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공학박사학위논문

Risk-based Process Safety Management in Industrial Process System

위험성에 기반한 산업공정시스템의 공정안전관리

2017년 8월

서울대학교 대학원

화학생물공학부

신 서 린

Abstract

Risk-based Process Safety Management in Industrial Process System

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Quantitative risk management was introduced to industrial process system at the late 1970s. At first, the number of incidents has decreased drastically until 1995, but after that time it shows an irregular pattern and even grows more than minimum value. Not only the growth of plant's number and facilities' deterioration affect on the number of accidents, but also operating conditions, which get complex for reducing energy or cost per product, have a strong influence on it. Furthermore, consequence of accidents increases because of population growth. Thus, an effective method for process safety management is necessary. Also, to be efficient, it should be specific for each system.

This thesis addresses risk-based process safety management in industrial process system. It is composed of storage, transportation, and process parts, and each process deals with solid, liquid, and gas phase materials respectively.

First part is coal silo. Due to the fact that coal stacked in the open air not only causes environmental issues, but also degradation in quality, coal became to be stored in a silo. However, the confined nature of the silo stimulated many coal dust explosions and these explosions has been repeating. Thus, to prevent these accidents, detailed cause of a specific dust explosion in silo is analyzed according to the pentagon of dust explosion in terms of design and operation of the silo. After presenting the general properties of coal dust and explosion cases, coal of a scene of the accident is compared. Through cause analysis, it is reasoned that what should be prepared or how to operate coal silo.

Second part is transportation through underground pipeline. Due to the long term usage and irregular maintenance for corrosion checks, catastrophic accidents have been increasing in underground pipelines. In this study, a new safety management methodology of underground pipeline, risk-based pipeline management, is suggested reflecting corrosion effect. First, principle of the risk-based pipeline management is suggested compared with an original method, qualitative measure. It is distinguished from the existing method by reflecting societal risk and corrosion in safety management of underground pipeline. And then, it is applied to an existing underground propylene pipeline in Ulsan Industrial Complex, South Korea. As a result of applying the risk-based pipeline management, risk integral is reduced by 56.8% compared to the qualitative measure. Finally, sensitivity analysis is conducted on variables, which affect the risk of the pipeline. This study would contribute to introduce quantitative measure to pipeline management and increase safety of pipeline.

The last part is gas treatment unit (GTU) in gas oil separation plant (GOSP). QRA only considers normal operating conditions so far. However, real plants are operated

with variables' trip. The objective of this study is to identify the effect of operating condition change on QRA. The methodology of dividing operating condition is introduced and applied to the GTU process. As a result, flow rate change barely affects on FN-curve. However, the changes of pressure and temperature increase the risk to 147% of normal condition with GTU process in GOSP. Thus, it can be concluded that when a process deals flammable material of high pressure or high temperature, QRA should reflect operating condition change. This study could contribute to improve accuracy of QRA.

Keywords: Quantitative risk assessment (QRA); Process safety management; Coal dust explosion; Underground pipeline; Corrosion; Dynamic risk assessment (DRA); Dynamic simulation

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CHAPTER 1 : Introduction

1.1. Research motivation

Quantitative risk management was introduced to industrial process system at the late 1970s [1]. Khan et al. analyzed past process accidents, which had damaged extensively [1]. At first, the number of incidents has decreased drastically until 1995, but after that time it shows irregular pattern and even grows more than minimum value (Figure 1-1). Also, Marsh research (Figure 1-2) shows that recent scale of damage is increased compared to the late 1970s [2]. This is because, not only the growth of plant's number and facilities' deterioration affect on the number of accidents, but also operating conditions, which get complex for reducing energy or cost per product, have a strong influence on it. Furthermore, consequence of accidents increases because of population growth. Thus, efficient and effective method for process safety management is necessary to prevent damage in industrial process system. Also, since process get complex, it should be specific for each system.

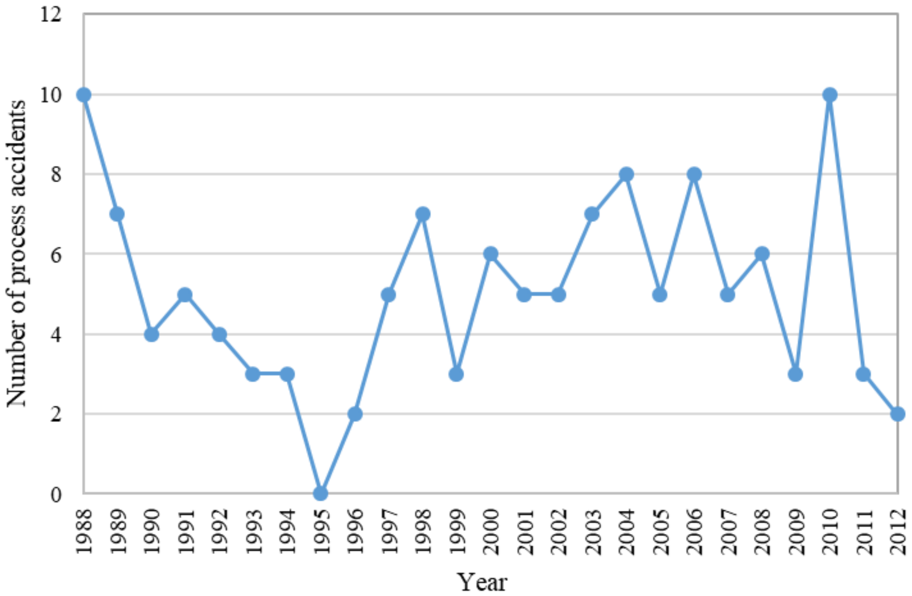


Figure 1-1. Process accident trend from 1988 to 2012.

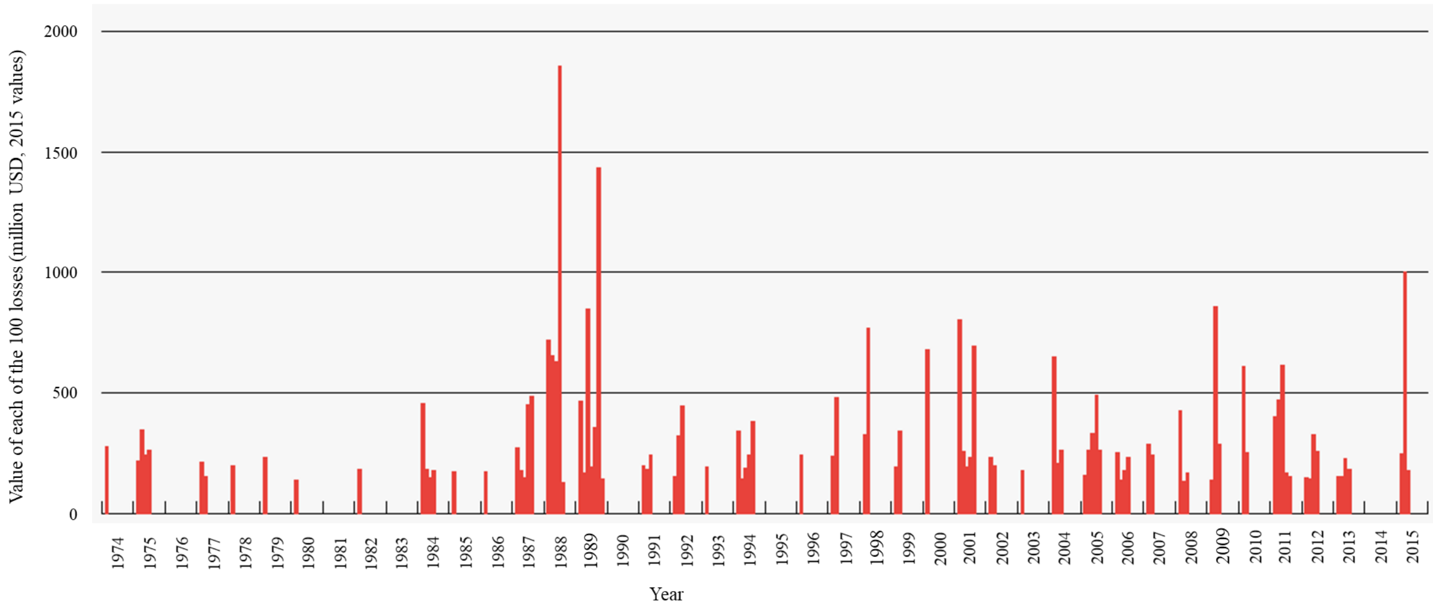


Figure 1-2. Distribution of the 100 largest losses.

1.2. Research objectives

The scope of this thesis is to apply risk-based process safety management in industrial process system. Industrial process system can be divided into storage, transportation, and process parts. Since process has get complex gradually, it is not effective to apply a single methodology of process safety management to all of the systems. Thus, representative systems are chosen for suggesting process safety managements from storage, transportation and process respectively. Also, in each part, solid, liquid, and gas are dealt individually to consider every phases. Object for each part is selected based on severity of the problem.

In storage part, dust explosion is treated. Dust explosions have occurred in succession and led to serious losses [3]. Among many flammable dusts, which could cause dust explosion, coal dust is picked out because coal is used in various industrial systems and has distinctive property, spontaneous ignition. Furthermore, coal dust explosion damages the severest harm for humans (Figure 1-3); 0.5 deaths and 3.2 injuries per accident [3]. Since coal demand keeps the status quo or decreases slightly or decreases slightly until 2030s [4, 5], demand of coal silo would stay constantly. Thus, safety of coal silo should be focused.

Next, transportation through underground pipeline is dealt. There are many other means of shipment for gas and oil, such as truck and ship. However, the portion of shipment through pipeline is large and the length of worldwide pipeline is about 3,500,000 km [6]. Compared to the amount of pipeline used, risk is scarcely managed; management criteria are mostly semi-quantitative and do not conduct risk assessment for accident case. Especially, underground pipelines are exposed to severer corrosion than over-ground pipelines [7]. Thus, methodology for pipeline safety management is concerned considering corrosion effect.

Lastly, specific operating condition change leads to others change, and these are not steady state but dynamic state. However, quantitative risk assessment (QRA) has been conducted only for steady state, normal condition. Thus, in process part, an effect of operating conditions change on QRA is analyzed. The object is gas treatment unit (GTU) in gas and oil separation plant (GOSP).

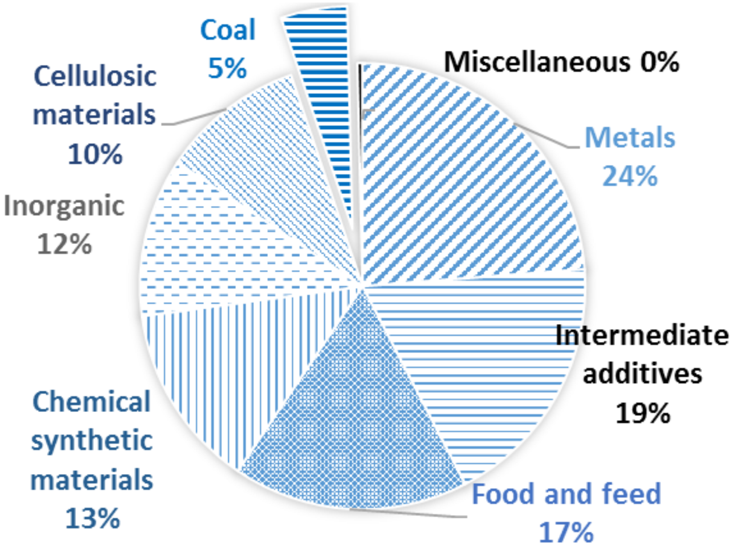


Figure 1-3. Ratio of dust explosion according to materials.

1.3. Outline of the thesis

Motivation and objectives of this thesis is presented in Chapter 1. Chapter 2 provides a cause analysis of a coal dust explosion case in coal silo. Based on this, methodology of process safety management is suggested. In Chapter 3, a risk-based underground pipeline safety management is suggested considering corrosion effect. For case study, an existing propylene pipeline information is applied. Chapter 4 describes an effect of operating condition changes on quantitative risk of process is considered focused on gas treatment unit in gas oil separation plant. Chapter 5 presents the conclusion and an outline for the future works.

CHAPTER 2 : Cause analysis of a dust explosion in coal silo*

(In this Chapter, specific information and data are removed for security reasons.)

2.1. Introduction

Coal is one of the most widely used fuels in the world, and it is classified into four classes by ASTM (American Society for Testing and Material) depending on the carbon, moisture, volatile matter contents, etc. as shown in Table 2-1 [2, 3]. Anthracite, which ranks highest among the coals, burns slowly and releases heat uniformly, but it cannot produce a coke, thus it has been used as domestic fuel mostly. Also, unlike the other coals, it is distributed unequally and reserved in small quantities, so that it rarely used in industry [2, 4] The other three coals, bituminous, sub-bituminous, and lignite, are employed in industry to generate electricity or make cokes, etc. Especially, demand of sub-bituminous has been increased from the 1970s to meet a standard of natural environment because of the lowest sulfur content among coals [4].

* The partial part of this chapter is taken from the report [1], in which the author participated.

Table 2-1. Composition and property ranges for various ranks of coal.

Rank	Anthracite	Bituminous	Sub-Bituminous	Lignite
Carbon (%)	75-85	65-80	55-70	35-45
Moisture (%)	3-6	2-15	10-25	24-45
Volatile matter (%)	2-12	15-45	28-45	24-32
Sulfur (%)	0.5-2.5	0.5-6	0.3-1.5	0.3-2.5
Ash (%)	4-15	4-15	3-10	3-15

These three industrially-used coals had been piled in yards in the past, but stacking in the air decreases the quality of coal because of slacking, oxidation, and combustion [4]. Furthermore, as concerns about environment has been increased, dispersion of coal dust should be prevented in the fields. Thus, storing coal in silo has proposed. Advent of coal silo is innovative because it can save a lot of coal in small area, prevent air pollution, and keep higher thermal efficiency by control of moisture, gas content, and temperature. However, the coal storage in the silo also has the problem. Because coal is combustible material, accumulation can cause the gas explosion or dust explosion. Volatile materials contained in coal, such as methane and carbon monoxide, trigger the gas explosion when the temperature and gas concentrations are satisfied. The conditions of the gas explosion are presented on Table 2-2 [6]. To be more concrete than lower flammable limit (LFL) or upper flammable limit (UFL), the compositions of explosive gas, oxygen, and nitrogen for gas explosion can be presented on triangular diagram. While, the coal dust explosion happens when five conditions, which are shown on Figure 2-1, are satisfied [6]. In terms of ignition temperature and fuel concentration, the conditions of gas explosion are harsher than the ones of dust explosion in the coal silo. Thus, it can be said that the probability of the coal dust explosion is higher than one of the gas explosion. Both explosions cause severe problems in industry, but this paper focuses on the dust explosion of coal.

Table 2-2. The conditions of the gas explosion.

	LFL (vol.%)	UFL (vol.%)	Autoignition temperature (°C)
Methane	5.0	15.0	600
Carbon monoxide	12.5	74.0	609

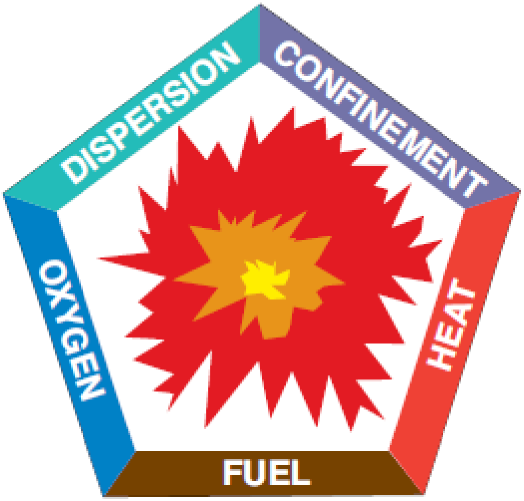


Figure 2-1. The dust explosion pentagon.

Dust explosion has attracted public attention from the 1780s, but methodical records have been found from the early 20^{th} century [7]. In the initial phase, the issue were like now; property and explosibility of dust, prevention method, and so on [8, 9]. The difference so far is that less deliberate results were obtained at that time. Cashdollar experimented with coal dust in 20 L chamber and gained its property data, which agreed with large-scale tests [10]. Douberly presented qualitative guidelines about fire prevention and detection, firefighting equipment, and training and firefighting [11]. Equipment types for fire prevention, such as CO monitoring, thermal monitoring, infrared scanning, and typical firefighting agents, are introduced, but it was not quantitative approach. While relief systems for silo protection against dust explosion were developed and integrated in the German and Euro code [12]. Abbasi et al. collected and organized cases, causes, consequences, and control of dust explosion in 2007 [7]. It is reported that coal took up 10% of dust explosions in USA. Reyes et al. proposed equations to calculate K_{st} (dust deflagration index) and P_{max} (maximum overpressure) quantitatively about pure substances [13]. This model cannot be adapted to coal, which is the mixture of carbon, hydrogen, sulfur, and so on. Vented silo designed with NFPA 68 and EN 14491 was simulated using CFD, the DESC code, and compared [14], and the DESC code simulating the effect of vent ducts on dust explosions were validated [15]. While dust explosion occurrence probability was computed by Hassan et al [16]. To sum up, so far coal properties have been researched and existing code only focusing on the explosion vent have been studied using CFD. Also, there are a few studies of silo design, but these are not coal specific or not quantitative and do not deal with operation. Since coal demand keep the status quo until 2030s [17, 18], the demand for the coal silo would holds steady. The problem is that there are no overall codes or guidelines to prevent dust explosion in the coal silo.

In this Chapter, cause analysis is conducted for a dust explosion in coal silo. And, based on this, process safety management for coal silo is presented. First, the general properties of coal dust and explosion cases are reviewed. Next, collected coal from the scene of an accident is analyzed. (Unfortunately, location or information of the accident is disclosed because of security problem.) And then, causes of the accident are analyzed and methodologies to prevent dust explosion in coal silo are suggested. This research would contribute to not only reduce the number of coal dust explosion, but also increase safety of other silo, which have a risk of dust explosion.

2.2. Coal dust explosion

According to national fire protection association (NFPA), dust is defined as solid, which diameter is smaller than 420 μm [19]. While, coal dust, which satisfies this size condition, is produced by drying, spalling, decrepiation, slacking, or etc. This dust brings about dust explosion when the five conditions (dust explosion pentagon, Figure 2-1) are fulfilled; fuel, dispersion, confinement, oxygen, and heat. That is, dust explosion can occur when coal dust exists in sufficient oxygen, and is dispersed in an enclosed space with heat source. Detailed conditions of dust explosion pentagon are related with minimum explosible dust concentration (MEC), minimum oxygen concentration (MOC), minimum ignition energy (MIE), minimum ignition temperature of dust cloud (MIT), and minimum ignition temperature of dust layer (LIT) (Table 2-3 [5, 20, 21]). MIE of coal (60 mJ) is relatively larger than other flammable dusts, such as aluminum (10 mJ). However, since dust, which has MIE less than 100 mJ, could ignite from weak electrostatic sources [22], coal should be managed well not to produce or accumulate electricity. Furthermore, ignition temperature get lower about less than half if the dust forms layer (LIT) rather than dispersed in the air (MIT), and LIT decreases as layer thickness of coal dust increases [21].

Table 2-3. Important parameters of dust explosibility.

Parameters	Unit	Values
MEC	g/m^3	40-60
MOC	Vol.%	10.5-15
MIE	mJ	60
MIT	°C	500-556
LIT	°C	180-240
P_{max}	barg	6.0-9.0
K_{st}	bar m/s	85-210
$(dP/dt)_{max}$	bar/s	300-400

Meanwhile, the intensity of dust explosion is connected with maximum explosion pressure (P_{max}), dust deflagration index (K_{st}), and maximum rate of pressure rise ($(dP/dt)_{max}$) [23] (Table 2-3). P_{max} is ranged about from 6 to 9 barg. K_{st} is divided into four class (St 0, St 1, St 2, and St 3) and coal usually belong to St 1 (less than 200 bar·m/s of K_{st}), which causes weak explosion [24]. However, some sub-Bituminous or Bituminous coal are affiliated with St 2 (200-300 bar·m/s) resulting in strong explosion. The explosibility increases as diameter of dust decreases. Also, early pressure, oxygen concentration, and temperature affect on the intensity of the explosion [10].

Dust explosion cases are collected and shown on Table 2-4. There are 35 coal dust explosions from 1978 to 2014 [7, 25, 26]. These accidents result in damage of property, human life, and environment. Naturally, since other four conditions are inevitable in coal silo, heat is the major trigger factor, although many causes of them are unknown yet. Mannan analyzed ignition sources [27]. There are fire or flame, sparks from electrical equipment, welding and cutting, static electricity, spontaneous combustion, and lightening. However, when coal dust explosion cases are analyzed, there are only hot surface, spontaneous ignition, fire or flame, and sparks from electrical equipment (Figure 2-2).

While, spontaneous ignition is characteristic property of coal. The process of it is like below [28]. First, oxygen is adsorbed onto coal. And then, coal and oxygen are chemically adsorbed each other, thus coal-oxygen complex is formed between room temperature and 70 °C. This complex goes through oxidation, which is exothermic reaction, and releases gaseous products. Since coal is insulator [11], heat is accumulated among oxidized coal. Thus far, it is slow reaction, in which temperature is less than 230 °C. However, after this, thermal runaway happens and coal reaches spontaneous combustion. These reactions are affected by moisture ratios of coal and atmosphere.

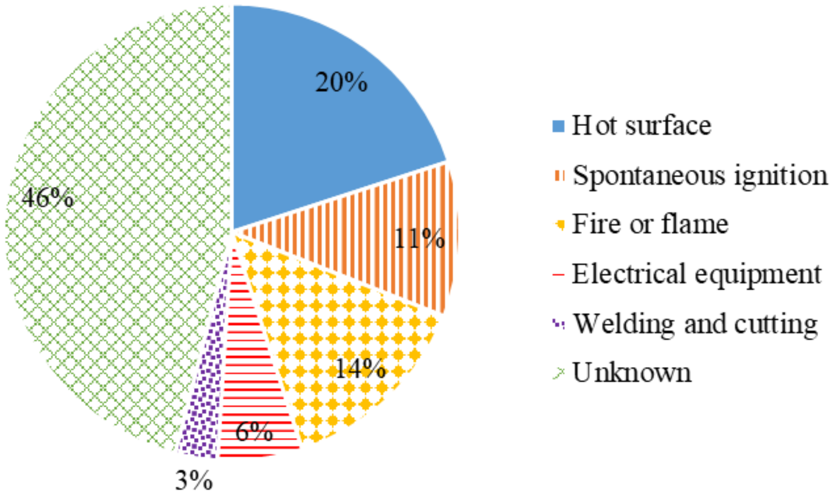


Figure 2-2. Ignition sources of dust explosion.

Table 2-4. Coal dust explosion cases.

Date	Location	Plant/Building	Dead /Injured	Cause	Reference
2000	USA	Charcoal storage area	1/0	Fire	CSB, 2006
2001	USA	Electric Services	No data	Unknown	CSB, 2006
2002	USA	Electric Services	1/0	Fire	CSB, 2006
2002	USA	Electric Services	No data	Hot surface	CSB, 2006
2003	USA		0/1	Unknown	CSB, 2006
2004	USA	Power plant	0//0	Unknown	CSB, 2006
2004	USA	Power plant	0/0	Unknown	CSB, 2006
2004	USA	No data	0/0	Unknown	CSB, 2006
2005	USA	Cement plant	0/0	Unknown	CSB, 2006
2007	South Korea	Power plant	No data	Spontaneous ignition	KOSHA
2009	USA	Power plant	0/5	Unknown	CSB, 2006
2011	South Korea	Cement Factory	No data	Spontaneous ignition	KOSHA
2011	USA	Coal silo	2/1	Unknown	CSB, 2006
2014	South Korea	Coal silo	0/0	Unknown	KOSHA

2.3. Coal analysis of the scene of accident

Object coal was obtained from the scene of an accident about a week later in the accident. As mentioned in section 2.1, the accident information cannot be revealed due to security concern. The analyses of coal are divided into measures of grain size and volatile elements, properties related with spontaneous combustion, and explosion qualities.

2.3.1. Grain size and ingredient analysis

For grain size analysis, laser diffraction particle size analyzer (Beckman coulter LS 13320) was used and average value of three measurements are presented. The volume ratio according to particle diameter is shown on Figure 2-3. The diameter is ranged from 0.4 to 2000 μm and average one is 642 μm. Generally, lower explosion limit (LEL) get lower and explosion pressure get higher as particle size decreases. Since the diameter is distributed over a wide range, LEL would be lower and explosion pressure would be higher in some area where particle is relatively smaller than other area.

Next, components' information is offered by distributor, and the coal has 39.13% volatile materials (air dried basis), and 24.63% moisture.

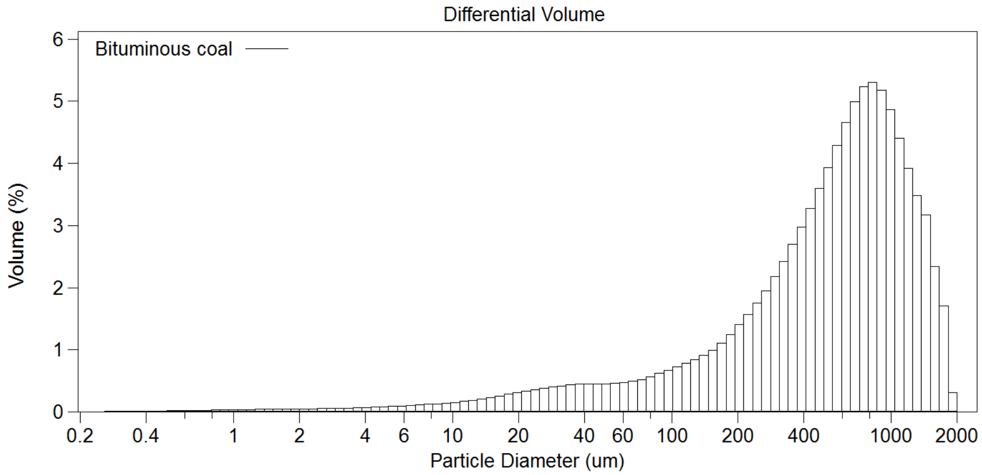


Figure 2-3. Result of grain size analysis.

2.3.2. Properties related with spontaneous ignition

In the silo, coal dust forms layer when there is no air current. This accumulated layer and dispersed dust in air can both trigger spontaneous combustion. While, if moisture in coal vaporizes, coal can save heat, since heat conductivity is decreased. Because removing coal (fuel) and air (oxygen) completely, which are conditions of spontaneous combustion, is impossible in the silo, the possibility of spontaneous ignition exists always. Thus, temperature of spontaneous ignition should be identified for managing coal silo. In this section, minimum temperature of spontaneous combustion is measured for dust layer by differential scanning calorimeter (DSC) and thermos gravimetric analysis (TGA), and dispersed dust by IEC 61241-2-1.

The result of DSC is shown on Figure 2-4. Around 40-100 °C, heat absorption is observed, which would be caused by evaporation of water. Definite exothermic reaction is presented from 236 to 522 °C, and the peak point is located at 418 °C. Thus, it can be said that 236 °C is identified as LIT by DSC. While, Figure 2-5 shows weight decreases according to increasing temperature of TGA. In the section, which temperature is less than 100 °C, evaporation of moisture causes losing weight. Between 200 and 500 °C, weight losses, and heat flow above 250 °C decreases drastically. The losses of this section (200-500 °C) are led by pyrolysis of volatile materials and fixed carbon. Above 500 °C, weight scarcely decreases because there are ashes. The result of TGA shows that ignition temperature of object is 250 °C and one of DSC does that it is 236 °C. Thus, we can conclude that estimated LIT are around 236-250 °C.

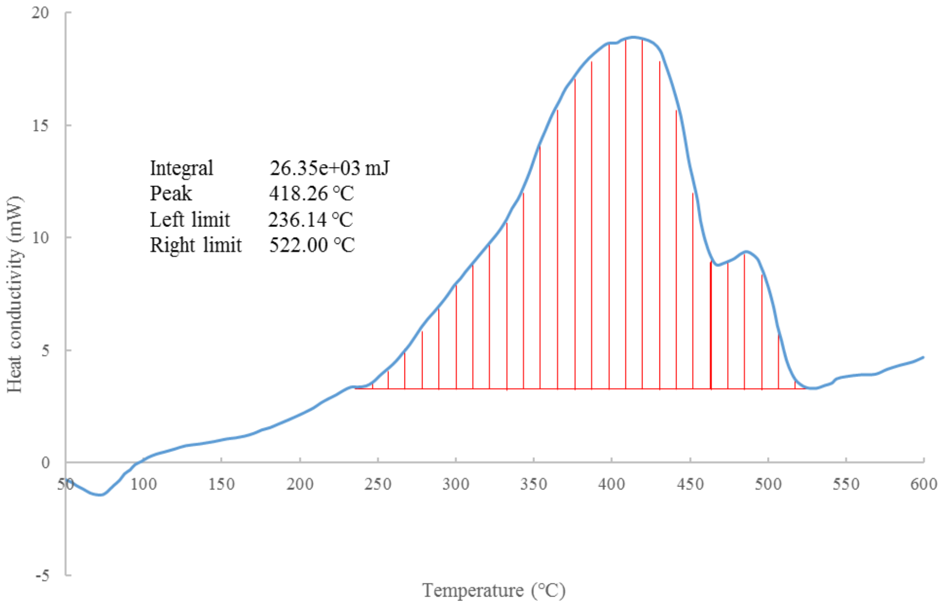


Figure 2-4. Result of DSC.

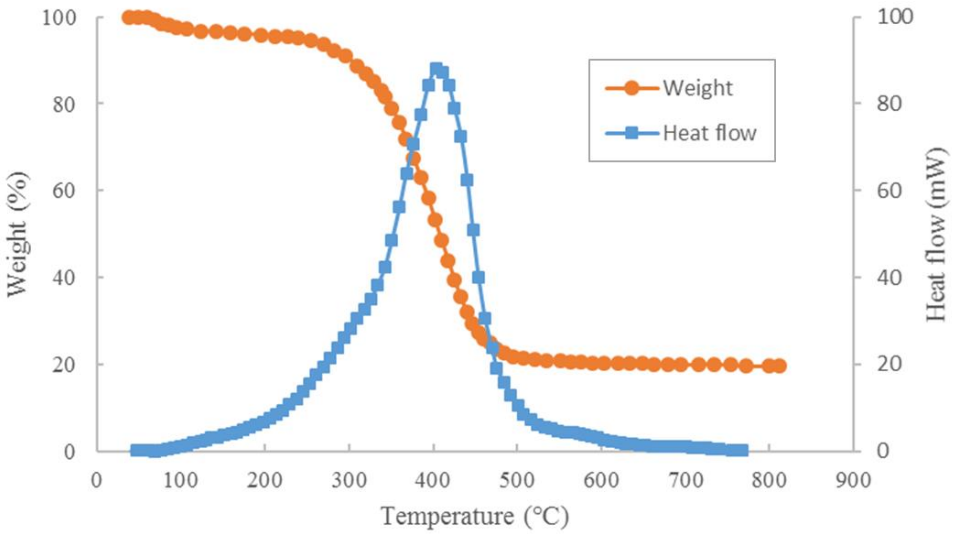


Figure 2-5. Result of TGA.

Meanwhile, MIT, minimum temperature of spontaneous ignition for dispersed dust, is measured based on the standard test specification (methods for determining the minimum ignition temperature of dust (IEC 61241-2-1)). It depends on dust concentration and is shown on Figure 2-6. Dust concentration of 500 g/m^3 shows the lowest MIT (600 °C). Less than 500 g/m^3, MIT increases as dust concentration decreases. It is because increasing distance of dust molecules less than 500 g/m^3 needs more pyrolyzed gases to be ignited. That is why more energy is required, which causes MIT to increase. On the other hand, in concentrations above 500 g/m^3, spaces between molecules are reduced with increasing concentration, which brings about decreasing oxygen for ignition per combustible material and increasing unburned substances. Except dust concentration, MIT also depends on volatile material, moisture content, and contact time with high temperature. This object coal was exposed on the open air for a few days before gathering, thus volatile materials vaporize. Therefore, it could be guessed that actual MIT might be lower than 600 °C.

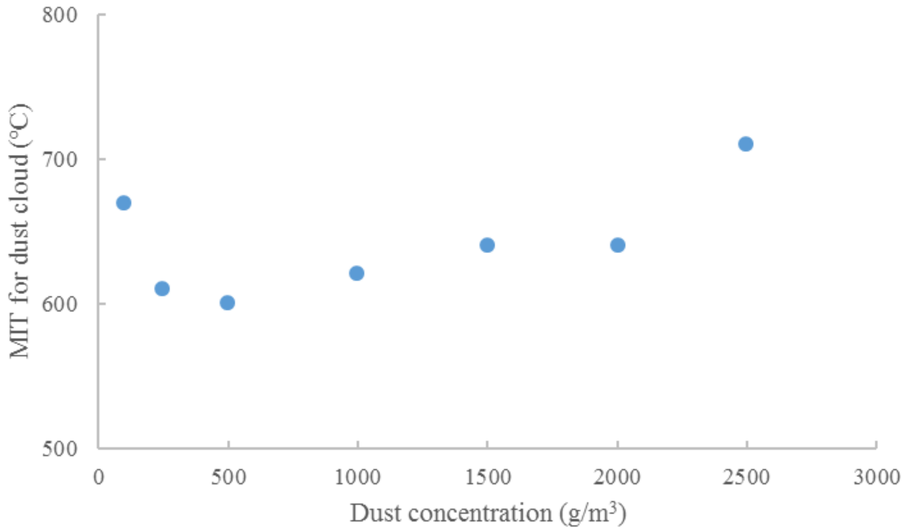


Figure 2-6. MIT according to dust concentration.

2.3.3. Properties related with dust explosion intensity

Particles less than 2 mm (average value is 642 µm) is inserted on Siwek 20 L chamber to confirm properties related with dust explosion intensity (LEL, P_{max}, $(dP/dt)_{max}$, and K_{st}). All the values are averaged one from three checks. LEL is obtained as 40 g/m^3. Next, explosion pressure is increased until it reaches 500 g/m^3, and P_{max} is 6.0 barg (Figure 2-7). Also, $(dP/dt)_{max}$ is 332 bar/s at the same concentration (Figure 2-8). As a result, we can calculate K_{st}, 90.1, according to Eqn. 1.

$$K_{st} = (dP/dt)_{max} \cdot V^{1/3} \quad \text{(Eqn. 1)}$$

Thus, this sample belong to St 1, but as mentioned before, it was collected a few days later, it might have bigger K_{st} value. K_{st} according to coal dust concentration is shown on Figure 2-7.

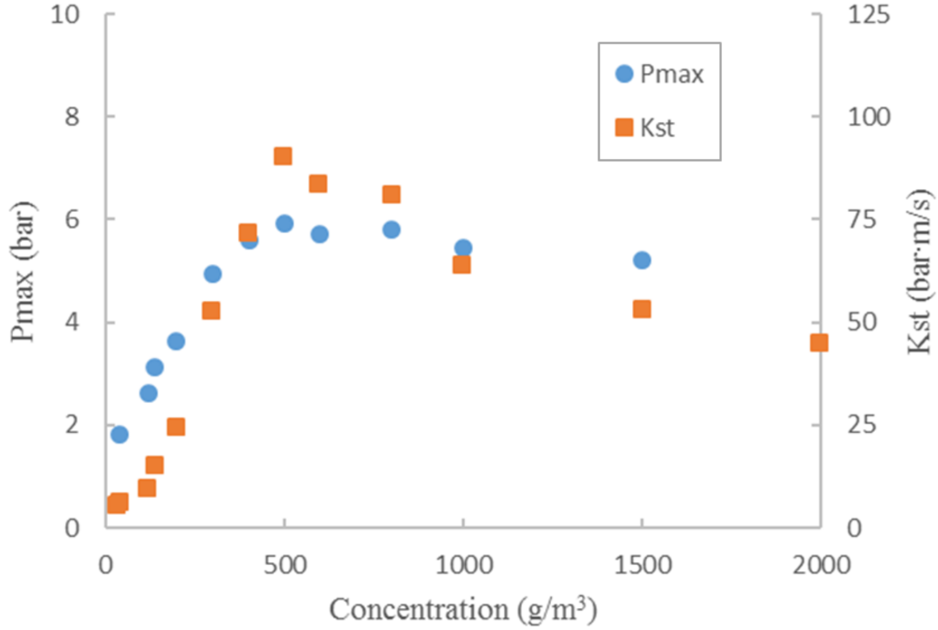


Figure 2-7. P_{max} and K_{st} according to dust concentration.

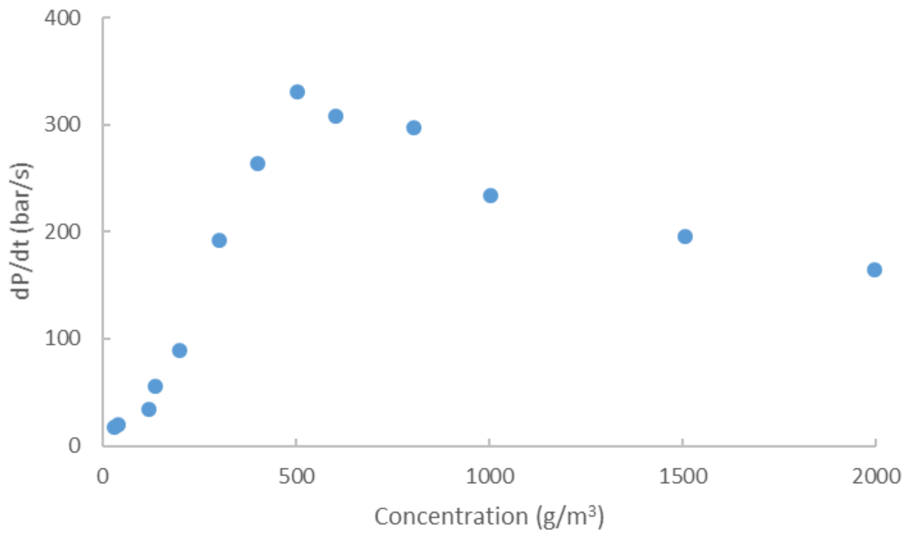


Figure 2-8. $(dP/dt)_{max}$ according to dust concentration.

2.4. Cause analysis of a coal dust explosion

For prevention of dust explosion, it is important to not satisfy condition of the dust explosion pentagon. Although causes of previous accidents are presented in section 2.2, it is not enough to suggest design or operation methodology for coal silo due to lack of information. Thus, in this section, cause of a specific dust explosion case is analyzed. Every condition (except fuel because silo stores flammable material, coal) is viewed from the perspective of structure and operation. Also, spin-off from the explosion, overpressure is considered. Meanwhile, the schematic diagram of the object silo is shown in Figure 2-9. It is classified as a closed silo, and coal is loaded from upside and downloaded from bottom side.

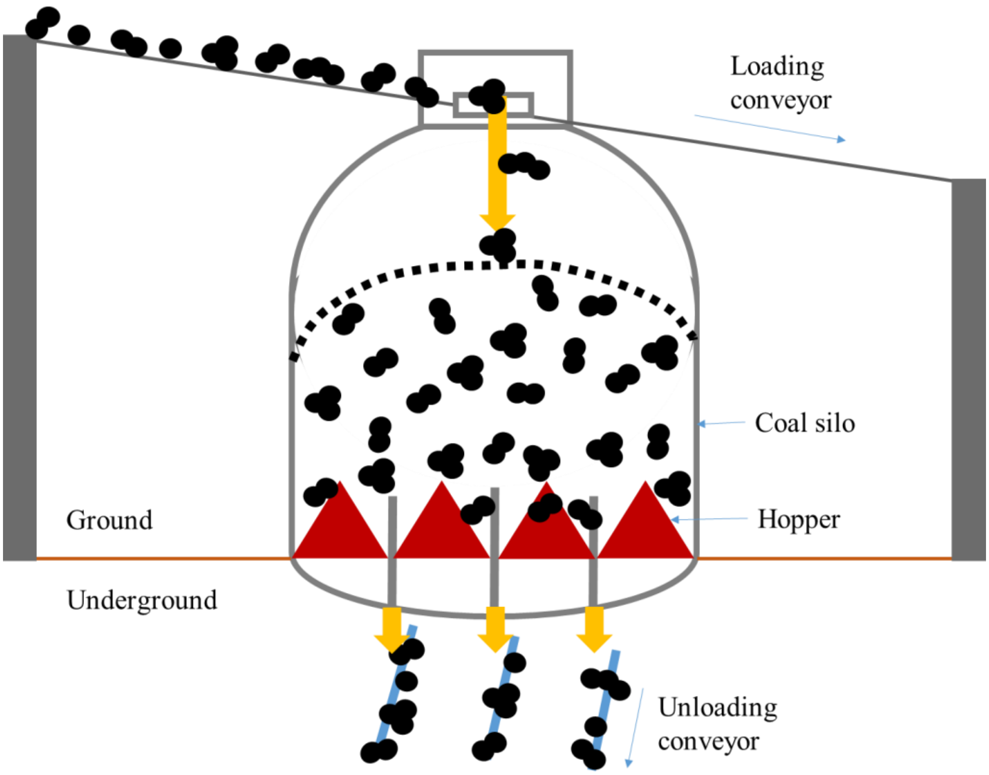


Figure 2-9. Structure of closed silo.

2.4.1. Confinement

Confinement is the most difficult to define, since a small section in a large volume could be dealt as a sealed space for a primary dust explosion. Also, the first explosion could cause additional ones, it is hard to find the primary sealed space. Thus, confinement condition has rarely been searched in the past accidents.

Meanwhile, silo could be divided into two types, open silo and closed one. Through open silo, truck or other means of transportation could enter, while closed silo has relatively small open area compared to open silo. In closed silo, coal is entered through top conveyor (loading system) and discharged through lower hopper (unloading system). Because the object silo was closed one, it could be thought that it had higher probability of confinement compared to open one.

Furthermore, the object had a sliding gate, which was located on the entrance for coal input. It was installed to prevent loss of nitrogen, which is input to decrease the oxygen concentration. Since the sliding gate was closed at the time of accident (Figure 2-10), it seems that this might form confinement condition. Thus, in the perspective of structure, any equipment, which block ventilation and form confinement environment, should be not permitted to install.

Figure 2-10. Closed sliding gate at the time of the incident.

2.4.2. Dispersion

In the process of coal input and output, it is inevitable to avoid dust dispersion. Thus, system of removing dust should be equipped such as water spray and bag filter. NFPA 15 [29] and NFPA 654 [30] could be referred respectively. In this silo, both water spray and bag filter were installed and satisfied specifications. In addition, periodic cleaning could remove dust.

Coal, in which the order of magnitude was 4 tons, had been put into the silo just 3-5 days before the accident. And, the order of 3 tons coal was pulling out at the time of the incident. Thus, it is fair that coal dust had occurred, and water spray and bag filter should have been operated at that time to avoid dust explosion. First, sprinkling water on coal could eliminate not only dust, but also created heat, because water vaporization needs heat. However, only on the second day among three days of injecting coal, about 0.6 % of water compared to coal weight was sprayed out. Also, according to the operation record, one bag filter, which was only located on top of the silo, was operated only several minutes just about two hours before the accident. There was even no regular cleaning. Thus, in sum, coal was mis-handled in dispersion part.

2.4.3. Oxygen

Perfect removal of oxygen would be impossible and unneeded for coal silo. Only keeping oxygen concentrations less than MOC is sufficient to prevent dust explosion. For this, injection system of nitrogen or other inert gases is necessary. The object silo had nitrogen injection system.

While, for monitoring oxygen concentration, sensor is necessary. To determine the number or sensors, commercial simulator, such as detect3D, could be used, which check if there is dead zone or not. Since MOC is about 10.5-20 % for coal, normally coal silo is operated not to exceed 10% of oxygen. According to the operation record, few days before the accident, oxygen concentration was about 18-19% when coal was input to the silo. It would be because oxygen was put together with coal. However, it had decreased slowly, and on the day of accident, it was less than 10%. Because there was a closed sliding gate and were only two oxygen sensors on top of the silo, thus we cannot predict oxygen concentration of lower part. Furthermore, since the accident happened during coal discharge, hopper was open. Nitrogen was input on the first day of coal injection. Thus, it is difficult to say that MOC was not satisfied in the overall silo.

2.4.4. Heat

Previous cause analysis of dust explosion has only focused on heat sources. As shown in section 2.2, heat sources can be divided into hot surface, fire or flame, spontaneous combustion, electrical equipment, and etc. First of all, design of the object silo is analyzed for each heat source. Hot surface can be detected by temperature sensor or IR camera. However, these can only monitor surface, not inside temperature, since coal is insulator [11]. Thus, to check the state of inside coal, carbon monoxide and methane sensors should be installed [11]. Especially, carbon monoxide is important because it is direct evidence of fire. If the concentration of carbon monoxide and methane increase, fire or spontaneous ignition would be progressing. The object was equipped all of these sensors; temperature sensor, gas sensors, and IR camera. Meanwhile, fire extinguishing system for fire or flame, such like liquid nitrogen injection or water spray, should be installed referring to NFPA 15 [29]. Unfortunately, the silo had only water spray. The equipped nitrogen injection system was just for reducing oxygen concentration. Next, extinction of static electricity takes from a few days to a few weeks. Thus, grounding or bounding is necessary. Especially, MIE of coal is about 60 mJ, relatively small value like weak electrostatic sources, grounding is essential. It could be consulted by NFPA 77 [31] and NFPA 499 [32]. However, this silo did not ground. Thus, the silo was not suitable in terms of design.

Meanwhile, in respect of operation, data from sensors are not reliable. Data of temperature sensor and IR camera showed unreasonable value, which cannot be attainable when there was no coal. Thus, it can be said that these equipment had not been managed properly that data is meaningless. In the case of that sensors are working right, silo should be managed with respect to temperature as shown in Table

2-5. First, as coal-oxygen complex is formed between room temperature and 70 °C, 40-70 °C is classified as warning temperature. Thus, in this section temperature should be checked frequently. While, since exothermic reaction (spontaneous ignition) proceeds drastically above 200 °C, all kinds of fire control should be adapted; liquid nitrogen injection, fire extinguishing system, water spray, and etc.

Next, according to the record, concentration of carbon monoxide was 220 ppm. It was the maximum value that the sensor could measure. Moreover, on the site, clinker was discovered, which is the proof of fire. In right operation, concentration of carbon monoxide should be less than 25-40 ppm. Thus, fire was apparent in this silo.

Lastly, although the object silo had equipped electrical instrument inside the silo, it could not remove static electricity, since it is not grounded. As coal had input two days before the accident, dust explosion caused by static electricity was possible, too. When it comes to heat condition, the object silo had not managed right in terms of both design and operation.

Table 2-5. Operation guideline on temperature.

Classification	Temperature (°C)	Prevention plan
Warning temperature	40-70	Check the temperature more frequently
Risky temperature	70-200	Check the temperature more frequently Recycle coal
Ignition temperature	>200	Inject liquid nitrogen Operate fire extinguishing system Spray water

2.4.5. Overpressure

Table 2-3 shows that P_{max} of coal dust is about 6-9 bar. When the coal silo is designed, it would be safe if the wall thickness can endure this overpressure. However, it is not economical to make the wall thick up to indure P_{max}. Thus, as a warning for dust explosion, there should be a measure to relieve pressure. It is a relief vent and the silo where the accident took place had it. Eckhoff suggested a way of sizing relief vent [33]. Also, NFPA 68 can be referred [19]. The equipped vent observe regulation. However, the vent was bolted up, thus it could not relax overpressure. Also, as shown on Figure 2-10, the silo was closed on top by the sliding gate. Thus, overpressure could not be removed, thus collapse was inevitable.

2.5. Summary and discussion

In this chapter, cause analysis is conducted for a dust explosion in coal silo. This chapter focuses on the specific accident based on the conditions of dust explosion pentagon. Each condition is analyzed in terms of design and operation. This study could contribute to improvement of not only coal silo, but also other silos, which store flammable material. Also, it has a significance, since risk-based process safety management is applied on storage.

CHAPTER 3 : Risk-based underground pipeline management considering corrosion effect

3.1. Introduction

The concerns about underground pipelines have been increasing nowadays due to the recent accidents. Table 3-1 [1-3] and Table 3-2 [4-10] shows typical accidents of underground pipeline since 2000. From classic examples, we can check the severity of underground pipeline accidents. For example, in 2004, 23-year-old underground pipeline carrying natural gas exploded so that 24 and 122 people were killed and injured respectively in Belgium (Ghislenghien). In 2010, natural gas pipeline explosion resulted in 8-killed and 58-injured in San Bruno, USA. In 2014, propylene released from 20-year-old pipeline in Kaohsiung, Taiwan, caused 32 fatalities and 321 injuries. Also, the accidents have occurred frequently in South Korea, especially Ulsan Industrial Complex, the biggest one in South Korea and among top 10 in the world. The Ulsan Industrial Complex had been buried underground pipelines since 1962, which means that these has been in use for more than 50 years. According to the Ministry of Trade Industry and Energy (MOTIE) report of South Korea [11], more than 60% have been used about 20 to 50 years among Ulsan underground pipelines (1,136 km), which carry gas, chemicals, or oil,. Also, about half (1,864 km) of the underground natural gas pipelines in South Korea have been used for more than 20 years [12]. Thus, we can reason inductively that these underground pipelines have been degrading due to aging. Although there have been no severe life damages in South Korea, we should focus on the pipelines issues because these have been degraded and the risk increased.

Table 3-1. Classic and Korean examples of underground pipeline accidents.

Classic examples				
Date	Location	Product	Dead/Injured	Reference
Aug. 19, 2000	New Mexico, USA	Natural gas	12/0	1, 2
Jul. 30, 2004	Ghislenghien, Belgium	Natural gas	24/122	1, 3
Sep. 9, 2010	San Bruno, USA	Natural gas	8/58	1
Nov. 22, 2013	Qingdao, China	Oil	62/136	1
Jul. 31, 2014	Kaohsiung, Taiwan	Propylene	32/321	1

Table 3-2. Korean examples of underground pipeline accidents.

Korean examples				
Date	Location	Product	Dead/Injured	Reference
Mar. 29, 2001	Ulsan, South Korea	Hydrogen	0/0	4
May 11, 2001	Ulsan, South Korea	Ammonia	0/0	4, 5
Jul. 16, 2003	Gwangyang, South Korea	BTX mixture	0/0	4, 6
Dec. 10, 2005	Yeosu, South Korea	Butane	0/0	4, 6
Jan. 3, 2014	Ulsan, South Korea	Propane	0/0	7
Feb. 22, 2014	Ulsan, South Korea	Mixed - Xylene	0/0	8
Oct. 27, 2014	Ulsan, South Korea	Hydrogen	0/0	9
Oct. 8, 2015	Ulsan, South Korea	Hydrogen	0/0	10

According to Figure 3-1 [13], corrosion is considered as the second largest cause of 5,960 pipeline's accidents (1988-Aug. 2008). The major cause, excavation damage, is avertible by making exact and detail underground piping map, or digging carefully. However, corrosion is inevitable in aging process. All pipelines go through internal corrosion, but only underground pipelines additionally experience external corrosion by interaction between soil and metal (pipeline) except plastic pipelines [14]. Naturally, the pipelines exposed to atmosphere can also be corroded. However, atmospheric mechanisms are relatively slower than the subsurface corrosion, so that it can be negligible [14]. Thus, when the safety of underground pipelines is considered, corrosion should be reflected.

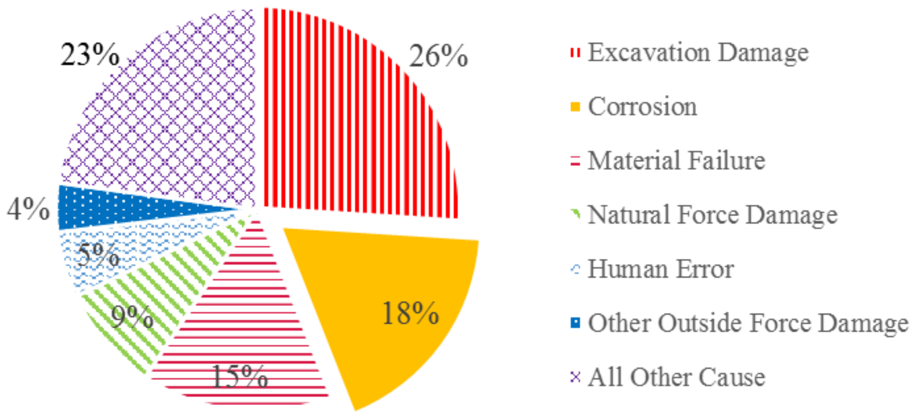


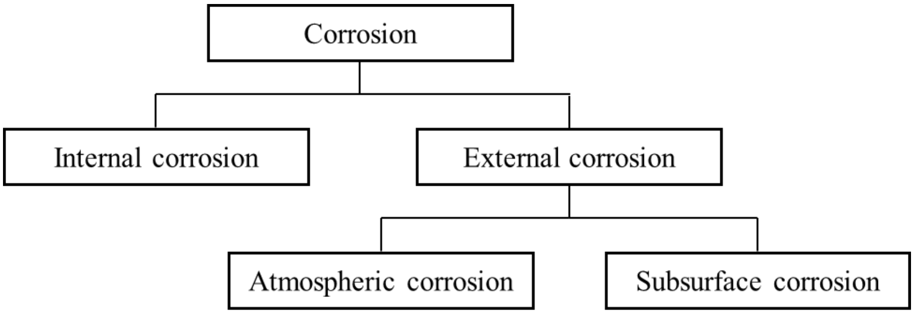
Figure 3-1. Root causes of pipeline incidents in onshore and offshore.

Usually, risk analysis has been conducted in various fields including nuclear power stations and chemical process industries [13, 15]. Also, it has been applied to the pipelines. In Europe, precautionary measure has been existed rather than acting after the accidents and it has been supervised by Major Accident Hazards Bureau (MAHB), European commission [16]. Major-accident hazard pipelines (MAHP) are chosen according to dangerous substances, pipeline operation thresholds (pressure, pipe diameter, or etc.), and severity of consequences of potential accidents based on 'major-accident hazard' legislation [16]. This method is based on qualitative risk analysis, and many EU countries had not used quantitative risk analysis (QRA) until early 2000s [16]. However, nowadays, they have tried to introduce QRA instead of the qualitative measures [16].

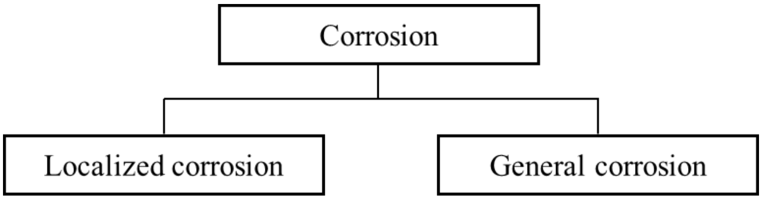
Acton et al. [17-22] have been researched on applying QRA to gas pipelines. They have developed a PIPESAFE package, which evaluates individual risk (IR) and societal risk (SR) for pipeline routing selection, assurance, and independent safety review. Lee et al. [23] researched about effect of reduction factor (inside or outside of building) on quantitative risk of high-pressure natural gas pipelines. Amir-Heidari et al. [24] applied QRA to Iran's natural gas distribution network. Linear risk integral (LRI) was suggested by Neunert [25] that helps to find out the specific location of pipeline, which needs risk reduction. However, all of these studies were about overall pipelines, not focused on underground pipelines. Furthermore, these are only focused on installation, not management.

Meanwhile, there are also QRA researches about underground pipelines. Spoelstra and Laheij [26] suggested a new QRA method for underground pipelines transporting hazardous substances, which is especially focused on calculating failure frequencies. Yang et al. [27-28] conducted QRA about underground gas storage caverns similar to that of underground pipelines. Using release rate, they calculated the overpressure, impulse or thermal radiation parameters, and these are applied to Probit function. The proposed model is validated [27] and applied to a sample so that parametric study is conducted [28]. Lee and Shin [29] performed the case studies and risk analysis for high-pressure underground natural gas pipelines. These studies about underground pipelines did not deal with corrosion effect, which is important factor in underground pipeline accidents. Also, as QRA for underground pipelines, interest is on installation and corrosion, which is an important safety factor in underground pipeline, is not dealt.

Underground pipelines can go through corrosion mechanisms as shown on Figure 3-2 [14]. First, according to corrosion location, it is catagorized by internal or external one (Figure 3-2 (a)). Internal corrosion depends on fluid, which is flowing inside the pipelines. Except corrosive materials, such as ammonia, benzene, xylene, and acrylonitrile, internal corrosion is disregardable [14], and can be prevented by internal lining. While, external corrosion occurs to pipeline surface and is divided into atmospheric and subsurface one. Atmospheric corrosion, which happens on the ground pipelines, is negligible, too, as mentioned before, and waterproof painting could block it. However, subsurface corrosion is the most severe one, thus painting, coating, galvanic anode, or cathodic protection by anodes with rectifier are required to protect from corrosion. Next, corrosion can be classified into a localized (pitting) corrosion and a general corrosion according to type (Figure 3-2 (b)). Pitting is wall thinning in specific points, while wall get thinned uniformly in general corrosion. Caleyo et al. [30] studied about pit depth distribution for different soil textural classes using Markov chain modelling. Meanwhile, Jo and Ahn [31] carried out QRA of underground natural gas pipeline assuming general corrosion. To calculate failure rate, correction factors are used and these are related with depth of cover, wall thickness, population density and prevention method [31]. However, Jo and Ahn reflect the general corrosion qualitatively; this means that correction factors of wall thickness are same in specific range [31].



(a)



(b)

Figure 3-2. Classifications of corrosion according to (a) location of corrosion and (b) type of corrosion.

In this study, considering subsurface and general corrosion effects, a new safety management methodology of underground pipeline, risk-based pipeline management, is suggested. For case study, an existing pipeline in Ulsan Industrial Complex is used, thus real pipeline information, geometry, population, and weather information are reflected. The QRA results of the qualitative measure, which have been used and are based on minimum wall thickness, and the risk-based pipeline management are compared. Also, sensitivity analysis is fulfilled on variables, which influence the risk of the pipeline.

3.2. Methodologies

3.2.1. Qualitative measure

Since early 2000s, QRA has been applied for pipeline installation. The procedure is shown in Figure 3-3, which is like general QRA. This methodology is effective in densely populated areas, such as Asia or Europe, but unfortunately a qualitative measure has been used in South Korea.

The qualitative measure includes minimum wall thickness and minimum required depth of covering pipeline. First minimum wall thickness is determined by ASME codes as given in Eqn. 3-1 [32-35].

$$t_m = \frac{P \cdot D_0}{2(S \cdot E + P \cdot y)} + A \quad \text{(Eqn. 3-1)}$$

This thickness makes pipeline endure pressure and stress. Additional thickness, *A*, is added when internal fluid is corrosive. For pipeline installation, thickness should be thicker than minimum one. And, pipeline can be used until thickness reaches minimum value. Thus, the original replacement schedule ($x_{original}$) is calculated by Eqn. 3-2 [39].

$$x_{original} = \frac{t_d - t_m}{CR} \quad \text{(Eqn. 3-2)}$$

Corrosion rate (CR) could be attained by prediction or theoretical sum of internal and external CR, which would be discussed in section 3.3.3.

While, the depth of pipeline is determined according to each country's law, and generally it should be more than 2 feet [36-37]. As lifespan of pipeline is related with minimum thickness, only thickness would be considered as the qualitative measure in this study and compared with the risk-based pipeline management.

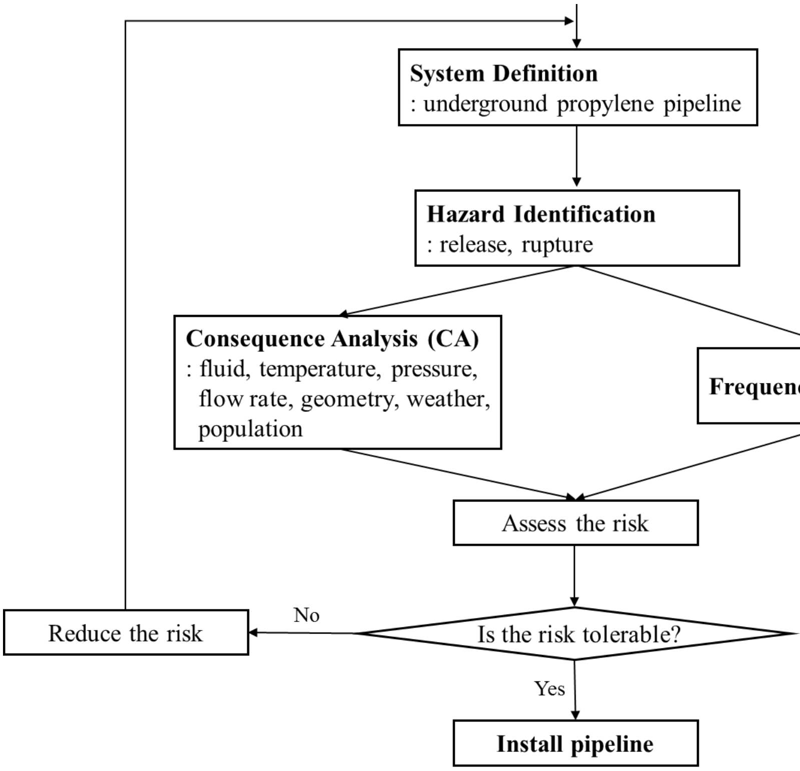


Figure 3-3. QRA for pipeline installation.

3.2.2. Risk-based pipeline management

The risk-based pipeline management is modified form of QRA to improve management methodology of pipeline. It is shown on Figure 3-4. As QRA procedure, system definition, hazard identification, CA, FA, and risk assessment are conducted in order. And then, lifespan of pipeline is determined to satisfy that the risk is in tolerable region, as low as reasonably practicable (ALARP). The standard of ALARP follows criteria of HSE [38] in this study. The difference with QRA is that when the risk is not tolerable, usable time is reduced one by one instead of risk reduction. This is based on assumption that the risk is tolerable when pipeline is installed. As a result, maximum value (x_{new}) is chosen as lifespan of pipeline.

In this study, the object pipeline is chosen as an underground propylene pipeline located in Ulsan Industrial Complex. For hazard identification, ETA is used for the cases of release and rupture. Following that, CA is conducted by Phast 6.7, which is a commercial software for QRA, and merged with FA.

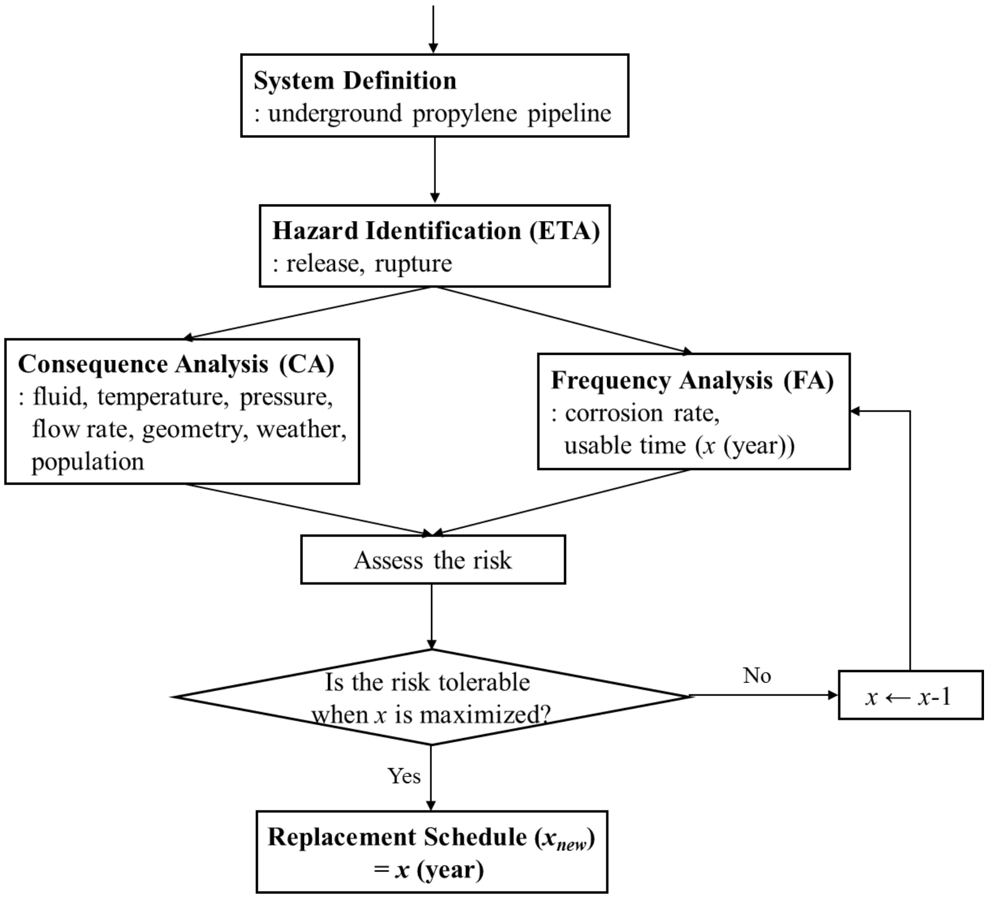


Figure 3-4. Risk-based pipeline management.

3.3. Quantitative risk management

3.3.1. Hazard Identification

Propylene is a flammable gas on normal condition, thus, fire or explosion could occur when propylene is released from pipeline. The properties of propylene are as shown on Table 3-3 [40-41]. Compared to spark from walking (22mJ) or spark of plug (25mJ), propylene has low minimum ignition energy (MIE), thus, fire breaks out easily if only MIE is considered. Fortunately, a flammable area between lower flammable limit (LFL) and upper flammable limit (UFL) is narrow so that probability of fire is reduced.

In this study, for hazard identification, ETA is chosen as a method, and the result is as shown on Figure 3-5 [42]. The propylene exists as at 19.6 barg and 20 °C in the object pipeline. The events are classified by ignition, ignition type, boiling liquid expanding vapor explosion (BLEVE), and explosion. Any leak can lead to a catastrophic disaster, which may include BLEVE, explosion, jet fire, fireball, or flash fire.

Table 3-3. Propylene property at normal temperature and pressure.

LFL (%) in air	UFL (%) in air	MIE (mJ) in air	Boiling point (°C)	Flash point (°C)	Auto-ignition temperature (°C)
2	11.1	0.28	-47.7	-108	458

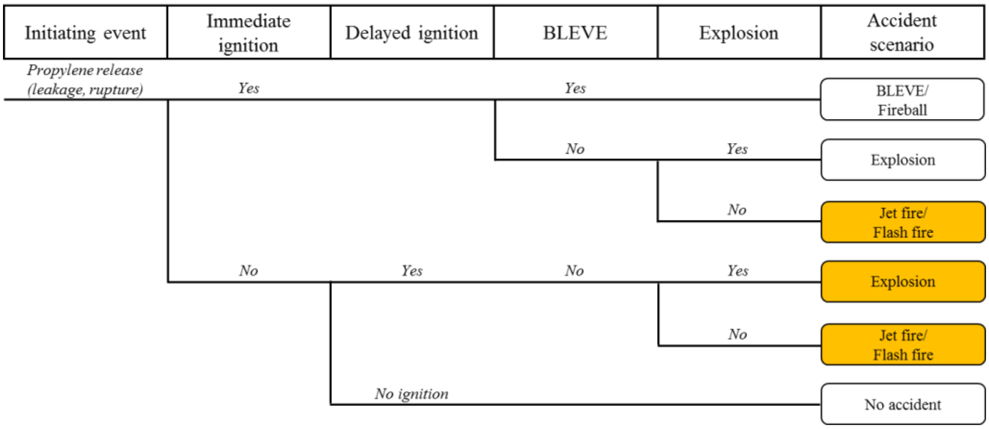


Figure 3-5. Event tree analysis of propylene release.

3.3.2. Consequence Assessment

Consequence assessment requires an information regarding pipeline, scenario, weather conditions, and population. The pipeline information is given in Table 3-4. This location of the existent pipeline is Ulsan Industrial Complex. Long pipeline scenario is chosen, because the ratio of length over diameter is more than 200. Third, average weather (air temperature, air stability, and wind speed of day and night) of Ulsan is adapted for the scenario [43]. Finally, the actual population of Ulsan is utilized consulting SGIS (Statistical Geographic Information Service) data [44]. These are merged and computed in Phast 6.7.

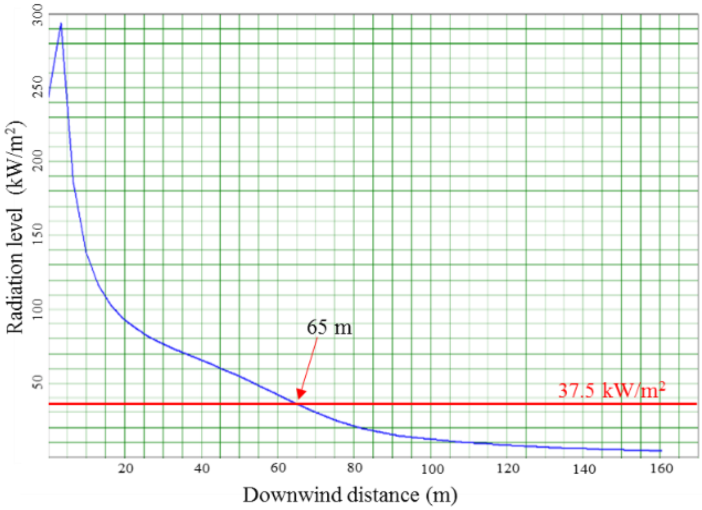
Using the above information except for population, CA is conducted. Among accident scenarios in Figure. 3-5, only yellow part (jet fire, flash fire, and late explosion) could happen. In the case of this pipeline release, BLEVE following overpressure and fireball is almost impossible because liquid propane cannot be leaked out instantaneously from pipeline. (Even, in the case of pipeline rupture, it takes time to release propylene.) For the same reason, early explosion does not occur. Meanwhile, when liquid propane is discharged, it expands because of pressure difference. According to calculation result, liquid fraction of released propane is 0.68. However, pool is not formed, since propane is dispersed in the air in the form of droplet. Thus, pool fire could not take place, too.

Table 3-4. Pipeline information.

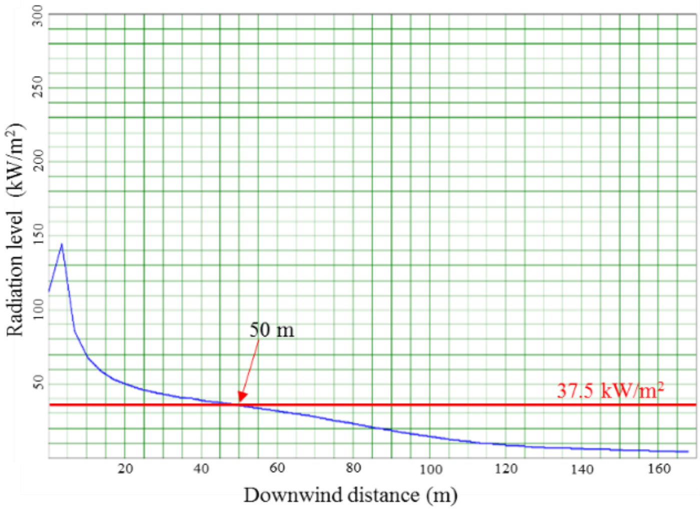
Installation data	Outside diameter (mm)	Length (m)	Designed wall thickness (mm)	Pressure (bar)	Temperature (°C)	Flow rate (kg/s)
1995	168.3	903	7.11	19.6	20	3.8

Possible scenarios are divided into day and night, and compared, since air temperature, wind speed, and air stability are different. (All figures in this section are based on worst scenario, pipeline rupture case.) First, in the case of jet fire (Figure. 3-6), radiation effect is severe in day because of wind speed. Faster wind speed in day makes the flammable zone of propylene to spread so that downwind distance of immediate human fatality level (37.5 kW/m2) increases. Thereby, possible fatalities of day (10 fatalities) is almost twice that of night (6 fatalities).

Next, dispersion aspects (Figure 3-7) are distinct. Vaporized propylene goes up in day compared to night, since surface temperature of day is higher than night and temperature inversion layer formed at night prevents rising surface air. Thus, because flammable zone of propylene is located in surface at night, damage is severe at night. As a same reason of dispersion, the area of possible flash fire (Figure 3-8) and late explosion (Figure 3-9) are bigger at night than in day.

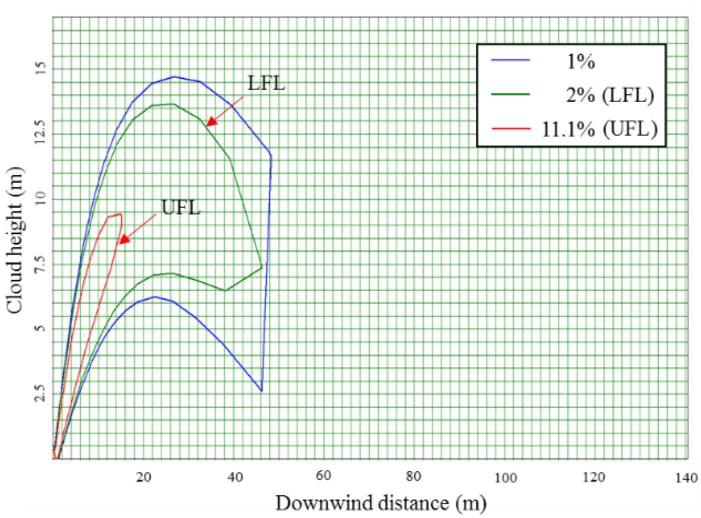


(a) Day

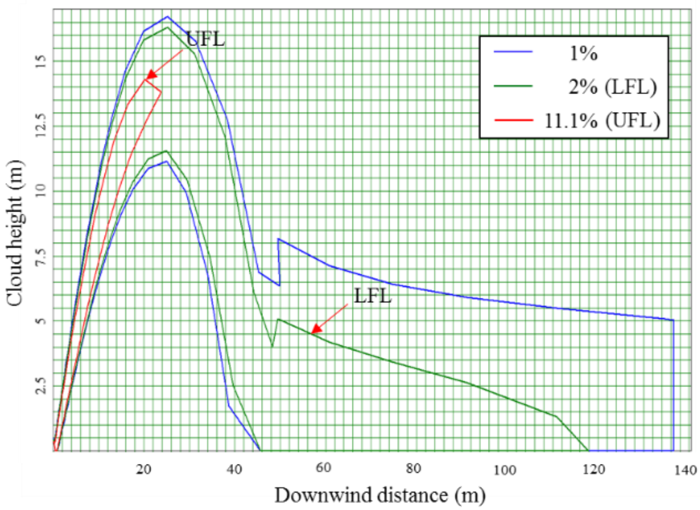


(b) Night

Figure 3-6. Result of jet fire.

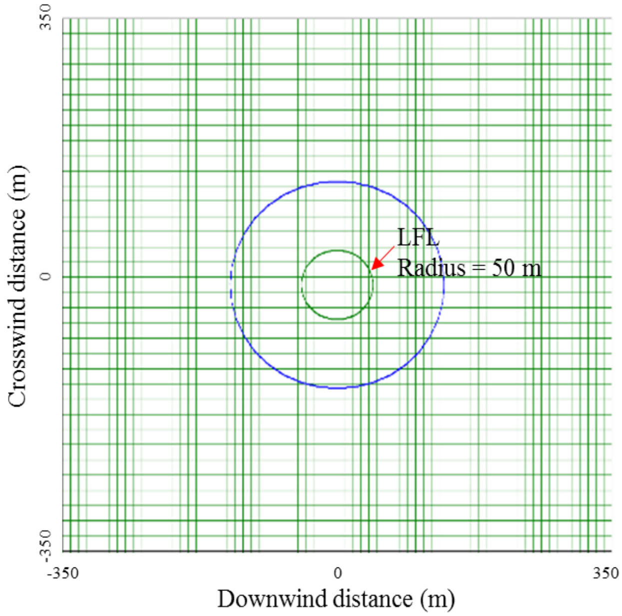


(a) Day

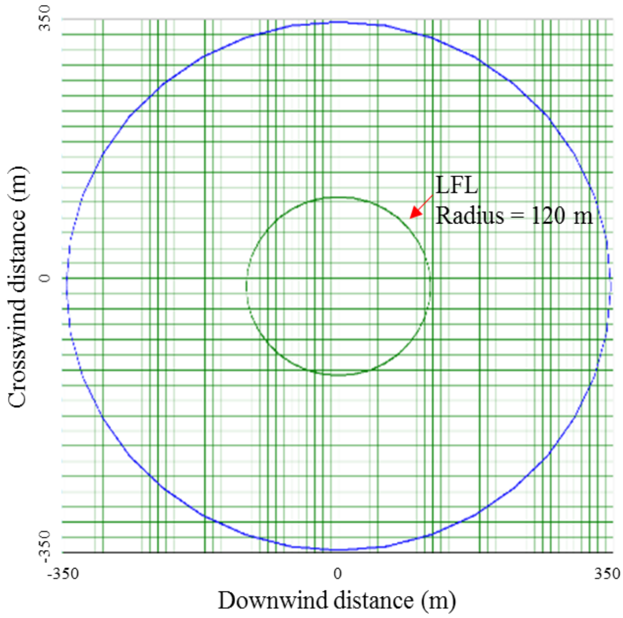


(b) Night

Figure 3-7. Result of dispersion.



(a) Day



(b) Night

Figure 3-8. Result of flash fire.

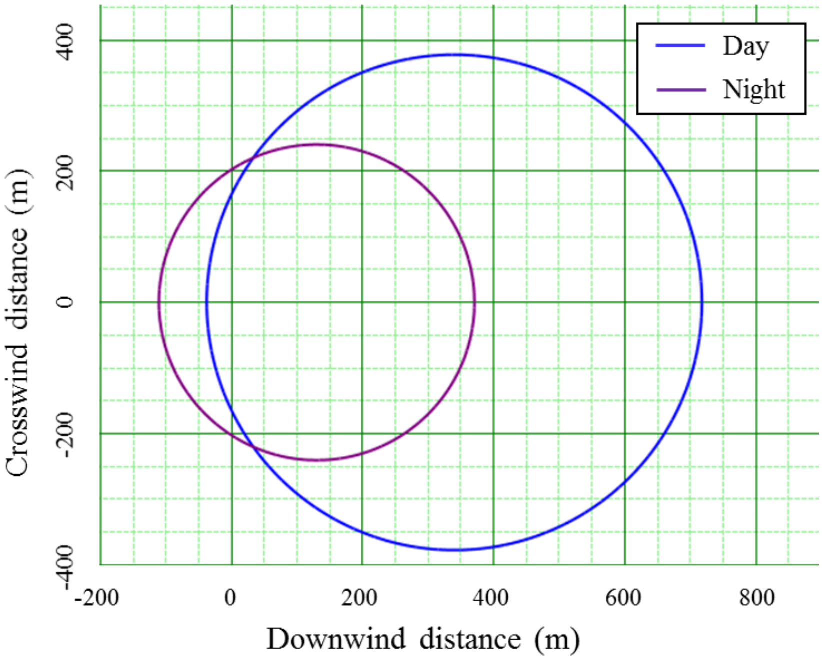


Figure 3-9. Worst case radius of late explosion.

3.3.3. Frequency Assessment

Failure frequency of propylene pipeline (f_f) are computed based on in-house data, which is about pipeline accident cases. This frequency depends on present wall thickness (t_p), as shown on Eqn. 3-3.

$$f_f = function(t_p) \quad \text{(Eqn. 3-3)}$$

In this equation, corrosion effect can be considered by predicting wall thickness according to CR. While, CR only considers general corrosion (The reason is shown on the last part of this section.) and present wall thickness (t_p) is calculated according to Eqn. 3-4, since corrosion proceeds as time (T) goes by.

$$t_p = t_d - CR \times T \quad \text{(Eqn. 3-4)}$$

Accurate CR could be attained by digging and measurement, but it could be difficult sometimes. In this case, theoretical value is used and it is calculated by Eqn. 3-5.

$$CR = CR_{internal} + CR_{external} \quad \text{(Eqn. 3-5)}$$

Internal CR ($CR_{internal}$) is consulted by Dechema [45] and Sandvik [46]. While, referring to API RP 581 [47], external CR ($CR_{external}$) is calculated as shown in Eqn. 3-6, which is affected by soil resistivity (F_{SR}), fluid temperature (F_T), cathodic protection (F_{CP}), and coating effectiveness (F_{CE}).

$$CR_{external} = CR_B \cdot F_{SR} \cdot F_T \cdot F_{CP} \cdot F_{CE} \quad \text{(3-6)}$$

Base CR (C_{RB}) is 0.13 mm/year [47]. According to pipeline information (Table 3-4), since pipeline temperature is 20 °C, F_T is 1.0 [47]. To decide other factors from API RP 581 [47], assessment for soil resistivity and indirect assessments (CIPS and DCVG) have been conducted. These results are listed on Table 3-5.

Table 3-5. Results of assessments.

Test type	Results	Factor value
Soil resistivity	1,686 Ω·cm	$F_{SR} = 1.0$
CIPS	-754 mV	$F_{CP} = 0.8$
DCVG	1 > %IR	$F_{CE} = 1.2$

As soil resistivity increases, it is hard that electron, which is supplied by anode, get out from pipeline to soil. The researched area of the pipeline has 1,686 Ω·cm as soil resistivity, which is moderately corrosive. CIPS is a measure to find out effectiveness of cathodic protection system. The measured potential difference should be less than -850 mV (maximum potential to protect pipeline from corrosion) to protect pipeline effectively from corrosion. The object pipeline uses galvanic anode, and the average value of CIPS is -754 mV, which means that the pipeline is not protected safely. Lastly, DCVG checks size and location of coating defects of pipelines. The pipeline is coated with polyethylene, and coating condition is good according to assessment, although it has been used more than 20 years. Thus, pitting is not considered in this case. As a result, 0.096 mm/year is gained as a total CR.

3.3.4. Pipeline installation and management

As mentioned in section 3.2.1, pipeline could be installed if it satisfies minimum wall thickness. Thus, the object pipeline in this study could have been equipped, since minimum wall thickness (2.93 mm) is thicker than designed one (7.11 mm). However, to check safety conservatively, SR should be confirmed. The FN curve of the pipeline when it was installed is shown on Figure 3-10. In this graph, we can find out that the curve belongs to ALARP region, thus it could be equipped.

Meanwhile, pipeline replacement schedule has been determined by Eqn. 3-2, and $x_{original}$ is 44 years (green line in Figure 3-11, which get out of ALARP). Since this pipeline has been used for 21 years (yellow line in Figure 3-11), thus it is still usable according to the qualitative measure. However, the pipeline could be operated within 31 years (x_{new}) not to exceed ALARP (red line in Figure 3-11) according to the risk-based pipeline management. Thus, pipeline replacement schedule is reduced to meet HSE standard [38]. In terms of risk integral, the qualitative measure has 1.74×10^{-5}/average-year as risk integral, while the risk-based pipeline management does 7.53×10^{-6}/average-year at the time of replacement. Thus, the suggested method could reduce risk integral by 56.8 %.

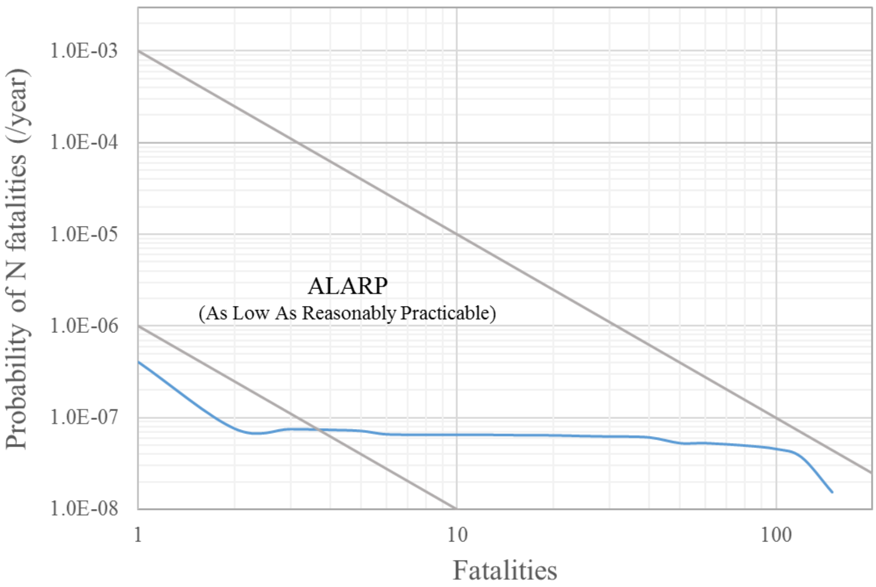


Figure 3-10. FN curve when the pipeline was installed.

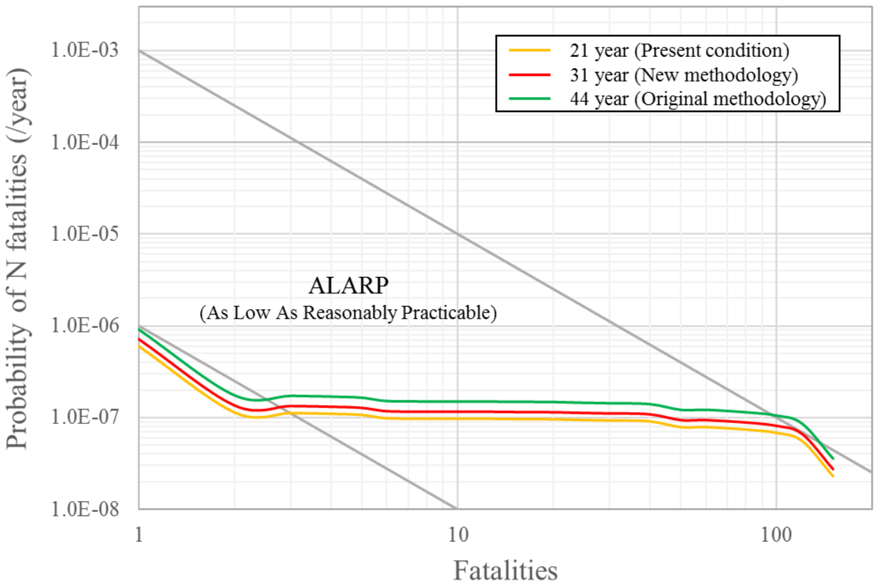


Figure 3-11. FN curve to determine pipeline replacement schedule.

3.4. Sensitivity Analysis

As analyzed in the former section, pipeline lifetime is reduced according to the risk-based pipeline management compared to the qualitative measure. Although the exact result is attained through the process as shown in section 3.3, we can also get insight from sensitivity analysis before performing QRA. It means that when temperature, pressure, flow rate, even material or etc. have changed, we can predict how the risk would be affected. The comparison standard is the object pipeline, which is used 31 years. First, when the temperature (20 °C) increases or decreases (red line in Figure 3-12), the risks are compared in Figure 3-13. Since propylene is generally shipped as a state of liquid, temperature range is chosen from 0 °C to 40 °C. As the temperature of fluid increases, liquid fraction after atmospheric expansion decreases, which makes propylene disperses easier. Though propylene is heavier than air, if it has higher temperature than air, it spreads upside. Thus, affected population reduces when propylene has high temperature. Also, the higher the temperature of propylene is, the smaller the release duration is, which results in reduced SR. Next, change of pressure (in the range of non-saturated liquid of propylene, 10-50 barg, green line in Figure 3-12) does not affect the risk (Figure 3-14), because the releases reach choked flow, thus mass release rates are same in these cases. (All of the pressures have same risk, blue line in Figure 3-14.) Third, the larger the pumped inflow rate is, the higher the risk is as shown on Figure 3-15 because of release quantity. Thus, pipeline, in which considerable quantity flows, should have thicker wall thickness to reduce the failure frequency.

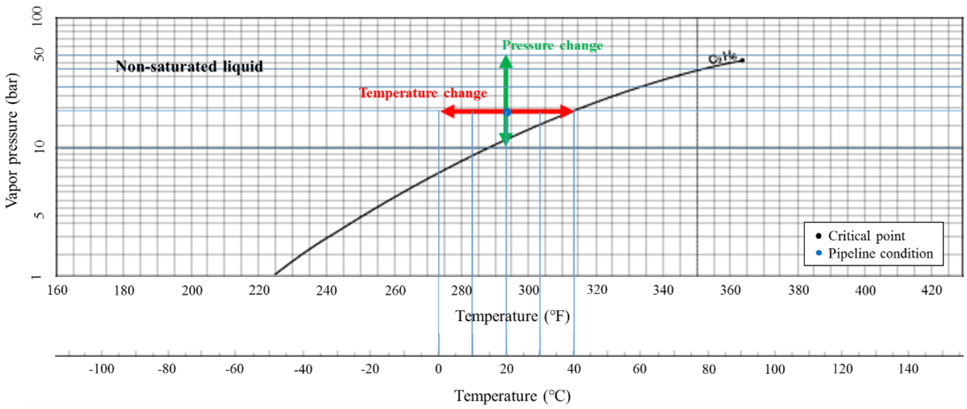


Figure 3-12. Vapor pressure curve of propylene.

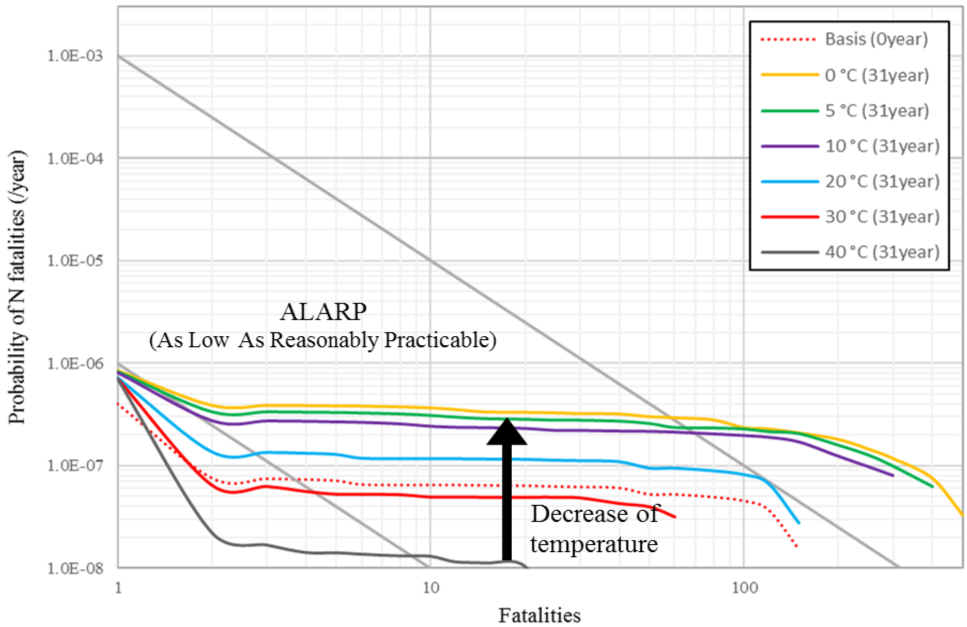


Figure 3-13. FN curves according to temperature change.

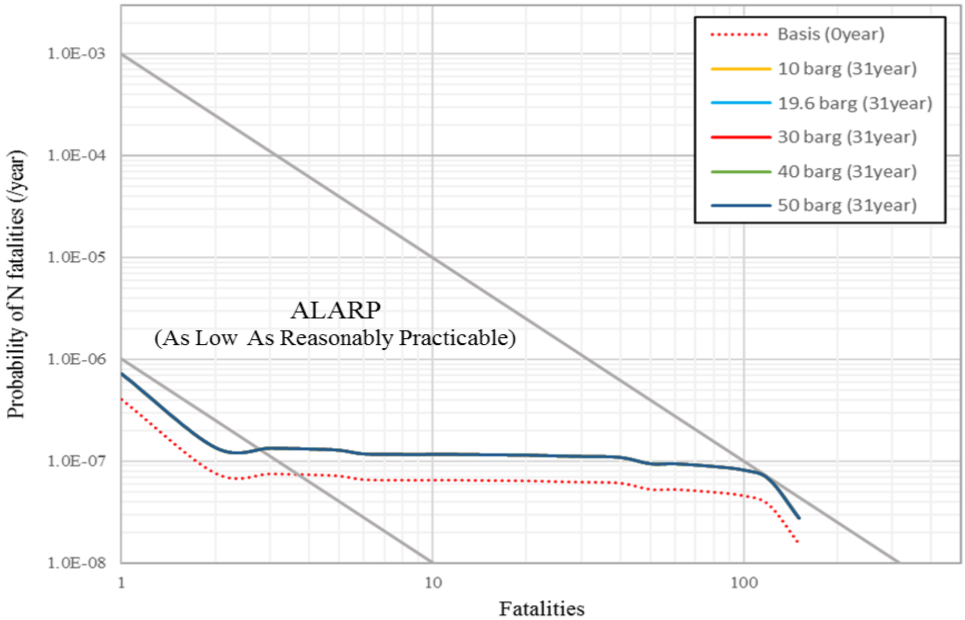


Figure 3-14. FN curves according to pressure change.

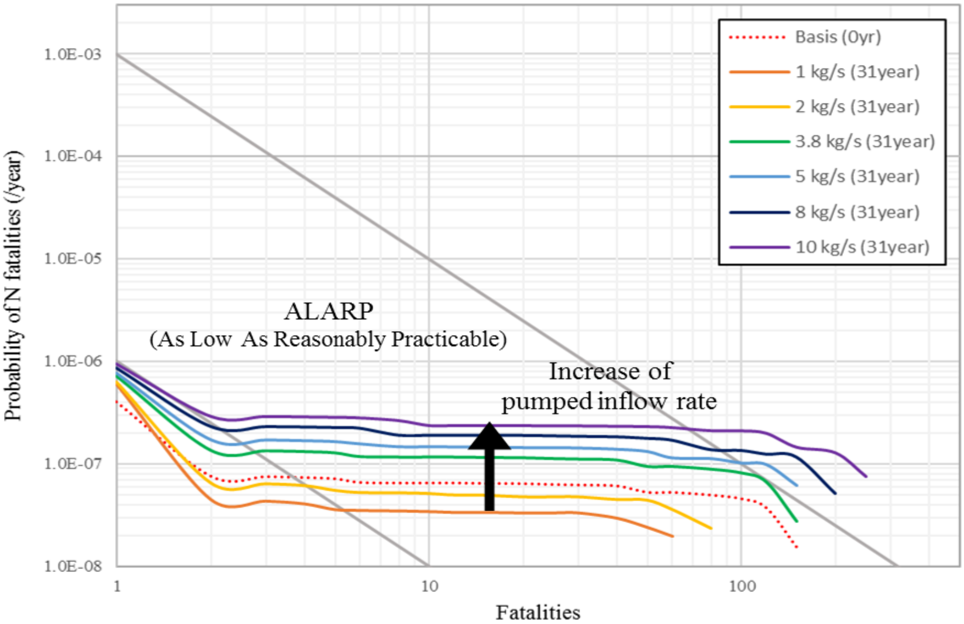


Figure 3-15. FN curves according to inflow rate change.

Also, the effects of materials could be predicted through properties such as flammability or toxicity. The properties of typical materials, which have done great damage by accidents or been carried in Ulsan Industrial Complex, are shown on Table 3-6 [40, 41, 48]. Although the exact consequence can be known after the CA, we can predict that, for example, acrylonitrile is riskier than ammonia, because acrylonitrile has lower immediately dangerous to life or health concentrations (IDLH). Generally, toxic material is riskier than flammable one. Also, the wider the flammable zone is, the broader the area of possible fire is. However, the lighter gases, such as hydrogen or methane, rise up, thus affected population could decrease.

Moreover, population and pipeline position from each other affect the risk. As mentioned earlier, QRA is sensitive to population. Thus, on densely populated area, such as Asia or Europe, SR analysis should be conducted rather than IR. Overpressure from one pipeline can make other pipelines' rupture, and mixing of two or more materials could cause reactions, thus risk could be more dangerous. This domino effect, releases of another pipelines caused by on pipeline, can be reflected to QRA by subdividing cases in event tree.

Table 3-6. Properties of typical materials.

Material	Type	LFL (%)	UFL (%)	Boiling point (°C)	MIE (mJ)	IDLH (ppm)
Propylene	Flammable	2	11.1	-47.7	0.28	-
Hydrogen	Flammable	4	74	-252.9	0.016	-
Methane	Flammable	4.4	16.5	-162	0.3	-
Ammonia	Flammable/ Toxic	15	28	-33.3	680	300
Acrylonitrile	Flammable/ Toxic	3	17	77	0.16	85
Methanol	Flammable/ Toxic	6.7	36	64.7	0.14	6,000
Benzene	Flammable/ Toxic	1.2	7.8	80.1	0.20	500

3.5. Summary and discussion

This chapter proposes the risk-based pipeline management considering corrosion, which is reflect in failure frequency. The methodology defines lifetime of pipeline as that which is the risk curve contains in ALARP. For a case study, the existing propylene pipeline is applied, and risk is decreased by 56.8 % compared to the qualitative measure. Also, sensitivity analysis is conducted to variables, which impact on the risk. This study could be applied to all of the pipelines instead of underground pipeline. It contributes to introduction of quantitative measure to the pipeline management.

CHAPTER 4 : Effect of operating condition change on QRA for gas treatment unit in gas oil separation plant*

4.1. Introduction

Quantitative risk assessment (QRA) has contributed to reduce the risk and the number of accidents in chemical plant from the late 1970s [2, 3]. For more than 40 years, there have been many researches to improve accuracy, effectiveness, or reliability of QRA. Specific methodology would be different, but the overall structure of QRA (Figure 4-1) has barely been changed; system definition, hazard identification, consequence and frequency assessment, risk assessment, risk reduction and risk management [1].

* The partial data of this chapter is taken from the author's published paper in the journal [1].

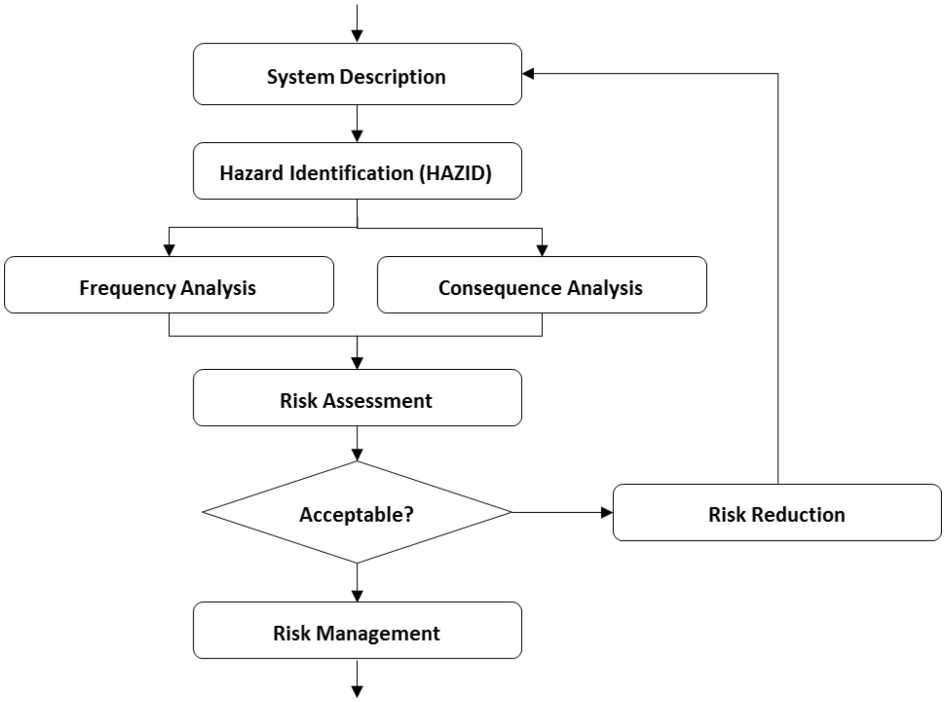


Figure 4-1. QRA procedure.

Meanwhile, recent trend of QRA research could be divided into advanced consequence modeling, risk assessment of rare events, and dynamic risk assessment (DRA). Advanced consequence modeling deals domino effect [4, 5] or uses computational fluid dynamics (CFD) [6, 7] for precise consequence assessment. For risk assessment of rare events, hierarchical Bayesian approach (HBA) is introduced to get a balanced result from rare events [8]. Lastly, DRA reflects the risk change, especially originated in update of failure frequency, according to the flow of time. This study focuses on DRA.

The target of DRA is removing uncertainty of failure frequency using incident record of an object plant. At the beginning of DRA, fault tree (FT) [9, 10], event tree (ET) [11], or Markov model [12] were used to update frequency. However, Bayesian network (BN) or bow-tie (BT), combination of FT and ET, approaches are preferred these days. In the cases of BN application, Kalantarinia et al. updated failure frequency of a storage vessel applying Bayesian theory to real time data [13]. Tan et al. employed BN on a high-sulfur natural gas gathering station [14]. While, Khakzad et al. suggested using BT to dynamic environment [15]. They improved BT to consider conditional dependency and not to be limited to static condition [16].

While, DRA has some weaknesses as shown in Figure 4-2 (a). All of these dynamic studies have a problem that these can only be applicable to existing plants used several years, since DRA needs past incident data. Furthermore, DRA reflects only frequency, not consequence by operating condition change. So far, QRA has been conducted on the assumption of normal condition. However, because operating condition changes more frequently than the occurrence of incidents, dynamic conditions should be reflected on QRA. To sum up, it needs to develop a new QRA technique, which could be applied to a start-up process and reflect operating condition change on both consequence and frequency assessment as shown in Figure 4-2 (b).

First of all, to find the necessity of the suggested research, it is needed to find out how much the operating condition change effects on QRA. Thus, this study focuses on to find out the effect. The object process is an existing gas treatment unit (GTU) of gas oil separation plant (GOSP), which was treated in the author's other paper [1]. The basic data is brought from the journal [1], but the topic is different. First, methodology for applying change of normal conditions (flow rate, pressure, and temperature) is presented. And then, risk assessment is conducted for each three changes. This paper contributes to recognize the importance of applying dynamic operating condition to QRA.

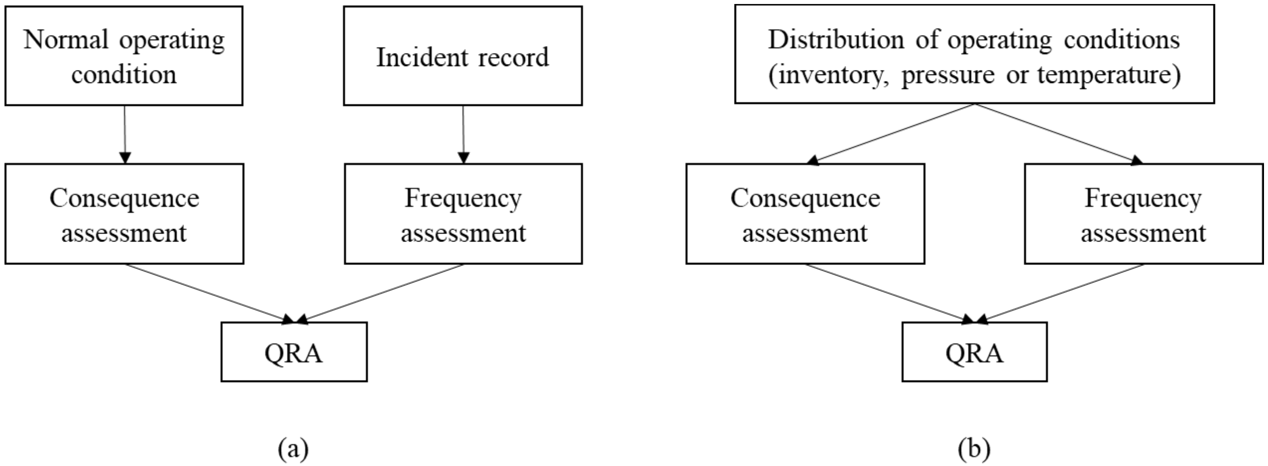


Figure 4-2. Methodology comparison of (a) DRA and (b) this study.

4.2. Methodology

4.2.1. Object process

The object process is a GTU of a GOSP, which was already handled in the author's other paper [1]. It is based on real data of an existing plant [17]. Detail information is presented in the paper [1].

GOSP is located close to a well for separation of oil and gas as soon as these are drilled. At a first separator, crude gas is extracted from oil and sent to the GTU process. In the GTU process, oil and water still remained in gas are removed, and high-purity gas is sent for power plant or integrated gas process plant (IGPP). The PFD is shown in Figure 4-3 [1]. Primarily separated gas is injected to the GTU process through pipeline P_01. And then, it is divided into two main streams. In scrubbers V_01 and V_03, remained oil is eliminated. Gas from top of scrubbers is compressed and then sent to chillers through pipeline P_02 and P_03. The refrigerated gas goes through secondary scrubbers V_02 and V_04. The gained oil heads for the three-phase separator V_05 through pipeline P_05 (1) and (2). The most high-purity gas passes cooler and face to power plant through pipeline P_04. In the three-phase separator V_05, crude oil goes back to oil section through pipeline P_06 (1) and (2). This GTU process is simulated by Aspen HYSYS V8.4. For QRA, both individual risk (IR) and societal risk (SR) are used and the standard of tolerability criteria follows criteria of HSE of UK [18].

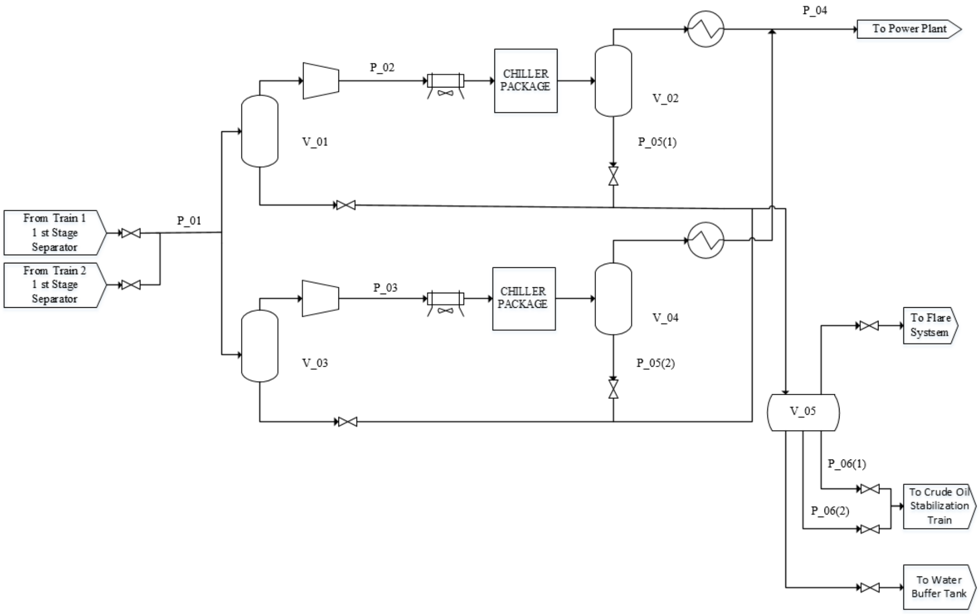


Figure 4-3. PFD of GTU [1].

4.2.2. Hazard identification (HAZID)

Although QRA can be conducted to all of units in the process, HAZID can simplify the course and reduce the time. Major hazard can be found referring to property of material, temperature, pressure, or flow rate. The searched hazard in the GTU process is same as in the journal [1] and presented in Table 4-1. The mixture of methane, ethane, propane, butane, pentane, hexane, octane, nonane, water, nitrogen dioxide, carbon dioxide, and hydrogen sulfide flows through major hazard points (P_01-06, V_01-05). All of these materials has flammability, and only hydrogen sulfide has toxicity. When applying QRA, isolation success (IS) and isolation failure (IF) are considered, which are suggested in the journal of Lee et al. [1]. This concept comes from success or failure of emergency shutdown (ESD)

Table 4-1. Major hazard and its operating conditions.

Unit	Description	Pressure (barg)	Temperature (°C)	Isolation success (kg)	Isolation failure (kg)
P_01	Piping to HP fuel gas suction scrubber (1&2)	13.3	65.0	4,076	23,526
P_02	Piping from HP fuel gas compressor (1) to HP fuel gas discharge cooler	35.7	147.6	2,055	11,780
P_03	Piping from HP fuel gas compressor (2) to HP fuel gas discharge cooler	35.7	147.6	2,040	11,765
P_04	Piping from HP fuel gas discharge super-heater to power plant	34.2	79.8	4,061	21,666
P_05	Piping from HP fuel gas discharge scrubber (1&2) to three-phase separator	34.7	34.8	932	2,071
P_06	Piping from three-phase separator hydrocarbon liquid outlet to crude oil stabilization train	12.0	27.3	499	1,452
V_01	Fuel gas suction scrubber (1)	13.3	64.7	40	40
V_02	HP fuel gas discharge scrubber (1)	34.7	34.8	220	220
V_03	Fuel gas suction scrubber (2)	13.3	64.7	40	40
V_04	HP fuel gas discharge scrubber (2)	34.7	34.8	220	220
V_05	Three-phase separator	12.0	27.3	1,600	1,600

4.2.3. Dynamic operating condition

According to process philosophy of the object GTU process, maximum working pressure and temperature are defined in the process design step to take account of operational fluctuation from the defined normal operating conditions. The trip setting for maximum cases is considered 10% higher or lower than normal pressure or temperature. Maximum and minimum flow rate is also 10% higher or lower than static condition respectively. Thus, flow rate, pressure, and temperature conditions are assumed that these are changing from 90 to 110% of normal environment (Figure 4-4). While, it is assumed that the distribution of the conditions follows beta distribution referring to Kalantarnia et al [13]. For calculating failure frequency, failure frequency at normal conditions is applied as presented in the previous paper [1]. At normal condition (*m*), failure frequency is f as shown in Eqn. 4-1.

$$f = \text{Failure frequency } (m) \qquad \text{(Eqn. 4-1)}$$

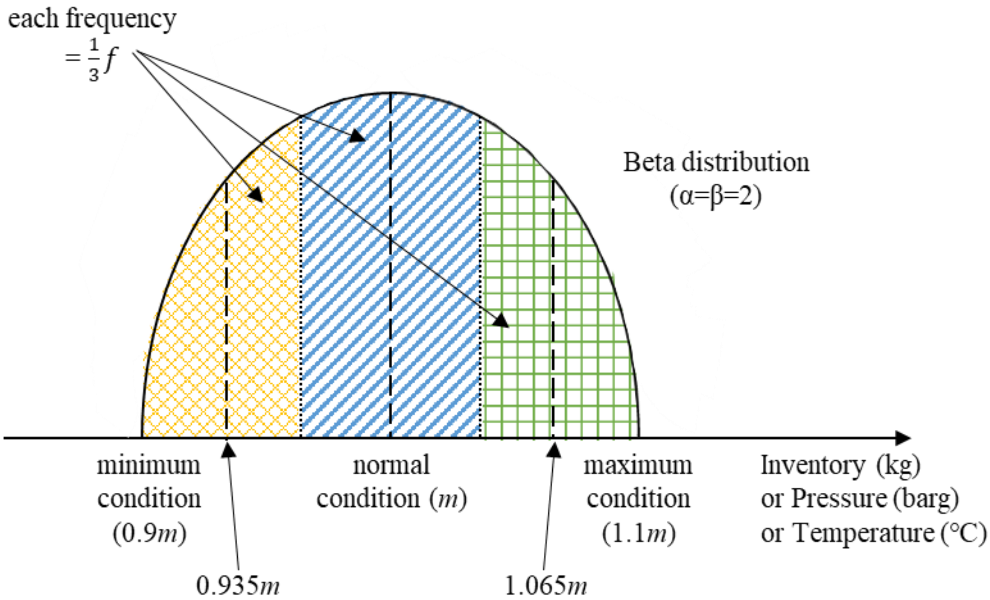


Figure 4-4. Distribution of operating condition.

Then f is divided into three, thus one third of f is used for frequencies of representative three operation values. In Figure 4-4, three operation values (0.935m, m, 1.065m) are chosen as representative values, which would be input for consequence assessment. Yellow, blue, and green parts have same area, a third of the area under the curve. The curve is a function, $y=c(x)$, then, the representative value z satisfies Eqn. 4-2.

$$(b-a) \times c(z) = \int_a^b c(x)dx \quad (a < z < b) \qquad \text{(Eqn. 4-2)}$$

For example, 0.938m and 1.062m satisfy Eqn. 4-3.

$$\frac{1}{3} \times \int_{0.9m}^{1.1m} c(x)dx = \int_{0.9m}^{0.938m} c(x)dx = \int_{0.938m}^{1.062m} c(x)dx = \int_{1.062m}^{1.1m} c(x)dx$$

(Eqn. 4-3)

And, according to Eqn. 4-4 and Eqn. 4-5, 0.935m and 1.065m are chosen as representative values.

$$\int_{0.9m}^{0.938m} c(x)dx = (0.938m - 0.9m) \times 0.935m \qquad \text{(Eqn. 4-4)}$$

$$\int_{1.062m}^{1.1m} c(x)dx = (1.1m - 1.062m) \times 1.065m \qquad \text{(Eqn. 4-5)}$$

To reflect dynamic circumstances, three representative values (0.935m, m, 1.065m) are used for consequence assessment instead of only one m, and failure frequency is updated by three $\frac{1}{3}f$.

4.3. Application

4.3.1 Flow rate distribution

Flow rate affects inventory of pipeline, and inventory quantities are calculated for IS and IF referring to Lee et al [1]. The differences of maximum and minimum inventories for IS in each equipment are less than 400 kg and ones for IF are less than 3,500 kg. Applying the inventories' trip of each pipelines and vessels, attained QRA is compared with the result of normal condition in Figure 4-5. It shows that there is no difference. The released materials in the case of accident are just flammable not toxic except hydrogen sulfide, in which quantity is less than 100ppm. Since the LC50 of hydrogen sulfide is 800 ppm for humans for 5 minutes' exposure, toxicity barely influences on the risk with such a small quantity. Also, flammability scarcely affects on a thinly populated area of the GTU plant. As a result, consequence is independent on inventory (or flow rate) in this GTU process.

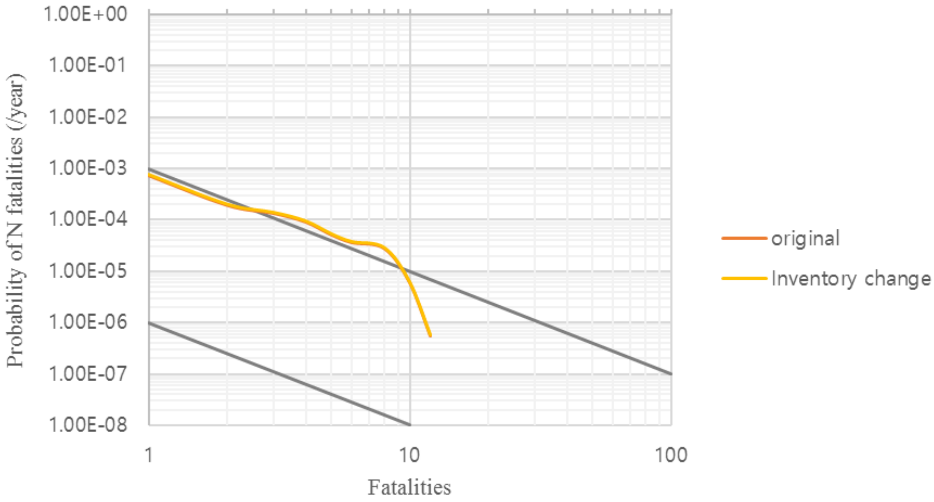


Figure 4-5. FN curve reflecting flow rate change.

4.3.2. Pressure and temperature distribution

Since pressure and temperature is interdependent, temperature should be modified to satisfy product specification when pressure has changed, and vice versa. First, conditions of changed pressure and readjusted temperature are applied to QRA. The maximum difference of pressure in each equipment is less than 5 barg. The result shows that the difference is observed in the front part of fatalities in Figure 4-6. Next, trip of temperature is observed. Maximum difference of temperature is less than 15 ℃. The result of temperature distribution shows in Figure 4-7, and it is almost same with Figure 4-6. The cause of risk increase in both the former and the letter is extension of the range of jet fire and flash fire.

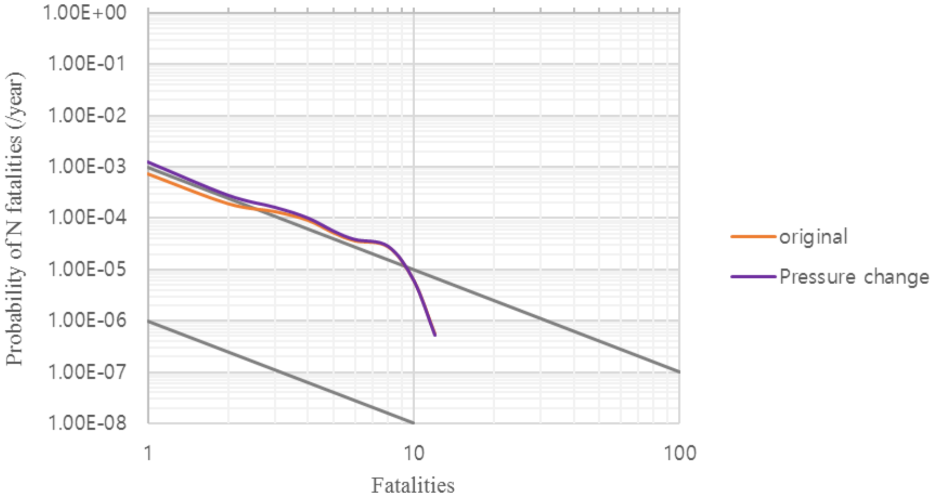


Figure 4-6. FN curve reflecting pressure change.

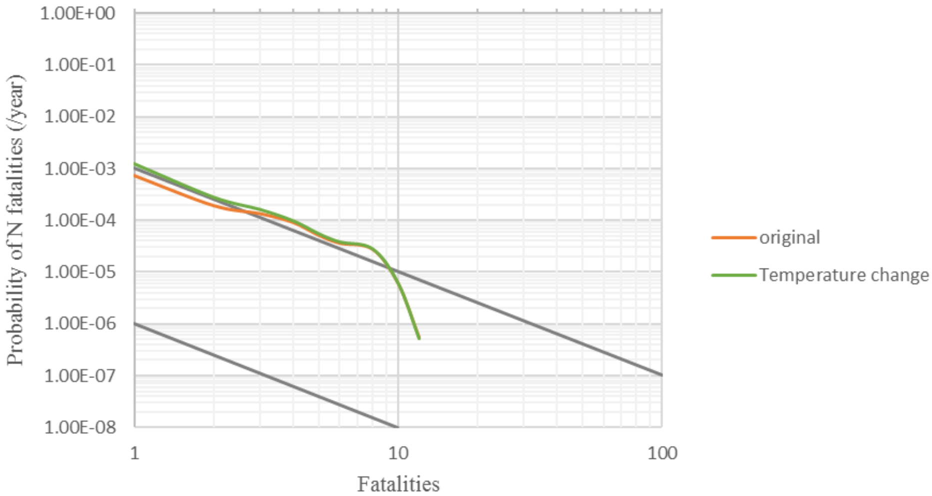


Figure 4-7. FN curve reflecting temperature change.

4.3.3. Comparison of risk integral

Risk integral of both pressure and temperature change is same as 0.001990 /year. These are 147% of the static QRA result, which is 0.001347 /year. This shows that changes of temperature or pressure affect QRA result. Thus, when the value of temperature or pressure is high enough to influence on state of matter, operating condition change should be reflected on QRA.

Risk integral can be divided into detail scenarios. According to Lee et al. [1], top cause of risk integral for normal condition is IF from P_06 with 10 mm hole. This scenario takes up almost 22% of risk integral for normal condition. However, when applying pressure or temperature changes to QRA, absolute value of P_06_IF_10 mm does not change, but ratio is decreased as 15.28% (Figure 4-8). While, risk integral ratios of P_02_IF_50 mm and P_03_IF_50 mm increase as 17.6% and 17.33% respectively. It is because P_02 and P_03 have relatively high pressure and high pressure compared to other pipelines or vessels.

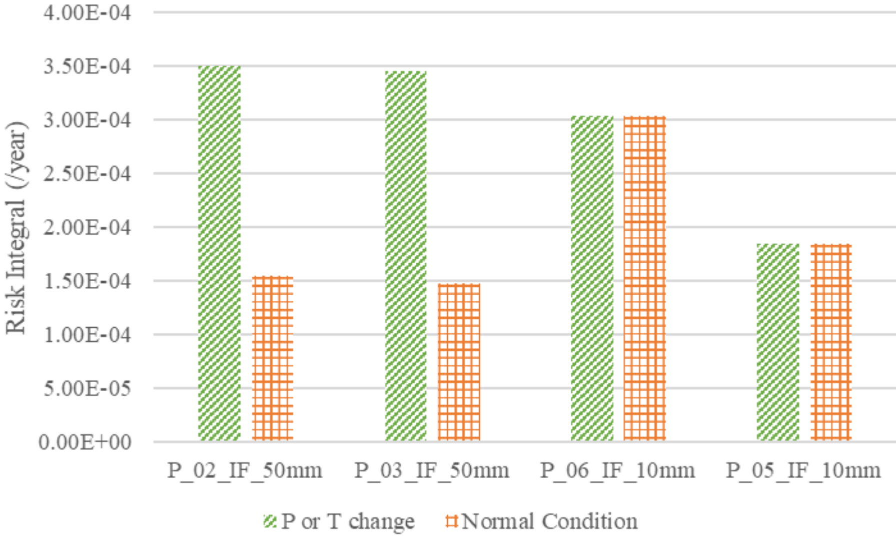


Figure 4-8. Risk integrals of major hazards

4.4. Summary and discussion

In this part, we can identify that operating condition change affects on QRA result. Operating conditions are changed in the range of trip setting, which is determined in process design stage. In the object GTU process, QRA is varied according to pressure and temperature, not to flow rate. Also, pressure and temperature change increase risk integral to 147% of normal condition. Thus, it can be concluded that change of operating condition should be reflected in QRA. Also, the higher pressure or temperature is, the bigger the QRA result. It is expected that operating condition change of toxic material would have greater effect on QRA rather than one of flammable one. For further studies, risk reduction could be conducted with this study.

CHAPTER 5 : Conclusions

5.1. Conclusion

This thesis has addressed the Risk-based Process Safety Management in Industrial Process System.

Firstly, in the storage part, cause of a dust explosion in coal silo is analyzed. Coal of the scene of the accident is compared to general properties of coal. The coal silo satisfies the pentagon of dust explosion (fuel, confinement, dispersion, oxygen, and heat). It has problems in the perspective of design and operation. Through this analysis, it can be known what should be prepared or how to operate coal silo to prevent dust explosion.

Next, in the transportation part, the risk-based underground pipeline management is suggested considering corrosion effect. It is applied to liquid propylene underground pipeline located in Ulsan industrial complex and decreases the risk by 56.8 % compared to the qualitative measure. Through sensitivity analysis, it is known that the object pipeline is influenced by temperature and flow rate, not by pressure. This study could be applied to all of the pipelines instead of underground pipeline. It contributes to introduction of quantitative measure to the pipeline management.

Lastly, effect of operating condition on QRA is identified. The changes of pressure and temperature increase the risk to 147% of normal condition with GTU process in GOSP. Thus, it can be concluded that when a process deals flammable material of high pressure or high temperature, QRA should reflect operating condition change.

This study contributes to improve accuracy of QRA.

5.2. Future works

Future studies about risk-based process safety management can be extended and applied in industrial process system, since safety consciousness has been raised. This thesis would inspire with importance of process-specific safety management.

The cause analysis of coal silo accident could be adapted to other silos storing flammable materials, such as aluminum or grain.

The risk-based underground pipeline management could be applied to all pipelines. Also, it could cause to law revision for pipeline safety.

The last study considering operating condition change would be more considerable in processes dealing with toxic substances.

Nomenclature

Chapter 2

Acronyms	
$(dP/dt)_{max}$	maximum rate of pressure rise
LFL	lower flammable limit
LIT	minimum ignition temperature of dust layer
MEC	minimum explosible dust concentration
MIE	minimum ignition energy
MIT	minimum ignition temperature of dust cloud
MOC	minimum oxygen concentration
K_{st}	dust deflagration index
P_{max}	maximum explosion pressure
UFL	upper flammable limit

Chapter 3

Acronyms	
ALARP	As Low As Reasonably Practicable
BLEVE	Boiling Liquid Expanding Vapor Explosion
CA	Consequence Analysis
CIPS	Close Interval Potential Survey
CR	Corrosion Rate
DCVG	Direct Current Voltage Gradient
ETA	Event Tree Analysis
FA	Frequency Analysis
IDLH	Immediately Dangerous to Life or Health concentrations
IR	Individual Risk
LFL	Lower Flammable Limit
MIE	Minimum Ignition Energy

QRA	Quantitative Risk Analysis
SR	Societal Risk
UFL	Upper Flammable Limit
Variables	
A	Additional thickness (mm)
CR_B	Base surface corrosion rate
$CR_{external}$	External corrosion rate
$CR_{internal}$	Internal corrosion rate
D_0	Outside diameter of pipeline (mm)
F_{CE}	Coating effectiveness factor
F_{CP}	Cathodic protection factor
F_{SR}	Soil resistivity factor
F_T	Temperature factor
f_f	Failure frequency
P	Internal design pressure (MPa)
SE	Maximum allowable stress (MPa)
S_Y	Minimum yield stress for pipeline (psi)
T	Pipeline usage time (year)
t_d	Designed pipeline wall thickness (mm)
t_m	Minimum pipeline wall thickness (mm)
t_p	Present pipeline wall thickness (mm)
x_{new}	Pipeline replacement schedule according to new methodology
$x_{original}$	Pipeline replacement schedule according to original methodology
y	Coefficient for calibrating pressure in Eqn. 1

Chapter 4

Acronyms	
BN	Bayesian Network
BT	Bow-Tie
CFD	Computational Fluid Dynamics
DRA	Dynamic Risk Assessment
ESD	Emergency ShutDown

ET	Event Tree
FT	Fault Tree
GOSP	Gas Oil Separation Plant
GTU	Gas Treatment Unit
HBA	Hierarchical Bayesian Approach
HP	High Pressure
IF	Isolation Failure
IGPP	Integrated Gas Process Plant
IS	Isolation Success
IR	Individual Risk
PFD	Process Flow Diagram
P&ID	Piping and Instrument Diagram
QRA	Quantitative Risk Assessment
SR	Societal Risk
Variables	
f	Failure frequency
m	Normal condition of inventory, pressure, or temperature
z	Representative value of normal condition

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Abstract in Korean (요 약)

1970 년대 후반부터 원자핵 분야로부터 화학 산업 공학 분야에 정량적 위험성 분석을 도입하였다. 정량적 위험성 분석의 도입 직후 1995년까지 화학 산업 공학 분야의 안전성이 향상되고 사고 수가 급격히 감소하였다. 그러나 인구 밀도가 증가하고 공정 운전 조건이 복잡해지면서 기존의 위험성 분석 방법은 사고를 방지하기에 역부족이게 되었다. 따라서 효율적이고 효과적인 공정 안전성 관리가 필요하게 되었다.

본 논문에서는 화학공정시스템의 세 가지 주요 구성 요소 (저장, 운송, 공정)에 대한 정량적 위험 관리의 새로운 방법을 제안하였고, 각각 고체, 액체, 기체 물질을 다루었다.

2단원은 석탄 저장 설비를 다루고 있다. 석탄의 야적은 석탄 품질 저하와 환경 문제를 유발하기 때문에 석탄을 사일로에 저장하게 되었다. 하지만 석탄의 밀폐로 인해 분진 폭발이 발생하게 되었고 사고가 반복되어 발생하고 있다. 따라서 이러한 사고를 방지하기 위해 특정 석탄 분진 폭발 사고에 대해 사일로의 설계 및 운영 측면에서 분진 폭발 5대 조건이 성립되는지 자세히 분석하였다. 이를 통해 석탄 사일로에 어떤 설비가 필요한지, 어떻게 운영해야 하는지에 대해 알 수 있다.

3단원에서는 지하 배관을 다루었다. 지하 배관의 노후화로 인해 전세계에서 지하 배관 사고가 빈번히 발생하고 있다. 따라서 이 단원에서는 위험성에 기반한 배관 관리 방법론을 제시하였고, 이 방법론은 지하 배관의 주요 위험 요인인 부식을 반영하였다. 먼저 기존의 정량적인 방법과 위험성에 기

반한 배관 관리 방법을 비교하여 제시한 뒤, 울산 산업 단지의 프로필렌 지하 배관에 적용하였다. 그 결과 새로운 방법론을 이용하면 위험 적분값이 기존 방법의 56.8%로 감소시킬 수 있었다. 또한 민감도 분석을 통해 대상 배관의 위험도는 온도와 유량의 영향을 받음을 확인할 수 있었다.

4단원은 가스 오일 분리 공장의 가스 처리 설비를 다루었다. 실제 공정은 운전 조건이 계속 변하는 상황 속에 운전되지만, 기존의 정량적 위험성 분석은 정상 상태 운전 조건에 대해서만 이루어졌다. 따라서 이 단원에서는 운전 조건 변화가 정량적 위험성 분석 결과에 어떤 영향을 미치는지에 대해 분석하였다. 먼저 운전 조건의 변화를 나눈 방법에 대해 제시하고 이를 적용하였다. 분석 결과, 대상 가스 처리 설비의 유량 변화는 정량적 위험성 분석에 거의 영향을 미치지 않은 반면, 온도와 압력 변화는 위험 적분값을 정상 운전 조건을 적용한 경우의 147%로 증가시켰다. 따라서 가연성 물질을 다루는 고온 고압 공정은 정량적 위험성 분석 시 운전 조건 변화를 반영할 필요가 있다. 이 연구는 정량적 위험성 분석의 정확도를 높이는 데 기여할 것으로 생각된다.

주요어: 정량적 위험성 분석; 공정 안전 관리; 석탄 분진 폭발; 지하 배관; 부식; 동적 위험성 평가; 동적 시뮬레이션

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