FCC Emergency Interlock System Application

by Lewis Pettengill – UOP LLC - PIC Senior Technical Leader

The Fluid Catalytic Cracking Process

Since the 1940's the Fluid Catalytic Cracking (FCC) process has proven itself as one of the most important of refinery processes. By cracking heavy vacuum and atmospheric gasoils into more valuable lighter products, this process provides feedstocks to numerous downstream units. It is the center of any major gasoline or light olefin complex. Products include light and heavy cycle oils, unstabilized gasoline as well as olefin-rich vapors.

Using catalyst of small particles that behave as a fluid when aerated, the process continuously circulates this material between a reactor and regenerator. Operating at high temperatures and moderate pressures, the catalyst is mixed with atomized hydrocarbon feed in the reactor riser. Vaporization of the feed and supplemental lift gases force the material up the riser to a termination device that, along with the reactor cyclones, separates the reaction products from the entrained catalyst. The spent catalyst falls into an annulus where steam "strips" away any remaining hydrocarbons and the reaction products travel from the cyclones to a fractionation column for separation into desired components.

In the course of cracking the large hydrocarbon molecules in the feedstock, a non-volatile carbonaceous material (commonly referred to as "coke") is deposited on the catalyst. The coke reduces cracking activity and is removed during regeneration.

After stripping, the spent catalyst descends through a standpipe and slide valve into the regenerator where air is used to burn the coke. Combustion of the coke liberates significant heat and the regenerated catalyst carries this back to the reaction zone.

Flue gas from the regenerator is separated from the catalyst using cyclones before discharging through a pressure reduction orifice chamber, a steam generation system (heat recovery) and finally to an electrostatic precipitator. The precipitator removes any remaining catalyst fines.

A power recovery turbo-expander is sometimes included while other locations include a CO Boiler to complete combustion from a partial-burn regenerator.

The Emergency Interlock System (EIS)

The FCC is a dynamic, high temperature process. Operational upsets can quickly cause serious problems leading to production loss or equipment damage. Proper detection of abnormal conditions and properly automated responses can assist operations avoid damage or injury. The immediate and precise response to abnormal unit conditions minimizes unit downtime, personnel and equipment damage, and helps ensure faster operational recovery.

The FCC EIS is an independent protection layer as identified in the ISA S.84 and IEC 61511 standards. These standards formalize the evaluation of interlock systems and are the accepted de facto industry guidelines. While an EIS is only part of the S.84 lifecycle, a refiner is expected to know both FCC Hazop and SIL determination analysis, have extensive knowledge of the process, and clearly understand the inherent process risks. A competently executed EIS can diminish those risks to an acceptable level.

Additionally, provisions can be made within the EIS to facilitate rapid and proper re-starts.

Inherent Process Risks in a Fluid Catalytic Cracking Unit

Operating between 1000 - 1400°F and 25 - 35 psig, with oxygen and hydrocarbon atmospheres separated by only standpipes of catalyst and differential pressures, the FCC presents considerable risks to both equipment and personnel. Reversal of flows between vessels results in extreme temperatures and equipment damage.

Catalyst containment is another concern. Both the reactor and regenerator use cyclones to separate the catalyst from reaction or combustion products. Catalyst carryover at the reactor can plug the main column bottom circulation circuits. Catalyst carry over from the regenerator can foul or damage boiler tubes, damage turbo-expander blades and possibly lead to an atmospheric release.

Coke deposition within the reactor is serious and irreversible problem. Too low an operating temperature leads to coke laydown on the reactor internals. Coke cannot be removed without shutting down the unit.

Proper combustion within the Regenerator is essential. Whether a partial or complete combustion regenerator, it is critical that the coke be burned off the catalyst at the same rate it is produced. In a complete combustion regenerator a small amount of excess oxygen is always maintained. Where a CO boiler is used, excess air is ensured by its forced draft fans.

Proper CO boiler operation is critical to electro-static precipitator function. Improper soot blowing can lead to tube surfaces covered in catalyst fines and excessive temperatures in the flue gases to the electro-static precipitator. Conversely, low temperatures can lead to corrosion due to condensation. Combustion air and burner problems can easily lead to flammable mixtures in the electro-static precipitator.

Operation of the Direct Fired Air Heater (DFAH) is fraught with risk. High exit temperatures can damage Regenerator internals. Improper combustion and loss of flame can lead to explosions.

Maintaining water circulation in steam generation equipment is essential to tube life. Just a few minutes of dry operation at elevated temperatures can irreparably damage this equipment.

Loss of the main air blower is a critical situation. The unit must be shutdown immediately.

Instrument purges are vital to all catalyst service instruments. Loss of gas purge will disable instrument transmitters, leaving operations “blind” to their process conditions.

With hydrocarbons, oxygen, high temperatures and dynamic operations in the mix, an FCC presents a challenge for risk reduction.

Emergency Interlock System Design

Referencing the ANSI/ISA S.84 Safety Life Cycle, the HAZOP study is an essential starting point of an FCC EIS. The hazard and operability study (HAZOP) is a systematic examination of the process that identifies and evaluates risks to personnel and equipment. Having played a significant role in the development and commercialization of the Fluid Catalytic Cracking Process, UOP has unique experience and lengthy institutional memory for evaluating such risks.

Once the risks are identified and a Safety Instrumented System (SIS) deemed necessary, Safety Integrity Levels (SIL) are defined that identify safety equipment performance levels required to reduce those risks to an acceptable value. Next, the proposed SIS is evaluated to ensure that its Safety Instrumented Function (SIF) meets the defined SIL level. Typically, these evaluations are based on the summation of component “Probability of Failure on Demand” performance and “Risk

Reduction Factors". Several methods exist for SIF evaluation, but all point toward defining a desired "Availability" and "Reliability" performance from the system.

"Availability", which defines system success, is typically expressed as a percentage. In essence, "Availability" is that the system does WHAT it needs to do, WHEN it is asked to do it. It is a function of (a) failure rates of individual devices, (b) the time required to repair those devices, and (c) the length of test interval of those devices.

Lack of "Availability" is typically due to covert, or hidden, failures. The system does NOT trip when asked to. Normal programmable logic controllers (PLC) are susceptible to high incidence of covert failures and should never be used as part of an SIS.

"Reliability" is a measure of (safe) system failures. Lack of "Reliability" causes spurious trips, unwanted downtime and lost profits.

To obtain sufficient levels of "Availability" and "Reliability", UOP uses two-out-of-three voting on input sensors, TUV-rated multiple-redundant fault-tolerant logic solvers, parallel solenoids on multiple shutdown valves and redundant power supplies. While not all risks warrant a Safety Instrumented Function, economic considerations do influence the robustness of an installed system. It is senseless to design, install, and operate an EIS without providing one that truly protects a refiner's FCC catalyst section from both safety and economic hazards.

Other EIS Considerations

Besides logic solver robustness, field equipment plays a major role in system performance. Perhaps most important are the catalyst slide valves. This equipment is expensive, heavy and employs both hydraulic and electronic subsystems. These valves must be able to close quickly when directed by the EIS. As such, a dedicated emergency hydraulic circuit with redundant parallel solenoids is used to isolate the regular hydraulic control and force the valve closed. Additionally, means are provided for online testing of the dedicated emergency hydraulic circuit - without upsetting the process.

A few refiners have actually installed redundant slide valves for their Spent and Regenerated services. UOP does not consider this approach necessary at this time.

Next, solenoids are critical to system performance. To avoid spurious trips, UOP's uses parallel solenoids for most shutdown valve services. Both solenoids must de-energize for the shutdown valve to close. This allows one solenoid to fail yet still maintain shutdown valve operation. Note that a two-out-of-three solenoid arrangement *is* available from a major solenoid manufacturer, complete with on-line testing features.

Transmitters require special consideration. UOP's default approach is to use a two-out-of-three (2-oo-3) voting arrangement. If two of the three installed sensors indicate an abnormal condition, then the logic solver acts to bring the process to a safe state. While two-out-of-two-with-diagnostics (2-oo-2D) offers similar performance, only TUV-rated safety transmitters should be considered for this installation. 2-oo-2D does enjoy an advantage for revamp installations where tapping of cold wall piping and vessels requires fewer connections.

EIS – BPCS Interfacing

Interfacing with the Basic Process Control System (BPCS) is another area where significant advantages can be gained during an EIS implementation. By using a logical "single-shot" from the EIS to place an associated BPCS controller in manual and its output to a predetermined value, the control loop's valve can also be closed during an EIS trip. Besides supplementing process isolation, the controller and valve are set for restart. Note that **no** credit can be taken in the SIF evaluation for this feature as software communication links are considered unreliable and failure in the BPCS cannot impede the effectiveness of the EIS.

Testing

Both pre-startup and interval testing are crucial to EIS performance. Experience has shown that software testing alone is insufficient to verify system performance prior to installation. UOP's approach is to build a hard-wired customer-specific process simulator for input-terminal to output-terminal testing. By adding component "burn-in" to the functional testing, premature component failure is apparent and installation and commissioning problems are minimized. Additionally, the process simulator is a great tool for DCS communication testing and operator training. UOP usually ships it to site for temporary use.

Interval testing is essential for maintaining "availability" performance. Some refiners use partial-stroke testing of their shutdown valves at predetermined intervals to verify that the valves will move when directed. Other refiners only test during planned shutdowns. Still others require an entire system test each time the unit trips. Whichever approach is used, the entire installed system should be tested systematically to identify any latent failures.

Maintenance and process bypasses

UOP is very wary of bypasses. We have seen the tragic consequences of their misuse in our industry and discourage their use except for very specific predetermined operation requirements.

On occasions where a specific process condition requires an interlock bypass, UOP will include one. An example being initial introduction of raw oil feed to the riser. The flow rate is below the trip point of low flow interlock. UOP automates some features of this bypass on most EIS's. During enforced restart procedures the bypass is active but disappears once the unit is above a predetermined throughput. This approach prevents a forgetful operator from removing the bypass when no longer needed.

Of note, several verification agencies are currently working to standardize bypass functionality.

Staged Responses

Staged responses to abnormal events allow faster restarts. By maintaining operation in unaffected areas, more of the catalyst section remains ready for recommissioning.

Most EIS responses involve diversion of raw oil, interruption of catalyst circulation, and maximization of riser lift steam. If the abnormal event or EIS response do not directly affect the operation of the regenerator, it can remain in service. Keeping catalyst temperatures elevated aids restarting.

Conversely, if the Regenerator cools below the auto-ignition temperature of the torch oil, the torch oil must be shutdown. This response prevents accumulation of unburned hydrocarbons or wetted catalyst. In this situation, the DFAH is used to reheat the regenerator catalyst inventory.

Next, loss of boiler water levels in flue gas heat recovery systems mandates either a flue gas bypass or a main air blower shutdown. Loss of main air prevents regenerator operation and does stop the **entire** reactor-regenerator section, including the electro-static precipitator.

Enforced Restart Procedures

Restart procedures call for defined operational steps, but first, an operator must understand the cause of the shutdown. “First Out” logic as well as Sequence of Events recording allows analysis of events. First Out identifies only the initiator of the shutdown and none of the subsequent responses. Sequence of Events recording identifies all events and while thorough, can be cumbersome for identifying the root cause. Regardless, the operator must identify and remedy the cause before restarting the unit.

In the UOP EIS, critical steps are enforced by preventing feed introduction until process conditions are within defined limits. The feed must be below a predetermined rate. (See the earlier discussion on automated bypasses.) Temperatures, differential pressures, catalyst inventory and circulation must all be ready before feed is introduced. The operator must restart the unit in a precise and controlled manner. Experience shows this approach more successful in restarting a unit.

Human Responses to “Abnormal Events” (General Discussion)

In the past UOP considered a well-trained experienced operator as the best protection against abnormal events. Field instrumentation was considered somewhat unreliable and the interlock systems employed were designed more to prevent spurious trips and maintain on-line efficiency. A general trend in the industry is towards fewer, less-experienced operators. Given the nature of human response to emergencies, it is possible that the operator will either delay action or make an error in judgment. An EIS supplements operator actions by responding promptly and correctly. Damage to equipment is prevented. Restarts are quick. Proper startup sequences are enforced.

Typical “Abnormal Events” to consider in an FCCU

Loss of Main Air

Loss of main air flow is one of the more significant emergencies during operation of the FCC unit. Catalyst circulation becomes untenable. Regenerator pressure will fall precipitously as will the catalyst slide valve differential pressures. The entire reactor-regenerator system needs to be stopped.

Typical responses

- Raw Oil feed must be diverted to the main column, but at a low rate. One does not want to flood the main column but keeping some liquid on the trays is important.
- Any other hydrocarbons (recycle, naphtha, lift gas, etc.) must be removed from the reactor riser.
- Steam must be added to the lower riser and to the feed distributors
- The special check valves must close to prevent backflow of catalyst into the main air blower.
- The direct fired air heater, if operating, must be shutdown.
- Torch oil, if operating, must be shutdown.
- Fluidizing air to the catalyst cooler (if one exists) must be minimized to maintain heat within the regenerator while maintaining purge air to the lances to prevent plugging.
- Both the regenerated and spent catalyst slide valves must be closed immediately.
- The regenerator recirculation catalyst slide valve must be closed immediately.

- Typically, the operator will establish a negative regenerator-reactor differential pressure using the DCS control of the flue gas slide valve.
- Typically, fuel gas is introduced into the light cycle oil stripper overhead line to allow the wet gas compressor to continue to operate (usually on full spillback).
- Main column pumparound flows should be decreased to hold heat in the main column. If the main column temperature falls too far, steam must be backed into the main column bottoms steam generators.
- If the stoppage is longer than a couple of hours, the instrumentation dry air purges must be stopped as they may enter the reactor and cause auto ignition of any coke present.

What to automate?

- Raw oil diversion. This response is easily accomplished by de-energizing the solenoid(s) of “coupled” oil to riser (fail-close) and divert to main column (fail-open) isolation valves.
- Set the raw oil rate to the main column. This feature can be either part of the logical “single shot” sent to the DCS, set by restriction orifice in the circulation line, or limited in the sizing of the divert isolation valve.
- Removal of all other hydrocarbons from the riser.
- Increase steam to the riser. The lift steam is typically a fail-open control valve. By de-energizing the solenoid(s) in the control air to its diaphragm, the valve will open to its maximum. Additional emergency steam remains available to the operator
- “Bump” the main air special check valves to ensure their closure. This response occurs when the valves’ solenoids are de-energized by the EIS.
- Shutdown of the DFAH, including pilots.
- Shutdown of torch oil.
- Minimize catalyst cooler fluidizing air.
- Closure of the spent catalyst slide valve.
- Closure of the regenerated catalyst slide valve.
- Closure of the regenerator recirculation catalyst slide valve.

What NOT to automate?

- Establishing a negative regenerator-reactor differential pressure.
- Fuel gas introduction to the light cycle oil stripper overhead line.
- Decrease of main column pumparound flows.
- Nitrogen flows on restart.

Loss of Feed

Typically, loss of feed (due to pump failure) increases reactor temperatures quickly, causing the reactor temperature controller to close the regenerated catalyst slide valve.

Loss of regenerated catalyst will cause a drop in reactor inventory, causing the reactor level controller to close the spent catalyst slide valve. Catalyst circulation will be lost.

Lack of coke formation on spent catalyst will suppress the temperatures in the regenerator.

Torch Oil will be needed to maintain regenerator temperatures.

Typically, fuel gas is introduced into the light cycle oil stripper overhead line to allow the wet gas compressor to continue to operate (usually on full spillback).

Main column pumparound flows should be decreased to hold heat in the main column. Main column bottoms recirculation is established using the bypass line to the raw oil charge line. If the main column temperature falls too far, steam must be backed into the main column bottoms steam generators.

If the stoppage is longer than a couple of hours, the instrumentation dry air purges must be stopped as they may enter the reactor and cause auto ignition of any coke present.

- Raw Oil feed circulation must be diverted to the main column in preparation for feed pump recovery.
- Any other hydrocarbons (recycle, naphtha, lift gas, etc.) must be removed from the reactor riser.
- Steam must be added to the lower riser and to the feed distributors
- Fluidizing air to the catalyst cooler (if one exists) must be minimized to maintain heat within the regenerator, but still be enough to keep the air lances from clogging with catalyst.
- Both the regenerated and spent catalyst slide valves must be closed immediately.

Note that the regenerator operation can be maintained. Torch oil, if the regenerator is above the auto-ignition temperature, will keep the catalyst hot. Internal circulation in the regenerator through the recirculation catalyst slide valve can continue. Typically, the regenerator is maintained at elevated temperatures until the feed pump is restored.

Loss of Slide Valve Differential

Loss of positive differential across either the spent or regenerated catalyst slide valves represents a critical situation. Migration of hydrocarbons into the regenerator's oxygen environment, or migration of oxygen into the reactor's hydrocarbon atmosphere can result in extreme temperatures, easily exceeding the mechanical limits of the vessels and damaging equipment.

Typical responses

- Close both the regenerated and spent catalyst slide valves immediately.
- Raw Oil feed must be diverted to the main column, but at a low rate.
- Any other hydrocarbons (recycle, naphtha, lift gas, etc.) must be removed from the reactor riser.
- Steam must be added to the lower riser. This can act as a buffer between the two atmospheres.

The regenerator can continue to operate, though at reduced rates. With the main air flow still viable, the regenerator can be kept in operation and at temperature with either torch oil or direct fired air heater. If a catalyst cooler exists, fluidization air is reduced to a minimum to minimize heat transfer from the regenerator.

This approach of keeping the regenerator in operation allows faster restarts once the differential pressure problem is solved.

Depending on the length of the unit trip, fuel gas is introduced into the light cycle oil stripper overhead, main column pumparound flows decreased, etc.

Loss of Wet Gas Compressor

Loss of the wet gas compressor will result in an immediate increase in the main column overhead pressure and the "secondary" pressure control loop will open the valve to flare. The unit can be kept on-stream, but it is necessary to decrease either throughput or reactor temperature to reduce the amount of flaring.

If the pressure upset is significant and of long enough duration, the differential pressures at the slide valves may reverse to the point that the EIS responds. Otherwise, the reactor-regenerator section continues to operate.

If the compressor cannot be restarted within hours, loss of product will compel a unit shutdown. Local environmental regulations may require immediate shutdown of the feed to the unit, to minimize flaring.

Low Riser Temperature

Low riser temperature will lead to coke formation on the reactor internals. As there is no way to remove the coke with the unit in operation and the buildup is cumulative, immediate action is required.

- Raw Oil feed must be diverted to the main column, but at a low rate.
- Any other hydrocarbons (recycle, naphtha, lift gas, etc.) must be removed from the reactor riser.
- Steam must be added to the lower riser. This can act as a buffer between the two atmospheres.
- Close both the regenerated and spent catalyst slide valves immediately.

The regenerator can continue to operate, though at reduced rates. If a catalyst cooler exists, fluidization air is reduced to a minimum to minimize heat transfer from the regenerator.

Again, the ability to maintain regenerator operation during this event allows faster restarts, which involves re-establishing hot catalyst circulation until the reactor temperature allows re-introduction of the feed.

Preventing Oil Soaked Catalyst

Oil soaked catalyst often refers to the scenario where the regenerated catalyst slide valve has closed yet feed continues to flow to the reactor riser**.** Without the catalyst to vaporize and crack the feed, oil fills the riser, overflows into the stripper and soaks the catalyst. It then enters the regenerator through the spent catalyst slide valve, where temperatures increase dramatically when the oil finally combusts. Additionally, unburned hydrocarbons may find their way to the electrostatic precipitator. The electrostatic precipitator (ESP) and CO boiler must be removed from service. The ESP must de-energized and grounded. All firing at the CO boiler must be stopped.

The EIS responds to closure of the regenerated catalyst slide valve, or low reactor temperature, by diverting the feed to the main column, removing other hydrocarbons, closing the slide valves and increasing the lift steam. Air remains flowing to the regenerator.

At the regenerator, oil soaked catalyst occurs when torch oil is present below its auto-ignition temperature. A temperature interlock at the regenerator prevents this from occurring.

Preventing Detonation in the Electrostatic Precipitator

Avoidance of unburned hydrocarbons at the electrostatic precipitator is the best prevention of detonation. By preventing torch oil usage at low temperatures in the regenerator and oil soaked catalyst in the reactor stripper, the EIS prevents unburned hydrocarbons from traveling to the electrostatic precipitator.

Further attention must be given to the CO boiler operation. Air distribution design ensures constant excess oxygen. Loss of flame or loss of combustion air must shutdown the boiler firing to prevent combustibles from entering the ESP.

Loss of the main air blower is another interlock that disables both the CO boiler and the ESP.

Reactor Stripper Level SIL Determination

Typically UOP does not see the abnormal level in the reactor stripper as a SIL event because no one is injured as a consequence. Obvious production losses occur but these are more an economic consequence. Perhaps an “economic integrity level” would be a more appropriate discussion.

Still, UOP’s EIS considers consequences from the abnormal level and installs 3 transmitters to monitor the reactor stripper catalyst level. A high stripper catalyst level will trip the feed and riser hydrocarbons as well as stop catalyst circulation and maximize lift steam. However, a delay in closing the spent catalyst slide valve (so long as its differential pressure remains positive) helps transfer the excess catalyst inventory back to the regenerator.

EIS Availability and Reliability

As mentioned earlier, high levels of availability and reliability provide a robust EIS that supplements operator actions during abnormal events. Availability is tied to logic solver performance, redundancy and voting of field sensors, and redundant final elements. Additionally, separation of EIS and BPCS functions avoids common mode failures. Finally, time to repair failed devices and interval testing play a role in achieving availability performance.

By using a logic solver that has processor redundancy, fault tolerance and extensive diagnostics, covert failures are avoided. Note that UOP insists on TUV-certified safety logic solvers for its projects. Normal PLC’s are not suitable for these applications.

Using multiple sensors at each location prevents a single failure from defeating system success. This arrangement minimizes false trips. Sensors with diagnostics allow even better performance.

Testing is another part of availability. Regular testing is key in discovering hidden failures in the system. Provisions must be made if online testing is the chosen approach. Slide valve actuators with emergency hydraulic circuits require a means of testing that does not upset an operating process. Inclusion of partial stroke testing for shutdown valves is another consideration.

The time to repair a failed component also enters into the calculations. If a component has failed, either identified by its own diagnostics or by testing, the duration of its repair before the system recovers is an integral part of the system’s availability performance.
Reliability is gained through use of multiple solenoids at shutdown valves. Redundant power from separate supplies adds to robustness. Multiple sensors prevent single points of failure.

Benefits of Installing an EIS

The FCC Process Unit is the heart of many major refinery complexes. Shutdowns quickly disturb downstream units by interrupting their feed source. The FCC Process Unit is both dynamic and high temperature where operational upsets quickly cause serious problems. Early and vigilant detection of abnormal events with proper and precise responses mitigates production or equipment damage. Minimization of recovery time from unit trips is also important.

The implementation of a robust Emergency Interlock System can assist the refiner with the automated shutdown of the catalyst section of the FCC unit. This automation avoids major equipment damage or injury while placing the FCC unit in a condition suitable for rapid re-starts.