Hydrocracker Safeguarding with SIS

White Paper

KENEXIS

>> INTRODUCTION

Emergency depressuring of Hydrocracking process units in refineries received a large amount of attention after the 1997 accident that occurred at Martinez, California. Many refiners decided that automatic depressuring of the unit when excess temperature was detected should be a safety instrumented function and replace the traditional manual depressuring. When attempting to implement the ISA 84.01 safety lifecycle, Refiners found that applying this safety instrumented function is quite difficult in terms of risk analysis to determine the required safety integrity level (SIL). This difficulty is due to the large number of measurements that can detect out of control conditions and variety of means for returning the process to a safe state, which all depend on the initial failure mode.

Many refiners decided that automatic depressuring of the unit when excess temperature was detected should be a safety instrumented function and replace the traditional manual depressuring

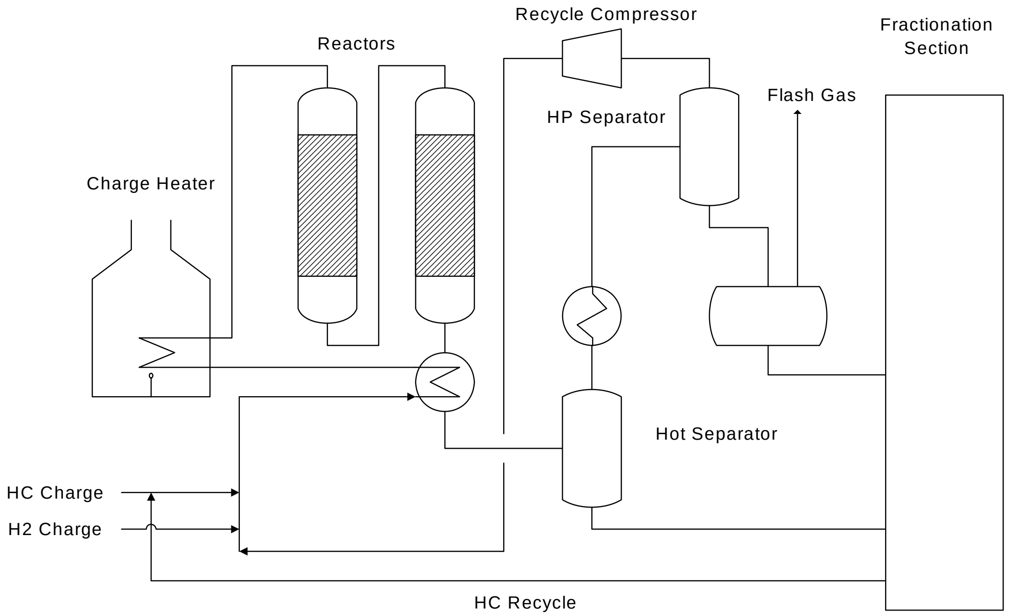
This white paper discusses the selection of a safety integrity level for the depressuring function. The Hydrocracking process is of great interest in terms of SIL selection because of the advanced methods that are required to provide reasonable results. Although simple methods are available and are even promoted in SIS standards, those methods typically provide results that are unacceptable when applied to the Hydrocracking runaway reaction problem. This white paper not only provides typical results of this type of study, but also provides an overview of some of the more advanced techniques that can be applied to the SIL selection methods along with guidelines for when more advanced techniques should be used.

Quantitative Risk Analysis (QRA) is rarely performed for selecting SIL. QRA requires highly trained analysts and increased effort when compared to qualitative methods. In addition, using the numerical results that are generated by the method requires that decision criteria that are also numerical, which many organizations do not desire to employ due to the perception of liability that is created. Even though QRA is not widely practiced for SIL selection, there are some situations where all of the other SIL selection methods, which are essentially various degrees of shortcutting QRA, are inadequate and will lead to artificially inflated requirements (i.e., a higher SIL, more equipment, frequent testing, and overall higher costs). An excellent example of this situation is the emergency depressuring of a Hydrocracker reactor section upon detection of a thermal runaway reaction. In order to improve SIL selection, a limited amount of QRA should be incorporated into the SIL selection procedures and to support decisions about the need for risk reduction alternatives. The key to effective implementation is only use small amount of QRA calculations to support your existing processes instead of trying to use QRA for every scenario.

2.0 HYDROCRACKING PROCESS AND HAZARDS

Many refineries employ Hydrocracking technology to convert heavy hydrocarbon oils into lighter and more valuable products. *Figure 1* presents a typical flow sheet for a single stage Hydrocracking process[1].

Figure 1 – Typical Hydrocracker Flow Sheet



The Hydrocracker unit is fed with hydrocarbon liquid and hydrogen. Hydrocrackers are capable of processing a wide range of liquid hydrocarbon feed stocks, but typically process heavy oils such as vacuum gas oils and atmospheric residuals. The hydrogen / hydrocarbon feed blend is typically heated in a fired heater and sent to the reactors where the cracking reaction occurs. After heat exchange, the hydrocarbon products are separated from hydrogen and light gases in a series of separators and flash drums. Hydrocarbon products are further processed in a fractionation section. Both heavy hydrocarbon liquids and hydrogen may be recycled.

Excessive cracking reactions can spiral out of control and result in a potential loss of integrity of the reactor vessel or piping due to excessive temperature.

The reactions taking place in the Hydrocracker process include cracking, whereby long chain hydrocarbons are broken into smaller chains, and hydrogenation, where any free radicals or double bonds are saturated. The end result is a hydrocarbon product whose average molecular weight is much smaller than the molecular weight of the feed. The overall reaction is significantly exothermic. Under some circumstances, there is a possibility that the heat generated in the reaction will increase the temperature of the catalyst bed, leading to increased reaction rates and more heat generation. This effect can spiral out of control and result in a potential loss of integrity of the reactor vessel or piping due to excessive temperature.

---

[1] Meyers, Robert A., "UOP UNICRACKING PROCESS FOR HYDROCRACKING", Handbook of Petroleum Refining Processes, Second Edition, McGraw-Hill, New York, NY, 1997, 7.41-7.49

High rate depressuring is capable of bringing the process to a safe state rapidly, but causes unwanted side effects such as intense flaring and equipment degradation due to hydrogen embrittlement.

The reaction occurs as liquid hydrocarbon contacts a fixed bed of catalyst with excess hydrogen at a high pressure. During normal operation, adding a cold hydrogen quench to sweep away the heat of reaction to the downstream heat exchangers controls temperature. In an emergency situation depressuring the reactor can stop the reaction. When a depressuring occurs, the reactor pressure and thus the partial pressure of hydrogen decreases. The decrease in hydrogen partial pressure essentially decreases the concentration of reactant available, and in accordance with traditional chemical reaction kinetics, the reaction rate quickly falls off. The speed at which the reaction rate falls is a function of how fast the reactor pressure drops. Many Hydrocrackers are equipped with two different means of depressuring: a slow system, and a fast system. Obviously, the fast system is capable of bringing the process to a safe state more rapidly, but causes unwanted side effects such as intense flaring and equipment degradation due to hydrogen embrittlement. In an emergency scenario, an operator will first attempt to bring the process under control using the slow depressuring and only use the fast depressuring system if the other is not capable of stopping the runaway reaction from continuing.

The analysis in this white paper focuses on a Safety Instrumented Function (SIF) that will initiate a fast depressuring upon detection of a high temperature condition in the hydrocracking reactors. This analysis is complicated by the fact that there is an additional SIF specified which causes a slow depressuring upon detection of low of recycle hydrogen flow. These two SIF prevent the same hazard from occurring, but do not completely overlap because the low recycle gas flow SIF does not protect against all of the possible initiators of runaway reaction.

3.0 BASIC SIL SELECTION METHODS

The white paper scenario employs a typical method for selecting SIL. The methodology is based on a hazard matrix to contain the tolerable risk decision criteria and use of layer of protection analysis to account for the impact of existing and proposed non-SIS engineered safeguards. The process includes the steps shown below.

1. Select the consequence severity category for this hazard
2. Select the category representing likelihood of the initiating event
3. Determine the required degrees of risk reduction based on the hazard matrix shown in *Figure 2*
4. Determine the number of independent protection layers
5. Calculate the required SIL by subtracting the number of independent protection layers from the required degrees of risk reduction.

The hazard matrix shown in *Figure 2* is a typical example of a matrix that is used in industry. In addition to qualitative descriptions of categories, such as "Severe" and "Rare", the categories are also associated with quantitative ranges. This paper will demonstrate that inclusion of quantitative ranges in qualitative tools, such as risk graph, will allow decision support through quantitative risk analysis (QRA) calculations. The example shown below was calibrated[2] using tolerable risk guidelines suggested by the UK Health and Safety Executive[3].

Figure 2 – Typical Hazard Matrix

Likelihood	Frequency Range (per year)				
Frequent	10 - 1	3	4	5	6
Moderate	1 – 0.1	2	3	4	5
Infrequent	0.1 – 0.01	1	2	3	4
Rare	$0.01 – 10^{-3}$	---	1	2	3
Remote	$10^{-3} – 10^{-4}$	---	---	1	2
* Calculated	$10^{-4} – 10^{-5}$	---	---	---	1
	Consequence Range (PLL)	0.001 – 0.01	0.01 – 0.1	0.1 – 1.0	1.0 – 10.0
	Consequence	Minor	Serious	Severe	Catastrophic

* This category should only be used when supported by quantitative frequency calculations

4.0 SIL SELECTION PROBLEMS

> *Short-cut risk analysis methods, yields poor results when the assumptions upon which the process is built are not valid.*

While the procedure shown above is typically very successful, a small percentage of scenarios that are analyzed (usually < 5%) do not yield satisfactory results (e.g., the selected SIL was higher than expected and yields an unacceptably costly / complex design compared to industry benchmarks). The method shown above as well as other short-cut risk analysis methods yields poor results when the assumptions upon which the method is built are not valid. For the white paper scenario, the following considerations make the simple hazard matrix protocol invalid.

---

[2] Marszal, E.M., and Scharpf, E.W., Safety Integrity Level Section – Systematic Methods including Layer of Protection Analysis, First Edition, Instrumentation, Systems, and Automation Society, Research Triangle Park, NC, 2002.

[3] United Kingdom Health and Safety Executive, The Setting of Safety Standards – A Report by an Interdepartmental Group of Advisors, Her Majesty's Stationery Office, London, 1996..

1. There are a large number of events that can result in a runaway reaction (initiating events).
2. None of the initiating events has a significantly larger frequency than the rest that it can be treated as representative of the overall risk.
3. The safeguards that are employed in the process are not effective against all initiating events.
4. There is a large number of SIF that are intended to prevent essentially the same hazardous event.
5. Multiple SIF share common equipment
6. BPCS protection functions share final elements with SIF.
7. Many of the SIF are not 100% effective in preventing all of the initiating events from propagating into an accident.
8. There are mitigating events that decrease the probability of the occurrence of an accident that do not fit the description of an independent protection layer as given in the SIL Selection Guidelines.

5.0 SUPPORTING SIL SELECTION WITH FAULT TREE ANALYSIS

Based on the reasons stated above, a SIL selection team should consider a detailed Fault Tree Analysis (FTA) to determine the estimated frequency of occurrence of this event. Although detailed analysis is typically required to estimate the frequency of the unwanted event, the consequence category selection can typically be done qualitatively with a reasonable degree of accuracy. The result of the FTA can then used to select a likelihood category, and subsequently the required SIL.

In general, a FTA is performed by identifying all of the basic events that can either be the root cause of the accident (i.e., initiating event), or can prevent the initiating event from propagating into the unwanted accident. It is important to note that the term “DCS Protective Function” is used throughout the discussion as a description of a layer of protection. When this term is used, the system that is being described is a basic process control system (BPCS) function that is separate from the SIS that is under study. The basic events are then logically related to each other using a graphical representation. The result of the fault tree analysis is the frequency, or probability, of the “top event” or unwanted accident, which is calculated using the probabilities and frequencies of the basic events and a graphical description of how they are logically related. A typical Hydrocracker application has at least nine (potentially more depending on configuration) initiating events that can cause a runaway reaction if no mitigating actions were taken after those events occurred. The events are shown below.

1. Recycle compressor failure

When a recycle compressor failure occurs, the flow rate of hydrogen through the reactor decreases. The decrease in hydrogen flow rate effects both the hydrogen-to-hydrocarbon ratio of the feed and also will stop the flow of quench gas. When this occurs, the heat removal with excess hydrogen stops, but the reaction continues to occur because there is still ample hydrogen available at a high pressure. Since the rate of heat removal loss is so great it is virtually impossible for an operator to prevent a runaway reaction from starting. Therefore, this scenario requires depressuring. Depressuring will either occur due to the low recycle gas flow SIF, which activates the slow depressuring upon loss of recycle flow, or manual activation of the slow depressuring.

2. Reactor internals failure

The failure of reactor internals, such as catalyst support screens and distribution boxes, can result in a temperature runaway. Failure of equipment located above a Hydrocracking catalyst bed will result in debris resting on top of the bed. The debris will cause flow misdistribution and channeling. As a result, the areas of the bed where flow has decreased will suffer a decrease in heat removal and increased temperature. The increased temperature may propagate into a runaway reaction. The thermal runaway in this scenario is much slower to develop than for the recycle compressor failure scenario. As a result, automatic control and operator intervention have a good chance of being able to prevent a runaway reaction by adjusting quench rates to the effected bed. While recovery from internals failure is possible, in some cases the damage is so severe that recovery is impossible and a depressuring must occur to bring process to a safe state.

3. Quench failure

Failure of quench control resulting in low or no quench flow could occur as the result of either controller failure or quench control valve failure. In either case, reactor temperatures would rise at a moderate rate as a result of loss of heat removal. Recovery from the failure is possible either through manual operation of the control valve from the control room, or hand-jacking the control valve in the field if control room operation is not possible.

4. Plugging and channeling due to coking and contamination

During the normal course of operation of the Hydrocracker, coking and plugging will occur in all of the catalyst beds. Coking and plugging can result in misdistribution of flow and channeling through the catalyst bed. As channeling occurs, heat removal from the catalyst bed will lose its uniformity, allowing hot spots to occur in areas where flow has decreased. The increased reaction in hot spots can result in a temperature runaway. The development of temperature runaway in this scenario is quite slow compared to other initiating events, allowing automatic control and operator intervention to prevent the runaway in most cases.

5. Improper catalyst loading results in channeling

Plugging and channeling can also occur as the result of poor catalyst loading. The mechanism for runaway reaction is identical to the mechanism described in the paragraph above. In this scenario, it is expected that the operator will not have enough information or time to detect the cause of the problem and the channeling could be quite severe. As a result, no credit is typically given for the operator being able to regain control of the process.

6. Bed temperature measurement failure leads to runaway

Failure of a bed temperature measurement can lead to a temperature runaway if the result of the failure is decreasing or stopping quench flow. An erroneous low bed temperature measurement will result in the automatic quench controller decreasing quench flow rate. The decreased, or stopped, quench flow will result in a moderately rapid temperature rise as the heat removal from the bed decreases. If failure of the temperature measurement can be detected, the reactor can be returned to normal operation by switching the temperature measurement used for control. In addition, manual operation of the quench valve from the control room will also prevent a runaway from occurring.

7. Failure of a recycle gas flow controller

Failure of the recycle gas flow controller in a position where flow is stopped or significantly reduced will result in a temperature runaway. This scenario will result in the same outcome as loss of the recycle compressor. In this scenario, there is an opportunity for recovery by operator intervention. Depending on the control loop’s failure mode, the operator can take manual control of the loop either from the control room or the field.

8. Change in feed flow rate and/or hydrogen-to-hydrocarbon ratio

A significant change in feed flow rate can result in a temperature runaway due to rapid change of the hydrogen-to-hydrocarbon ratio. Significant changes in feed flow rate are the result of failures in feed flow controllers and feed pumps. The temperature rise that will occur in this scenario is moderately fast, but recovery is possible through automatic and manual adjustment of quench rates and readjustment of feed flow rates. In addition to manual and automatic attempts to recover control of the process, a DCS function can be employed to loss of hydrocarbon feed and subsequently perform a slow depressuring.

9. Failure of fired heater outlet temperature control causes high heater outlet temperature

Excessive temperature of the reactor feed can also result in temperature runaway, under certain circumstances. Excessive temperature of the reactor feed is possible as the result of a failure of temperature control of the charge heater such that maximum firing occurs. This failure may result in reactor inlet temperatures that are so high that maximum quench rates cannot bring the reactant temperature back down to the stable range. If this failure occurs, the operator has the capability of bringing the process back under control by manually operating the failed temperature control loop. If manual temperature control fails, the operator also has the option of manually stopping the heater, which will bring the process to a safe state.

All of the initiating events described above can result in a runaway reaction none of the listed corrective actions are taken. Once a runaway reaction reaches the point where normal control cannot be re-established, the process can be brought back to a safe state by either manual or automatic depressuring. As described above, there are two different depressuring systems, one for slow depressuring and another for fast depressuring. In order to minimize the negative impact of a depressuring on the process equipment, the slow depressuring is always attempted first.

A slow depressuring can be activated by a manual switch in the control room or in the white paper scenario by exceeding the high-high temperature, as determined by a DCS protective function. In either case, the slow depressuring valve is opened by de-energizing its associated solenoid valve. Even if the slow depressuring system is activated, there is a possibility that it will not decrease the reaction rate quickly enough to prevent the runaway from propagating. In this case, a fast depressuring will also be required to bring the process to a safe state. Although failure of the slow depressuring to stop a runaway reaction has been postulated, no instances where this has occurred are known to the authors of this paper.

A fast depressuring can also be activated by a manual switch in the control room or by exceeding the high-high-high temperature (in the white paper scenario), as determined by a DCS protective function. In either case, the fast depressuring valve is opened by de-energizing its associated solenoid valve. If a fast depressuring is attempted from the control room and fails, the depressuring can then be accomplished by opening a manual depressuring valve in the field.

A fault tree was developed that represents the information presented above. This fault tree was quantified based on a variety of information sources. Control system and instrumentation failure rates were derived from public and private databases of industrial equipment failure rates. Failure rates of large piece of process equipment can be categorized using expert judgment failure statistics. Other mitigating events probabilities can also be quantified using industry data but in some cases conservative expert judgment is required.

Based on the failure characteristics determined by the team, the frequency of the top event can be calculated. Kenexis recommends the use of fault tree analysis software that is capable of performing minimal cut set analysis to perform this task, as gate-by-gate hand calculations will deliver poor results. It is important to note that the calculated event frequency makes assumptions about the integrity of SIF that are used to prevent the runaway reaction in various ways. The scenario under study contains two SIF that can mitigate a runaway reaction, depending on the initiating event that causes the runaway. Specifically, there is a SIF which will cause a fast depressuring upon detection of high temperature at the reactor outlet (this is the SIF for which this SIL selection analysis is being performed), and there is also a SIF that will perform a slow depressuring upon detection of loss of recycle gas flow.

When two functions are available to prevent a single hazard, one SIF should be arbitrarily assigned a proposed SIL, typically SIL 1, and the balance of the required risk reduction should be allocated to the remaining SIF to determine its required SIL level.

When two or more SIF are used to perform to mitigate the same hazard; theoretically, there are an infinite number of combinations of allocation of risk reduction between the two SIF that will yield a valid result. Since the SIL selection process can only yield the required SIL for a single function, other means are required to allocate required risk reduction to one of the SIF. When this occurs one of the SIF should have a SIL arbitrarily assigned, such as assigning a SIL of 1 to the loss of recycle gas depressuring SIF, and then the SIL required of the high temperature depressuring SIF was calculated based on the residual risk. When more than one SIF is available to prevent a single hazard, all of the SIF except one should be arbitrarily assigned a SIL, and the balance should be "made up" with the remaining SIF. The "arbitrary" assignment should start out by assigning a SIL of 1 (i.e., lowest cost) to the SIF that is most expensive to install and maintain.

6.0 INCORPORATION OF FAULT TREE ANALYSIS RESULTS

A fault tree built and quantified for this scenario represents the frequency at which the runaway reaction will occur without considering the benefit of the SIF that is under consideration. The SIF under consideration is "high reactor temperature causes fast depressuring". The FTA, in this scenario will result in a quantitative frequency at which this event is expected to occur. While some organizations have quantitative risk acceptance criteria that use this frequency result directly, those criteria are not required. As an option to directly using the frequency results, the FTA outcome can simply be used as support in selection of a likelihood category from the matrix tables. This approach is facilitated if the risk matrix category tables are set up to explicitly show numerical ranges. It is important to note that the FTA result will already incorporate the layers of protection that are available to prevent the initiating events from propagating into the unwanted accident. As a result, they should not be applied again. The required level of risk reduction can then be obtained from a hazard matrix in, such as the one in Figure 2. This required risk reduction value is the required SIL for this scenario. For example, if the FTA calculated a value that fell into the "remote" category for likelihood and the consequence was determine to fall into the "severe" category, a SIL requirement of SIL 1 is obtained for this SIF, based on the hazard matrix in Figure 2. The numbers in the hazard matrix represent the orders of magnitude of risk reduction that are required to make a given situation tolerable. Note that in some cases the required risk reduction can be 5 or 6. According to the SIS standards, SIS are only capable or performing up to 3 (ISA) or 4(IEC) orders of magnitude of risk reduction. If the analysis process yields a need for risk reduction of 5 or 6, this cannot be accomplished with a single SIF alone. Practically speaking, SIL 4 is not obtainable with existing technology, and even SIL 3 is extremely costly over the lifecycle of a process.

It is also important to note that the approach where the SIF can be considered outside of the fault tree may not be appropriate. This situation will occur when the SIF under study utilizes some of the same equipment as other SIF or BPCS and operator intervention protection layers. In this case, the SIF under study would also need to be included in the fault tree. Using this approach, the design of all of the SIF would need to be iteratively altered until the FTA result yields a likelihood category, that for a given consequence does not require any further risk reduction, in accordance with the tolerable risk matrix.

7.0 CONCLUSION

Short-cut methods that are commonly used for SIL selection such as hazard matrices, risk graph, and even LOPA are effective in most situations. However, there are some scenarios where selecting SIL using these tools provides unsatisfactory results, usually because the selected SIL was significantly higher than original expectations and good engineering judgment dictates. In these scenarios supporting these qualitative tools with quantitative risk analysis (QRA) calculations will provide more reasonable and accurate results. The results of the additional quantitative analysis can easily be incorporated into a risk analysis tool's format if inclusion of this type of analysis is planned during the construction of the tool.

The high temperature emergency depressuring of a Hydrocracker reactor is an example of a situation where the short-cut methods cannot provide a realistic result due to the complexity and interrelationship of the multiple safeguards and multiple initiating events. Use of additional QRA will allow SIL to be effectively assigned for the multiple SIF involved in mitigating this hazard.

KENEXIS' CAPABILITY AND EXPERIENCE FOR HYDROCRACKER SIS TECHNOLOGY

Implementing the ISA and IEC consensus standards is not a trivial activity because they require understanding of the risks of a hydrocracker process and how to effectively manage risk using an integrated system comprised of instrumentation, logic solvers, and final control elements. Furthermore, these new standards come at a time when business face ever-increasing pressures to reduce costs and increase profits. In the face of these challenges, Kenexis is an engineering consulting company that can help you implement standards for Safety Instrumented Systems and cost-effectively manage your risks.

Kenexis' innovative strategy for Safety Life Cycle services is built on the foundations of:

- Risk Analysis Expertise
- Substantial Experience in the Process Industries
- Excellence in Control System Engineering

Kenexis provides consulting and engineering services, training, and tools to make implementing safety instrumented systems cost effective. Whether designing new safety systems, making major upgrades, or even managing existing installations, Kenexis can help.

Safety Integrity Level Selection

The amount of risk reduction required of the SIS is specified by the Safety Integrity Level (SIL). Kenexis provides procedures, tools, and expert advice to help you select your SIL requirements. It's important to know that your equipment costs could multiply unnecessarily if you select a stringent SIL rating when it's not needed.

Safety Requirements Specification

This document specifies what actions the SIS should take, and how effective it needs to be. Kenexis offers coaching and templates to help you prepare the specification that most effectively meets your SIL requirements.

Safety Integrity Level Verification

You are required to verify that the as-designed system meets the required SIL rating. This can be a complex exercise in reliability analysis. Kenexis can help by providing essential tools for your use, or by having our staff perform an independent verification.

Operation and Maintenance / Function Testing

A key step is having procedures to operate, maintain and regularly test the SIS. We help develop and execute procedures needed to effectively test your equipment and demonstrate it meets the SIL target. We also assist in meeting the requirements of Pre-Startup Acceptance Testing and validation.

Kenexis has ample experience in the analysis, design, and implementation of Hydrocracking technologies from a variety of licensors. Kenexis' experts have developed SIS design basis packages for the following projects.

Unicracker SIS Upgrade – 2001 – Northern California US

Isocracker SIS Upgrade – 2002 – Gulf Coast US

Unicracker Addition – 2003 – Mid-Continent US

Unicracker Addition – 2004 – North-Midwest US

Unicracker Addition – 2005/6 – Gulf Coast US

About the Authors

Ed Marszal, PE, CFSE
Kenexis
edward.marszal@kenexis.com
2929 Kenny Road, Suite 225
Columbus, OH 43221
+1 (614) 451-7031

Ed Marszal has over ten years of experience in instrumentation, safety systems design and risk analysis. Mr. Marszal has worked with UOP, a developer and supplier of process units to the petroleum and petrochemical industries, where he performed field verification of control and safety instrumented systems at customer sites world-wide. At UOP, he also designed and managed development of custom control and safety system projects. After leaving UOP, he joined a risk management consulting firm specializing in financial risk analysis and process safety management. In this position he performed and managed risk assessment projects that included quantitative consequence and likelihood analysis, including development of EPA Risk Management Programs with off site consequence analysis. He has solid experience in numerous projects involving evaluation of the integrity of safety systems, financial risk analysis and system design. Mr. Marszal has a BSChE from Ohio State University. He is a registered professional engineer in the States of Ohio and Illinois, USA, and the certified functional safety expert (CFSE). Mr. Marszal is a senior member of the Instrumentation, Systems, and Automation Society (ISA) and has held numerous positions of responsibility in that organization, and also a member of the National Fire Protection Association (NFPA), and the American Institute of Chemical Engineers (AIChE).

Kevin Mitchell, PE, CFSE
Kenexis
kevin.mitchell@kenexis.com
2929 Kenny Road, Suite 225
Columbus, OH 43221
+1 (614) 451-7031

Kevin Mitchell has over ten years of experience in chemical process safety and risk management. During much of this time he worked as a consulting engineer for DNV and ERM-Risk, helping companies in the petroleum and chemical industries implement process safety technology and management systems. Mr. Mitchell specializes in state-of-the-art assessment of the risk of toxic, flammable, and explosive materials on people, property, the environment, and, ultimately, the business. He uses risk assessment and cost-benefit analysis to assist in making engineering and business decisions. Mr. Mitchell has defined safety integrity requirements for clients using the principals of risk assessment in over 100 project assignments covering such diverse operations as oil & gas production, refining, petrochemical, specialty chemical, plastic resin, transportation, and general manufacturing. He also has extensive experience in investigating major chemical accidents to identify causes and develop lessons-learned. Mr. Mitchell has a BS in Chemical Engineering from The University of Minnesota and is a Registered Professional Engineer in the state of Ohio. He is also a member of the American Institute of Chemical Engineers and the Instrumentation, Systems, and Automation Society. He has numerous technical publications and is a Certified Functional Safety Expert (CFSE).