ASPES 2009, Volume 1, Issue 1 ISSN 1937-7991
Editor: Rafiq Islam, pp.

FLAMMABILITY AND INDIVIDUAL RISK ASSESSMENT FOR NATURAL GAS PIPELINES

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ABSTRACT

Natural gas and oil are mainly supplied and transmitted through pipelines. The safety and risk factors for transporting natural gas through pipelines is an important issue. This paper develops a comprehensive model for the individual risk assessment for natural gas pipelines. Presently available models related to pipeline risk assessment are also examined and their shortcomings identified. To overcome these limitations, a new concept of individual risk is introduced. It combines the flammability limit with existing individual risk for an accidental scenario. The new model determines the major accidental area within a locality surrounded by pipelines. Finally, the proposed model is validated using field data. This innovative model applies to any natural gas pipeline risk assessment scenario.

Keywords: natural gas pipelines; flammability limit; individual risk; explosion hazard.

1. INTRODUCTION

Natural gas is one of the most widely used domestic fuels in industrialized countries. The consumption of natural gas is continuously increasing. As a result, complex piping systems are being installed to transport and distribute the gas for end users. These pipeline networks are mostly installed in urban zones, i.e. in highly populated areas. Therefore, accidental gas releases can cause significant environmental damages, economic losses and injury to the population (Khan et al., 2006). Moreover, gas piping systems are mostly installed at underground. They are often damaged by various activities. It is reported that approximately 67% of accidents involving natural gas occur in piping systems (Arnaldos et al., 1998).

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The failure of natural gas pipelines may occur due to natural or man-made disasters such as earthquake, hurricane, sabotage, overpressure, flood, corrosion, or fatigue failures. The failure rate is also influenced by design factors, construction conditions, maintenance policy, technology usage and environmental factors. All kinds of accidents in pipelines are determined by the risk assessment and management (Ramanathan, 2001). Risk assessment is the process of obtaining a quantitative estimate of a risk by evaluating its probability and consequences. Risk is generally referred to the potential for human harm. This risk represents a hazardous scenario, which is a physical or societal situation. If encountered, it could initiate a range of undesirable consequences. The most frequent cause is perforation of the pipe or complete fracture. Gas will be released to the environment at a flow rate depending on the hole diameter and the pressure in the pipe until the release is stopped automatically by means of a regulator, as a reaction to excessive flow rate, or manually.

Natural gas pipelines failures are potentially hazardous events especially in urban areas and near roads. Therefore people around the pipeline routes are subject to significant risk from pipeline failure. The hazard distance associated with the pipeline ranges from under 20 m for a smaller pipeline at lower pressure, up to over 300 m for a larger one at higher pressure (Jo and Ahn, 2002). So it is essential to study the level of pipeline safety for a better risk assessment and management.

To determine the individual risk of an explosion hazard, flammability limits data are essential in a natural gas pipeline. Flammability limits are commonly used indices to represent the flammability characteristics of gases. These limits can be defined as those fuel-air ratios within which flame propagation can be possible and beyond which flames cannot propagate. By definition there are two flammability limits namely lower flammability limit (LFL) and upper flammability limit (UFL). LFL can be defined as the leanest fuel limit up to which the flame can propagate and the richest limit is called as UFL (Liao et al., 2005). The flammability limit criterion, and other related parameters have been broadly discussed in the available literature (Vanderstraeten et al., 1997; Kenneth et al., 2000; Kevin et al., 2000; Pfahi et al., 2000; Wierzba and Ale, 2000; Mishra and Rahman, 2003; Takahashi et al., 2003). The objectives of this study are to predict a future outcome with certainty and to eliminate future risk. This study introduces a new dimension of risk assessment combining risk due to flammability limit and lethal failure in the accident scenarios.

2. Pipeline Risk Management

Natural gas pipelines are an elongated pressure container with unlimited flow. They transport large quantities of natural gas at elevated pressures. The pipelines represent a hazardous risk to nearby population and facilities, in addition to business interruption concerns. Although underground burial of pipelines is recommended, it does not prevent pipeline accidents from happening, since gas leakage and pipeline failure are still possible. A means for emergency isolation should be supplied at pipeline entries and exits from various facilities. For integrity assurances, pipelines should be verified regularly for failures and leakages at vulnerable locations including weld joints and flange connections. These are usually checked using testing techniques, such as ultrasound, x-ray, and die penetrants.

The primary factor affecting pipeline hazardous incidents in normal situations is corrosion. Therefore, it is important to take care of the pipelines by using proper anti-corrosion materials. Furthermore, pipeline failure can result from third party activity, sabotage, or natural disasters. Figure 1 illustrates the risk management approach for natural gas pipelines comprising the following steps:

1. Piping system identification;
2. Operations information;
3. Risk assessment;
4. Strategy;
5. Actions;
6. Evaluation.

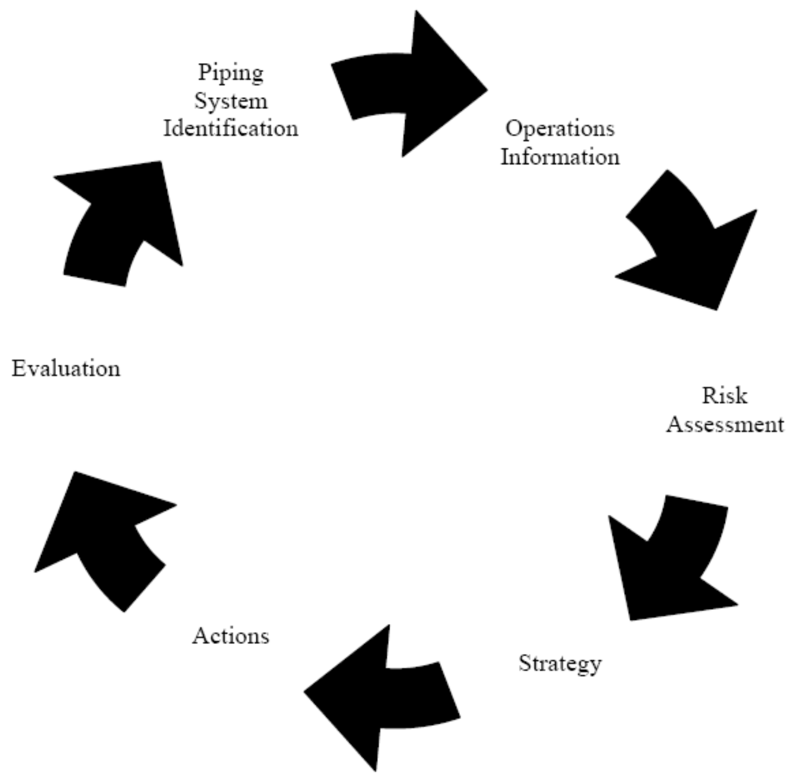

Figure 1. Risk management for natural gas pipelines.

3. RISK ASSESSMENT

In order to assess the risk regarding the natural gas pipeline, it is necessary to evaluate probable undesirable consequences resulting from any pipeline leakage or rupture.

The quantitative risk can be estimated due to flammability limit for a natural gas pipeline. Risk has been described as individual risk, societal risk, maximum individual risk, average individual risk of exposed population, average individual risk of total population, and average rate of death (TNO Purple Book, 1999; Jo and Ahn, 2002 and 2005). This study will demonstrate how the individual risk is influenced by flammability limits and other related parameters.

The failure rate of pipelines depends on various parameters such as soil conditions, coating type and properties, design considerations, and pipeline age. So a long pipeline is divided into sections due to significant changes of these parameters. Considering a constant failure rate, the individual risk (Jo and Ahn, 2005) can be written as:

$$IR = \sum_i \varphi_i \int_{l_-}^{l_+} p_i dl \qquad (1)$$

where

φ_i = Failure rate per unit length of the pipeline associated with the accident scenario *i* due to soil condition, coating, design and age, *1/year km*

l = Pipeline length, *m*

p_i= Lethality associated with the accident scenario *i*

$l_\pm$ = Ends of the interacting section of the pipeline in which an accident poses hazard to the specified location, *m*

The release of gas through a hole on the pipeline causes explosion and fire in the natural gas pipeline and the surrounding area, which creates accidents. The effected section causes a hazard distance. The release rate of natural gas and hazard distance are correlated (Jo and Ahn, 2002):

$$r_h = 10.285\sqrt{Q_{eff}} \qquad (2)$$

where

Q_{eff} = Effective release rate from a hole on a pipeline carrying natural gas, *kg/sec*

r_h = Hazard distance, *m*

The hazard distance is the distance within which there is more than one percent chance of fatality due to the radiational heat of jet fire from pipeline rupture. Figure 2 shows the geometric relations among the variables in specified location from a natural gas pipeline. From this figure, the interacting section of a straight pipeline, *h*, from a specified location, is estimated by the following equation (Jo and Ahn, 2005):

$$l_\pm = \sqrt{106Q_{eff} - h^2} \qquad (3)$$

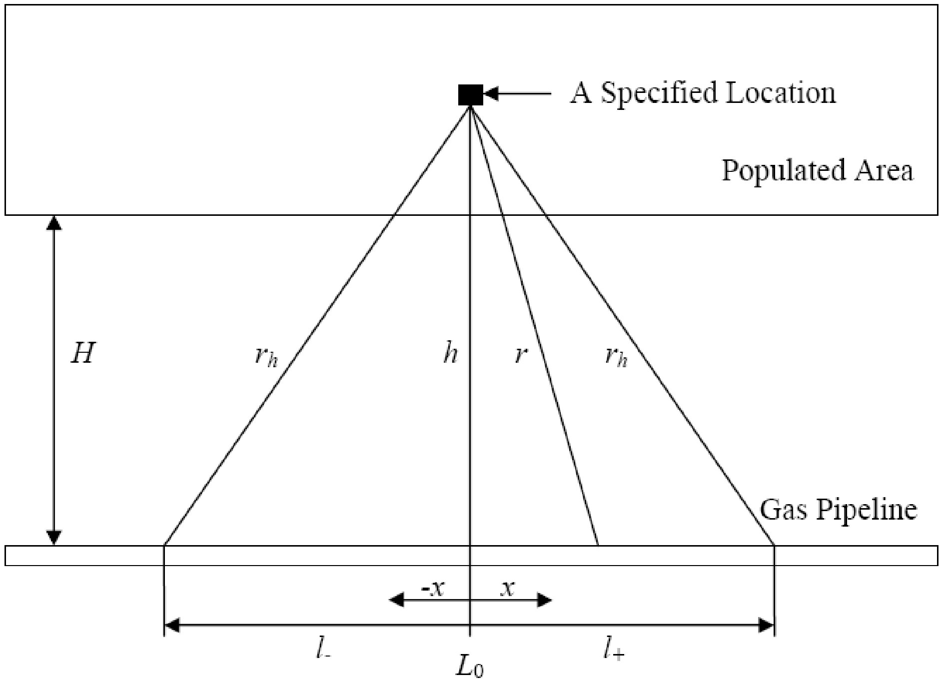

Figure 2. Individual risk variables (Redrawn from Jo and Ahn, 2005).

Jo and Ahn (2005) show the different causes of failure based on hole size and other activities. The external interference by third party activity is the major cause of key accidents related to hole size. Therefore, a more detailed concept is extremely required to analyze the external interference. The third party activity on pipeline depends on several factors, such as pipe diameter, cover depth, wall thickness, population density, and prevention method. The failure rate of a pipeline can be estimated by some researchers (Jo and Ahn, 2005; John et al., 2001).

4. Effects of Composition on Flammability Limit

An experimental study is usually conducted to investigate the effects of concentration or dilution in natural gas – air mixture by adding CO_2, N_2 gas. The limit ranges are 85-90% of N_2 and 15-10% of CO_2 by volume. This is quite practical considering natural gas stoichiometric combustion at ambient temperature. Flammability experiments have been performed to simulate real explosions in order to prevent hazards in the practical applications (Liao et al., 2005). Table 1 shows the flammability limit data for methane-air and natural gas-air flames according to Liao et al. (2005).

LFL depends on the composition of fuel mixture in air. This value can be estimated by LeChatelier’s rule (Liao et al., 2005):

$$LFL = \frac{100}{\sum (C_i / LFL_i)} \tag{4}$$

where
LFL = Lower flammability limit of mixture (vol. %)
C_i = Concentration of component i in the gas mixture on an air-free basis (vol. %)
LFL_i = Lower flammability limit for component i (vol. %)

Table 1. Flammability limit data (vol %) for methane-air and natural gas-air flames (quiescent mixtures with spark ignition)

Mixture	Test Condition	LFL (vol %)	UFL (vol %)
NG-air	1.57 L chamber	5.0	15.6
	LeChatelier's rule	4.98	-
Methane-air	8 L chamber	5.0	-
	20 L chamber	4.9	15.9
	120 L chamber	5.0	15.7
	25.5 m^3 sphere	4.9, 5.1 $\pm$ 0.1	-
	Flammability tube	4.9	15.0

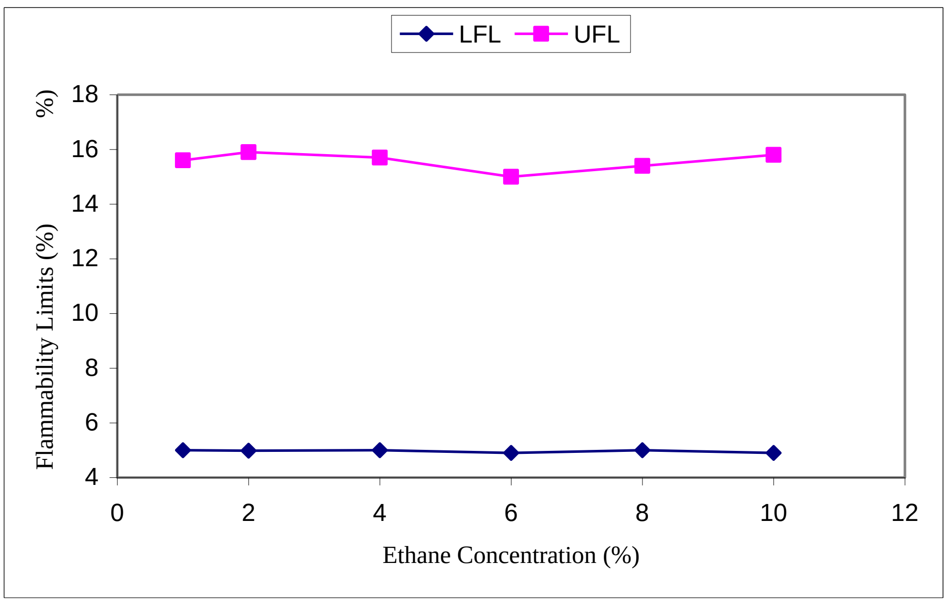

Figure 3. Dependence of NG flammability limits on ethane.

The estimation of LeChatelier's rule is shown in Table 1 and is plotted in Figure 3 as well. The reliance of natural gas flammability limit upon ethane concentration has been studied by Liao et al. (2005) that is presented in Figure 3. Here it is shown that the flammability region is slightly extended with the increase of ethane content in natural gas. LFL is almost 5% in volume and UFL is about 15%. The flammability limits are 3.0 to 12.5 in volume for ethane-air mixture. Their equivalent ratios are 0.512 and 2.506. The ratios are 0.486 and 1.707 with methane respectively. It is noted that the increase of ethane content in natural gas is extending the UFL in equivalence ratio but there is no remarkable change in LFL. Liao et al. (2005) show the effect of diluent ratio (ϕ_r) on flammability ratio. According to them, the increase of diluent ratio decreases the flammability region. The reason has been identified that the addition of diluents decreases the temperature of flame, which decreases the burning velocity. So, flammability limit goes narrower. Normally, CO_2 is more influential than N_2 addition. Shebeko et al. (2002) presented an analytical evaluation of flammability limits on ternary gaseous mixtures of fuel-air diluent. His prediction is shown in Figure 3 with dashed line.

5. INDIVIDUAL RISK BASED ON FLAMMABILITY

Figure 4 shows the incidental zone founded on basic fluid dynamics. The accidental scenario represents this incidental zone. If an explosion takes place for any reason, the incidental zone will be definitely covered by projectile theory of fluid dynamics. This concept is the basic difference from the model of Jo and Ahn (2005), which is shown in Figure 2. An accident due to flammability is considered here as the main cause of the incident. In Figure 4, OB is the maximum distance covered by the fire flame within which a fatality or injury can take place. BA and BC are the maximum distances traveled by the flame.

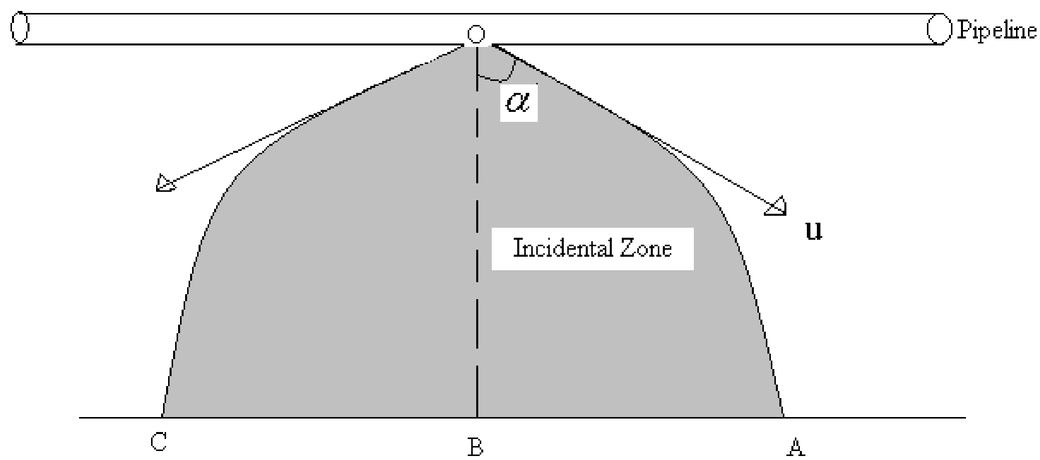

Figure 4. The relation of variables related with IRf .

The velocity of the natural gas evolved through the hole can be written as:

$$u = 1.273 \frac{q_{\min}}{d_{hole}^2} \tag{5}$$

where

$q_{\min}$ = Minimum gas flow rate evolved through the hole that causes an explosion $= f(u, d_{hole})$, ft^3/sec

d_{hole} = Diameter of the hole through which gas passes, *ft*

Hazard distance or maximum distance covered by gas particles can be written as:

$$h_{\max} = \frac{1}{2} ut \cos \alpha \tag{6}$$

where:

$h_{\max}$ = Hazard distance, *ft*

u = Velocity of gas, $ft/\sec$

t = Travel time to reach the hazard distance, *sec*

α = Angle between velocity of gas and hazard distance, *degree*

Figure 4 shows the geometric relations among the variables in specified location from a natural gas pipeline. From this figure, the interacting section of a straight pipeline, $l_{\pm}$ from specified location, B, and the angle, α are estimated by the following equations:

$$l_{\pm} = \frac{1}{2} ut \sin \alpha \tag{7}$$

and

$$\alpha = \tan^{-1}\left(\frac{l}{h_{\max}}\right) \tag{8}$$

The individual risk (IR_f) due to flammability limit in a natural pipeline can be written as:

$$IR_f = \sum_i \frac{\varphi_i}{100} \int_{-l}^{+l} \int_0^{h_{\max}} \left(UFL_i - LFL_i\right) dh\,dl \tag{9}$$

where

φ_i = The failure rate per unit length of the pipeline associated with the accident scenario i due to flammability

l = Pipeline length, *ft*

UFL, LFL = Upper and lower flammability limit

$l_{\pm}$ = Ends of the interacting section of the pipeline in which an accident poses hazard to the specified location, *ft*

Figure 5 shows the number of incidents with pipeline distance from the source of gas. The data has been collected from the US office of pipeline safety, incident summary statistics from 1986 to August, 2005 (Web site 1). In this figure, the number of incidents are oscillating pattern within the region of 67775 and 259136 miles, however, beyond this distance, the rate of incidents show an abnormal pattern. It might be the cause of other factors, such as natural disaster, human activities.

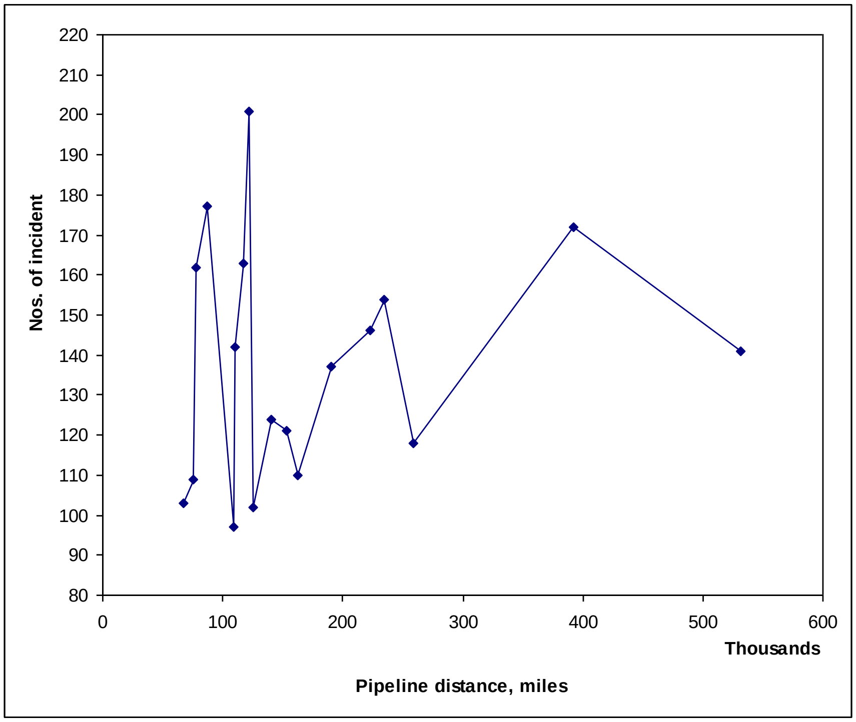

Figure 5. Incident related with pipeline distance.

There is no available model that handles both flammability limit and lethality for measuring individual risk. It is difficult to get the data for the particular reason of accidental scenario due to flammability. Based on available information and data dealing with this issue, the proposed model can be easily verified with any sets of data with confidence. In this study, 10% of accidental scenarios are assumed to be due to flammability (Web site 1). Using these data, the proposed model (Equation 9) is tested and results are shown in Figure 6. It shows the individual risk due to flammability with number of injuries. The normal trend of the curve is increasing with the increase of number of incident which leads to a separate scenario of accidents due to flammability. This chart also shows that there is a great impact of flammability on accidental scenario.

Figure 7 shows the probability of individual risk due to flammability with pipeline distance using Equation 9. Here it has been assumed that the *UFL* and *LFL* are 15.6 and 5.0 for the calculation. $q_{\min}$ is considered as $1\,ft^3/\sec$, $\alpha = 45^0$, $t = 1$ min and $d_{hole} = 0.5$ ft for a case study. The available literature shows that the maximum value of h is 66 *ft* and l is 99 *ft* . Here the calculation shows that h is 80.5 ft and l is 129.93 ft. These values seem to be quite reasonable. The individual risk due to flammability is decreasing with pipeline distance from the gas supply center. However, the trend is quite unpredictable and more frequent in an accident scenario within the pipeline range of 124,931 miles. This graph also shows that there is a great impact of flammability on accidental scenario.

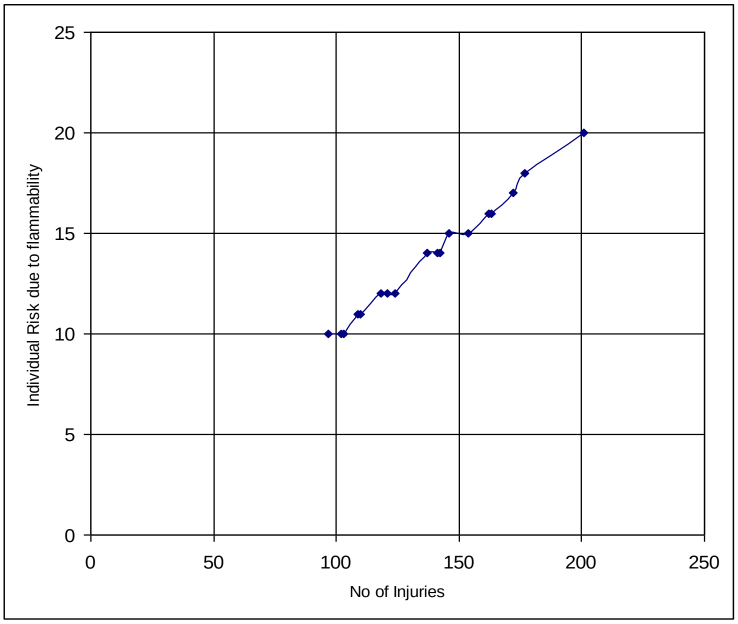

Figure 6. Individual risk due to flammability with number of injuries.

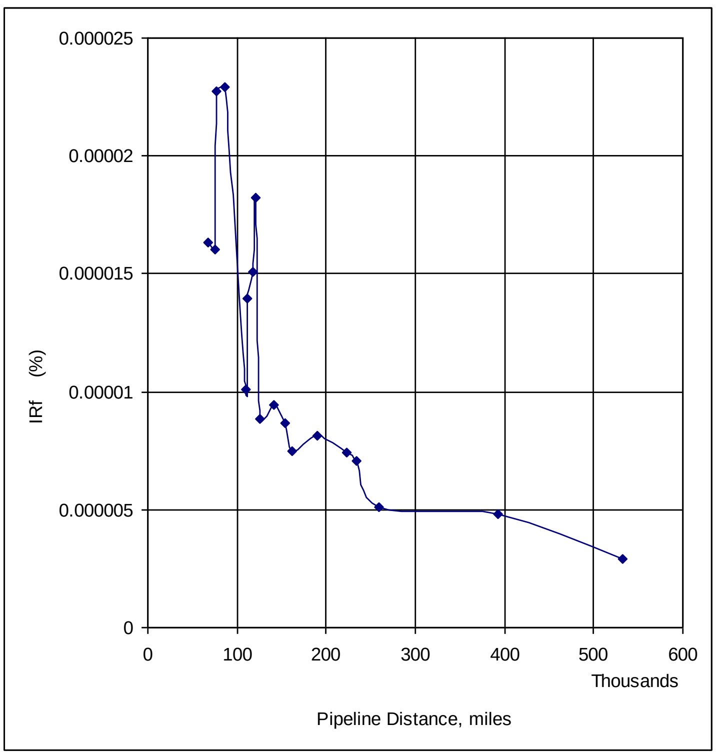

Figure 7. Percent of Individual risk due to flammability with Pipeline Distance.

Now combining Equation 1 and 9, a combined individual risk in a natural gas pipeline is obtained:

$$IR_T = IR + IR_f \qquad (10)$$

This equation represents a true scenario of an individual risk due to lethality and flammability of natural gas. The lethality of natural gas pipeline depends on operating pressure, pipeline diameter, distance from the gas supply to pipeline and the length of the pipeline from the gas supply or compressing station to the failure point.

CONCLUSION

Extensive pipeline network for natural gas supply system possesses many risks. Appropriate risk management should be followed to ensure safe natural gas pipelines. Individual risk is one of the important elements for quantitative risk assessment. Considering the limitations in conventional risk assessment, a novel method is developed for measuring individual risk combining all probable scenarios and parameters associated with practical situations taking into account gas flammability. These parameters can be calculated directly by using the pipeline geographical and historical data. By using the proposed method, the risk management can be more appealing from practical point of view. The proposed model is found to be innovative using pipeline and incident statistical data. The method can be applied to pipeline management during the planning, design, and construction stages. It may also be employed for maintenance and modification of a pipeline network.

ACKNOWLEDGEMENT

The authors would like to thank the Atlantic Canada Opportunities Agency (ACOA) for funding this project under the Atlantic Innovation Fund (AIF). The authors would like to thank Dr. M. Zubair Kalam, SCAL Expert, ADCO, Abu Dhabi, UAE; Dr. Ali S. Al-Bemani, Vice-President, Sultan Qaboos University, Oman; and Dr. Mohammad Tamim, Professor, PMRE, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh for their valuable contribution while accomplishing this research project.

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