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SIL ASSESSMENT FOR TAIL GAS TREATING PROCESS USING LAYER OF PROTECTION ANALYSIS

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Abstract. *A tail gas treating process is one of pollution control processes in refineries and natural gas processing plants required to manage process safety. Based on IEC 61511 safety lifecycle, the safety must be maintained during all design, operation, and maintenance activities. This paper addresses an allocation of specific functions performed by a safety instrumented system (SIS) to protection layers in analysis phase of the safety lifecycle for the studied tail gas treating process. An application of layer of protection analysis (LOPA) process to evaluate three scenarios identified in a prior hazard and risk assessment by using a hazard and operability (HAZOP) study is proposed. The results obtained from the proposed assessment are the specifications of the safety function requirements and the safety integrity requirements. The safety integrity level (SIL) determination results can be utilized as the criterions for the safety instrumented function (SIF) design and engineering in order to conform the required SIL.*

Keywords: Tail gas treating process, Safety lifecycle, SIS, LOPA, HAZOP, SIL, SIF

1. **Introduction.** Tail gas treatment is a crucial final treating process to many sulfur recovery units (SRUs) in refineries and natural gas processing plants for increasing the total sulfur recovery as well as for decreasing the environment pollutants. The tail gas treating process is a critical system that requires a safety instrumented system (SIS) for performing safety instrumented functions (SIFs) such as alarms, interlocks, and trips to mitigate process hazards by bringing the process to a safe state in the event of safe operating condition transgression [1,2]. Based on the safety lifecycle from the IEC 61511 standard, each hazard that requires the use of SIS for mitigation must be assigned a target safety integrity level (SIL) to determine the required level of risk reduction [3]. There are two dominant methods used for SIL determination: risk graph (RG) and layer of protection analysis (LOPA) [4,5]. The RG can be employed as a first screening tool for a large number of safety functions required to be analyzed because of its relative simplicity, while the LOPA can be utilized as an effective tool for offering more meticulous and comprehensive analysis. Therefore, the LOPA is relatively slow compared to the RG, because it is a more intensive method whereby all known process hazards and all known layers of protection are closely examined [6,7]. This paper aims to present an example of SIL assessment for providing step-by-step guidance to apply the LOPA performed as a precursor to installing the SIS in the studied tail gas treating process. An evaluation of three scenarios identified in a prior hazard identification exercise by using hazard and operability (HAZOP) analysis is described as an illustrative case study.

This article is organized in five sections including this introduction. Section 2 introduces key details of the studied tail gas treating process. Section 3 and Section 4 describe the proposed SIL assessment using LOPA and the obtained results, respectively. Section 5 gives some final conclusions and possible direction of future work.

2. **Studied Tail Gas Treating Process.** Figure 1 displays a simplified block diagram of the studied tail gas treating process [2] for reducing unrecovered sulfur vapor and sulfur dioxide contained in the tail gas from an SRU to enhance sulfur recovery efficiency before discharge to atmosphere. The SRU tail gas fed to the treating process is preheated before feeding the reactor for preventing sulfur condensation. The heated gas is sent to the hydrogenation reactor for converting sulfur compounds into hydrogen sulfide (H_2S). The hot gas from the reactor is then cooled by heat transfer process in the cooler. The process gas is further cooled by direct contact with the externally cooled recycle water stream in the contact condenser. The cooled gas is sent to the amine absorber, where the amine removes the H_2S in the gas stream. The treated gas from the absorber is burned in the incinerator. From the HAZOP process for identification of safety hazards and operability problems in the studied tail gas treating process, the SIS performing three SIFs is defined to detect the hazard and bring the process to safe state when the specified conditions are violated as summarized in Table 1. The SIF2-A and SIF2-B are defined for detecting the abnormally low level of the reactor effluent cooler and the abnormally high temperature of the reactor, respectively, while the SIF2-C is identified for detecting the abnormally low level of the contact condenser. The piping and instrumentation diagram (P&ID) of these three identified SIFs is shown in Figure 2.

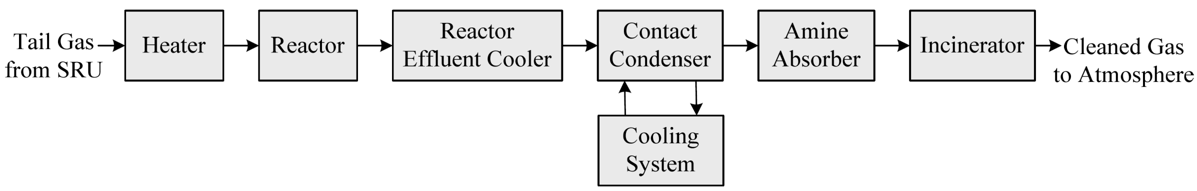

Figure 1. Simplified block diagram of the studied tail gas treating process [2]

Table 1. Three SIFs identified from HAZOP analysis

SIF No.	Equipment	Tag	Description
SIF2-A	Cooler (E-103)	LZA-103A/B/C	Low-Low Level Trip
SIF2-B	Reactor (R-101)	TZA-101A/B	High-High Temperature Trip
SIF2-C	Condenser (C-101)	LZA-101A/B/C	Low-Low Level Trip

3. **Proposed SIL Assessment.** The SIL is a discrete level (one out of a possible four) for indicating the safety integrity requirements of the safety instrumented function [3]. The SIL 1 and SIL 4 are the minimum level and maximum level of safety integrity, respectively. In order to determine the amount of defined risk reduction to be provided by three SIFs performed by the SIS in analysis phase of the safety life cycle for the studied tail gas treating process, six major steps of the LOPA approach can be discussed as follows.

Step 1: Identify the consequences of the hazard scenarios. This step involves the probability of occurrence of the hazardous event if the identified SIFs are not installed. The consequence identification includes the examination of personal safety, environmental impact, and asset loss. Table 2 gives the risk tolerance criteria categorized into five groups with hazardous situations occurring per year. The higher tolerable frequency results in the lower desired SIL level assigned to the SIF.

Step 2: Select the incident scenarios. For the studied tail gas treating process, three incident scenarios determined in HAZOP analysis are adapted to the input that the LOPA approach requires. Tables 3-5 show the severity level of the identified SIF2-A, SIF2-B, and SIF-2C, respectively, which is the same classification as the risk tolerance

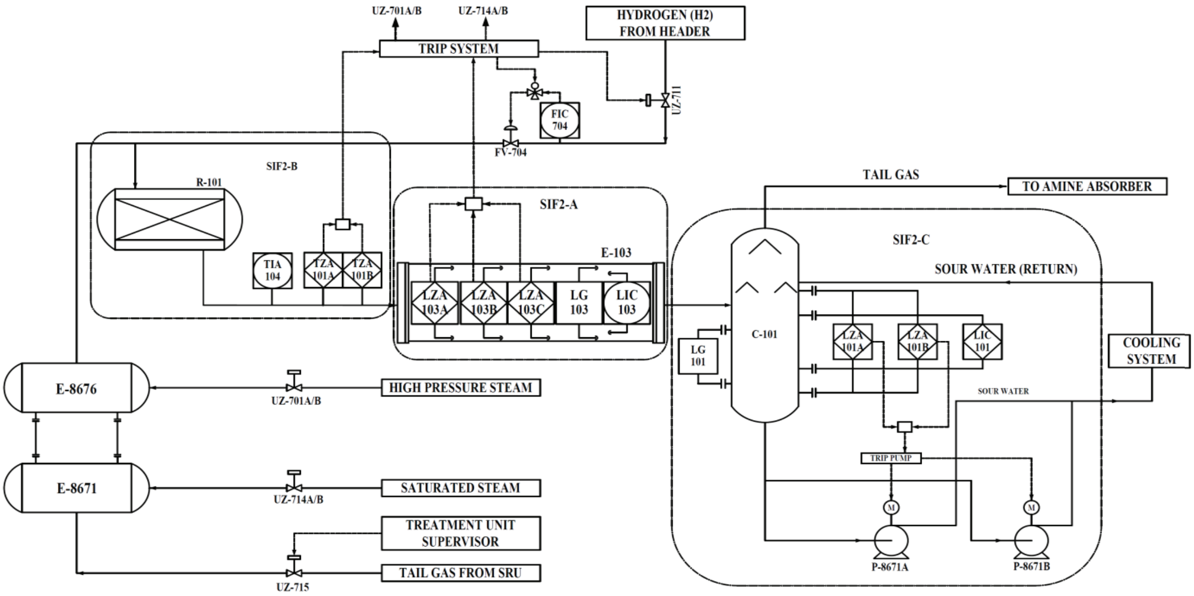

Figure 2. P&ID of SIFs identified for the studied process

Table 2. Risk tolerance criteria for hazard event

Item	Very Low	Minor	Moderate	Major	Massive
Personal Safety	No impact	Minor injury	Serious injury, Death to one person	Death to several persons	Death to many people
Environmental Impact	No release	Release with slight damage to environment	Release within fence significant damage to environment	Release outside fence major with temporary damage to environment	Release outside fence major with permanent damage to environment
Asset Loss (USD)	<1,000	1,000-10,000	10,000-100,000	100,000-1,000,000	>1,000,000
Tolerance Frequency (per year)	≤ 1	$\leq$ 1.00E-01	$\leq$ 1.00E-02	$\leq$ 1.00E-03	$\leq$ 1.00E-04

Table 3. Severity level for the SIF2-A safety instrumented function

Risk Receptor	Severity	Level	Tolerance Frequency (1/yr)
Personal Safety	No impact to people	Very Low	1
Environmental Impact	Release with slight damage to environment	Minor	1.00E-01
Asset Loss	700,000 USD	Major	1.00E-03

criteria of Table 2. The levels of Very Low, Minor, Moderate, Major, and Massive are suggested.

Step 3: Identify the initiating events and frequencies. Initiating events of incident scenarios are the reasons why process deviations occur, and they can be the results of various root causes such as equipment failures, human failures, and external events. Each incident scenario has a single initiating event, and its frequency is expressed

Table 4. Severity level for the SIF2-B safety instrumented function

Risk Receptor	Severity	Level	Tolerance Frequency (1/yr)
Personal Safety	Two fatalities	Major	1.00E-03
Environmental Impact	H_2S release within fence significant damage to environment	Moderate	1.00E-02
Asset Loss	1,940,000 USD	Massive	1.00E-04

Table 5. Severity level for SIF2-C safety instrumented function

Risk Receptor	Severity	Level	Tolerance Frequency (1/yr)
Personal Safety	Minor injury	Minor	1.00E-01
Environmental Impact	Release with slight damage to environment	Minor	1.00E-01
Asset Loss	80,000 USD	Moderate	1.00E-02

in events per year. The initiating events of the selected incident scenarios are the results of the control system component failures. The failures of LIC-103, FIC-101, and LIC-101 are the initiating events of SIF2-A, SIF2-B, and SIF2-C, respectively. The frequencies of these identified initiating events can be achieved from the company data, which are equal to 1.00E-01 per year.

Step 4: Identify the independent protection layers and associated probability of failure on demand. Protection layers can be considered independent protection layers (IPLs) when they are designed and managed to the strictness necessary to achieve the core attributes such as reliability, integrity, functionality, and independence. Depending on the scenario and the system attributes, there can be different categories of IPLs. The effectiveness of each IPL is quantified as probability of failure on demand (PFD). In case of the designed SIS, there is no IPL that can completely mitigate all identified initiating events. The alarm statuses of the LIC-103, FIC-101, and LIC-101 are not taken into account for the IPLs, because the failures of these control systems are the initiating events.

Step 5: Calculate the intermediate event frequencies. The intermediate event frequency, $f_{IE,i}$, for a certain initiating event, i, is the expected frequency of the consequence with the credited IPLs in place. It can be calculated by

$$f_{IE,i} = f_i \times \prod_{j=1}^{J} PFD_{ij} \tag{1}$$

where f_i is the frequency of initiating event i, the number of IPLs ranges from 1 to J, and each IPL has a PFD denoted PFD_{ij}. For the designed SIS, the intermediate event frequencies of the SIF2-A, SIF2-B, and SIF2-C as shown in Tables 6-8, respectively, are equal to their initiating event frequencies (1.00E-01 per year), because there is no credited IPL in place for each initiating event. Table 9 summarizes the LOPA worksheet for the studied tail gas treating process.

Step 6: Determine the risk reduction factor. To determine the risk reduction factor (RRF), the unmitigated intermediate event frequency (shown in Tables 6-8) is compared against the mitigated event frequency (shown in Tables 3-5), which can be

Table 6. Intermediate event frequency of SIF2-A

		PFD for Personal Safety	PFD for Environmental Impact	PFD for Asset Loss	Frequency
Initiating Event	LIC-103 Failure	1.00E-01			(1/year)
IPL	N/A	N/A	N/A	N/A	–
Intermediate Event Frequency		1.00E-01	1.00E-01	1.00E-01	(1/year)

Table 7. Intermediate event frequency of SIF2-B

		PFD for Personal Safety	PFD for Environmental Impact	PFD for Asset Loss	Frequency
Initiating Event	FIC-101 Failure	1.00E-01			(1/year)
IPL	N/A	N/A	N/A	N/A	–
Intermediate Event Frequency		1.00E-01	1.00E-01	1.00E-01	(1/year)

Table 8. Intermediate event frequency of SIF2-C

		PFD for Personal Safety	PFD for Environmental Impact	PFD for Asset Loss	Frequency
Initiating Event	LIC-101 Failure	1.00E-01			(1/year)
IPL	N/A	N/A	N/A	N/A	–
Intermediate Event Frequency		1.00E-01	1.00E-01	1.00E-01	(1/year)

written as

$$RRF = \frac{\text{Intermediate event frequency}}{\text{Mitigated event frequency}} \tag{2}$$

or

$$PFD_{avg} = 1/RRF \tag{3}$$

where PFD_{avg} is the target average probability of failure on demand of the identified SIF, which can be converted to the required SIL for rating the severity of the potential hazard.

4. **SIL Assessment Results.** Substituting values of the intermediate event frequency and the mitigated event frequency from Tables 6 and 3, respectively, into (2), the required risk reduction factor of the SIF2-A safety instrumented function for the studied tail gas treating process can be achieved as given in Table 10. Its target SIL can be derived by taking account of this calculated RRF (or $1/PFD_{avg}$) [3], which is equal to SIL 2. Similarly, the required risk reduction factor, average probability of failure on demand, and target SIL levels of the SIF2-B and SIF2-C safety instrumented functions can be summarized in Tables 11 and 12, respectively. The SIL 3 system is required to fulfill the needs for the SIF2-B, while the SIL 1 system is required to satisfy the needs for the SIF2-C. The obtained SIL levels from the proposed assessment can further be employed as the criterions for the design and engineering of identified SIFs that meet their safety integrity requirements in realization phase of the safety life cycle.

5. **Conclusions.** The safety instrumented functions for three hazard scenarios of the studied tail gas treating process have been introduced. The guidance consisting of six steps for LOPA risk assessment to determine the target safety integrity level for each identified safety instrumented function has been described. The SIL assessment is the process to establish the risk reduction to be obtained by the defined SIF. The higher SIL

rating number indicates the higher severity and grater safety system requirements. In the future research, protections provided by the independent protection layers to reduce the risk of each scenario will be considered.

Table 9. LOPA worksheet for the studied tail gas treating process

Hazard Scenario		Initiating Event		Consequence	IPL
		Description	Frequency (per year)		
SIF2-A	Very Low Level in E-103	LIC-103 Failure	1.00E-01	-No impact to people, -Release with slight damage to environment, -Potential damage to E-103 and plant shut down for one day, -Estimated 700,000 USD in production loss	N/A
SIF2-B	Very High Temperature in R-101	FIC-101 Failure	1.00E-01	-Two fatalities. -H_2S release within fence significant damage to environment, -Potential damage to R-101 and plant shut down for two days, -Estimated 1,940,000 USD in production loss and asset loss	N/A
SIF2-C	Very low level in C-101	LIC-101 Failure	1.00E-01	-Minor injury, -Release with slight damage to environment, -Potential damage to pumps -Estimated 80,000 USD in asset loss	N/A

Table 10. Results for determining the SIL of SIF2-A

Item	Risk Reduction Factor	PFD_{avg}	SIL
Personal Safety	0.1	10	–
Environmental Impact	1	1	
Asset Loss	100	1.00E-02	
Overall Risk Reduction	100	1.00E-02	
Target SIL			SIL 2

Table 11. Results for determining the SIL of SIF2-B

Item	Risk Reduction Factor	PFD_{avg}	SIL
Personal Safety	100	1.00E-02	–
Environmental Impact	10	1.00E-01	
Asset Loss	1000	1.00E-03	
Overall Risk Reduction	1000	1.00E-03	
Target SIL			SIL 3

Table 12. Results for determining the SIL of SIF2-C

Item	Risk Reduction Factor	PFD_{avg}	SIL
Personal Safety	1	1	–
Environmental Impact	1	1	
Asset Loss	10	1.00E-01	
Overall Risk Reduction	10	1.00E-01	
Target SIL			SIL 1

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