Cat Cracker Seminar
August 21-22, 2018
Royal Sonesta Hotel
Houston, TX

CAT-18-980

Simulation as a Tool for Learning from Historical FCCU Operations

Presented By:

Sam Clark
Senior Project Engineer, Chemical
CPFD LLC
Albuquerque, NM

Simulation as a Tool for Learning from Historical FCCU Operations

Peter Blaser, Sam Clark, John Pendergrass, Ray Fletcher

CPFD, LLC
10899 Montgomery Blvd. NE, Suite A, Albuquerque, NM 87111 USA
E-mail: peter.blaser@cpfd-software.com

Trends Observed
Almost all FCC engineers can readily identify individuals that are generally known to have a deep knowledge of FCCU operations. These individuals, for the purposes of this discussion, will be referred to as subject matter experts (SMEs)[1]. The demographics are often similar; the FCC SME typically has as much as 40 years' experience, has likely worked at multiple refiners, technology licensors and/or catalyst companies, might be an independent consultant today and, critical to this discussion, usually doesn't envision working another 10 years!

While the gap between SMEs and others exists in multiple industries and is nothing new, it seems the gap has been widening in recent years. Several trends have been observed which relate to a declining number of individuals with deep FCCU expertise[2]:

<u>Trend #1: Retirements of SMEs.</u>
The first trend noted is the recent and near-term retirement of existing SMEs. While those with extensive experience are nearly always closer to retirement than those new to a field, a disproportionate number of FCC SMEs are reaching the end of their careers concurrently. Several factors contribute to this.

According to a recent retiree: "*The late 1970s and early 1980s saw a lot of engineering grads entering petrochem and refining. It was a good job and you could make a good living at a time when other options for chemical engineers were limited. That dropped significantly after say '83 or '84. Oil prices dropped, times were tighter and new fields like biotech started to attract the graduates.*"

Another SME added: "*More recent graduates see the smoke stacks, rather than the technology. It's challenging to attract young talent, and then can be hard to keep them. As a result, I rarely see anyone in their 40s in refineries*." More engineering graduates entered refining about 35-40 years ago than say 25-35 years ago. Putting it all together, we're facing a wave of retirements of a disproportional amount of specialists with fewer poised to take their place.

<u>Trend #2: Decreased Development of new SMEs.</u>
While the retirement of those entering the workforce 35-40 years ago is expected, the second half of the picture – the shortage of deeply experienced replacements – merits further exploration. Put

simply, training of new SMEs is not what it used to be. This can partly be attributed to an emphasis on diversity of experience, a trend which is consistent with the broader culture.

One SME commented, "…*anyone good is put on a track to perhaps one day become a refinery manager, so they're moved every couple years or so*." Another added: "*I'm not sure if it's companies moving people, or people wanting to move. This generation wants a diversity of experience.*" A third SME agreed: "*Engineers seem more aggressive in moving up a career ladder, whether that be within a company or switching companies. This can be a good thing – they get a diversity of learning, show initiative, they open new opportunities for others – but there is some inherent danger here. It's scary when people learn just enough to move on to the next role, but never more.*"

While diversity of experience is important to a managerial career path, it can be detrimental to the deep learning necessary for the development of technical expertise. Technical expertise involves finding something you love, learning all you can about it, gaining direct experience, and sticking with it for a very long time. Fewer engineers have career paths available to them which allow for the long-term focus necessary to develop deep expertise. At the same time more companies opt to out-source such expertise, but with fewer SMEs being developed, this trend does not bode well for the long-term future[3].

<u>Trend #3: Extended FCCU operational cycles.</u>
FCCU operational cycles between turnarounds have also been increasing. Over the past 40 years, run lengths have increased from 18-24 months to as much as 5-7 years. While this represents significant progress, it has reduced the opportunities for operators and engineers to learn about all aspects of unit operation, including start-up, shut-down and turnaround.

Consider an engineer with a 4 year rotation on an FCCU back in a time when the operational cycle was 24 months. That engineer would have seen two start-ups, two full runs, two turnaround planning seasons, two shutdowns and two turnarounds. Today, it is possible to have an operator on a unit for 5 years or longer, who has never shut the unit down. While uptime is critical to refinery operations, it lessens the opportunity for FCCU expertise development.

<u>Trend #4: Increased instrumentation and automation</u>.
This last trend is probably the least intuitive. Instrumentation and related automation of FCCUs has vastly improved in recent years. Like the previous trend, this is a good thing yet comes with an unexpected side effect, namely the reduced frequency of opportunities to learn more.

According to one FCC SME: "*Instrumentation has become very good, to the point where some operators can now just sit and watch much of the time. But that means they get less practice on the unit, especially with tasks such as start-up, shut-down and emergency response. This is a good thing overall – the system will automatically act to protect people and the unit from damage, but it can't handle everything. The surprises then become more surprising and if the operator isn't an oldtimer, the operator can freeze.*" Another SME added: "*digitalization changed things. There's more data and more automation, but a less full understanding. People used to operate units, now instrumentation runs units.*"

FCCU Simulation

The trends mentioned above are not all-encompassing. However, these were selected to highlight the challenges refiners face related to the development of specialty expertise related to the FCCU in particular.

Some of the trends have positive aspects. The increased instrumentation trend, for example, opens the possibility of further digitalization and use of big-data analytics for problem-solving and optimization. Another positive trend, and central to this discussion, is the widespread use of simulation of FCCUs which is frequently used when anticipating changes to design or operating conditions, and is often performed prior to a turnaround. Simulation has been shown to identify root causes of underperformance, test the effects of potential changes prior to implementation, and minimize the risk of unforeseen negative consequences of changes.

This simulation trend also has a side effect. While most simulation is applied in a forward-looking sense – asking questions about the effects of changes prior to implementation – the first step in the simulation process is to establish baseline behavior, enabling a direct comparison of the effects of changes with historical operations. Thus, the side effect is that simulation becomes a tool for learning from historical FCCU operations and can augment the other means of learning available to an FCC engineer seeking to develop deep expertise. Two case studies follow where simulation was used to solve a problem. In both cases, the historical lessons learned are emphasized.

Case Study #1

Figure 1. The Geelong Refinery

The first example[4] is taken from Viva Energy's Geelong Refinery (Figure 1). The Geelong Refinery, formerly part of the Royal Dutch Shell group, is one of four refineries in Australia and employs more than 700 people. The refinery processes approximately 120,000 barrels per day (bpd) of crude and supplies over 50% of Victoria's, and 10% of Australia's, fuel. The refinery also provides feedstocks for the neighboring LyondellBasell polypropylene plant.

Geelong Refinery's 40,000 bpd resid cracker (RCCU) was built in 1992 and underwent multiple hardware changes during a turnaround (TAR) in 2011. Following startup afterburn, defined here as the temperature difference between the regenerator dense phase and flue gas line, became prevalent. The full burn unit was operated very close to the flue gas temperature constraint, but what really concerned the operators were frequent dynamic flue gas temperature spikes; the temperatures would suddenly and unexpectedly rise requiring immediate and frequent operator intervention. These caused the refiner to ultimately reduce rates below plan by almost 10 % for certain feedstocks, impacting overall refinery economics by tens of thousands of dollars per day. The dynamic afterburn events showed no correlation with any measured process conditions, even after utilization of advanced analytic techniques by refinery engineers.

In preparation for their 2016 TAR, engineers began to ask questions during TAR planning discussions. What really happened in 2011? Multiple hardware changes were made but process conditions also changed over time. If the hardware changes were the primary cause, was it one change in particular or the combination of multiple changes which together decreased robustness and stability? And, if additional changes were planned, would they help or perhaps even make things worse?

These questions prompted refinery staff to utilize simulation to learn from the historical behavior before looking forward to 2016 TAR planning. Historical, then-current, and then-future configurations were tested via three-dimensional, transient simulation of the gas-catalyst hydrodynamics, thermal behavior, and coke-combustion kinetics[5].

The computational model domain for the Geelong refinery's RCCU regenerator is shown in Figure 2. While details of internals cannot be shown, the major components are listed. Twelve primary cyclones are distributed around the circumference of the upper vessel with diplegs returning catalyst to the regenerator bed. A single regenerated catalyst standpipe hopper is used to withdraw regenerated catalyst near the top of the bed. Spent catalyst from the reactor stripper enters the regenerator in the middle of the bed via a spent catalyst inlet device (SCID). The air grid is also modeled, with boundary conditions defined for each air grid nozzle. Finally, two catalyst coolers withdraw catalyst from the dense bed, remove heat, and return catalyst at the bottom of the vessel.

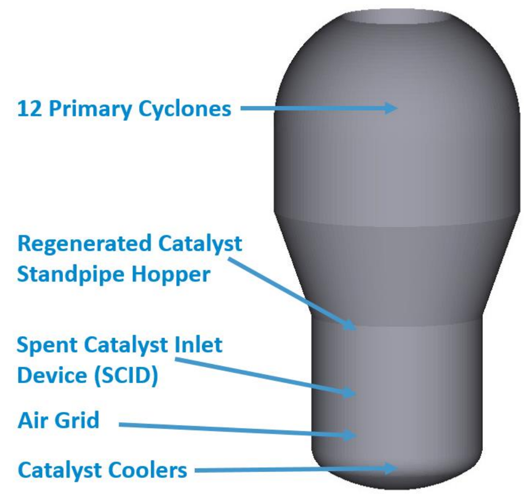

Figure 2. Regenerator Modeling Domain

Before simulating potential changes, the model was first used to understand the current and historical operations. The primary purpose of the baseline models was to identify the root cause of the afterburn thereby enabling targeted changes and a benchmark against which future improvements could be quantified in a virtual environment. Thus, the pre-2011 and post-2011 operations were both simulated before decisions were finalized regarding the 2016 TAR.

Figure 3 shows a summary of the changes made in 2011 (* relative to pre-2011 operations). Design changes include the installation of a new SCID as well as the removal of the hoppers at the top of the catalyst coolers. Around the same time operating conditions changed significantly. Following the turnaround the catalyst circulation was increased by 4.4% and the air rate was increased even more, by nearly 15%. The SCID changes necessitated major changes to SCID aeration, while minor changes to cat cooler operations also occurred.

	2011 Changes*
Design	
SCID	New design
Cat cooler	Hoppers removed
Operational	
Catalyst circulation	+ 4.4%
Air rate	+14.7%
SCID aeration	Major changes
Cat cooler	Minor changes

Figure 3. Summary of 2011 Changes

With so many changes the question remained: which change, if any, would prove to be the root cause? After all, the regenerator experienced both design and operational changes in the periods before and after the 2011 TAR. Which of these caused the increased afterburn and dynamic temperature spikes resulting in frequent panel operator intervention, conservatism and ultimately reduced throughput?

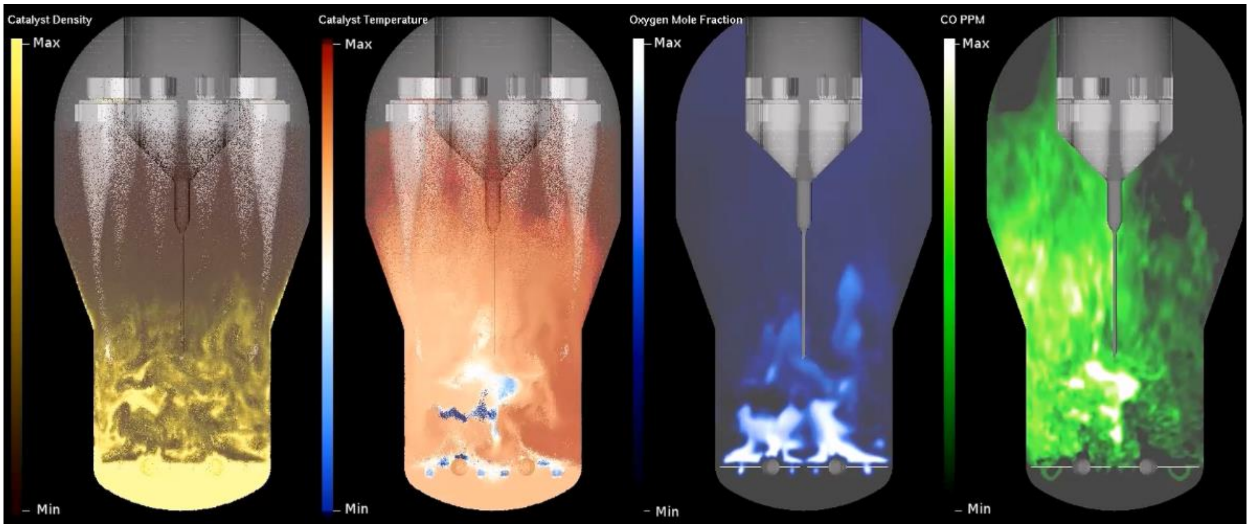

Figure 4. Sample Baseline Results

Sample results from the baseline model are shown in Figure 4. The figure shown is a snapshot in time from the transient simulation results.

The view on the left of Figure 4 shows catalyst colored by density. Several distinct fluidization zones are observed in the image. Poor fluidization is observed below the air manifold, as expected. A well-fluidized dense bed is visible from the air grid up to an elevation around the area change. Above here, the bubbles and turbulent mixing behavior observed within the dense phase give way to a splash zone and subsequent dilute phase, which persists up to the cyclone inlet elevations. All gas exits the regenerator at the cyclone inlets, and virtually no catalyst is present in the upper dome.

The second view from the left in Figure 4 shows the same catalyst particles colored by temperature. Again, several observations are easily made. The particles are relatively cool right at the air grid near the bottom and on the left, or west, side corresponding to the spent catalyst inlet location. The catalyst quickly heats to the regenerator operating temperature as it mixes and the coke combusts. The bed temperatures vary in both the radial and axial directions, with the highest particle temperatures present in the upper dilute phase, where the catalyst density is low. This is expected – if combustion occurs with less particle mass present, the resulting temperature rise is greater.

The second view from the right in Figure 4 shows oxygen (O_2) on a centerline slice through the model. Oxygen is high where injected and decreases with elevation. The O_2 is observed to break through the dense bed in bubbles and excess O_2 is apparent in the dilute phase through the top of the model.

The right-most frame in Figure 4 shows carbon monoxide (CO) on the same centerline slice. This view is particularly telling; much more CO is present on the west side of the unit, and a significant amount of CO enters the cyclones on the west. In practical terms, this full burn regenerator is operating somewhat like a partial burn unit, but only on the west side!

The CO imbalance provided the Viva Energy engineers with their first clue toward potential root cause of the afterburn problem. While it may be obvious that temperature spikes in the flue gas line were related to localized combustion of CO with O_2, the mechanism for the presence of CO, in spite of high concentrations of excess O_2, was becoming clearer. While lots of O_2 was present, it was not evenly mixed with the CO in the unit, resulting in the downstream combustion. However, the question remained, why was the CO higher on the west than the east?

To answer this question, the distribution of spent catalyst was investigated. Figure 5 shows only the spent catalyst which has a residence time less than 10 seconds, colored by temperature. An elevation view is shown on the top and a plan view on the bottom. The pre-2011 and post-2011 configurations are compared on the left and right of the figure, respectively.

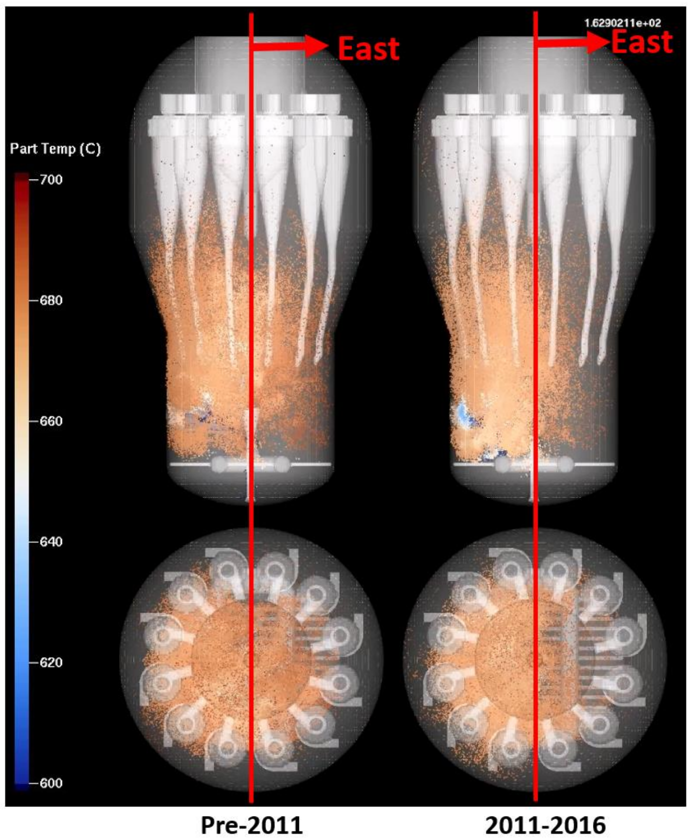

Figure 5. Maldistribution of Spent Catalyst

Visually, it appeared from Figure 5 that the pre-2011 configuration did a better job of rapidly distributing the spent catalyst across the regenerator. However, with simulation results, a quantitative analysis for each computational particle is possible, and was undertaken here. The quantitative results were more telling. While only 21% of the pre-2011 particles with less than 10 seconds of residence time were found on the east side of the unit, the post-2011 case was much worse; only 11% of the post-2011 particles crossed the unit centerline in fewer than 10 seconds.

Based on this, it was concluded that the 2011 changes introduced more maldistribution of air and catalyst in the regenerator. Put another way, the post-2011 case performed about half as well at distributing the spent catalyst all the way across the unit. This maldistribution clearly affected the elevated CO concentrations observed on the west side, nearest the SCID, but also affected O_2 much higher in the regenerator. Figure 6 shows the O_2 mole fraction on a cut plane at the cyclone elevations. The increase in O_2 maldistribution in the post-2011 simulation is apparent, further contributing toward the dynamic temperature spikes.

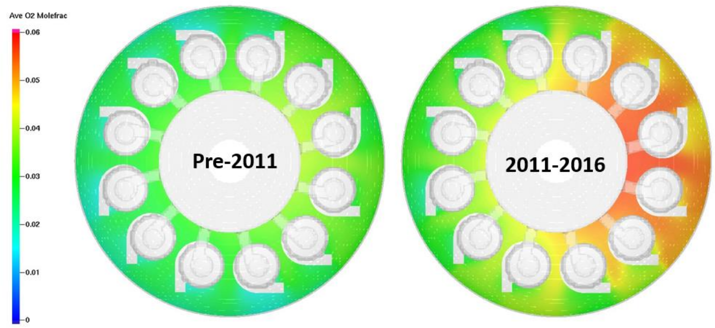

Figure 6. Maldistribution of Excess O_2

While no operational data are available for gas compositions within the regenerator itself, the flue gas compositions were measured further downstream and compared with simulation results exiting the regenerator as shown in Figure 7 for both the pre-2011 and post-2011 configurations. Both the magnitude and trends agree between the simulations and measured data. The slightly higher excess O_2 concentrations predicted by the simulation are expected; the simulation composition is measured at the cyclone inlets whereas the refinery measurements are downstream of the third stage separator. Additional combustion in the flue gas line will lower the simulation O_2 concentrations between these two locations, as evidenced by the observed afterburn.

The excess O_2 validation showed that the simulation results reflected reality. Excess O_2 was mixing with CO in the plenum resulting in the reduced performance, and the root cause was located much lower in the regenerator vessel itself, likely the SCID. The ability of the model to match historical observations gave refinery engineers confidence that the model could predict the effects of future changes.

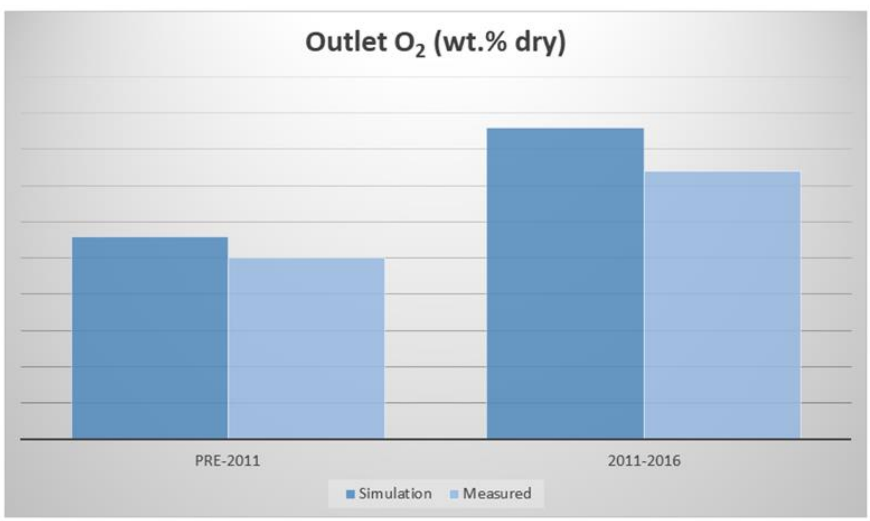

Figure 7. Excess O_2 Validation

The same model was then used to test proposed changes, which are beyond the purpose of this work. In short, simulation showed that the subsequent changes were expected to address the major root cause of maldistribution constraining system operation and gave the Geelong Refinery staff confidence in the planned changes in advance of the 2016 TAR.

Success was confirmed via post-TAR operational data. The data from 12 month periods immediately before and after the 2016 TAR revealed that, following start-up, the average afterburn was 5°C lower, the maximum daily throughput was 4% higher, while the number of panel operator interventions was reduced by 75%. Afterburn is no longer a regular topic of operational meetings at the Geelong Refinery!

While this represents a success story in itself, the focus of this discussion relates to how the simulation findings can be used to learn from historical operations. For example, this case shows how a problem in one FCCU component can find its cause elsewhere; the afterburn observed in the flue gas plenum was strongly affected by the spent catalyst distributor. Simulation enables identification of root causes of behavior as well as decoupling of multiple design and operational changes. By comparing multiple cases, the FCC specialist can obtain a cause-and-effect understanding which is not feasible to obtain on the actual unit, or else could take decades to discern.

Visualization of simulation results provides engineers with an understanding of the gas-catalyst hydrodynamics, thermal behavior and gas-catalyst reactions within the FCCU and, at the same time, provides a basis for communication with others. Here is how Ken Peccatiello, an FCC specialist with 41 years' experience, describes this effect:

> "*When I see something on the unit, I close my eyes and I let my mind run though it… but my language is not good enough to express what's [happening] to somebody else. The [simulation] actually takes what's going on in here – and sometimes even better than what's going on in here – and puts it in such a manner so that everybody can actually see it with their own eyes… They can see it for themselves and it's not a biased view. There's no bias in numbers. It's there, it's black and white, right and wrong, and it's there for everybody to see. I love the stuff.*"

Case Study #2

Our second example comes from a prominent refinery located in the eastern half of North America[6]. The refiner planned to replace FCC regenerator cyclones during a 2015 TAR. The pre-2015 configuration had three cyclone pairs, evenly spaced around the circumference. The proposed changes involved larger, high-efficiency cyclones and a modified arrangement with one secondary cyclone located in the center of the unit.

Simulation was performed prior to installation, and suggested maldistribution could be a problem. Figure 8 shows the CO at the cyclone elevations. While a non-uniformity was present in the then-current (pre-2015) configuration, the simulation predicted that the non-uniformity was expected to increase with the proposed changes. While there was insufficient time available to make major changes prior to the TAR, this information prompted the refiner to modify the air grid orientation prior to installation, in an effort to direct more air to the CO-rich region observed on the right of Figure 8.

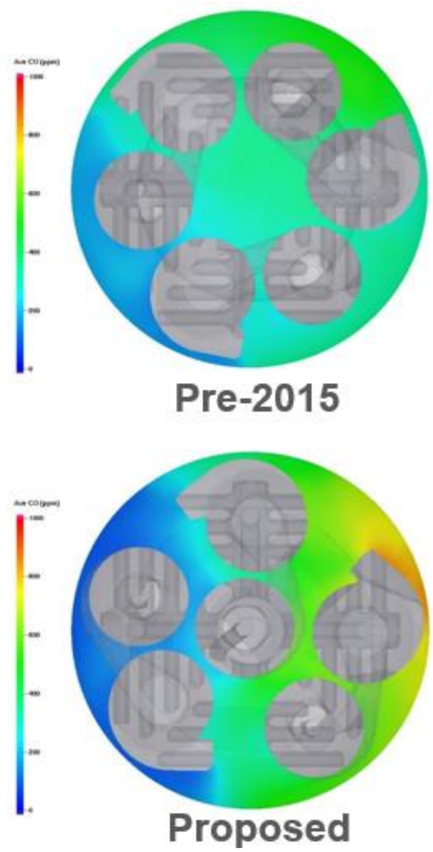

Figure 8. CO Maldistribution

A significant degradation in performance was observed immediately following start-up. FCCU emissions, while within instantaneous compliance limits, were projected to exceed the 365 day average limits by summer 2016. Notably NOx increased to 10% over the limit with CO, which was not problematic for this full burn unit in the past, increasing as high as 43% over the 365-day limit. At the same time, the refiner began to experience episodes of high particulate emissions. Once initiated, the catalyst loss events would continue until the regenerator dense bed level was decreased to below the secondary cyclone dipleg elevations, at which point the excessive losses would cease. All this was accompanied by a marked increase in afterburn.

A radioactive tracer study was performed[7]. Figure 9 shows the air distribution as measured at the air grid elevation, and reveals that more than half of the air passed two of the six detectors, predominantly on the south side of the unit. Based on this, damage was suspected as a potential root cause of the poor performance.

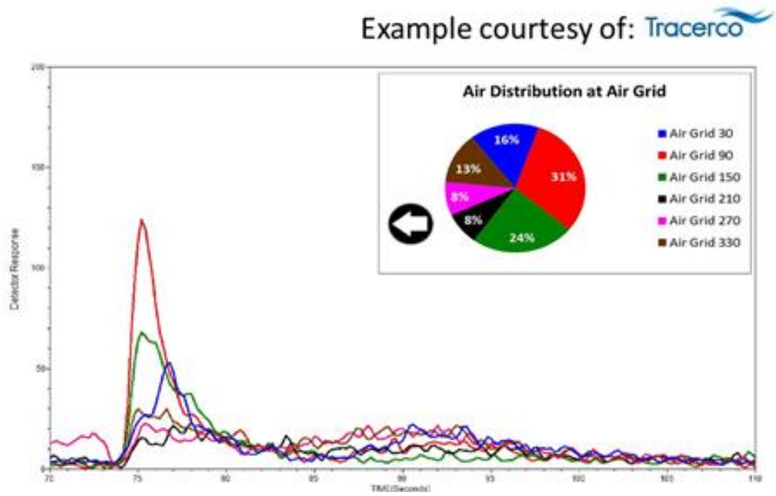

Figure 9. Air Distribution at Air Grid Elevation

The refinery scheduled an FCC shut shutdown for early 2016 to correct anticipated damage to regenerator internals, but the question remained: what if damage was not the root cause of underperformance?

The simulation results were revisited to investigate the possibility of an alternative explanation for the high air flow on the south side of the regenerator. The image on the right side of Figure 10 shows regions where the combustion air velocity greatly exceeds the superficial velocity. It is observed that much of the air bypasses the regenerator dense bed on the right, or south, side. This side corresponds to the location of the spent catalyst distributor, as shown on the left side of Figure 10. The gas from one of the four air grid quadrants was observed to collect and channel on the underside of the spent catalyst distributor, resulting in the unbalanced flow patterns observed via the tracer study. Based on this, the hypothesis of air grid damage seemed less likely to be the root cause of the gas stream compared with prior engineering design.

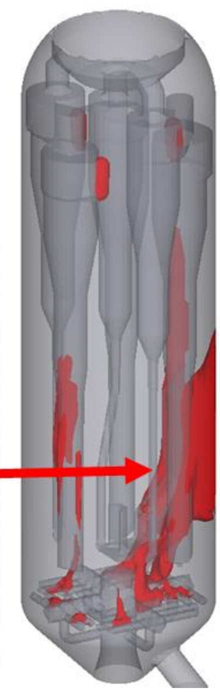

Figure 10. Spent Catalyst Distributor Affecting Gas Channeling

An analysis of spent catalyst mixing uniformity yielded similar results. The maldistribution of spent catalyst, and significant bypassing of combustion air, resulted in a fluidized bed with significant non-uniform behavior. Different regions of the regenerator were subjected to differing temperatures and coke loadings directly affecting the combustion and reaction pathways for formation of CO, NOx and other flue gases, with the primary cause being the performance of the spent catalyst distributor.

With only a few weeks prior to shutdown, it was not feasible to plan for any significant changes to the spent catalyst distributor. Instead the refinery engineers asked the question: what changes were possible to implement during the shutdown if no damage was found? Several potential modifications were identified as possible and reasonable, including the orientation of the air grid, the discharge directions for the cyclone dipleg trickle valves, and the discharge elevation for the secondary diplegs.

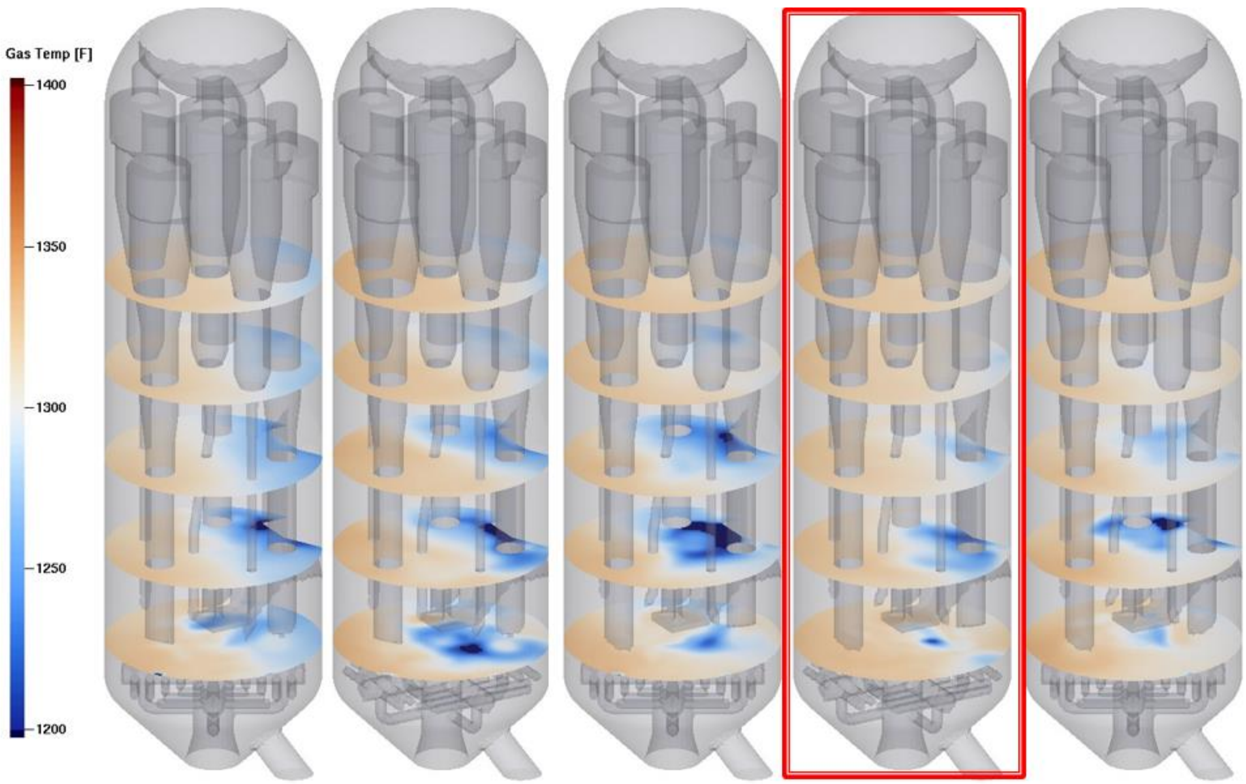

Figure 11. Virtual Testing Results

Virtual testing was performed on multiple options concurrently with sample results shown in Figure 11. While none of the configurations addressed root cause, as expected since none addressed the spent catalyst distributor, some alternatives were found to result in more uniform flows and distributions, while others were expected to exacerbate the problem. The highlighted case as shown in Figure 11 was found to have the most uniform temperature profile of the alternatives. Subsequent analysis of the simulation results, presented elsewhere[8], gave the refinery engineers and management confidence to make the change in case no damage was found during shutdown.

During shutdown no air grid damage was discovered and the best option, based on the virtual testing results, was implemented. Following startup the refinery observed immediate improvements in NOx, CO and particulate emissions with all emissions constraints being met following additional optimization of air injection rates. At the time of writing, no reports of the intermittent catalyst loss phenomenon have been received since the 2016 shutdown.

Several lessons can be learned from simulation of the historical FCCU operations here. First, based on the limited data available, it could be tempting to attribute root cause of the emissions and catalyst losses on multiple components, but such conclusions would have proven incorrect. The 2015 hardware change involved cyclones, so it could be reasonable to conclude the cyclones were to blame. However, the same cyclones were present both before and after the 2016 shutdown. Similarly, air grid damage was suspected, but simulation revealed a deeper underlying issue, which could easily have been overlooked. The root cause analysis and subsequent virtual testing of alternatives, all enabled by simulation, gave the project team the information necessary to make an informed decision.

Secondly, it is important to note that improvements were possible in this case, even though the root cause could not be practically addressed. The sensitivity of performance to seemingly minor changes in components has likely always been present for this unit. However, by comparing multiple cases through simulation, much information was obtained, enabling a counter-intuitive, timely solution.

Third, this case illustrates the importance of using all available information and resources together, whenever possible. Refinery engineers, technology suppliers, testing companies, hardware vendors, third-party consultants, catalyst suppliers, simulation specialists and corporate resources all have a view of the FCCU, and better solutions are often found when all parties work together. In this case, simulation was used to provide an objective basis complementing other expertise.

Lastly, while not the main thrust of this work, this case illustrates the importance of early planning. If the original simulations were performed sooner, time may have been available for the refinery to further act on the preliminary concerns raised before the 2015 TAR, rather than in a subsequent shutdown. All refiners are encouraged to consider a proactive baseline modeling strategy. Such a strategy enables rapid response to surprise behavior and is part of any overall digitalization plan.

Concluding Thoughts

There is no shortcut to developing deep technical expertise. Development of FCCU expertise requires passion, practice, and persistence. According to Ken Peccatiello, to become a specialist:

> *"… first you got to like it… you got to realize that in our world there are two paths: there is a managerial ladder and then there's a technical ladder. And the managerial ladder is fast… and that's really well recognized and well respected. The technical ladder is not quite as well understood. You spend a lot of time developing that proficiency, and you spend a lot of time learning everything you can about something, and that develops over time. It takes 30 years! This is the long view… you don't look at the next 5 years, you look at the next 30 years – that's when you start looking at what do I need to do to get there… It's not something you can learn from a book, you have to learn by doing."*

Several SMEs related their stories in a similar manner with statements like, "*you must love what you do and work really hard*", or "*I wanted to be on the FCCU because that's where the action was.*" In short, if someone is going to dedicate the majority of their working life to obtaining deep expertise in a specialty field, they have to be passionate about it.

Can simulation help with the passion? Yes! Engineers graduating today come from a digital world, and have an expectation that digital technologies will be used in their work places. This helps address the challenge of attracting recent graduates to refining; attracting talent involves providing them with the tools and environments they find appealing. Furthermore, as these case studies have highlighted, simulation is impactful, further enhancing career satisfaction. Career satisfaction, over time, can reinforce the passion needed for development of deep expertise. The FCCU is at the heart of many refineries and simulation is one way to attract the best and brightest to such a critical component of our industry, and then retain such talent.

While the FCCU SME demographics are changing, so too are the tools available to FCC engineers. Simulation will never replace FCC expertise, but rather is a tool to be used by engineers to enhance and accelerate learning. By allocating proper time and resources to use simulation, first to understand current and historical operations before jumping to problem solving, companies are investing in the development of their technical staff while increasing their ability to retain legacy knowledge and archiving experience.

Notes

[1] The term subject matter expert (SME) is in widespread use and thus is used throughout this paper. However, some SMEs make a distinction between the title of "expert" and the descriptor of having "expertise", with preference given to the latter. "Expert" can imply knowing all there is to know, whereas many SMEs hold their deep knowledge and experience (i.e. expertise) with humility, realizing there is much remaining unknown and awaiting discovery. Regardless of the real distinction, SME is used here to imply a specialist having deep knowledge and experience with FCCUs.

[2] Many of the trends discussed here were amplified by personal interviews with multiple FCC SMEs including Steve Kalota, Tom Lorsbach, Bob Ludolph, Phil Niccum, and Ken Peccatiello. The authors are grateful for their support and insights.

[3] General trends are discussed here with the focus on American refiners, and exceptions to the trend have been noted. Many of those interviewed mentioned multiple companies with a culture of SME development or individuals in leadership who do a particularly good job of mentoring and training, contrary to the general trend.

[4] This case study was originally presented as "Application of CPFD® Modeling to Support RCCU Hardware Changes at the Viva Energy Geelong Refinery" at the 2018 Asian Refining Technology Conference, April 23-25, 2018 in Kuala Lumpur, Malaysia. Additional details can be found in the September 2018 issue of Hydrocarbon Processing in the article entitled "Viva Energy's Geelong Refinery Reduces FCCU Turnaround Risk" by Peter Blaser, John Gabites, Angus Brooke, and John Pendergrass.

[5] All simulations in this work were performed using Barracuda Virtual Reactor® from CPFD, LLC.

[6] This case study was originally presented as "The Experience of a Team of Experts to Resolve Severe FCC Regenerator Maldistribution" at the 2016 AFPM Cat Cracker Seminar, August 23-24, 2016 in Houston, TX (AFPM CAT-16-17).

[7] Radioactive tracer results provided courtesy of Tracerco.

[8] Additional details, including videos of transient results, can be found in a recorded webinar, available for playback at: http://cpfd-software.com/resources/webinars/2017-ertc-presentation-resolving-severe-regenerator-maldistribution