MODERN DESIGN AND TROUBLESHOOTING TOOLS CREATE A SUCCESSFUL FCC REVAMP

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ABSTRACT

Based on a refiner’s need for increased conversion and selectivity for propylene production, UOP revamped an existing UOP™ Stacked FCC unit to include Optimix™ feed distributors, VSS™ riser disengaging, and a modern reactor stripper design. The new reactor internals were sized for an increased feedrate, but the existing reactor shell had to be retained to maintain a constant structure and foundation load. Internal clearances were closer than would typically be used for a new reactor system. New internals were installed in the existing reactor stripper.

The post-revamp operation has exceeded the process performance for propylene yield represented for the revamp. However, catalyst containment in the reactor was not as good as represented. A joint Risk Management plan was developed by OMV and UOP to identify all possible causes of the problem, establish the necessary means to allow for safe continued operation with the higher catalyst losses and the increased risk of erosion, and develop a long term solution.
Considerable troubleshooting was performed to identify the root cause of the catalyst losses including gamma scans, tracer scans, X-ray imaging and physical testing of the catalyst in the main column bottoms. In addition, UOP’s Engineering group reviewed design parameters, as-built equipment, and utilized computational fluid dynamic simulations. After the root cause analysis was complete, a risk/cost comparison was developed to arrive at the final solution. The resulting design modifications were engineered by UOP and installed by the refiner. The modifications have proven to be successful in eliminating the catalyst loss from the unit while preserving the yield performance.

**INTRODUCTION**

The OMV FCC unit is a classic UOP stacked FCC unit originally designed for 10,250 BPD of fresh feed (with a combined feed ratio of 1.7) and started up in 1963. In the years since then, it has been revamped several times to increase capacity and to incorporate various technology improvements. In 1998, the refiner decided to revamp the unit to increase capacity slightly, but more important, to increase the unit’s conversion and to double the propylene (C\(_3\)\(^\equiv\)) yield. There is a nearby petrochemical facility and C\(_3\)\(^\equiv\) value is greater than other FCC products.

The revamp design basis was set at 26,815 BPD with a minimum C\(_3\)\(^\equiv\) yield target of 8.2 wt-% of feed. To achieve this target, the design incorporated UOP’s Optimix feed distributors, the VSS riser disengager, and new reactor stripper internals. The configuration of the reactor revamp is shown in Figure 1. A new gas plant was also designed by UOP to accommodate the increased LPG product. The revamp was implemented and the unit started operation in August, 2000.
POST-REVAMP PERFORMANCE

After the unit was restarted, and after a period of time to adjust the unit to the new operating conditions and catalyst properties (including ZSM-5 additive), the feed rate and C₃⁺ yield targets were achieved. However, from the start of operation, it was seen that catalyst containment in the reactor was not achieving its target as evidenced by catalyst in the main column bottoms product.

For a revamp to be considered successful, all aspects of the unit operation have to be satisfactory. It is not enough just to achieve the target capacity if the feedstock quality has to be better than design, or if the product yields are not consistent with revamp representations. In this case, the process performance was achieved, but the revamp was not considered to be successful because of the catalyst losses to the main column. The losses were not sufficient to cause an immediate shutdown but were high enough to warrant an investigation to identify the root cause and find a solution. The target losses from the reactor were less than 0.5 tons per day and the actual initial loss rate varied between 3 to 5 tons per day at somewhat lower than designed unit throughput. Reactor steam rates were reduced to the minimum allowable, the unit feedrate was increased to almost design values with catalyst losses less than 3 tons per day, improving the profitability of the unit.

OMV - UOP RISK MANAGEMENT PLAN

A highly experienced multidisciplinary team of UOP FCC specialists and OMV refinery personnel was assembled to work on this problem. The goals were to identify all possible causes of the problem, establish the necessary means to allow for safe continued operation with the higher catalyst losses and the increased risk of erosion, and develop a long term solution. The plan was divided into several areas of activity for efficient completion.

Operational and inspection activities included:

- Monitoring of main column bottoms exchangers for changes in temperature that would indicate catalyst fouling
- Reviewing piping configuration for areas of high velocity that need extra on-line inspection
- Control of the main column bottoms flows to minimize velocities
- Regular inspection of the main column bottoms pumps

Engineering design activities included:

- Developing additional specifications to increase the wear resistance of pumps and control valves
- Providing specifications for a filtration/settling system in the event that the developed solution was not 100% effective
The investigations and evaluations by the engineering team encompassed several lines of inquiry and activity in order to solve the catalyst loss problem. In addition, on-site operational testing of the FCC unit was conducted to confirm technical observations and conclusions. The investigation team applied Six Sigma methodologies to list all possible causes, identify the associated contributing factors of the catalyst losses, and gather data to either support or eliminate each possible cause. Figures 2 and 3 show typical logic diagrams used for this analysis.

**Figure 2**

*Possible Causes of Catalyst Loss*

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Root Causes                  Problem

Cyclones Overloaded

Poor Cyclone Design          High Catalyst Losses

Cyclone Bypassing
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**Figure 3**

*Possible Causes and Contributors of Catalyst Loss*

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Root Causes                  Contributing Factors                  Problem

Cyclones Overloaded

Low YSS Efficiency
Maldistribution of Solids

Poor Cyclone Design

Cyclone Design Dimensions
Cyclone Outlet Tube Design

Cyclone Bypassing

Backup
Cyclone Outlet Tube Design
Improperly Operating Flapper Valve

Hole in Cyclone
Inlet Flow Patterns

High Catalyst Losses
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The problem was unusual because the VSS design has been successfully used in many prior revamps. In 1998, when this design was done, UOP had the following VSS operating experience:

- 18 units in operation
- Three curved riser units
- Various VSS configurations with two, three, and four arms
- Various operating conditions
- No catalyst containment problems

**ENGINEERING EVALUATION OF THE VSS REACTOR DESIGN**

The project design parameters and components for both design and actual operating conditions were reviewed for any errors or deviations from established normal design and revamp criteria. Parameters included velocities, fluxes and geometric relationships. This was important since new reactor internals were installed into an existing reactor vessel and some deviation or compromise from normal design criteria may have occurred. Additionally, benchmarking analysis of other successfully operating VSS reactor designs was completed to identify any parameters that were beyond UOP’s current range of operating experience. No deviations from established guidelines were discovered.

**DETAILED CYCLONE DESIGN AND PERFORMANCE REVIEW**

UOP contacted the cyclone vendor to obtain a detailed validation of the cyclone design provided for this reactor revamp project, including construction drawing review. Parameters included inlet and outlet velocities, ratios of inlet duct dimensions, and L/D ratios. The design cyclone parameters were checked against design and actual operating conditions. The design efficiency was confirmed to be adequate for the given process conditions. The flapper valve dimensions had been modified slightly from the original project specification, but were in good working condition and had been calibrated for the desired test weight during the revamp turnaround.

**ON-SITE OPERATIONAL TESTING**

Operations monitoring, testing and documentation of the rate of catalyst losses from the reactor was conducted continuously beginning shortly after the FCC unit started up. By testing various FCC operating conditions to assess the response of the catalyst losses to changes in reactor conditions, it was found that the catalyst loss rate varied with both changes in feed rate and catalyst circulation rate. The loss rate was less sensitive to changes in cyclone velocity and delta P.

External source gamma scanning was conducted to assist in troubleshooting the cause of the catalyst loss problem. The gamma ray source was set up to shoot through the diplegs to detect the presence of catalyst. This scan was compared to a blank calibration done prior to operation.
The gamma scanning indicated that the North West reactor cyclone dipleg appeared to contain no catalyst level. An empty dipleg represents an abnormal condition and seemed likely to be associated with the high catalyst losses. None of the diplegs showed a high catalyst level indicating a plugged dipleg or a stuck closed flapper valve.

Additional testing in the unit using two other techniques was done to further investigate the apparent problem in the North West dipleg:

- Catalyst phase tracer and vapor phase tracer injections into the unit to check normal and abnormal flow paths of vapor and catalyst through the reactor
- Long exposure x-ray film of the reactor dipleg counter-weighted flapper valves to look for indications that one of the flapper valves was stuck and not responding correctly to changes in dipleg catalyst flux

Radioactive gas was injected into the reactor annulus to check for preferential flow or higher velocity to any one cyclone. Figures 4 and 5 show the location of the injection and the tracer results at the cyclone outlets. The conclusion was that there was no apparent backflow up the diplegs and the gas distribution in the reactor was reasonably even.

Radioactive catalyst was injected into the riser to follow the path of solids in the system. One of the limitations of tracer testing is that it is not a weight balanced test. The flow indications are only based on the energy detected and are relative to the tracer concentration and distance from the detectors. Data interpretation and the assumptions made are critical to the analysis. In this case, the intent was to determine if there was preferential flow of solids to any one cyclone resulting in overloading of that cyclone. The results showed that the catalyst distribution to each of the four cyclones was 25% +/- 3%. It was concluded that solid maldistribution to the cyclones was not the problem.
Long exposure X-ray film was set up to shoot the cyclone dipleg flapper valves in operation. This test would show if the valves were fixed open or closed, and if the edges of the flapper were blurred, that the valve was moving. Figure 6 shows an x-ray of the North West flapper valve that was suspected of mis-operation by the gamma scan test. All four flapper valves were X-rayed and the results tabulated. Using the observed valve openings (max and min), the flow in each dipleg was calculated by several methods as shown in Figure 7. The conclusion was that the diplegs were operating well below their maximum flux and the VSS separation efficiency was operating well above its design value. Based upon maximum achievable flapper valve and dipleg flow, the system would still operate properly even if the VSS separation efficiency was reduced to 65%. However, with the actual dipleg catalyst flux being very low, potential defluidiziation of the diplegs, which could contribute to cyclone bypassing, was a concern.

**COMPUTATIONAL FLUID DYNAMICS (CFD) COMPUTER MODELING**

Computer modeling of complex multiphase flowing systems (in this case vapor and solid phases) is a powerful tool that is being used as a design and troubleshooting tool for fluidized systems such as the FCC process. The computer modeling techniques and software used for this are known as computational fluid dynamics (CFD). UOP has actively developed expertise in the area of CFD modeling and uses CFD routinely in our FCC process technology.
UOP conducted a CFD modeling effort as part of the program to investigate and understand the cause of the catalyst losses from the reactor. The CFD model predicted the hydrodynamic characteristics and catalyst separation performance of the riser, the VSS primary separation device, VSS outlet duct and cyclone inlet conditions. The three-dimensional model required for modeling the catalyst separation system is quite complex and computationally intense.
Individual model runs can require as much as a full day or two of computer time to converge on a solution. In general, the CFD modeling work is built up sequentially as outlined below:

- Develop the baseline system using actual operating conditions
- Use the model for comparison among similar designs
- Use the model to test the effectiveness of physical modifications to the catalyst separation system

The CFD model was developed as shown in Figure 8. The model consisted of the VSS chamber and disengaging arms, the connecting duct, and the cyclone inlets. The objective was to determine the effects of maldistribution and identify gas and catalyst flow patterns throughout the system.

The as-built cyclones included a conical internal gas tube rather than the more typical cylindrical gas tube. Although this type of geometry was used successfully in other units, it resulted in the top of the gas tube being closer to the gas inlet stream than the bottom of the tube. The top of the gas tube was 34mm from the projected cyclone gas inlet. The physical constraints of the existing reactor also caused the cyclone inlet geometry to be slightly different from other VSS designs.

The CFD modeling results showed that the flow patterns developed in the cyclone led to the possibility that some catalyst would be able to bypass the cyclone. Keep in mind that the catalyst loss relative to the circulating catalyst is extremely small, and the model may not be sensitive enough to exactly calculate such small quantities. The normal catalyst circulation rate to the cyclones is about 320,000 lb/hr, and the collection efficiency is expected to be 99.99%. The actual cyclone efficiency for the 3 ton/day loss was 99.91%, a small delta to be able to accurately model. However, the model did show that flow patterns could exist to cause such a catalyst loss.
Figure 9 shows the velocity flow vectors at the cyclone inlets, and the possible flow of catalyst directly towards the cyclone gas tube that may be contributing to the catalyst loss. Figure 10 shows that the particle size distribution (PSD) of the recovered catalyst was consistent with a cyclone efficiency phenomenon rather than losing whole e-cat. This sample was taken after the problem had been ongoing for a while, and the e-cat average particle size (APS) reflects the loss of fines that had been occurring. It is interesting to note that even though the e-cat APS increased to a maximum of 105 micron, because of the straight standpipes and slide valve control, no problems of catalyst circulation were ever experienced.

Figure 9

Flow Entering Cyclone at Top of Duct

Figure 10

OMV Catalyst Samples Particle Size Distribution

- Net MCB Ash (APS 61 microns) 07-Sep-2000
- E-Cat (APS 92 microns) 11-Sep-2000
RECOMMENDATIONS

The investigations and evaluations eliminated several of the possible causes and associated contributing factors. Cyclone bypassing was determined to be the root cause of the catalyst losses. To address the contributors to cyclone bypassing, several possible solutions were developed. A risk/cost comparison was developed for each of these to arrive at the final solution. The analysis included lead time of new equipment, equipment cost, mechanical work duration, degree of complexity, and estimation of probability of success. The work of the team resulted in three main recommendations:

- Reduce the dipleg size to 8" and install new flapper valves based on UOP current specifications, including new quality control requirements for shop testing
- Replace the cyclone gas tube with a cylindrical tube
- Modify the cyclone inlet duct to eliminate potential flow to the cyclone gas tube

The combined effect of these modifications was to provide more clearance between the cyclone inlet stream and the gas outlet tube. The cyclone inlet duct was thought to have the highest probability of being the cause of the inlet bypassing but the data did not clearly identify a single root cause. The refiner chose to implement all the modifications in order to ensure the maximum probability of success. Engineering drawings for the modifications were completed and material was obtained to make the modifications. UOP also worked with OMV to optimize the construction planning and sequencing. For future maintenance reasons and to shorten the turnaround time, new cyclones were installed rather than modifying the existing ones in-situ.

IMPLEMENTATION

The unit was shut down in August 2001, and careful inspection of the reactor internals was conducted to verify that the conclusions reached using the diagnostic tools were correct. The catalyst in each cyclone dipleg was drained and weighed and the variation was less than 2 pounds, confirming proper dipleg operation. The flapper valves were in good condition and moved freely. The cyclone inlets showed some signs of catalyst flow and the cyclone gas outlet tube had some erosion on the bottom edge. The evidence supported the conclusion that the cyclone inlet configuration and the proximity of the gas outlet tube were the highest probable causes of the catalyst losses. The recommended modifications were installed and the unit restarted without incident. The catalyst losses from the reactor were reduced to less than 0.1 ton/day. This value is well below the original design estimate. The yield pattern previously experienced remained unchanged. The feed rate for the test run was 27,700 BPD with a C3\textsuperscript{=} yield of 8.5 wt-% of feed, both above design values. Operational monitoring and equipment inspections were returned to normal levels.
CONCLUSION

As feed and product values change in the marketplace, revamping the FCC unit to “follow the value” remains a prime opportunity for optimizing the profitability of the refinery. Modest investments in the FCC unit can result in high returns and maximize the cash flow from existing assets. No revamp is without some degree of risk, however, since equipment is often being pushed to or beyond normal design limits. Even in the case of proven technologies, design differences due to scale factors or physical constraints could lead to costly troubleshooting and repair efforts. Shortfalls in expected performance will reduce the benefits of the revamp. It is important to work with companies experienced in revamp engineering, effective in troubleshooting, and dedicated to 100% customer satisfaction to resolve any problems. Modern design and diagnostic tools such as CFD modeling, radioactive tracers, and innovative X-ray techniques can greatly reduce the risk associated with multiphase complex systems. When applied by experienced FCC specialists, empirical data combined with theoretical models provides a powerful synergy for success.