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FCC Operations Benchmarking: A Valuable Tool for Identifying Opportunities for Improved Profitability

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Engelhard has worked extensively with Astron International to develop benchmarking tools for analyzing FCC Unit and catalyst performance. Operating data from hundreds of FCCUs can be analyzed to determine best in class performance as well as pinpoint areas for improvement. The database can be sorted to analyze effects of multiple variables, including hardware effects such as riser termination devices and catalyst coolers, as well as by feed type and catalyst technology. Benchmarking allows refiners to validate their performance against their peer group as well as the world. In this paper, the following topics are explored:

- catalyst changes in the marketplace from 2002 through 2005
- advanced riser termination devices with state of the art feed injection are compared to open reactor systems
- a major feed change to an operating FCC is looked at relative to the entire FCC database, and,
- Performance of catalysts derived from Engelhard's Distributed Matrix Structure (DMS) platform is investigated relative to all other catalyst technologies.

Benchmarking Development

Engelhard first began a concentrated benchmarking effort in the early 1990s to analyze industry trends (reference 1, 2). In 2004, Engelhard partnered with Astron International, Inc. to improve our capabilities for both operating data and equilibrium catalyst performance benchmarking, resulting in the development of a powerful Web based FCC benchmarking application. This application allows Engelhard to easily manage, update, search, and produce charts and reports that clearly show important shifts in FCC operation due to catalyst, technology, or feedstock changes and identify opportunities for improving unit performance.

The significant features of the Benchmarking application are:

1. Web based for centralized and secure access with a Web browser
2. Integrated with Engelhard's LIMS system for near real time update of Equilibrium catalyst analyses
3. Standardized Excel based data import feature for uploading FCC operating data
4. Powerful parametric search with query builder for precise and infinitely flexible searches
5. Powerful charting features to create XY and histogram charts downloadable in Excel
6. Powerful reporting features to create standard comparison reports downloadable in Excel
7. Personalized features to save charts and reports for quick retrieval

Engelhard uses our benchmarking capabilities as a strong part of our technical service program. This tool allows us to show an individual unit's performance relative to the majority of the market, and areas for improvement are readily apparent. Figure 1 illustrates the hierarchy of the benchmarking process.

Engelhard has used benchmarking to rank the performance of a particular FCC relative to other units operating at comparable conditions, to complement FCC catalyst testing which has some inherent risk due to complications of prepping the catalysts to effectively mimic actual operations, and as a tool to help guide future Engelhard Research and Development focus.

In all cases, Engelhard treats unit operating data as confidential and will not disclose the origin of the data unless there is prior consent from the data source. Any charts shown will not include sufficient information to identify the unit or operating company.

Benchmarking Example #1 – Time Based Events

One of the simpler applications of benchmarking is to explore changes over time; any input into the benchmarking application can be viewed on a time basis, meaning it is possible to look at how the following FCC operating effects change with time:

- Conversion levels
- Product properties
- Heat balance conditions
- Feed properties, and
- Catalyst properties

Benchmarking can also be performed looking at how particular units move relative to the rest of the database with time; in this fashion, benchmarking can illustrate success or failure of individual locations optimization efforts.

In this paper, we show some examples of how equilibrium catalyst properties have moved over time, comparing 2002 to 2005. Figure 2 shows a histogram of equilibrium catalyst rare earth oxide levels in 2002 and 2005. In this chart, data from approximately 200 FCCs are plotted, representing the vast majority of the North American units as well as a representative global distribution. Rare earth has increased over the last 3 years, with the major changes seen with fewer units operating in the region of 2 weight percent rare earth oxide. There is a marked rise in units operating between 3 and 4 weight percent rare earth oxide in 2005 relative to 2002. The average rare earth levels of all units' catalyst are up by approximately 0.3 weight percent which is approximately a 15 % increase. In 1994, the average rare earth oxide level for the entire United States was 1.2 wt %; there is a dramatic increase upward over the 11 year time period. The West Coast of the U.S. averaged 2.3 wt % rare earth oxide in 1994 (2).

For the same time period, equilibrium catalyst activity is up by only 0.2 weight percent, with the 2002 average being 71.6 weight percent while the 2005 average activity is 71.8 weight percent. The histogram (Figure 3) shows that the 2005 data set is more tightly clustered around a 74 – 76 activity, as determined by Engelhard's FACT measurement. In 1994, the entire U.S. FCC population had an average activity of 67.8 wt % (MAT, measured value equivalent to FACT). At that time, the West Coast area of the US averaged 71.3 wt % activity (2).

Equilibrium catalyst metals are shown in the following table:

Table 1: Metals Average Values

	Nickel (PPM)	Vanadium (PPM)	Mg (Wt %)
2002	1615	1680	0.19
2005	1380	1830	0.34

Nickel is down approximately 15 % in 2005, while measured vanadium shows an increase of approximately 9 %. There is a substantial change in magnesium loadings, which likely indicates more units using SOx reduction chemistries. Since most SOx reduction additives include rare earth, magnesium, and vanadium, this also impacts the observed vanadium loadings.

Benchmarking Example #2 - FCC Unit Hardware Effects

There are numerous hardware features that can be selected for benchmarking. Engelhard has previously presented some information observed for two-stage regeneration design effect on equilibrium catalyst activity versus vanadium loadings at similar catalyst age (reference 3). Other possibilities include catalyst cooler operating effects, oxygen enrichment, and unit geometry.

In this paper, advanced riser termination device (RTD) performance is compared to open reactor systems; in this instance, actual operating units with and without advanced RTDs are compared to see if the two types of unit operations show any separation in performance. For the benchmarking effort, all licensors' recent technologies are considered equal; the data set called 'Advanced RTD' includes various designs of two-stage cyclones that are coupled together, two stage systems consisting of a contained modified inertial separator direct coupled with an upper cyclone, as well as post-riser quench operation. The inertial separator data set refers to the reaction systems that have an active vapor space that operates at near riser outlet temperature.

Advanced RTDs are generally thought of providing a major advantage in the reduction of post-riser cracking, meaning a significant advantage should be apparent in dry gas yield and delta coke effects. Engelhard's benchmarking analysis confirms the dry gas advantage; inertial separators show a penalty in dry gas production at any riser outlet temperature when compared to Advanced RTDs (Figure 4). Due to the lower gas selectivity of Advanced RTD operation, it is also evident from the data that many refiners elect to operate at higher riser outlet temperatures.

Expectations in the industry vary regarding final FCC conversion levels after installation of an advanced RTD. Looking at the benchmark data set, it is seen that there is almost no separation in chosen conversion levels for a given feed K-factor (Figure 5), confirming the expected trend.

However, even with little change in overall conversion level, there is an advantage in C3+ liquid volume yields, particularly at operating conversion levels less than 80 volume percent (Figure 6). The volume swell is directly influenced by the favorable change in coke and dry gas yields.

To summarize what Engelhard found in 1994 (1, Table 9), when looking at units that went from open reaction systems to installation of an advanced riser termination device, the following changes were seen:

Table 2: Changing From Inertial Terminator to Advanced Riser Termination

Refinery	**1**	**2**	**3**	**4**
Riser Outlet Temperature (ºF)	+25	+11	+19	+46
Regeneration Temperature (ºF)	-32	-27	+16	+8
Conversion (Vol %)	+3.1	+1.4	+4.2	+1.2
Dry Gas (Wt %)	-1.7	-0.7	+0.2	+0.5
Change in C3+ Liquid Yield (Vol %)	+5.3	+0.2	+0.3	-0.7
Change in Fresh Catalyst REO (Wt %)	+1.1	+0.9	+1.6	+0.2
Change in Ecat Total Surface Area (m2/g)	+20	+70	+12	+33
Change in Ecat Activity (MAT, Wt %)	+5	+5	+7	+2

Overall, the conclusion was that installation of an Advanced RTD could give significant yield advantages and dramatically improve unit performance. Note that Refinery 1 observed a +6 volume percent increase in LPG production, accounting for the entire volume balance shift.

Observing the benchmark today, Engelhard concludes that refiners that have opted for Advanced RTD installation operate with an improved volume gain relative to the inertial separator data set. This seems to be an intentional choice rising from unit limitations and constraining severity.

Benchmarking Example #3 – Major FCC Feedstock Change

In recent years, there have been several FCC units that experience major changes in feed properties. These changes involve going from a gas oil operation to resid processing, where the typical issues faced are keeping the FCC regenerator temperature and catalyst contaminants low enough to avoid excessive catalyst deactivation while maximizing cat to oil ratios and riser conditions to generate favorable yields

There are also cases of essentially the opposite; units that previously processed resid that for varying reasons choose to start processing highly hydrotreated gas oils, or sometimes hydrocracker bottoms. In these cases, the FCC heat balance is extremely important as catalyst circulation limits may manifest themselves with the dramatic changes in regenerator temperature that are likely to occur.

For this example, an FCC unit previously processed resid and changed their feed sourcing to a hydrotreated gas oil. The API gravity of the two feeds was approximately 21º API for the resid and 26º API for the gas oil. The K-factor for the resid was calculated to be approximately 11.6 while the gas oil K-factor was approximately 11.7.

When the unit began processing the new gas oil feed stock, the regen operation was dramatically different, with temperature coming down approximately 80º F (Figure 7); this resulted in a huge increase in catalyst to oil ratio. An important consideration is that while this was a dramatic change for this unit, the operation shifted to a best in class operating line in terms of regen temperature relative to reactor temperature. There are numerous other FCC operations that are bracketing this operating region; even with this severe change in unit heat balance, the unit did not expand the operating map of observed performance.

Exploring the change experienced in overall liquid yield, a dramatic change resulted from the feed stock going from resid to gas oil. The unit previously operated at the poorest conversion to volume balance operating line observed in the entire benchmark and was shifted upwards by approximately 2.5 volume percent to near the best operating line (Figure 8).

In the operating mode change, catalyst technology and required addition rates were also adjusted. On resid operation, the unit typically operated at what would be described as the best operating line in terms of equilibrium catalyst activity. With gas oil processing, it was found that lower activity was more economical, and catalyst composition and consumption were changed dramatically; the resulting optimum was more in the center of the operating map (Figure 9).

This example illustrates that the universal FCC operating window is well defined in the Engelhard benchmarking database. Best in class performance can be achieved in many cases and is fairly predictable on an empirical basis; this can be used to validate or refute projections where operation is expected to change dramatically. It has been observed that for various reasons, yield projections may inadvertently violate this well defined operating window; the benchmark process provides a check on the validity of estimates.

Benchmarking Example #4 - the Distributed Matrix Structures Platform Technology

The Distributed Matrix Structures (DMS) platform technology was first introduced in 2000 with the commercial launch of NaphthaMax® fluid catalytic cracking (FCC) catalyst, and has since been demonstrated in over 100 commercial FCC unit operations. This unique catalyst pore architecture combines optimized porosity for heavy feed molecule diffusion with selective zeolite based cracking to achieve deep bottoms conversion with low coke formation (4, 5).

The structure imparted by the novel DMS matrix is designed to provide enhanced diffusion of the feed molecules to pre-cracking sites located on the external, exposed surface of highly dispersed zeolite crystals. The feed initially cracks on the zeolite surface itself, rather than on an active amorphous matrix material, as is the case with other FCC catalyst technologies. This provides better selectivities, with reduced coke formation, characteristic of zeolite cracking. The secondary diffusion of the cracked products to the internal crystalline zeolite surface is also minimized, resulting in less overcracking. The net result is high bottoms conversion with low coke, and higher yields of valued gasoline and light olefin products.

This unique structure is illustrated in the SEM micrograph of the interior of a catalyst particle in Figure 10 . The well-developed pore structure is evident, and essentially the entire exposed pore surface is covered with zeolite crystallites. The external surfaces of these crystallites are exposed and accessible to the hydrocarbon feed molecules, which diffuse readily through the controlled pore structure. While other catalyst technologies may feature similar or even higher total pore volumes, they do not have the same morphology and inherent zeolite based cracking pattern imparted by the DMS structure.

Benchmarking the DMS Platform Technology Performance

The DMS platform products that are analyzed for this study are:

- NaphthaMax, a DMS product for maximizing naphtha yield with gas oil feed
- Flex-Tec, the DMS product for the most severe resid processing conditions
- Endurance, the DMS product for moderate resid operations, and
- Converter, a DMS product used as an additive in conjunction with other base catalysts

The data set selected for NaphthaMax performance was for equilibrium catalysts from gas oil operation with combined equilibrium catalyst metals of less than 2000 ppm, represented as nickel plus vanadium. The time period selected was for the second half of 2005. This data set for this time period included 17 FCC operations using NaphthaMax out of a total data set of 111 FCCU operations. There are over 100 successful commercial applications of the DMS platform technology; other applications of the platform are included within the 111 identified FCC operations, with only the NaphthaMax operations identified separately.

For the gas oil data set, NaphthaMax demonstrates extremely coke selective bottoms upgrading that differentiates itself from the rest of the technology offerings (Figure 11). At any level of coke production, the combined NaphthaMax performance yields between 1 and 2 weight percent lower bottoms yield. Additionally, Figure 12 shows the excellent coke selectivity of the NaphthaMax data set relative to the other catalyst offerings; at any coke production level, there is approximately 1.75 weight percent higher conversion for NaphthaMax compared to the other gas oil catalysts.

While the NaphthaMax performance looks excellent, it is also important to note that at any given conversion level, the NaphthaMax series tends to have higher metals loading as calculated by equivalent nickel levels (Figure 13). The coke selectivity and activity maintenance are excellent even with higher overall metals loadings.

The DMS resid products are analyzed in a benchmark data set filtered to represent resid processing where combined metals on equilibrium catalyst are at least 2500 ppm nickel plus vanadium, and units where at least 15 % of the FCC feedstock boils above 1050°F. There are four data series shown on each chart; Flex-Tec, Converter, and Endurance represent the DMS technology platform, with the remaining series being all other ‘state of the art’ catalysts.

One of the most important aspects of the DMS technology platform is the ability to achieve bottoms upgrading with excellent coke selectivity; this is demonstrated in Figure 14, where the benefits inherent in Flex-Tec, Converter, and Endurance are shown relative to the other offerings in industry. Similarly, Figure 15 shows very high activity at any given level of coke production for the DMS resid applications; the conversion obtained per unit of coke production is high.

The metals tolerance of Flex-Tec shows superior performance relative to other technologies as demonstrated when looking at ACE hydrogen yield compared to the catalyst equivalent nickel content (Ni + V/4 + Cu + Fe/10 – 4/3 Sb), shown in Figure 16.

Vanadium tolerance of individual units is dependent on hardware and operating conditions (temperature, regenerator geometry, and combustion mode). Looking at strictly equilibrium catalyst vanadium levels and activity (Figure 17), the DMS platform resid offerings maintain high activity at varying vanadium levels.

Finally, looking at operating data for all of the FCC Units contained in the benchmark at the end of 2005, there is marked advantage of the DMS platform to sustain higher equilibrium catalyst activities at any given catalyst addition rate, expressed as pounds of catalyst added per barrel of feed (Figure 18). Additionally, the operating data also shows the actual unit performance of slurry production and conversion for all units, with the DMS platform clearly showing favorable performance, yielding approximately 1 volume percent lower slurry at any given conversion level (Figure 19).

Conclusions

Engelhard Corporation has incorporated benchmarking as an important tool in routine FCC data discussions for some time. Engelhard uses benchmarking to validate unit data as well as identify areas for improved performance. Additionally, units can be operating very well and may not realize their success relative to the FCC unit population.

The FCC unit operating envelope is continually being expanded; this expansion usually comes in small increments, so operational changes that indicate major step out performance should be approached with caution as it is often difficult or impossible to dramatically expand the known operating map unless the operation is already at the boundary. Engelhard will continue to further develop and use benchmarking to analyze FCC operations and define new and improved operating envelopes.

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2) "FCC Catalyst Trends : Responding to the Challenges of the 1990's"
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4) "NaphthaMax™ – Breakthrough FCC Catalyst Technology for Short Contact Time Applications"
J. B. McLean and D. M. Stockwell
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5) "The Role of Porosity in the Cracking Selectivity of FCC Catalysts"
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Figure 1: Benchmarking Application and Work Process

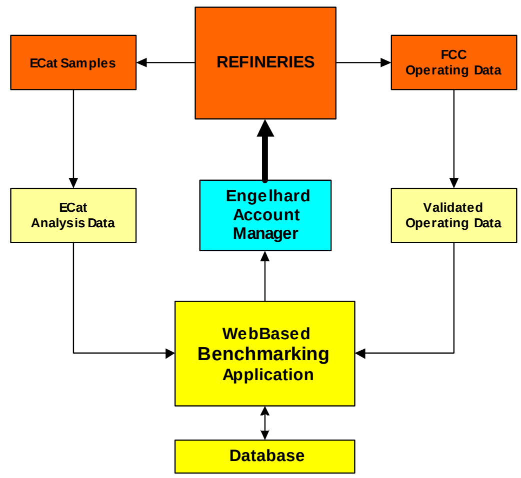

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Figure 2: 2005 Equilibrium Catalyst Shows Rare Earth Level Up Slightly Over 3 Years, Dramatically Up Over 11 Years

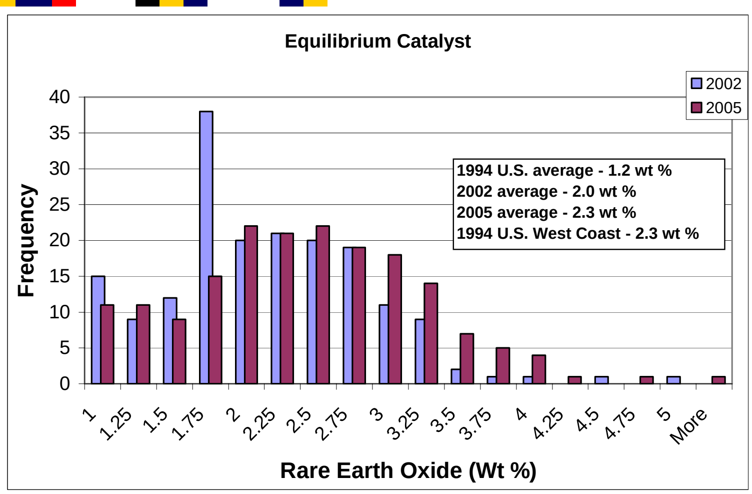

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Figure 3: Equilibrium Activity Shows Slight Change Over 3 Years, Large Increase Since 1994

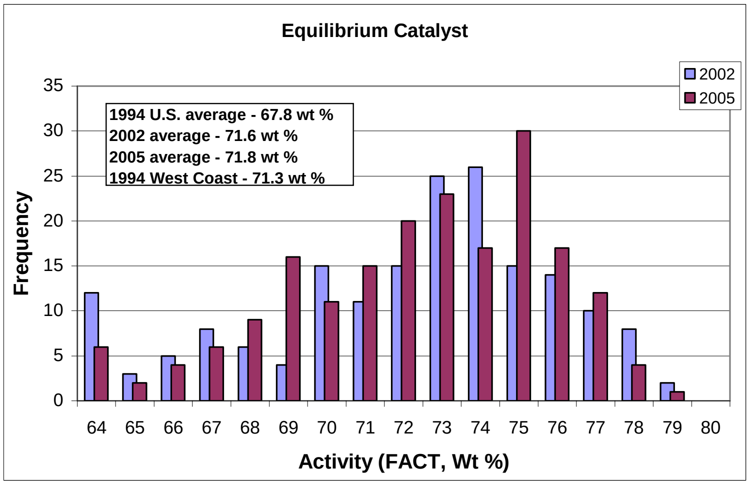

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Figure 4: Advanced Riser Terminators Display Significant Dry Gas Advantage

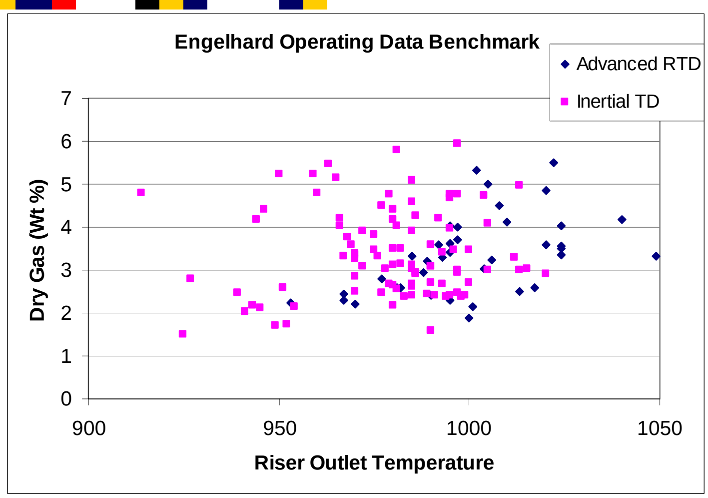

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Figure 5: Advanced RTD Shows Same Conversion Trend as Inertial Terminators

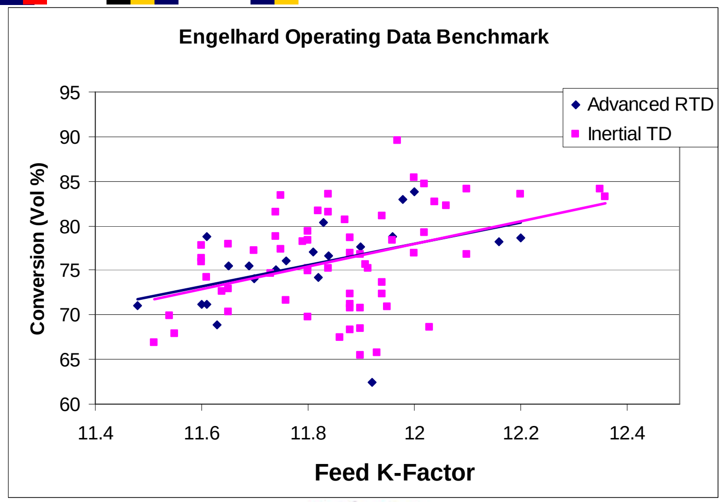

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Figure 6: Advanced RTD Does Have Volume Balance Advantage To ~ 80 % Conversion

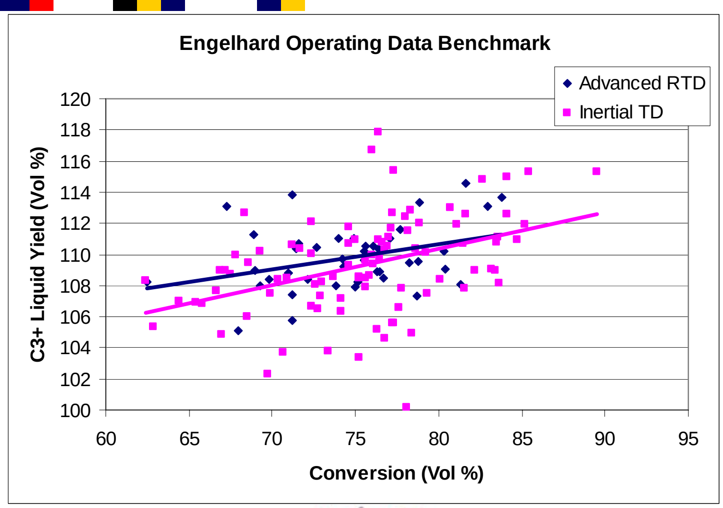

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Figure 7: Regen Temperature Dropped 80+ F When Processing Gas Oil Feed

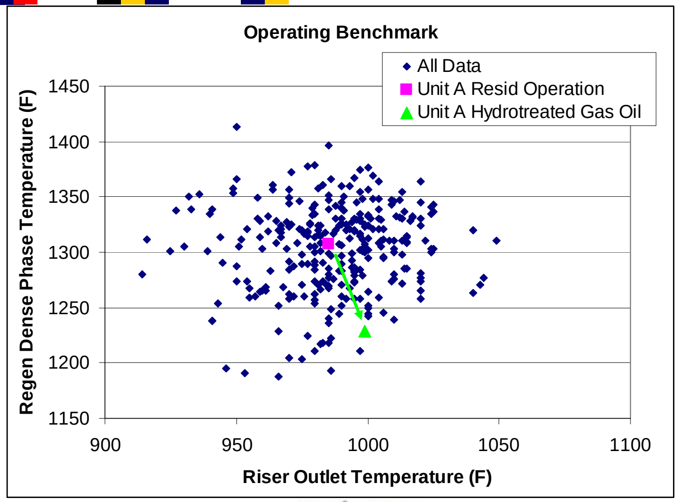

Figure 8: Dramatic Increase in C3+ Liquid Yield Observed While Processing Gas Oil

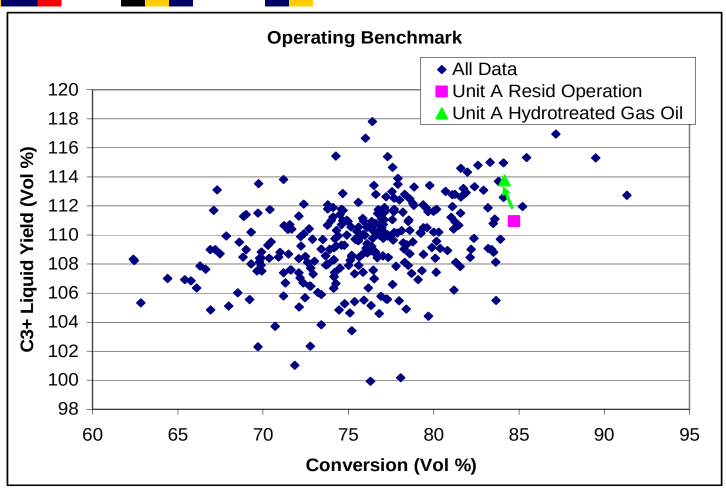

Figure 9: Unit Ended at Lower Ecat Activity and Much Lower Addition Rates During Gas Oil Operation

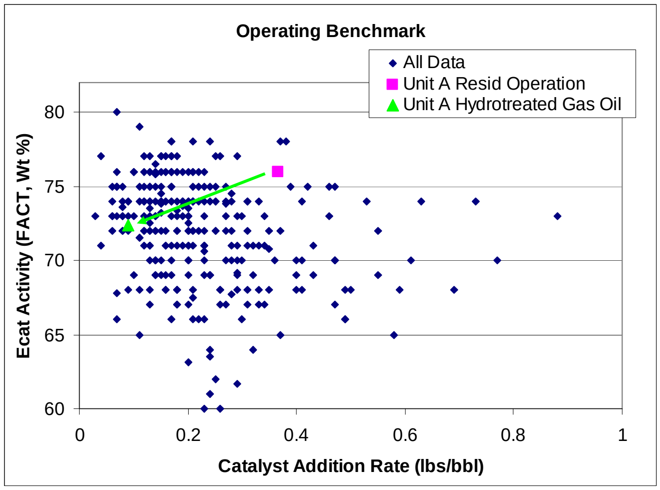

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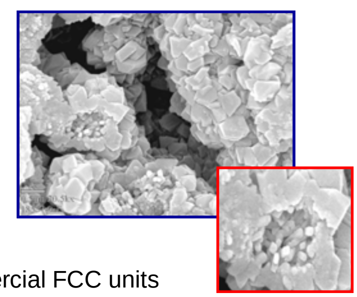
Figure 10: Distributed Matrix Structures

A Technology Platform for Advanced FCC Catalytic Solutions

- Distributed Matrix Structures (DMS)
  - a unique and novel FCC matrix
  - combines optimized porosity with high activity
  - enhanced diffusion of heavy feed molecules
  - selective precracking with exposed zeolite



- Successful operation in more than 100 commercial FCC units
- Multiple FCC catalyst and additive products address a variety of applications

2004 FROST & SULLIVAN Technology Leadership Award

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Figure 11: NaphthaMax Demonstrates Coke Selective Bottoms Upgrading

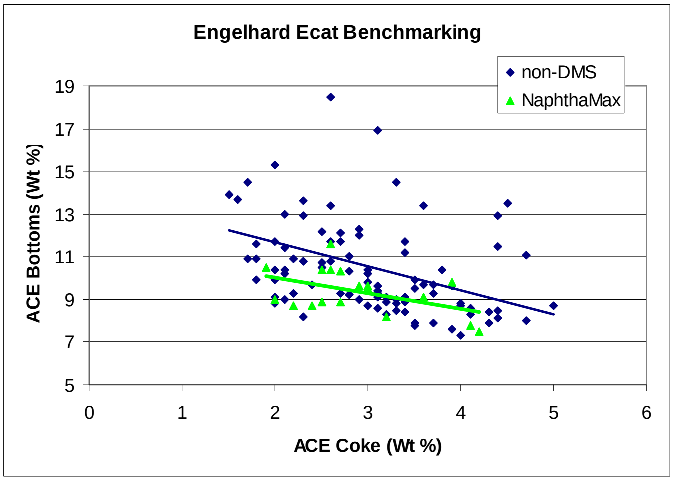

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Figure 12: NaphthaMax Operation Shows Outstanding Coke Selectivity

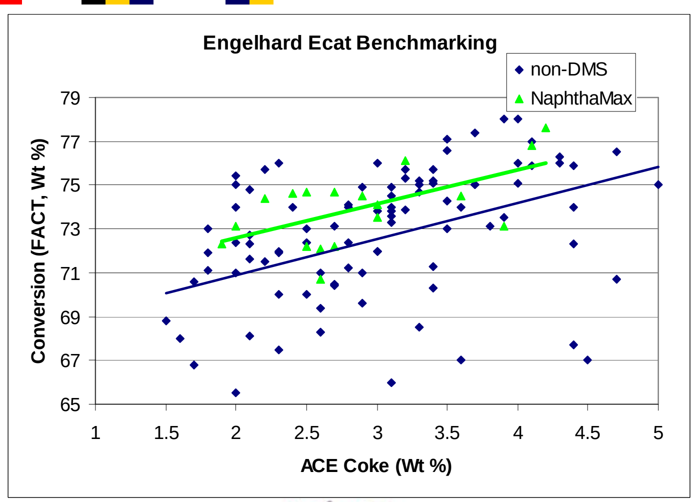

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Figure 13: NaphthaMax Operation Shows Slightly Higher Conversion at Constant Equivalent Nickel Loading

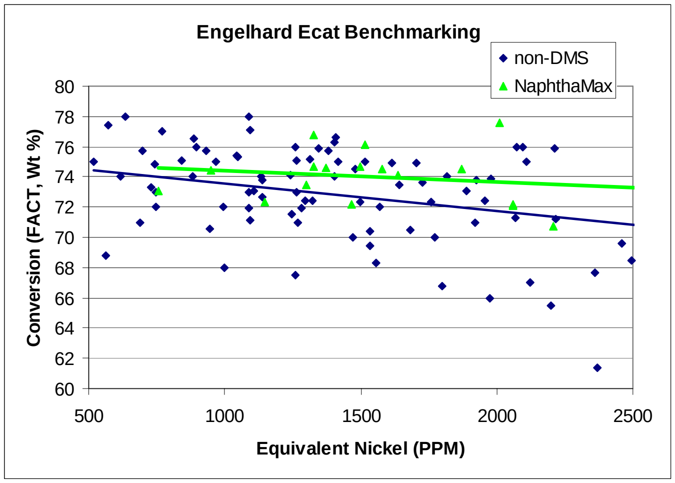

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Figure 14: Resid DMS Technology Demonstrates Coke Selective Bottoms Upgrading

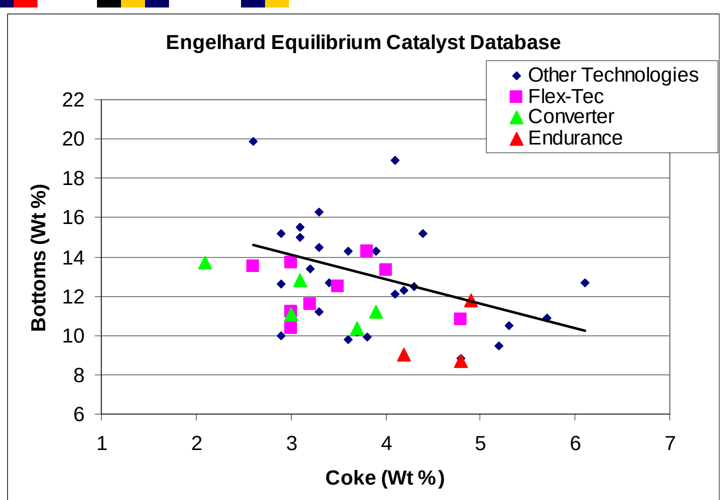

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Figure 15: Resid DMS Technology Shows Excellent Coke Selectivity

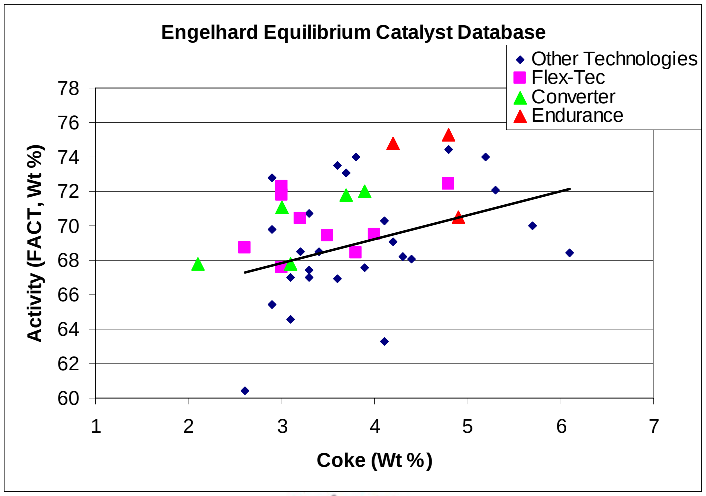

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Figure 16: Hydrogen Make a Function of Metals Trapping

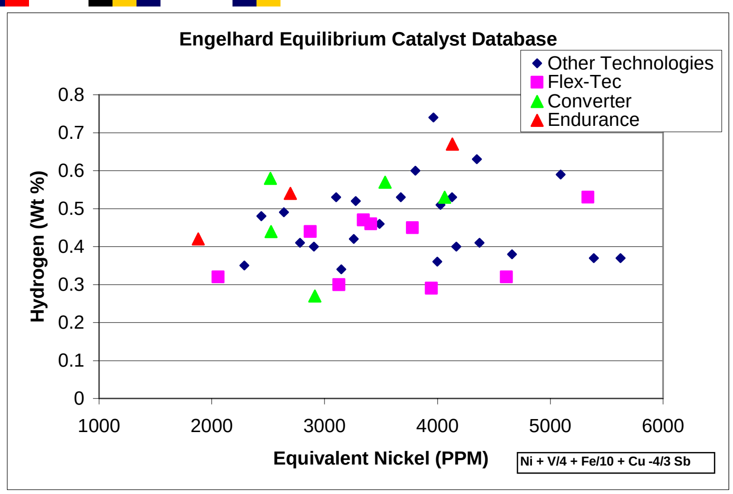

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Figure 17: Resid DMS Technology Demonstrates Outstanding Vanadium Tolerance

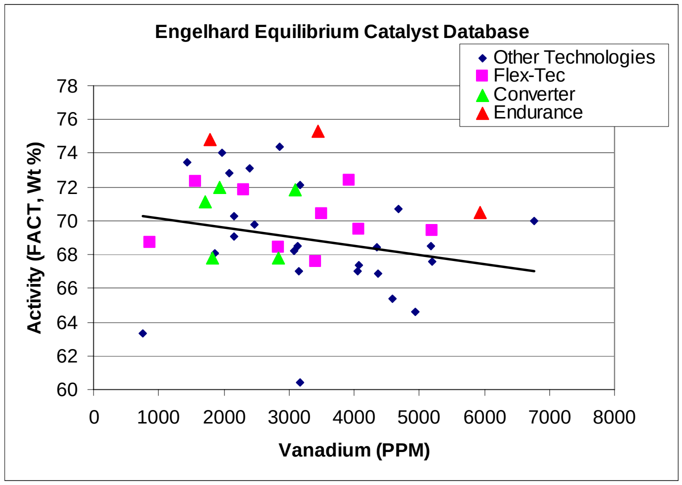

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Figure 18: Catalyst Addition Rates Comparing the DMS Technology Platform to non-DMS Materials

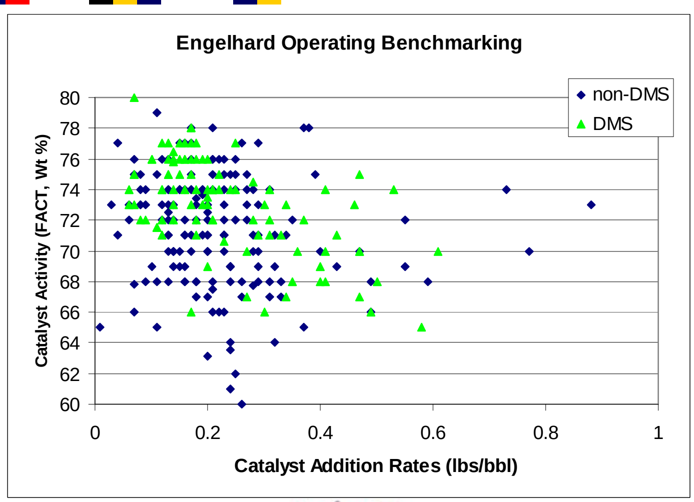

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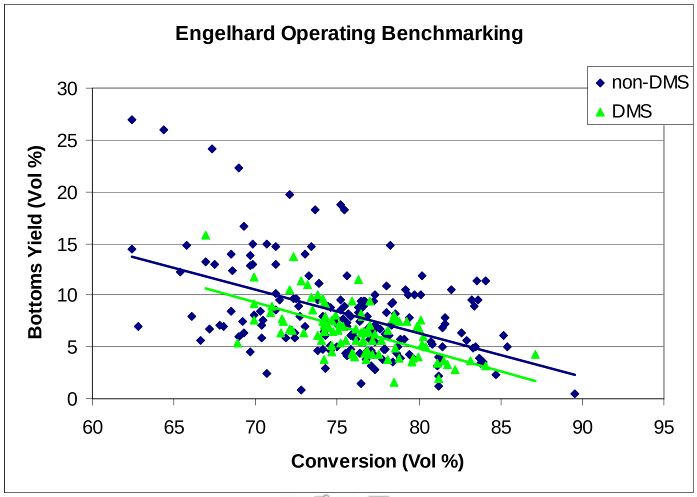
Figure 19: DMS Technology Platform Shows Improved Bottoms Upgrading Relative to Other Technologies



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