

Burner Management System Safety Integrity Level Selection

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ABSTRACT

This paper will discuss how quantitative methods can be utilized to select the appropriate Safety Integrity Level associated with Burner Management Systems. Identifying the required amount of risk reduction is extremely important especially when evaluating existing legacy Burner Management Systems. Selection of an overly conservative Safety Integrity Level can have significant cost impacts. These costs will either be associated with increased Safety Instrumented System functional testing or complete removal / upgrade of the existing Burner Management System. In today's highly competitive business environment, unnecessary costs of any kind cannot be tolerated.

INTRODUCTION

Burner Management Systems have been typically designed in the past through applying the prescriptive requirements contained in codes / standards such as NFPA 85 – Boiler and Combustion Systems Hazard Code or API 556 – Instrumentation and Control Systems for Fired Heaters and Steam Generators. These documents provide detailed guidance on the quantity and types of sensors / valves required for the Burner Management System along with the logic necessary to safely trip the unit. These codes / standards do not adequately address different risk levels associated with a Burner Management System. For instance, if your boiler was located next to a control room, which was staffed 24-hrs/day risk to personnel, is significantly greater than if it was located in a remote unoccupied area of the facility. In addition, these prescriptive standards provide minimal guidance regarding the use of programmable electronic based logic solvers.

New performance-based standards are now being utilized (i.e. IEC 61508, IEC 61511 and ANSI/ISA S84.01) to design safety systems in general. These standards provide a set of criteria that must be met

depending upon the amount of risk reduction required as determined by the end user. Thus, these standards are specifically written to address the risks associated with a given facility. Therefore, these standards when properly applied provide a wealth of information regarding the proper use and design of a programmable electronic based logic solver in a safety application. Thus, when evaluating a Burner Management System both the prescriptive codes / standards (NFPA, API) and the performance based standards (IEC, ANSI/ISA) should be followed to ensure the Burner Management System is properly designed and reduces a facilities risk to a tolerable level.

A furnace explosion requires both a sufficient flammable mixture and sufficient energy for ignition within the furnace. The ignition requirements for an explosive charge are very small, making it almost impossible to protect against all possible sources of ignition, such as static electricity discharges, hot slag, and hot furnace surfaces. Therefore, the practical means of avoiding a furnace explosion is the prevention of an explosive accumulation. The explosive accumulation is formed in the following basic ways:

- A flammable input into any furnace atmosphere (loss of ignition)
- A fuel-rich input into an air-rich atmosphere (fuel interruption)
- An air-rich input into an fuel-rich atmosphere (air interruption)

The specific safety interlocking depends upon the physical characteristics of the firing system and the type of fuel or fuels being fired. All Burner Management Systems, however are typically concerned with the following functions:

- A pre-firing purge of the furnace.
- Establishment of the appropriate permissives for firing the ignition fuel (i.e. purge complete, fuel pressure within limits).
- Establishment of the appropriate permissives, including ignition permissives, for the main (load-carrying) fuel.
- Continuous monitoring of the firing conditions and other key operating parameters.
- Emergency shutdown of portions or all of the firing equipment when required.
- A post-firing purge.

CONSEQUENCE & LIKELIHOOD ESTIMATION

Effective consequence and likelihood estimation are critical components in the Safety Integrity Level selection process. If the consequence estimation is too severe or the likelihood too aggressive the final selected Safety Integrity Level may be too high, which will result in an over designed and very costly Safety Instrumented System. While this approach is conservative, in today's highly competitive business environment facilities cannot afford to over design their safety systems if they desire to remain in operation. Conversely, if the consequence estimation is too low or the likelihood too lax, the facility's risks may not have been adequately reduced by the Safety Instrumented System. In fact the Safety Integrity Level selection process may not have required a Safety Instrumented System at all depending upon the consequence, likelihood and layers of protection considered. In this scenario, the company is operating beyond its risk threshold with an increased danger to personnel, the environment

and / or their capital investments. Once again in a competitive business environment, this is an unacceptable position for a facility.

Thus, accurate estimation the consequence and likelihood of a Burner Management System failure is critical to determining the required Safety Integrity Level, which in turn determines the design requirements for the Burner Management System.

CALCULATION OF SAFETY INTEGRITY LEVEL

To determine the consequence associated with fired equipment one will need to evaluate some or all of the following effect zones. An effect zone is defined as the area over which a particular incident outcome case produces an effect based upon a specified criterion (i.e. overpressure).

- Vapor Cloud Explosion Effect Zone
- Physical Explosion Effect Zone
- Pool Fire Effect Zone (liquid fuels only)

Calculation of the above effect zones can be quite complex and labor intensive. However, the Environmental Protection Agency has developed simplified protocols for Risk Management Planning. These protocols utilize equivalent TNT methodologies as contained in the Federal Emergency Management Agency, Handbook of Chemical Analysis Procedures. These scenarios reflect a “worst case scenario” which will yield conservative results that can be readily utilized in the Safety Integrity Level selection process.

SEVEN STEP METHOD

These “worst case scenario” techniques can be simplified in a seven step method to yield required Safety Integrity Levels.

STEP 1: Vapor Cloud Explosion Effect Zone can be calculated as follows:

1. Determine the maximum flammable mass that could be present in combustion chamber
2. Determine the heat of combustion for the flammable material (use la Chatelier’s Principle for Mixtures if required)
3. Calculate the equivalent weight of TNT per the following equation:

$$m_{TNT} = [m_{flammable} \times \frac{\Delta H_c}{1155} \times Y_f] \quad \text{Equation 1}$$

Where,

m_{TNT} is the equivalent weight of TNT, lbs.

$m_{flammable}$ is the flammable mass, lbs.

ΔH_c is the heat of combustion, kcal/kg.

1155 is the heat of combustion of TNT.

Y_f is the explosive yield factor, which EPA has defined as 10%.

4. Calculate the radius for the circular impact zone per the following equation:

$$d(\text{ft}) = m_{\text{TNT}}^{1/3} e^{3.5031-0.724\ln(O_p)+0.0398(\ln O_p)^2} \quad \text{Equation 2}$$

Where,

d is the distance to a given overpressure, ft.

O_p is the peak overpressure, psi, which is typically three (3) psi for calculation of fatalities.

5. Calculate the Vapor Cloud Explosion Effect Zone per the following equation:

$$\text{VCE}_{\text{EffectZone}} = \pi \times d^2 \quad \text{Equation 3}$$

Where,

$\text{VCE}_{\text{EffectZone}}$ is the Vapor Cloud Explosion Effect Zone, ft^2 .

d is the distance to a given overpressure, ft.

STEP 2: Physical Explosion Effect Zone can be calculated as follows:

1. Determine the vessel rupture pressure, psia
2. Convert pressure in vessel to equivalent weight of TNT per the following equation:

$$m_{\text{TNT}} = 9.25 \times 10^{-5} \times P \times V \times \ln\left(\frac{P}{14.7}\right) \quad \text{Equation 4}$$

Where,

m_{TNT} is the equivalent weight of TNT, lbs.

P is the bursting pressure of the vessel, psia.

V is the volume of the vessel, ft^3 .

3. Calculate the radius for the circular impact zone per the following equation:

$$d(\text{ft}) = m_{\text{TNT}}^{1/3} e^{3.5031-0.724\ln(O_p)+0.0398(\ln O_p)^2} \quad \text{Equation 5}$$

Where,

d is the distance to a given overpressure, ft.

O_p is the peak overpressure, psi, which is typically three (3) psi for calculation of fatalities.

4. Calculate the Physical Explosion Effect Zone per the following equation:

$$PE_{\text{EffectZone}} = \pi \times d^2 \quad \text{Equation 6}$$

Where,

$PE_{\text{EffectZone}}$ is the Physical Explosion Effect Zone, ft².
 d is the distance to a given overpressure, ft.

STEP 3: Pool Fire Effect Zone (for liquid fuels only) can be calculated as follows:

1. Determine the area of the flammable pool. If the area is confined, use the confinement area. If not calculate the area for a 1-cm deep pool per the following equation:

$$A_{\text{Pool}} = \pi \times d^2 \quad \text{Equation 7}$$

Where,

A_{Pool} is the flammable pool area, ft².
 d is the distance to a given overpressure, ft.

2. Calculate the Pool Fire Factor as follows for liquids with boiling points above ambient temperature:

$$PFF = H_c \times \frac{0.0001}{5000 \times \pi \times (H_v + C_p \times (T_b - 298))}^{-0.5} \quad \text{Equation 8A}$$

where

H_c is the heat of combustion, J/Kg.
 H_v is the heat of vaporization, J/Kg.
 C_p is liquid heat capacity, J/Kg-K°.
 T_b is the Boiling Temperature, K°.

Calculate the Pool Fire Factor as follows for liquids with boiling points below ambient temperature:

$$PFF = H_c \times \frac{0.0001}{5000 \times \pi \times H_v}^{-0.5} \quad \text{Equation 8B}$$

where

H_c is the heat of combustion, J/Kg.
 H_v is the heat of vaporization, J/Kg.
 C_p is liquid heat capacity, J/Kg-K°.
 T_b is the Boiling Temperature, K°.

3. Calculate the radius for the circular impact zone per the following equation:

$$d(\text{ft}) = 70.71 \times \left(\frac{1}{R \times 1000} \right)^{-0.5} \times \text{PFF} \times (A)^{-0.5} \quad \text{Equation 9}$$

Where,

d is the distance to endpoint, ft.

R is the radiation intensity endpoint, kW/m², which shall be 12.5 kW//m² for calculation of fatalities.

PFF is the Pool Fire Factor.

A is the area of the pool, ft².

5. Calculate the Pool Fire Effect Zone per the following equation:

$$\text{PF}_{\text{EffectZone}} = \pi \times d^2 \quad \text{Equation 10}$$

Where,

PF_{EffectZone} is the Pool Fire Effect Zone, ft².

d is the distance to a radiation endpoint, ft.

STEP 4: Personnel Density can be calculated as follows:

1. Utilize the largest of the areas calculated in STEPS 1- 3 above. Overlay the effect zone on a General Arrangement Drawing.
2. Calculate the number of Personnel / ft² in the effect zone.
3. Calculate the Probable Loss of Life per the following equation:

$$\text{PLL} = \text{MEZ}_{\text{Area}} \times V \times P \quad \text{Equation 11}$$

Where,

MEZ_{Area} is Maximum Effect Zone Area, ft².

V is the Vulnerability Factor, where 0.6 is typically used if the effect zone is indoors and 0.3 is typically used if the effect zone is outdoors.

P is the personnel density, people/ft².

PLL is Probable Loss of Life (i.e. number of fatalities in the effect zone).

STEP 5: Perform a Layer of Protection Analysis to determine the frequency for each hazardous event, F_{LOPA}. Note outcome frequencies should be added together for the same consequence (i.e. vapor cloud explosion). Refer to CCPS “Layer of Protection Analysis, Simplified Process Risk Assessment” for additional details on performing Layer of Protection Analysis.

STEP 6: Determine the Probability of Failure on Demand as follows:

1. Determine the Frequency Target per the following equation:

$$F_{\text{Target}} = \frac{F_{\text{IndividualRisk}}}{\text{PLL}} \quad \text{Equation 12}$$

Where,

F_{Target} is the risk target, failure/year.

$F_{\text{IndividualRisk}}$ individual risk target, failure/year.

PLL is Probable Loss of Life (i.e. number of fatalities in the effect zone).

2. Calculate the Probability of Failure on Demand per the following equation:

$$\text{PFD} = \frac{F_{\text{Target}}}{F_{\text{LOPA}}} \quad \text{Equation 13}$$

Where,

PFD is Probability of Failure of Demand.

F_{Target} is the risk target, failure/year.

F_{LOPA} is the frequency of the event per the Layer of Protection Analysis, failure/year.

STEP 7: Determine the require Safety Integrity Level as follows:

$$\text{RRF} = \frac{1}{\text{PFD}} \quad \text{Equation 14}$$

Where,

RRF is Risk Reduction Factor.

PFD is Probability of Failure of Demand.

SIL is then determined by the following:

SIL 1 = 10 < RRF < 100

SIL 2 = 100 < RRF < 1000

SIL 2 = 1000 < RRF < 10000

COMPANY STANDARD CALCULATIONS

Any Safety Integrity Level selection method adopted by a company needs to be easy to use and yield results quickly. A labor intensive and time-consuming Safety Integrity Level selection method will surely be abandoned when companies attempt to apply the method to the hundreds or thousands of Safety Instrumented Function evaluations that they will need to perform. Thus, to make the Seven Step procedure described above easier to utilize, it is recommended that companies develop a “cookbook approach” that standardizes the types of fuels utilized in the company in following manner:

1. Develop a spreadsheet application for each type of most common types of fuels the company utilizes in their fired equipment to calculate each of the three (3) the effect zones.
2. Develop a supporting procedure on calculation of personnel densities.
3. Develop a spreadsheet application that provides a framework for Layer of Protection Analysis for each of the standard Safety Instrumented Functions for Burner Management Systems.
4. Develop a supporting procedure to include guidance on how to perform a Layer of Protection Analysis. This procedure should include lookup tables and guidance verbiage on how to determine frequencies of initiating events for the Layer of Protection Analysis.
5. Develop a Cost – Benefit Analysis spreadsheet application to support justification of the project.

If such a company procedure were developed, then it would allow multiple remote plant sites to quickly, efficiently and consistently evaluate Safety Integrity Level requirements for their Burner Management Systems. This would allow facilities to make sound business decisions regarding the risks associated with their fired equipment.

SAMPLE CALCULATIONS

The following sample calculation shall be performed for a single Safety Instrumented Function for a Burner Management System to document the ease in which one can calculate the required Safety Integrity Level.

Process Background: A commodity chemical company desires to determine the Safety Integrity Level requirements for their existing single burner, natural gas (85% Methane, 15% Ethane) fired boiler. The boiler was installed in 1985 and utilizes a general purpose PLC as the logic solver for the Burner Management System. The boiler is operating efficiently and the company does not want to upgrade the Burner Management System at this time due to capital cash constraints unless required. Therefore, management wants an evaluation to be performed to determine if they are operating within their tolerable risk limits. A small control room is located forty (40) feet from the boiler front. One (1) boiler operator is present in this control room eighteen (18) hours a day on average. The control room is general-purpose construction and not designed to withstand an explosion. Maintenance technicians are present in the Boiler area 20% of the time. The boiler has a combustion chamber volume of 40,000 ft³. The boiler maximum operating pressure is 250 psig and it is estimated its burst pressure is four (4) times the maximum operating pressure. The volume of the steam drum is 10,000 ft³. A General Arrangement Drawing review produced an area of 10,000 ft² for the boiler building. The boiler typically operates for fifty-one (51) weeks out of the year for twenty-four (24) hours per day.

Hazard: Low fuel gas pressure causes loss of flame and accumulation of unburned natural gas mixture, which may explode if ignited.

Sensors: Fuel gas low pressure switch and loss of flame sensor.

Final Elements: Double Block and Bleed valves on the natural gas fuel and pilot supply lines.

STEP 1: Vapor Cloud Explosion Effect Zone

$$m_{TNT} = \left[\frac{m_{flammable} \times \Delta H_c \times Y_f}{1155} \right]$$

$$m_{TNT} = [165 \text{ lbs} \times 11859/1155 \times 0.10]$$

$$m_{TNT} = 169 \text{ lbs}$$

$$d(\text{ft}) = m_{TNT}^{1/3} e^{3.5031 - 0.724 \ln(O_p) + 0.0398 (\ln O_p)^2}$$

$$d(\text{ft}) = 169^{1/3} e^{3.5031 - 0.724 \ln(3.0) + 0.0398 (\ln 3.0)^2}$$

$$d(\text{ft}) = 87 \text{ ft}$$

$$VCE_{\text{EffectZone}} = \pi \times d^2$$

$$VCE_{\text{EffectZone}} = 23,808 \text{ ft}^2$$

STEP 2: Physical Explosion Effect Zone (Not required for this Safety Instrumented Function)

STEP 3: Pool Fire Effect Zone – Not Required for Natural Gas

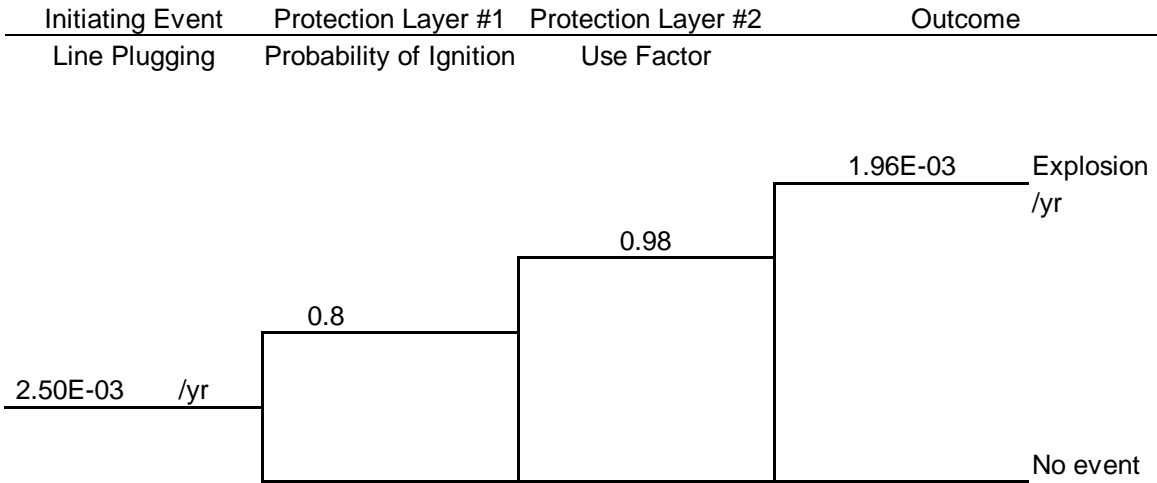
STEP 4: Personnel Density

$$PLL = MEZ_{\text{Area}} \times V \times P$$

$$PLL = 23,808 \times 0.6 \times (1 \times 18/24 + 1 \times 4.8/24)/10,000$$

$$PLL = 1.357$$

STEP 5: Layer of Protection Analysis



STEP 6: Probability of Failure on Demand

$$F_{\text{Target}} = \frac{F_{\text{IndividualRisk}}}{\text{PLL}}$$

$$F_{\text{Target}} = \frac{1 \times 10^{-4}}{1.357}$$

$$F_{\text{Target}} = 7.37 \times 10^{-5} / \text{yr}$$

$$\text{PFD} = \frac{F_{\text{Target}}}{F_{\text{LOPA}}}$$

$$\text{PFD} = \frac{7.37 \times 10^{-5}}{1.96 \times 10^{-3}}$$

$$\text{PFD} = 3.76 \times 10^{-2}$$

STEP 7: Determine the require Safety Integrity Level

$$\text{RRF} = 1/\text{PFD}$$

$$\text{RRF} = 1/3.76 \times 10^{-2}$$

$$\text{RRF} = 27$$

Where $10 < \text{RRF} < 100$ is SIL 1.

Thus, the above low fuel pressure Safety Instrumented Function needs to be designed as a SIL 1 interlock with a RRF of at least 27. This information could then be utilized to evaluate the existing Burner Management System to see if it meets the required SIL or needs to be re-designed.

Table 1

SIF Performance Metrics	
Safety Instrumented Function	Preview
Average Probability of Failure on Demand (PFDavg)	2.17E-02
Safety Integrity Level	1
Safety Integrity Level (Architectural Constraints)	1
Risk Reduction Factor	46
MTTFS (years)	3.38

A summary of SIL calculations for a general purpose PLC with a one-year test interval are depicted above. As can be seen for this particular Safety Instrumented Function, the existing Burner Management System architecture is sufficient to meet the requirement of SIL 1 with a RRF of at least 27. Thus, the existing design is acceptable as is and will simply need to be functionally tested on an annual basis.

CONCLUSION

Quantitative Risk Analysis methods can be complex and time consuming. However, using the simplified “worst-case” scenario concepts contained in the EPA’s Risk Management Program Guidance for Offsite Consequence Analysis one can quickly, efficiently and accurately determine Safety Integrity Level requirements for Burner Management Systems. Accurate Safety Integrity Level selection is critical when analyzing existing systems. If one is overly conservative, the resultant Safety Integrity Level may require removal and upgrade of the existing Burner Management System. In today’s highly competitive business environment, unnecessary costs of any kind cannot be tolerated.

DISCLAIMER

Although it is believed that the information in this paper is factual, no warranty or representation, expressed or implied, is made with respect to any or all of the content thereof, and no legal responsibility is assumed therefore. The examples shown are simply for illustration, and as such do not necessarily represent any company’s guidelines. The readers should use data, methodology, formulas, and guidelines that are appropriate for their situations.

REFERENCES

1. ANSI/ISA S84.01-1996, *Application of Safety Instrumented Systems for the Process Industries*, The Instrumentation, Systems, and Automation Society, Research Triangle Park, NC, 1996.
2. IEC 61508, *Functional Safety of Electrical/Electronic/Programmable Safety-related Systems, Part 1-7*, Geneva: International Electrotechnical Commission, 1998.
3. IEC d61511, *Functional Safety: Safety Instrumented Systems for the Process Industry Sector, Parts 1-3*, Geneva: International Electrotechnical Commission, Draft in Progress.
4. EPA, *Risk Management Program Guidance for Offsite Consequence Analysis*, Chemical Emergency Preparedness and Prevention Office, 1999
5. Lees, F.P., *Loss Prevention in the Process Industries*, Butterworth-Heinmann, 2nd Edition, 2001
6. Singer, J.G., P.E., *Combustion Fossil Power*, Combustion Engineering, Inc., 1991
7. Center for Chemical Process Safety (CCPS), *Layer of Protection Analysis, Simplified Process Risk Assessment*, American Institute of Chemical Engineers, New York, NY 2001.
8. FEMA, *Handbook of Chemical Hazard Analysis Procedures*