Safety Integrity Evaluation of Crude Oil heater According to IEC 61508 Standard

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Abstract: The main object of this paper is to evaluate safety barriers intervening against overpressure implemented on a crude oil heater using layers of protection analysis approach suggested in IEC 61508 (International Electrotechnical Commission) Standard for the determination of safety requirements are illustrated. Accident scenarios are pre-identified using Hazard an Operability approach, Fault tree approach is required for an effective risk assessment process. In order to better appreciate accident scenarios, PHAST (Process Hazard Analysis Software Tool) is utilized to simulate them.

Keywords: Risk analysis, Safety instrumented system, Safety integrity level, Probability of failure on demand, IEC 61508, Crude oil heater, Hazard an Operability, Fault tree, Layer of protection analysis.

1. INTRODUCTION

IEC 61508standards provides a structured approach relying on hazards identification in order to establish safety requirements for safety instrumented systems (SISs) [1].
LOPA (layer of protection analysis) starts with data developed in qualitative hazard evaluation such as HAZOP (Hazard and Operability) and accounts for each identified hazard by documenting the initiating cause and the protection layers. If risk reduction is required in the form of a Safety Instrumented Function (SIF), LOPA allows determining the appropriate Safety Integrity Level (SIL) for the SIF [2].
Safety Instrumented System (SIS) is an independent system to reduce potential risk of process.
A SIS is classically made up of three main subsystems (Fig.1): sensing elements(S), logic solvers (LS), and final elements (FE) [4]. IEC 61508 makes a direct relationship between the risk reduction to be attained and the performance requirements for the SIS.fig1illustrate IEC 61508 approach [2].

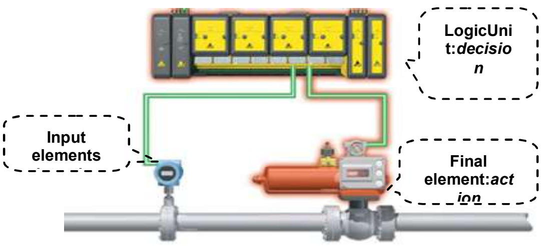

Fig. 1. Typical SIS configuration [5].

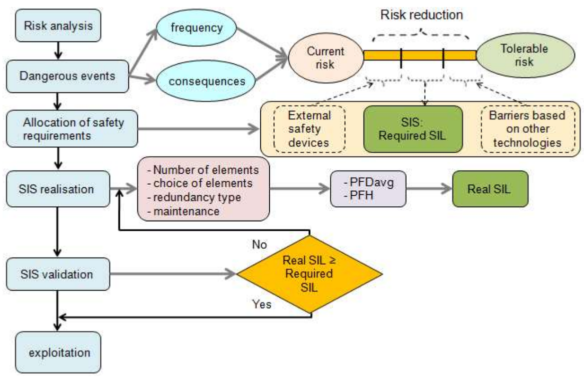

Fig.2. IEC 61508 approach: risk and safety integrity level [1]

In this context, the main purpose of this paper is to verify that the intended safety integrity level of a safety instrumented system of Skikda's refinery crude oil heater is achieved. Otherwise propose a solution to ameliorate the safety instrumented system to mitigate the studied scenario.
We began with risks analysis related to the studied system in order to identify potential hazards and estimate their likelihood and severity using HAZOP approach, to asset risks FTA (Fault Tree Analysis) is used which is the most used and recommended approach in reliability and safety studies, it is designed by Graphical Interface for reliability Forecasting software GRIF. Finally, the LOPA approach is used in order to establish any further need on safety barriers so that the tolerable risk criteria is achieved.
Safety Integrity Level is classification of failures into specific levels. IEC 61508

standards establishes four risk levels as shown in the Tab.1 [3].

Tab.1. different safety systems protecting stabilizer-a reflux drum [3]

SIL	PFD_{avg}	Availability Required
4	$\geq 10^{-5}$ to< 10^{-4}	99.99% ~ 99.999%
3	$\geq 10^{-4}$ to< 10^{-3}	99.90% ~ 99.99%
2	$\geq 10^{-3}$ to< 10^{-2}	99.00 ~ 99.90%
1	$\geq 10^{-2}$ to< 10^{-1}	90.00% ~ 99.00%

2. PROPOSED METHODOLOGY

The methodology followed to achieve the objective of this study is summarized as follows:

A. Functional description of the studied plant.
B. Risk analysis related to the studied plant using Hazard and Operability approach
C. Risk estimation and assessment using Fault Tree Analysis.
D. Accident simulation scenarios for determination of impact zones using Process Hazard Analysis Software.
E. Safety integrity level assignment using Layer of protection analysis approach designed by PHA-pro software
F. Realization and validation of the Safety instrumented system (real SIL).

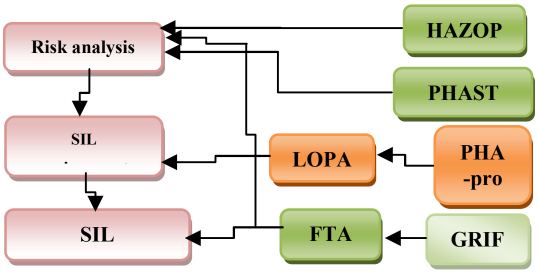

Fig.3. Methodology steps

3. APPLICATION OF THE PROPOSED METHODOLOGY

A. Functional description of the studied plant.

The system chosen to illustrate and demonstrate the IEC61508 approach pertains to an atmospheric crude oil heater (Fig. 4), located at distillation unit in Skikda refinery Algeria

Preheated crude is heated and partially vaporized in the Heater F-1 A. The heat necessary for its distillation is absorbed in the radiation section. Vaporized fluid comes out from the fired heater, enters the transfer line, and then the flash area of column C1. The heater has eight passes with an individual flow control and low flow cut off. A pass balancer has been added for the heater to achieve uniform coil outlet temperature. The input to pass balancer is the total crude flow to the heater; heater pass flow and heater pass outlet temperature. The flow of crude through each pass is measured and controlled through FIC-2. Low inlet flow alarm is indicated by FAL-2. Inlet side Temperature of each pass is indicated through 2 indicators in each one. The pass balancer then sets the individuals pass flow to achieve uniform outlet temperature.
The outlet has a temperature control, which controls the fuel firing. Crude outlet temperature is indicated and controlled by TI-48, TIC-13. Temperature is controlled through temperature pressure cascade control in burner fuel Gas line. PIC-5 has been installed in the fuel gas line for controlling the crude outlet temperature. The eight coils of each fired heater are equipped with two thermocouples TI-24~39.

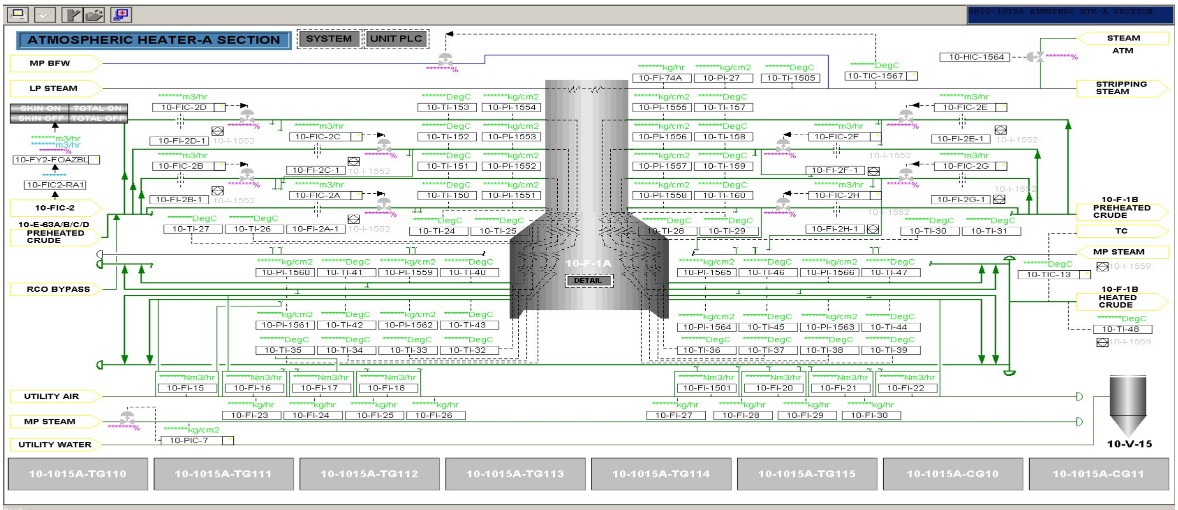

Fig. 4. Diagram related to the crude oil heater [6].

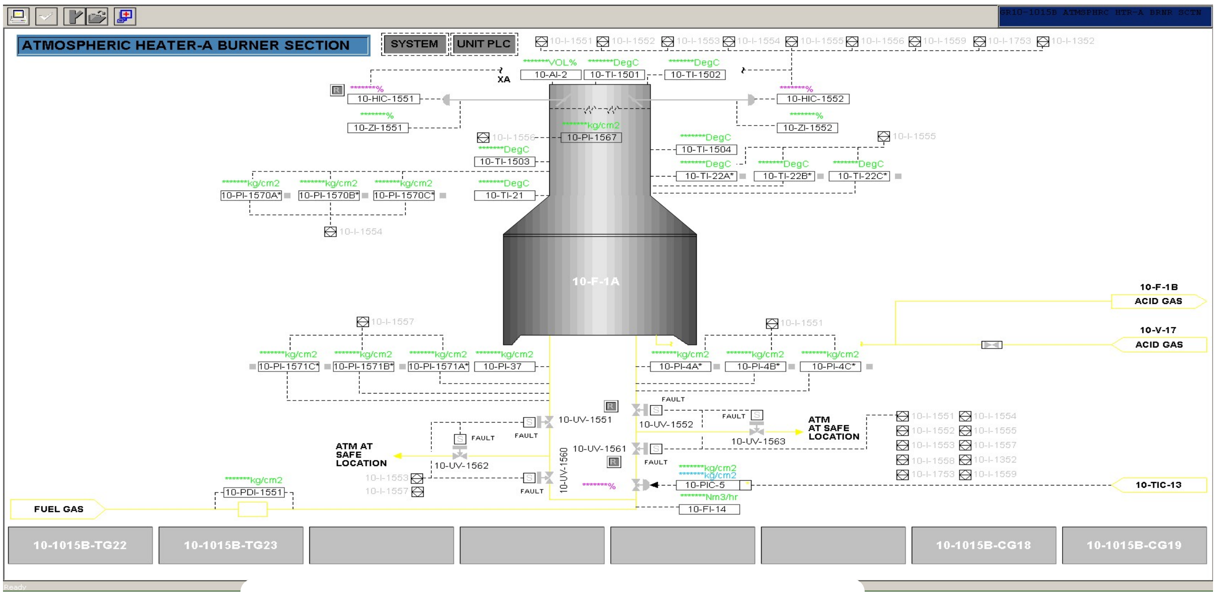

Fig. 5. Diagram related to the crude oil heater [6].

Tab.2. different safety systems protecting crude oil heater [3]

Interlock NO.	Actuated by	Action upon
10-I-1551	PALL-4 A/B/C (Fuel gassupply pressure isverylow)2oo3 votinglogic PAHH-4 A/B/C (Fuel gassupply pressure isvery high) 2oo3 votinglogic	- Close 10-UV-1552, 10-UV-1561 - Open 10-UV-1563 - Close 10-XX-1 (Acid Gas) - Open dampers (10-F-1A) - Open 10-UV-1751(RCO circulation) - Close 10-UV-1752(RCO rundown)
10-I-1552	10-FT-2A-1 to 2H-1 (Typ. For eachpass to beactuated by anyone of them)	- Close 10-UV-1552, 10-UV-1561 - Open 10-UV-1563 - Close 10-XX-1 (Acid Gas) - Open dampers (10-F-1A) - Open 10-UV-1751(RCO circulation) - Close 10-UV-1752(RCO rundown)
10-I-1553	10-HS-1551 A/B (To belocated at least 15m awayfrom the heater at safe location)	- Close 10-UV-1552, 10-UV-1561 - Close 10-UV-1551, 10-UV-1560 (Pilot gas supply) - Open 10-UV-1563, 10-UV-1562 - Close 10-XX-1(Acid Gas) - Open dampers(10-F-1A) - Open 10-UV-1751(RCO circulation) - Close 10-UV-1752 (RCO rundown)
10-I-1554	PAHH-1570 A/B/C (Heater combustion chamber) 2oo3 votinglogic	- Close 10-UV-1552, 10-UV-1561 - Open 10-UV-1563 - Close 10-XX-1(Acid Gas) - Open dampers(10-F-1A) - Open 10-UV-1751(RCO circulation) - Close 10-UV-1752(RCO rundown)
10-I-1555	TAHH-22 A/B/C (Heater combustion chamber) 2oo3 votinglogic	- Close 10-UV-1552, 10-UV-1561 - Open 10-UV-1563 - Close 10-XX-1(Acid Gas) - Open dampers(10-F-1A) - Open 10-UV-1751(RCO circulation) - Close 10-UV-1752(RCO rundown)
10-I-1556	PAH-1567 (High Pressure in the heater)	- Open dumpers (10-F-1A)
10-I-1557	PALL-1571 A/B/C (VeryLow Pressure in Heater Combustion Chamber) 2oo3 PAHH-1571 A/B/C (Very High Pressure in Heater Combustion Chamber) 2oo3	- Close 10-UV-1552, 10-UV-1561 - Close 10-UV-1551 10-UV- 1560 - Open 10-UV-1563, 10-UV-1562 - Close 10-XX-1 (Acid Gas) - Open dampers (10-F-1A)
10-I-1558	ZSL-1551 Activated ZSH-1551 Not Activated	- Close 10-UV-1552, 10-UV-1561 - Open 10-UV-1563 - Close 10-XX-1 (Acid gas)
	ZSL-1560 Activated ZSH-1560 Not Activated	- Close 10-UV-1552, 10-UV-1561 - Open 10-UV-1563 - Close 10-XX-1 (Acid Gas)
10-I-1559	TAHH-48 (Very High Temperature of HeatedCrude)	- Open 10-UV-1563 - Close 10-UV-1552, 10-UV-1561 - Close 10-XX-1(Acid Gas) - Open dampers(10-F-1 A) - Open 10-UV-1751(RCO circulation) - Close 10-UV-1752(RCO rundown)

B. Risk analysis related to the studied plant using Hazard and operability approach

The first step in the IEC 61508 approach consists of conducting risk analysis to identify potential hazards of the studied system. To do this, HAZOP has been utilized. This tool is based on the analysis of the system characteristic parameters deviations (flow, pressure, temperature, etc.) in order to identify situations leading to hazardous events and their respective safeguards. The final result of HAZOP expresses each of these events in terms of severity (S) and likelihood (F). An extract of the HAZOP study with respect to the deviation "more pressure inside the fire box is given in Table 4 The corporate severity and frequency tables are given in Table 3respectively. In order to appreciate the magnitude of the consequences risk acceptance matrix for Skikda refinery (RA1K) is given in tab.3.

Tab.3. Tolerable risk acceptance frequencies for Skikda refinery [8].

	Probability				
Severity	E: $P < 10^{-5}$	D: $10^{-4} > p > 10^{-5}$	C: $10^{-3} > P > 10^{-4}$	B: $10^{-2} > P > 10^{-3}$	A: $P > 10^{-2}$
G5: Disastrous	Yellow	Red	Red	Red	Red
G4: Catastrophic	Yellow	Yellow	Red	Red	Red
G3: Important	Yellow	Yellow	Yellow	Red	Red
G2: Serious	Green	Green	Yellow	Yellow	Red
G1: Moderate	Green	Green	Green	Green	Yellow

L	Low risk (accepted)
M	Moderate risk (tolerated)
H	High risk (not accepted)

For our study we have chosen two possible deviations which can lead to catastrophic accidents (more flow of Fuel Gas and More pressure).

Tab.4. HAZOP Analysis "More flow of FG " and "More pressure" related to crude oil heater 10-F-A1

deviation		Causes	Consequences	Protection means Warnings	criticality		
parameter	**Guide word**				**G**	**P**	**C**
Flow of FG to Heater	More	- PV-5 stuck open -bypass open	- High pressure of FG to main burner, with potential to lift the burner flame off the burner tip, with potential for flame-out	- PAH on PIC-5 sounds alarm - TAH on TIC-13 sounds alarm - TAHH on TI-48 sounds alarm - TAH on TI-22 sounds alarm for heating in convection section - TAHH on TI-22 sounds alarm, and activates interlock I-1555	2	2	M
			-Pressure in fire box will increase due to increased burning	- PAH on PI-1567 in convection section Sounds alarm - PAHH on PI-1570A/B/C - 2oo3 triggers interlock I-1554	2	3	M
			-Steam temperature will increase due to more heat input	- TIC-1557 opens TV-1557 to add more MP BFW to control steam outlet temperature - PSV-1552A/B set at 5.5kg/cm2g	2	1	L
Pressure	More	-One or two stack - dampers stuck closed	Pressure in fire box will increase, with potential for unburned gas and poor flame pattern	- PAH on PI-1567 sounds alarm - PAHH on PI-1570A/B/C - 2oo3 triggers interlock I-1554 - AAL on AI-2 sounds alarm on low O2 - Dampers are fitted with a minimum stop to avoid jamming closed	2	2	M

C. Risk estimation and assessment using Fault Tree Analysis

The use of Fault Tree allows us to determine quantitative values concerning the reliability and the failure frequency. The computation of these values depends on the complexity of the studied system. In this paper we used the GRIF(Graphical Interface for reliability Forecasting) software (Graphic Interactive for Reliability Forecasting) [9], which can calculate different measures including: the unconditional failure intensity w (t) and the unavailability Q (t). To calculate these two measures, it is necessary to use reliability and failure data which are shown in Tab. 5. The chosen scenario is fire box explosion (Fig.6).

Tab.6. Probability of failure on demand PFD of components used in GRIF [10, 11]

Component	PFD	Component	PFD
PAHH	$3{,}3883.10^{-3}$	HY	4.10^{-7}
UV	$1{,}344.10^{-4}$	XY	4.10^{-7}
UY	4.10^{-7}	XX	$1{,}344.10^{-4}$
FV	10^{-2}	FIC	10^{-2}
TIC	10^{-2}	PIC	10^{-2}
PV	10^{-2}	PCV	10^{-3}
FIC	10^{-2}	UV-1551-1552-1560-1561	10^{-3}
HIC	4.10^{-3}	Air handling unit	2.10^{-4}
Human error	10^{-1}		

The Fault Tree allows us to determine quantitative values concerning the reliability and the failure frequency [12].

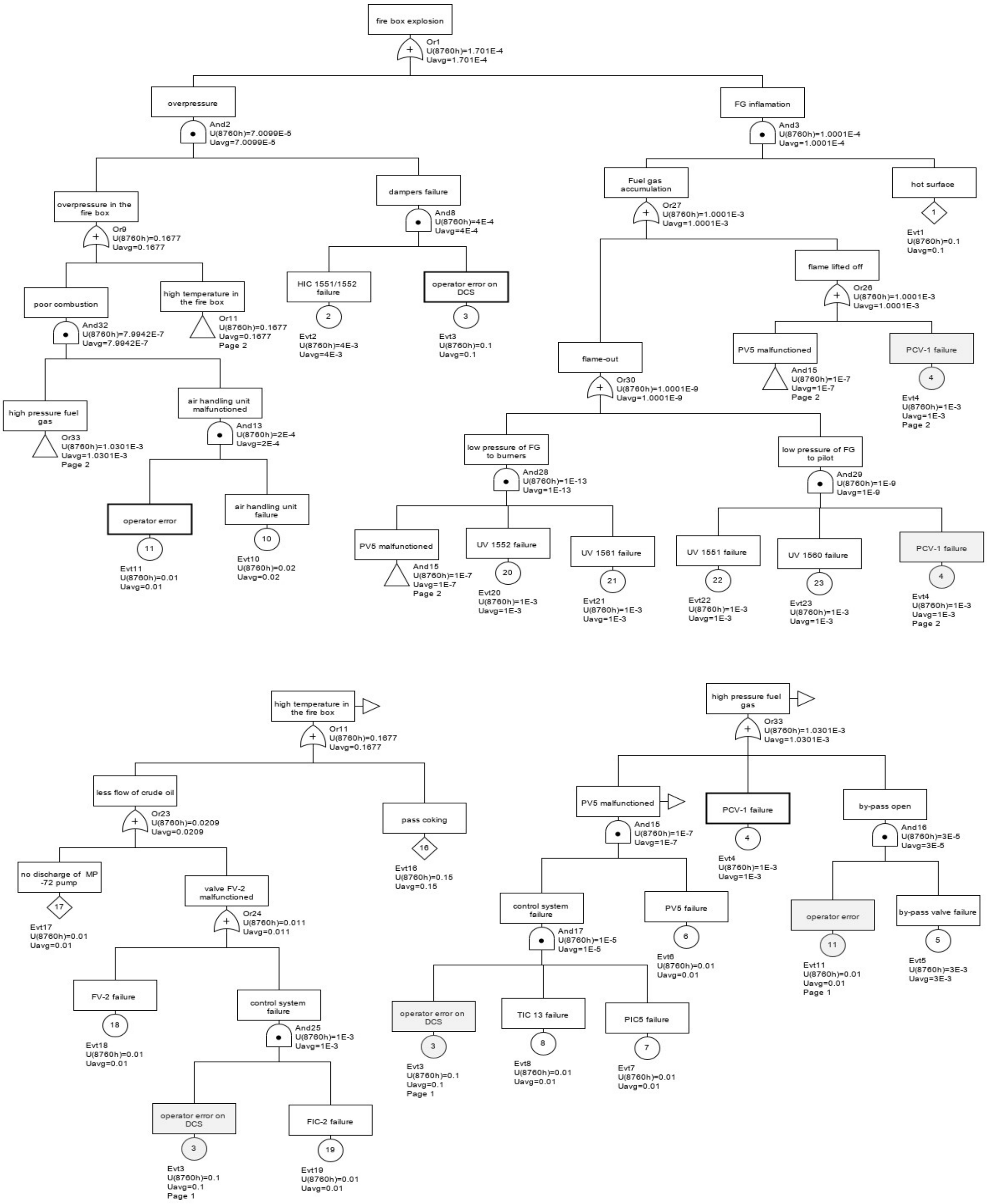

Fig.6. Fault Tree of the consequence "fire box explosion

Accident simulation scenarios for determination of impact zonesusing PHAST

After identifying consequences, PHAST [13] is used to simulate threat zones. In our study, the explosion of the fire box is the chosen event to be simulated (Fig.7 and 8).

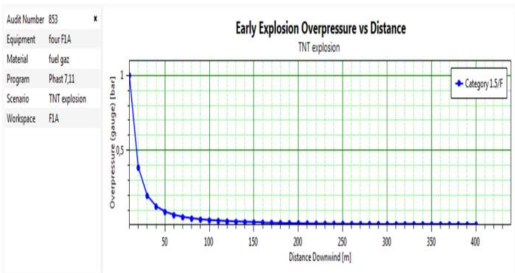

Fig.7. Early explosion overpressure vs distance.

Fig.7 showed that the overpressure resulting from the explosion of the combustion chamber reaches the value of 1 bar, this value decreased rapidly in a distance of 10 m to the value of 0.4 bars, from this value; the overpressure decreases relatively and tends towards 0 as it moves away from the center of the explosion.

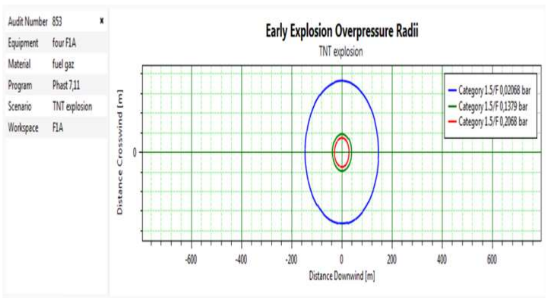

Fig.8. Early explosion overpressure radii.

The obtained distances (radii) in fig.2 from the combustion related to the overpressure values are presented in the table below:

Tab.7. The given distances from the combustion chamber (radii).

Overpressure (Bar)	Effects threshold	Radii (m)
0,02068	Irreversible Effects Threshold (IET)	148 m
0,1379	Lethal effects threshold (LET 1%)	40 m
0,2068	Lethal effects threshold (LET 5%)	32

D. SIL assignment using Layer of protection analysis approach designed by process Hazard Analysis softwarePHA-pro

LOPA is a semi-quantitative method commonly used for the determination of the required SIL [14]. It helps companies identify potential problems in order to eliminate or reduce them.

Fig.9shows what numerical values are required for the scenarios components. In order to evaluate the adequacy of risk mitigation measures, the risk tolerance criteria need to be established. The criteria are usually based on benchmark values from industry data, company history and/or statistical data.

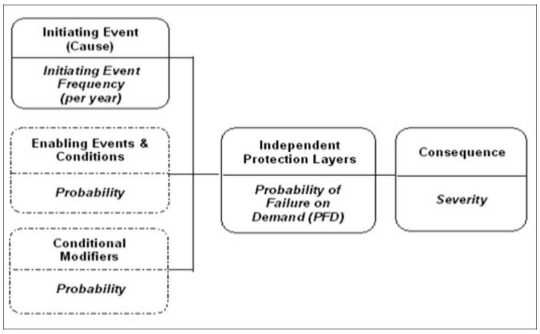

Fig.9. Components in a LOPA scenario and the required numerical inputs [15]

For scenarios in which the initiating event frequency is less than twice the test frequency for an IPL i.e. "low demand mode", the frequency (likelihood) for the undesired consequence is calculated by the following equation [16].

LOPA can be represented mathematically using the following computational equation, which multiplies the frequency of an initiating event by the probabilities that each independent protection layer will fail to perform its intended function [17].

$$f_i^C = IEF_i \times PFD_{i1} \times PFD_{i2} \times \ldots \times PFD_{ij} \quad (1)$$

f_i^C = Frequency of the consequence occurring for scenario i., Typical units are per year (Low Demand) or per hour (High Demand).

IEF_i = Frequency of the IE for scenario i., Typical units are per year.

PFDij = Probability of Failure on Demand of Independent Protection Layer j for scenario i.

The following table (tab. 7) provides SIL correlations with availability and PFD [15].

Tab.8. Safety integrity level based on PFD [16].

SIL	Availability Required	PFD	1/PFD
4	>99.99%	10^{-5} to 10^{-4}	100,000 to 10,000
3	99.90 - 99.99%	10^{-4} to 10^{-3}	10,000 to 1,000
2	99.00 - 99.90%	10^{-3} to 10^{-2}	1,000 to 100
1	90.00 - 99.00%	10^{-2} to 10^{-1}	100 to 10

Tab.8 shows the severity and describes the consequences in order to determine the severity of each consequence.
Tab.9 shows the likelihood and describes the frequency in order to determine the consequence frequency.

Tab.9. Severity categories [16].

Severity	description	Simplified injury/fatality categorization
1	Low consequence	PERSONNEL-Minor injury or no injury, no lost time; COMMUNITY-No injury ,hazard or annoyance to public; ENVIRONMENT-Recordable event with no agency notification or permit violation; FATALITY-Minimal equipment damage at an estimated cost less than 100,000 dollars with no loss of production.
2	Low consequence	Same category 1
3	Medium conseque nce	PERSONNEL-Single injury, not severe, possible lost time; COMMUNITY- Odor or noise annoyance complaint from the public; ENVIRONMENT-Release that results in agency notification or permit violation; FATALITY-Some equipment damage at an estimated cost greater than 100,000 dollars with minimal loss of production.
4	High consequence	PERSONNEL-one or more severe injuries, COMMUNITY- one or more injuries; ENVIRONMENT-Significant release with serious offsite impact; FATALITY-Major damage to process area(s) at an estimated cost greater than 1,000,000 dollars or some loss of production.
5	Very high consequence	PERSONNEL-fatality or permanently disabling injury; COMMUNITY- one or more severe injuries; ENVIRONMENT-Significant release with serious offsite impact and more likely than not to cause immediate or long-term health effects ; FATALITY-Major or total destruction of process area(s) at an estimated cost greater than 10,000,000 dollars or a significant loss of production.

Tab.10. Likelihood description [16].

Likelihood	Description
1	Consequence Frequency = 1E-6 to 1E-7 per year
2	Consequence Frequency = 1E-5 to 1E-6 per year
3	Consequence Frequency = 1E-4 to 1E-5 per year
4	Consequence Frequency = 1E-3 to 1E-4 per year
5	Consequence Frequency = 1E-2 to 1E-3 per year
6	Consequence Frequency = 1E-1 to 1E-2 per year
7	Consequence Frequency = 1 to 1E-1 per year (or higher)

The risk matrix method is used to assign risk tolerance criteria in this study.

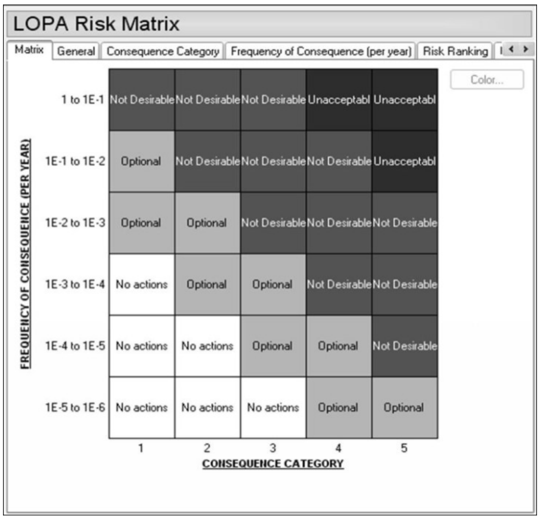

Fig.10. LOPA matrix[16].

LOPA is used to determine the required SIL related to the safety instrumented system which is set up to deal with the high pressure inside the heater.

The initiating events are:
- Dumpers stuck closed.
- Pressure indicator controller PIC-5 failures.
- Temperature indicator controller TIC-13 failures.

The obtained results are shown and represented in tab.10.

Tab.11.LOPA related to high pressure inside the heater

Critical Hazardous Scenario	Consequence		Risk Tolerance Criteria (Frequency per Year)		Initiating Event		Enabling Event or Condition		Conditional Modifiers		Unmitigated Event			Safeguard (Non-IPLs)	Independent Protection Layers						Mitigated Event		
	Description	S	Unacceptable	Tolerable	Description	Freq	Description	Prob	Description	Prob	UMEF	L	RR		Description	Types of IPLs	PFD	TPFD	1/Total PFD	SIL Equiv	MEF	L	RR
pressure high high inside the heater	Increasing in high pressure leads to	5	1,00E-04	1,00E-06	1. dampers stuck closed	1,00E-01	1. distillation plant in service	1,00E-01	1. Probability of fatal injury	1,00E-01	3,00E-05	2	7	1. operating manual	1. Interlock I-1554 activate PAHH-1570 (A/B/C feed valves closure of FG (10-UV-1552 and 10-UV-1561), closure of SWS (10-XX-1) valve, Opening of (10-UV-1563) valve to atmosphere , opening of RCO circulation valve (10-UV-1751), closure of Rundown RCO valve (10-UV 1752)	SIS	1,00E-01	1,00E-04	10000	SIL 3	3,00E-09	1	5
									2. Probability of personnel affected	1,00E-01				2. inspection programs preventive maintenance	2. explosion hatches	Process Design	1,00E-01						
									3. Probability of ignition	3,00E-01					3. Alarm on l'AI-2 (low rate of oxygen).	Non-IPL Safeguard	1,00E-01						
															4. PAHH on le PI-1567	SIS	1,00E-01						
					2. PIC-5/TIC-13 failure	1,00E-01	1. distillation plant in service	1,00E-01	1. Probability of fatal injury	1,00E-01	9,00E-05	3	8	1. operating manual	1. L'interlock I-1554 qui génère une alarme PAHH-1570(A/B/C	SIS	1,00E-01	1,00E-04	10000	SIL 3	9,00E-09	1	5
									2. Probability of personnel affected	3,00E-01				2. inspection programs preventive maintenance	2. Explosion hatches	Process Design	1,00E-01						
									3. Probability of ignition	3,00E-01					3. PAHH on PI-1567 with sound alarm	SIS	1,00E-01						
															4. Alarm on AI-2 (low oxygen rate).		1,00E-01						

E. Realization and validation of the SIS (real SIL)

The final step is the validation of the SIS, the purpose of this step is to check the real SIL so we can judge if it is suitable to the SIS in our system, otherwise we propose another safety barrier or modify the architecture of our SIS. The best method to do that is Fault Tree, so it is chosen to evaluate the real SIL

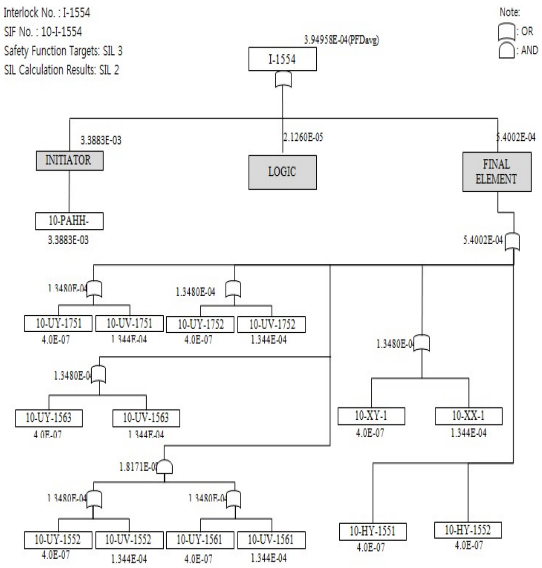

Fig.11. Fault Tree related to the SIS.

Using information of tabl.5 and Fault Tree in fig.11allowsustodefinethe real SIL related to the studied SIS in our system. The obtained result of PFD is 3,94958.10^{-3}, so the real SIL ofour SIS is SIL 2.

4. Results and discussion

Following what mentioned before the required SIL for our studied SIS is SIL3 based on the result of PFD obtained by using LOPA, while the real SIL is SIL 2 based on the result of PFD obtained by using Fault Tree (3,94958.10^{-3}). As we can see the real SIL is not enough to meet the requirements of our SIS, for that a modification of the SIS is necessary to reach the required SIL.

In this context we propose to modify the architecture of the SIS by modifying the architecture of pressure transmitter, the existing is 1001, so we propose the architecture 2003 as it is represented in fig.12.

Validation of the results using Fault Tree

After modifying the architecture of the pressure transmitter from 1001 to 2003, weuse Fault Tree to calculate the new PFD of our SIS, so we can determine the value of the new SIL. The modifiedarchitectureofthepressure transmitter isrepresented in fig.12. The obtainedresultsof Fault Treeareshown in the same figure.

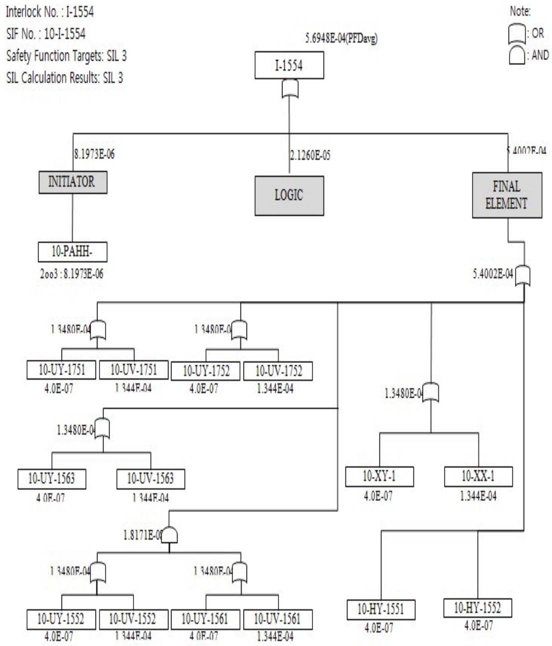

Fig.12. Fault Tree related to the proposed architecture of the SIS.

Using information of tab.5 and Fault Tree in fig.12 allows usto define the new real SIL relatedto our studied SIS. The new obtained PFD after the modification is 5,6948.10^{-4}, so the new SIL of the modified SIS will be SIL3.

5. Recommendations

Based on the obtained results after the proposed modification we confirm the proposed architecture of the level transmitter, so we recommend to:

- Modify the architecture of the pressure transmitter (PT-1570) of our SIS (I-1554) from 1001 to 2003.
- Increase the test frequency of the SIS, the test should be every six months instead of one year (4380 h instead of 8760 h), that leads to decrease the PFD value, so the SIL could be higher.

6. Conclusion

The main objective of this work was to evaluate a safety instrumented system using HAZOP-LOPA Fault Tree methodology. We have first introduced the main steps of the proposed methodology. Then, we have briefly described the system on which we have illustrated this approach.

The illustration was initiated by a risk analysis conducted using the HAZOP method. It has shown that the failure of the pressure regulation system constitutes an important source for triggering the accidental process. The application of LOPA for determining the necessary risk reduction, which must be provided by the safety instrumented system (SIS), gave usas a result SIL3, while the real SIL was obtained by using Fault Tree based on the calculation of the PFD, the result of PFD ($3,94958.10^{-3}$) allows us to determine the value of SIL2. The real SIL is not enough to reach the required risk reduction.
To reach the SIL target a modification has been proposed. It consists to modify the architecture of the pressure transmitter from 1001 to 2003. Calculations after the proposed modification gave us the needed value of PFD ($5,6948.10^{-4}$), so the new SIL after modification will be SIL3 as required.

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