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CONTRIBUTION TO THE DETERMINATION OF THE SILs REQUIRED FOR THE SAFETY OF PETROLEUM INSTALLATIONS: CASE STUDY OF THE PROPANE STORAGE TANK (BALLOON)

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Abstract: *Petroleum thermohydraulic systems are high-risk facilities whose analytical methods such as HAZOP can be applied as a risk analysis tool. However, this type of method is used to qualitatively indicate the existence of security barriers or to treat them in a dependent manner without taking into account the notion of independence between safety barriers. In this article, the semi-quantitative LOPA (Layer of Protection Analysis) method was applied to a propane storage tank (V306) in order to identify the scenarios that present a high risk by clearly indicating the level of safety integrity (SIL) required to ensure tolerable safety. The SIL will also be assessed by the "Risk Graph" method, which allows us to exploit expert opinions and compare its results with those obtained by the LOPA method. The independent protection layers (IPLs) evaluated as well as the Safety Instrumented System (SIS) proposed for the propane storage tank refer to the functional standards IEC 61508 and IEC 61511.*

Key words: *LOPA, semi-quantitative, propane storage tank, SIL, SIS, IPL, IEC 61508.*

ABBREVIATIONS

ATEX: Explosive atmosphere
BLEVE: Boiling Liquid Expanding Vapors Explosion
DCS: Distributed Control System
FT: Fault Tree
GPL: Liquefied Petroleum Gas
IEC: International Electrotechnical Commission
LAL: Level Alarm Low
LI: Level Indicator
PAH: Pressure Alarm high
PFD: Probability of Failure on Demand
PFDavg: Average Probability of Failure on Demand
PI: Pressure Indicator
POI: Plant Operator Intervention
PSV: Pressure Safety Valve
SDV: Shut down valve
SIF: Safety Instrumented Function
SIL: Safety Integrity Level
SIS: Safety Instrumented System
SONATRACH: National Society for Research, Production, Transport, Transformation and Marketing of Hydrocarbons
UVCE: Unconfined Vapor Cloud Explosion

1. INTRODUCTION

Risk is omnipresent in the Algerian company. Managers and their teams try, with varying degrees of success, to integrate and control them in decision-making and operational processes. However, today the company operates in increasingly complex political, economic and social environments and systems in which threats tend to grow and turn into disasters, most often resulting in damage to organizations that can go until the sudden, temporary or definitive cessation of the company's activities and by operating losses that could jeopardize the sustainability of the company [1, 2]. Everything goes smoky especially for high risk industries such as hydrocarbons (Fires, explosions, toxic waste discharges, production shutdown, etc.) [3]. This industry may present a risk for the population and the environment. It is necessary to know and understand your risks in order to manage them adequately [4]. As a result, the Algerian company is obliged to integrate a strategy of continuity into the general policy of the company (objectives to be achieved, development and growth strategy) to determine the expected level of risk control allowing

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companies to better understand and manage the critical risks that may temporarily or permanently affect their property assets and their activities. As a case study, we took the propane storage tank (V306) which is located in the GPL of Hassi R'mel (SONATRACH, Algeria).

2. WORK METHODOLOGY

High-risk installations must be operated under strict safety conditions. This is why the primary duty of the operator, in facilities likely to be the site of a major accident, is to focus on controlling risk. There are many ways to do this duty. However, the most effective method in this field of activity is the LOPA method (Layer of Protection Analysis) [5]. Thanks to this type of analysis, it is possible to understand which are the most risky steps in the process and, if necessary, to propose appropriate corrective and preventive measures [6, 7]. This method is favored by the scientific community because of its low demand for quantitative values giving it the semi-quantitative character. Thus, the LOPA method recommends evaluating the effectiveness of safety barriers independently by replacing the notion of safety barriers with the new requirement "layers of protection" [8, 9,10].

In this article we will start by reviewing the methods used in determining the SIL (Safety Integrity Level) by defining the main concepts necessary to understand their progress. Then, we will apply these methods on a propane storage tank (V306) which is located in the GPL of Hassi R'mel (SONATRACH, Algeria). Finally, improvements will be proposed and a new assessment will be carried out while meeting the required SIL.

3. SIL ALLOCATION METHODS

Functional safety is a subset of overall safety which depends on the proper functioning of safety-related systems. The IEC 61511 standard describes the various methods for determining SIL, including the qualitative risk graph method and the semi-quantitative LOPA (Layer of Protection Analysis) method.

3.1 Risk Graph

The "Risk Graph" is a tool based on methods described in the German publication DIN 19250 published in 1994 and constitute a popular approach to determine the SIL [11, 12] of parameters described in the following table:

Table 1

Classification of risk parameters according to the standard IEC 61511 [13].

Risk graph parameter	category	Classification
Consequence of the dangerous event	CA	Minor injury
	CB	Marginal: one death or permanent injury
	CC	Critical: several deaths
	CD	Catastrophic: many deaths
Frequency and exposure time	FA	Rare
	FB	Frequent
Possibility of avoiding the dangerous event	PA	Possible
	PB	Not likely
Probability of the unwanted occurrence	W1	Very low
	W2	Low
	W3	Relatively high
Consequence of the dangerous event	CA	Minor injury

As its name suggests, the conventional risk graph allows a graphical representation that is simple to apply in the professional field while incorporating expert opinions when choosing the categories of parameters.

3.2 Layer of Protection Analysis (LOPA)

LOPA is a risk assessment methodology that uses simplified rules to express risk based on both the frequency and severity of potential consequences. It is defined as a simplified risk assessment of a ''Cause - One consequence'' pair [13]. Conceptually, LOPA is used to understand how a deviation in a process can lead to a dangerous consequence if not interrupted by the proper functioning of the independent protection layers (IPL). An IPL is a barrier that serves to prevent a scenario from spreading to a severe consequence without being influenced by the initiating event or by the action (or inaction) of any other layer of protection in the same scenario. The types of IPL are well illustrated in Figure 1 of the AICHE-CCPS which presented the seven IPLs most used by industries.

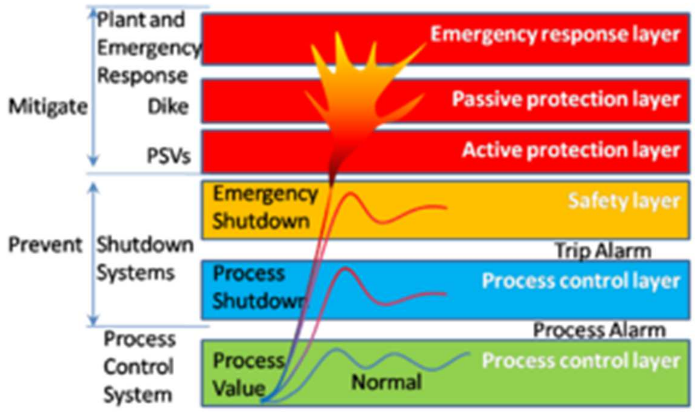

Fig. 1. Layers of Protection [5].

The frequency of the consequence occurring is given by the following formula:

$$f_c^i = IEF_i*(PFD_{i1}*PFD_{i2}*..*PFD_{ij})*P^{pers} \quad (1)$$

Where:

f_c^i: Frequency of the consequence occurring for scenario i (Low or High demand)

IEF_i: Frequency of the initiating event (IE) for scenario i ($Year^{-1}$)

PFD_{ij}: Probability of failure on demand of independent protection layer j for scenario i

P^{Pers}: Probability that a person is present in the affected area.

In addition to design and organizational measures, it should be noted that a single SIS (Safety Instrumented System) can accomplish several SIFs (safety instrumented function) whose safety integrity levels can take the following values:

SIL 1 ($10^{-1} \geq PFD \geq 10^{-2}$): These SISs are normally implemented with a single sensor, a single logic solver, and a single final control element.

SIL 2 ($10^{-2} \geq PFD \geq 10^{-3}$): These SISs are generally redundant (sensor, processing unit and actuator).

SIL 3 ($10^{-3} \geq PFD \geq 10^{-4}$): These SISs are fully redundant and require careful design and functional testing (proof testing) to achieve low PFD.

SIL 4 ($10^{-4} \geq PFD \geq 10^{-5}$): These SISs are included in the IEC61508 and IEC61511 standards, but they are difficult to design.

The steps of the LOPA method can be summarized in Figure 2 in eight steps.

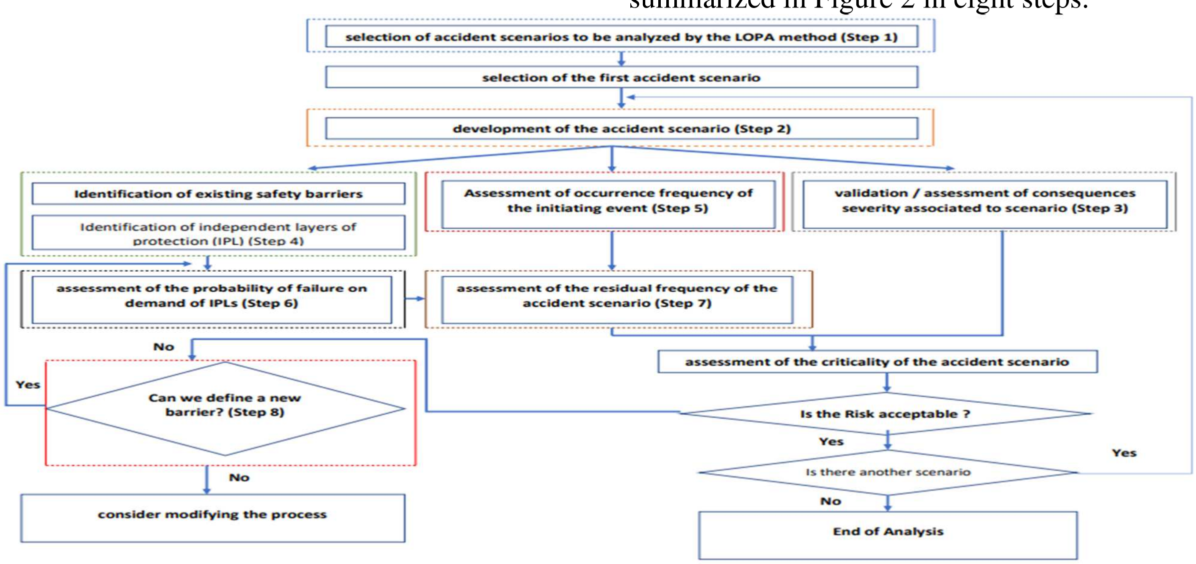

Fig. 2. LOPA steps [14]

These steps will be developed in detail in the next section.

4. RESULTS AND DISCUSSION

The propane storage tank referenced in figure 3 by V-306 is a storage point that converts propane gas to the V-302 accumulator to compensate for the losses of propane in the refrigeration loop (Figure 3).

The following table gives the nomenclature of important component in the process of producing propane.

Table 2

The list of propane production equipment.

Symbols	Nomenclature
E-301	Depropanizer preheating exchanger
E-302	Depropanizer head product condenser
H-301	Depropanizer reboiler
P-301	Depropanizer reflux pump
PK 360	Propane dryer unit
P-303	Propane booster pump
T-301	Depropanizer
V-301	Depropanizer reflux balloon
V-306	Storage tank
V-361	Regeneration gas purge pot PK 360
F-301	Filter

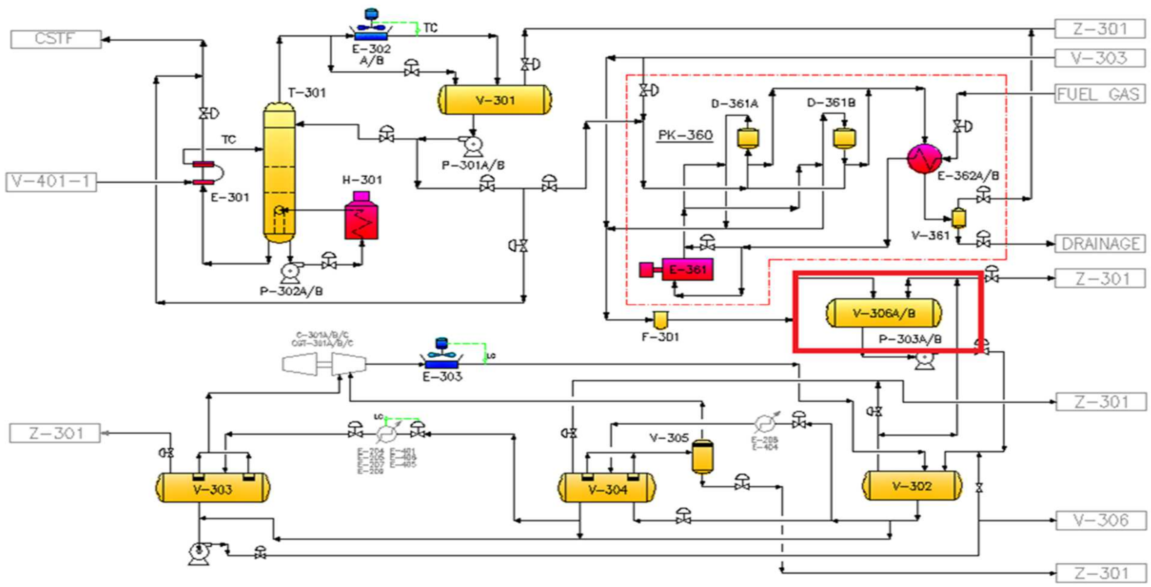

Fig. 3. Location of the V-306 storage tank in the propane production section

To carry out the risk assessment of the V306 storage tank, it is necessary to follow the following steps.

4.1 Establishment of risk acceptability criteria

In our study, the assessment of the acceptability of the scenarios will be carried out using a risk matrix that has been developed by the company taking into account the surrounding conditions of the Hassi R'Mel region. This matrix is composed of four levels of probability and four levels of severity (4 × 4) of which the degree of severity and probability of occurrence takes its maximum value on the fourth scale. This matrix will allow us to assess and judge the acceptability of accident scenarios according to their criticalities.

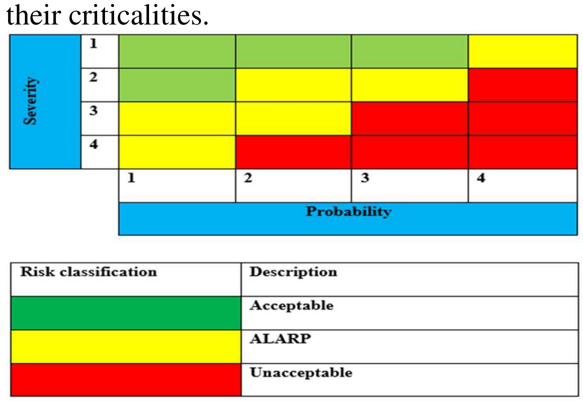

Fig. 4. Risk matrix adopted by SONATRACH (Hassi R'mel).

The meanings of the frequency and severity values are described in the Annexes 4-5.

Therefore, the level of conventional risk can be calculated by the following formula:

$$\text{Risk} = \text{Frequency} * \text{Severity} \qquad (2)$$

4.2 Development and selection of accident scenarios and safety barriers

Identifying accident scenarios is a key step in the risk analysis process. The HAZOP (Hazard and Operability Study) method was considered for our system in order to identify accident scenarios and identify the different causes, consequences as well as the various existing safety barriers. The results obtained for the three scenarios are summarized in the following table and the analysis in detail will be described in Annex 6.

Table 3

The accident scenarios and their criticalities according to the GPL of Hassi R'mel (SONATRACH).

initiating event	Frequency (/Year)	Consequences	Probability level	Severity level	Criticality level
1. pressure build-up of V302 (refrigeration loop)	1.00E-02	1. Ruin of V306 with widespread fire and risk of fatality for operators	2	4	8
2. Leak at the flange in the bottom of V306	1.00E-02	2. Risk of Fire / UVCE in the area with injury to operators or even fatalities	2	4	8
3. Fire in V306 zone	1.00E-04	3. BLEVE explosion of V306 tank Fatalities in large numbers.	2	4	8

4.3 Determination of the SILs required for the safety of the V306 propane tank

4.3.1 Application of the Risk Graph method

Once the accident scenarios are identified, the risk graph method can be applied to assign each scenario its required SIL. Since this method is purely qualitative, expert judgment in the workplace helped us to select the categories of the parameters of the risk graph. Figure (5) shows that all scenarios must meet at least the requirements of a SIL 3 in order to reduce the risks to a tolerable level.

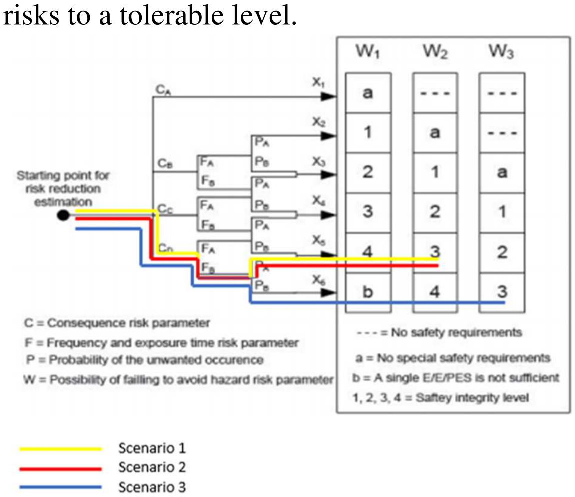

Fig. 5. Determination of SIL by the risk graph method

4.3.2 Application of the LOPA method

After having determined the SIL required by the qualitative risk graph method, we will also apply the semi-quantitative LOPA method and compare the values of the SILs found by this method with those of the risk graph.

4.3.2.1 Identification of independent protection layers

Among the safety barriers previously identified by the HAZOP method, there are safety barriers which are IPL qualified and which must have the following three conditions:

I. Effectiveness

For an IPL, its efficiency depends on its ability to perform a required safety function for a given period of time and under specific operating conditions.

II. Independence

A safety barrier is IPL qualified, if its operation does not depend on the operation of other safety barriers or on the operation of the system itself.

III. Testability

An IPL should be designed to allow periodic testing of their effectiveness.

Following these three principles, the independent protection layers as well as their retained PFDs are presented below for each scenario.

Table 4

The PFDs of the protection layers of scenario 01.

Protection Layers	components	components PFD	Layer's PFD
PICV3003	PICV3003	1.00E-02 [5]	1.00E-02
Alarm, operator and HV (safety valve)	PI 3003	9.02E-03 [15]	0.21 (See Annex 01)
	DCS	1.00E-01 [5]	
	PAH3003	1.00 E -03 [16]	
	Operator	1.00E -01 [5, 16]	
PSV	PSV3011/12	1.00E-02 [5, 16]	1.00E-04

Table 5

The PFDs of the protection layers of scenario 02.

Protection Layers	components	components PFD	Layer's PFD
LI 3005, alarm LAL, operator and HV (safety valve)	Alarm LAL3005	1.00 E -03	0.22 (See Annex 02)
	LI 3005	1.7.E-02 [15]	
	operator	1.00E-01	
	DCS	1.00E-01	
	HV3014	1.00E-02	
	HV3004	1.00E-02	

Table 6

The PFDs of the protection layers of scenario 03.

Protection Layers	components	components PFD	Layer's PFD
PICV3003	PICV3003	1.00E-02	1.00E-02
Alarm, operator, HV and Cooling crown	PI 3003	9.00E-03	0.21 (See Annex 03)
	DCS	1.00E-01	
	PAH3003	1.00 E -03	
	Operator	0.1	
	HV3014	1.00E-02	
	HV3004	1.00E-02	
	Cooling crown	1.00E-02 [8, 16]	

4.3.2.2 Determination of the frequency of accident scenarios

The accident scenarios selected for LOPA will be presented in the form of Event Trees in figures 6-8 to provide a graphical presentation of the sequences of events starting from an initiating event to arrive at a given frequency of consequence.

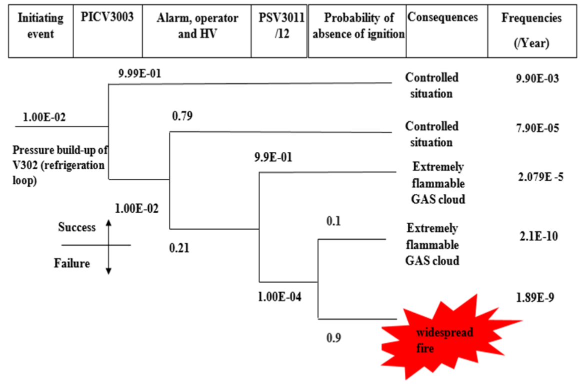

Fig. 6. Scenario 01 Event tree

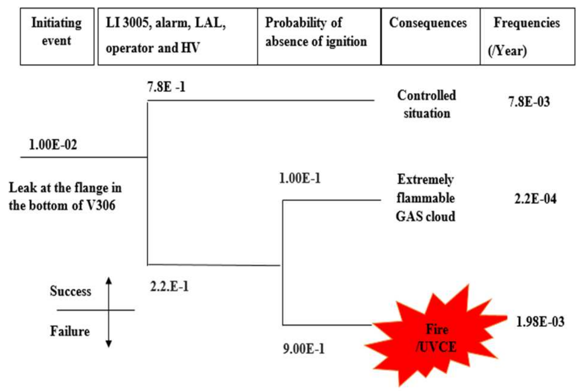

Fig. 7. Scenario 02 Event tree

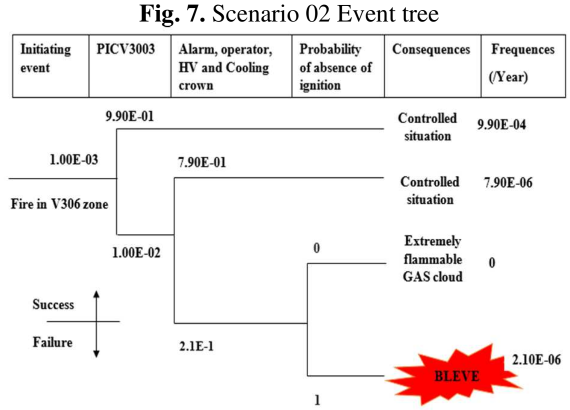

Fig. 8. Scenario 03 Event tree

4.3.2.3. Risk assessment according to acceptability criteria

The evaluation of the accident scenarios established by the Event Tree method will be carried out according to the acceptability criteria by comparing the risk before and after the implementation of the IPL (Figure 9).

The values of the consequence frequencies will be multiplied by the probability that a person will be present in the study area. The latter takes the value of 0.5 because of the rounds carried out by the operators [5].

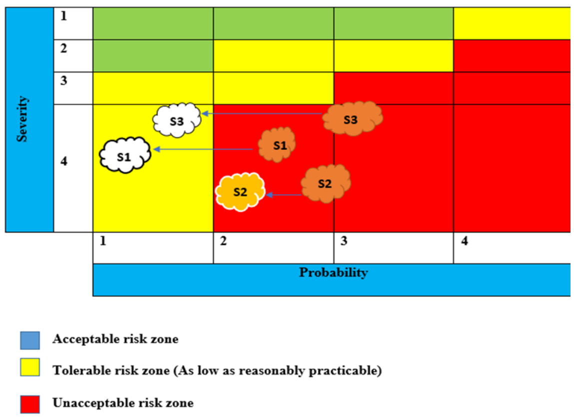

Fig. 9. Assessment of scenarios by the risk matrix

It is obviously from figure (9) that all the scenarios can be considered tolerable (ALARP) with the exception of the second scenario 'flange leak in the bottom of V306 (FIRE / UVCE)' which immediately requires a reduction of risk.

4.3.2.4 Calculation of the required safety integrity level (SIL)

This calculation will only be done for Scenario II which presented an unacceptable level of risk for the ‘’ Fire / UVCE ’’ consequence. The recommended SIL can be given by the following ratio:

$$\text{SIL required} = \frac{\text{Tolerable frequency}}{\text{Accident frequency}} \quad (3)$$

by applying formula 1, we have:

$$f_c^2 = 1.98 * 10^{-3} * 0.5 = 9.9E - 04\,(Year^{-1})$$

Therefore, with a tolerable frequency <1.0E-6 (Year^{-1}), the SIL required is:

$$\text{SIL required} = \frac{1.0E\text{-}06}{9.9E\text{-}03} = 1.01\,E\text{-}03\ \text{Year}^{-1}$$

So, we need to add at least one SIS which corresponds to the SIL II to have a tolerable level of safety. This SIL level is higher than that given by the qualitative risk graph method.

4.4 Recommendations

Before starting this step, we must first choose the level of the SIL at which improvements will be proposed. Among the two SIL values found by the risk graph and LOPA, we decided to base our recommendations on the value found by the LOPA method for the following reasons:

- The risk graph is based on subjective expert judgments which generally require multidisciplinary experience;
- The LOPA method is based on mathematical calculations and formulas, which gives it the character of a more reliable scientific approach;
- The LOPA method encompasses all the dependent safety barriers in a single independent protection layer whose PFD must be calculated according to the PFDs of the safety barriers;
- The choice between the risk category scales in the “Risk Graph” can strongly influence the SIL level required for the system.

In addition to this, we notice that the two values of the SIL have a difference of magnitude of order 1 which can be interpreted by the error difference between the two methods.

4.4.1 Proposition of SIS

To meet the requirement of the LOPA method, we proposed to add a safety instrumented system (SIS) composed of the following three elements:

- Two catalytic gas detectors in active redundancy which detect the presence of dangerous gases and warn the operator of the potential risk;
- A logic solver (minimum SILII) which receives information from the detector and makes the decision to activate the final element;
- Two redundant valves (end elements), which have the role of isolating the circuit by reducing the probability of the formation of an explosive atmosphere.

The architecture of this SIS is shown in figure 10.

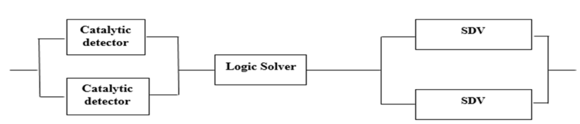

Fig. 10. Architecture of the proposed SIS loop.

Before calculating the overall SIL level of the architecture, we must first calculate the PFDavg of each redundancy between two identical elements by the following formula:

$$PFD_{avg} = \frac{\lambda^2 * \tau^2}{3} \quad (4)$$

Where

λ: Component failure rate during operation or on demand.
τ: Interval between 2 consecutive tests.

For τ=8760h:

λ(Catalytic detector)= $2.38\,E-6\,h^{-1}$,

λ(Logic Solver)= $0.01\,h^{-1}$,

λ(SDV)= $9.77\,E-6\,h^{-1}$ [15].

PFD avg of catalytic detectors = SIL III =

$$\frac{[(2.38\,E-6)^2 * (8760)^2]}{3} = 1.45\,E-4\,(h^{-1});$$

PFD avg of Logic Solver= $0.01\,h^{-1}$ = SIL II;
PFD avg of SDV= SIL II =

$$\frac{[(9.77\,E-6)^2 * (8760)^2]}{3} = 2.44\,E-3\,(h^{-1}).$$

So for the NOON type configuration [9], the overall SIL of the SIS is equal to SIL II.

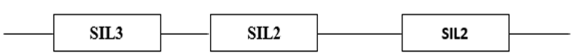

Fig. 11. Global architecture of the SIS

SIL (global) = MIN (SIL 3, SIL2, SIL 2) = SIL 2.

After repositioning scenario II on the criticality matrix, we notice that the risk is reduced to a tolerable level (ALARP).

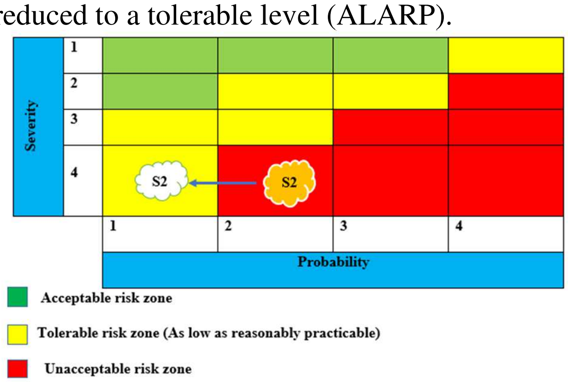

Fig. 12. Reassessment of scenario 02 by the risk matrix after the proposed improvement.

This proposal not only minimizes the probability of occurrence of the scenario but also its severity by reducing the volume of dispersed gas.

5. CONCLUSION

In this article, we have considered the LOPA method and risk graph to assess accident scenarios for the V306 propane storage tank. These two methods confirmed that the flange leak scenario at the bottom of V306 needs to be reinforced with at least one additional protection layer of SILII. The SIL of the proposed SIS architecture was calculated based on the rules for combining channel SILs and the Average Probability of Failure on Demand formulas.

Despite the practicability and simplicity of the conventional LOPA method, the assignment of a safety integrity level (SIL) to a PFD value close to the lower or upper limits of the standardized intervals of SILs, may present a divergence between the level of system security actually required and the affected SIL. For this, other approaches such as fuzzy logic methods can bring us more information about the required SIL.

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7. ANNEXES

Annex 1

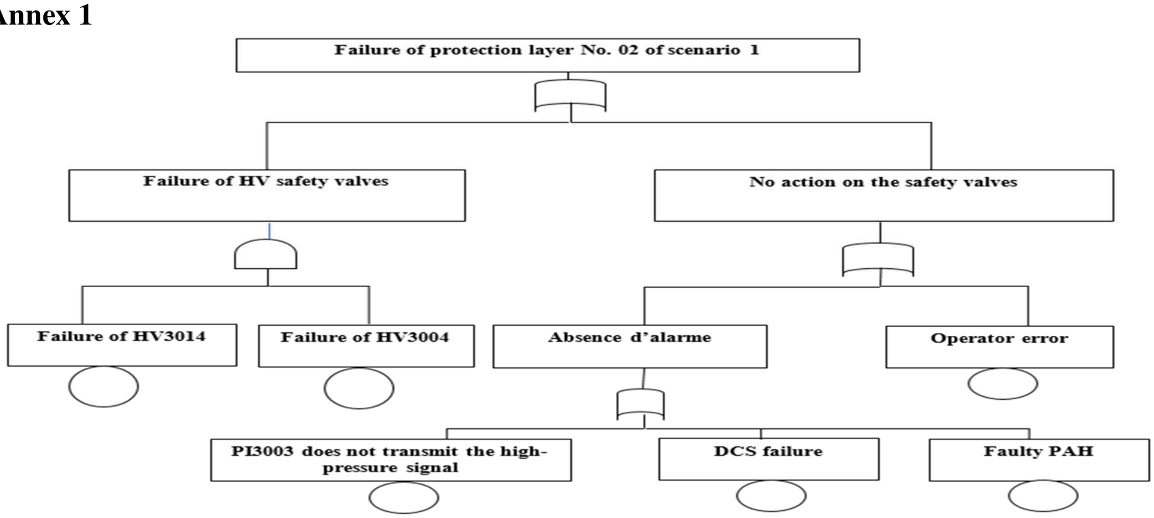

Fig. 13. Fault Tree of protection layer number 2 of scenario 01

Annex 2

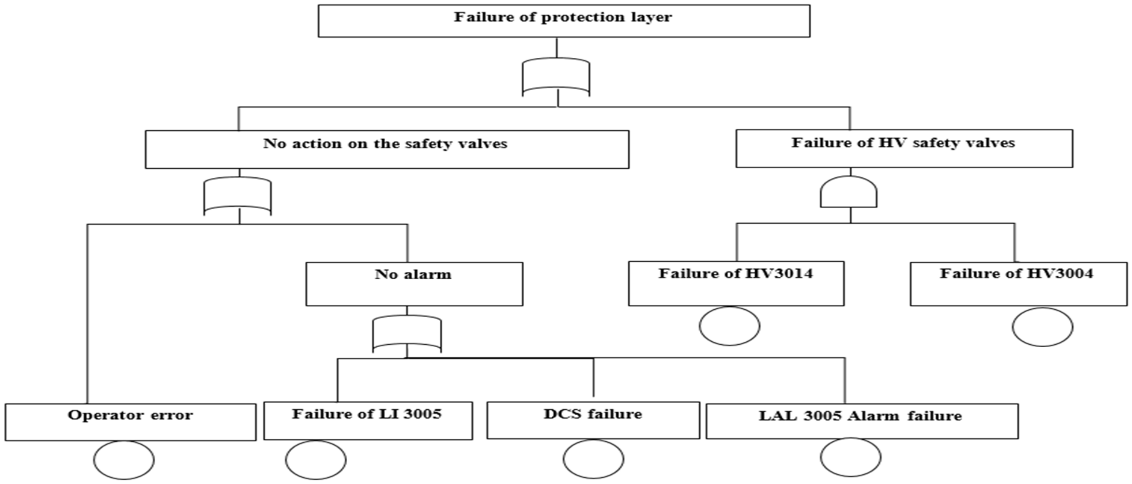

Fig. 14. Fault Tree of protection layer of scenario 02

Annex 3

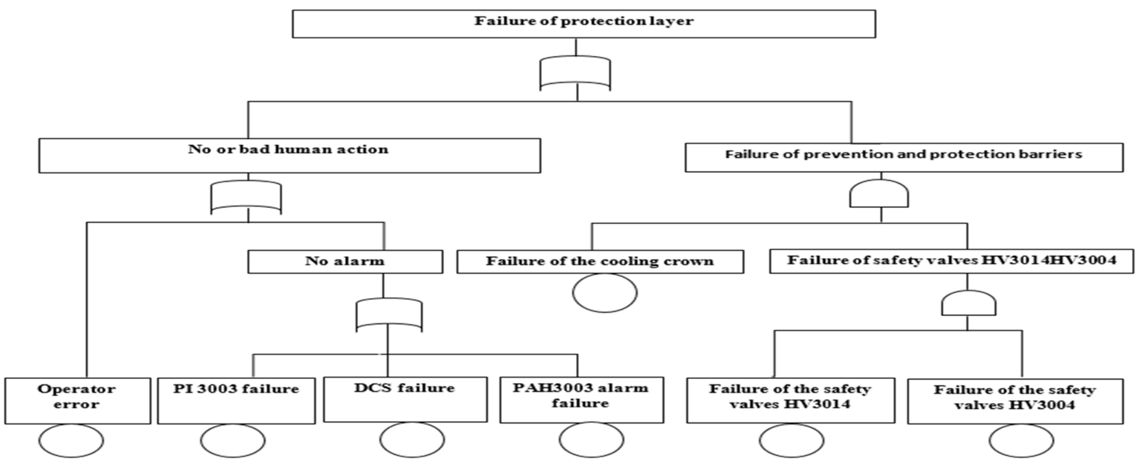

Fig. 15. Fault Tree of protection layer of scenario 03

Annex 4

Table 7

Severity scale.

Severity	personal	Environnement	Public	Production/goods
G4	Several deaths	Pollution out of limits and able to endure over a long period of time	deaths	Significant damage and total shutdown of production
G3	Permanent incapacity or 1 death	Uncontrolled internal pollution or pollution outside the limits but under control	Significant injuries	Localized damage and partial unit shutdown
G2	Significant injuries	Internal and controlled pollution	Minor injuries	Minor damage and short stop of production
G1	Minor injuries	Minor	No impact	No damage, no downtime

Annex 5

Table 8

Frequency scale.

Probability	Description	Frequency
P4	Very probable : occurs frequently in SONATRACH.	1/ year
P3	Probable : occurs (or could occur) at SONATRACH / could occur during the lifetime of the installation.	10-2 à 10-1/year
P2	Unlikely: Already (or could be) met in an organization similar to SONATRACH	10-4 à 10-2/year
P1	Improbable (or extremely rare): Never met or heard of but physically possible.	<10-4/year

Annex 6

Table 9

Results of risk analysis using the HAZOP method

Deviation	Causes	Consequences	S	F	C	Safety barriers		
						Prevention	Protection	Intervention
Return flow	pressure build-up of V302 (refrigera tion loop)	Ruin of V306 with widespread fire and risk of fatality for operators	4	2	8	-ATEX zone. -PI 3003 pressure transmitter gives the high pressure alarm PAH3003 for operator to open the safety valve HV3004 or 3014 to the torch. -The PICV3003 valve of V306 calibrated at 23 kg / cm2 towards the torch. -The PSV3011/12 of V306 calibrated at 24kg/cm2 towards the atmosphere.	Deluge system at V306 controlled remotely or locally	Firefighting systems
Not enough level	Leak at the flange in the bottom of V306	Risk of Fire / UVCE in the area with injury to operators or even fatalities	4	2	8	-LI 3005 level transmitter -Alarm LAL3005 -Operator well formed	/	Intervention operating plan (POI)
						-Suitable seals		Firefighting systems
More pressure	Fire in V306 zone	BLEVE explosion of V306 tank	4	2	8	-Firefighting systems	Cooling crown	-Intervention operating plan (POI)
		Fatalities in large numbers	4	2	8	-Closing the fire source by actuating the valves remotely from the control room -The PICV3003 safety valve from V306 to torch		

CONTRIBUTIE LA DETERMINAREA SIL-URILOR NECESARE PENTRU SIGURANTA INSTALATIILOR PETROLIERE: STUDIU DE CAZ AL REZERVORULUI DE STOCARE A PROPANULUI (BALON)

Rezumat: Sistemele termohidraulice petroliere sunt instalații cu risc ridicat ale căror metode analitice precum HAZOP pot fi aplicate ca instrument de analiză a riscurilor. Cu toate acestea, acest tip de metodă este utilizată pentru a indica calitativ existența barierelor de securitate sau

pentru a le trata într-o manieră dependentă fără a lua în considerare noțiunea de independență între barierele de siguranță. În acest articol, metoda semicantitativă LOPA (Layer Of Protection Analysis) a fost aplicată unui rezervor de stocare a propanului (V306) pentru a identifica scenariile care prezintă un risc ridicat, indicând clar nivelul de integritate a siguranței (SIL) necesar pentru asigurați o siguranță tolerabilă. SIL va fi, de asemenea, evaluat prin metoda „Grafic de risc”, care ne permite să exploatăm opiniile experților și să comparăm rezultatele sale cu cele obținute prin metoda LOPA. Straturile de protecție independente (IPL) evaluate, precum și sistemul instrumentat de siguranță (SIS) propus pentru rezervorul de stocare a propanului se referă la standardele funcționale de siguranță IEC 61508 și IEC 61511.
Cuvinte cheie : LOPA, semi-cantitativ, rezervor de stocare a propanului, SIL, SIS, IPL, IEC 61508.

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