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PREDICTING THE RISK OF A LOSS OF CONTAINMENT FROM A NOVEL LNG PROPULSION SYSTEM USING A FUZZY LOGIC-LOPA METHOD

Main Author
Dino G DiMattia
Canada

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ABSTRACT

A key component of the liquefied natural gas (LNG) value chain is LNG shipping. Since the inaugural LNG transport vessel, the Methane Princess, came into operation in 1964 the world fleet of LNG tankers has grown to over 300. The LNG industry has an excellent safety record and innovations to improve safety and the economics of LNG transport are continuous and included propulsion systems. Several design options for LNG carrier propulsion systems have been and continue to be developed, diverging from conventional dual fuel steam turbines. These systems include dual fuel electric drive, slow speed diesel engines and gas turbine electric drives.

With the increasing cost of heavy fuel oil (HFO) and diesel, the relatively low price of gas is raising interest in gas turbine propulsion systems. Such a system may consist of one or two gas turbines and one steam turbine generator, with an exhaust waste heat recovery system. This combination of gas turbine and electric steam system (COGES) would predominantly be used to drive LNG carriers in concert with an auxiliary smaller diesel generator to handle low demand operations as efficiency of the main power set drops with lower loading. In addition, as part of this drive system, fuel gas pressure would be boosted by screw type gas compressors. Focus is placed in this area where a loss of containment can lead to a high pressure gas release.

With no operating history or data associated with this drive system, in this application, it is important to estimate the potential risk of placing such a process into LNG tanker operations. Fuzzy logic is an effective means of dealing with complex scenarios that lack data or operating experience. In order to assess the risk of this component of the propulsion system, a combination of accepted risk assessment tools can be utilized, including the application of fuzzy logic to a Layers of Protection Analysis (LOPA) technique for what-if risk assessments. The fuzzy logic-LOPA method provides an effective means of estimating risk for new designs and applications.

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1. INTRODUCTION

Propulsion systems (e.g. dual fuel electric driven, diesel driven engines and gas turbine engines electric driven) for LNG carriers continue to be an area of development. LNG tankers have been traditionally propelled by steam turbines, which are relatively straight forward and reliable for utilizing natural boil-off gas, but inefficient in terms of fuel consumption. Developments in cargo insulation technology have led to lower boil-off rates such that the advantages of more efficient propulsions systems can be realized. In an effort to improve propulsion system efficiencies, in the light of increasing size of carriers, several propulsion system studies have been conducted [1]. Though gas turbines are well established for power generation systems and as a prime mover of compressors it is relatively recently been reconsidered as a propulsion system for LNG tankers.

In the early 1970's the Norwegian LNG/ethylene carrier, Lucian was fitted with a multi-fuel gas turbine propulsion system with a recuperator heat recovery system [2]. The Lucian traded solely as an LPG carrier and hence utilized only liquid fuel because boil-off gas was not available. The gas turbine propulsion system was never used and eventually changed-out. As such, the gas turbine drive system concept has no actual operating experience, for LNG carriers (LNGC), and hence is still considered a novel propulsion system.

The risk of fire associated with a gas turbine propulsion system has been previously studied [1]. This work applies a fuzzy-logic Layers of Protection of Analysis to a loss of containment scenario associated with this gas turbine propulsion system in order to evaluate the degree of risk mitigation of independent protection layers (IPLs). LOPA provides three primary benefits from its application, which are as follows:

- Hazards are directly associated with remedial actions.
- Focus is on scenario based hazards, which allows for direct applications to what-if risk assessments.
- Identifies a wide range of mitigating alternatives from safety systems modifications to procedural changes.

LOPA is a semi-quantitative approach to the evaluation of the frequency of potential incidents and the probability of failure of these protection layers. The application of LOPA requires the estimation of the severity of the consequences and the mitigated frequency of the initiating event for risk calculations. Information to develop LOPA is often scarce or uncertain. Fuzzy logic can be useful in this situation to develop expert systems in order to allow a risk determination. Through a fuzzy logic-LOPA (fLOPA) methodology generic data and expert opinion combine to estimate risk and has been previously applied to pipeline ruptures [3] and ammonia refrigeration systems [4].

2. GAS TURBINE PROPULSION SYSTEM

The power station for this set-up includes gas turbine(s) in conjunction with a steam turbine generator set. The gas turbines and steam turbine form a combined gas turbine and electric steam system. The system also includes a conventional gas combustion unit designed to dispose of 100% of the boil off gas when it cannot be totally consumed by the combined gas electric set. The fuel gas system is equipped with screw type compressors for boosting the supply pressure. This fuel gas supply system can supply enough gas to meet the ship's maximum power requirements while maintaining cargo tank pressure requirements. The thermal efficiency of a simple cycle gas turbine can be improved to a point of being comparable to a modern diesel set-up by inclusion of a waste heat recovery system [5].

There are several concepts that could be applied of which one is shown in Figure 1 [2]. It is made up of single large combined gas turbine generator with dual fuel capacity with two diesel generator sets as auxiliaries. The gas turbine is used while the tanker is sailing. The two diesel engines act as back-up if the turbines fails and while in port one or two of diesel gensets manage the harbor load. It is possible to use a smaller additional turbine in lieu of the diesels but can be lead to higher initial capital cost and elevated operating expenditures over the life cycle of the ship.

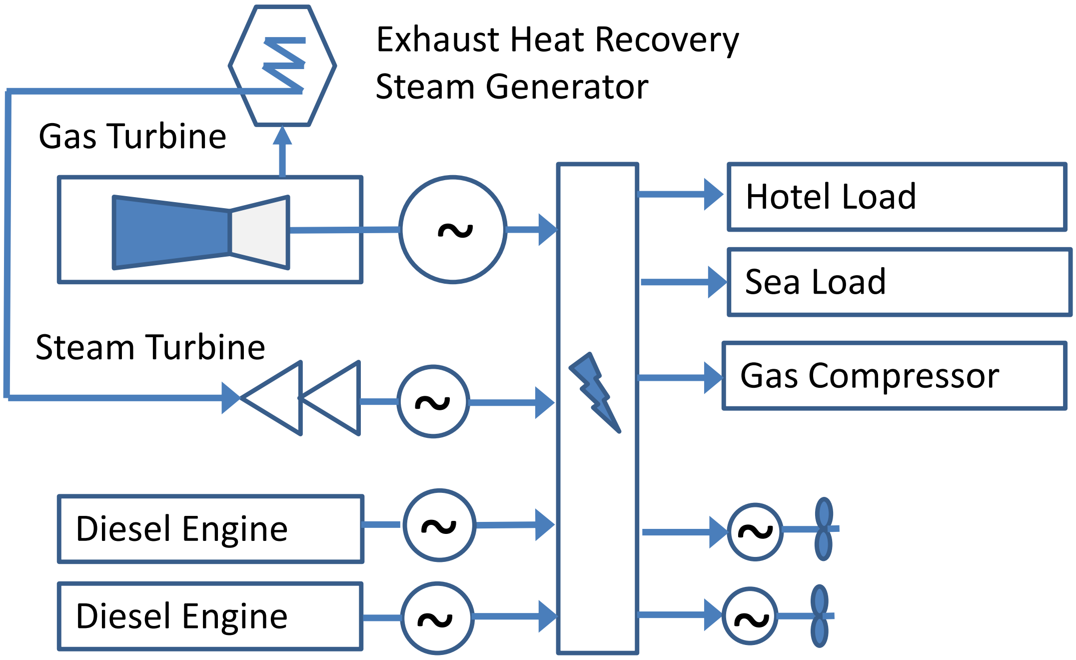

Figure 1: Gas Turbine Electric Propulsion System [2]

A key feature of this proposal is that the system is designed on the basis of using gas (boil-off gas plus vaporized LNG) as the primary fuel source. The pressurization of this gas is the focus area for the risk scenario discussed later in this paper. A key advantage of utilizing gas as a fuel source is lower environmental emissions, as well as economic incentives due to the relatively low price.

2.1 Risk from Fuel Gas Supply

There are several systems that can be evaluated for this form or propulsion system (e.g. combustion unit, gas turbine, fuel gas compression) as well multiple hazard concerns (e.g. overpressure, loss of containment, fire). In the turbine room fuel gas lines are double piped and have voting gas detection systems along with a forced ventilation system to disperse leaked gas. Moon et al. [1] found that the fuel gas compression supply system had several novel aspects associated with its design and presented an area of concern associated with a loss of containment.

A detailed description of the dispersion and fire study can be found in Moon et al. [1]. The risk of a loss of containment may result from an over pressure blocked flow scenario that is initiated from one of several initiators including failure of the high pressure shutdown safety system. The risks associated with LNG fires are well documented [6], [7] and present a credible risk to crew and environment.

3. LAYERS OF PROTECTION ANALYSIS

LOPA was developed to determine the Safety Integrity Level (SIL) of safety instrumented functions, as published in 2001, by the Center of Chemical Process Safety (CCPS) [8]. LOPA is based on the concept of protective layers and is a useful analytical engineering tool for accessing the adequacy of protection layers used to mitigate risks, such as fire and explosions on LNG Tankers (Figure 2). The LOPA tool is an effective way of assessing the adequacy of these indpendent protection layers (IPLs). As there is no perfect protection barrier, several may be needed to achieve a risk that is as low as reasonably practicable (ALARP). LOPA leverages other often used hazard analysis techniques and applies semi-quantitive measures to the evaluation of incident frequency and failure probability of protection layers [9]. During a what-if risk assessment a multi-discipline team assesses probability and consequences and hence the risk from

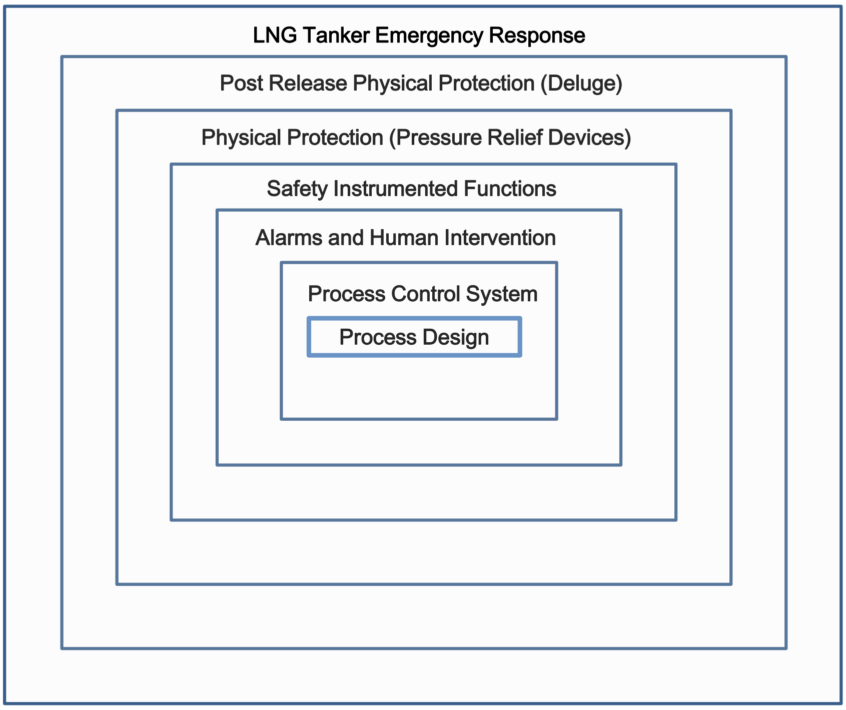

Figure 2: Independent Layers of Protection [4]

process variations such as high operating pressure. The RA team will typically list all the existing applicable safeguards before proposing additional mitigators if the existing items are not adequate to reduce the risk to an acceptable level. Figure 3 provides an illustration of LOPA, as a path in an event tree representing a worst case scenario. Each IPL, if successful, reduces the frequency of the event occurring and is represented by increasingly smaller arrows in the figure. LOPA works with a cause and consequence pair as compared to an event tree, which provides all possible consequences. The LOPA method requires failure data and the Probability of Failure on Demand (PFD) of the independent protection layers available to mitigate the scenarios that represent the higher risks that may occur.

During the evaluation of risk, during a what-if RA, the process does not typically call for a determination of the independence of the existing mitigators. An improved assessment of the risk may be possible based on the integrity of the individual components. The LOPA methodology can be used to identify independent protection layers that may be either active or passive in nature. The criteria to meet IPL criteria [8] is as follows:

- Specificity - The IPL is capable of detecting and preventing or mitigating the consequences specified such as a fire.

- Independence – The IPL is independent of other protection layers identified and is not affected by the failure of another protection layer. The IPL must also be independent of the root cause.

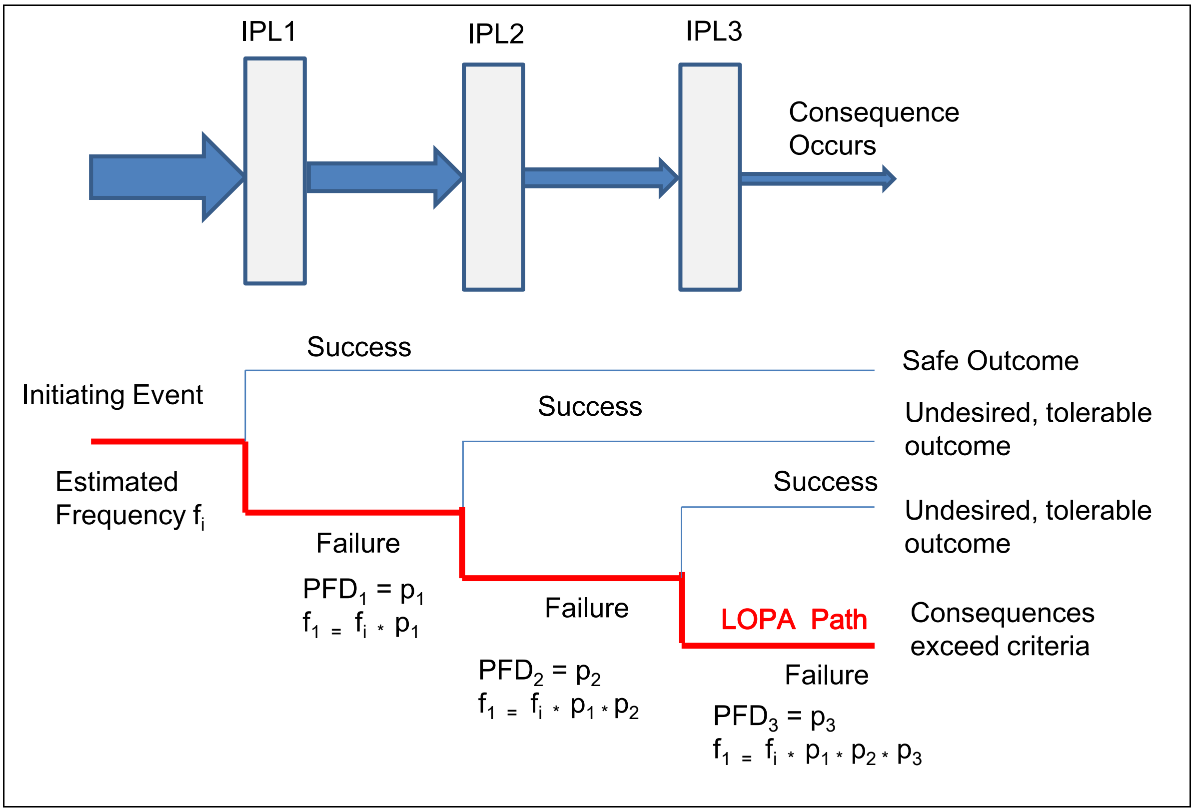

Figure 3: Event Tree showing LOPA Path [4]

- Dependability – The protection afforded by the IPL thatreduces the risk by a known and specified amount.
- Auditability – The IPL design allows for periodic validation of its function.

Examples of independent protection layers include:

- Deluge systems
- Fire and gas systems
- Pressure relief devices
- Blast and fire walls
- Operating procedures
- Process Control Systems
- Safety Instrumented Systems

LOPA provides criteria and restrictions for the evaluation of IPLs and helps to remove subjectivity without conducting quantified risk evaluation techniques. LOPA is flexible and can be used at any point in the life cycle process. LOPA is often applied for existing processes after qualitative risk analysis have been completed. This provides the LOPA with a list of hazard scenarios and the corresponding existing safe guards as well as the associated risk in terms of probability and consequence. The LOPA process is illustrated in Figure 4 for which the six main steps are as follows:

1. Record all reference documentation, which may include RA documentation, flare reports, design documents.

2. Document the process deviation and hazard scenario such as high pressure resulting in a loss of containment.

3. Identify the initiating cause for the process deviation and determine the frequency of each initiator for example loss of pressure control.

4. Determine the consequence of the hazard scenario. The consequences may include economic (operational), health and safety of individuals, environment and reputation.

5. List IPLs that can mitigate the root causes. For each IPL determine the range of the probability of failure on demand (PFD) for example the PFD for an SIS system is the same as it's Safety Integrity Level (SIL).

6. Provide recommendations that are specfic in nature. The recommendations are optional in nature and cover the full spectrum of opportunity to prevent the root causes from occuring.

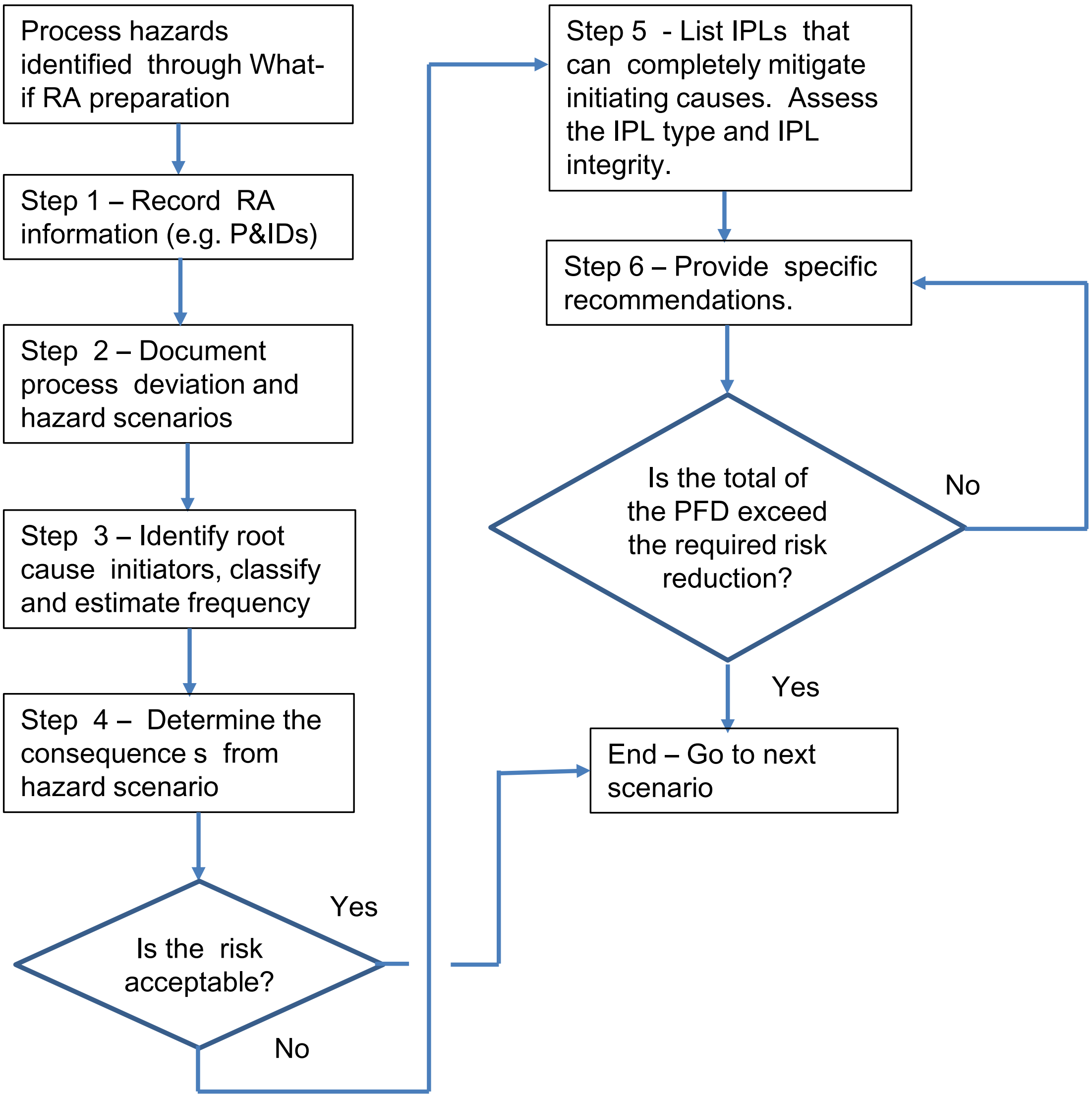

Figure 4: LOPA Methodology [4]

3.1 Fuzzy Logic

Fuzzy logic or fuzzy set analysis's primary benefit is to approximate system behavior where analytical functions or numerical relations do not exist [4]. LOPA is modified to reduce the uncertainty associated with initiating event frequency and probability of failure of the IPLs. This has been achieved by applying Bayesian logic to update generic data with plant specific data [10]. Unfortunately, information to develop LOPA can be sparse and uncertain. Markowski and Mannan [11] developed fuzzy LOPA to address this concern of uncertainty in complex systems. When there is a lack of data, the analysis relies on expert judgment to determine the values of the variables required for risk determination. Fuzzy sets as presented by Zadeh [12] have been demonstrated to be very useful in this scenario permitting the construction of expert systems.

Fuzzy logic or fuzzy set analysis and possibility theory, are used when there is uncertainty and imprecision in data, as related to safety issues connected to risk determination and has been used in conjunction with LOPA for assessment of risks associated with pipelines [3]. Uncertainty may be manifested in the probability failure data for each IPL, the severity of consequences and the change in severity after the application of an IPL. Based on fuzzy logic, the LOPA method is used to represent the knowledge available in standards and industry practice as applied to this component of the propulsion system. Fuzzy inference systems previously developed for severity and risk estimation are leveraged in for this case study [11], [3]. Frequency of the mitigated scenario is calculated using generic data for the initiating event frequency and PFD of the independent protection layers. Finally, the risk fuzzy inference system uses the frequency and severity values obtained to determine the risk for each scenario.

Fuzzy sets theory is grounded on the concept of membership. This permits mathematical structure for vague concepts. Traditional set theory states that an element belongs or does not belong to a set. In fuzzy sets theory an element may belong to set to some degree. This is called membership and has a value between 0 and 1. The most important fuzzy sets are those that have membership functions that can be represented as mathematical functions. The fuzzy sets are useful in describing qualitative data and linguistic variables. This work is based on the Continuous Universe of Discourse [11] for the concept of variable frequency and various linguistic values in the context of safety in this application. A membership function deliminates the sub ranges and is identified with a linguistic label (e.g. unlikely, low, medium, high) with a corresponding value to the set (Figure 5). Gaussian type distributions, for the input/output variables, and the corresponding ranges are taken from Reyes [4] and based on the look-up tables by CCPS [8]. The membership value, from 0 to 1 is determined by the Log_{10} of the mitigated frequency (F). Fuzzy modeling requires the transformation of the input in three steps before realizing the output as seen in Figure 6.

By applying a fuzzy probabilistic approach for event trees, typical for LOPA applications, a fuzzy reliability (probability failure) is calculated. Through the use of a risk matrix, a fuzzy risk assessment is conducted. Arithmetic operations with fuzzy sets are accomplished by extending fuzziness into a function through the extension principle, as elaborated in Ross [13]. There are several fuzzy logic methods that are utilized based on the data available to generate the system's membership functions and If-Then rules. When information is sparse the model is developed based on the physical principles of the system and instead of a mathematical correlation the model is made up of If-Then rules. The fuzzy modelling used in this work is linguistic, for which fuzzy sets and If-Then rules are applied to represent the linguistic variables.

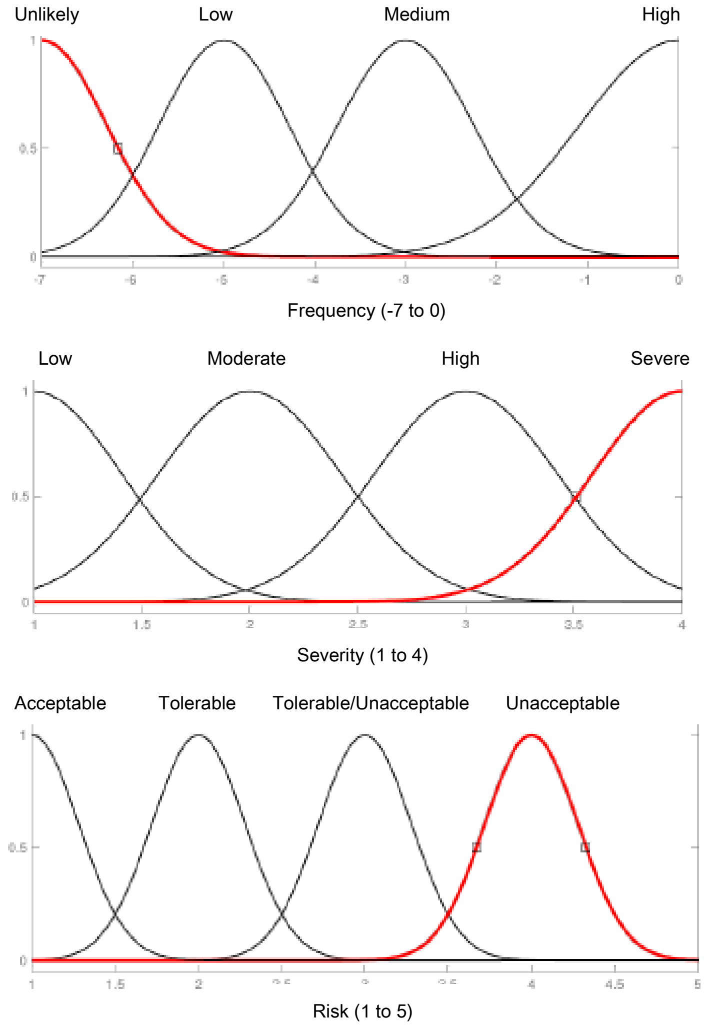

Figure 5: Membership Functions for Fuzzy Risk Assessment [4]

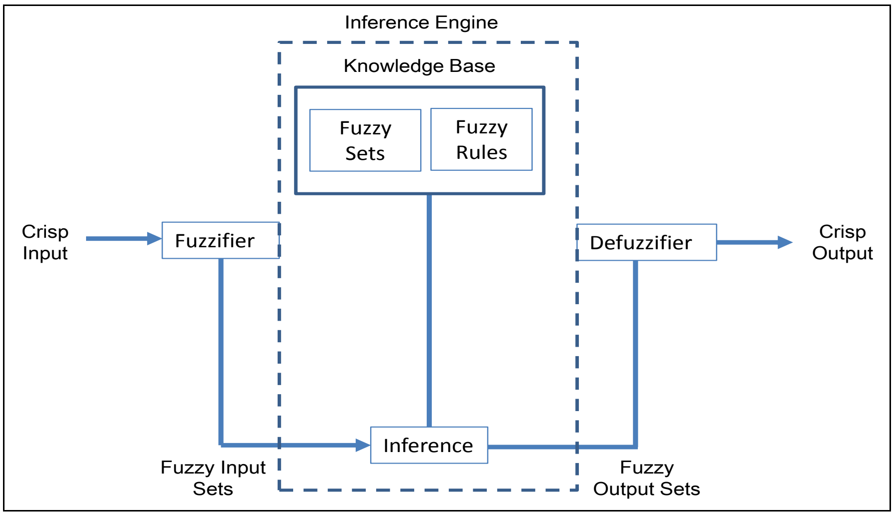

Figure 6: Fuzzy Logic System Structure [3]

The application of fLOPA begins with the incident scenario information and applies three subsystems. The result is a crisp value of the risk for the given scenario. Information to develop the fuzzy inference systems can be obtained from expert opinion, standards and literature information. From this information the linguistic variables and the relationship between them is established. Next the fuzzy sets and membership functions are defined. The fuzzy sets represent the linguistic variables of the fuzzy system. Finally the If-Then rules are established that represent the general knowledge of the gas compression system, following the Mamdani model [4]. Figure 7 shows the three sub systems comprising of the following:

- Fuzzy event tree – calculates the frequency of the accident scenario
- Severity Fuzzy Inference System – calculates the severity of the consequence of the scenario
- Risk Fuzzy Inference System – calculates a crisp risk index for decision making

Defuzzification (the process of producing a quantifiable result in fuzzy logic) determines the assessed risk for the each accident scenario. There are several defuzzification methods of which the most common is the centroid method for the Mamdani methodology [11]. The centroid method is a weighted average defuzzification method used to calculate an output value (crisp output). A more detailed description of classical and fuzzy sets theory, including fuzzification and Defuzzification methods, can be found in Reyes [4].

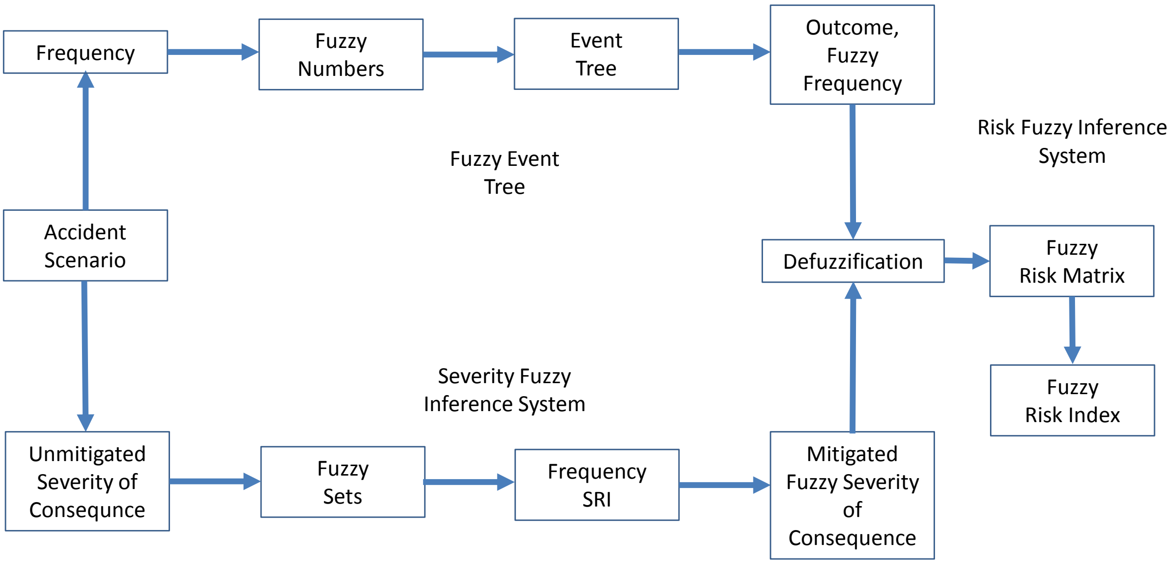

Figure 7: fLOPA Structure (SRI = Severity Risk Index) [3]

3.2 Risk Matrix

The qualitative evaluation of the risk associated from incidents is commonly reflected through the use of a risk matrix, such as that provided by OSHA shown in Table 1.

	Severity			
Frequency	**1**	**2**	**3**	**4**
4	C	B	A	A
3	C	B	B	A
2	D	C	B	B
1	D	D	C	C

Table 1: OSHA Risk Matrix [4]

The severity range for the OSHA risk matrix is as follows:

- Level 4 – potential for multiple life threatening injuries or fatalities
- Level 3 – potential for single life threatening injury or fatality
- Level 2 – potential for an injury requiring doctor's care
- Level 1 – local area, no injury to potential injuries, no more than 1st aid treatment

The frequency range for the OSHA risk matrix is as follows:

- Level 4 – Events occur on a yearly basis
- Level 3 – Events occur several times during the life cycle of the system
- Level 2 – Events occur a few times during the life cycle of the system
- Level 1 – Events not expected to occur during the lifetime of the system

The fLOPA methodology to assess the gas compression scenario is based on the OSHA risk matrix presented above. The linguistic variables, fuzzy numbers and If-Then rules are developed to represent the knowledge contained in this risk matrix. The Frequency Event Table (Table 2), Severity Fuzzy Inference System (Table 3) (U = unacceptable, T = tolerable, TU = tolerable unacceptable, A = acceptable) and the Risk Fuzzy Inference System (Table 4), used by Reyes [4], are applied here for the assessing this risk scenario for the gas compression system. The original linguistic categories in Table 2 (frequency) were adapted by Reyes [4] to the OSHA risk matrix (Table 1) and are defined later in this section.

Frequency Linguistic term	Meaning	Frequency (1/yr)
Very High (VH)	Frequently met in industry	f > 10-1
High (H)	Quite possible	$10^{-2} \leq f \leq 10^{-1}$
Moderate (M)	Occasional	$10^{-3} \leq f \leq 10^{-2}$
Low (L)	Unusual but possible	$10^{-4} \leq f \leq 10^{-3}$
Very Low (L)	Not likely to occur	$10^{-5} \leq f \leq 10^{-4}$
Unlikely (L)	Highly unlikely	$10^{-6} \leq f \leq 10^{-5}$
Remote (R)	Practically impossible	$f \leq 10^{-6}$

Table 2: Categorization of Outcome Frequency [4]

Severity Rules	**Extension of Medical Treatment**		
No. of Injuries	**First Aid**	**Doctor's Care**	**Advanced Care**
High	Moderate	High	Severe
Intermediate	Moderate	High	High
Moderate	Low	Moderate	Moderate

Table 3: If-Then Rules [4].

If Number of Injuries is (_) AND medical treatment is (_) THEN Severity is (_)

Risk Rules		**Severity**			
		1	**2**	**3**	**4**
Frequency		**Low**	**Moderate**	**High**	**Severe**
4	High	T (2)	TU (3)	U (4)	U (4)
3	Medium	T (2)	TU (3)	TU (3)	U (4)
2	Low	A (1)	T (2)	TU (3)	TU (3)
1	Unlikely	A (1)	A (1)	T (2)	T (2)

Table 4: Risk Rules [4]

If Frequency is (_) AND Severity is (_) THEN Risk is (_)

The fuzzy sets and linguistic terms for the Risk Table have been adapted from [4] and are as follows:

Frequency (F):

- High (4) – Events occur yearly, $10^{-2} \leq F < 1$
- Medium (3) – Events occur several times during lifecycle, $10^{-4} \leq F \leq 10^{-1}$
- Low (2) – Events expected to occur a few times during lifecycle, $10^{-6} \leq F \leq 10^{-3}$
- Unlikely (1) - Events not expected to occur during lifecycle, $10^{-7} \leq F \leq 10^{-5}$
  Note: for F less than 10^{-7} the frequency will be considered unlikely

Consequence Severity (C):

- Severe (4) – Potential for multiple life-threatening injuries or fatalities, $3 < C \leq 4$
- High (3) - Potential for single life-threatening injuries or fatalities, $2 < C \leq 4$
- Moderate (2) - Potential for an injury requiring doctor's aid, $1 < C \leq 3$
- Low (1) – No injury to injury requiring no more than 1st aid, $1 < C \leq 2$

Risk (R):

- Unacceptable (U) – Risk must be reduced immediately, $3 < R < 5$
- Tolerable-Unacceptable (TU) – Improvements in the medium term. $2 < R < 4$
- Tolerable (T) – Actions based on ALARP principles
- Acceptable - No action required

4. RISK SCENARIO

The incident chosen for this case study pertains solely to the fuel gas compression system for this form of propulsion set-up. The scenario details are as follows:

- Scenario – Pressure shutdown device (PAHH), downstream of fuel gas compressor fails to activate, due to improper calibration work, due to human error. PAHH setting far exceeds the design rating of the pipe.

Any blockage downstream (e.g. closed manual valve) of the positive displacement fuel gas screw compressor can generate an overpressure scenario that could lead to loss of containment, if not managed appropriately. As ignition of a flammable gas release may lead to fire and possible explosion it is assumed that a single person is injured in this low traffic area. The level of medical attention for the individual in this area is assumed to be physician's (nurse's) care. The independent protection layers applied to this scenario are as follows:

- Process pressure transmitter providing operator with a high alarm (PAH) allowing procedure to be followed to reduce pressure – mean failure probability of $1.0 * 10^{-1}$ [8]
- Pressure safety valve (PSV) – mean failure probability of $0.212 * 10^{-3}$ [14]
- Gas Detection – mean failure probability of $1.0 * 10^{-2}$ [4]

The initiating event, human error, is predicted to have a frequency of $1.0*10^{-2}$. The total probability of failure on demand of the three independent protection layers in Table 5 is $2.12*10^{-7}$. The frequency of the mitigated consequence is $2.12*10^{-9}$. Based on earlier definitions [4] for frequency (F) the scenario is considered to be unlikely as the frequency of the mitigated consequence is lower than the unlikely frequency (F) range of 10^{-7} to 10^{-5}. This is also reflected by the frequency (F) member function (Figure 5), which is the Log_{10} value of F (-8.69).

Since the area would not be frequented it is assumed in this scenario that a single individual may be exposed to the release and can be injured (not life threatening). Because of the multiple protection layers the injury is considered moderate, with an estimated severity of 2.0. An unlikely F in combination with a moderate C (2) translates to an acceptable risk (A) and no more action is required.

Depending on the scenario's IPLs and/or the number and extent of potential injuries the risk result may be untenable requiring further mitigation through additional IPLs. The process is then repeated to predict a new risk level. This illustrates the flexibility of fLOPA, for example, if there were less IPLs applied in the above scenario (i.e. no gas detection) the resulting mitigated frequency is $2.12*10^{-7}$, for which the Log_{10} is -6.67 falling into both an unlikely and low frequency range. Assuming this missing IPL generates an escalation of the event and the individual is more seriously hurt the estimated severity level climbs to 3.0.

The resulting risk, derived from the inference engine, based on If-Then rules and defuzzified, is estimated graphically to be approximately 2.4 falling in a T/TU region. Actions should be taken for improvements (e.g. install gas detection in compressor room, limit access, ventilation). Based on the actions taken a new risk level can be determined.

Scenario 1	Loss of Containment: Pressure alarm high high (PAHH) downstream of fuel gas compressor is not calibrated correctly due to human error and fails to initiate safety actions associated with achieving high high pressure.		
Item	**Description**	**Probability**	**Frequency (per year)**
Consequence	High pressure gas release with subsequent jet flame		
Initiating Event	PAHH activation is too high – Human Error		$1*10^{-2}$
Enabling Event or Condition	Maintenance work		
Frequency of Unmitigated Consequence (μ_u)			$1*10^{-2}$
Independent Protection Layers	1st IPL to be activated - Operator follows procedure to reduce pressure (PAH) 2nd IPL to be activated - Pressure Safety Valve 3rd IPL to be activated - Gas Detection		$1.0*10^{-1}$ $0.212*10^{-3}$ $1.0*10^{-2}$
Total PFD for IPL(s)	$PFD_{Total} = IPL_1 * IPL_2 * IPL_3$ $PFD_{Total} = (1.0*10^{-1})*(0.212*10^{-3})*(1.0*10^{-2})$		$2.12*10^{-7}$
Frequency of Mitigated Consequence per annum (F)	$F = PFD_{Total}*\mu_u = (1*10^{-2})*(2.12*10^{-7})*(1.0*10^{-2})$ $F = 2.12*10^{-9}$ $Log (F) = Log_{10} (2 * 10^{-9}) = -8.69$		$2.12*10^{-9}$ **Unlikely** -8.69
Severity (result of a combination of magnitude of loss – 3 input terms)	1) Life threatening injuries = 0 2) Injuries = 1 3) Medical Treatment = physician's care	Fuzzy Severity Index: 2.0 **Moderate**	
Risk Tolerance Criteria Met (Yes / No)	1.0 Acceptable but actions are available to be ALARP.		
Actions to Meet Risk Tolerance Criteria	None required. The frequency of mitigated consequence is very low and may be considered remote. Opportunities to meet principle of ALARP are as follows: i) move gas detection to within enclosure, if external. ii) limit access to compressor room. iii) enhance compressor room ventilation to lower gas concentration.		
Re-risk Calculation	n/a		
Notes	a) The scenario impacts local area only b) Nurse's care is assumed equivalent to a doctor's care		

Table 5: Fuzzy LOPA Worksheet

5. CONCLUSIONS

The application of fuzzy logic to a layer of protection analysis is readily adaptable to existing risk assessment formats and leverages known frequency and failure data in a manner that facilitates discernable when compared to solely applying LOPA and as such may provide the user an enhanced understanding of the riskiness of the scenario and help understand the effectiveness of the IPLs. The scenario presented in this work illustrates the effectiveness of good design practices and the value of implementing mitigation strategies particularly at the design phase of projects as compared to brownfield modifications which are typically more difficult to facilitate.

The fuzzy logic-LOPA methodology can be changed according to the criteria set out for the risk assessment. It has utility for new and existing facilities and fits well with a traditional risk assessment format. The method’s flexibility applies well to situations where there is a degree of uncertainty that may be associated with a general lack of operating experience. The method takes into account expert knowledge in the form of industry standards and design practices, from which a membership function can be developed and a fuzzy inference system can be used to estimate risk.

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