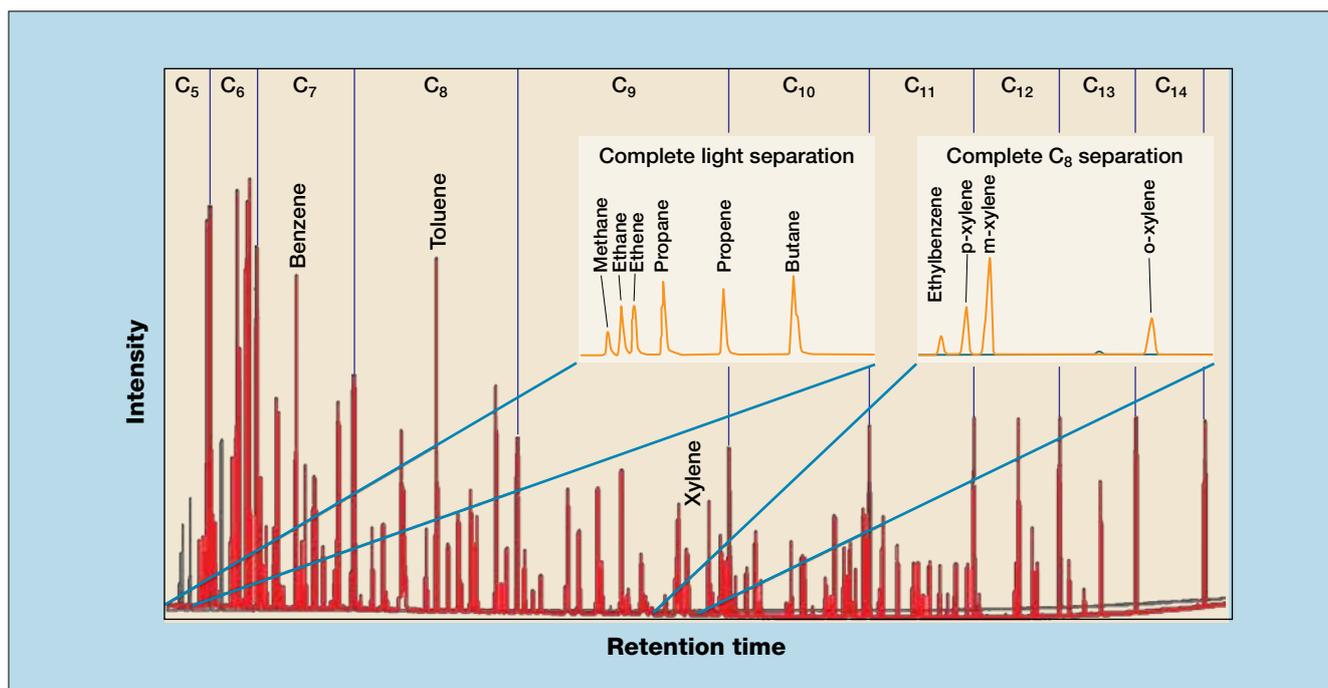
**Figure 4** Composition of naphtha feed and reformer products as PIANOU distribution (paraffins, aromatics, iso-paraffins, naphthenes, olefins, unknowns), split by carbon number

product spectrum is below 1 wt% and >99 wt% of more than 100 separated substances in the GC chromatograms are assigned to specific compounds.

### Analytics

In HTE, it is essential to have a fast and reliable analytical set-up. Not one but 16 reactors need to be sampled and, depending on the catalyst deactivation, enough data points need to be collected during a 24-hour period. This is even more critical if the unit is operated under iso-RON conditions and analytical results are used to control reactor temperatures to compensate decay. Combining fast analysis with the

required resolution for complex multi-component product mixtures and long term column stability with minimal drift (>1000 h) was a challenging task that was resolved by a sophisticated multi-column/multi-detector set-up in several gas chromatographs. The full gas phase spectrum of hydrocarbons up to C<sub>14</sub> is detected and more than 100 compounds are separated and assigned. An exemplary chromatogram of naphtha (red) is shown in **Figure 5** together with a C<sub>1</sub>-C<sub>14</sub> n-paraffin standard (blue). Smaller windows display chromatograms of supplemental columns for complete C<sub>1</sub>-C<sub>6</sub> light and aromatics separation. If reformat is further



**Figure 5** Exemplary chromatogram of a C<sub>1-14</sub> paraffin standard (blue) and full range naphtha (red). Key components such as BTX are indicated

processed by petrochemical and aromatics processes, the distribution of xylene isomers is of high interest and o-, m-, and p-xylene are measured with full base-line separation. Argon is used as an internal standard and the argon concentration provides additional information on the feed distribution for each measurement. Events such as plugging by excessive coking, physical disintegration of catalysts, leakages or other events would result in lower argon concentrations for the respective reactors and are immediately detected. Hydrogen, as a precious byproduct in naphtha reforming, is quantified to complete the analysis of products. Obviously, this complex interplay of multiple GCs, columns and detectors needs to be synchronised with the process control of the unit and the amount of data generated for 16 positions is too big to be managed manually.

#### RON models

Research and motor octane numbers (RONs/MONs) describe the resistance of fuels to pre-ignition or knocking, traditionally measured by engine knocking tests (CFR engine). Unfortunately, knocking tests require large samples of reformat (approx. 1 l) and lots of time, and are not suitable for on-line measurement of product streams in smaller test units. Therefore, considerable research has been carried out to find alternative ways to determine the RON. Though near-infrared (NIR) analysers offer a fast and continuous RON measurement for smaller amounts in the liquid phase, they need additional process steps such as condensation or pressure build-up to liquefy reformat products. The approach in this case study calculates the RON using online GC analysis in the gas phase. Several models for RON calculation based on individual compounds were proposed in the last few decades and reviewed in the literature.<sup>4</sup> Existing linear models are based on the product sum of compound percentages (measured by GC) and the individual octane number, whereas non-linear models

include additional interactions between compounds. The respective individual octane numbers of pure compounds (octane numbers, ON) or pure compounds in blends (blend octane numbers, BON) were determined by extensive knocking tests in the 1950s and are available in the literature for most compounds. Apart from using either linear or non-linear approaches, models differ from each other by taking either weight, volume or molar fractions into account, or by using either octane or blend octane numbers. For the sake of simplicity, some models use lumping and assign one octane number to component groups with similar octane numbers. In this case study, several literature models were evaluated by comparing

## The resolution of chromatograms and a short sampling interval are of equal importance and a good compromise needs to be found

calculated RONs based on GC analysis with measured RONs through engine knocking tests for several reformat samples. The model showing the best match with the engine knocking tests ( $\pm 1$  RON) was selected to calculate RONs in this study.

#### Data processing

Up to this point, the analytical set-up provides a detailed hydrocarbon analysis, which can be converted to RON using an appropriate calculation model. This is sufficient for assessing catalyst performance at one or multiple constant temperatures. However, commercial reformers operate with constant RON output and the RON decrease in fixed bed reformers is compensated by the gradual increase in reactor temperature. This iso-RON operation requires

regular RON measurements with sampling frequency depending on catalyst deactivation rate. Clearly, this time interval is much shorter for CCR reforming catalysts with fast deactivation compared to fixed bed reforming catalysts with a longer cycle length, although operating the latter under accelerated decay conditions also requires shorter sampling intervals. In high throughput testing, the number of data points per time interval depends on the number of parallel reactors on stream and the length of the GC method. The resolution of chromatograms (number of identified products and precision of RON determination) and a short sampling interval are of equal importance and a good compromise needs to be found.

In this case study, the analysis of 16 positions by sequential sampling and a compact GC method yields a measurement for each position every couple of hours. Each measurement contains chromatograms of multiple columns with more than 100 peaks and requires immediate evaluation to calculate the RON for temperature adjustment. This evaluation needs to be done automatically 24/7 and process automation and software integration are essential. The data evaluation workflow starts at the unit when experiments are set up. The software package hteControl<sup>4</sup> manages all components of the reactor system and collects and monitors trend data of thousands of process parameters. The operator can create workflows by visually dragging individual process steps such as parameter changes (temperatures, pressures, flow rates, or any controllable parameter) and sampling sequences of reactors into a flowchart, including options to place them sequentially, in parallel or in loops. These pre-defined workflows are executed automatically and can be configured weeks in advance. During execution, hteControl<sup>4</sup> triggers and collects GC measurements and merges the analytical data with selected process control parameters. Subsequent to each sampling, the merged data is uploaded into the

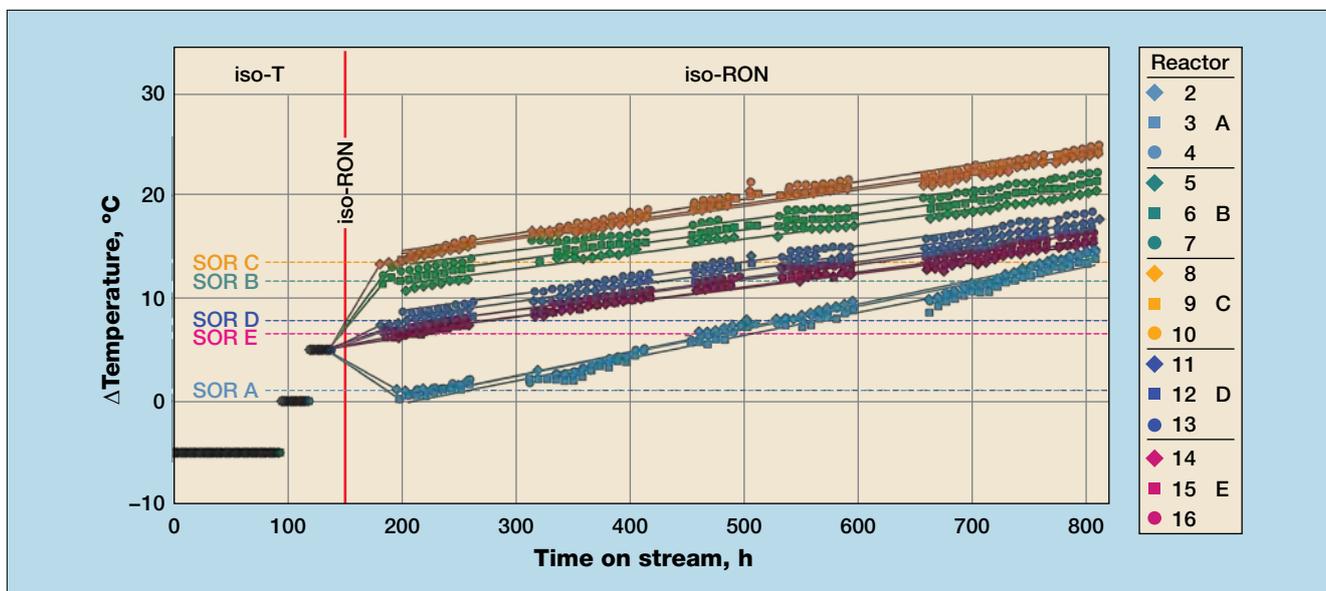


Figure 6 Temperature (activity) versus TOS

database myhte<sup>4</sup>, which is based on a client-server architecture. The server can be hosted in the intranet or cloud, for example, and is connected to a relational database. Data from all relevant steps in the workflow is gathered and stored in the database. The user can plan synthesis steps, reactors loadings or offline analyses and monitor progress remotely. As soon as catalysts are on stream and hteControl<sup>4</sup> starts uploading its data, the user can follow the screening progress in real time, check compound assignment and column stability and assess performance parameters by user-defined report formats, including plots and visualised screening data. In myhte<sup>4</sup>, global peak identification automatically converts peak areas and retention times by pre-defined and flexible assignment sets into compound concentrations. These compound concentrations are either processed individually or grouped into lumps according to their carbon number and component classes such as n-paraffins, iso-paraffins, aromatics, naphthenes or olefins (PIANO). User-defined calculation algorithms are executed automatically and yield conversions, selectivities, PIANO distributions, and ultimately the RON according to corresponding models. The RON, in turn, is fed back to hteControl<sup>4</sup>, which adjusts the reactor temperature accordingly. This

self-optimisation process is secured by several safety trips in case of analytical issues (for instance, column drift or failure, false compound assignment) or unit problems such as plugging.

Availability of all data (screening results, catalyst properties, offline samples) in the same format and in one database is essential for further data analysis such as data mining, statistics, evaluation of studies based on design of experiments (DoE) and fitting of kinetic models. One can go back in time, compare and merge data of former studies with current results or include corrections based on recently gained knowledge. In summary, this integrated software solution, including the hteControl<sup>4</sup> process control software and the myhte<sup>4</sup> database, makes dealing with large data quantities much easier and brings out the best in high throughput experimentation.

#### Start-up and activation

Returning to the practical workflow

at the unit, the loaded reactors are installed in the unit. In parallel testing, a uniform feed distribution, besides high precision in temperature and pressure distribution, is essential for reproducibility, and even minor deviations would cause different space velocities in the reactors and influence the product selectivity. Pressure tests and measurements of flow distribution and flow balance are performed for all 16 channels to ensure that all flows going into the unit are leaving the unit and are evenly distributed among all feed strands. If the flow distribution is below  $100 \pm 2\%$  for all 16 channels, the unit is started up and ready for catalyst activation.

The activation procedure of naphtha reforming catalysts can consist of several sequential steps, including drying of the catalysts to remove residual moisture, reduction of platinum and promoter metals with hydrogen, and, if these are fixed bed reforming catalysts, in situ sulphiding to reduce hyperac-

#### Process parameters of case study

Catalysts	Fixed bed reforming, semi-regenerative
Feed	Heavy naphtha, IBP-FBP: 66-204°C
p, bar	10-20 barg
T, °C	480-540
H <sub>2</sub> /HC ratio, molar	2-4
WHSV, h <sup>-1</sup>	2-5
Target RON	98-102

Table 1

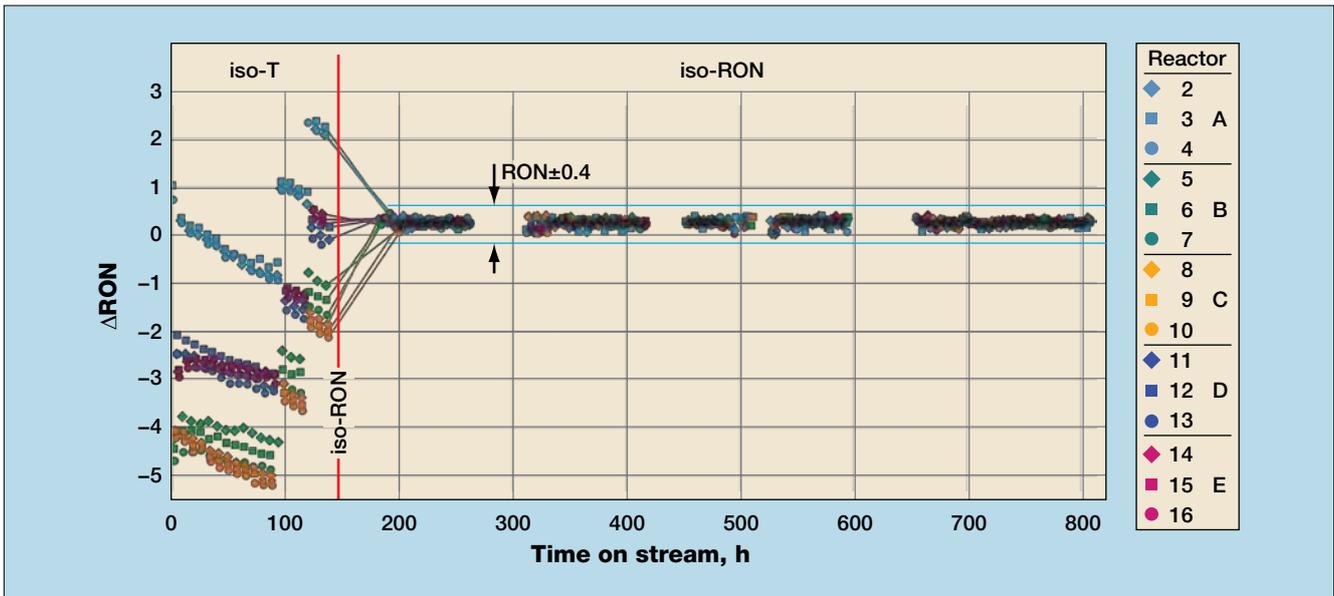


Figure 7 RON versus TOS

tive metal sites and initial hydrogenolysis activity. The activation plays an important role in catalyst performance and requires a high level of reproducibility to guarantee the same reduction state of metals and overall sulphur level. If the catalysts differ considerably in terms of platinum content or additional promoter metals, each catalyst can be sulphided by means of an individual procedure. Final treatment with hydrogen purges the unit and removes reversibly bound sulphur on the catalysts.

Subsequently, the unit conditions are adjusted to values within the parameter ranges shown in Table 1.

If the start of run (SOR) temperatures anticipated for the target RON are not known beforehand, the temperature RON correlation for each catalyst is obtained by measuring the RON at a couple of temperatures.

#### Results and discussion

The catalysts, designed for semi-regenerative operation in fixed bed reforming, were tested over 1000 hours TOS according to the parameter ranges shown in Table 1, including a complex test design with variations of target RON, temperature, pressure, WHSV,  $H_2/HC$  ratio, feedstock and spiking. The focus here will be on iso-

temperature and iso-RON operation at constant total pressure, WHSV and  $H_2/HC$ .

Selected data from this case study is plotted in Figures 6 to 8, in which the RON, temperature (activity) and  $C_5+$  yield are plotted against TOS. These parameters are strongly related to each other and will be discussed together.

All catalysts were started up at the same constant temperature, which was increased by  $5^\circ C$  steps after 100 h TOS (see Figure 6). As expected for different catalysts, the same temperature results in different RONs (see Figure 7) that are subjected to run-in behaviour and subsequent decay. Catalyst A

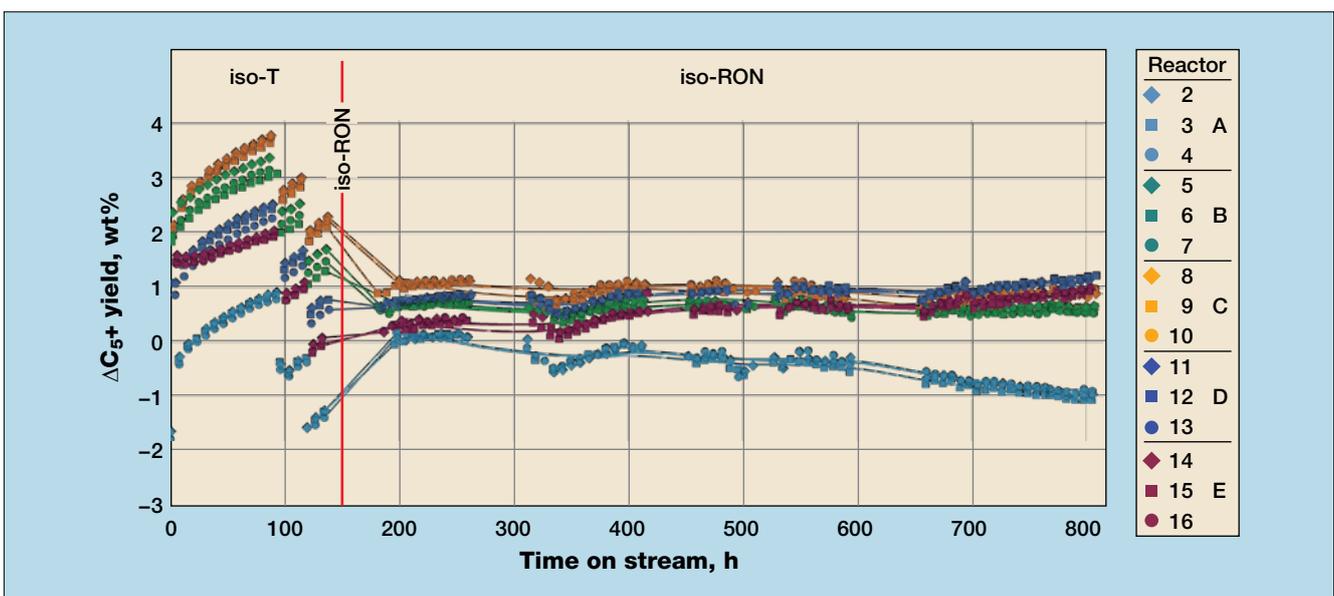
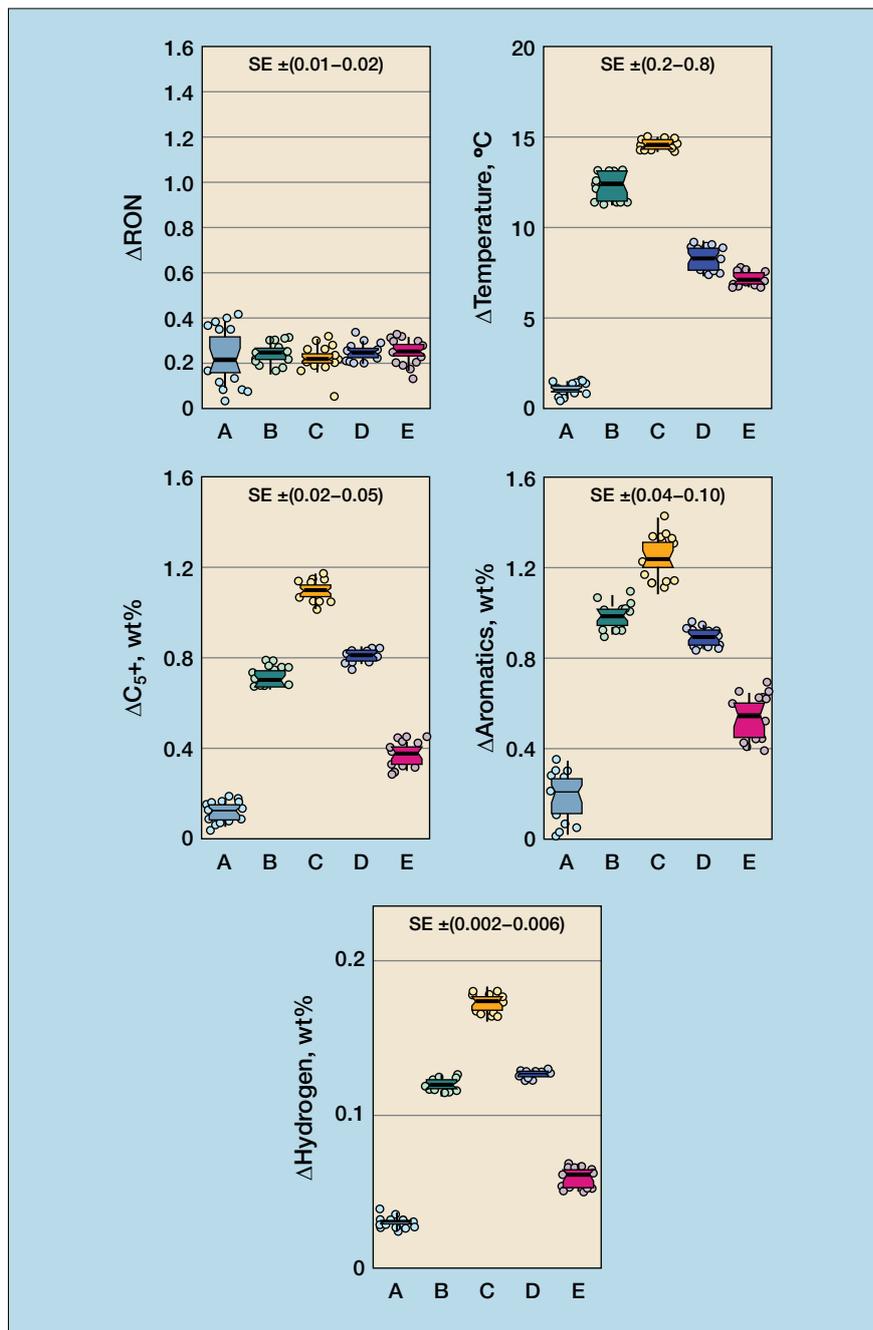


Figure 8 Reformate  $C_5+$  yield versus TOS

produces reformat with a significantly higher RON compared to the other catalysts, combined with strong run-in and decay behaviour. On the contrary, catalysts B and E produce reformat with a lower RON and are quite stable. Increasing the temperatures improves the RON and the correlation between temperature and RON becomes evident, allowing the calculation of start of run (SOR) temperatures (dashed lines in **Figure 6**). The picture changes when looking at the  $C_5+$  yield in **Figure 8** with a reversed catalyst rating compared to the RON. Catalyst A with the highest RON produces the lowest  $C_5+$  yield and hence the highest light yield and hydrocracking activity. Increasing the temperature favours the latter for all catalysts and reduces the  $C_5+$  yield. In summary, catalyst deactivation at a constant temperature occurs by gradually decreasing the RON and increasing  $C_5+$ , indicating that catalyst functionalities for desired reactions (dehydrogenation, dehydrocyclisation and isomerisation) and undesired reactions (hydrocracking, hydrogenolysis) are both affected.

The iso-RON operation was started at 150 h TOS and **Figure 7** demonstrates that the RON values are converging towards the target RON with a precision of  $\Delta RON < \pm 0.4$ . Consequently, the temperatures in **Figure 6** diverge to the SOR temperatures and, from there on, the RON decline is automatically compensated by automated temperature adjustment. At a constant RON, the temperature can be used to describe the activity of the catalyst and the slope of temperature increase can act as a descriptor for deactivation. Accordingly, a low initial temperature of catalyst A indicates high initial activity and the high slope of the temperature increase reflects strong decay. Catalyst E combines slightly less initial activity with the lowest decay of all catalysts and outperforms catalyst A in terms of activity at 800 h TOS and higher. The crucial performance parameter stability or cycle length for fixed bed reforming catalysts can be



**Figure 9** Statistical evaluation of performance parameters and corresponding catalyst rating for 200-260 h TOS. Standard error (SE) range and precision are shown in brackets

estimated by extrapolating the temperature increase to the point at which the heater limit is reached. This assumes a constant temperature increase, which can fail above a certain temperature and deactivation state. Furthermore, this extrapolation does not take decreasing  $C_5+$  yields at higher temperatures into account, below which operation would not be economical. More information on the long term performance is obtained by measuring the full cycle length of a catalyst by extending the measurement time or using

accelerated decay conditions (lower hydrogen partial pressure, lower total pressure, higher WHSV or higher target RON). On the other hand, high severity and aggressive protocols far from real conditions will speed up testing, but do not necessarily represent the deactivation behaviour and performance of catalysts in commercial reformers. Thus, a good compromise between the amount of time required and severity needs to be found.

Examination of  $C_5+$  yield in **Figure 8** under iso-RON conditions illustrates that formerly distinct

differences become very small and it is evident that a clear and reliable distinction of catalysts with similar  $C_5+$  yields (for instance, catalysts B and D) is only possible by having the statistical back-up of multiple positions. Deactivation and a corresponding temperature increase at proceeding TOS results in further differentiation, allowing the performance of aged catalysts to be assessed. While  $C_5+$  yield looks stable for the majority of catalysts, catalyst A shows a significant decrease and demonstrates that testing catalysts for a longer TOS can yield important additional information. This becomes more evident when taking a closer look at the remaining catalysts and catalyst B in particular, which starts with the highest  $C_5+$  yield but declines slightly and is overtaken by catalysts D and E at some point. The catalyst ranking for the initial performance of fresh catalysts can therefore be different to the performance of aged catalysts. Since  $C_5+$  yield at constant RON is directly related to economic return, selecting a catalyst on the market based on an independent catalyst test in addition to comparing performance data on paper can reduce risks and increase profitability in the long term. In addition, such a test demonstrates the capability of these catalysts to deal with the projected real feeds of a given refinery. Looking back to **Figure 4**, the feed composition and the corresponding high octane reformat illustrates the variety of reactions taking place, including the dehydrogenation of naphthenes and the dehydrocyclisation, isomerisation, hydrocracking and hydrogenolysis of paraffins and iso-paraffins.

In **Figure 9**, the performance parameters and corresponding catalyst ratings in terms of each parameter are shown for 200-260 h TOS. The standard error range is shown in brackets and systematic TOS effects were taken into account by first order linear regression. It is apparent that the target value for the RON is closely met. The activity is indicated by the temperature required to reach the target RON and exhibits differences of up to

14°C for the SOR temperatures. The  $C_5+$  yield shows high reproducibility (SE  $< \pm 0.05$ ) and a clear ranking even for catalysts B and D, which could barely be differentiated without the statistical back-up. The same ranking is also reflected in the aromatics and hydrogen yields. One exception is catalyst B, which produces more aromatics compared to catalyst D and should therefore have a higher hydrogen yield. Apparently, the hydrogen is consumed by hydrocracking, which is indicated by a lower  $C_5+$  yield of catalyst B. In general, the standard error ranges of these performance parameters are very small and indicate high accuracy and reproducibility, thereby leading to a reliable ranking of catalysts. At the end, refiners can make a catalyst

## Precise operation at a constant RON is accomplished by utilising integrated software solutions for process control, analytics and data evaluation

selection based on their preference regarding activity, selectivity, stability and catalyst cost.

### Conclusions

Despite various challenges, high throughput testing of naphtha reforming catalysts in 16 parallel reactors was achieved successfully under commercially relevant conditions. Keys to success include careful loading of the reactors, a sophisticated unit set-up with high reproducibility, and fast and accurate analytics. The semi-adiabatic reactor set-up in multiple reaction zones is very close to industrial practice and redundant positions of the same catalyst provide results with high statistical significance. Precise operation at a constant RON is accomplished by utilising inte-

grated software solutions for process control, analytics and data evaluation. All data is centralised in one database and in one format which offers effective data handling, advanced data analysis and fully automated data processing.

The results provide precise, fast and industrially meaningful differentiation of catalysts by activity, selectivity and stability, and deliver all information necessary to identify the best performance in R&D or commercial operation.

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