Proceedings of the Seventh IASTED International Conference
POWER AND ENERGY SYSTEMS
November 28 - December 1, 2004, Clearwater Beach, FL, USA

INDIVIDUAL RISK ANALYSIS OF TRANSMISSION PIPELINE CARRYING NATURAL GAS

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Abstract

Unlike other hazardous plant, the transmission pipelines carrying natural gas are not within secure industrial site, but are routed across land out of owned by the pipeline company. If the natural gas is accidentally released and ignited, the hazard distance associated with these pipelines to people and property is known to over 300m for a larger one at higher pressure. Therefore, pipeline operators and regulators must address the associated public safety issues.

This paper focuses on a method to calculate explicitly the individual risk of transmission pipeline carrying natural gas with reasonable accident scenarios for route planning in relation to the pipelines proximity to surrounding building. The minimum proximity distances between pipelines and buildings is based on the rupture of the pipeline and the distances where chosen to correspond to a radiation level of approximately 32 kW/m^2. In the design criteria of steel pipelines for high pressure gas transmission(IGE/TD/1), the minimum building proximity distances for rural area are located between 10^{-5} and 10^{-6} of individual risk. Therefore, the risk from natural gas transmission pipeline is low comparing with other risk from traffic or chemical industries.

Key Words: risk analysis, transmission gas pipeline, individual risk, minimum proximity, fatal length, jet fire.

1. Introduction

Transmission pipelines carrying natural gas are not on secure industrial site as a potentially hazardous plant, but are routed across the land i.e., busy city or a network of superhighways. Consequently, there is the ever-present potential for third parties to interfere with the integrity of these pipelines. In addition, the combination of third-party interference and pipeline route might suggest that people around the pipelines are subject to significant risk from the pipeline failure. If the natural gas is accidentally released and ignited, the hazard distance associated with these pipelines to people and property had been found to range from under 20 m for a smaller pipeline at lower pressure, up to over 300m for a larger one at higher pressure[1].

Historically, mechanical interference during excavations and other activities close to the pipelines has been a major cause of transmission pipeline incidents. In South Korea, there have been no public fatalities due to failures of the transmission natural gas pipeline until now. Though rare, an accident occurs such as the methane pipeline rupture in Edison, New Jersey, in 1994, it receives significant media and public attention due to its dramatic nature. Such occasion is good example of the importance of public perception when addressing risk issues. Pipeline operators and regulators must address the associated public safety issues.

The individual risk is defined as the probabilities of death per one year of exposure to an individual at a certain distance away from hazard source. It is usually expressed in the form of iso-risk contours around the hazard source. In the case of pipelines, the iso-risk contour is usually parallel with the pipeline. It is useful to determine the route of new pipeline at the planning stage. When a pipeline is passing close to a town or any other populated area, societal risk has to be evaluated with individual risk to check acceptable or not with the risk criteria of the pipeline. Many countries, including Australia, the Netherlands and the UK, employ numerical criteria in judging tolerability or acceptability in terms of safety. One approach is to set an upper limit of tolerability beyond which one must not go and a lower limit of negligible risk; in between is a grey area where risk reduction measures must be considered and discussed on the grounds of reasonableness and cost-benefit. The US is also moving to risk based management/cost-benefit oriented approach. The criteria are summarised by the ALARP triangle[2]. ALARP stands for "As Low As Reasonably Practicable", which ranges from intolerable level(10^{-4}/year) to a broadly acceptable level(10^{-6}/year). These risk criteria have to be consisted with the minimum proximity of the pipeline to normally-occupied buildings. But in the codes related to the gas pipeline of Korea, the risk is considered implicitly and the codes do not denote the minimum proximity. This paper focuses on a method to calculate explicitly the individual risk of transmission pipeline carrying natural gas with reasonable accident scenarios for route planning related to the pipelines proximity to surrounding building.

2. Individual risk

The individual risk can be estimated by integrating the likelihood of accident multiplied by the fatality at the location from all accident scenarios along the pipeline. It can be written as the following equation.

$$IR = \sum_i \int_0^L \varphi_i P_i dL \qquad (1)$$

where the subscript i denotes the accident scenarios, φ_i is failure rate per unit length of the pipeline associated with the accident scenario i, L is the pipeline length, and P_i is lethality associated with the accident scenario i.

The accident scenarios of natural gas pipelines to quantitative risk assessment are explosion and jet fire sustained with gas release from medium, and great hole pierced on the pipeline[3]. The failure rate of pipeline may vary with different conditions along the route of pipeline, such as soil conditions, coating conditions, design conditions, or age of pipeline. Thus the pipeline has to be divided into sections whenever those conditions are changed significantly. By assuming constant failure rate within a section of pipeline, the individual risk can be estimated by the following equation.

$$IR = \sum_i \varphi_i \int_0^L P_i dL \qquad (2)$$

The integrated value of the lethality depends on operating pressure, pipe diameter, distance from a specified point of interest to the pipeline, and the length of the pipeline from gas supply or compressing station to the failure point. By defining the integrated part as fatal length, the equation can be expressed simply as following.

$$IR = \sum_i L_{FL,i} \varphi_i \qquad (3)$$

where $L_{FL,i}$ is the fatal length associated with accident scenario i.

The fatal length means a weighted length of pipeline within which an accident has the fatal effect on the person at a specified location. The individual risk can be estimated simply by summation of the fatal lengths multiplied failure rate for all accident scenarios. The failure rate and fatal length will be discussed in the next sections.

2.1 Failure rate

Failure rate of a pipeline has the unit of the number of failure per year and per unit length of the pipeline, 1/yr.km, with assuming uniform condition along the pipeline section of interest. It is somewhat different from the case of point source of accident in which the rate is defined as the number of failure per year. Failure rate of the pipeline in each accident scenario may be estimated by:

$$\varphi_i = \sum_j \varphi_{i,j,0} \mathrm{K}_j (a_1, a_2, a_3, \cdots) \qquad (4)$$

where φ_i is the expected failure rate per unit pipeline length(1/yr.km), $\varphi_{i,j,0}$ is the basic failure rate per unit length of pipeline(1/yr.km), K_j is the correction function associated with failure causes, a_k is the variables of the correction function, the subscript i denotes an accident scenario such as that of small, medium, and great hole pierced on the pipeline, and the subscript j denotes the failure causes such as external interference, construction defects, corrosion, ground movement, and others.

It should be recognized that a pipeline does not have usually the constant probability of failure over its entire length. As conditions vary along the route of the pipeline, so does the probability. Therefore the pipeline has to be divided into sections according to the condition, such as soil, coating, design, cathodic protection, or age of pipeline. The failure rate in a particular section of pipeline depends on many variables, such as the above conditions, depth of cover, hydrostatic test, survey, patrol, training, and so on. It is very difficult to include the effects of those variables on the failure rate because accident data may not be sufficient for statistical analysis. Generally for the risk analysis, the failure rate of pipeline is estimated simply with some variables from historical data. The failure rate of major gas pipelines in Western Europe is reported by the European Gas Pipeline Incident Data Group[4]. It is currently based on the experience of 1.5 million kilometer-years in eight countries of Western Europe[5]. As shown in table 1, the external interference by third party activity is the leading cause to generate the medium or great hole. The consequence of small hole is ignorable due to insignificant release rate of natural gas[3]. The failure rates for medium and great hole are 2.243 x 10^{-4} 1/yr.km and 7.475 x 10^{-5} 1/yr.km, respectively. These values are an order of magnitude higher than the values estimated from DOT data or British Gas Transco data[6]. In this work, we adapt the EGIG data conservatively.

2.2 Consequences

The accident scenarios of high pressure natural gas pipeline associated with fatalities can be selected very few scenarios from investigating real accident. An unconfined vapour cloud explosion produces negligible overpressure with the flame travelling through gas and air mixture. When objects such as buildings are near or amidst an ignited gas cloud, they restrict the free expansion of

Table 1. Failure frequencies based on failure causes and hole size(EGIG, 1993).

Failure causes	Failure frequency [1/yr.km]	Percentage of total failure rate	Percentage of different hole size[%]		
			Small	Medium	Great
External interference	3.0×10^{-4}	51 %	25	56	19
Construction defects	1.1×10^{-4}	19 %	69	25	6
Corrosion	8.1×10^{-5}	14 %	97	3	<1
Ground movement	3.6×10^{-5}	6 %	29	31	40
Others/unknown	5.4×10^{-5}	10 %	74	25	<1
Total failure rate	5.75×10^{-4}	100 %	48	39	13

The hole sizes are defined as follows: Small hole: hole size is lower than 2cm; Medium hole: hole size ranges from 2cm up to the pipe diameter; Great hole: Full bore rupture or hole size is greater than the pipe diameter.

combustion products and cause a significant overpressure to build up[7]. A typical brick building may be destroyed by an explosion overpressure of 0.07 bars. This overpressure could be generated by very small quantity on the order of one thousands of enclosure volume[8]. Therefore, the buildings could be destroyed by semi-confined explosion of gas either outside the building or migrated into the building. The possibility of a significant flash fire resulting from delayed remote ignition is extremely low due to the buoyant nature of the vapour, which generally precludes the formation of a persistent vapour cloud at ground level. Dominant hazards are, therefore, the collapse of buildings from explosion and the heat effect of thermal radiation from a sustained jet fire, which may be preceded by a short-lived fireball. When a person is afflicted from the two events at the same time, the death probability should be considered for the intersection of both events to avoid the overestimation. The hazard distance from the explosion is shorter than that from the jet fire which may follow the explosion, if an accident point is not very close to gas supply station[1]. It implies that death probability by the explosion should be included in that of jet fire followed it. The death probability at a specified location from an accident of natural gas pipeline can be estimated then simply by considering only the thermal effect of the jet fire.

2.2.1 Thermal radiation

The heat flux at a certain distance from a jet fire depends on the shape of flame. A jet flame can be idealized as a series of point source heat emitters spread along the length of the flame. The total heat flux reaching a given point is obtained by summing the radiation received from each point source emitter. By collapsing the set of heat emitters into a single point source emitter located at ground level, the total heat flux received by ground level damage receptor is estimated conservatively. This assumption has advantage to avoid tedious calculation and it gives very simple equation for risk assessment, even though the result has some error. Therefore, heat flux at a certain distance from the fire source, which is defined by the receiver per unit area, can be calculated as suggested in API RP 521[9].

$$I = \frac{\eta \tau_a Q_{eff} H_c}{4\pi r^2} \tag{5}$$

where I is radiational heat flux at the location of interest, η is the ratio of total heat radiated to total heat released from fire, τ_a is atmospheric transmissivity, Q_{eff} is effective gas release rate from the hole, H_c is the heat of combustion and r is radial distance from flame center to the location of interest.

Radiation fraction(η) cannot be estimated theoretically, and is normally estimated from the data measured with radiometer. For methane, it is suggested as 0.2 from laboratory experimental data[10]. Atmospheric transmissivity is a measure telling how much radiant heat absorbed and reflected by the atmosphere between fire and the location of interest. It is dependent upon the amount of water vapour in the air[11].

$$\tau_a = 2.02\left(P_w \overline{H}\, r\right)^{-0.09} \tag{6}$$

where P_w is vapour pressure of the saturated water and $\overline{H}$ is the relative humidity.

The Republic of Korea lies on the east coast of the Eurasian Continent adjacent to the West Pacific. During the winter, from December to January, it is cold and dry under the dominant influence of the Siberian air mass. Meanwhile, the summer, from June to August, is hot and humid with frequent heavy rainfalls associated with the East-Asian Monsoon. The annual mean temperature is about 12°C and the humidity is about 65%. By using the vapour pressure of water as 3086 N/m^2 corresponding to the average temperature and the average humidity, the transmissivity can be expressed with radial distance from flame source to the location of interest as the following equation.

$$\tau_a = 1.0189\, r^{-0.09} \tag{7}$$

Then, the thermal radiation at a specified location from the jet flame of natural gas can be written in terms of gas release rate and the radial distance, by substituting the heat of combustion of the natural gas at room temperature as 5.002×10^7 *J/kg*.

$$I = 8.11\times10^5\, Q_{eff}\, r^{-2.09} \tag{8}$$

2.2.2 Gas release rate

The gas release rate from a hole of pipeline varies with time. Within seconds of failure, the release rate will have dropped to a fraction of the peak initial value. It will decay even further over time until steady-state. The peak initial release can be estimated by assuming the sonic flow through an orifice as following equation[12].

$$Q_{peak} = \frac{\pi d^2 \alpha}{4}\sqrt{\gamma\rho_0 p_0\left[\frac{2}{\gamma+1}\right]^{\frac{\gamma+1}{\gamma-1}}} \quad (9)$$

where α is the dimensionless hole size which is the ratio of effective hole area to the pipe cross-sectional area, d is the pipeline diameter, ρ_0 is stagnation density of gas at operating conditions, p_0 is stagnation pressure at operating conditions, and γ is the specific heat ratio of gas.

The release rate through a hole on the pipeline at steady-state can be estimated approximately by assuming choke flow at the release point[13].

$$Q_{steady-state} = \frac{Q_{peak}}{\sqrt{1+\frac{4\alpha^2 f_F L}{d}\left(\frac{2}{\gamma+1}\right)^{\frac{2}{\gamma-1}}}} \quad (10)$$

where f_F is Fanning friction factor and L is the pipeline length from the gas supply station to the release point.

The numerator in the above equation is the release rate without friction loss through the pipeline, while the denominator acts as a decay factor due to the wall friction loss at steady-state. The effective release rate associated with the death probability of a person from a fire would depend on the time exactly when ignition occurs. The death probability could be estimated by approximating the transient jet fire as a steady-state fire that is fed by the gas released at the effective rate. The effective release rate, CQ_{peak}, is a fractional multiple of the peak initial release rate. It can be used to obtain the heat flux comparable to that from the real transient fire ignited in slight delay. In general, the most appropriate value for the decay factor would depend on the pipe size being considered, the pressure at the time of failure, the assumed time to ignition, and the time period required to cause harm to people. In one-dimensional transient flow through the arrested crack tip of a tube with constant cross-section, the decay factor is expressed as the following equation[14].

$$C = \left[1-\frac{\gamma-1}{\gamma+1}\right]^{\frac{2\gamma}{\gamma-1}} \quad (11)$$

In a study of risks from hazardous pipelines in the UK conducted by A. D. Little Ltd.[15], the authors quoted 0.25 as the decay factor. A more conservative value of 0.3 is adopted here for the factor. It is not to underestimate the intensity of the sustained fire associated with nearly immediate ignition of leaked gas from large diameter pipelines. For a rupture near the gas supplying station, however, the decay factor appears at steady-state greater than 0.3 which is estimated by the denominator of Eq. (10). Therefore, the decay factor has to be taken the lager value between 0.3 and the value at steady-state.

By assuming the specific heat ratio $\gamma = 1.42$, gas density at atmosphere $\rho = 0.68\, kg/m^3$, and Fanning friction factor $f_F = 0.0026$ conservatively for steel pipeline, the effective rate of gas release through a hole on the pipeline can be expressed as the following equation.

For an accident near the gas supplying station:

$$Q_{eff,i} = \frac{1.783\times10^{-3} A_P\, \alpha_i\, p_0}{\sqrt{1+4.196\times10^{-3}\alpha_i^{\,2} L/d}}, \quad \alpha_i^{\,2}\frac{L}{d} \le 2410 \quad (12)$$

For an accident far away from the gas supplying station:

$$Q_{eff,i} = 5.349\times10^{-4} A_P\, \alpha_i\, p_0, \quad \alpha_i^{\,2}\frac{L}{d} > 2410 \quad (13)$$

where A_p is the cross-section of the pipeline.

2.2.3 Death probability

The probability of death from an accident can be estimated as the following equation[16].

$$P = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\Pr-5} e^{-s^2/2} ds \quad (14)$$

Argument of the function is the probability unit, $\Pr$, characterizing the dose-effect relationship between the doses of such concrete harmful load as pressure, heat, or toxicity, and such recipient categories as death or injuries.

$$\Pr = a + b\ln(D) \quad (15)$$

where a and b are empirical constants that reflect the hazard specifics of a harmful load studied and the susceptibility of recipients to the load, while D is a dose of the load for a given exposure time.

For the fatality of a person from heat effect, it can be expressed as the following equation(AIChE/CCPS, 2000).

$$\Pr = -14.9 + 2.56\ln\left(\frac{tI^{4/3}}{10^4}\right) \quad (16)$$

where t is the exposure time and I is the radiational heat flux at a specified location of interest.

The duration of exposure depends on so many circumstances that it would not be possible in fact to establish any specific rule to evaluate the degree of harm. Rausch recommends a value of 30 seconds as exposure time for the people[17]. Therefore, Probit equation for death at a specified location from the jet flame of natural gas can be written as the following equation by using Eqs. (8) and (16).

$$\Pr = 16.67 + 3.4\ln(Q/r^{2.09}) \quad (17)$$

where r is the distance from a specified location to the fire.

The probability of death at a specified location from an accident of natural gas pipeline can be estimated now simply with only one dimensional variable, $Q/r^{2.09}$.

2.2.4 Fatal length

The fatal length could be defined here as the pipeline length weighted by the death probability at a specified location. It can be evaluated by the integration of the death probability associated with hypothetical accidents over the entire pipeline. The probability of death from a jet fire, which is the dominant accident in the natural gas pipeline as discussed in the previous section, depends on the effective rate of gas release and the distance from the fire to the specified location. Fatal length at a certain distance from the pipeline can be estimated directly from Fig. 1. It is calculated by assuming the release rate as constant along the pipeline. This assumption is valid when the location of accident is not close to the gas supplying station.

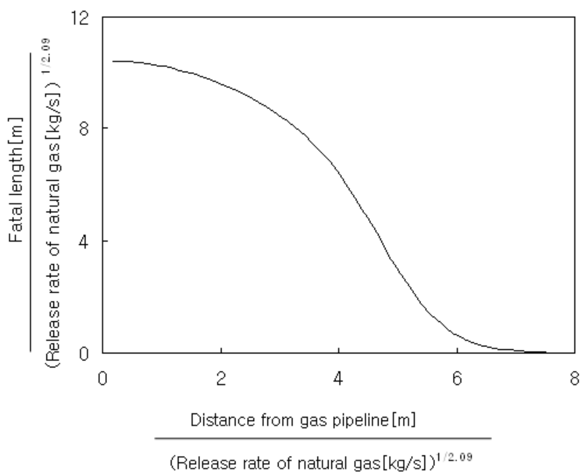

Figure 1. Fatal length of natural gas pipeline with release rate.

3. Individual Risk Analysis and Discussions

The individual risk can be solved explicitly by using the Eq. (13) and Fig. 1, when the location of interest is far away from the gas supply station. The maximum risk with average temperature and humidity of South Korea is obtained approximately at just above the pipeline with the failure rates of medium and great hole as 2.243 x 10^{-4} 1/yr.km and 7.475 x 10^{-5} 1/yr.km, respectively.

$$IR_{\max} \cong 1.09857 \times 10^{-5} \sqrt{pd^2} \qquad (18)$$

where the p is operation pressure and d is the pipeline diameter.

The risk is directly proportion to the diameter of pipeline and square root of the operating pressure. The diameter of transmission pipeline of natural gas is rarely exceeding one meter and the operating pressure is not exceeding 100 bar. The individual risk of natural gas transmission pipeline, therefore, is always lower then 10^{-4} per year. It is located in the level of As Low As Reasonable Practicable(ALARP) region of the criteria of UK in hazardous industries.

The distance from the pipeline for iso-individual risk contour, such as 10^{-6}, 10^{-5} or 10^{-4}, depends approximately on the diameter of pipeline and square root of the operating pressure.

$$H = a\sqrt{pd^2} + b \qquad (19)$$

where the a and b are coefficient of the equation which are estimated by lest square method and listed in table 2.

In the design criteria of steel pipelines for high pressure gas transmission[18], the minimum building proximity distances for rural area is located between 10^{-4} and 10^{-5} of individual risk. This minimum proximity distances between pipelines and buildings are based on the rupture of the pipeline. These distances are corresponding approximately to the radiation level of 32 kW/m^2. Considering one order changing of failure rate from British Gas Transco data than that from EGIG data, the minimum proximity lies between 10^{-5} and 10^{-6} of individual risk. Therefore, the risk from natural gas transmission pipeline is broadly accepted risk.

Table 2: Coefficients of equation (19) with risk levels (T = 285 K, $\bar{H}$ = 65 %)

Individual Risk	1.00E-04	5.00E-05	1.00E-05	5.00E-06	1.00E-06
a	53.28431	20.32762	30.67457	32.67509	35.34244
b	-467.413	-55.8151	-26.4722	-19.1336	-2.83841

The distance of a given individual risk can be estimated explicitly with pipeline diameter, pipeline length, and operation pressure by using the eqns (20), (21), and (22) for near field and by using the eqn (19) for far field of gas supplying station. These equations can be usable in safety guidelines.

4. Conclusions

Quantitative risk assessment recently has become important in controlling the risk level effectively in gas pipeline management. This work proposes a simple method of individual risk assessment for natural gas pipeline and introduces the parameters of fatal length. With currently acceptable criteria taken into account for individual risk, the minimum proximity of the pipeline to occupied buildings is approximately proportional to the square root of the operating pressure of the pipeline. And it decreases with the pipeline length due to resistance of gas flow through the pipeline. The risk of natural gas transmission pipeline is lower than that of traffic or chemical industries. The proposed method for individual risk assessment explicitly may be useful for setting safety guideline.

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