APPLICATION OF COMBUSTION ANALYZERS IN SAFETY INSTRUMENTED SYSTEMS

Larry E. Sieker, PE
150 Freeport Road Pittsburgh, PA 15238
Ametek Process Instruments

KEYWORDS

SIS, SIL, IEC 61511, API RP 556, O2, CO break through, Methane, Zirconium Oxide, Catalytic Bead,TDL

ABSTRACT

The combustion process has always been considered having the potential for a hazardous event which could lead to personnel injury or loss of production. To mitigate this risk, the process industry is now implementing Safety Instrumented Systems which can identify hazardous operating conditions and correctly respond in such a way to bring the combustion process back to a safe operating condition or implement an automatically controlled shutdown sequence to reduce the risk of operator error causing a catastrophic event. Oxygen and combustible flue gas analyzers are now being utilized in these combustion Safety Instrumented Systems (SIS) to identify hazardous operating conditions and automatically return the process to a safe state.

The standards of IEC 61511 and API RP 556 will be reviewed as they apply to flue gas analyzers, as well as the process variables of the oxygen and combustible analyzer available for implementation into the SIS system for combustion monitoring, and the resultant actions required to return the process to a safe condition.

PROCESS INDUSTRY RISK

On March 23, 2005, a fire and explosion occurred at a Texas City refinery, killing 15 workers and injuring 170 others. The refiner was charged with criminal violations of federal environmental laws and has been subject to multiple lawsuits from the victim's families. OSHA has since slapped the refiner with a then-record fine for hundreds of safety violations, and subsequently, imposed an even larger fine after claiming the refiner had failed to implement safety improvements after the disaster.

Preventing process accidents requires vigilance. The passing of time without a process accident is not necessarily an indication that all is well and may contribute to a dangerous and growing sense of complacency. When people lose an appreciation for how safety systems were intended to work, safety systems and controls can deteriorate, lessons can be forgotten, and hazards and deviations from operating procedures can be accepted. Workers and supervisors can increasingly rely on how things were done before, rather than relying on sound engineering principles and necessary controls and safeguards. People can forget to be afraid.

Most all in the industry are aware of the potential hazards of firing and controlling combustion processes. The idea of heating a hydrocarbon feed thru radiant and convective tubes to extreme temperatures within a metal structure containing a "controlled" fire seems like an invitation to disaster. Further, the variability in fuel quality, low emission burners, aged heaters and boilers, and the desire to increase production thru the unit would seem to push the limits of proper control and safety.

The realization that "incidents will happen" has led the refiner to implement safety systems for combustion which are independent of the Basic Process Control System (BPCS) and will identify hazardous operating situations and either take control of the process and shut it down in a safe sequence or provide a permissive function to operations so that no further control action can take place until the process returns to a safe state.

These systems implemented for process safety are referred to as Safety Instrumented Systems (SIS).

STAANDARD IEC 61508 (International Electrotechnical Commission)

The current standard for Safety Instrumented Systems (SIS) is by the International Electrotechnical Commission (IEC) and is detailed in IEC 61508 "Functional Safety of Electrical/ Electronic/ Programmable Electronic safety-related systems." ANSI./ISA-84.00.01 was released in the USA market and has since adopted IEC 61508 as the international standard.

This IEC 61508 standard was designed as an umbrella document that covers multiple applications and industries and designed to be the “blue print” for the design standards of SIS. Released in the year 2000, it details the procedure of identifying process hazards and risks, identifying hardware and software specification, commissioning, validating and documenting of the SIS process as well as the eventual decommissioning of the SIS. A key part of this standard is that the design of the SIS is by committee and not just an individual. All personnel from process engineering, operations, environmental, validation, and maintenance are involved in the specification and implementation of the system. This complete involvement of all plant disciplines insures that all aspects of the process, its control, the potential hazards, required periodic validation, and eventual decommissioning are addressed to insure maximum safety integrity. Once OSHA in the United States stated that ISA 84.01 is “a recognized and generally accepted good engineering practice for SIS”, the standard became accepted by many process companies in North America, leading them to start implementing SIS for process risk reduction. When IEC 61508 passed for the first time in February 2000, ANSI/ ISA adopted it as the international standard for functional safety and a truly world standard was now recognized.

The Safety Life Cycle

The Safety Life Cycle (SLC) is one of the most fundamental concepts detailed in IEC 61508 and ANSI/ISA 84.01. This common sense engineering procedure can be summarized in three steps: 1) Analyze the problem, 2) Design the solution, 3) Verify that the solution solves the problem

The problem analysis involves hazard identification and risk assessment. Potential indentified hazards with enough risk may warrant the design of an SIS and the required safety level and redundancy of measurement needed. Once a Safety Integrated Level (SIL) is assigned, a failure probability calculation and risk reduction factor (RRF) calculation are done to verify that the SIS design meets the risk reduction target. If the design does not meet the risk reduction goals, better equipment can be chosen or redundancy of equipment can be employed to increase the risk reduction.

THE SAFETY INSTRUMENTED FUNCTION AND THE SAFETY INTEGRITY LEVEL

A Safety Instrumented Function (SIF) is defined as a “function to be implemented by a SIS which is intended to achieve or maintain a safe state for the process, with respect to a specific hazardous event”. A SIS can consist of one or many SIF functions and each SIF usually incorporates one or more sensors for redundancy. During a “Hazard Analysis & Risk Assessment”, the SIS committee will review the various control parameters in a particular SIF for a process and determine each control loops potential to bring the process to a catastrophic state either by control, final element, soft logic and/or operator failure, and is assigned a risk level, or "Safety Instrumented Level" (SIL), which dictates the required equipment integrity and redundancy required to achieve the required SIS availability to mitigate a potential event. The basic factors considered for determining the required SIL level are the potential severity of the event, the frequency of the event occurring, and how much risk needs to be reduced to place the potential event into an acceptable level of risk. This is typically a qualitative calculation of the Risk Reduction Factor (RRF) expressed as follows:

Required Risk Reduction Factor = Mean Time between the Hazard/Demand Rate of the Event

An example would be a process heater where on average a burner flames out once a year, flooding the firebox with high levels of carbon monoxide and methane which could cause the heater to explode. Management has dictated that an explosion cannot be tolerated but once in every 500 years. This would be then a Required Risk Reduction or a calculated RRF of 500.

Table I. Correlation between Overall risk Level and Required Safety System Performance.

Risk Level	IEC/ISA/AlChE Safety Integrity Level	Required Safety Availability	Probability of Failure on Demand	Risk Reduction Factor
(Note 1)	4	>99.99%	<.0001	>10,000
High	3	99.9-99.99%	.001-.0001	1,000-10,000
Medium	2	99-99.9%	.01-.001	100-1000
Low	1	90-99%	.1-.01	10-100
Notes: **1. Sil 4 is not used in the process industry. It is intended to represent other industries, such as transportation, aerospace, or nuclear.** **2. Field devices are included in the above performace requirements.**				

Also considered in the SIL rating is the required safety availability and probability of failure on demand. These are based on the field analyzers, final elements, and logic system specified which have a determined probability of failure/ probability of operating properly if a hazardous event happens. An SIS is invisible to the control operator. It stands in wait to function as programmed and may not have to be utilized for years. The design of the system must take into account the longevity and dependability of the equipment. Several manufacturers now make available SIL certified equipment which have been reviewed and tested by a third party agency to IEC 61508 and IEC 61511, and publish the failure rate data in as much the same way as temperature specifications or accuracy figures, as well as having their equipment certified to a specific SIL level. These SIL analyzer certifications tend to document the reliability and self diagnostics available within the analyzer to insure reliable operation. In cases where third party testing has not been completed, the user themselves can compile their own repair histories on specific analyzers and instrumentation and compute their own failure rate data.

STANDARD API RP 556

As with any combustion safety system, the proper and safe operation is dependent on an effective control algorithm to monitor and identify potential harmful or catastrophic situations. Further, the need to reduce risk in combustion processes throughout a company's many locations dictate that each site utilize the same proven control and safety standard to eliminate rouge, patched or insufficient software. The API standard RP556, April 2011 "Instrumentation, Control, and Protective Systems for Gas Fired Heaters" is currently being utilized in the United States for process heater control and SIS installations. API RP556 provides guidelines that specifically apply for gas fired heaters in petroleum production, refineries, petrochemical, and chemical plants.

COMBUSTION ANALYZER

The combustion analyzer has been a necessary component of fired heater control for many years. In its simplest form, the combustion analyzer provides an excess oxygen (O_2) reading so that an air to fuel ratio can be maintained throughout the firing range of the process heater. The analyzer is typically installed in the convective area of the process in close proximity to the top of the radiant section so that the analyzer can provides a realistic value of how much extra air was added to combust the fuel. This excess air set point is considered a "safety factor", so that by adding more air than required for complete combustion, operations can have a "control cushion" so that if conditions change dramatically, the combustion process will not swing to a "fuel rich" situation where fuel is not completely consumed and the potential for a hazardous event could occur. Hazardous events created by a fuel rich situation would include burner flame-out, carbon monoxide flood, black stack, convective section burning, slag formation, an explosion, etc. In this regard, most refiners have opted to control with a higher than necessary set point of O_2 to insure a fuel rich situation is avoided. This insurance does have a price, though. The high O_2 set points for safety results in less efficient combustion, using more fuel gas than necessary and higher NO_x emissions.

Most refiners today realize the need to run process heaters at their lowest level of excess O_2 to insure a complete burn of fuel for efficiency, and to reduce NO_x without sacrificing safety. Therefore, the combustion analyzer now used to control process heaters incorporates, besides the excess O_2 sensor, an additional sensor for "part per million" (ppm) "CO" or ppm "combustibles" for feedback on the O_2 set point. The combined O_2 and CO combustion analyzer can provide an output to control combustion air to a specific set point based on a specific firing rate and then use the CO output as feedback on how effective the O_2 set point is. An O_2 set point with no trace of CO in the combustion gas would mean that a lower O_2 set point could be achieved without affecting safety and reduce NO_x emissions. An O_2 set point with over 500 ppm CO in the combustion gas would mean the O_2 set point would need to be increased to completely burn the fuel and avoid a potential combustion swing into a “fuel rich” operating area.

SIS JUSTIFICATION

A large progressive US refiner had been using O_2 and combustible analyzers for many years to establish as low as an O_2 combustion set point as they could achieve safely for efficiency and emissions reductions by using the combustible reading as a fine tune adjustment to the primary O_2 set point. The use of combustible reading allowed them to slightly alter their operating O_2 set point to take into account variations of fuel quality, burner performance, and heat rate demand and maintain maximum control quality and efficiency. However, tight control of a combustion process does mean that unexpected deviations or upsets can get out of control quickly and in the interest of safety, an independent system was needed beyond the level of process control to insure that if a hazardous situation did occur, it could be dealt with so as to automatically take control of the situation and respond in an appropriate way to bring the process back to a safe level or achieve a proper shutdown sequence to minimize a hazardous result and insure maximum safety. The typical operator response to large concentrations (or flooding) of CO or combustibles in a process heater is to increase combustion air, which in most cases causes a hazardous event.

The refiner’s hazard identification and risk assessment of their process heater events refinery-wide revealed that there were only two major incidences where process heater safety was compromised and shutdowns were common: 1) Heater light off / heater shutdown due to methane accumulation, and 2) CO or combustible flood where there was a rapid accumulation of partially burned combustibles whereas the control system and/or operator error performed the wrong actions to diffuse the situation and resulted in a hazardous event.

The refiner decided to implement an SIS system independent of the BPCS for all process heaters corporate wide as to insure that all process heaters are monitored by a safety instrumented system that would take control of a hazardous event and insure that process safety interlocks prevent any errors from the control system or operations that would bring the process back into control or if needed, to provide an appropriate shutdown sequence to take place to bring the process to a safe state.

Combustion analyzers incorporating oxygen, combustibles, and methane outputs were utilized to provide the appropriate monitoring functions to implement the SIS functions required by the API RP 559, Section 3.4.4.1 standard.

API RP 559 3.4.4.1

ACCUMULATION OF COMBUSTIBLES WITHIN THE FIREBOX (LOSS OF FLAME, SUBSTOICHIOMETRIC COMBUSTION, OR TUBE LEAKS)

Potential hazards

The afterburning in the radiant, convection, or stack sections may result in the overheating and failure of tubes, tube supports, and/or refractory systems.

An explosion may result with the partial or total destruction of the fired heater which may be hazardous to the personnel in the operating area.

Considerations

At operating conditions, it is possible for a heater to accumulate combustibles at firebox temperatures above the auto-ignition temperature if there is insufficient air to consume all of the fuel. Fuel-rich combustion produces hot flue gas with residual combustibles that can explode if mixed with fresh air too quickly. This is most likely to occur when a furnace transitions suddenly from rich combustion to lean combustion.

At start up conditions, the accumulation of combustibles within the firebox should not be permitted to exceed 25% of the lower explosion limit (LEL) before corrective action is initiated.

Excessively fuel lean combustion with low firebox temperature may lead to gradual accumulation of combustibles within the firebox.

The following control overrides should be considered to keep the heater within operating limits and prevent a heater shutdown:

- Low Oxygen override to the Fuel Controller - With the event of a low oxygen alarm, the fuel gas controller is not permitted to increase fuel rate until oxygen is restored to normal operating levels.

- High Combustible override to the Fuel Controller - With the event of combustibles being over 500 ppm level, fuel gas flow must be decreased before combustion air can increase.

To mitigate the process hazards associated with the accumulation of combustibles in the firebox and to prevent flame out, fuel gas valves should be closed in response to:

- Low or High Fuel gas Burner Pressure
- Low Draft (High Firebox Pressure)
- Failure of Stack Damper to Open
- High Liquid Level in Fuel Gas Drum

ANALYZER IMPLEMENTATION FOR SIS

The existing combustion analyzer used for process heater control could not be used in the implementation of the safety system due to the inherent philosophy of SIS. If the combustion control analyzer was used in the safety system and malfunctioned or failed, this would create a situation is which the SIS system is designed to avoid. A completely independent system from the BPCS is needed to monitor the process and bring it to a safe state or shutdown in a controlled manner.

The SIF (Safety Instrumented Function) which incorporates the O_2 and combustible analyzer (measurement) was determined to be a SIL 2 Safety Integrity Level from the plant history of the analyzer maintenance, calibration, and repair records. Further, due to flue gas stratification, multiple burners, and the effective monitoring area of the convection section, it was determined that multiple combustion analyzers were needed to provide a comprehensive measurement of O_2, CO flood and/ or methane accumulation to insure an absolute response for control override or shutdown. The amount of installed analyzers for the SIS system was determined by radiant section area/ burner arrangement or by multiple combustion cells within one heater.

In most heater installations, this consisted of two analyzers mounted within 6 feet apart at the same elevation, located at the bottom of the convection section, monitoring combustible gases exiting the radiant section of the process heater. The O_2, CO, and methane readings of each analyzer were compared with each other, as a diagnostic function, so that if any reading deviated from each other within a certain tolerance, a “notice” alarm would be generated as a diagnostic tool to insure the health of the SIS system and the accuracies of the analyzers. These “deviation alarms” could not be set at the catalog accuracies of the combustion analyzer sensors since the independent analyzers (sensors) were reading different flue gas locations. Typical deviation alarms are 0.3% oxygen, 200 PPM combustibles, and 5000 PPM methane.

If a “notice” alarm was generated, a technician would be dispatched to determine if the analyzers were function normally. The calibration frequencies of the combustion analyzers are usually recommended as quarterly, yet there is a benefit to more frequent calibration. The “probability of safety on demand” increases with more frequent calibration, which can reduce the required SIL needed for the Safety Integrated Function that the combustion analyzer requires. An analyzer calibration frequency of monthly is typical. A remote calibration function where the analyzer can calibrate itself on a timed cycle allows independent verification without technician involvement.

To prohibit premature trips or false corrective actions from the SIS, the combustion analyzers are configured in the safety logic as a 2oo2 or a 2oo3 voting scenario whereas either both have to agree or two out of three agree to initiate the appropriate safety action, depending on the number of analyzers installed. This insures that momentary stratification or analyzer malfunction does not cause a non necessary corrective action.

COMBUSTION ANALYZER TECHNOLOGY

Close coupled extractive zirconium oxide (ZrO_2) based O_2 analyzers are the analyzer of choice for the SIS measurements. Typically installed for combustion control with fast response of excess oxygen levels in hot dirty flue gas, their ability to measure near the radiant zone with gas temperatures up to 2000F, and an established reliability record in the application, provides the most reliable and accepted measurement for oxygen. ZrO_2 sensors provide an extractive “point type” measurement and are “net oxygen” analyzers which are heated and utilize platinum electrodes with catalytic properties to determine oxygen concentrations of flue gas. They will, however, burn any combustible compounds with oxidation potential such as hydrocarbons, CO, hydrogen, and high concentrations of sulphur dioxide. During combustible flood conditions, H_2 and CO are the largest combustible components and they will consume oxygen in the flue gas sample as they combust on the zirconium cell. The ratio of consumption of combustibles to oxygen is 2:1, thereby, if 1000ppm combustibles is present in the flue gas, 500ppm of O_2 will be consumed from the flue gas sample. This decrease of the oxygen reading due to the burning of combustibles is normally considered negligible. The operating principle of a zirconium oxide sensor having to operate at 695 deg. C to function does create concern that the sensor could cause combustible vapors to ignite on heater light off, shut down, or in a “non-operational heater” outage state. Precautions are met by the installation of “flame arrestors” before and after the measurement section of the analyzer to suppress any ignition as well as the possibility of back-purging the sensor with instrument air to prevent vapors from entering the sensor, or removal of sensor power in an outage situation.

The addition of catalytic bead type combustible sensors can be added to the close coupled extractive analyzer O_2 sample system to provide independent measurements of PPM combustibles and percent levels of methane. These sensors, treated with a catalyst to allow combustible compounds to burn on them at below ignition temperatures, are calibrated with combustible gas they are designed to detect. The PPM combustible detector will respond to CO as well as H_2, which both are normally present in fuel rich combustion when burning hydrocarbons, and this reading is considered the feedback for O_2 trim as well as the indication of a CO flood condition. The methane detector is calibrated strictly for methane and is utilized as a permissive for a "Purge & Light Off" cycle to detect any methane present before the burners are lit. It can be also utilized on shutdown where combustible fuel can accumulate as the process heater begins to cool.

Recent advances in tunable diode laser (TDL) technology have made this analyzer a viable option as well for installations in SIS for O_2 and CO monitoring where a single point measurement provided by close coupled extractive analyzers cannot provide a representative sample of flue gas concentrations. Normally mounted in an across duct configuration, specific wavelengths for O_2 and CO can transmitted across the heater duct up to 100 feet to a detector mounted on the other side looking for IR energy absorbance at the specific wavelengths of the specific gas of interest. The larger the target gas concentration, the larger the IR absorbance is detected. The installation of TDL analyzers usually requires two separate installations, one for O_2 and another for CO, since each need different lasers frequencies for detection. Recent advances will provide the capability of incorporating two lasers in one enclosure for the ability of a dual gas measurement. The location of installation is usually either across the radiant section or across the top of the convection section due to the need to transmit across the heater with no internal structures interfering with the IR transmission. TDL analyzers do provide a "duct average" which can be useful in overall combustion performance and burner operation. Calibration or verification of the TDL analyzer with calibration gas cannot be achieved due to the nature of an "across the duct" type measurement. Units either have to be removed from the process for bench calibration or the process can be "spiked" to insure the TDL analyzer responds.

DISCUSSION

The reliable identification of low combustion oxygen and a CO or combustible flood condition in a process heater or fired process is critical to the effectiveness of a SIS system. The ability of combustion analyzers to provide accurate readings quickly and have enough diagnostic and verification capabilities insure performance when needed year after year should be paramount to the decision of which type of measurement technology to choose.

Close coupled extractive O_2, combustible, and methane analyzers have years of installed plant performance data to calculate mean time to failure as well as have established predictive maintenance, calibration, verification, and repair procedures in place. Typical installations in the bottom of the convection section are cost effective with one flange mounting for all gases of interest in the SIS design. Close coupled analyzers can be challenged, verified or calibrated automatically or on demand to insure optimum performance and availability. Yet, this configuration does only provide a "point type" measurement and not a duct average, so that stratification of gas flow concentration could be an issue. Furthermore, combustibles or CO detection can be in the 20-30 second T90 response time do to the thermal detection of the catalytic bead detector and the inherent delay of having flame arrestors in the detection flow loop.

TDL analyzers can offer faster detection time in the 5 second T90 range and do provide an across duct type measurement, which can be helpful in early detection of a CO flood condition. They can be mounted in the hot, radiant section to provide measurement across the burner row and do not need flame arrestors or aspiration air. TDL technology does lack the ability to challenge the analyzer with calibration gas to insure proper operation and calibration, nor has much useful data been made available for SIS failure and reliability calculations due to its minimal field reliability history. The installations can be costly by having to cut through refractory on both sides of the process and provide man-ways for both the detector and transmitter service access.

CONCLUSION

What is acceptable risk for catastrophic events when operating fired combustion processes in a petrochemical complex? If there are 2000 process heaters or large boilers in the United States and if only one had a catastrophic combustion event every year, a plant's risk might only be 1 in 2000 per year. Is that acceptable if loss of life or environmental damage was the result? What if the risk can be reduced to 1 in 2000 per 100 years? Even one large event in 50 years could cause the federal government to step in to regulating industry safety or impose severe monetary damages as recent disasters have shown.

It is obvious that the process industry needs to demonstrate a willingness to make plants as safe as possible and reduce catastrophic events to an acceptable/ tolerable amount of risk. The implementation of an SIS on the combustion process demonstrates industries investment into plant and environmental safety, as well as documents their risk assessment and detailed plan for catastrophic event prevention. If an event was to happen with a standardized SIS implementation in place, who could argue that they did not do all they could do to reduce the risk of the event and invested in an engineered risk reduction "as low as reasonably practical" for the safety of their personnel, the community, and the environment? A Safety Integrated System for the combustion process is a worthy investment.

REFERENCES

BOOKS

1. Gruhn, Paul and Cheddie, Harry: *Safety Shutdown Systems: Design, Analysis, and Justification.* (ISA, 1998), ISBN 1-55617-665-1

2. Goble, William and Cheddie, Harry: *Safety Instrumented Systems Verification: Practical Probabilistic Calculations.* (ISA, 2005), ISBN 1-55617-909-X

3. O'Brien, Chris and Bredemeyer, Lindsey: *Final Elements: & the IEC 61508 and IEC 61511 Functional Safety Standards.* (Exida, 2009), ISBN-13: 978-1-934977-01-9

REPORTS

1. Baker III, James Panel Chair: *Baker Panel Report: The BP US Refineries Independent Review Panel.* (January 2007), http://www.bp.com/baker_panel_report.

2. Goble, Dr. William M: *Safety Integrity Level Verification-Process and Problems.* (Dec 2000).

STANDARDS

1. American Petroleum Institute: *Instrumentation, Control, and Protective Systems for Gas Fired Heaters.* (April 2011), API Recommended Practice 556, second addition.