LAYER OF PROTECTION ANALYSIS APPLIED TO AMMONIA REFRIGERATION SYSTEMS

A Thesis

by

GERALD ZUNIGA REYES

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2008

Major Subject: Chemical Engineering

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Approved by:

Chair of Committee,	M. Sam Mannan
Committee Members,	Kenneth R. Hall
	César O. Malavé
Head of Department,	Michael Pishko

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ABSTRACT

Layer of Protection Analysis Applied to Ammonia Refrigeration Systems.

(December 2008)

Gerald Zuniga Reyes, B.S., Universidad Nacional de Colombia

Chair of Advisory Committee: Dr. Sam Mannan

Ammonia refrigeration systems are widely used in industry. Demand of these systems is expected to increase due to the advantages of ammonia as refrigerant and because ammonia is considered a green refrigerant. Therefore, it is important to evaluate the risks in existing and future ammonia refrigeration systems to ensure their safety.

LOPA (Layer of Protection Analysis) is one of the best ways to estimate the risk. It provides quantified risk results with less effort and time than other methods. LOPA analyses one cause-consequence scenario per time. It requires failure data and PFD (Probability of Failure on Demand) of the independent protection layers available to prevent the scenario. Complete application of LOPA requires the estimation of the severity of the consequences and the mitigated frequency of the initiating event for risk calculations.

Especially in existing ammonia refrigeration systems, information to develop LOPA is sometimes scarce and uncertain. In these cases, the analysis relies on expert opinion to determine the values of the variables required for risk estimation. Fuzzy Logic has demonstrated to be useful in this situation allowing the construction of expert systems.

Based on fuzzy logic, the LOPA method was adapted to represent the knowledge available in standards and good industry practices for ammonia refrigeration. Fuzzy inference systems were developed for severity and risk calculation. Severity fuzzy inference system uses the number of life threatening injuries or deaths, number of injuries and type of medical attention required to calculate the severity risk index. 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 of the scenario.

The methodology was applied to four scenarios. Risk indexes were calculated and compared with the traditional approach and risk decisions were made.

In conclusion, the fuzzy logic LOPA method provides good approximations of the risk for ammonia refrigeration systems. The technique can be useful for risk assessment of existing ammonia refrigeration systems.

DEDICATION

To my parents, Manuel Zuniga and Myriam Reyes

To my brothers, Danghelly, Andrea and Luis Manuel

To my wife, Diana Bonilla

To my family

ACKNOWLEDGMENTS

I would like to thank my committee chair, Dr. Sam Mannan, and my committee members, Dr. Kenneth Hall, and Dr. César Malavé, for their guidance and support throughout the course of this research.

Thanks also to my friends and colleagues and the department faculty and staff for making my time at Texas A&M University a great experience. I also want to extend my gratitude to Mike Sawyer and the members and staff of the Mary Kay O'Connor Process Safety Center for full support and help.

Finally, thanks to my mother and father for their encouragement, to my uncle Alvaro Reyes for his support and to my wife for her patience and love.

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NOMENCLATURE

AIChE	American Institute of Chemical Engineers
ACGIH	American Conference of Governmental Industrial Hygienists
API	American Petroleum Institute
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CCPS	Center for the Chemical Process Safety
EPA	Environmental Protection Agency
FIS	Fuzzy Inference System
IDLH	Immediately Dangerous to Life and Health
NFPA	National Fire Protection Association
HAZOP	Hazard and Operability
IIAR	International Institute for Ammonia Refrigeration
LOPA	Layer of Protection Analysis
LFL	Lower Flammability Limit
NIOSH	National Institute for Occupational Safety and Health
ODP	Ozone Depletion Potential
OREDA	Offshore Reliability Data
OSHA	Occupational Safety & Health Administration
PFD	Probability of Failure in Demand
PHA	Process Hazard Analysis
PSM	Process Safety Management
P&ID	Piping and Instrumentation Diagram
QRA	Quantitative Risk Analysis
RPM	Risk Management Program
SIF	Safety Instrumented Function
SIL	Safety Integrity Level
SIS	Safety Instrumented System

TLV	Threshold Limit Value
UFP	Upper Flammability Limit

1. INTRODUCTION

1.1. BACKGROUND

Ammonia (NH_3) has been used as a refrigerant since the nineteenth century. Today, food processing and cold storage industries are the main users of ammonia refrigeration systems. New applications using ammonia as refrigerant are under development and their use is expected to increase because of the thermodynamic and environmental characteristics of ammonia.

The advantages of ammonia as refrigerant include: low molecular weight (17.03), low boiling point (-28 °F at 0 psig), and high latent heat of vaporization (1371.2 kJ/kg at boiling point and 1.013 bar). Also, ammonia has environmental advantages because it is not considered a greenhouse gas and it has an Ozone Depletion Potential (ODP) of 0.00 when released to the atmosphere [1]. These characteristics make ammonia an efficient and environmentally friendly refrigerant. In contrast, fluorocarbon based refrigerants are under severe environmental regulations and the costs of installation and operation are higher than those for ammonia refrigeration systems [2].

However, ammonia is toxic, flammable, explosive and corrosive. Table 1.1 presents a summary of the properties of ammonia. Several incidents have occurred in ammonia refrigeration facilities but well designed and maintained facilities have good safety records [3]. OSHA's Process Safety Management program (PSM) and EPA's Risk Management Program (RMP) are mandatory for large facilities using ammonia as refrigerant [2]. Nevertheless, risk assessment is required regardless the size of the ammonia refrigeration system.

This thesis follows the style of Process Safety Progress.

Table 1.1 Summary of properties of ammonia [1]

Boiling Point	-28 F
Weight per gallon of liquid at -28 F	5.69 pounds
Weight per gallon of liquid at 60 F	5.15 pounds
Specific gravity of the liquid (water=1)	0.619
Specific gravity of the gas (air=1)	0.588
Flammable limits in air	16-25%
Ignition temperature	1204 F
Vapor pressure at 0 F	16 psi
Vapor pressure at 68 F	110 psi
Vapor pressure at 100 F	198 psi
One cubic foot of liquid at 60 F expands to	850 cubic foot of gas
Reactivity	Easily absorbed by water
	Corrodes copper, zinc and their alloys.
	Compatible with iron, steel
	Highly reactive with mercury
	Incompatibility with polyisobutylenes, PVC and styrene copolymers
Major exposure hazards	Inhalation, skin contact, eyes contact, ingestion
Occupational exposure limits	OSHA PEL: 35 ppm

Layer of Protection Analysis (LOPA) is a recent developed risk assessment methodology. LOPA quantifies the risk quickly and allows the use of multiple types of logic. When generic and historical data are available, Bayesian logic is used for updating the data [4]. Instead, Fuzzy logic applies for scarce or highly uncertain data to allow the risk calculations. 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 they provide reasonably accurate outcomes useful in systems analysis.

This research will develop the LOPA methodology using fuzzy logic to combine generic data and expert opinion to estimate the risk in ammonia refrigeration systems. The method will provide a tool for risk decision and safety improvement, especially, for existing facilities.

1.2. LITERATURE REVIEW

In order to develop the LOPA risk assessment technique, it is required to review the ammonia refrigeration systems and its hazards. Also, the LOPA technique application and the Fuzzy Logic incorporated in LOPA.

1.2.1. AMMONIA REFRIGERATION SYSTEMS

Ammonia is widely used in mechanical refrigeration systems. These systems are divided into mechanical vapor compression and absorption refrigeration according to the driving force. Heat is the driving force for absorption systems and mechanical energy for mechanical vapor compression. This work focuses on mechanical vapor compression refrigeration systems.

The vapor compression refrigeration cycle is presented in figure 1.1. The cycle is based on the latent heat of the working fluid and the increasing of the fluid boiling points with pressure. A typical process using ammonia as refrigerant is presented in figure 1.2. The refrigeration cycle takes place in four stages [6]. Ammonia at – 40 F and 0.7 bar is compressed to 12.5 bar with increasing in temperature. Next, ammonia condenses and leaves the condenser at 86 F. Liquid ammonia flows through the expansion valve, reducing its pressure to 0.7 bar. Simultaneously, temperature falls to – 40 F because 25% of the liquid evaporates. The liquid-gas mixture flows trough the evaporator absorbing heat from the surroundings. All the liquid ammonia evaporates and returns to the compressor to start the cycle again.

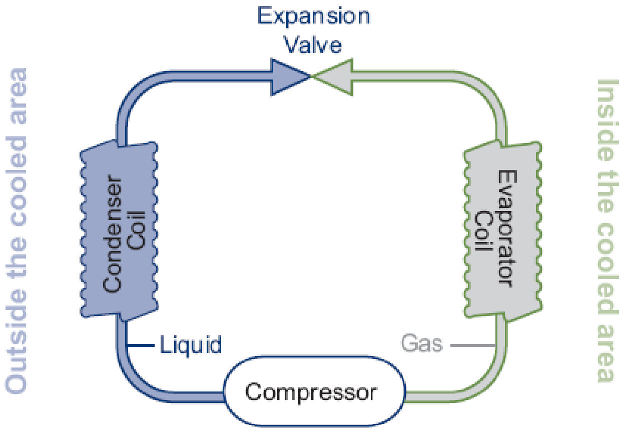


Figure 1.1 Vapor compression refrigeration cycle [5]

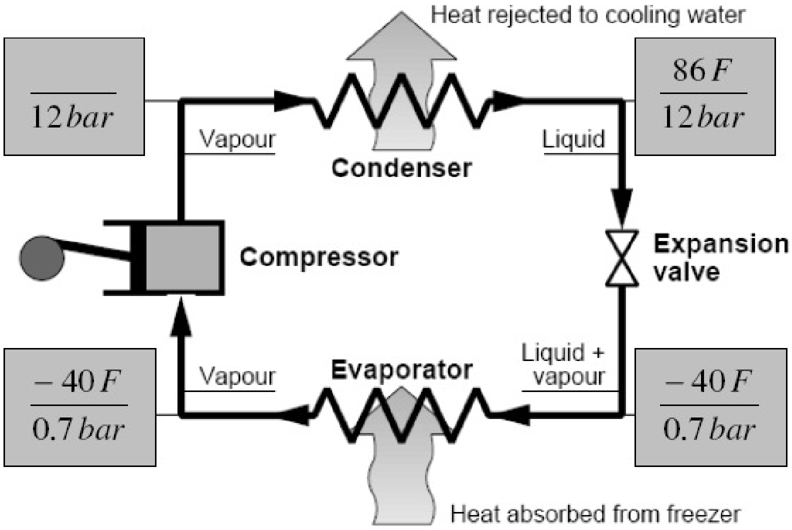


Figure 1.2 Simplified ammonia vapor compression system [6]

Industrial systems are more complicated looking for efficiency and flexibility. Several stages for compression and expansion are common. Also, the cycle is divided in sub-cycles and a central system provides refrigerant to different points of use. Appendix A includes the physical properties of ammonia. Appendix B presents the P&IDs for the typical industrial ammonia refrigeration system used in this research.

1.2.2. HAZARDS IN AMMONIA REFRIGERATION SYSTEMS

Hazards in ammonia refrigeration systems are associated with the chemical and physical characteristics of ammonia and the temperatures and pressures in the system. In general, hazards for ammonia refrigeration systems can be classified in [7]:

- Hazards from the effect of low temperature: brittleness of materials at low temperatures, freezing of enclosed liquid, thermal stresses, changes of volume due to changes in temperature.
- Hazards from excessive pressure caused by: increase in the pressure of condensation or pressure of saturated vapor, expansion of liquid refrigerant in a closed space without the presence of vapor and fire.
- Hazards from direct effect of the liquid phase: excessive charge of the equipment, presence of liquid in the compressors, liquid hammer in piping and loss of lubrication due to emulsification of oil.
- Hazards from escape of refrigerants: fire, explosion, toxicity, freezing of skin, and asphyxiation.
- Hazards from the moving parts of machinery: injuries, hearing loss from excessive noise, damage due to vibration and ignition of material due to broken parts.
- Hazards from operation: excessive temperature at discharge, liquid slugging, erroneous operation, reduction in mechanical strength caused by corrosion, erosion, thermal stress, liquid hammer or vibration.

- Hazards from corrosion. This category requires special consideration because the alternate frosting and defrosting of some parts of the system and the covering of equipment with insulation.

In order to help with the communication of the ammonia hazards, there are several safety classifications for ammonia [1]. The National Fire Protection Association (NFPA) classifies ammonia as rating 3 for health hazards due to the corrosive effects on the skin. Rating 1 for fire hazards because it considers that it is difficult to ignite, and rating 0 for reactivity hazards because does not react violently with other substances.

Other classifications as ASHRAE, consider ammonia as “low flammability” because the heat of combustion is lower than 8174 Btu/lb and the LFL is above 14%. Also considers ammonia as “high toxicity” refrigerant because higher toxicity results from TLV are lower than 400 ppm. API, NIOSH, ACGIH and the National Research Council have their own classifications.

Fire and explosion hazards of ammonia are presented in table 1.2. Ammonia is considered low flammability because in an outdoor situation, its flammability limits are difficult to reach [1]. However, in confined spaces hazardous situations are possible and can cause fires and explosions.

Low peak pressures and slow rate of pressure rise are characteristic of ammonia explosions [1]. Table 1.3 presents the explosion pressures for ammonia compared with pentane. Ammonia explosions are less violent and damaging than hydrocarbon explosions [8].

Table 1.2 Fire and explosion hazards of ammonia [1]

Fire and Explosion Hazards	
Flash Point	N/A
Flammability limits	LFL 15 – 16%
	UFL 25 – 28%

Table 1.3 Explosion pressures of ammonia and methane [1]

Explosion characteristic	Ammonia	Methane
Peak Pressure	~ 60 psig	~ 105 psig
Rate of Pressure Rise	440 psi/second	3000 psi/second

Ammonia fires are extinguished with water fog or spray, except if a pool of liquid ammonia is present [1]. Fire extinguishing procedures include using water to mitigate vapors and vacate the area if concentration exceeds 5%.

Health hazards data of ammonia are inhalation, ingestion, skin contact and eye contact. Ammonia has an irritating odor that alerts of dangerous exposure. Odor threshold concentrations range from 1 ppm to 50 ppm. Nevertheless, acclimation occurs with chronic exposition to low concentrations of ammonia.

Effects of ammonia to health are severe because it is absorbed by the water in the tissues quickly. The IDLH is 500 ppm and a short exposure to 5,000 ppm can cause permanent injury or death [1]. Table 1.4 presents some ammonia concentrations and responses.

Reactivity hazards are present if ammonia is in contact with strong acids, chlorine, bromine, mercury, silver and hypochlorites. Also, if temperature is higher of 600 F ammonia decomposes generating hydrogen.

Table 1.4 Ammonia concentrations and responses [1]

Concentration	Response
400 ppm	Immediate throat irritation
1,700 ppm	Cough
2,400 ppm	Threat to life after 30 minutes
>5,000 ppm	High likelihood of mortality with short exposure

Because all those hazards related to ammonia, several safety regulations were developed for ammonia refrigeration systems. They include the OSHA PSM 29 CFR Part 1910.119 and the EPA RPM 40 CFR Part 68. Common elements for both regulations are hazard review, mechanical integrity, emergency response and operator training. IIAR has guidelines for OSHA and EPA regulations [9] [10] and also guidelines for equipment design and installation [11], operation [12] safety and operation procedures [13], start-up inspection and maintenance [14], water contamination [15], minimum safety criteria [16], room ventilation [17], machinery room design [18], identification of ammonia refrigeration piping [19], and guidelines for avoiding component failure caused by abnormal pressure or shock [20].

1.2.3. LOPA

LOPA is a semi-quantitative risk assessment methodology. It was developed to determine the Safety Integrity Level (SIL) of Safety Instrumented Functions (SIF) [21]. The book “Layer of Protection Analysis, Simplified risk assessment” published by the Center of Chemical Process Safety (CCPS) of the American Institute of Chemical Engineers [22], has made LOPA accessible to the public since 2001.

LOPA is based on the concept of protective layers. In order to prevent the occurrence of an undesired consequence, a protection barrier is implemented. If this barrier works well, no more protection layers are required. However, there is no perfect protection barrier and several are needed to reduce the risk to tolerable levels. LOPA is useful to reduce the risk of a process to a tolerable level through the analysis of independent protection layers (IPLs).

IPLs satisfy the criteria of specificity, independence, dependability and auditability [22]. An IPL has to be independent of other protection layers available against an undesired consequence, and also has to be independent of the initiating cause. The criterion of specificity indicates that an IPL detects, prevents or mitigates the consequences of specific hazardous events. Additionally, an IPL reduces the risk by a known and specific amount and it is designed to allow auditing the protective function [23].

Applying LOPA is possible at any stage in the lifecycle of a project [22]. Typically LOPA is developed after a Process Hazard Analysis (PHA), for example a Hazard and Operability Analysis (HAZOP) [22]. Figure 1.3 shows the main steps of LOPA and the relationship with HAZOP.

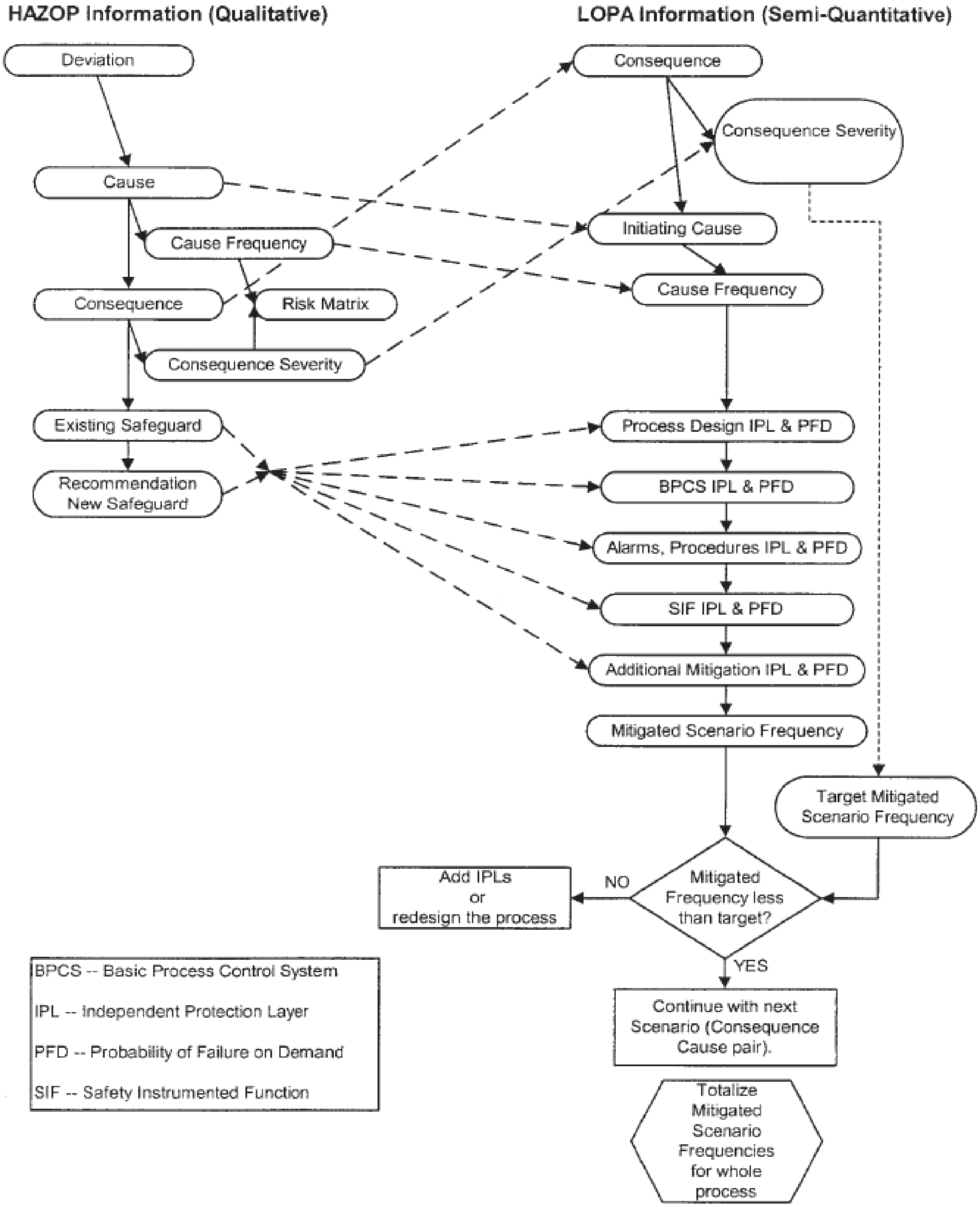


Figure 1.3 LOPA and HAZOP [24]

In addition, LOPA is used for capital improvement planning, management of change, mechanical integrity programs, risk-based maintenance programs, operator training, emergency response planning, design of overpressure protection, evaluating facility sitting risks, accident investigations and evaluation for taking a safety system out of service [22].

Modifications to the original LOPA methodology have the purpose of reducing the uncertainty associated with the initiating event frequency and probability of failure of the IPLs. For example, Bayesian Logic has been applied to LOPA and it can update the generic data with plant specific data [4].

This work applies the Fuzzy LOPA model developed by Markowski and Mannan [25], enhanced with the methodology for developing scenarios for LOPA [26].

1.2.4. FUZZY LOGIC

Fuzzy Sets theory was developed by Lotfi Zadeh in the 60´s [27]. It was developed to deal with imprecise, ambiguous, or missing input information that are typical of many problems [28]. The idea behind fuzzy logic is to mimic how a person makes decisions.

There are several successful applications of fuzzy logic. Fields of application includes process control, civil engineering, reliability engineering, and human reliability [29]. In process safety and risk assessment the fuzzy sets theory has been applied in fault tree analysis [30] [31], toxicity index [32], failure modes and effect analysis [33], safety and operability assessment of process plants [34] [35], hazardous materials transportation [36], inherently safety index [37], ranking of fire hazards of chemical substances and installations [38], safety critical systems [39], risk matrix [40] and LOPA [25].

Uncertainties characterize classical LOPA. In general, a constant conservative value for the failure probability for each IPL is used. This value is provided by an expert and can be imprecise. Other sources of uncertainties in LOPA are the categorization of the severity of the consequences and the change of the severity after the IPL activation. As a result, estimates of risk tend to be very conservative or overestimated [25]. The classical approach uses rough estimates of the probabilities to solve the problem. On the contrary, LOPA is a typical case where fuzzy sets theory can be applied.

The fuzzy sets theory is based on the idea of membership. They allow the definition of vague concepts into mathematical structure [41]. In traditional sets theory an element belongs to a given set or not. In contrast, an element can belong to a set in some degree in fuzzy sets theory. The degree is called membership (μ) and it takes values between 0 and 1. Among the different fuzzy sets, the most important are the sets with membership functions that can be represented as mathematical functions [38]. Typical representations include triangles and trapezoids. Called fuzzy numbers, the fuzzy sets are very useful describing linguistic variables and qualitative data. Figure 1.4 presents the classical and fuzzy sets.

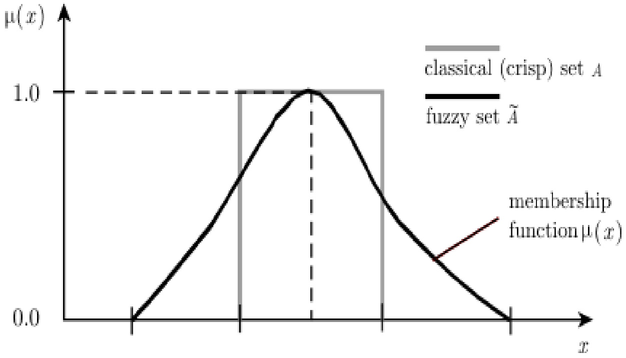


Figure 1.4 Classical and fuzzy sets [28]

Examples of fuzzy sets and membership functions in this work are presented in figure 1.5. Gaussian membership functions, triangular and trapezoidal are the most common.

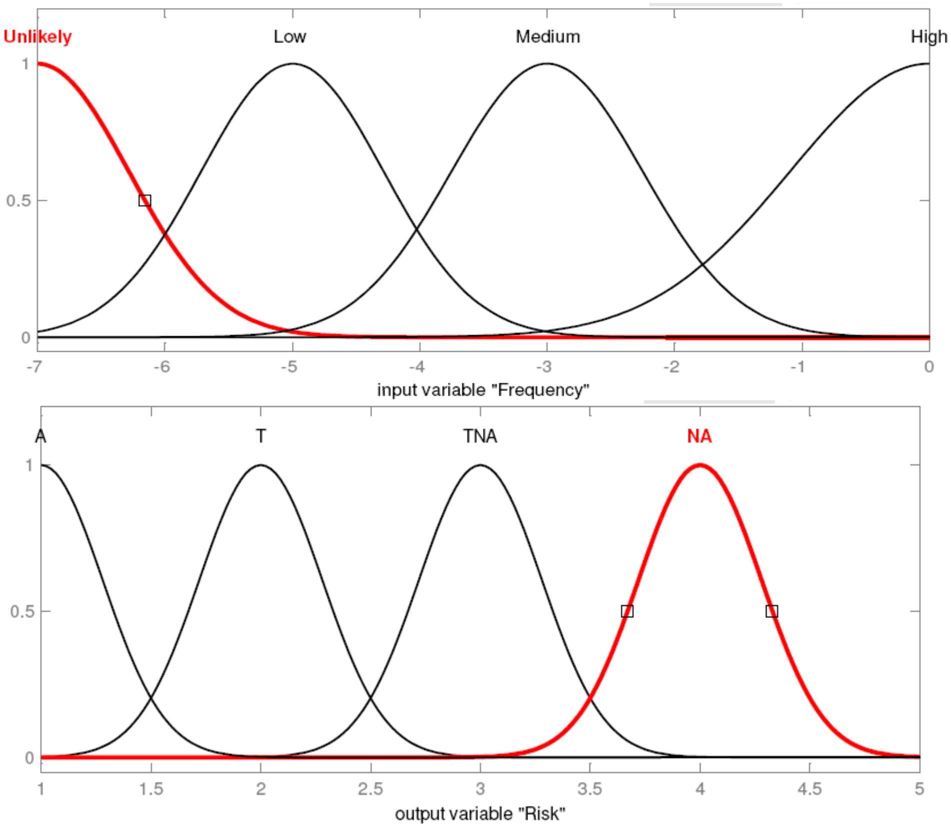


Figure 1.5 Fuzzy sets and membership functions

Fuzzy modeling requires transformation of the input variables in three steps before obtaining output information [42]. Figure 1.6 shows the structure of a fuzzy logic system and the transformation steps.

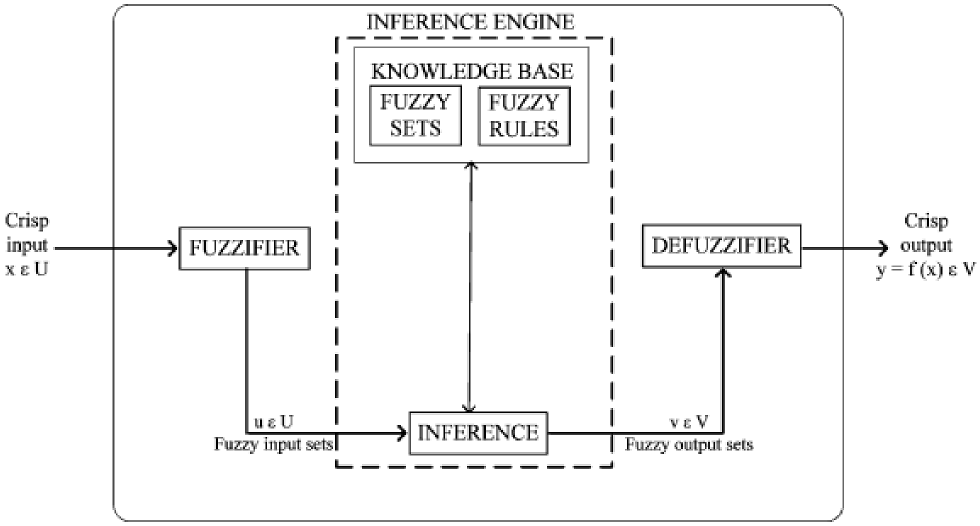


Figure 1.6 Fuzzy logic system structure [40]

Fuzzification transforms the input crisp value in one or more fuzzy sets. These sets represent the perception of the input variable. After that, the Fuzzy Inference System (FIS) processes the fuzzy input sets with a set of *if-then-else* rules. The result is a fuzzy output. Next, the fuzzy output sets from all the rules are weighted and averaged into one final crisp value.

Developing the knowledge base of the system is the objective of fuzzy modeling methodologies. Human experts help to build the system. They determine the fuzzy sets and the membership functions. Also, experts structure the set of rules based on how they interpret the characteristics of the variables of the system [42].

One of the most popular fuzzy models is the Mamdani model [43]. It is also the model used in this work and it is formulated with respect to the fuzzy rules.

$$\forall r \in R:\ if \quad \underset{1\le i\le n}{\wedge}\left(x_i \in A_i^r\right) \quad then \underset{1\le j\le m}{\wedge}\left(y_j \in B_j^r\right)$$

where:

R is the set of linguistic rules
n is the number of input variables
m is the number of output variables
x_i, $1 \leq i \leq n$ are the input variables
A_i^r, $1 \leq j \leq n$ *are* the fuzzy sets defined on the respective universes
y_j, $1 \leq j \leq m$ are the output variables
B_j^r, $1 \leq j \leq m$ *are* the fuzzy sets defined for the output variables

Finally, the deffuzification method used in this work is the centroid method. This is the most important deffuzification method and gives the center of area under the curve that represents the membership function of the fuzzy output [26].

In this research, the fuzzy logic model for LOPA applies three sub systems. The fuzzy event tree (F-ET) calculates the frequency of the scenario. The severity fuzzy inference system (S-FIS) works in parallel with the F-ET system and estimates the severity of the consequences for the incident scenario. Finally, with the outputs of these systems the risk fuzzy inference system (R-FIS) provides a crisp risk index for further analysis and comparison [28].

2. METHODOLOGY DESCRIPTION

2.1. LOPA

LOPA is a semi-quantitative risk assessment methodology. It is based on the concept of protective layers. Figure 2.1 shows the concept of layers of defense against a possible accident. In order to prevent the occurrence of an undesired consequence, a protection barrier is implemented. If the barrier works well, no more protection layers are required. However, there is no perfect protection barrier and several are needed to reduce the risk to tolerable levels. LOPA is useful to reduce the risk of a process to a tolerable level through the analysis of independent protection layers (IPLs).

Figure 2.1 Layers of defense against undesired accidents

Another representation for LOPA in the context of quantitative risk analysis (QRA), is presented in figure 2.2. Each ILP reduces the frequency of the event if it is successful. LOPA corresponds to a path in the event tree. Usually, this path leads to the worst consequence. Whereas the event tree shows all the possible consequences, LOPA works only with a cause and consequence pair. The objective is to choose the scenarios that represent the higher risk to the system.

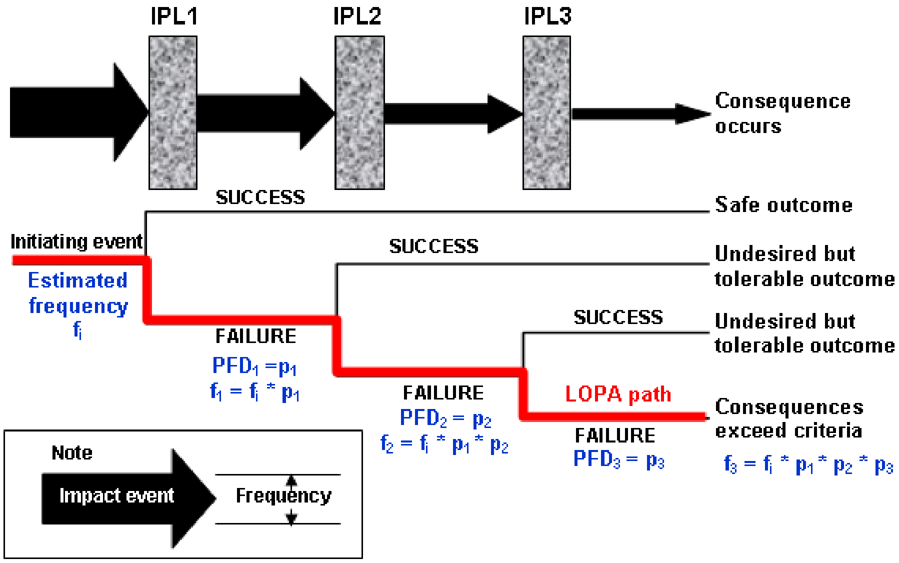


Figure 2.2 Comparison of LOPA and event tree analysis [22]

LOPA methodology is developed in several steps. Figure 2.3 shows a cyclic pattern in application of LOPA. The steps are summarized as follows:

Step 1. Indentify the consequence to screen the scenarios.

Based on the information generated in PHA, scenarios are screened based on the consequence. The limits of the consequence criteria depend on the company or the analyst. Some criteria only include the magnitude of the release while others include the harm to the people, the environment and the property.

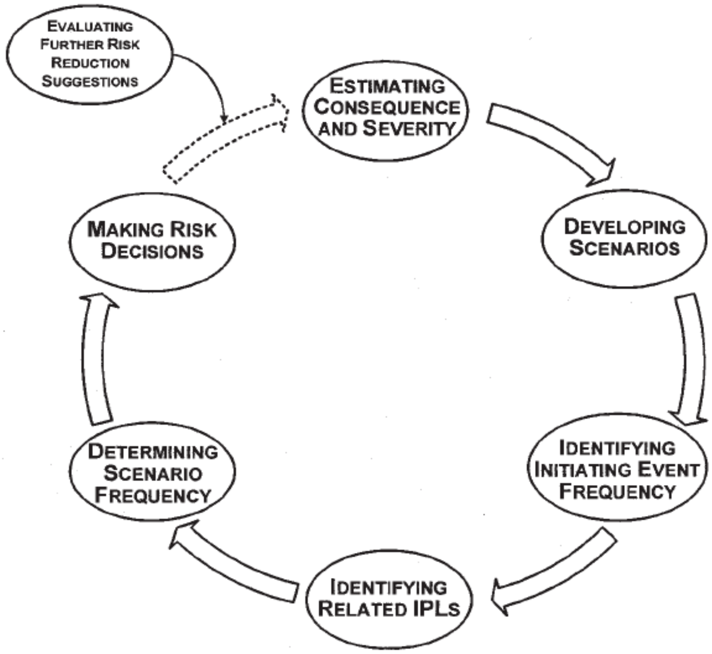


Figure 2.3 LOPA steps [25]

Step 2. Select an accident scenario.

The scenario is a cause-consequence pair. Only one pair goes through the entire process at a time. Scenarios are indentified in another analysis, for example PHA.

Step 3. Identify the initiating event of the scenario and determine the initiating event frequency (events per year).

Initiating events have to lead to the consequence if all the safeguards fail. Ideally, frequency of the initiating events should be available from plant specific data, but they are difficult to find. Other option is to work with generic data such as OREDA [44] and CCPS [25]. In this case, the information is statistically reliable but does not consider the specific characteristics of the case under study. The last approach to obtain initiating event frequency is to combine generic and specific plant data using Bayesian logic.

Step 4. Identify the IPLs and estimate the probability of failure on demand of each IPL.

Safeguards indentified in the qualitative analysis are screened using the criteria of independence to determine if they can be considered independent protection layers. This step includes the estimation of the probability of failure on demand (PFD) for each IPL in the same way as frequency of the initiating event.

Step 5. Estimate the risk for the scenario by mathematically combining the consequence, initiating event, and IPL data.

In the more general case the frequency of the consequence is determine as follows:

$$f_i^c = f_i^I \times \prod_{j=1}^{J} PFD_{ij}$$

$$f_i^c = f_i^I \times PFD_{i1} \times PFD_{i2} \times .... \times PFD_{iJ}$$

where

f_i^c = frequency for consequence C for initiating event i

f_i^I = initiating event frequency for initiating event i

PFD_{ij} = Probability of failure on demand of the jth IPL that protects against consequence C for initiating event i.

Step 6. Evaluate the risk to reach a decision concerning the scenario.

Risk estimation for each scenario is compared with the tolerable risk criteria established by the organization. Generic criteria are also available for comparison. CCPS [22] presents two risk criteria based on inclusion of human harm in the risk. Without human harm the tolerable risk is less than 1×10^{-5} /year and action required criteria is less than 1×10^{-4} /year. When considering human harm the maximum tolerable risk criteria is less than 1×10^{-5} /year and action required criteria is less than 1×10^{-3} /year.

2.2. FUZZY LOGIC

The motivation for developing fuzzy logic and fuzzy models is based on the fact that traditional bivalued logic and probability theory are not enough to solve problems characterized by high uncertainty, complexity and ambiguity [46].

Risk assessment of ammonia refrigeration systems is a real-world problem where a large number of factors and variables interact in non-linear fashions and uncertainty is non-statistical in principle. The objective of this project is the fuzzification of the risk assessment for ammonia refrigeration systems through the application of the Fuzzy LOPA model.

2.2.1. FUZZY SETS

The traditional approach considers a crisp set characterized by a function that takes values of one or zero when an element belongs or does not belong to the set. The function is called the characteristic function and can be generalized by assigning values in the interval [0,1]. In this way, when the characteristic function has the value of one or zero, the case is reduced to the characteristic function for crisp sets.

When the characteristic function takes values between one and zero, it represents partial degrees of membership of the element to the set. The generalized characteristic function is called the membership function and it is defined as:

$$\mu_A : X \rightarrow [0,1] \qquad \text{where} \qquad x \in X$$

X is a classical set of objects called the universe and the generic elements of the universe are denoted as *x*. The fuzzy set *A*, is a subset of *X* and does not have a sharp boundary due to the membership function ranging from 0 to 1. The complete characterization of A can be expressed as:

$$A = \{(x, \mu_A(x)), x \in X\}$$

Typical membership functions are shown in figure 2.4. Types are a) trapezoidal, b) triangular, c) Gaussian and d) bell-shaped.

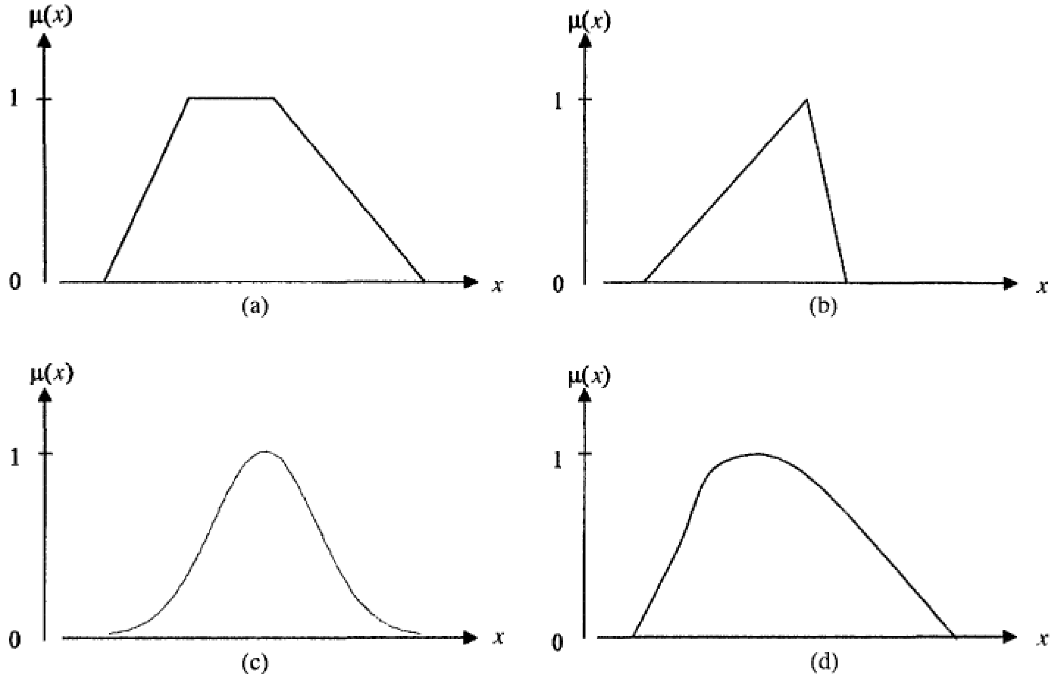


Figure 2.4 Membership functions

This research uses continuous universe of discourse. Accordingly, the range of the universe *X* is partitioned into overlapping subranges. A membership function delimitates the subranges and it is identified with a linguistic label that determines the linguistic value to the set. This concept is represented in figure 2.5 for the concept of the variable frequency and the different linguistic values in the context of process safety.

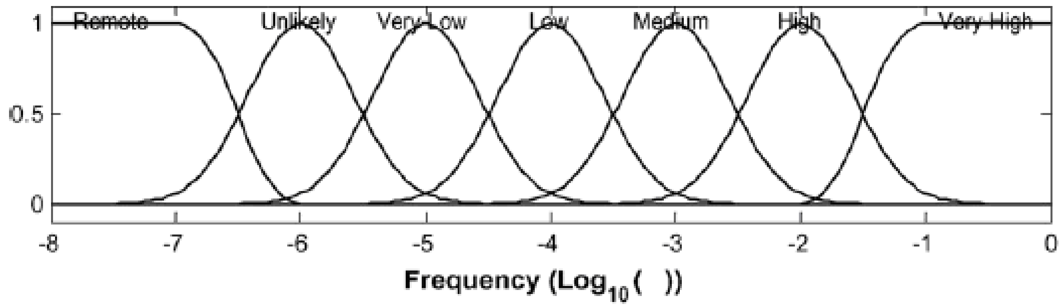


Figure 2.5 Linguistic variable frequency and linguistic values (i.e. unlikely) [25]

The continuous grade of membership allows the description of vague concepts more properly. For example, statements such as “numbers greater than 100” and “about $10” can be represented as fuzzy sets as shown in figure 2.6.

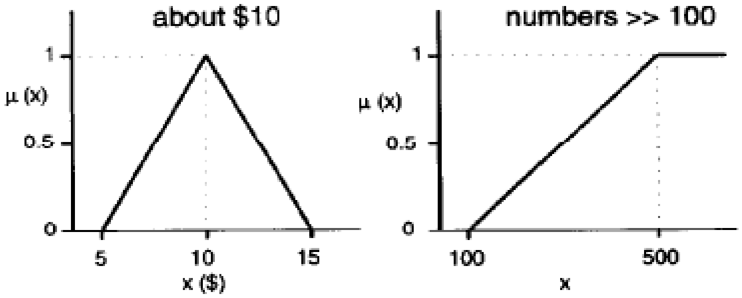


Figure 2.6 Fuzzy sets representing vague linguistic statements [41]

2.2.2. LOGICAL AND MATHEMATICAL OPERATIONS WITH FUZZY SETS

Fuzzy sets allow the use of logical and mathematical operations. When the membership value is one or zero, the results are the same as the operations on ordinary sets. For example given two fuzzy sets *A* and *B*, the intersection and union are defined as follows [27]:

$$\begin{aligned} \forall x \in X, \quad & \mu_{A \cup B}(x) = \max(\mu_A(x), \mu_B(x)), \\ \forall x \in X, \quad & \mu_{A \cap B}(x) = \min(\mu_A(x), \mu_B(x)), \end{aligned}$$

Here, $\mu_{A \cap B}(x)$ and $\mu_{A \cup B}(x)$ represent the membership functions of $A \cap B$ and $A \cup B$ respectively. The fuzzy union and intersection satisfy the Morgan's law and the distributive and associative properties of classical sets. With the evolution of the fuzzy logic theory, several aggregation operators have been developed. Their function is the combination of several fuzzy sets into one single set [27].

In addition, arithmetic operations are possible with fuzzy sets through the extension principle. The extension principle permits the fuzzification of mathematical structures based on set theory [45]. For example, using the extension principle, the arithmetic operation $*$ is extended into $\otimes$ to combine fuzzy numbers according to:

$$\begin{aligned} & A \otimes B = C \\ & C = \{(z, \mu_C(z))\} \\ & z = x * y \\ & \mu_{A \otimes B} = \sup \min[\mu_A(x).\mu_B(y)] \\ & \forall x \in A, \forall y \in B \end{aligned}$$

2.2.3. FUZZY SYSTEMS DESIGN

There are several fuzzy logic methodologies [46]. They are used according to the data available to generate the membership functions of the system. When data are available, fuzzy neural networks can be used to generate membership functions and IF-THEN rules. When information is insufficient, the model is developed based on the physical principles of the systems. Instead of an equation the fuzzy model is composed by IF-THEN rules derived from these principles.

Other type of fuzzy modeling does not use IF-THEN rules. Instead, it works on the theory of fuzzy relational equations, but the linguistic meaning is not explicit and interpretation is more abstract.

The fuzzy modeling method used in this research is based on linguistic modeling. Fuzzy sets and IF-THEN rules represent the selected linguistic variables.

2.2.4. MAMDANI MODEL

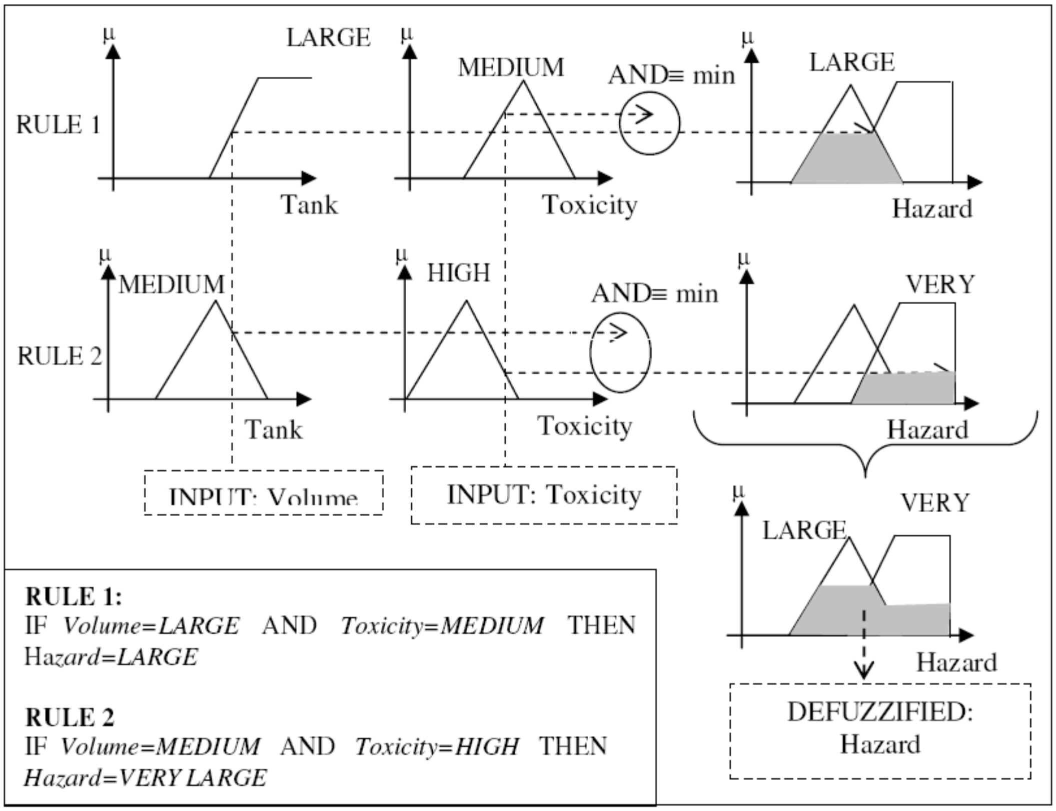
Among the methods based of fuzzy rules, the Mamdani model [43] is the more applicable to this case. Previous work has demonstrated the advantages of using this method in process safety risk assessment [25] [46]. The Mamdani model is easier to understand and the output can be defined as a fuzzy set. The result is a better interpretation of the fuzzy sets and the fuzzy rules.

The Mamdani model uses groups of rules such as:

Rule 1: **IF** x is A_{i1} **AND** y is C_{j1} **THEN** z is E_{k1}
Rule 2: **IF** x is A_{i2} **AND** y is C_{j2} **THEN** z is E_{k2}
…
Rule r: **IF** x is A_{ir} **AND** y is C_{jr} **THEN** z is E_{kr}

where A, C and E are fuzzy sets; *x*, *y* and *z* are the linguistic variables, and r corresponds to the number of rules. Connector AND can be replaced by OR according to the model requirements. They are evaluated as the intersection and union operators.

After the rules have been evaluated, the fuzzy outcomes E_{kr} are aggregated with $E = \bigcup_{r=1}^{n} E_{k\,r}$. Finally the fuzzy value E represents the outcome of the whole inference system. Next, E is deffuzified in order to get a crisp value. Mathematical structure and definition of the aggregation methods has been presented in literature [47]. Figure 2.7, presents the Mamdani method applied to hazard estimation.



RULE 1:
IF *Volume=LARGE* AND *Toxicity=MEDIUM* THEN Hazard=*LARGE*

RULE 2
IF *Volume=MEDIUM* AND *Toxicity=HIGH* THEN *Hazard=VERY LARGE*

Figure 2.7 Mamdani fuzzy inference algorithm [46]

2.2.5. DEFFUZIFICATION METHOD

Deffuzification converts the fuzzy outcome of the fuzzy model into a crisp number. It is defined as a function F^{-1} that maps the fuzzy set A to an element x of the support of the output. Deffuzification is represented as.

$$F^{-1} : F(x) \rightarrow x$$

Several deffuzification methods have been developed. The most important are the centroid, center of area and maxima methods. This research uses the centroid method. It is the most widely used method for the Mamdani method.

The centroid method calculates the center of gravity of the area delimited by the membership function of the output set [25][46]

$$F^{-1} : \frac{\int \mu_A(x) x \, dx}{\int \mu_A(x) \, dx}$$

3. DEVELOPMENT OF THE METHODOLOGY

3.1. OVERALL RESEARCH FLOW

The present methodology combines both the methodology for developing LOPA scenarios and the Fuzzy Logic LOPA. These approaches provide a framework to develop the base for an expert system of ammonia refrigeration risk assessment. Figure 3.1 presents the overall research flow diagram.

Ammonia refrigeration systems are well understood. They are considered as a mature technology and no changes in the main system have been developed in recent years.

3.2. DEVELOPMENT OF INCIDENT SCENARIOS FOR LOPA

Developing the incident scenario is critical for LOPA development. Usually, this activity is developed during the process hazard analysis (PHA). For example, information from HAZOP is used in LOPA as it is shown in figure 3.1.

This research is based on the methodology developed by Markowski and Mannan [25] for LOPA scenarios development. Their methodology is based on the LOPA framework and it can be considered as a basis for and expert system. It consists of the following steps as presented in figure 3.2:

1. Selection of hazardous target process
2. Loss event selection
3. Identification of an appropriate initiating event
4. Severity of consequences estimation
5. Identification of independent protection layers
6. Documentation – event tree

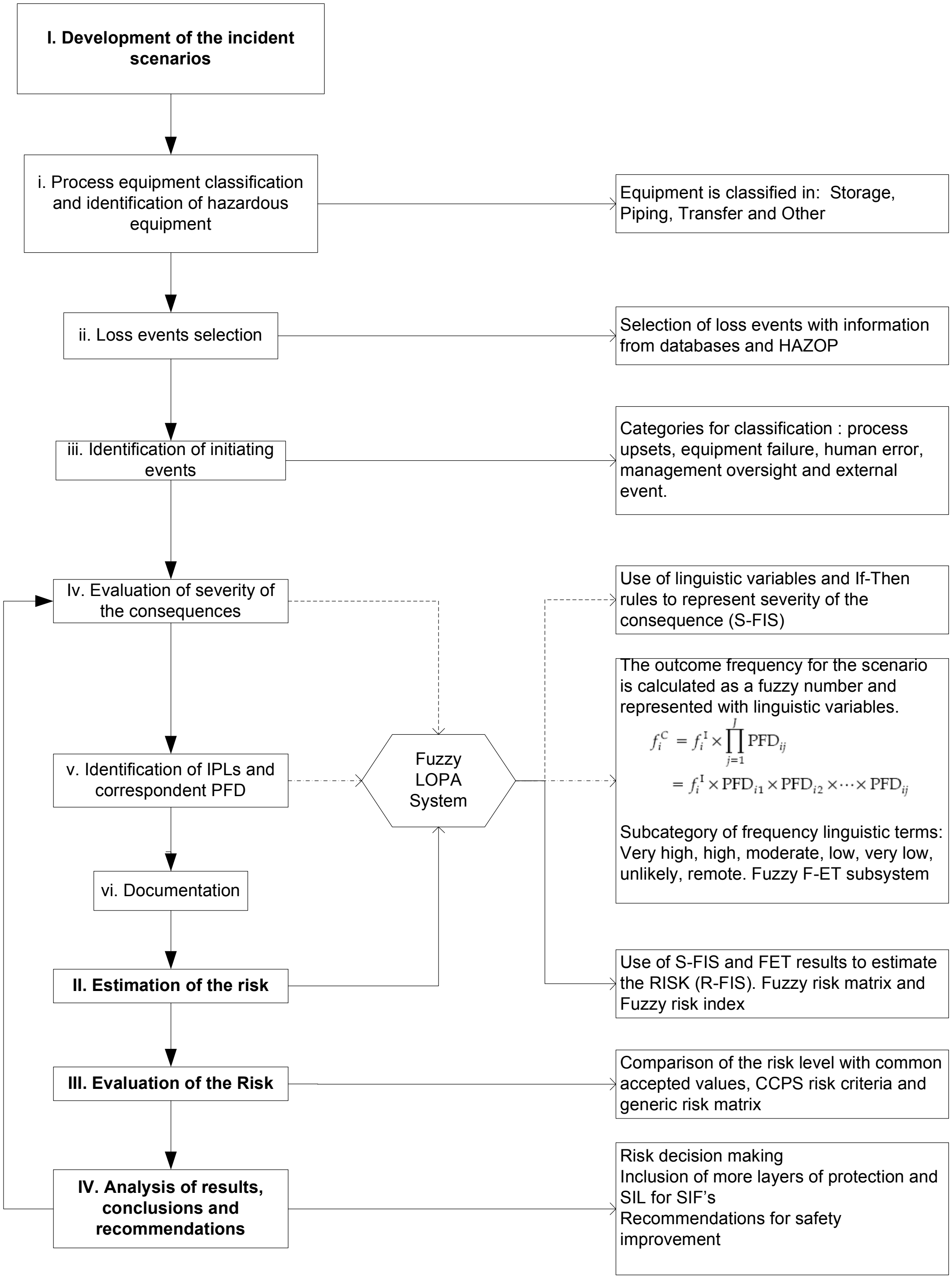


Figure 3.1 Methodology of the research

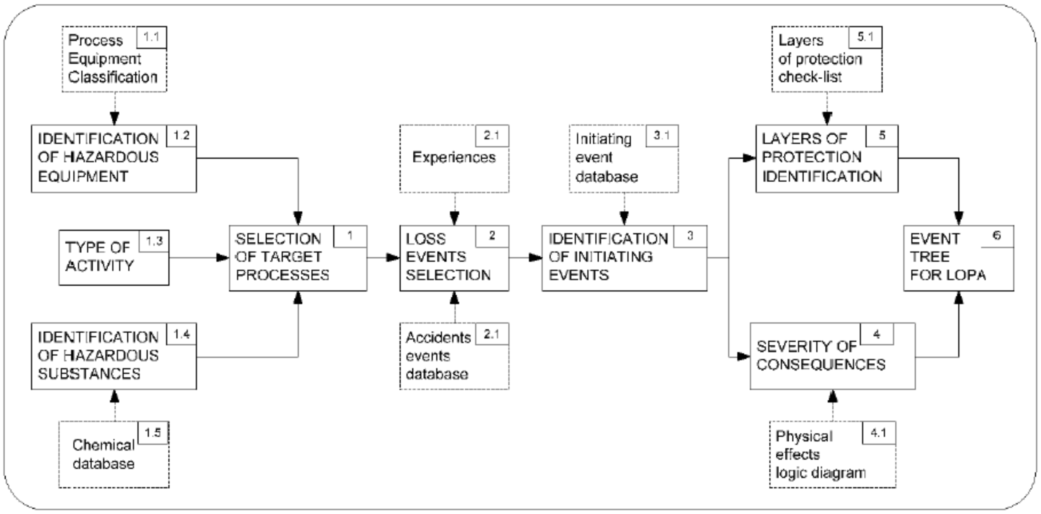


Figure 3.2 Development of the scenarios methodology [25]

The previous structure is adapted in this research to the ammonia refrigeration system to include the Fuzzy Logic structure. The final methodology is described in the following sections.

3.2.1. PROCESS EQUIPMENT CLASSIFICATION AND IDENTIFICATION OF HAZARDOUS EQUIPMENT

Ammonia refrigeration equipment is classified in five groups of equipment with specific codes: storage (EQ1), process (EQ2), piping (EQ3), transfer (EQ4) and other (EQ5). The detailed classification is presented in Appendix C. One specific activity is associated to the equipment. The original methodology has six different types of activity: chemical batch reaction, chemical continuous reaction, electrochemical operation, physical operation, onsite storage and outside storage and distribution. These activities are shown in Appendix D.

In ammonia refrigeration systems only physical operation and onsite storage are present. The codes for this type of activity classification are PhO for physical operation and OnS for onsite storage.

Finally, hazardous substances in the system are classified according to the flammability, explosivity and reactivity characteristics. There are ten categories in the original methodology presented in Appendix E. For ammonia refrigeration systems several categories apply to ammonia. For this reason, only the names of the hazardous substances are used, ammonia and ammonia-lube oil mixtures.

3.2.2. LOSS EVENTS SELECTION

Potential loss events for hazardous processes are classified in thirteen categories. Only nine categories of the original classification are applicable for the ammonia refrigeration systems case: fire, explosion, physical explosion, pipe leak rupture, tank leak rupture, vessel collapse, release substance to water, release substance to ground, and other. Appendix F presents the loss event categories used for this research.

3.2.2.1. HAZOP

This research is based on real HAZOP studies developed in industry. Appendix B presents the P&IDs and HAZOP results for a typical ammonia refrigeration facility. This specific HAZOP study is used to develop the LOPA scenarios. Node 1 was validated through a validation session and the results are included in Appendix B.

3.2.3. IDENTIFICATION OF INITIATING EVENTS

Initiating events are classified into five categories: process upsets, technical failures, human errors, management oversights and external events. Each category has more detailed descriptions of the initiation events. They are presented in Appendix G. Assignment of a particular category is based on expert opinion.

3.2.4. SEVERITY OF THE CONSEQUENCES

Severities of the consequences are classified using the fuzzy logic approach. The section 3.3.3 covers this topic in detail.

3.2.5. IDENTIFICATION OF THE LAYERS OF PROTECTION

The safeguards identified in the HAZOP study are analyzed according to the CCPS methodology [22]. Only those safeguards that satisfy the criteria of specificity, independence, dependability and auditability are considered as IPLs for LOPA.

Codification for IPLs is presented in Appendix H. Main categories are prevention layers, protection layers and mitigation layers. Each sub category has a specific code.

3.2.6. DOCUMENTATION OF THE SCENARIOS

Information for each scenario is organized in LOPA worksheets. Figure 3.3 presents the CCPS LOPA worksheet [22]. With the methodology for developing incident scenarios for LOPA a tag is included in the worksheet. This tag provides information about the entire scenario. For example, a scenario code: <LE1-A5-F-V-PU1-(LSH/PSV/FFS)>, means “Rupture of storage tank with flammable liquid, failure of high level sensor and pressure safety valve, and unsuccessful fire fighting system with catastrophic severity of the consequences”.

3.3. FUZZY LOPA MODEL

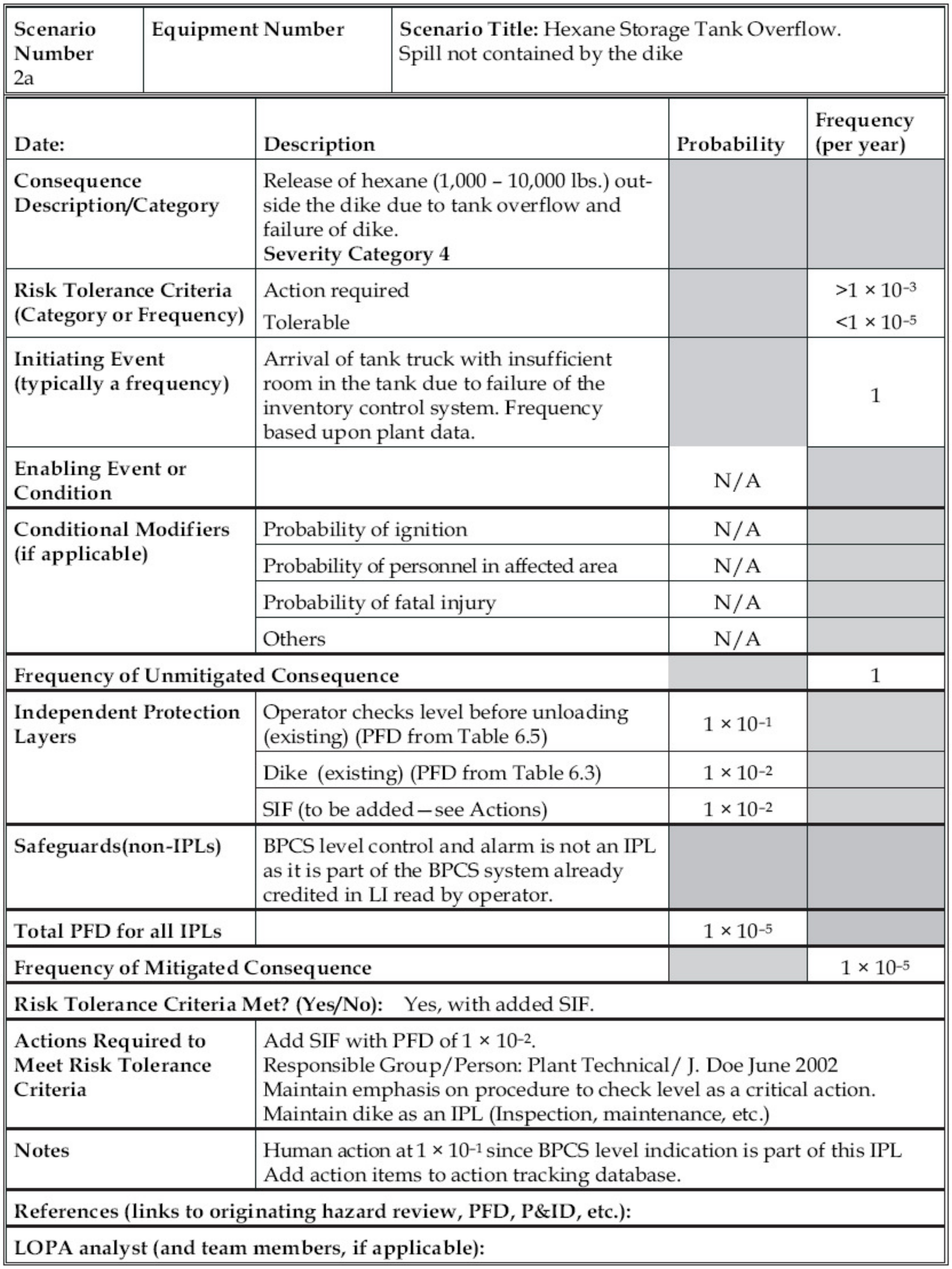
The fuzzy logic application to LOPA developed by Markowski and Mannan [25] is called fLOPA. The application begins with the information of the incident scenario and applies three sub systems as presented in figure 18. The outcome is a crisp value of the risk for the scenario.

Information to develop the fuzzy inference systems for LOPA was obtained from ammonia refrigeration standards, literature and expert opinion. This information was critical to identify the linguistic variables and the relationship between them. The main objective is to determine the IF-THEN rules for the different subsystems.

The second step is to define the fuzzy sets and the membership functions. These fuzzy sets represent the linguistic variables of the LOPA system.

Finally, IF-THEN rules are developed following the Mamdani model [43]. They represent the general knowledge about the ammonia refrigeration system. With the membership functions for the variables and the set of IF-THEN rules the inference system is applicable to different scenarios.

fLOPA applies three subsystems as it is shown in figure 3.4. The Fuzzy Event Tree (F-ET) calculates the frequency of accident scenario. The Severity Fuzzy Inference System (S-FIS) calculates the severity of the consequence for the scenario and works in parallel with the F-ET. These two systems provide the information for the Risk Fuzzy Inference System (R-FIS). This system calculates a crisp risk index to be used for decision making.



Scenario Number 2a	Equipment Number	**Scenario Title:** Hexane Storage Tank Overflow. Spill not contained by the dike

Date:	Description	Probability	Frequency (per year)
Consequence Description/Category	Release of hexane (1,000 – 10,000 lbs.) outside the dike due to tank overflow and failure of dike. **Severity Category 4**		
Risk Tolerance Criteria (Category or Frequency)	Action required Tolerable		$>1 \times 10^{-3}$ $<1 \times 10^{-5}$
Initiating Event (typically a frequency)	Arrival of tank truck with insufficient room in the tank due to failure of the inventory control system. Frequency based upon plant data.		1
Enabling Event or Condition		N/A	
Conditional Modifiers (if applicable)	Probability of ignition	N/A	
	Probability of personnel in affected area	N/A	
	Probability of fatal injury	N/A	
	Others	N/A	
Frequency of Unmitigated Consequence			1
Independent Protection Layers	Operator checks level before unloading (existing) (PFD from Table 6.5)	1×10^{-1}	
	Dike (existing) (PFD from Table 6.3)	1×10^{-2}	
	SIF (to be added—see Actions)	1×10^{-2}	
Safeguards(non-IPLs)	BPCS level control and alarm is not an IPL as it is part of the BPCS system already credited in LI read by operator.		
Total PFD for all IPLs		1×10^{-5}	
Frequency of Mitigated Consequence			1×10^{-5}
Risk Tolerance Criteria Met? (Yes/No): Yes, with added SIF.			
Actions Required to Meet Risk Tolerance Criteria	Add SIF with PFD of 1×10^{-2}. Responsible Group/Person: Plant Technical/ J. Doe June 2002 Maintain emphasis on procedure to check level as a critical action. Maintain dike as an IPL (Inspection, maintenance, etc.)		
Notes	Human action at 1×10^{-1} since BPCS level indication is part of this IPL Add action items to action tracking database.		
References (links to originating hazard review, PFD, P&ID, etc.):			
LOPA analyst (and team members, if applicable):			

Figure 3.3 CCPS LOPA work sheet

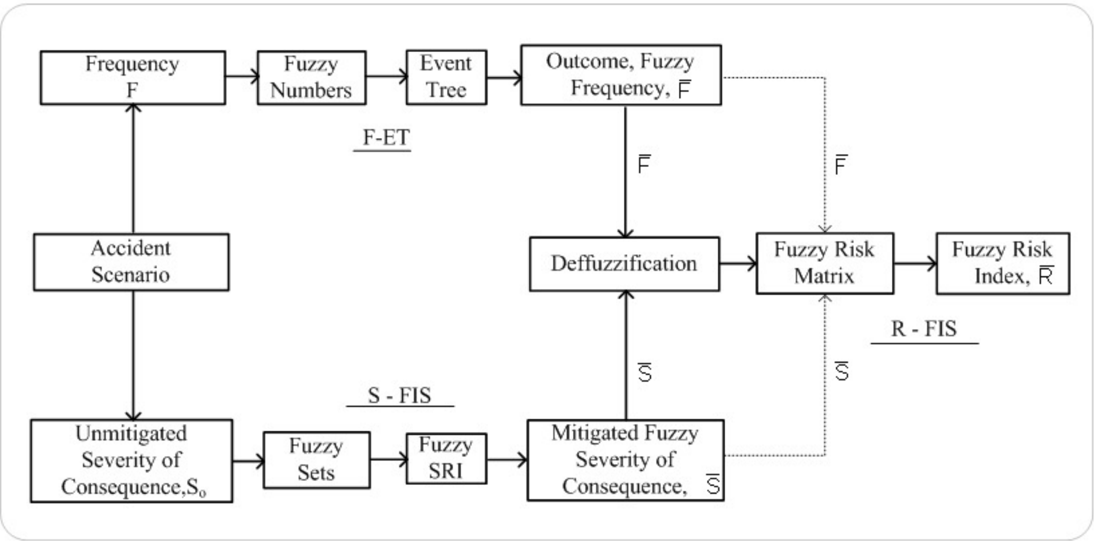


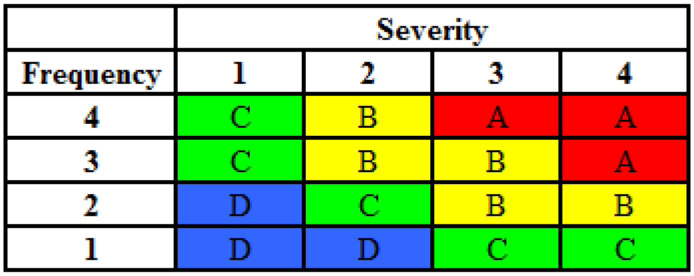
Figure 3.4 Structure of fLOPA [25]

3.3.1. IIAR'S OSHA COMPLIANCE RISK MATRIX

OSHA's PSM requires qualitative evaluation of the possible consequences in ammonia refrigeration systems [9]. Risk matrix is used to this purpose. Ranking the risk is developed following the next steps:

1) Consequences of each scenario identified in the PHA and the engineering and administrative controls (E/A) are compared with the consequences scale. The number that better matches the severity of the consequence is recorded.
2) Considering the severity category founded in step 1, the E/A controls and the information for the scenario, a frequency value is selected among the four possible categories.
3) With the severity of the consequence and the frequency values, the risk of the scenario is obtained from the risk matrix.

The risk matrix is presented in figure 3.5. Risk ranges from high risks identified with the letter A, to low risks "D".



	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

Figure 3.5 OSHA's risk matrix

Ranges of frequency and severity of the consequence are described in tables 3.1 and 3.2 respectively.

Table 3.1 Severity range for OSHA's risk matrix [9]

Severity Range	Qualitative Safety Consequence Criteria
Level 4 Incident	Potential for multiple life-threatening injuries or fatalities
Level 3 Incident	Potential for a single life-threatening injury or fatality
Level 2 Incident	Potential for an injury requiring a physician's care
Level 1 Incident	Restricted to local vicinity, with potential injuries requiring no more than first aid

Table 3.2 Frequency range for OSHA's risk matrix [9]

Frequency Range	Qualitative Frequency Criteria
Level 4	Events expected to occur yearly. Examples include single instrument or valve failures; hose leaks; or human error.
Level 3	Events expected to occur several times during the lifetime of the refrigeration system. Examples include dual instrument or valve failures; hose ruptures; or piping leaks
Level 2	Events expected to occur no more than a few times during the lifetime of the refrigeration system. Examples include: combinations of instrument failures and human errors; or full-bore failures of small process lines or fittings
Level 1	Events not expected to occur during the lifetime of the refrigeration system. Examples include multiple instrument or valve failures or human errors; or spontaneous failures of tanks or process vessels.

In this research, the Fuzzy-LOPA methodology is developed with the information provided by the IIAR's OSHA Risk Matrix. The linguistic variables, fuzzy numbers and IF-THEN rules are designed to represent the knowledge contained in this specific risk matrix. The following sections show how the methodology is implemented.

3.3.2. FREQUENCY EVENT TREE

The original methodology transforms the frequency calculation of an accident scenario into the domain of fuzzy logic. The objective is to avoid the increasing complexity if many rules are formulated to represent this case as an inference system. When k variables are represented by n membership functions, the number of rules is k^n.

This problem is called “rule explosion” [25]. Avoiding this problem is possible through the adaptation of the classical expression:

$$f_i^c = f_i^I \times \prod_{j=1}^{J} PFD_{i\,j}$$

$$f_i^c = f_i^I \times PFD_{i1} \times PFD_{i2} \times .... \times PFD_{iJ}$$

in terms of the operations with fuzzy numbers as:

$$\bar{f}_i^c = \bar{f}_i^I \otimes \prod_{j=1}^{J} \overline{PFD}_{i\,j}$$

where

$$\bar{f}_i^c = \left\{\left(z, \mu_{\bar{f}}(z)\right)\right\}$$

$$z = f_i^I \times \prod_{j=1}^{J} PFD_{i\,j}$$

$$\mu_{\bar{f}}(z) = \sup\min\left[\mu_{f_i^I}(x).\mu_1(y)...\mu_j(j)\right]$$

The previous aggregation method of fuzzy numbers gives a fuzzy outcome; in this case, the frequency of the initiating event. After the defuzzification process, a crisp frequency value is available for the risk inference system.

A disadvantage of the previous procedure is that after defuzzification of the fuzzy frequency, the crisp frequency value requires fuzzification again in order to apply the risk inference system. The result is a more complex solution of the problem of risk assessment for ammonia refrigeration systems using the LOPA methodology.

This research avoids the previous problem working directly with the frequency values of the traditional approach as an input variable for the risk fuzzy inference system and defining the membership function accordingly. Therefore, is easier for the analyst to apply the fuzzy methodology.

Also, the original linguistic categories are adapted to the IIAR's OSHAS risk compliance matrix. Table 3.3 presents the original categorization.

Table 3.3 Categorization of the outcome frequency [25]

Subcategory of Frequency-Linguistic term	Meaning	Range of Frequency [1/year]
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 (VL)	No likely to occur	$10^{-5} \leq f \leq 10^{-4}$
Unlikely (U)	High unlikely	$10^{-6} \leq f \leq 10^{-5}$
Remote (R)	Practically impossible	$f \leq 10^{-6}$

3.3.3. SEVERITY FUZZY INFERENCE SYSTEM (S-FIS)

The severity of the consequences for a specific release scenario can be determined by a quantitative risk analysis. However, there are uncertainties related with the modeling of the release and the prediction of the severities for specific cases. To overcome this problem, a fuzzy inference system can be applied.

Basically, the development of the severity inference system involves the design of the membership functions for the input and output variables, and the design of the IF-THEN rules. The final outcome is a crisp value for severity of the consequence for the specific scenario.

In this research, the original methodology has been modified because ammonia is the only substance of interest. In addition, the knowledge about ammonia refrigeration systems from expert opinion and regulations is included.

According to the IIAR's OSHA risk compliance matrix, the severity of the consequence is result of the combination of magnitude of the loss, expressed in terms of life threatening injuries or fatalities, injuries and the extension of the medical care required. These three variables constitute the inputs to the inference system.

Life threatening injuries or fatalities variable (LT-F) has two categories or linguistic values applicable to this case, LT-F equal to one, and LTF>1. IIAR considers that more that one life threatening injury or fatality leads to a catastrophic risk scenario, whereas one threatening injury or fatality represents a high risk scenario. Figure 3.6 shows the membership function for this input variable.

The universe of discourse is x = [0, 10]; number 10 is used for cases with more that 10 fatalities or life threatening injuries.

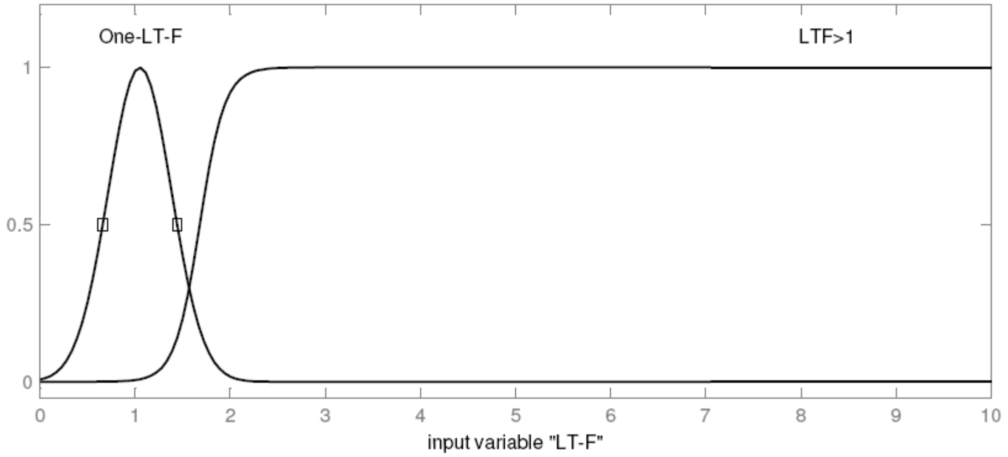


Figure 3.6 Membership function for life threatening injuries or fatalities variable

The number of injuries and extension of the medical treatment are the others input variables of the severity inference system. These work together to determine the severity of the accident or release based on injuries that do not lead to fatalities. The membership functions are shown in figure 3.7 and 3.8. The universe of discourse for the injuries variable corresponds to the number of cases from 0 to 10 cases, and the linguistic values are low, moderate and high number of injuries.

Extension of medical treatment is categorized in a scale from 1 to 3. The value has to be an entire number which is determined by the expert opinion about the medical attention for the people injured after the release. The fuzzy numbers and linguistic variables associated are first aid, physician care and advanced medical care.

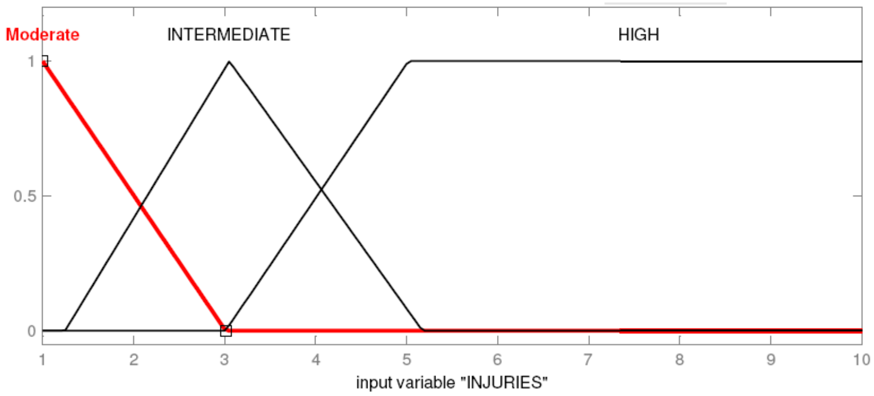


Figure 3.7 Membership functions of the variable injuries

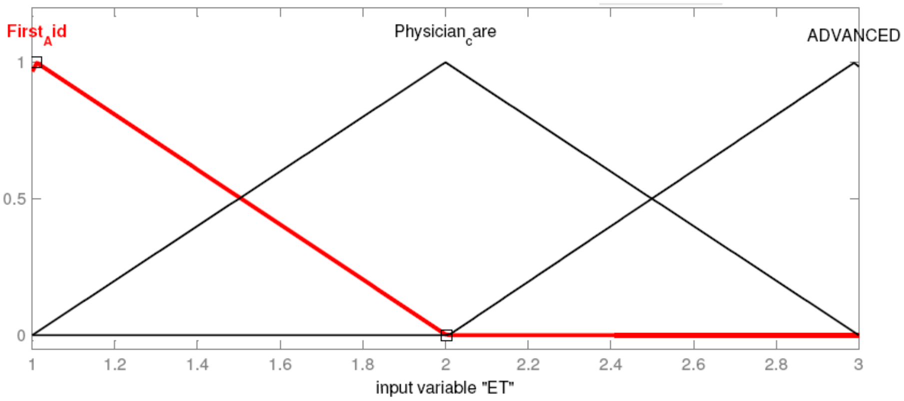


Figure 3.8 Membership functions of the variable extension of treatment

The LT-F and Injuries variables, represent the expert opinion about the presence of personal in the different sections of the ammonia refrigeration system. Also, they contain information about the size of the ammonia release, duration of the incident and number of safeguards available.

Figure 3.9 and 3.10 show the membership function for the output severity of the incident and the fuzzy graph obtained after defuzzification of all possible combination of outputs. The form of fuzzy set is based in previous works [25]. The linguistic terms used are Low, Moderate, High and Catastrophic.

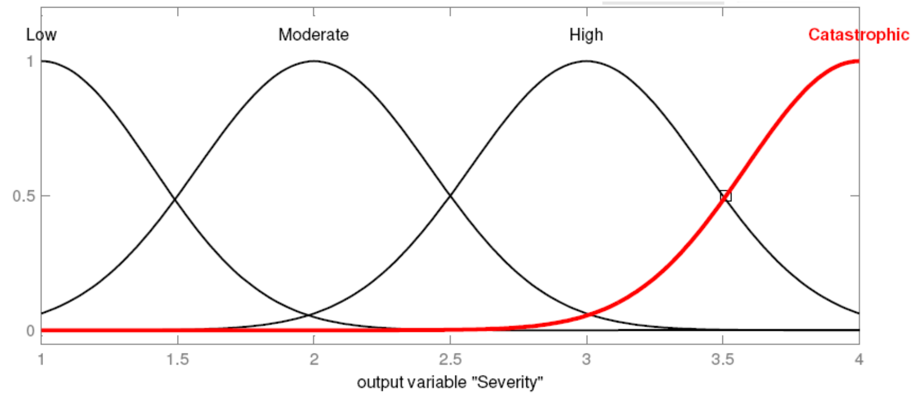


Figure 3.9 Membership function of the output variable severity

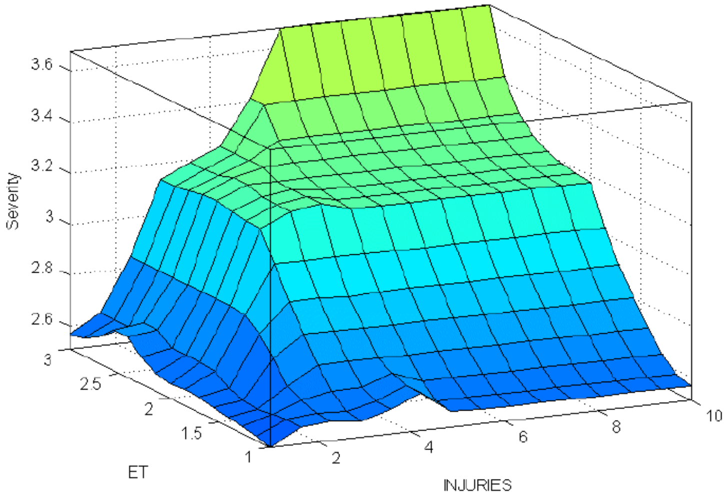


Figure 3.10 Fuzzy severity surface

Rules to estimate the severity of the accident are presented in table 3.4 as a matrix.

Table 3.4 IF-Then rules for severity. IF *Number of Injuries* is (__) AND *Extension of Medical Treatment* is (___) THEN *Severity* is (___)

Severity Rules	**Extension of Medical Treatment**		
Number of Injuries	*First Aid*	*Physician Care*	*Advanced*
High	Moderate	High	Catastrophic
Intermediate	Moderate	High	High
Moderate	Low	Moderate	Moderate

3.3.4. RISK FUZZY INFERENCE SYSTEM

Among the different risk assessment methods, the most frequently used is the risk matrix. It allows ranking the risk of the process for further action through risk management activities. For ammonia refrigeration systems, the IIAR's OSHA Risk Matrix is applied [9]. This research develops a fuzzy logic version of the IIAR's OSHA Risk Matrix.

Developing the fuzzy risk matrix for ammonia refrigeration systems requires the implementation of the Risk Fuzzy Inference System (R-FIS). Input variables to the system are the frequency of the scenario and the output of the Severity Fuzzy Inference System (S-FIS). The outcome of the inference system is the fuzzy risk index and a final crisp risk value.

Severity of the scenario is represented in the same was as it is used in the S-FIS system. For the case of the frequency of the initiating event, the membership functions are presented in figure 3.11. The linguistic terms associated with the variable are: Very Low, Low, Medium and High. Definition of the membership functions type for the frequency and risk variables is based on the works of Markowski and Mannan [25].

Gaussian type is used for the input and outcome variables and the ranges were obtained from the look-up tables provided by CCPS [22].

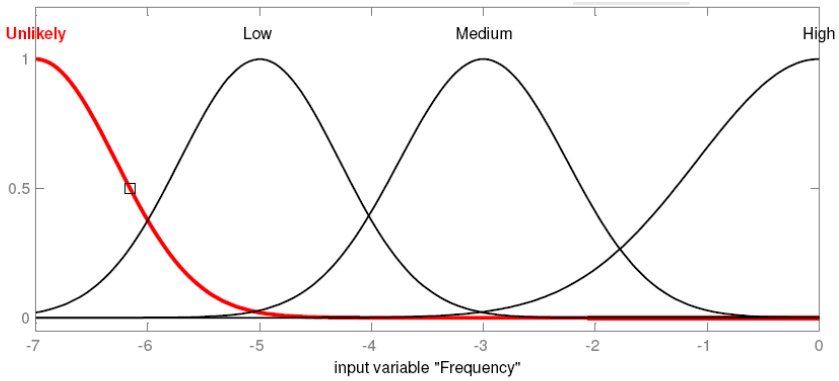


Figure 3.11 Membership functions for frequency of the initiating event

The membership functions for the risk outcome are presented in figure 3.12. The linguistic terms for risk are: Acceptable, Tolerable, Tolerable not Acceptable and Non Acceptable, and their definition are presented in table 3.5. Finally, the set of rules for the risk fuzzy inference system and the surface risk after evaluation of all the rules are presented in table 3.6 and figure 3.13 respectively.

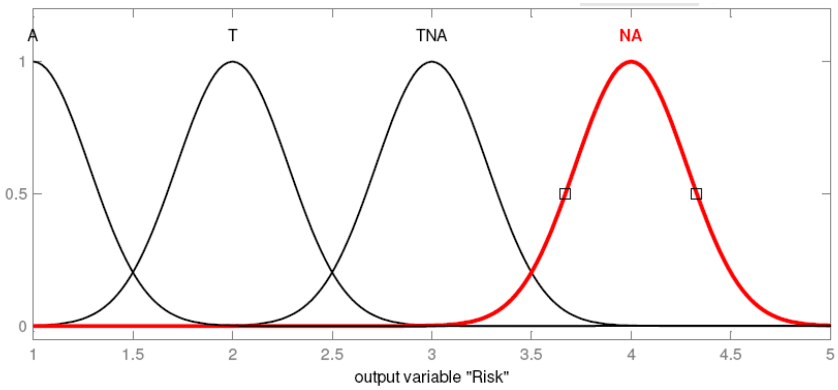


Figure 3.12 Membership functions for risk

Table 3.5 Fuzzy sets and linguistic terms for fuzzy risk matrix

Linguistic variables	Linguistic Term	Definition	Description Range	Universe of Discourse
Frequency (F)	High	Events expected to occur yearly.	$10^{-2} \leq F < 1$	$X_F \in (1, 10^{-7})$
	Medium	Events expected to occur several times during the lifetime of the refrigeration system.	$10^{-4} \leq F < 10^{-1}$	
	Low	Events expected to occur no more than a few times during the lifetime of the refrigeration system.	$10^{-6} \leq F < 10^{-3}$	
	Unlikely	Events not expected to occur during the lifetime of the refrigeration system.	$10^{-7} \leq F < 10^{-5}$	
Severity of consequences	Catastrophic	Potential for multiple life-threatening injuries or fatalities	$3 < C \leq 4$	$X_C \in (1, 4)$
	High	Potential for a single life-threatening injury or fatality	$2 < C \leq 4$	
	Moderate	Potential for an injury requiring a physician's care	$1 < C \leq 3$	
	Low	Restricted to local vicinity, with potential injuries requiring no more than first aid	$1 < C \leq 2$	
Risk	Acceptable (A)	No action required	$0 \leq R \leq 2$	$X_R \in (1,5)$
	Tolerable (T)	Action based on ALARP principles	$1 \leq R \leq 3$	
	Tolerable-unacceptable (TNA)	Indication for improvements in the medium term	$2 \leq R \leq 4$	
	Unacceptable (NA)	Must be reduced immediately	$3 \leq R \leq 5$	

Table 3.6 Risk rules. IF *Frequency* is (__) AND *Severity* is (___) THEN *Severity* is (___)

Risk Rules		**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)

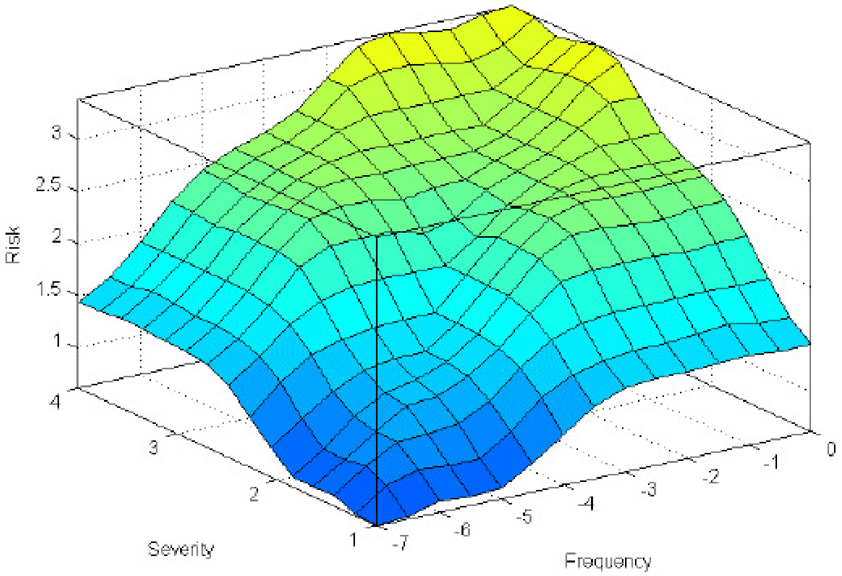


Figure 3.13 Fuzzy risk surface

4. RESULTS OF THE METHODOLOGY AND VALIDATION

4.1. HAZOP VALIDATION AND SCENARIO MAKING

The HAZOP studies for ammonia refrigeration system were obtained from a consulting firm in the Houston area. From these studies, one was selected and represents a typical facility. The case was selected as the model for this research. Appendix B presents the P&IDs and HAZOP results.

Thirty one nodes are part of the study. Node one is the ammonia receiver. It is one of the most critical units in the systems because it contains a large amount of ammonia under high pressure. Charging of ammonia for starting up and making up are also considered in the analysis of this node. These operations increase the risk of ammonia release in the facility. For the reasons above, node one is selected for the validation session of the existing HAZOP.

The validation session was done by a team which consisted of two post doctors, and four graduate students from the Artie Mcferrin department of chemical engineering at Texas A&M University and the Mary Kay O'Connor Process Safety Center on July 3, 2008. The results are shown in Appendix B as complement of the original HAZOP study.

Even though the HAZOP validation session was focused only in one node, the group agreed in the deep, format, presentation and completeness of the HAZOP study and the P&IDs. In this way, information from other nodes was made available for developing of the LOPA scenarios.

Four scenarios were selected for this research based on the most common incidents reported by EPA [3]. Scenarios are presented in table 4.1. Appendix I, presents the results of the scenario classification and codification.

Table 4.1 LOPA incident scenarios

Scenario No.	Node No.	Causes	Consequences	Scenarios
1	1	Hose failure	Release of ammonia to atmosphere resulting in respiratory injury and/or chemical burn to personnel in close proximity and potential environmental issue.	Failure of charging hose during charging of receiver tank
2	1	Truck pump set too high-Operator Error	Rapid charging of ammonia to Receiver vessel resulting in high pressure in RC-301 with release of ammonia	Rapid charging of ammonia to Receiver vessel resulting in high pressure in RC-301
3	2	Inadvertent loss of oil seal on Recirculating Pump.	Release of ammonia in machine room (loss of containment)	Loss of oil seal in recirculation pump with potential release in machinery room
4	3	PV-40041 sticks open	Subsequent hot suction discharge gas blow through to IC-302 and pressure increase in IC-302 with potential for hydraulic shock in line HPL-5013 and failure valve (potential for loss of containment)	Loss of level in PD-301 (Transfer Station)

4.2. TABLES FOR FREQUENCY RATES AND PROBABILITY

The following tables show the initiating event frequency data and the probability of failure on demand (PFD) used in this research. This section is a summary of the information required to calculate the reduced event frequency according to the LOPA methodology. Sources of the information are included in the tables. CCPS [22] [48], OREDA [44] and direct manufacturer information [49] were used in this research.

Table 4.2 Frequency of the initiating events

Class	Frequency Data			
Event	Min/Lower	Typical/Mean	Max/Upper	Reference
Hose failure	8.7×10^{-5}	5×10^{-3}	1.9×10^{-2}	[48], CCPS, p 187
Human Error, Operator failure/opportunity	10^{-3}	10^{-2}	10^{-1}	[22], CCPS, p.71
Pump seal failure	10^{-2}	10^{-1}	10^{-1}	[22], CCPS, p.71
Pressure valve fails open	2.4×10^{-3}	3.14×10^{-2}	1.08×10^{-1}	[48], CCPS, p.201

Assuming that there is periodical testing of equipment and the unplanned demands occur at a random time within the testing cycle, the PFD can be approximately estimated by:

$$PFD = \frac{\lambda T_{test}}{2}$$

where T_{test} is the proof test interval. In this research a test interval of 1 year is assumed. In this way frequency data is converted to PFD.

Table 4.3 Failure probabilities of IPLs

Class	Probability Data			
IPL	Min/Lower	Typical/Mean	Max/Upper	Reference
Operator follows procedure to shutdown operation.	1 x 10^{-1}	1x 10^{-1}	1	[22], CCPS,
PSV	0.0079 x10^{-3}	0.212 x 10^{-3}	0.798 x 10^{-3}	[48], CCPS,
Low Level Shutdown		7.5 x 10^{-4}		[48], CCPS,
BPCS	1 x 10^{-2}	1x 10^{-1}	1x 10^{-1}	[22], CCPS,
Level detector and alarm		2.6 x 10^{-1}		[48], CCPS,
Pressure alarm	8.7 x 10^{-5}	2.1 x 10^{-2}	8.1 x 10^{-2}	[44], OREDA
Ventilation system failure. Motor driven fans. Fail while running	1.5 x 10^{-2}	4 x10^{-2}	1 x 10^{-1}	[48], CCPS,
Ventilation system failure. Motor driven fans. Fail to start on Demand	9.44 x 10^{-3}	2.08 x10^{-2}	7.69 x10^{-1}	[48], CCPS,
Ammonia Detector		1 x10^{-2}		[49], General Monitors

4.3. RESULTS OF RISKS

4.3.1. HIGH PRESSURE RECEIVER (NODE1)

In the high pressure receiver area, two scenarios were developed.

4.3.1.1. SCENARIO 1 – FAILURE OF CHARGING HOSE

Ammonia can be released during charging operation if rupture of the charging hose occurs. Personnel working in the surroundings can be affected seriously due to inhalation and chemical burn. Also, depending on the localization of the receiver tank, the risk for an explosion exits. Environment can be affected but the impact is less severe when compared with the consequences for people in the area. Due to ammonia vaporization, the temperature decreases, freezing of enclosed liquid in piping and thermal stresses can occur, leading to other accident scenarios.

The rupture frequency of the charging hose and the PFD for the IPL are presented in table 4.1. Next, the initiating event frequency for the scenario is obtained.

Severity is determined using the severity fuzzy inference system (S-FIS). This accident affects mainly workers in the area because it is a liquid release of ammonia. The number of possible fatalities or life threatening injuries is assumed to be one, and the number of injures is three, the operator of the tank truck, the supervisor of the operation and another company worker. The level of medical attention is physician care. The estimated severity index is 3 and the fuzzy risk index is 3. It corresponds to the linguistic variable TNA for risk. This scenario is tolerable but more action is required in the medium term.

In order to reduce the risk, it is possible to reduce the severity and the frequency of the initiating event. If the occupancy of the working area is reduced to two people and the ventilation system of the machinery room is operating during the charging of ammonia, the evaluation of the fuzzy severity index gives 1.9.

Finally the risk index gives 2.08 and the risk becomes tolerable. Figure 4.1 shows the contribution of all the risk rules and the risk index for scenario 1, and table 4.4 presents the LOPA worksheet for this case.

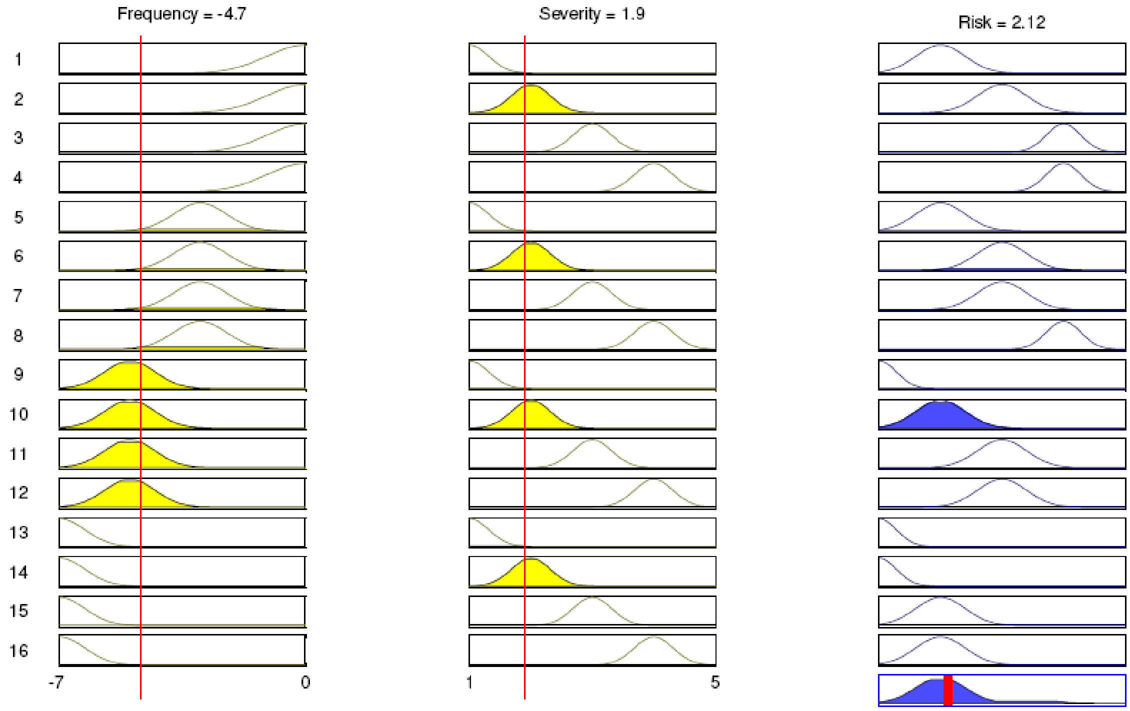


Figure 4.1 Final rules inference for scenario 1

Table 4.4 LOPA worksheet scenario 1

Scenario No. **1** EQ19-PhO-S1-LE8-HR7-OP	**Scenario Title:** Human error-Uncoupling of charging hose during charging of receiver tank **Scenario Identification:**	**Node No.** **1**

Date	**Description**	**Probability**	**Frequency (per year)**
Consequence Description/Category	Release of ammonia to atmosphere resulting in respiratory injury and/or chemical burn to personnel in close proximity and potential environmental issue.		
Risk Tolerance Criteria (Frequency)			
Initiating event (frequency)	Hose failure		5 x 10^{-3}
Enabling event or condition		N/A	
Frequency of Unmitigated Consequence			5 x 10^{-3}
Independent Protection Layers	Operator follows procedure to shutdown operation.		1 x 10^{-1}
Total PFD for all IPLs			1 x 10^{-1}
Frequency of Mitigated Consequence (/year)	Frequency (F) (Log F)		5 x 10^{-4} (-3.3)
Severity	Life threatening: 1 Injuries: 3 Medical treatment: Physician Care	Fuzzy Severity Index: 3	
Risk Tolerance Criteria Met? (Yes/No)	TNA (3) – More action required	Yes, but additional improvements are required	
Actions required to meet Risk Tolerance Criteria	Reducing the occupation of the zone to 2 people wearing protective clothes. Also, because the hose goes trough the machine room, during charging operation the fans of the ventilation system should be turned on. PFD= 4 x 10^{-2}		
Risk calculation after actions required	F = 2 x 10^{-5} ; Log F = - 4.7; Fuzzy Severity index: 1.9; Fuzzy Risk Index: T (2.1)		
Notes	Safeguards: Pre-startup check, Personnel monitoring, BPCS-level control and alarm. Human action with PFD as IPL because the BPCS level indicator is part of this IPL. Human action with 10 min response time.		

If only severity is modified, the outcome of the S-FIS is 2.8 and the risk is still TNA. By the other hand, if only the use of the ventilation system acting as an IPL is considered, the result is a risk index of 2.9, obtaining the same level of risk of the initial case.

With the original IIAR's OSHA risk compliance matrix, the scenario 1 is high severity due to the possibility of one fatality. The frequency is considered medium and the final outcome for risk is TNA (3). This is the same result as the fuzzy LOPA method presented above.

In order to reduce the risk, the key is to find the optimum combination of additional IPLs and reduction of severity. Frequency ranges for low and very low event frequency are $10^{-6} \leq F< 10^{-3}$ and $10^{-7} \leq F< 10^{-5}$ respectively. In this way, the options for PDF of new IPLs added to the system with the purpose of reducing the initiating event frequency from 5×10^{-4} to the low and very low level are multiple. This situation let the analyst the problem of determine the proper IPLs to satisfy the risk criteria. The fuzzy LOPA method helps to evaluate the options consistently.

4.3.1.2. SCENARIO 2 – RAPID CHARGING OF AMMONIA RESULTING IN HIGH PRESSURE

This scenario analyzes the rapid charging of ammonia into the high pressure receiver due to human error setting up the tank truck pump. The consequence is the overpressure of the receiver and release of ammonia in the plant, affecting the personnel, community and environment.

The frequency of the initiating event is taken from CCPS [22]. The typical value for human error is considered for the calculations. According to table 4.1 the frequency of human error following procedures is 1×10^{-2}/opportunity.

The independent protection layers to consider are: process safety valves and inherently safer design. Process safety valves (PSV) are installed on the top of receiver

RC-301. They are installed in the 1oo2 voting multiple system. It is assumed that one PSV has the relief capacity for any possible overpressure. Because the PSV are the same type, common cause factor (β) is considered. The calculation of the PFD is performed according to:

$$\begin{aligned} PFD &= (PFD_{1oo1})^2 + \left(\frac{\beta\lambda T_{test}}{2}\right) \\ &= (PFD_{1oo1})^2 + \beta(PFD_{1oo1}) \end{aligned}$$

The (β) factor for valves with a common pipe connection to a storage tank is considered as 30%, because the shared pipeline contributes to the common cause failure.

Inherently safer design is an optional IPL that could be considered according to the criteria of the LOPA analyst. In this scenario the maximum allowable working pressure (MAWP) is 250 psig and the tank has been hydrotested up to 350 psig. Use of MAWP as an IPL requires proper inspection and maintenance. In this research it is considered that the tank is under mechanical integrity program but inherently safer design is only a safeguard. Table 4.5 presents the LOPA worksheet and the PFD for the protection layers

Frequency of the mitigated consequence is 6.4 x 10^{-7}/year. According to the membership function for frequency, the event can be considered “unlikely” but also it could be part of the “low” frequency set. Fuzzy logic helps to consider both contributions. Through the evaluation of the IF-THEN rules, each contribution of frequency is weighted and included in the final outcome of risk. Figure 4.2 shows the contribution of all the risk rules and the risk index for scenario 2.

Table 4.5 LOPA worksheet scenario 2

Scenario No. **2** EQ11-PhO-S1-LE5-HR3-RV	**Scenario Title:** Rapid charging of ammonia to Receiver vessel resulting in high pressure in RC-301		**Node No.** **1**
Date	**Description**	**Probability**	**Frequency (per year)**
Consequence Description/Category	Rapid charging of ammonia to Receiver vessel resulting in high pressure in RC-301 with release of ammonia		
Risk Tolerance Criteria (Frequency)			
Initiating event (frequency)	Truck pump set too high-Operator Error Human Error.		1 x 10^{-2}
Enabling event or condition			
Frequency of Unmitigated Consequence			1 x 10^{-2}
Independent Protection Layers	PSV-90011/90021		6.4 x 10^{-5}
Total PFD for all IPLs			6.4 x 10^{-5}
Frequency of Mitigated Consequence (/year)	Frequency (F) (Log F)		6.4 x 10^{-7} (-6.2)
Severity	Life threatening injuries: >3 Injuries: 6 Medical treatment: Physician Care	Fuzzy Severity Index: 3.5	
Risk Tolerance Criteria Met? (Yes/No)	2,5 (TNA-0.4, T-0.6)–	Yes, Tolerable level of risk	
Actions required to meet Risk Tolerance Criteria	No more action required		
Risk calculation after actions required			
Notes	Safeguards: MAWP is 250 psig (Hydrotested to 375 psig), BPCS: Level detector, pressure indicator		

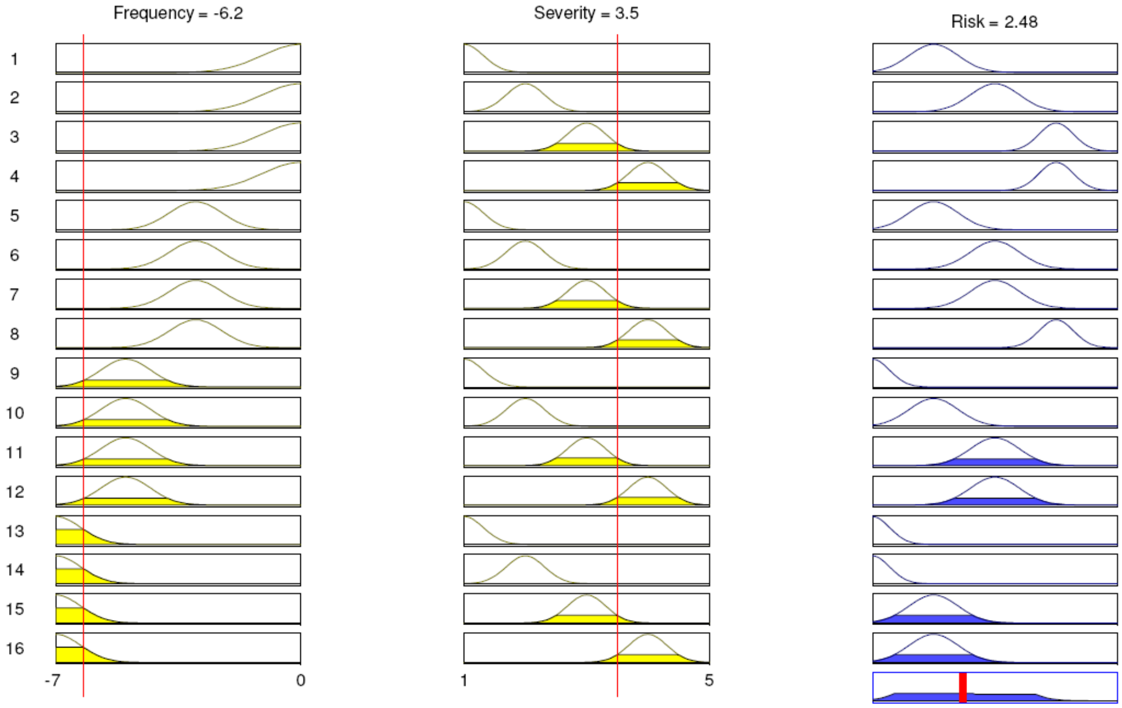


Figure 4.2 Final rules inference for scenario 2

Severity corresponds to an incident that affects people in the vicinity of the facility because it is a gas release of ammonia. For this case it is assumed that no fatalities occur but there are several life-threatening-injuries and the less serious injured people requiring physician care attention. Fuzzy severity risk index is 3.5 and the risk fuzzy inference system gives a risk index of 2.5. Table 4.6 shows the risk values for the fuzzy system and the traditional risk matrix.

The risk fuzzy value has the grade of membership is higher for the Tolerable fuzzy set, the linguistic risk term is Tolerable, and the scenario requires only actions to reduce the risk ALARP.

The traditional approach using the IIAR's OSHA categorization gives a severity level of "catastrophic" and a frequency that could be "low" or "unlikely" category. Depending on the frequency category selected, the risk could be Tolerable unacceptable (TNA) or Tolerable (T). Again, the expert opinion is required to determine which category is appropriate to this scenario. If the approach is conservative, the category tolerable non-acceptable should be selected, and additional action is required in the medium term. Otherwise, the risk is Tolerable and the ALARP criteria prevail.

Table 4.6 Fuzzy and traditional risk results for scenario 2

	Fuzzy value	Traditional Risk Matrix
Risk	2,5 (TNA-0.4, T-0.6)–	3 (TNA- if frequency is low)
		2 (T – if frequency unlikely)

4.3.2. LOW PRESSURE RECIRCULATOR (NODE 2)

The low pressure recirculator RV 301 is an intermediate storage tank for ammonia that works around 10 psig. Appendix B presents the P&ID for this unit. It receives the low pressure ammonia from the spiral freezer. This type of freezer is the most common in the refrigeration industry. It consists of rails that guide a belt to the refrigerated space. It is suitable for continuous product freezing operation.

The function of RV-301 is to receive and recirculate ammonia to the spiral freezer and provide low pressure ammonia to the low and high stage compression system.

4.3.2.1. SCENARIO 3 – LOSS OF SEAL OIL ON RECIRCULATING PUMP

This scenario analyzes the loss of seal in rotating equipment. Failure of the seal in refrigerant pumps is one frequent cause of ammonia release according to EPA [3]. IIAR's Guidelines [11] [14] recommend isolation, ventilation and defrost of the ammonia pumps monthly.

The Cause of the accident scenario is the loss of seal in the refrigeration pump connected to the low pressure receiver RV-301. Frequency of the initiating event is 1×10^{-1} according to the look up table 4.2.

Several safeguards that could be helpful to avoid or mitigate this scenario are present. Mechanical integrity plan, inspection and procedures are useful to prevent malfunction of the equipment but they can not be considered as independent layers of protection. There are two safeguards that can be considered as IPLs, Low Alarm Level (LAL) on Seal Oil followed by operator action after alarm and low level shutdown on pumps. Table 4.7 shows the LOPA worksheet for this scenario.

Table 4.7 LOPA worksheet scenario 3

Scenario No. **3** EQ11-PhO-S1-LE5-TF12-OP-LLS	**Scenario Title:** Loss of oil seal in recirculation pump with potential release in machinery room	**Node No.** **11**

Date	**Description**	**Probability**	**Frequency (per year)**
Consequence Description/Category	Release of ammonia in machine room (loss of containment)		
Risk Tolerance Criteria (Frequency)			
Initiating event (frequency)	Inadvertent loss of oil seal on Recirculating Pump.		1×10^{-1}
Enabling event or condition			
Frequency of Unmitigated Consequence			1×10^{-1}
Independent Protection Layers	LAL on Seal Oil and Operator follows procedure to shutdown operation after alarm.		1.3×10^{-1}
	Low Level Shutdown on Pumps PU-701A/B		7.5×10^{-4}
Total PFD for all IPLs			1×10^{-4}
Frequency of Mitigated Consequence (/year)	Frequency (F) (Log F)		1×10^{-5} (-5)
Severity	Life threatening injuries: 0 Injuries: 2 Medical treatment: First Aid	Fuzzy Severity Index: 1.8 (Moderate)	
Risk Tolerance Criteria Met? (Yes/No)	2,06 (T)	Yes, Tolerable level of risk	
Actions required to meet Risk Tolerance Criteria	No more action required		
Risk calculation after actions required			
Notes	Other safeguards : ammonia detectors and alarms		

Mitigated event frequency calculation gives 1 x 10^{-5}/year. This frequency is considered category “low” according to the membership ranges for frequency in table 3.5 and figure 3.11.

After released, it is considered that ammonia causes only injures that require first aid. It is assumed that the rate of the release is very low and the ammonia detector activates the alarm. This accident impacts a low occupied area because personnel visit this area for inspection only. Severity is calculated considering this information and the severity fuzzy index is 1.8. Looking at the fuzzy set for severity, it is noticed that this value has more membership with the moderate category (0.6) than the low category (0.2).

Fuzzy risk calculation gives a value of 2.06 that corresponds to the tolerable level of risk (T). Future actions are based in the ALARP concept. In contrast, the traditional risk matrix gives a scenario with low severity. Scenario 3 frequency belongs to the categories low and unlikely, but the final outcome for both cases is a risk value of 1. Table 4.8 shows the results for the traditional LOPA and fuzzy LOPA analysis.

Fuzzy LOPA provides different values for severity and risk than the traditional LOPA. They are explained by the fact that in the S-FIS, severity is also determined by the number of people injured. Traditional severity index considers only the type of medical attention required. This higher severity determines the value of risk in the fuzzy logic LOPA method.

Table 4.8 Scenario 3 results

Scenario 3 evaluation	Traditional LOPA			Fuzzy LOPA			
Frequency	Severity	Risk Value	Risk Category	Severity	Severity Linguistic category	Risk	Risk Linguistic category
1 x 10^{-5}	1	1	Acceptable	1.8	Moderate	2.06	Tolerable (T)

4.3.3. SUCTION ACCUMULATOR ST-301 (NODE 3)

In general, ammonia refrigeration systems work over-feeded. It is common in this case to use gas driven systems instead of mechanical devices to make the ammonia flow through the units. The design is inherently safer because avoids the use of pumps where parts such as bearings and seals require special maintenance.

In operation, the liquid and vapor mixture is returned from the evaporator to the accumulator vessel. Phase separation occurs and separated the dry vapor is directed to the compressor. Liquid in the accumulator is drained by gravity to a dump trap (PD 301) and intermittently transferred to a controlled-pressure receiver (CPR), vessel IC-302 in this case. From IC-302, partially subcooled liquid refrigerant is fed to the evaporator at the recirculating rate required for return to the suction accumulator. This configuration provides liquid refrigerant protection for the compressor and increases the use of the internal transfer surface of the evaporator.

4.3.3.1. SCENARIO 4 – LOSS OF LEVEL IN TRANSFER STATION

This scenario analyzes the failure of a pressure valve in the system. If the pressure valve PV- 40041 remains open, dump trap PD-301 loss ammonia level. Hot suction discharge gas from the compressor discharge flows through HPL-5013, increasing the pressure in the pressure receiver IC-302. High pressure gas can cause a hydraulic shock in the pipeline HPL-5013 with possible failure of valves in the line and release of high pressure ammonia gas. Appendix B presents the P&IDs and HAZOP for the scenario.

The cause of the incident is the failure of a pressure valve. The frequency of the spurious trip to close a pressure valve may be estimated with the CCPS data. For this scenario, one IPL is available. Pressure alarm followed by procedures to shutdown. The PFD of the pressure alarm is estimated with the OREDA data. It provides the failure frequency of a pressure sensor. The data is converted into PFD by using frequency-PFD conversion method. CCPS provides the PFD of the operator following procedures after alarm. It is assumed that the pressure alarm and the operator following procedures are independent each other and Boolean algebra is used to estimate the PFD of the IPL. Frequencies and PFDs are presented in tables 4.2 and 4.3 respectively. The mitigated event frequency is 3.7x 10^{-3}/year. Table 4.9 shows the LOPA worksheet for the scenario.

This scenario is considered serious and the severity fuzzy index is estimated. It is assumed that there are one life threatening case and three injuries that require physician care. With these conditions, the outcome is a severity index of 3. The final fuzzy risk index gives a value of 3.09. This value corresponds to the category Tolerable-unacceptable. It means that the scenario is acceptable but more action is required in the middle term.

Table 4.9 LOPA worksheet scenario 4

Scenario No. 4 EQ1-PhO-S1-LE5-TF2-OP-LPA	**Scenario Title:** Loss of level in PD-301 (Transfer Station)		**Node No. 3**
Date	**Description**	**Probability**	**Frequency (per year)**
Consequence Description/Category	Subsequent hot suction discharge gas blow through to IC-302 and pressure increase in IC-302 with potential for hydraulic shock in line HPL-5013 and failure valve (potential for loss of containment)		
Risk Tolerance Criteria (Frequency)			
Initiating event (frequency)	PV-40041 sticks open		3.1 x 10^{-2}
Enabling event or condition			
Frequency of Unmitigated Consequence			3.1 x 10^{-2}
Independent Protection Layers	Pressure alarm followed by procedures Operator follows procedure to shutdown		1.21 x 10^{-1}
Total PFD for all IPLs			1.21 x 10^{-1}
Frequency of Mitigated Consequence (/year)	Frequency (F) (Log F)		3.7x 10^{-3} (-2.4)
Severity	Life threatening injuries: 1 Injuries: 3 Medical treatment: Physician Care	Fuzzy Severity Index: 3 (High)	
Risk Tolerance Criteria Met? (Yes/No)	3.09 (TNA)	Yes, but additional improvements are required	
Actions required to meet Risk Tolerance Criteria	**Severity Reduction:** Ammonia Detection (SIL 2-Manufacturer) PFD= 1 x 10^{-2} Ventilation system, PFD = 2.08 x 10^{-1} Final configuration PFD: 2.2 x 10^{-1} **Frequency Reduction:** Detection system and Alarms, SIF with SIL 2 activates if PV-40041 fails		
Risk calculation after actions required	F = 8 x 10^{-6} ; Log F = - 5.09; Fuzzy Severity index: 2; Fuzzy Risk Index: T (2)		
Notes	Safeguards: Local Level Indication on PD-301, LAH-3014, LAHH-3013. Consider preparation of an emergency mitigation procedure for restoration of PD-301 to safe operating condition without creating a potential for thermal shock when closing off hot gas to PD-301		

Table 4.10 presents the results for risk. Traditional LOPA and fuzzy-LOPA estimate the same level of risk. However, fuzzy LOPA allows the analysis of mitigation layers of protection according to the CCPS guidelines [22]. A detection system for ammonia that activates the ventilation system is a mitigation protection layer. The PDF is obtained through the combination of the PFD for the ventilation system when it is required to start, and the PFD of the detection system. Boolean algebra applied to this system gives a PFD value of 2.2x 10^{-1}.

Including this mitigation IPL, the number of injuries is the same but the type of medical care changes to first aid. The fuzzy severity index is 2, and the mitigated frequency of the initiating event is 8.1x 10^{-4}. With these data, the fuzzy risk inference system calculates a risk value of 3. In this case the mitigation IPL is not enough to reduce the risk.

Additional actions to reduce the risks include installing a Safety Instrumented Function (SIF) with a Safety Integrity Level (SIL) of 2. SIF activates in case the pressure valve fails. The new reduced event frequency and fuzzy risk index are 8.1x 10^{-6} and 2 (Tolerable) respectively.

Table 4.10 **S**cenario 4 results

Scenario 4 evaluation	Traditional LOPA			Fuzzy LOPA			
Frequency	Severity	Risk Value	Risk Category	Severity	Severity Linguistic category	Risk	Risk Linguistic category
3.7 x 10^{-3}	3	3	Tolerable-unacceptable (TNA)	3	High	3	Tolerable-unacceptable (TNA)

5. SUMMARY AND CONCLUSIONS

5.1. SUMMARY

Ammonia systems are the refrigeration system of preference for the cold storage and food processing. Its use is expected to be increased because its operation is economical, efficient and environmentally friendly. Although ammonia refrigeration systems have these advantages, ammonia is flammable and toxic. Therefore, it is very important to evaluate and control the risks of using ammonia in new and existing facilities.

LOPA is a very cost effective way to determine the risk in chemical processes. It requires less time and effort and provides quantified results. However, information in many cases is scarce or highly uncertain for applying risk assessment techniques, especially in old facilities without appropriate records and practices. Fuzzy logic was developed to work with this type of conditions. Based on the idea of mimic how humans make decisions, fuzzy logic is a useful alternative to develop expert systems.

This research applies fuzzy logic to develop the basis for an ammonia refrigeration LOPA expert system. It was developed to represent available knowledge about the process from ammonia refrigeration standards. IIAR's OSHA risk matrix is the base for developing the different fuzzy sets that allow the construction of the two main inference systems used in this research.

The severity fuzzy inference system calculates the severity of a LOPA scenario as a result of the combination of three fuzzy sets, number of life threatening or deaths, number of injuries and type of medical attention required.

The Risk Fuzzy Inference System calculates the risk of a scenario with the fuzzy severity index and the mitigated frequency of the initiating event for the same scenario. The result is the representation of the IIAR's OSHA knowledge into the domain of fuzzy logic with the use of fuzzy inference systems. The utility of this work is to help the development of an expert system for LOPA application to ammonia refrigeration systems. With the HAZOP information of a real system, four scenarios were identified in a typical ammonia refrigeration system. The failure frequencies of initiating events and PFDs of the IPLs were obtained from available literature. The fuzzy LOPA methodology estimate the quantitative risk for each scenario. Based on the category of the risk index, risk decisions are made.

In order to improve the safety of the system, recommendations were made to reduce the risk to tolerable levels using the fuzzy LOPA method. Table 5.1 shows the summary of the risk values and the recommendations. Additionally, table 5.2 presents the comparison of results using the traditional LOPA and risk matrix with the fuzzy LOPA method and fuzzy risk matrix.

Table 5.1 Risk summary of the accident scenarios

No of Scenario	Scenarios	Failure Frequecny (/year)	Fuzzy Severity Index	Fuzzy Risk ranking	Criteria met	Recommendations
1	Failure of charging hose during charging of receiver tank	5 x 10^{-4}	3 (High)	3	Yeas, but more action is required in the middle term	1. Reduction in occupation of the zone. Personnel wears protective cloths 2. Ventilation system is on during charging 3. Mechanical integrity program for the ammonia provider
2	Rapid charging of ammonia to receiver vessel resulting in high pressure in RC-301	6.4 x 10^{-7}	3.5 (High and catastrophic)	2.5	Yes, Tolerable	1. Mechanical integrity plan. 2. Installation of Pressure alarm
3	Loss of oil seal in recirculation pump with potential release in machinery room	1 x 10^{-5}	1.8 (Moderate)	2.06	Yes, Tolerable	1. Installation of ammonia detector and alarms.
4	Loss of level in PD-301 (Transfer Station)	3.7x 10^{-3}	3 (High)	3.09	Yes but additional action is required	1. Ammonia detector and alarms. 2. SIF (SIL 2) activates on pressure valve failure

Table 5.2 Comparison of the accident scenarios

Scenario	Frequency (F)	Traditional LOPA -Risk Matrix		Fuzzy logic LOPA		
		Severity	Risk	Severity		Fuzzy Risk Index
1	5×10^{-4}	3	3	High	3	3 (TNA)
2	6.4×10^{-7}	3	3 (F = low) 2 (F = unlikely)	High & Catastrophic	3.5	2,5 (TNA-0.4, T-0.6)
3	1×10^{-5}	1	1 F=low, unlikely	Moderate	1.8	2,06 (T)
4	3.7×10^{-3}	3	3	High	3	3.09 (TNA)

5.2. CONCLUSIONS

This work has introduced a modified fuzzy logic LOPA methodology for risk estimation in ammonia refrigeration systems. It produced comparable risk results as it is shown in table 5.1. The method takes into account the expert knowledge available in the form of standards and good industry practices for ammonia refrigeration systems. Membership functions were developed based on this information, scenarios were classified, and fuzzy inference systems estimate the severity and risk index. They represent the knowledge base of the fuzzy system. In this way, the method serves as a framework for developing an expert system for ammonia refrigeration system that helps in the implementation of OSHA's PSM program.

The fuzzy logic LOPA method is user friendly. Membership functions can be modified according to the criteria of the expert developing the risk assessment. This feature facilitates the expert work especially when assessing old refrigeration systems where appropriate information is scarce.

The results show that the method is helpful analyzing mitigation IPLs. Impact of severity and frequency reduction on the risk is easily determined and compared when mitigation IPL is considered.

In conclusion, this work shows that the fuzzy logic LOPA method is a useful tool to assess the risk in ammonia refrigeration systems and because it is flexible and user friendly, it can be implemented once the scenario is detected during a HAZOP or PHA studies.

5.3. FUTURE WORK

To further improve of the method, membership functions for maintenance, training of the employees and other non quantitative variables can be implemented. Whereas these characteristics are not easy to include in traditional LOPA, the fuzzy logic LOPA method works with this information represented in fuzzy sets.

This work was based on OSHA's PSM. For this reason, on site facility consequences were mainly considered. As an improvement, outside facility consequences can be included and EPA's Risk Management Program for Ammonia Refrigeration has to be considered.

Finally, improvements related with the development of databases and software that eliminates the use of the Matlab's fuzzy logic tool box is required. This computer aided tool will constitute the expert system for ammonia refrigeration systems based on fuzzy logic.

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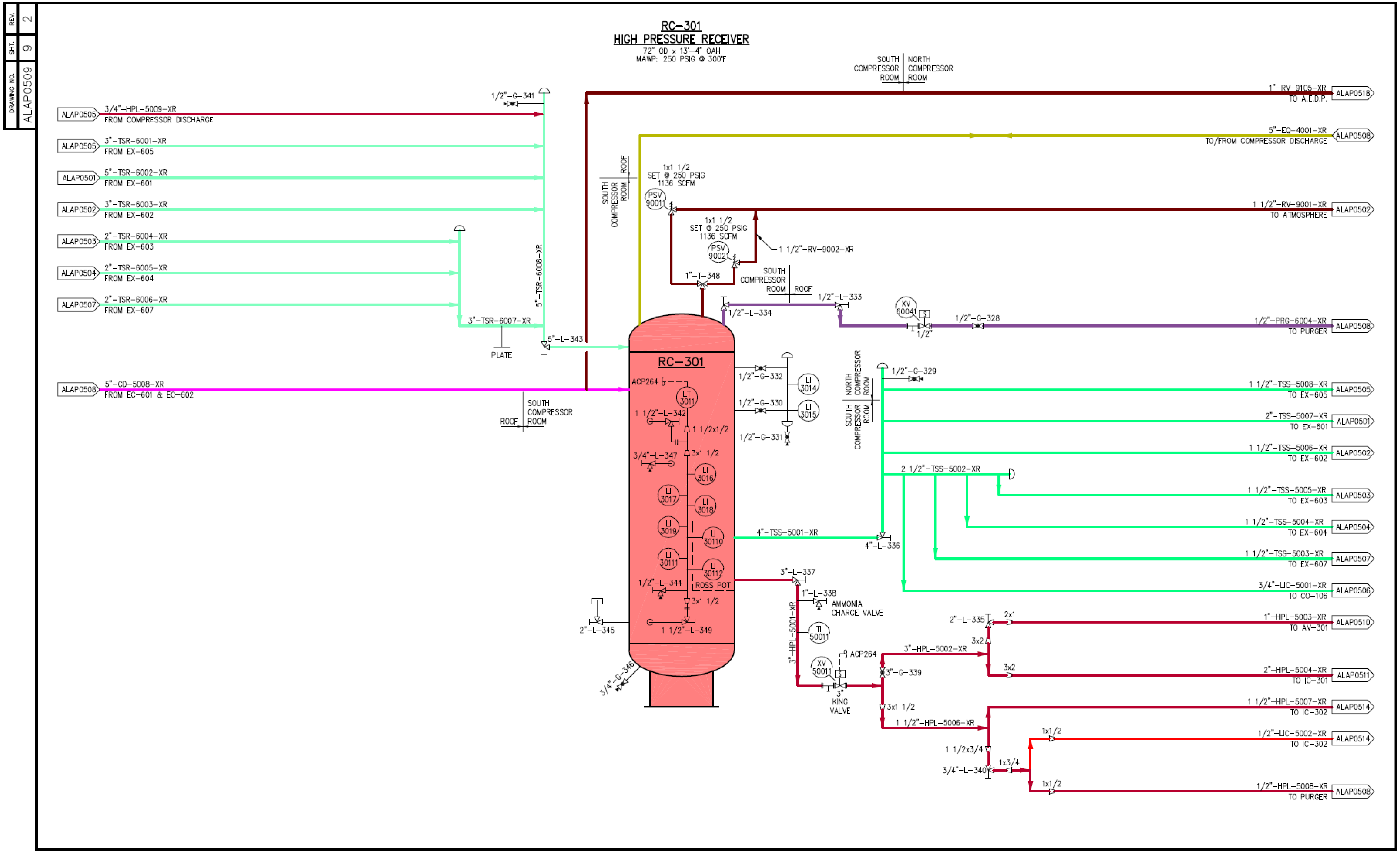
APPENDIX A

PHYSICAL PROPERTIES OF AMMONIA

PROPERTY	VALUE
Molecular weight	17.03
Color	None
Physical state	Gas
Freezinf point	- 108 F @ P =1 atm
Boiling point	- 28.01 F @ P =1 atm
Critical pressure	1657 psia
Critical temperature	271 F
Specific Gravity	0.596 @ 32 F/1 atm/vapor
	0.62 @ 60 F/liquid
Specific volume	20.8 ft^3/lb @ 32 F/1 atm/vapor
Odor threshold	5 – 50 ppm
Upper flammability limit	25 - 28 %
Lower flammability limit	15 - 16%
Ignition temperature	1204 F

APPENDIX B

AMMONIA REFRIGERATION SYSTEMS P&IDs AND HAZOP STUDY


RC–301
HIGH PRESSURE RECEIVER
72" OD x 13'–4" OAH
MAWP: 250 PSIG @ 300°F
SOUTH COMPRESSOR ROOM
NORTH COMPRESSOR ROOM
ROOF
1"–RV–9105–XR
TO A.E.D.P.
ALAP0518
5"–EQ–4001–XR
TO/FROM COMPRESSOR DISCHARGE
ALAP0508
1x1 1/2
SET @ 250 PSIG
1136 SCFM
PSV 90011
1 1/2"–RV–9001–XR
TO ATMOSPHERE
ALAP0502
PSV 90021
1 1/2"–RV–9002–XR
1"–T–348
1/2"–L–333
1/2"–L–334
XV 60041
1/2"–G–328
1/2"
1/2"–PRG–6004–XR
TO PURGER
ALAP0508
1/2"–G–341
ALAP0505
3/4"–HPL–5009–XR
FROM COMPRESSOR DISCHARGE
ALAP0505
3"–TSR–6001–XR
FROM EX–605
ALAP0501
5"–TSR–6002–XR
FROM EX–601
ALAP0502
3"–TSR–6003–XR
FROM EX–602
ALAP0503
2"–TSR–6004–XR
FROM EX–603
ALAP0504
2"–TSR–6005–XR
FROM EX–604
ALAP0507
2"–TSR–6006–XR
FROM EX–607
5"–TSR–6008–XR
3"–TSR–6007–XR
5"–L–343
PLATE
ALAP0508
5"–CD–500B–XR
FROM EC–601 & EC–602
RC–301
ACP264
LT 3011
1 1/2"–L–342
1 1/2x1/2
3/4"–L–347
3x1 1/2
LI 3016
LI 3017
LI 3018
LI 3019
LI 30110
LI 30111
LI 30112
1/2"–L–344
ROSS POT
3x1 1/2
1 1/2"–L–349
2"–L–345
3/4"–G–346
1/2"–G–332
1/2"–G–330
1/2"–G–331
LI 3014
LI 3015
1/2"–G–329
4"–TSS–5001–XR
4"–L–336
1 1/2"–TSS–5008–XR
TO EX–605
ALAP0505
2"–TSS–5007–XR
TO EX–601
ALAP0501
1 1/2"–TSS–5006–XR
TO EX–602
ALAP0502
2 1/2"–TSS–5002–XR
1 1/2"–TSS–5005–XR
TO EX–603
ALAP0503
1 1/2"–TSS–5004–XR
TO EX–604
ALAP0504
1 1/2"–TSS–5003–XR
TO EX–607
ALAP0507
3/4"–LIC–5001–XR
TO CO–106
ALAP0506
3"–L–337
1"–L–338
AMMONIA
CHARGE VALVE
3"–HPL–5001–XR
TI 50011
XV 50011
ACP264
3"
KING
VALVE
3"–HPL–5002–XR
3"–G–339
3x1 1/2
1 1/2"–HPL–5006–XR
2"–L–335
2x1
3x2
3x2
1"–HPL–5003–XR
TO AV–301
ALAP0510
2"–HPL–5004–XR
TO IC–301
ALAP0511
1 1/2"–HPL–5007–XR
TO IC–302
ALAP0514
1x1/2
1/2"–LIC–5002–XR
TO IC–302
ALAP0514
1 1/2x3/4
3/4"–L–340
1x3/4
1x1/2
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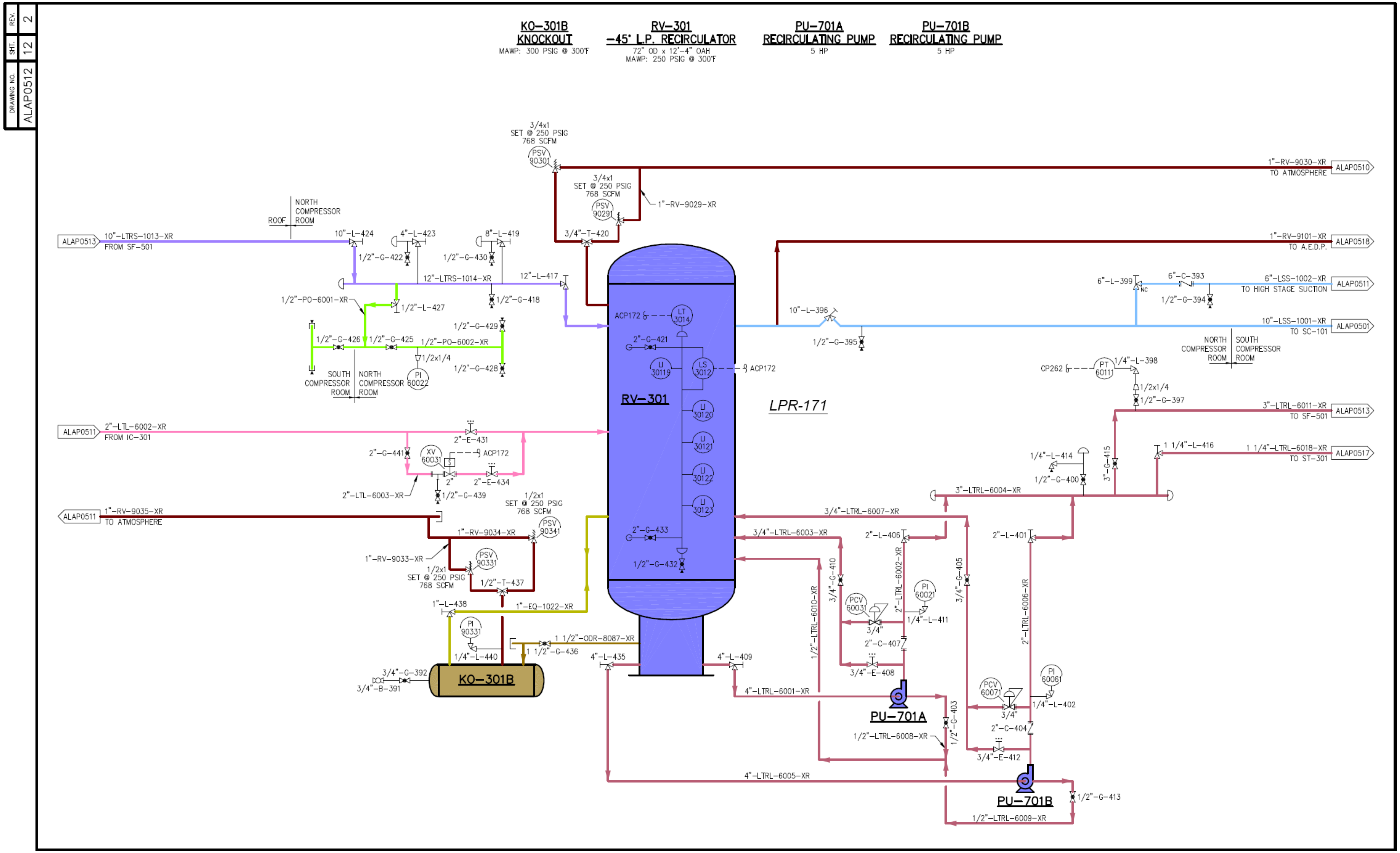
TO PURGER
ALAP0508
DRAWING NO.
ALAP0509
SHT.
9
REV.
2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KNOCKOUT
MAWP: 300 PSIG @ 300°F
RV–301
–45° L.P. RECIRCULATOR
72" OD x 12'–4" OAH
MAWP: 250 PSIG @ 300°F
PU–701A
RECIRCULATING PUMP
5 HP
PU–701B
RECIRCULATING PUMP
5 HP
DRAWING NO.
ALAP0512
SHT.
12
REV.
2
LPR-171
RV–301
KO–301B
PU–701A
PU–701B
3/4x1
SET @ 250 PSIG
768 SCFM
PSV 90301
3/4x1
SET @ 250 PSIG
768 SCFM
PSV 90291
1"–RV–9029–XR
3/4"–T–420
1"–RV–9030–XR
TO ATMOSPHERE
ALAP0510
1"–RV–9101–XR
TO A.E.D.P.
ALAP0518
6"–L–399
NC
6"–C–393
1/2"–G–394
6"–LSS–1002–XR
TO HIGH STAGE SUCTION
ALAP0511
10"–L–396
1/2"–G–395
10"–LSS–1001–XR
TO SC–101
ALAP0501
NORTH COMPRESSOR ROOM
SOUTH COMPRESSOR ROOM
CP262
PT 60111
1/4"–L–398
1/2x1/4
1/2"–G–397
3"–LTRL–6011–XR
TO SF–501
ALAP0513
1/4"–L–414
1/2"–G–400
3"–G–415
1 1/4"–L–416
1 1/4"–LTRL–6018–XR
TO ST–301
ALAP0517
3"–LTRL–6004–XR
3/4"–LTRL–6007–XR
3/4"–LTRL–6003–XR
2"–L–406
2"–LTRL–6002–XR
3/4"–G–410
PCV 60031
3/4"
PI 60021
1/4"–L–411
2"–C–407
3/4"–E–408
1/2"–LTRL–6010–XR
3/4"–G–405
2"–L–401
2"–LTRL–6006–XR
PCV 60071
3/4"
PI 60061
1/4"–L–402
2"–C–404
3/4"–E–412
1/2"–G–403
1/2"–LTRL–6008–XR
4"–L–409
4"–LTRL–6001–XR
4"–L–435
4"–LTRL–6005–XR
1/2"–G–413
1/2"–LTRL–6009–XR
ACP172
LT 3014
2"–G–421
LI 30119
LS 3012
ACP172
LI 30120
LI 30121
LI 30122
LI 30123
2"–G–433
1/2"–G–432
ALAP0513
10"–LTRS–1013–XR
FROM SF–501
ROOF
NORTH COMPRESSOR ROOM
10"–L–424
4"–L–423
1/2"–G–422
8"–L–419
1/2"–G–430
12"–LTRS–1014–XR
12"–L–417
1/2"–G–418
1/2"–PO–6001–XR
1/2"–L–427
1/2"–G–429
1/2"–G–426
1/2"–G–425
1/2"–PO–6002–XR
1/2x1/4
1/2"–G–428
PI 60022
SOUTH COMPRESSOR ROOM
NORTH COMPRESSOR ROOM
ALAP0511
2"–LTL–6002–XR
FROM IC–301
2"–E–431
2"–G–441
XV 60031
S
ACP172
2"
2"–E–434
2"–LTL–6003–XR
1/2"–G–439
ALAP0511
1"–RV–9035–XR
TO ATMOSPHERE
1/2x1
SET @ 250 PSIG
768 SCFM
PSV 90341
1"–RV–9034–XR
1"–RV–9033–XR
PSV 90331
1/2x1
SET @ 250 PSIG
768 SCFM
1/2"–T–437
1"–L–438
1"–EQ–1022–XR
PI 90331
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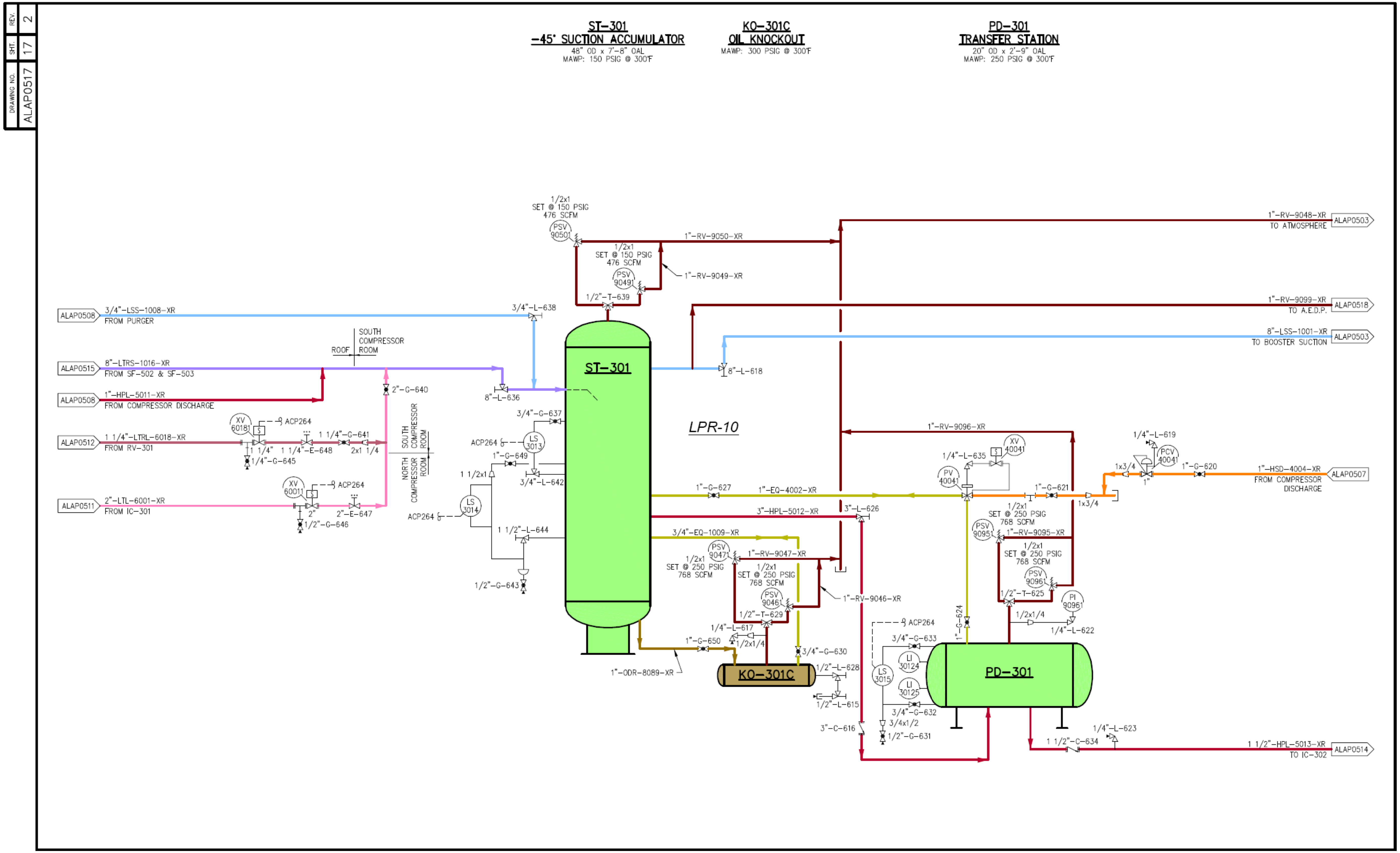
3/4"–B–391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REV. 2
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MAWP: 150 PSIG @ 300°F
KO-301C
OIL KNOCKOUT
MAWP: 300 PSIG @ 300°F
PD-301
TRANSFER STATION
20" OD x 2'-9" OAL
MAWP: 250 PSIG @ 300°F
LPR-10
ST-301
KO-301C
PD-301
1/2x1
SET @ 150 PSIG
476 SCFM
PSV 9050
1"-RV-9050-XR
1/2x1
SET @ 150 PSIG
476 SCFM
PSV 9049
1"-RV-9049-XR
1/2"-T-639
1"-RV-9048-XR
TO ATMOSPHERE
ALAP0503
1"-RV-9099-XR
TO A.E.D.P.
ALAP0518
8"-LSS-1001-XR
TO BOOSTER SUCTION
ALAP0503
8"-L-618
ALAP0508
3/4"-LSS-1008-XR
FROM PURGER
3/4"-L-638
SOUTH COMPRESSOR ROOM
ROOF
ALAP0515
8"-LTRS-1016-XR
FROM SF-502 & SF-503
8"-L-636
ALAP0508
1"-HPL-5011-XR
FROM COMPRESSOR DISCHARGE
2"-G-640
XV 6018
ACP264
ALAP0512
1 1/4"-LTRL-6018-XR
FROM RV-301
1 1/4"
1 1/4"-E-648
1 1/4"-G-641
2x1 1/4
1/4"-G-645
SOUTH COMPRESSOR ROOM
NORTH COMPRESSOR ROOM
XV 6001
ACP264
ALAP0511
2"-LTL-6001-XR
FROM IC-301
2"
2"-E-647
1/2"-G-646
3/4"-G-637
ACP264
LS 3013
1"-G-649
1 1/2x1
3/4"-L-642
ACP264
LS 3014
1 1/2"-L-644
1/2"-G-643
1"-RV-9096-XR
1"-G-627
1"-EQ-4002-XR
3"-HPL-5012-XR
3"-L-626
3/4"-EQ-1009-XR
PSV 9047
1/2x1
SET @ 250 PSIG
768 SCFM
1"-RV-9047-XR
1/2x1
SET @ 250 PSIG
768 SCFM
PSV 9046
1/2"-T-629
1"-RV-9046-XR
1/4"-L-617
1/2x1/4
1"-G-650
3/4"-G-630
1"-ODR-8089-XR
1/2"-L-628
1/2"-L-615
3"-C-616
1/4"-L-635
XV 40041
PV 40041
1/4"-L-619
PCV 40041
1x3/4
1"
1"-G-620
ALAP0507
1"-HSD-4004-XR
FROM COMPRESSOR DISCHARGE
1"-G-621
1x3/4
1/2x1
SET @ 250 PSIG
768 SCFM
PSV 9095
1"-RV-9095-XR
1/2x1
SET @ 250 PSIG
768 SCFM
PSV 9096
1/2"-T-625
PI 9096
1/2x1/4
1/4"-L-622
1"-G-624
ACP264
3/4"-G-633
LI 30124
LS 3015
LI 30125
3/4"-G-632
3/4x1/2
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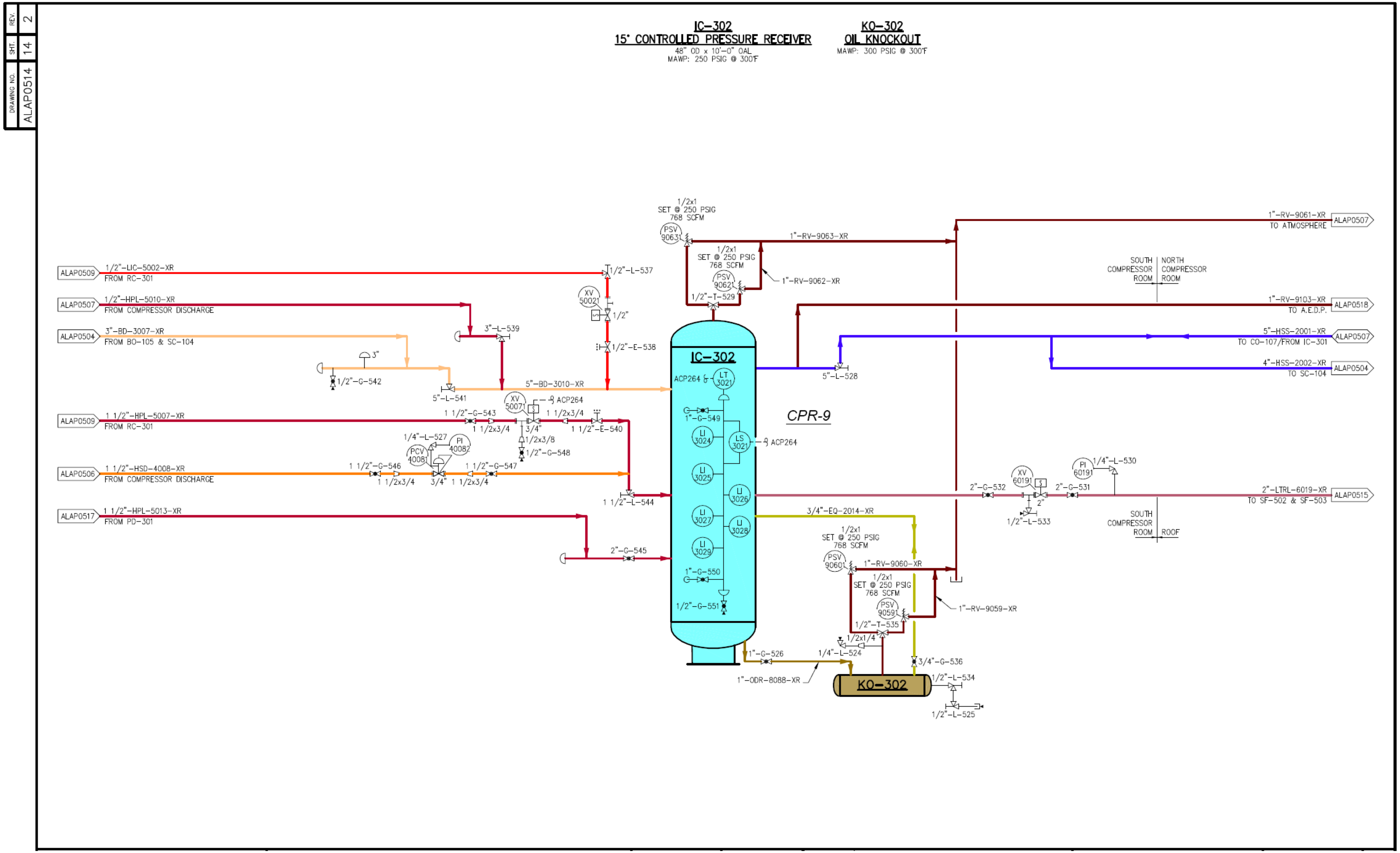
1/4"-L-623
1 1/2"-C-634
1 1/2"-HPL-5013-XR
TO IC-302
ALAP0514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15' CONTROLLED PRESSURE RECEIVER
48" OD x 10'-0" OAL
MAWP: 250 PSIG @ 300°F
KO-302
OIL KNOCKOUT
MAWP: 300 PSIG @ 300°F
DRAWING NO. ALAP0514
SHT. 14
REV. 2
CPR-9
IC-302
KO-302
ALAP0509 1/2"-LIC-5002-XR FROM RC-301
ALAP0507 1/2"-HPL-5010-XR FROM COMPRESSOR DISCHARGE
ALAP0504 3"-BD-3007-XR FROM BO-105 & SC-104
ALAP0509 1 1/2"-HPL-5007-XR FROM RC-301
ALAP0506 1 1/2"-HSD-4008-XR FROM COMPRESSOR DISCHARGE
ALAP0517 1 1/2"-HPL-5013-XR FROM PD-301
1"-RV-9061-XR TO ATMOSPHERE ALAP0507
1"-RV-9103-XR TO A.E.D.P. ALAP0518
5"-HSS-2001-XR TO CO-107/FROM IC-301 ALAP0507
4"-HSS-2002-XR TO SC-104 ALAP0504
2"-LTRL-6019-XR TO SF-502 & SF-503 ALAP0515
SOUTH COMPRESSOR ROOM | NORTH COMPRESSOR ROOM
SOUTH COMPRESSOR ROOM | ROOF
1/2x1 SET @ 250 PSIG 768 SCFM PSV 9063
1"-RV-9063-XR
1/2x1 SET @ 250 PSIG 768 SCFM PSV 9062
1"-RV-9062-XR
1/2"-T-529
1/2"-L-537
XV 5002
1/2"
3"-L-539
1/2"-E-538
3"
1/2"-G-542
5"-L-541
5"-BD-3010-XR
XV 5007
ACP264
1 1/2"-G-543
1 1/2x3/4
3/4"
1 1/2x3/4
1 1/2"-E-540
1/2x3/8
1/2"-G-548
1/4"-L-527
PI 4008
PCV 4008
1 1/2"-G-546
1 1/2x3/4
3/4"
1 1/2x3/4
1 1/2"-G-547
1 1/2"-L-544
2"-G-545
5"-L-528
ACP264
LT 3021
1"-G-549
LI 3024
LS 3021
ACP264
LI 3025
LI 3026
LI 3027
LI 3028
LI 3029
1"-G-550
1/2"-G-551
1"-G-526
1"-ODR-8088-XR
1/4"-L-524
1/2x1/4
3/4"-EQ-2014-XR
1/2x1 SET @ 250 PSIG 768 SCFM PSV 9060
1"-RV-9060-XR
1/2x1 SET @ 250 PSIG 768 SCFM PSV 9059
1"-RV-9059-XR
1/2"-T-535
3/4"-G-536
1/2"-L-534
1/2"-L-525
2"-G-532
XV 6019
2"
1/2"-L-533
2"-G-531
PI 6019
1/4"-L-530

NODE REF: 1 DOCUMENT REF: AL-A-P-0509
DOCUMENT TITLE: High Pressure Receiver - RC-301

ITEM: Ammonia Charging
This node involves the charging of anhydrous ammonia from a vendor tank truck to the High Pressure Receiver RC-301. This operation is conducted for initial charging of the refrigeration system and when additional ammonia is required, e.g. equipment added to system. The ammonia is delivered via truck to the facility via a charging hose through the machine room. Vessel RC-301, lines RV-9002, and RV-9001 are included. Ammonia truck driver has own PPE and he connects hose from truck to angle valve on RC-301 discharge line (HPL-5001). Company 1 personnel opens valve after driver connects hose and performs leak check. Company 1 PPE consists of gloves, face shield, and respirator and NH3 meter accessible.

DEVIATION	CAUSE	CONSEQUENCE	SAFEGUARDS	ACTION
Flow No/Low	Inadvertent valve closure, flow switch failure, failure of truck pump,	Failure to fill Receiver with sufficient charge of ammonia; operability issue		Charging hose connection lock, dike around receiver, detection system, water spray system (water fog)
	Inadvertent uncoupling of charging hose	Release of ammonia to atmosphere resulting in respiratory injury and/or chemical burn to personnel in close proximity and potential environmental issue Freq: [3] Ctgy: [1] [2] [3] Svrty: [2] [3] [3] Risk: [3] [4] [4]	Pre-startup check Personnel monitoring charging can quickly mitigate incident	
Flow More/High	Excessive pressure on ammonia truck or truck pump set too high	Rapid charging of ammonia to Receiver vessel resulting in high pressure in RC-301 Freq: [3] Ctgy: [1] [2] [3] Svrty: [3] [2] [3] Risk: [4] [3] [4]	PSV-90011/90021 RC-301 MAWP is 250 psig Hydrotested to 375 psig Level indicators	Pressure indicator on top of RC-301 to shutdown truck pump, flow meter valve L-338.

NODE REF: 1 (continued) DOCUMENT REF: AL-A-P-0509
ITEM: Ammonia Charging

DEVIATION	CAUSE	CONSEQUENCE	SAFEGUARDS	ACTION
Flow Reverse	Ammonia truck has low pressure (pressure in truck is lower than RC-301)	Initial backflow of ammonia from RC-301 into truck resulting in subsequent failure to charge or delay in charging refrigeration system; operability issue	Typical pressure on RC-301 is 140 psig; max 180 psig	Check valve between valve L-338 and pump
Flow Other Than	Truck contains ammonia grade other than refrigeration	Lower grade ammonia may contain water resulting in subsequent freezing in small bore lines and eventual failure of the line (loss of containment) NOTE: Loss of containment can result in severe personnel respiratory injuries, chemical burns, and environmental issues Freq: [3] Ctgy: [1] [2] [3] Svrty: [2] [2] [2] Risk: [3] [3] [3]	Procedure: Company 1 checks truck manifest to ensure refrigeration grade ammonia	
Press No/Low	See No/Low flow issues			
Press More/High	See High/More Flow issues			
Temp No/Low	None identified			

NODE REF: 1 (continued) DOCUMENT REF: AL-A-P-0509
ITEM: Ammonia Charging

DEVIATION	CAUSE	CONSEQUENCE	SAFEGUARDS	ACTION
Temp More/High	None identified			
Controls Issue	Ammonia charge to system without safework practice in place	Personnel omission or comission error during charging resulting in an inadvertent release of ammonia to the atmosphere and potential for personnel injury Freq: [2] Ctgy: [1] [2] [3] Svrty: [2] [2] [3] Risk: [2] [2] [3]	None	Consider preparation of a safework practice/procedure for the delivery (charging) of ammonia into the refrigeration system and developing a safety job analysis
ACTION NO: 1 ASSIGNED TO: Company 1				
Human Factors Issue	Personnel disconnect ammonia charging hose without purging line clear	Inadvertent exposure to residual ammonia in hose resulting in chemical burn and/or respiratory injury Freq: [3] Ctgy: [1] [2] [3] Svrty: [2] [3] [3] Risk: [3] [4] [4]	Connection hose has valve on end to preclude spillage of ammonia Truck driver disconnects hose	Operating procedure
Siting Issue	Location of RC-301 requires routing of charging hose through machine room	See other consequences noted in this node		Procedure for charging, PPE. Work permit.
Level No/Low	None identified. Valves L-345 and G-346 open.	Ammonia release. Operability issues due to low level.	Level indicators	Check location of level indicators below 30% capacity required for RC-301. Low-low level indicator.

NODE REF: 1 (continued) DOCUMENT REF: AL-A-P-0509
ITEM: Ammonia Charging

DEVIATION	CAUSE	CONSEQUENCE	SAFEGUARDS	ACTION
Level More/High	Ammonia is continuously charged from truck into RC-301	Eventual overfilling of RC-301 with ammonia resulting in high pressure in RC-301 and backflow to the condensers Freq: [3] Ctgy: [1] [2] [3] Svrty: [3] [3] [2] Risk: [4] [4] [3]	PSV-90011/90021 RC-301 MAWP is 250 psig LT-3011 (LAH-3011) Local level indication on RC-301 (sight glass)	Check valve in line CD-5008-XR

NODE REF: 2 DOCUMENT REF: AL-A-P-0512/0517
DOCUMENT TITLE: -45 Low Pressure Recirculator - RV-301

ITEM: Low Temperature Recirculated Liquid to ST-301
This node involves the low temperature recirculated liquid from RV-301 Recirculating Pumps, PU-701A/B to the -45 Suction Accumulator, ST-301 through XV-60181, including the recycle lines from PU-701A/B back to RV-301. Also included is low temperature liquid line 2"-LTL-6001-XR from IC-301 through XV-60011 to ST-301. Equipment PU-107A/B and lines LTRL-6005, LTRL-6001, LTRL-6008, LTRL-6003, LTRL-6007, LTRL-6009, LTRL-6010, LTRL-6006, LTRL-6002, LTRL-6004, LTRL-6018, and LTL-6001 are included.

DEVIATION	CAUSE	CONSEQUENCE	SAFEGUARDS	ACTION
Flow No/Low	Inadvertent loss of Recirculating Pump or failure of pump motor	Eventual high level in RV-301 (See Node 10) Reverse flow from ST-301 to check valve of pump discharge		
	XV-60181 fails or is inadvertently commanded closed	Recirculation of liquid through pumps; operability issue		
	XV-60011 fails or is inadvertently commanded closed	High level in IC-301 (See Node 3)		
Flow More/High	None identified			
Flow Reverse	None identified			
Flow Other Than	None identified			

NODE REF: 2 (continued) DOCUMENT REF: AL-A-P-0512/0517
ITEM: Low Temperature Recirculated Liquid to ST-301

DEVIATION	CAUSE	CONSEQUENCE	SAFEGUARDS	ACTION
Press No/Low	PCV-60031 or PCV-60071 inadvertently fails	Low pressure to Suction Accumulator resulting in low flow (See No/Low Flow this Node)		
Press More/High	Angle valve on pump discharge is inadvertently closed	Deadhead pump resulting in high pressure and eventual damage to pump Freq: [2] Ctgy: [1] [2] [3] Svrty: [3] Risk: [3]	Hand expansion valves to RV-301 open PCV-60031 and PCV-60071	
Temp No/Low	None identified			
Temp More/High	None identified			
Controls Issue	Inadvertent loss of oil seal on Recirculating Pump	Failure of pump seal results in release of ammonia in machine room (loss of containment)	LAL on Seal Oil Low Level Shutdown on Pump PU-701A/B PAL on pumps	

NOTE: Discharge pressure on Recirculating pumps is approximately 40 psig

NODE REF: 3 DOCUMENT REF: AL-A-P-0517/0514
DOCUMENT TITLE: -45 Suction Accumulator - ST-301

ITEM: High Pressure Liquid to IC-302
This node involves the high pressure liquid from ST-301 to the Transfer Station, PD-301 to the 15 Controlled Pressure Receiver, IC-302. The MAWP of PD-301 is 250 psig @ 300 F. PD-301, its associated instrumentation, equalization line 1"-EQ-4002-XR, and overpressure protection is included in this node. Overpressure protection for PD-301 is provided by dual 1/2 x 1 PSVs (90951 and 90961). Vessel PD-301 and lines HPL-5012, HPL-5013, EQ-4002, RV-9095 and RV-9096 are included.

DEVIATION	CAUSE	CONSEQUENCE	SAFEGUARDS	ACTION
Controls Issue	Continuous thermal cycling of line EQ-4002 and PD-301	Eventual exterior corrosion of piping and top of PD-301 resulting in degraded integrity of line and subsequent loss of containment Freq: [2] Ctgy: [1] [2] [3] Svrty: [2] [2] [2] Risk: [2] [2] [2]	None	Consider conducting mechanical inspection of line EQ-4002 and PD-301 to ensure that integrity of piping and vessel is adequate for design temperatures and pressures

ACTION NO: 6 ASSIGNED TO: Company 1/Contractor

NODE REF: 3 (continued) DOCUMENT REF: AL-A-P-0517/0514
ITEM: High Pressure Liquid to IC-302

DEVIATION	CAUSE	CONSEQUENCE	SAFEGUARDS	ACTION
Level No/Low	PV-40041 sticks open or timer fails to close PV-40041	Eventual loss of level in PD-301 resulting in subsequent hot suction discharge gas blow through to IC-302 and pressure increase in IC-302 with potential for hydraulic shock in line HPL-5013 and failure valve (potential for loss of containment) Freq: [3] Ctgy: [1] [2] [3] Svrty: [2] [2] [2] Risk: [3] [3] [3]	Local Level Indication on PD-301 LAH-3014 LAHH-3013	Consider preparation of an emergency mitigation procedure for restoration of PD-301 to safe operating condition without creating a potential for thermal shock when closing off hot gas to PD-301
ACTION NO: 7 ASSIGNED TO: Company 1				
Level More/High	PV-40041 fails to cycle to hot gas mode	Eventual flooding of PD-301 and subsequently build level in ST-301 (See High Level in Node 13)		

APPENDIX C

CLASSIFICATION OF HAZARDOUS EQUIPMENT

Group of Equipment	Main Category	Name of Equipment	Type of Equipment	Code
Storage Equipment	Pressure storage	Pressure Vessel		EQ1
Process Equipment	Heat transfer equipment	Evaporators	Forced Air Evaporator Coils	EQ2
			Shell & Tube Evaporators	EQ3
			Plate Heat Exchanger Evaporator	EQ4
		Condensers	Air cooled Condensers & Desuperheaters	EQ5
			Evaporative Condensers	EQ6
			Shell & Tube Condensers and Double Pipe Condensers	EQ7
			Plate Heat Exchanger Condensers	EQ8
Piping	Supply: inlet/outlet piping			EQ9
	Intra piping			EQ10
Transfer	Pumps	Refrigerant Pumps	Mechanical pumps used in the closed-circuit ammonia refrigeration system	EQ11
	Compressors	Rotary vane booster compressor		EQ12
		Reciprocating	Booster	EQ13
			High stage compressor	EQ14
		Rotary screw	Booster	EQ15
			High stage compressor	EQ16
		Centrifugal	Booster	EQ17
			High stage compressor	EQ18
	Transfer interface	Loading and unloading equipment	Charging Hoses	EQ19

Group of Equipment	Main Category	Name of Equipment	Type of Equipment	Code
Other	Valves	Refrigerant Valves	Solenoid valves	EQ20
			hand-operated stop valves	EQ21
			thermostatic expansion valves;	EQ22
			automatic expansion valves;	EQ23
			highside float valves;	EQ24
			lowside float valves;	EQ25
			oil drain float valves	EQ26
			automatic liquid refrigerant drain valves;	EQ27
			evaporator pressure regulators;	EQ28
			hot gas bypass regulators;	EQ29
			check valves;	EQ30
			motorized valves;	EQ31
			flow regulators;	EQ32
			refrigerant-containing pats of pilot operated	EQ33
			and refrigerant pressure actuated condensing water regulators.	EQ34
	Control	Controls Electric & Pneumatic	Sensing devices	EQ35
	Pressure relief	Pressure Relief Devices	Pressure relief devices installed in pressure vessels.	EQ36
	Indicators	Visual Indicators	Bull's eyes, tubular glass and flat "armored gas" linear sight glasses/sight columns	EQ37
	Purge	Purge System		EQ38
	Filters	Oil Filters		EQ39

APPENDIX D

ACTIVITIES CLASSIFICATION

Activity Type	Ammonia Refrigeration System	Code
Chemical	none	ChO
Electrochemical	none	EIO
Physical	Evaporation, compression, condensation, expansion and filtration of ammonia	PhO

APPENDIX E

CLASSIFICATION OF HAZARDOUS SUBSTANCES

S/No	Category
1	Very toxic
2	Toxic
3	Oxidizing
4	Explosive
5	Flammable liquid
6	Highly flammable liquids
7	Extremely flammable gases and liquids
8	Dangerous for the environment
9	Any classification: reacts violently with water
10	Any classification: contact with water liberates toxic gas

APPENDIX F

LOSS EVENT DATABASE

No.	Loss Event	Description	Code
1	Fire	Combustion of flammable substance with thermal radiation effects	LE1
2	Explosion	Rapid combustion of flammable vapor with generation of heat radiation as well as overpressure effects	LE2
3	Physical Explosion	Release of physical energy with generation of overpressure as result of rupture of system under pressure	LE3
4	Pipe leak rupture	Release of substance as a result of loss of containment of the pipe	LE4
5	Tank leak rupture	Release of substance as a result of loss of containment of the tank	LE5
6	Vessel collapse	Structural damage of the vessel due to internal or external forces	LE6
7	Release substance to water	Loss of containment and direct release of substance to water bodies	LE7
8	Release substance to ground	Loss of containment and direct release of substance to ground	LE8
9	Other	Any other event leading to losses	LE9

APPENDIX G

DATABASE FOR INITIATING EVENTS

#	Process Upsets	Code	Deviation-Hazardous event
1	Overfilling	PU1	Increase Level-Temperature - Two phase flow in compressors/ no flow to compressors
2	Overpressure	PU2	Directly leads to loss event
3	Flash evaporation	PU3	Vapor generation, cooling down
4	Condensation/Cooling	PU4	Vacuum generation
5	Incompatibility of the substances and/or containment	PU5	Unwanted effects, chemical reaction or heat effects
6	Errors in operation	PU6	Operation deviation wich may lead to loss event
7	Rapid change of condition	PU7	Weaknesses of material structure

#	Technical Failure	Code	Deviation-Hazardous event
1	Vessel/piping/equipment failure	TF1	Loss of physical integrity and accidental event
2	Failure/malfunctioning of BPCS (any element)	TF2	Change of operating conditions leads to deviation and hazardous event or interruption of business
3	Alarm system failure	TF3	No reaction for the deviation
4	Failure of SIS	TF4	Failure to shurdown or ESD and release trough physical protection system or accidental release
5	Failure of active system (sprinkler system, supression system)	TF5	Hazardous event formation
6	Failure of physical protection (i.e.PSV)	TF6	Accidental release of substance
7	Passive protection failure	TF7	Increase impact event
8	Corrosion (Internal or external)	TF8	Attenuation of durability leading to failure of equipment and accidental event
9	Stress material	TF9	Attenuation of durability leading to failure of equipment and accidental event
10	Material defect	TF10	Degradation of material strenght
11	Thermal load or heavy load	TF11	Stresses, Reduction of durability
12	Failure of sealing or packing	TF12	Accidental event
13	Failure caused by vibration/hydraulic hammer	TF13	Treakness of the construction materials

#	Human Failure	Code	Deviation-Hazardous event
1	Exceeding prescribed limits	HR1	Reduction of reliability and durability of components
2	Failure to follow prescribed procedures and neglet of obvious safe practice	HR2	Creation of different intermediate deviation and hazardous events
3	Improper use of tools, equipemnt, facilities	HR3	Creation of different intermediate deviation and hazardous events
4	Design and sofware errors	HR4	Operating difficulties and possibly for different failures and errors
5	Errors in construction	HR5	Further failures and hazardous events
6	No reaction on alarms	HR6	Development of accident event sequence
7	Accidental faulty disconnection or connection	HR7	Process upsets and technical failures

#	Management Oversights	Code	Deviation-Hazardous event
1	No safety policy	MO1	No systematic approach and generation of errors and oversights
2	Inadequate and7or unclear procedures	MO2	Operator errors and process failure
3	Inadequate training	MO3	Lack of knowledge and improper behavior in hazardous situtations
4	Inadequate or lack of supervision	MO4	Facility in error making
5	No or inadequate audits	MO5	No environment for improvements
6	Management organization inadequate and no set up of range responsibilities	MO6	Lack of supervision
7	No internal comunication	MO7	Lack of knowledge, error repeating
8	Inadequate or lack of process hazard analysis	MO8	In proper decision making process concerning layer of protection
9	Inadequate or poor design	MO9	Process upsets and/or technical failures
10	Poor housekeeping	MO10	Hazards not recognized

#	External events	Code	Deviation-Hazardous event
1	Sabotage/ terrorism	EE1	Accident event and further impac event
2	Arson	EE2	
3	Impact event	EE3	
4	External fire	EE4	
5	Domino effect	EE5	Secondary accident event
6	Hurricane/Tornados	EE6	
7	Flooding/snow fall	EE7	

APPENDIX H

CODIFICATION FOR INDEPENDENT PROTECTION LAYERS

LAYER OF PROTECTION		
Prevention Layer	Safety system	Acronym
	Process design	GEP, INH, SAF
	BPCS (Detector-logic solver-active element) in DCS, mBPCS manual	TAL, LAHL, TSH, PSH, LOC, RPM
	Operator supervision and intervention alarm	OP
	Back up system	BuS
	Cathodic protection system	CPS
	Explosion proof equipment	EX
	Inertizing and solution	IN-DIL
Protection layer	Automatic SIS-TRIPS and isolation system	SD, ESD
	Critical alarms	CA
	Physical Protection	
	Double containment	DC
	Relieve valve/ venting	RV/VEN
	Dumping	DU
	Pressure safety element	PSE
	Grounding – bounding	GG – BG
	Emergency cooling	EC
	Dikes	DI
	Material disposal system – flares, scrubber/adsorber, incinerator, sewage	MDS
	Passive system (fire walls/explosion walls)	FW/EXW
	Fireproofing and blast resistance material and structures	FPRS
	Fire and gas detector system	F&GD
	Flame arrestors	FA
	Detonation filter	DF
	Inhibitor trip system	ITS
Mitigation layer	Plant emergency response (active system:	
	Fire suppression system	FSS
	Fire fighting system	FFS
	Personal protective equipment	PPE
	Community response, fire brigade	FB

APPENDIX I

SCENARIO CLASSIFICATION

SCENARIO 1 IDENTIFICATION

	Group of equipment	**Main Category**	**Name of Equipment**	**Type of Equipment**	**Code**
Equipment Classification	Transfer	Transfer Interface	Loading and unloading equipment	Charging Hoses	EQ19

	Type of equipment	**Activity/Process**	**Code**
Activity Classification	Process Equipment	Physical Operation	PhO

	Substance	**Hazards**	**Code**
Substance Class	Ammonia Anhydrous	Toxic, Explosive, Flammable	S1

	Type of Loss Event	**Code**
Loss Event Selection	Release substance to ground	LE8

	Category	**Description**	**Code**
Initiating Event Classification	Human error	Accidental Faulty Disconnection or connection	HR7

	Category	**Code**
IPLS	Operator supervision and intervention on alarm	OP

Final code scenario 1: EQ19-PhO-S1-LE8-HR7-OP

SCENARIO 2 IDENTIFICATION

Equipment Classification	**Group of equipment**	**Main Category**	**Name of Equipment**	**Type of Equipment**	**Code**
	Transfer	Pumps	Refrigerant Pump	Mechanical pump	EQ11

Activity Classification	**Type of equipment**	**Activity/Process**	**Code**
	Process Equipment	Physical Operation	PhO

Substance Class	**Substance**	**Hazards**	**Code**
	Ammonia Anhydrous	Toxic, Explosive, Flammable	S1

Loss Event Selection	**Type of Loss Event**	**Code**
	Tank leak rupture	LE5

Initiating Event Classification	**Category**	**Description**	**Code**
	Human Failure	Improper use of tools, equipment and facilities	HR3

IPLS	**Category**	**Code**
	PSV	RV

Final code scenario 2: EQ11-PhO-S1-LE5-HR3-RV

SCENARIO 3 IDENTIFICATION

	Group of equipment	Main Category	Name of Equipment	Type of Equipment	Code
Equipment Classification	Transfer	Pumps	Refrigerant Pump	Mechanical pump	EQ11

	Type of equipment	Activity/Process	Code
Activity Classification	Process Equipment	Physical Operation	PhO

	Substance	Hazards	Code
Substance Class	Ammonia Anhydrous	Toxic, Explosive, Flammable	S1

	Type of Loss Event	Code
Loss Event Selection	Tank leak rupture	LE5

	Category	Description	Code
Initiating Event Classification	Technical Failure	Failure of sealing	TF12

	Category	Code
IPLS	Operator supervision and intervention on alarm	OP
	BPCS, low level shutdown	LLS

Final code scenario 3: EQ11-PhO-S1-LE5-TF12-OP-LLS

SCENARIO 4 IDENTIFICATION

Equipment Classification	**Group of equipment**	**Main Category**	**Name of Equipment**	**Type of Equipment**	**Code**
	Storage	Pressure storage	Transfer Station	Pressure vessel	EQ1

Activity Classification	**Type of equipment**	**Activity/Process**	**Code**
	Process Equipment	Physical Operation	PhO

Substance Class	**Substance**	**Hazards**	**Code**
	Ammonia Anhydrous	Toxic, Explosive, Flammable	S1

Loss Event Selection	**Type of Loss Event**	**Code**
	Tank leak rupture	LE5

Initiating Event Classification	**Category**	**Description**	**Code**
	Technical Failure	Failure of BPCS element	TF2

IPLS	**Category**	**Code**
	Operator supervision and intervention on alarm	OP
	BPCS, pressure alarm	LPA

Final code scenario 4: EQ1-PhO-S1-LE5-TF2-OP-LPA

VITA

Name	Gerald Zuniga Reyes
Address	Jack E. Brown Eng. Building, Office 422, Texas A&M University
Email address	gerald.zuniga@gmail.com
Education:	B.S., Chemical Engineering, Universidad Nacional de Colombia, 1997 M.S., Chemical Engineering, Texas A&M University, 2008