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LAYER OF PROTECTION ANALYSIS OF SODIUM HYPOCHLORITE PLANT IN A CHLOR-ALKALI INDUSTRY: A FUZZY LOPA APPROACH

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Abstract*: Decision making is considered as one of the major activities in any Risk Control strategies associated with the industry arena. Several methods are used to quantify the risk and subsequently map it according to respective importance. It becomes difficult to take critical decisions with vague information presented about the competing parameters. Layer of Protection Analysis (LOPA) is a powerful analytical tool that can be used for risk assessment. It can be used for analyzing risk, catastrophic failures and assessing the adequacy of protection layers to mitigate process risk. It is a hazard analysis technique that includes hazard identification and hazard quantification and allows determining the risk associated with the various hazardous processes by utilizing their severity and the likelihood of the events being initiated. LOPA is carried out based on the information developed during qualitative hazard evaluation procedures such as Hazard and Operability study (HAZOP) and Process Hazard Analysis (PHA). Fuzzy Layer of Protection Analysis (Fuzzy LOPA) presents a new approach to risk assessment based on fuzzy logic and degrees of memberships. This work particularly focuses on applying a Fuzzy Layer of Protection Analysis (Fuzzy LOPA) to mitigate the accident scenarios associated with sodium hypochlorite plant in a chlor-alkali industry by providing various Independent Protection Layers (IPLs) to reduce the risk levels of the scenarios to acceptable limits. The protection provided helps in reducing the risks posed by the plant by a large amount in an effective manner. It is evident from this study, that the fuzzy LOPA methodology provides a better risk estimation compared to classical LOPA and helps in prioritizing the possible hazardous events of process industries and improves the overall safety of the plant.

Keywords: *Layer of Protection Analysis, Fuzzy LOPA, Sodium Hypochlorite Plant, Chlor-Alkali Industry*

I INTRODUCTION

Layer of Protection Analysis (LOPA) is a risk analysis tool which is widely used in the process industries[1,2]. It is a simple method to evaluate the adequacy of the different layers of protection provided to mitigate a consequence resulting from an initiating event. This technique is very useful in developing risk reduction measures [3].The fundamentals of LOPA is an accident scenario which is initiated by different causes also called as "initiating events" and ends at "consequences" with different levels of severity. The method can be used to analyze a wide range of risk issues and also serves as a highly effective aid in decision making [4].Fuzzy logic is applied in LOPA for risk calculation when the data is scarce or highly uncertain[5]. Fuzzy LOPA provide a better ranking when compared to classical LOPA. This method helps to suggest additional mitigation and safe guards to reduce the risk level and which will improve overall safety of the plant. When compared to quantitative risk analysis methods, LOPA requires less time and is cost effective in carrying out the risk assessment procedures [5]. Application of fuzzy logic in LOPA helps in solving conflicts in decision making process. This is achieved by providing a consistent, simplified framework for estimating the risk associated with incident outcomes cases and by providing better understanding of the concepts of risk [5]. In the process of LOPA analysis a detailed study of the operations and practices in the process industry having insufficient safeguards or protection layers could be easily identified[6]. This further enables to focus on those particular risk areas and to render the risk to acceptable limits. Risk assessment of the process industries requires detailed information of the failure frequency rates of the instruments and equipment of the plant which maybe uncertain and imprecise. Fuzzy logic is developed as an emerging tool, to model the real life problems, where is uncertainty and lack of information Zadeh [7]. This paper explores the benefits of application of fuzzy logic in Layer of Protection Analysis (LOPA). This method is applied in a sodium hypochlorite plant associated with a chlor-alkal industry. This study is performed for the accident scenario of sodium hypochlorite plant in a chlor-alkali industry using fuzzy layer of protection analysis. A comparative study of the results obtained by classical LOPA and Fuzzy LOPA of the above plant is also done.

II LAYER OF PROTECTION ANALYSIS (LOPA)

A number for tools are used for risk analysis such as Hazard and operability studies (HAZOP), fault tree analysis and event tree analysis. Risk analysis tools can be classified in to two major groups: qualitative and quantitative. There are so many advantages and disadvantages for these two groups of risk analysis tools. The Layer of Protection Analysis (LOPA) is emerged as a tool which will give the advantages both qualitative and quantitative techniques. LOPA can be commonly used in the chemical process industries. LOPA analyse the adequacy of the layer of protection provided for a cause–consequence pair which are identified form other analysis like HAZOP. [8]. LOPA is a tool to identify the scenarios that present the most significant risk to the plant of analysis and to determine the consequences associated with the plant. The effect of these consequences could be reduced by the application of protection layers or inherently safer design principles [3]. The layers of protection help to prevent an initiating event from developing into an incident or to mitigate the consequence of an incident when it occurs. LOPA uses a relatively simple, scenario based approach that can be used to effectively address various risk related issues, which helps in providing a timely and cost-effective methodology to conduct analysis as an aid to decision making[4]. For a particular accident scenario, only one protection layer must work successfully in order to prevent the consequence [3]. However, we cannot rely only on the single layer of protection. The reason behind this logic is that the layer of protection, whether it is human related or machine related have probability of failure on demand (PFD). In order to reduce the risk, a number of layer of protection with certain PFDs are provided. This will prevent the system to reach an undesired consequence in case of an initiating event. In LOPA a scenario is defined as a combination of cause–consequence pair. Causes means the initiating events and the consequences means the undesired event which will happen if the layer of protections are not in place or not in working conditions[9]. In addition to the above pair, there may be an additional item in the scenario, which is named as enabling conditions. The position of the enabling conditions is in between the causes and consequences[10].

LOPA assumes that accident scenario is represented by one typical pair of events: cause-consequence[8] and it takes place as a result of failure of independent protection layer (IPL) which is a part of a multilayer system. Event tree (Figure1) analysis can be used for the estimation of frequency of the consequence. Probability of initiating event and PFDs of the IPLs are essential for estimating the frequency of the consequence [3].

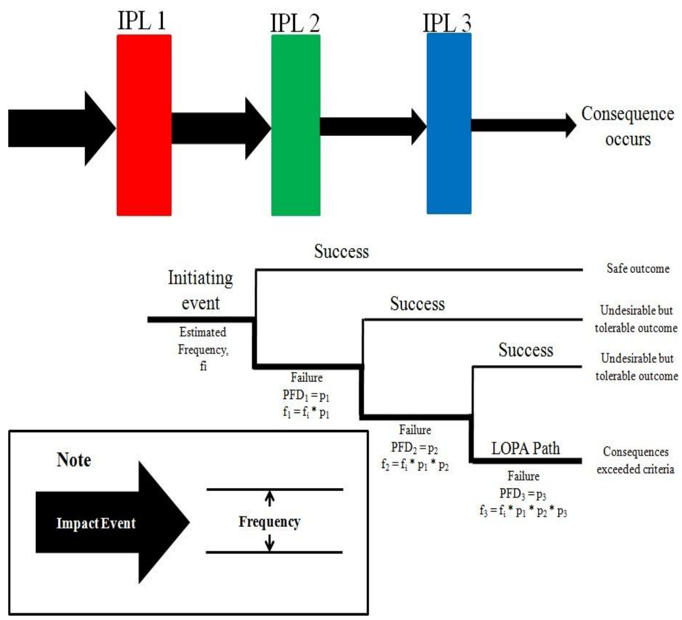

Figure 1. LOPA event tree

III FUZZY LOGIC

The major purpose of developing fuzzy logic and fuzzy models is because the binary logic and probability theory are not enough to solve problems characterized by high uncertainty, complexity and ambiguity. Fuzzy logic is a multi-valued logic which deals with ambiguous, imprecise or missing information. Fuzzy logic or fuzzy sets theory was developed by Lofti Zadeh in 1960s. In this logic, the truth values of variables may be any real number between 0 and 1. It's a type of logic that recognizes the values between 0 and 1. That means it is useful in modeling the situations which are not simply true or false. Fuzzy logic can useful for representing the degree of truth and false involved in the problem. Fuzzy logic mimics human control logic and hence it is considered as one of the best method for handling information with vague characteristics. Fuzzy logic is used in many of the control system applications [11]. An algorithm of fuzzy logic developed by Chanamool & Naenna [12] has the following steps.

- Define the linguistic variables and terms
- Construction of the membership functions
- Construction of the rule base
- Convert crisp input data into fuzzy values using membership functions
- Evaluate the rules in the rule base
- Combine the results of each rule
- Convert the output data into non fuzzy values.

First of all fuzzification process of the input values are done. Crisp input data are converted into fuzzy values using linguistic variables and membership functions. In the inference processing, if then rules (Fig. 2) for the fuzzy logic system (Fig.3) are generated. A defuzzification step is the final step, which converts the fuzzy output to crisp output.

1. If (freq is unlikely) and (severity is low) then (risk is acc) (1)
2. If (freq is unlikely) and (severity is moderate) then (risk is acc) (1)
3. If (freq is unlikely) and (severity is high) then (risk is tol) (1)
4. If (freq is unlikely) and (severity is catastrophic) then (risk is tol) (1)
5. If (freq is low) and (severity is low) then (risk is acc) (1)
6. If (freq is low) and (severity is moderate) then (risk is tol) (1)
7. If (freq is low) and (severity is high) then (risk is tol-ac) (1)
8. If (freq is low) and (severity is catastrophic) then (risk is tol-ac) (1)
9. If (freq is medium) and (severity is low) then (risk is tol) (1)
10. If (freq is medium) and (severity is moderate) then (risk is tol-ac) (1)
11. If (freq is medium) and (severity is high) then (risk is tol-ac) (1)
12. If (freq is medium) and (severity is catastrophic) then (risk is na) (1)
13. If (freq is high) and (severity is low) then (risk is tol) (1)
14. If (freq is high) and (severity is moderate) then (risk is tol-ac) (1)
15. If (freq is high) and (severity is high) then (risk is na) (1)
16. If (freq is high) and (severity is catastrophic) then (risk is na) (1)

Figure 2. If then rules generated for controlling the output

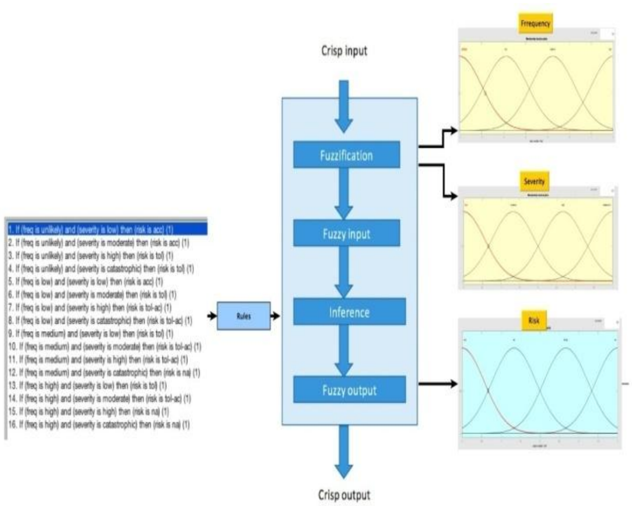

Figure 3. Schematic of Fuzzy logic System

IV FUZZY LOPA

The limitations of the LOPA mostly connected with lack failure rate and the uncertainty in tabulating the failure rate of the IPLs and safeguards. Fuzzy logic can rectify the problems related to lack of failure rate and uncertainly during the LOPA analysis. A large number of uncertain parameters and variables are involved in the LOPA analysis associated with the risk assessment of process industries. Different methods are used to tackle this situation, which includes classical statistic, probabilistic, sensitivity analysis and possibility methods [13]. Fuzzy logic proved as one of the best methods to deal with uncertainty and lack of information. The fuzzy concept reflects how people think and attempt to model our sense of words, our decision making and common sense[13].

The fuzzy LOPA model consists of three main sub systems such as frequency Fuzzy Logic System (F), Severity Fuzzy Logic System, (S), and fuzzy risk matrix. [14]. By using appropriate fuzzy arithmetic and fuzzy reasoning, the final crisp risk index can be achieved. This crisp fuzzy risk index is used for decision-making in risk management processes. Fuzzification process covert the input crisp parameters to one or more fuzzy sets during fuzzification process. These sets represent the input variable. The fuzzy inference system processes the fuzzy input variable with *if-then-else* rules. The result obtained is a fuzzy output from which the rules are aggregated final crisp value. The defuzzification method used for the study is the centroid method. The conventional risk matrix is simple to be implemented, but it leads to inconsistent results. Fuzzy logic has a positive impact when applied to conventional risk matrix for the risk determination process.

Through the use of membership functions, fuzzy logic represents knowledge that can be quantitative and qualitative in nature. Expert systems can be built based on fuzzy logic and can provide reasonably accurate outcomes useful in system analysis. The fuzzy set theory is based on the idea of membership. They allow the definition of vague concepts into mathematical structure. In traditional sets theory, whether an element belongs to a particular set or not is checked. In contrast, an element can belong to a set in some degree in fuzzy set theory. The degree is called membership and it takes values between 0 and 1. Among the different fuzzy set, the most important is the sets with membership functions that can be represented as mathematical functions [15]. Typical representations include Triangles, Gaussian and Trapezoids and are very useful in describing linguistic variables and qualitative data.The process industries and plants are highly complex and involve different technologies and large numbers of apparatus and equipments. As the system will be more complex, the information available with the plant will be less precise. The best method to deal with all the types of uncertainty including lack of knowledge, imprecision and vagueness associated with such complex systems is Fuzzy Logic.

V FUZZY LOPA METHODOLOGY

The Fuzzy LOPA methodology is developed into the following steps which are summarized as follows

Step 1: Study of process and process flow diagrams.
Step 2: Hazard and Operability Study (HAZOP).
Step 3: Identification of incidents and risks.
Step 4: Identifying the scenarios.
Step 5: Identifying the initiating event of the scenario.
Step 6: Determining initiating event frequency.
Step 7: Identifying the Independent Protection Layer (IPL).
Step 8: Estimating Probability of Failure on Demand (PFD) for each IPL.
Step 9: Estimation of risk.
Step 10: Analysis of risk.

The fuzzy LOPA methodology begins with a detailed study of the process involved in the plant and study of its process flow diagrams which is then followed by HAZOP study. The possible threats and incidents within the plant along with the help of HAZOP are considered as an accident pair, constituting of a single cause-consequence pair. A risk matrix(Fig. 4)can be used to rank different scenarios of the plant, in case of too many scenarios are present. This method helps to separate down scenarios with higher risk level and lower risk levels. Using this methodology, the scenarios with higher risks are selected for the study. Once the scenarios are developed and selected for the fuzzy LOPA study, the next step carried out was, identified the initiating event of the scenarios and their initiating event frequency (per year). Then the Independent Protection Layers (IPL) of the scenarios was identified and the probability of failure on demand for the same was estimated. The failure data were either obtained directly from the industry or from the respective failure data books and references.

For fuzzy logic application, membership functions for the variables frequency (Fig.5a), severity (Fig.5b) and risk are assigned(Fig. 5c). Various types of membership functions used are triangular, trapezoidal, Gaussian, and bell shaped. The Gaussian membership function has been used for this study as it gives more precise and robust results when combined with overlapping descriptive ranges for the variables. The input variables of frequency and severity data are given to fuzzy inference system for fuzzification, which in turns provides a crisp output for risk after defuzzification. The IF-THEN rules are used to estimate risk in the fuzz y logic system. In frequency event tree system, the methodology involves transformation of calculated frequency into the domain of fuzzy logic. The severity fuzzy inference system is another input to the fuzzy LOPA systems along with the frequency event tree, where the descriptive ranges for the severity is classified into four levels ranging from 1 to 4. The Gaussian membership function along with overlapping intervals is used in all the system.

FREQUENCY	SEVERITY			
	1	2	3	4
4	C	B	A	A
3	C	B	B	A
2	D	C	B	B
1	D	D	C	C

Figure 4. Conventional risk matrix

The risk matrix is modified to obtain the risk rules for the assessment using fuzzy LOPA methodology. The risk rules for the calculation of risk along with its corresponding linguistic terms for frequency, severity and risk are shown in the Fig. 6. The risk levels 1, 2, 3 and 4 is represented as A (Acceptable), T (Tolerable), TNA (Tolerable-Unacceptable) and NA (Unacceptable) respectively.

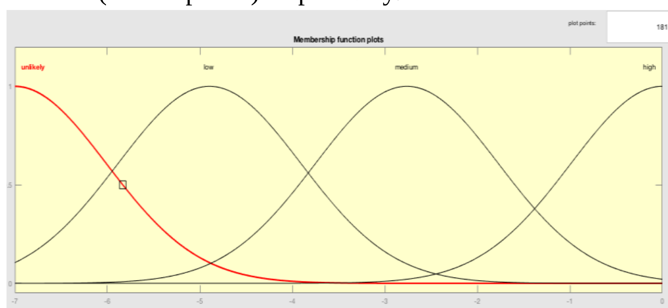

Figure5a Membership functions for input variable 'frequency'

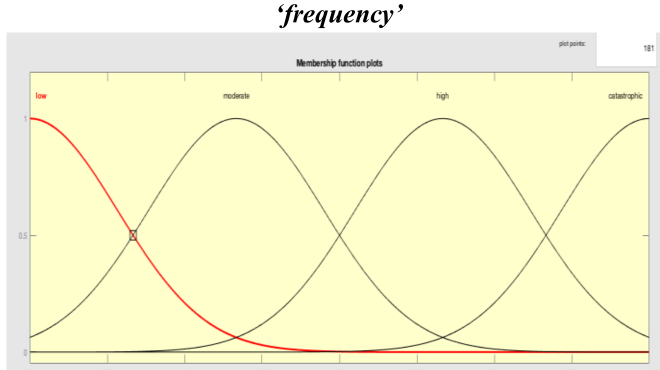

Figure5b Membership functions for input variable 'severity'

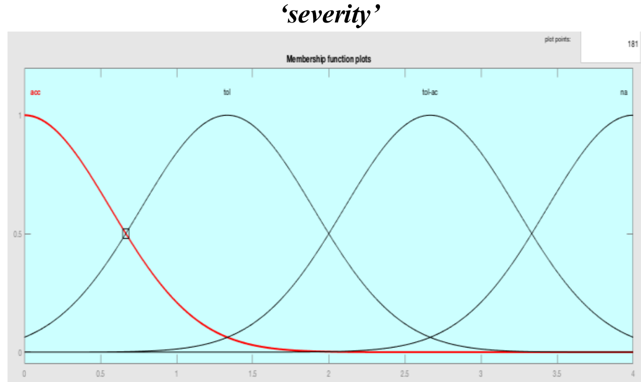

Figure 5c Membership functions for output variable 'risk

Region		Severity			
		1	2	3	4
Frequency		Low	Moderate	High	Catastrophic
4	High	T(2)	TNA(3)	NA(4)	NA(4)
3	Medium	T(2)	TNA(3)	TNA(3)	NA(4)
2	Low	A(1)	T(2)	TNA(3)	TNA(3)
1	Unlikely	A(1)	A(1)	T(2)	T(2)

Figure 6 Risk rules for fuzzy LOPA (modified risk matrix)

VI CASE STUDY

The fuzzy LOPA methodology developed by[13]is applied to sodium hypochlorite plant(Fig.7) associated with a chlor–alkali industry located in south India. The sodium Hypochlorite Plant which has been selected for the fuzzy LOPA study is one of the major hazardous plant in a chlor-alkali industry. In a chlor-alakali plant electrolysis is the major process that takes place and the purified brine is taken along with the initial electrolyte as input and sodium hypochlorite crystals obtained as finished product from the process. The generation of H_2, O_2 and Cl_2 gases pose a threat to explosion and the presence of dichromate which is a cancer causing substance makes the plant highly hazardous.

HAZOP study of the plant is conducted as the first step. The P&IDs and HAZOP study sheets was referred for developing the scenarios for higher degrees of risk along with expertise opinion. Based on possible incidents and risks, a total of 12 cause-consequence (Table 1) pairs were selected and subjected to risk matrix. Based on the initial assessment 4 accident scenarios (Table 2) with the highest risk levels were selected for the study. The initiating event and its frequency (Table 3), protection layers and probability of failure on demand data (Table 4) were obtained from failure data books [16,17]. Table 5 provides Fuzzy Sets and Linguistic terms for fuzzy risk matrix. Table6 Provides the Independent Protection layers used for different scenarios.

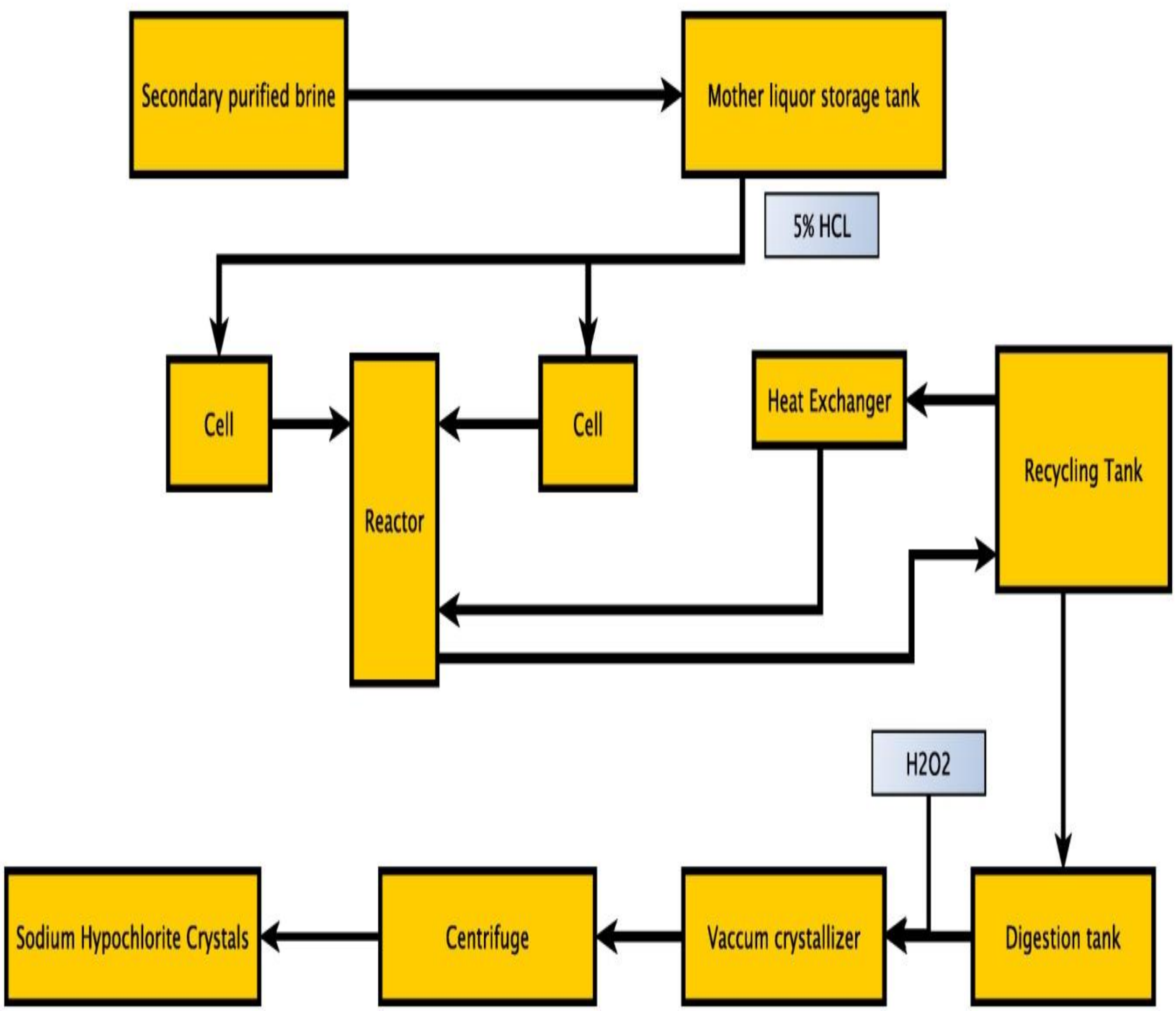

Figure 7 Block Diagram

Table 1 Risk level estimation of accident scenarios

Sl. No.	Cause	Frequency Range	Consequence	Severity Range	RISK
1	FCV-209 malfunctioning	Level 2	Level in 30 T1 increases and discharge pressure of 30 P1 A/B increase	Level 2	**C**
2	Uncontrolled purge N_2 is coming to 20 K1, K2 through HV-201 due to malfunctioning	Level 2	Cell gas pressure increases and water seal will blow off	Level 4	**B**
3	More of O_2/Cl_2 generation due to improper HCl addition and higher current	Level 3	Explosive gas mixture formation	Level 3	**B**
4	Rectifier higher DC current more than indication	Level 2	Cell Temperature increases	Level 2	**C**
5	Pump 20 P1 A/B tripped	Level 3	No circulation of electrolyte in cooler, will lead to rise in temperature	Level 1	**C**
6	Due to cell operation disturbance- pH, temp, NaCl, NaClO3	Level 2	Explosive mixture formation in the cell gas, Hydrogen scrubber, vents. It can explode.	Level 4	**B**
7	Moisture content in crystals. This is due to conc. Of crystals slurry getting low. Clogging of slots in centrifuge basket.	Level 2	Moisture content will go up by 4% leading to corrosion	Level 2	**C**
8	Dissolved gases from the electrolyte (Hydrogen, Chlorine, Oxygen etc.)	Level 3	Chance of formation of Explosive mixture in the gas phase of 20T1 or 20T2	Level 4	**A**
9	Due to agitator gearbox, oil seal leakage will trip inside reactor	Level 2	Cause voltage increase in electrolyzer for activation of anode coatings as well as foaming, entertainment of H2 with liquor to digester	Level 2	**C**
10	Due to improper venting gases generated will slightly pressurize	Level 2	Leakages at the top of the reactor. Liquid pump will also be affected.	Level 2	**C**
11	Column isn't drained fully and flushed with DM water	Level 1	Chlorate and HCl mixing will generate ClO2 explosive mixture	Level 4	**C**
12	Discharge is nil	Level 2	Discharge line will get pressurized, may crack piping	Level 2	**C**

Table 2 Selected scenarios with initiating events

Sl. No.	Cause	Consequence	Initiating Event
1	Uncontrolled purge N_2 is coming to 20 K1, K2 through HV-201 due to malfunctioning	Cell gas pressure increases and water seal will blow off	Valve Failure
2	More of O_2/Cl_2 generation due to improper HCl addition and higher current	Explosive gas mixture formation	Human Error
3	Due to cell operation disturbance- pH, temp, NaCl, NaCIO3	Explosive mixture formation in the cell gas, Hydrogen scrubber, vents. It can explode.	Temperature Sensor Failure
4	Dissolved gases from the electrolyte (Hydrogen, Chlorine, Oxygen etc.)	Chance of formation of Explosive mixture in the gas phase of 20T1 or 20T2	Valve Failure

Table 3 Initiating event frequency

Class	Frequency Data			
Event	**Min/Lower**	**Typical/Mean**	**Max/Upper**	**Reference**
Valve failure (Manual)	1.2×10^{-4}	1.33×10^{-3}	4.4×10^{-3}	CCPS (Guidelines for Process Equipment Reliability Data)
Human Error, Operator failure/opportunity	10^{-3}	10^{-2}	10^{-1}	CCPS (Layer of Protection Analysis)
Temperature Sensor failure	1.75×10^{-4}	4×10^{-2}	1.48×10^{-1}	OREDA
Valve failure (Flow control)	1.23×10^{-3}	1.44×10^{-1}	4.84×10^{-1}	OREDA

Table 4 Probability of failure on demand of the IPLs

Class	Probability Data			
IPL	Min/Lower	Typical/Mean	Max/upper	Reference
Flow indicator transmitter	8.4×10^{-3}	4.8×10^{-1}	1.92	CCPS (Guidelines for Process Equipment Reliability Data)
Pressure Switch (electrical)	2.3×10^{-3}	2.17×10^{-2}	8.41×10^{-1}	CCPS (Guidelines for Process Equipment Reliability Data
Pressure indicator transmitter	7×10^{-4}	4×10^{-2}	1.67	CCPS (Guidelines for Process Equipment Reliability Data
FICA	3.2×10^{-3}	1.43×10^{-2}	3.2×10^{-2}	OREDA
AIA	4×10^{-3}	8×10^{-2}	3.75×10^{-1}	OREDA
Flame arrestor	10^{-3}	10^{-2}	10^{-1}	CCPS (Layer of Protection Analysis)
Air Scrubber	1.7×10^{-4}	3×10^{-3}	4×10^{-2}	OREDA

Table 5 Fuzzy Sets and Linguistic terms for fuzzy risk matrix

Linguistic Variables	**Linguistic Terms**	**Description Range**
Frequency	High	$10^{-2}<F<1$
	Medium	$10^{-4}<F<10^{-1}$
	Low	$10^{-6}<F<10^{-3}$
	Unlikely	$10^{-7}<F<10^{-5}$
Severity	Catastrophic	3<C<4
	High	2<C<4
	Moderate	1<C<3
	Low	1<C<2
RISK	Acceptable (A)	0<R<2
	Tolerable (T)	1<R<3
	Tolerable-Unacceptable (TNA)	2<R<4
	Unacceptable (NA)	3<R<4

Table 6 Independent Protection layers used for different of the scenarios

Scenario	Independent Protection Layers (IPLs)
Scenario 1	1. FIT-210 2. PSL-211 with HV-201 provided for Nitrogen
Scenario 2	1. HCl addition with pH measurement, AIA-202, 203 and FICA-203 control is provided. 2. Oxygen analyzer AIA-401 with tripping of electrolyzer at 2.7% O_2 3. PIT-403 is provided
Scenario 3	1. N_2 Purging to electrolyzer, flame arrestor 40S2 is provided.
Scenario 4	1. Air/Nitrogen sweep is fed to 20T2 so that it will be purged to 20D1

Table 7 LOPA Worksheet for Scenario 1

Scenario 1	Scenario title: Uncontrolled purge N_2 is coming to 20 K1, K2 through HV-201 due to malfunctioning		Node No. 3
Date	Description	Probability	Frequency (per year)
Consequence description/category	Cell gas pressure increases and water seal will blow off		
Risk Tolerance criteria (Frequency)			
Initiating Event (Frequency)	Valve Failure		1.33×10^{-3}
Enabling event or condition		N/A	
Frequency of unmitigated consequence			1.33×10^{-3}
Independent Protection Layers	FIT-210	4.8×10^{-1}	
	PSL-211 with HV-201 provided for Nitrogen	2.17×10^{-2}	
Total PFD for all IPLs		1.04×10^{-2}	
Frequency of mitigated consequence (/year)	Frequency (F) Log F		1.385×10^{-5} -4.86
Severity		Fuzzy severity index = 4	
Risk Tolerance criteria met? (Yes/NO)	TNA (3.04) – More action required	Yes, but additional improvements are required	
Actions required to meet Risk Tolerance criteria	Frequency reduction: Pressure indicating transmitter PFD = 4×10^{-2}		
Risk calculation after actions required	F = 5.54×10^{-7}; Log = -6.26; Fuzzy Severity index = 4 Fuzzy risk index = TA(2.33)		

Table 8 Comparison of risk indices of classical LOPA and fuzzy LOPA

Scenario	Frequency (F)	Severity	Classical LOPA Risk Index	Fuzzy LOPA Risk index	Risk Criteria
1	1.385 x 10^{-5}	4	3 (TNA)	3.04	Tolerable-unacceptable
2	4.57 x 10^{-7}	3	2 (T)	2.25	Tolerable
3	4 x 10^{-4}	4	4 (NA)	3.88	Unacceptable
4	4.32 x 10^{-4}	4	4 (NA)	3.89	Unacceptable

Table 9 Initial and reduced risk indices of classical and fuzzy LOPA

Scenario	Initial Risk Index		Final Risk Index	
	Classical LOPA	Fuzzy LOPA	Classical LOPA	Fuzzy LOPA
Scenario 1	3 (TNA)	3.04	2 (T)	2.33
Scenario 2	2 (T)	2.25	2 (T)	2.25
Scenario 3	4 (NA)	3.88	2 (T)	2.17
Scenario 4	4 (NA)	3.89	2 (T)	2.30

VII RESULTS

The output Fuzzy LOPA rules obtained from MATLAB for scenarios 1 is shown in Fig. 8 and the corresponding LOPA worksheets in shown in Table 7 for scenario 1.

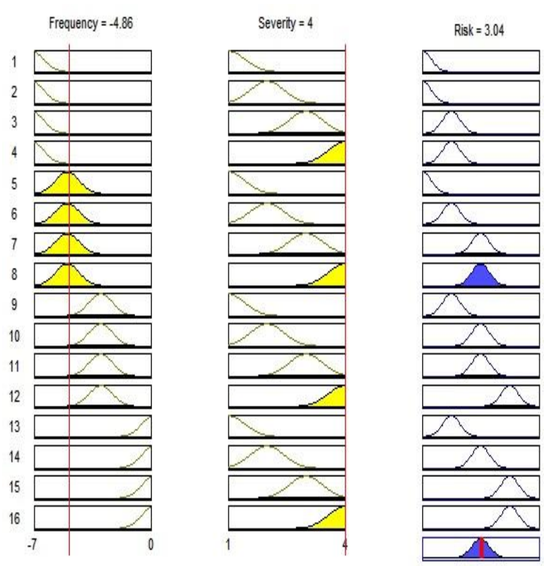

Figure 8 Rules for scenario 1

Similarly for output LOPA rules were obtained for other scenarios. LOPA worksheets were prepared for other scenarios.

A comparison of risk indices estimated using classical LOPA and Fuzzy LOPA for the selected scenarios of the sodium hypochlorite plant is given in Table 8. Table 9 showing the initial and the reduced risk levels after introducing the IPLs.

VIII CONCLUSIONS

The fuzzy Layer of Protection Analysis methodology can be successfully applied for the risk estimation of process industry and provides a better risk assessment compared to that of classical LOPA methodology. The fuzzy LOPA method is user friendly and the membership functions can be modified according to the criteria for developing risk assessment. This method is a useful tool to assess risk as it is flexible and can be implemented once the scenario is detected during a HAZOP or PHA studies. The methodology gives comparable risk values of classical LOPA and fuzzy LOPA which is helpful in analyzing the Independent Protection Layers. The first, third and fourth scenarios were found to be having comparatively higher values of risk, that is, risk levels of the range 3 (Tolerable-Unacceptable) and 4 (Unacceptable), whereas the second scenario was found to be in the Tolerable limit of risk. The possible outcome or consequence of the scenarios can be brought down to safe limits with suggestion of additional protection layers based on the fuzzy LOPA risk assessment. Fuzzy LOPA methodology is also very useful in ranking the accident scenarios, thereby helping in giving priority and safety monitoring systems to such scenarios. The quantitative risk estimated through fuzzy LOPA methodology aids in making risk decision to enhance safety and improve efficiency of the chemical process plants.

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