Safe Separation Distances From Natural Gas Transmission Pipelines

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Abstract

Accidental rupture of natural gas transmission pipelines with subsequent ignition of the escaping gas can result in the loss of life and property. A method for evaluating distances at which the pipelines can be safely set back from the community, called safe separation distances, is proposed herein, in which the point source method for determining heat flux is coupled with relationships for predicting both the mass release rate from the rupture and the flame height of the ignited gas. The method is utilized to develop charts for predicting safe separation distances based on pipeline operating pressure and nominal pipeline diameter.

Introduction

Increased development of formerly sparsely populated areas has resulted in instances of encroachment of natural gas transmission pipeline rights-of-way (ROWs). Accidental ruptures of these pipelines with subsequent ignition of the escaping gas can result in the loss of life and property near these lines. A description of the effects of such accidents can be found in the pipeline accident reports prepared by the National Transportation Safety Board (NTSB), the independent Federal agency that investigates pipeline accidents occurring in the United States.

One example of the destructive effects of pipeline ruptures was the explosion, in Edison, New Jersey, of a 36-inch pipeline operating at a pressure of 970 psig. This accident occurred on March 23, 1994 and severely affected a nearby apartment complex. The apartment complex sustained $12.4 million in damages, which included the loss of eight apartment buildings, severe damage to six buildings and minor damage to several other building (NTSB, 1995). This accident served as the basis for the evaluation, described in this paper, of the proximity at which pipelines can be safely sited near a community. These distances are called "safe separation distances."

In general, both the United States and foreign countries address the establishment of separation distances either directly, or indirectly through the designation of various location or population classes. In those instances where a defined allowable ROW has been established, the width of the ROW from the pipe centerline is relatively small (less than 100 feet) and is generally intended to protect the pipe rather than the public. Separation distances have also been developed by some countries based on the concept of risk assessment. This paper describes the development of a methodology to estimate actual separation distances required, based upon the effects of a rupture of a natural gas transmission pipeline of a specified diameter and operating pressure. The methodology is developed, in part, with data collected from prior investigations of actual natural gas transmission pipeline accidents.

Literature Review

The purpose of the literature review was to gain an understanding of prior research concerning both natural gas pipeline accidents and the determination of safe separation distances from natural gas transmission pipelines. Activities associated with the literature review included review of NTSB files and Commodity Pipeline Occurrence Reports prepared by the Canadian Transportation Safety Board (TSB). Other activities consisted of discussions of the issue of safe separation distances with the European Gas Pipeline Incident Data Group located in the Netherlands, the NTSB, the Canadian TSB, the Canadian National Energy Board, the United States Environmental Protection Agency, the American Gas Association, the Research and Special Programs Administration, the Gas Research Institute, and the Township of Edison. Finally, various texts and technical journals of the oil and gas pipeline industry were reviewed pertaining to pipelines, hazard assessment, heat transfer and fluid flow.

In general, the literature review revealed that there has been limited studies to date concerning the determination of safety separation distances. The prior research reviewed is predominantly concerned with predicting the loss of product during an actual pipeline rupture (i.e., blowdown), rather than directed to concerns associated with establishment of adequate safe separation distances for the public.

The modelling of product loss during a pipeline rupture, which is an important factor related to the establishment of a safe separation distance therefrom, is, as indicated in a number of research papers reviewed, difficult to simulate. This is due to disparity amongst researchers as to the conditions under which the blowdown is modelled (e.g., adiabatic or isothermal; whether the fluid is viscous or nonviscous, etc.).

The literature review also revealed that the available database of information associated with actual natural gas pipeline accident occurrences in the United States and Canada is limited. For example, the pipeline accident reports (PARs) prepared by the NTSB do not consistently report parameters such as the total volume of gas lost in an accident, or the location of the closest valves upstream and downstream of the pipeline rupture. Furthermore, supporting information for the more dated PARs (in the PAR dockets in Washington, DC) is periodically destroyed. The Commodity Pipeline Occurrence Reports prepared by the Canadian TSB are similar to the PARs in that there are also inconsistencies in the extent of information contained in these reports.

Because of the aforementioned reasons, it was concluded that an approach to advance the state-of-the-art in the discipline of pipeline risk analysis is to develop a reliable estimation technique to conservatively predict safe separation distances to be articulated between the public and the ruptured natural gas pipeline.

Methodology

The simplified approach for estimating safe separation distances was developed based upon assumptions that the damage from a pipeline rupture is primarily due to the thermal radiation produced by the ignited gas behaving like a vertical jet flame. The thermal radiation will produce an impact area, the extent of which can be determined through the estimation of a "burn radius". The major variables associated with the burn radius resulting from a pipeline rupture are the size of the pipeline and its operating pressure (which directly affects the mass flow rate in the pipeline). The appropriateness of this approach in providing results of an accuracy suitable for regulatory agencies to utilize for establishing zoning guidelines was confirmed by comparing results from the aforementioned model with actual burn radii found in a limited number of accident investigations conducted by the NTSB in which sufficient data was obtained to verify the subject model herein.

As indicated above, an assumption is made that the damage from a pipeline rupture is primarily due to the thermal radiation produced by the ignited gas. Therefore, a safe separation distance is defined as the distance beyond which a pre-established level of thermal radiation damage will not likely occur. Other damage (such as projectile damage from pipeline fragments or damage due to over pressures from explosions) is not considered. This assumption is consistent with the results from investigations of actual pipeline ruptures, in which damage was found to be caused primarily from the fire. Therefore, the safe separation distance from a pipeline can be defined in terms of the distance needed to protect against a specified heat flux. This specified heat flux will produce an area of thermal radiation damage in the vicinity of the pipeline which can be estimated by calculating the burn radius.

Use of the Point Source Method

The point source method forms the basis for the estimation of safe separation distances. The following equation is presented from the work of Oenbring and Sifferman (1980):

$$K = FQ/(4\pi D^2) \qquad (1)$$

where K = radiation heat flux from a flame (Btu/hr ft^2); F = fraction of total heat radiated; Q = total heat content of the flared gas (Btu/hr); and D = distance from point source to receptor (ft).

Those authors provide the source for Equation (1) as being the American Petroleum Institute (API) document API RP-521. In a later version of this document (API, 1990), API provides the revised equation:

$$D = (\tau FQ/(4\pi K))^{1/2} \quad (2)$$

where τ = the fraction of thermal radiation transmitted through the atmosphere.

Application of the point source method is shown in Figure 1, where ignition of escaping gas from a pipeline rupture results in a flame of height "H". The point source is placed in the center of the flame at H/2, and the burn radius (BR) is found from the Pythagorean Theorem:

$$BR = \{D^2 - (H/2)^2\}^{1/2} \quad (3)$$

By inserting Equation 2 into Equation 3, the following relationship is obtained:

$$BR = \{(\tau FQ/(4\pi K)) - (H/2)^2\}^{1/2} \quad (4)$$

This is the basic form of the burn radius equation. The burn radius is function of the transmissivity of the thermal radiation through the atmosphere, the fraction of total heat radiated, the heat content of the escaping gas, the specified heat flux (or level of damage), and the flame height.

Based on information provided by various researchers for methane (NFPA, 1988), the value of F can be reasonably estimated to be 0.2. Calculation of the transmissivity of thermal radiation through the atmosphere was performed using the method of Brzustowsi and Sommer (1973), as discussed by API (API. 1990). By assuming a relative humidity of 50% and a distance to the flame of 500 feet (both of which are reasonable values for pipeline accident scenarios), the atmospheric transmissivity is determined to be 0.746. Inserting the values of τ and F into Equation 4, the equation for the burn radius becomes:

$$BR = \{(0.011873Q/K) - (H/2)^2\}^{1/2} \quad (5)$$

The total heat content of the escaping gas (Q) in Btu/hr can be found by multiplying the heat content of natural gas (1,000 Btu/scf) by the volumetric flow rate of the escaping gas (scf/hr):

$$Q = 1{,}000(V') \quad (6)$$

where V' = volumetric flow rate (scf/hr). If Equation 6 is inserted into Equation 5, the expression for the burn radius becomes:

$$BR = \{(11.873(V')/K - (H/S)^2\}^{1/2} \quad (7)$$

Determination of Gas Flow Rate

The volumetric flowrate of the escaping gas, V', can be found using a modified form of an equation, found in the Pipe Line Rules of Thumb Handbook, (McAllister, 1993), which is used when calculating the volume of gas lost through a puncture or blowdown. This equation is expressed as:

$$Q = D^2P_1 \quad (8)$$

where: Q = volume of gas in Mcf/hr at a

pressure of 14.9 psi, 60°F with a specific gravity of 0.60; D = diameter of the nipple or orifice in inches; and P_1 = absolute pressure in psi at some nearby point upstream from the opening.

Equation 8 is modified by examining the rates of gas lost through actual pipeline ruptures (see Table 1) and comparing these rates with values obtained using the equation. Based on this evaluation, Equation 8 was modified to be:

$$V' = (1,000)(0.34)D^2P \qquad (9)$$

where V′ = gas flow rate, scf/hr; D = pipeline diameter, inches; and P = incident operating pressure, psia. It should be noted that multiplication by 1,000 in Equation 9 converts Mcf/hr to scf/hr. Equation 9 reflects the fact that insertion of the maximum initial flow rate into the point source equation will not accurately reflect thermal radiation conditions, since the heat flux at a given receptor location will decrease with the decreasing gas flow. Therefore, V′ can be considered to be a representative gas flow rate.

Determination of Flame Height

In a manner similar to the method for determining the expression for gas flow rate, the information obtained from actual pipeline accidents can be used to estimate flame height. Hawthrome, Weddell and Hottell (1949) developed an equation that, for a given gas, expressed the flame length as being directly proportional to the jet (or nozzle) diameter. This observation can be applied to the NTSB pipeline accident data of Table 2, where estimation of flame heights are provided. If the assumption is made that the jet diameter is equal to the pipeline diameter for a full bore rupture, the following relationship is obtained:

$$\begin{aligned} H &= 147(D/12) \\ &= 12.25(D) \qquad (10) \end{aligned}$$

where D = pipeline diameter (in).

By inserting Equation 9 and Equation 10 into Equation 7, the final burn radius equation is found:

$$BR = D\{(4,036.82)P/K - 37.52\}^{1/2} \qquad (11)$$

where BR = burn radius (ft); D = pipeline diameter (in); P = incident operating pressure (psia); and K = heat flux (Btu/hr ft^2).

Equation 11 provides a means by which the burn radius (and hence the safe separation distance) can be found knowing only the pipeline diameter, incident operating pressure and the level of damage (i.e., heat flux) to be considered. Since pipeline operating pressures are typically specified as gauge pressures, Equation 11 can be modified for application to gauge pressures by substituting the quantity (P′ + 14.7) for P, where P′ is the incident operating pressure in psig.

Heat Flux Values

Several examples of heat flux values corresponding to specific consequences are provided in Table 3. These values were obtained from a review of the literature.

From these heat flux values, it can be seen that the level of thermal radiation damage may not only depend on the intensity of the heat flux, but also on the length of time that the receptor is receiving that heat flux. For example, at a heat flux intensity of 9,985 Btu/hr ft^2, spontaneous ignition of wooden building occurs *after a few minutes.* Similarly, the maximum tolerable heat flux for *short-term* exposure for people is 2,000 Btu/hr ft^2. Therefore, a safe separation distance is considered to afford protection from a certain level of heat flux for a specific time period. If that time period is exceeded, damage may occur.

In order to estimate a safe separation distance, a level of protection is chosen, such as protecting wooden buildings from spontaneous ignition for a few minutes. The corresponding heat flux is found and inserted into Equation 11 as the appropriate K-value.

Construction of Charts to Predict Safe Separation Distances

The following procedure is used to construct charts for the estimation of safe separation distances. The first step involves deciding the degree of thermal radiation damage to consider. For example, the damage might be spontaneous ignition of wooden buildings after a few minutes exposure to the ignited gas. Protection for a few minutes may allow enough time for emergency responders to arrive at the scene and initiate protective measures (such as watering down the building). Based on the information provided in Table 3, the heat flux corresponding to the specified level of damage is 9,985 Btu/hr ft^2. This value is inserted into Equation 11 for K:

$$BR = D\{(4{,}036.82)P/9{,}985) - 37.52\}^{1/2} \quad (12)$$

Equation 12 is an expression of the burn radius as a function of only diameter and incident operating pressure. For various pipeline diameters, charts are then constructed of the burn radius (on the y-axis) and the incident operating pressure (on the x-axis). In the example, a pipeline diameter of 36" can be used with incident operating pressures in the range of 575 psia to 1,200 psia to construct a chart similar to the one shown in Figure 2. Once the chart is completed, it can be used either to determine a safe separation distance given a specified incident operating pressure, or to determine the incident operating pressure required to maintain a specified safe separation distance.

Charts for estimating safe separation distances (or burn radii) were developed for heat flux values of 3,962 Btu/hr ft^2 (piloted ignition of wood); 6,340 Btu/hr ft^2 (blistering of bare skin in 4 seconds and 1 percent lethality in 20 seconds); 9,510 Btu/hr ft^2 (causes third degree burns in 30 seconds); and 9,985 Btu/hr ft^2 (spontaneous ignition of wooden structures after a few minutes). The charts have been developed for pipeline diameters of 14", 16", 18", 20", 24", 30" and 36", with incident operating pressures in the range of 575 psia to 1,200 psia. It should be noted that the charts do not consider that portion of the heat flux due to solar radiation. An accurate value of the solar heat flux would be dependent on factors such as the weather conditions, the time of day and the time of year. Since the solar heat flux amounts to only a few hundred Btu/hr ft^2 while the non-solar heat flux is several thousand Btu/hr ft^2, omission of this factor will not significantly affect the results.

Comparison of Method to Pipeline Accident Data and to Previous Research

Equation 11 was evaluated by first comparing the calculated values for burn radii to data from documented pipeline accidents that occurred in the United States. The previously-mentioned accident that occurred in Edison, New Jersey is presented here as an example of the analysis that was performed.

The PAR (NTSB, 1995) for the Edison, New Jersey accident describes the rupture of a 36 inch natural gas transmission pipeline owned and operated by the Texas Eastern Transmission Corporation. The rupture occurred at approximately 11:55 p.m. on March 23, 1994, on the property of Quality Materials, Inc. in Edison, New Jersey. Ignition of the escaping gas occurred within 2 minutes after the rupture, producing flames 400 to 500 feet high. While no deaths were directly attributed to the accident, the rupture produced extensive damage including the destruction of several buildings of a nearby apartment complex. The total cost of the damage exceeded 25 million dollars. The NTSB determined that the probable caused of the rupture was mechanical damage to the exterior pipeline surface. The damage reduced the pipeline wall thickness and probably resulted in a crack that grew to a critical size.

As indicated previously, the rupture occurred at approximately 11:55 p.m., with ignition of the gas less than two minutes later. Based on the PAR, the Edison Township Fire Department arrived at the accident scene at approximately 12:02 a.m. According to information provided by the Township of Edison (personal communication, 1996) there were several buildings that were involved in fire upon arrival of the Fire Department, and there were other buildings that would have burned if those structures were not wetted down.

If buildings were set back from the pipeline at a distance beyond the location of the buildings which were involved in fire after a few minutes exposure to thermal radiation, then this distance would have provided protection for a few minutes from spontaneous ignition. Using information from the files of the NTSB, the distance from the rupture and the approximate midpoint of the footprint for the building farthest from the rupture (that was becoming involved in fire when the Fire Department arrived) was determined to be approximately 772 feet.

In order to use Equation 11, an appropriate heat flux must first be selected. Since the concern is protecting structures from spontaneous ignition for several minutes, a heat flux of 9,985 Btu/hr ft^2 from Table 3 is selected. Inserting this value for heat flux into Equation 11, as well as the applying the pipeline diameter of 36 inches and the incident operating pressure of 984.7 psia, the burn radius becomes:

$$BR = 36\{[(4{,}036.82)(984.7)/(9{,}985)] - 37.52\}^{1/2}$$
$$= 684 \text{ feet}$$

The estimated burn radius differs from the actual burn radius by less than 12 percent. It can therefore be seen that the predicted burn radius does in fact approximate the distance to those buildings which were involved in fire a few minutes after the rupture.

A burn radius can likewise be estimated for determining the distance beyond which buildings will not ignite at all. For the Edison accident, this distance would extend beyond the location of those buildings which were wetted down. In order to predict the distance with Equation 11, a heat flux of 3,962 Btu/hr ft² is selected. This is the heat flux at which piloted ignition of wood occurs, so that wood is not expected to ignite below this heat flux. From equation 11, the burn radius becomes:

$$BR = 36\{[(4{,}036.82)(984.7)/(3{,}962)] - 37.52\}^{1/2} = 1{,}119 \text{ feet}$$

The actual distance from the rupture point to the midpoint of the building farthest from the rupture that was wetted down was likewise found using the information from the NTSB files for this accident. This distance was determined to be 1,101 feet. The predicted burn radius is therefore very similar to the actual distance, with a difference of less that 2 percent.

The following example illustrates the analysis of a safe separation distance for a pipeline accident for which less information is available (NTSB, 1986). The accident occurred in Jacksonville, Louisiana, on November 25, 1984. The pipeline had a diameter of 30 inches and was operating at 1,016 psig (1,030.7 psia). A non-symmetrical damage area was produced, with the rupture incinerating an area 900 feet north, 500 feet south and 180 feet to the east and west of the rupture. If the burn radius is considered to be the maximum linear distance from the rupture to the edge of the incinerated area, the radius is then 900 feet. Again, using Equation 11 and a heat flux of 3,962 Btu/hr ft² (i.e., a conservative value for heat flux which will cause an area to be burned), the estimated burn radius becomes:

$$BR = 30\{[(4{,}036.82)(1030.7)/3{,}962)] - 37.52\}^{1/2} = 955 \text{ feet}$$

The estimated burn radius differs from the actual burn radius by only 6 percent.

Comparison to Separation Distances Developed through Hazard Analysis

Separation distances produced by Equation 11 were compared to separation distances developed through the principles of hazard analysis. For example, Hill and Catmur performed a study for the British Health and Safety Executive (1995) to evaluate how risks from various hazardous pipelines compared. As part of the study, distances from a vertical flame jet to a heat flux level of 10 kW/m² (3,170 Btu/hr ft²) are provided for the pipelines under consideration. The flame was simulated as an inclined line source with a receptor 1.5 meters (4.92 feet) high at ground level. Furthermore, the authors indicate that the model which was used provides the maximum view factor between the source and receptor, with the thermal radiation being a function of the flame's emissivity, the transmissivity of the air, the view factor and the radiant energy of the burning compound.

A comparison was made between those distances and the distances estimated using Equation 11. This comparison is presented in Table 4, for all of the natural gas pipelines involved in the study. It can be seen that even outside the range of diameters and pressures for which Equation 11 was developed that this relationship still produces results which approximate those of the British. The higher percent differences reflected in the last three entries of Table 4 are probably due to the use of low operating pressures, either singly or in combination with small diameters, which are outside the range for which Equation 11 was developed.

A comparison was likewise made between separation distances determined through use of Equation 11 and the separation distances imposed in regulations developed by the Dutch. The following discussion is based on information from personal communications with N.V. Nederlandse Gasunie (November 30, 1995, June 21, 1996, September 30, 1996). The first type of separation distance which the Dutch developed is called a proximity, or building distance. This is the distance between a pipeline and residential buildings (or special structures) and corresponds to a 10^{-6} individual risk. The second type of distance is called a survey, or effect distance. This distance is determined for the purpose of identifying the location classification and corresponds to a 10^{-8} individual risk.

The Dutch regulations specify three ranges of operating pressures (in English units: 304.8 to 739.9 psia; 739.9 to 1,175.0 psia; and 1,175.0 to 1,610.1 psia) and pipeline diameters from 2 inches to 48 inches. Although the midpoints of the Dutch pressure ranges are approximately 522.3 psia, 957.4 psia, and 1,392.6 psia, the three pressures which will be used in Equation 11 for the purpose of comparison are 522.3 psia; 957.4 psia and 1,200.0 psia. The pressure of 1,200.0 psia is used in lieu of 1,392.6 psia since 1,200.0 psia represents the upper limit of pressure used to develop Equation 11, yet still lies within the third range.

The comparison is presented in Table 5. It can be seen that Equation 11 estimates significantly larger separation distances than the building distances determined by the Dutch. However, as shown through the analyses of the Edison, New Jersey accidents, the building distances developed by the Dutch will not be protective of structures. For a 36-inch diameter pipeline, the maximum building distance is 148 feet. This distance would clearly not have been protective of structures for the aforementioned accident.

Although the building distances and burn radii do not correspond, the trends in both at conditions of constant pressure (with varying diameter) and constant diameter (with varying pressure) do correspond closely. If pressure is held constant, then the following ratio is produced when using Equation 11:

$$BR_1/BR_2 = [D_1\{(4{,}036.82)P/K) - 37.52\}^{1/2}]/[D_2\{(4{,}036.82)P/K) - 37.52\}^{1/2}] = D_1/D_2 \quad (13)$$

Where the subscripts 1 and 2 correspond to conditions at the two diameters. If diameters are held constant, then Equation 11 produces the following ratios:

$$BR_1/BR_2 = [D\{(4{,}036.82)P_1/K) - 37.52\}^{1/2}]/[D\{(4{,}036.82)P_2/K) - 37.52\}^{1/2}]$$
$$= [\{((4{,}036.82)P_1/K) - 37.52\}/\{((4{,}036.82)P_2/K) - 37.52\}]^{1/2} \quad (14)$$

Where the subscripts 1 and 2 now correspond to conditions at the two pressures.

Tables 6 and 7 respectively present the comparison of building distances for constant pressure and diameter. It can be seen that both the Dutch approach and Equation 11 produce very similar trends (i.e. similar ratios) whether conditions of constant pressure or constant diameter are evaluated.

Uncertainties

The uncertainties in the value of the burn radius produced by Equation 11 are the result of the assumptions that were made during development of this equation. As indicated previously, an assumption was made that the damage from a pipeline rupture is primarily due to the thermal radiation produced by the ignited gas. Other damage (such as projectile damage from pipeline fragments) is not considered. This assumption is consistent with the results from investigations of actual pipeline ruptures, in which damage was found to be caused primarily from the fire.

For development of Equation 11, the escaping gas is assumed to behave, once ignited, like a vertical jet flame. A release from a pressurized system (such as a pipeline) can produce other scenarios such as dispersion of the unignited gas, formation of a fireball, development of a flash fire or a vapor cloud explosion (NFPA, 1988; Hill and Catmur, 1995; AICHE, 1994). Furthermore, the rupture orientation may be such that a flame jet, if it exists, may not be truly vertical. Assuming that all of these scenarios can occur increases the number of variables to be considered, in that the probabilities of each scenario happening (either alone or in combination with other scenarios) must be determined.

Should these other scenarios occur, there is no certainty that they will contribute significantly to the overall thermal radiation damage. For example, the dispersion of unignited gas would not produce thermal radiation damage. Vapor cloud explosions can produce damage through the generation of over pressures (Crawley, 1982). However, thermal radiation was found to be the primary cause of damage in natural gas pipeline ruptures. With regard to the development of a flash fire, very little information is currently available concerning the thermal radiation produced (AICHE, 1994). Thermal radiation hazards from burning vapor clouds are considered less significant than blast effects, and combustion associated with a flash fire lasts no more than a few tens of seconds (AICHE, 1994). While fireballs produce the highest radiation intensity, these events can be assumed to last only 10-30 seconds (Hockley and Rew, 1996). Formulas for fireball diameter, duration and hazard distances have been published (AICHE, 1994) which are functions of the mass of the fuel. However, in the case of a pipeline rupture the mass of fuel involved in a fireball is difficult to predict since the release rate varies with time.

Although there are uncertainties associated with the development of Equation 11, the analyses that were performed served to demonstrate that the assumptions made during the development of Equation 11 are appropriate. Equation 11 can be used to provide estimations of burn radii for various pipeline diameters and incident operating pressures. However, it must be stressed that safe separation distances determined through the use of Equation 11 are *estimations*. There are numerous variables, several of which have been considered in this chapter, which will influence the burn radius associated with a pipeline rupture. The advantage to using the method described in this paper is that the method is straightforward and provides reasonable estimates of actual burn radii.

Conclusions

The work described in this paper has led to the development of a method for estimating safe separation distances from natural gas transmission pipelines. This method was verified based on information from actual pipeline accidents, and provides a means to determine the safe separation distance, as a measurement of the burn radius, through knowledge of the pipeline's diameter and incident operating pressure. The method can be used by regulators to determine the distances at which future development might be placed from existing pipelines or, perhaps more realistically, the method can be used to evaluate appropriate incident operating pressures for pipelines which traverse densely populated areas.

The procedure described in this paper is easy to apply and does not require extensive computational efforts. The method is applicable to pipelines with diameters ranging from 14 inches to 36 inches and incident operating pressures from 575 psia to 1,200 psia, which constitute the majority of natural gas transmission pipelines in service in the United States. For levels of thermal radiation damage corresponding to heat flux values from 3,962 Btu/hr ft^2 to 9,985 Btu/hr ft^2, the method will predict safe separation distances ranging from 195 feet to 1,200 feet. The range of heat flux values noted above are applicable to the major consequences to life, limb and property that should be of interest to most analysts.

Although there are areas amenable to refinement, the methodology will provide reasonable estimates of safe separation distances for the ranges of diameters, incident operating pressures and values of heat flux that have been previously identified.

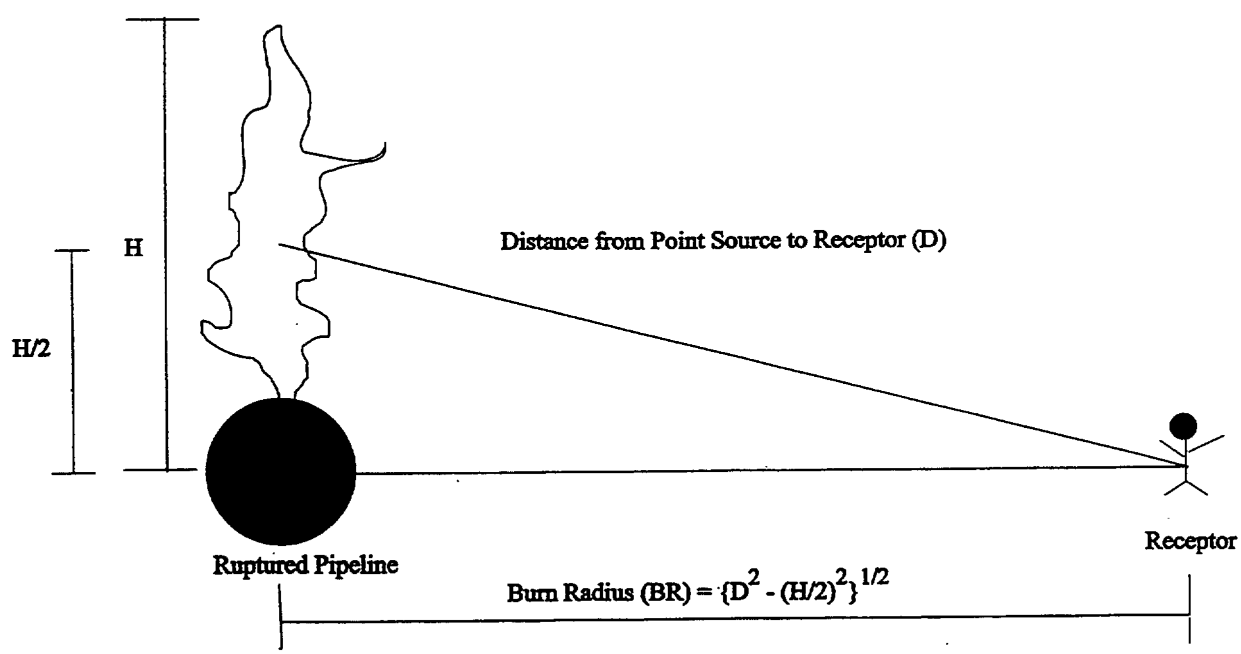

FIG. 1. Point Source Method Applied to Pipeline Rupture

FIG. 2. Burn Radius Chart

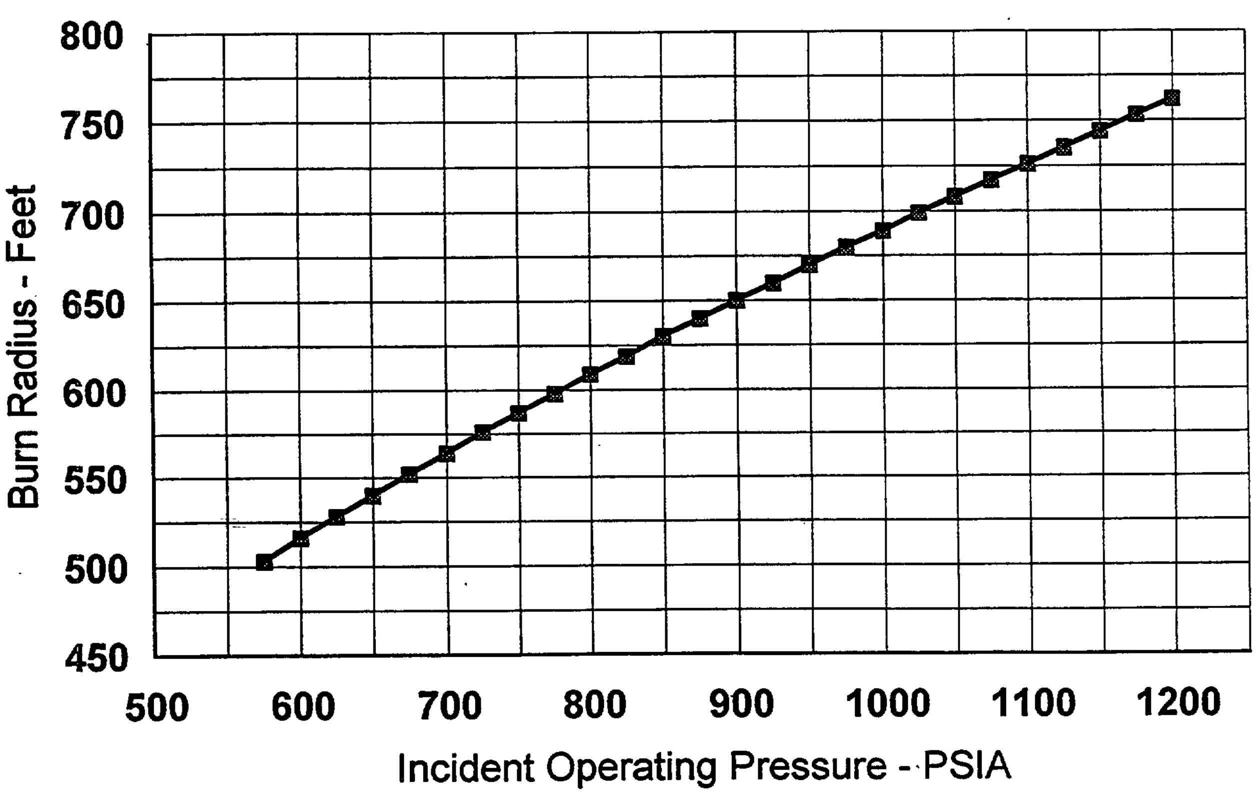

TABLE 1. Pipeline Rupture Parameters

Accident Report Number	Investigating Agency	Pipeline Diameter Inches	Incident Operating Pressure psia	Isolation time hours	Total Volume of Gas Lost, scf
P90H0606	TSB	12.75	696.7	2.75	3.78×10^7
83-02	NTSB	20	834.7	1.42	4.68×10^7
P91H0041	TSB	20	933.7	0.75	3.13×10^6
79-FP006	NTSB	30	574.7	2.83	2.01×10^8
P90H1006	TSB	30	726.7	0.58	8.73×10^7
95-01	NTSB	36	984.7	2.50	2.97×10^8
P94H0036	TSB	36	1014.7	0.63	1.48×10^8
P94H0003	TSB	42	1221.7	6.67	3.52×10^8

TABLE 2. Flame Height Data

Accident Report Number	Investigating Agency	Diameter (D) Inches	Diameter (D/12) Feet	Reported Flame Height (H) Feet	H/(D/12)
86-009	NTSB	20	1.67	300	180
95-01	NTSB	36	3.00	450	150
77-01	NTSB	20	1.67	200	120
71-01	NTSB	14	1.17	125	107
87-01	NTSB	30	2.50	450	180

TABLE 3. Examples of Heat Flux Values

Heat Flux Btu/hr ft²	Heat Flux kW/m²	Reference	Consequence
317	1	AICHE (1994)	Solar Heat flux during a hot summer day
2,000	6.5	Crawley (1982)	Maximum tolerable heat flux for short-term (i.e., 20 seconds) exposure for people.
3,962*	12.6	Hockey and Rew (1996) AICHE (1994) Technica International, Ltd. (1988)	Piloted ignition of wood exposed to this heat flux for a prolonged period. Also, plastic tubing melts.
9,985*	31.5	Department of Housing And Urban Development (1975)	Wooden buildings, paper, window drapes and trees will spontaneously ignite after a few minutes exposure.

*Calculated using the relationship 1 Btu/hr ft² = 3.1546 Watts/square meter (W/m²).

TABLE 4. Comparison of Natural Gas Pipelines

Pipeline Diameter Inches	Pressure Barg	Pressure Psia	Separation Distances-Feet British*	Separation Distances-Feet Equation 11	Percent Difference
42	70	1030.0	1,385	1,499	8.2
24	70	1030.0	820	857	4.5
16	70	1030.0	564	571	1.2
6	70	1030.0	226	214	5.3
24	16	246.8	443	399	9.9
24	7	116.2	351	252	28.2
6	16	246.8	138	100	27.5
6	7	116.2	95	63	33.7

*Converted from meters using the relationship 1 meter equals 3.2808 feet.

TABLE 5. Comparison of Building Distances to Safe Separation Distance

	Distance from Pipeline - Feet* From Dutch Regulations			Safe Separation Distance - Feet Using Equation 11		
Diameter Inch	35 Bar 522.3 psia	65 Bar 957.4 psia	95 Bar 1392.6 psia	35 Bar 522.3 psia	65 Bar 957.4 psia	95 Bar 1200.0 psia
14	56	66	82	184	262	296
16	66	66	82	211	299	339
18	**	66	82	237	337	381
24	**	82	82	316	449	508
30	**	98	115	395	561	635
36	**	115	148	474	673	762

Notes: * Distances converted from meters to feet using the relationship 1 meter equals 3.2808 feet.
** Distances determined on a case by case basis.

TABLE 6. Ratios of Building and Separation Distances at Various Diameters (Constant Pressure)

	Ratios of Building Distances (Using Dutch Regulations)			Ratios of Separation Distances (Using Equation 11)		
Diameter Ratio Selected	35 Bar 522.3 psia	65 Bar 957.4 psia	95 Bar 1392.6 psia	35 Bar 522.3 psia	65 Bar 957.4 psia	95 Bar 1200.0 psia
16"/14"	1.18	1.00	1.00	1.14	1.14	1.14
18"/14"	----	1.00	1.00	1.29	1.29	1.29
24"/14"	----	1.24	1.00	1.71	1.71	1.71
30"/14"	----	1.48	1.40	2.14	2.14	2.14
36"/14"	----	1.74	1.80	2.57	2.57	2.57
18"/16"	----	1.00	1.00	1.13	1.13	1.13
24"/16"	----	1.24	1.00	1.50	1.50	1.50
30"/16"	----	1.48	1.40	1.88	1.88	1.88
36"/16"	----	1.74	1.80	2.25	2.25	2.25
24"/18"	----	1.24	1.00	1.33	1.33	1.33
30"/18"	----	1.48	1.40	1.67	1.67	1.67
36"/18"	----	1.74	1.80	2.00	2.00	2.00
30"/24"	----	1.20	1.40	1.25	1.25	1.25
36"/24"	----	1.40	1.80	1.50	1.50	1.50
36"/30"	----	1.17	1.29	1.20	1.20	1.20

TABLE 7. Ratios of Building and Separation Distances at Various Pressures (Constant Diameter)

	Ratios of Building Distances (Using Dutch Regulations)			Ratios of Separation Distances (Using Equation 11)		
OD	957.4/522.3 psia	1,392.6/522.3 psia	1,392.6/957.4 psia	957.4/522.3 psia	1,200.0/522.3 psia	1,200.0/957.4 psia
14"	1.18	1.46	1.24	1.42	1.61	1.13
16"	1.00	1.24	1.24	1.42	1.61	1.13
18"	----	----	1.24	1.42	1.61	1.13
24"	----	----	1.00	1.42	1.61	1.13
30"	----	----	1.17	1.42	1.61	1.13
36"	----	----	1.29	1.42	1.61	1.13

APPENDIX I. REFERENCES

Arkla Energy Resources Pipeline Rupture & Fire Near Cale, Arkansas 02-24-86. National Transportation Safety Board accident file, Washington, D.C.

Guide for Pressure-Relieving and Depressuring Systems. API Recommended Practice 521. (1990). American Petroleum Institute, Washington, D.C.

Brzustowski, T.A., and Sommer, E.C., Jr. (1973). "Predicting Radiant Heating from Flares." From *Proceedings - Division of Refining.* American Petroleum Institute, Vol. 53, Washington, D.C., 865-893.

Crawley, F.K. (1982). "The Effects of the Ignition of a Major Fuel Spillage." *I. Chem. E. Symposium Series No. 71.* 125-145.

Factual Pipeline Accident Report Basic Report (AR-01) FTW-79-F-P006 United Texas Transmission Co. (1979). National Transportation Safety Board, Washington, D.C.

Guidelines for Evaluating the Characteristics of Vapor Cloud Explosions, Flash Fires, and BLEVEs. (1994). Center for Chemical Process Safety of the American Institute of Chemical Engineers, New York, N.Y.

Hawthorne, W.R., Weddell, D.S., and Hottell, H.C. (1949). "Mixing and Combustion in Turbulent Gas Jets." *Third Symposium on Combustion, Flame and Explosion Phenomena.* Combustion Institute, 266-288.

Hill, R.T., and Catmur, J.R. (1995). "Risks from Hazardous Pipelines in the United Kingdom." *HSE Contract Research Report No. 82/1994.*

Hockey, S.M., and Rew, P.J. (1996). "Review of Human Response to Thermal Radiation." *HSE Contract Research Report No. 97/1996.*

Mobil Oil Corporation High-Pressure Natural

Natural Gas Pipeline, Near Houston, Texas September 9, 1969. (1971). National Transportation Safety Board, Washington, D.C.

Northern Natural Gas Company Pipeline Puncture, Explosion and Fire Hudson, Iowa November 4, 1982. (1983). National Transportation Safety Board, Washington, D.C.

Natural Gas Pipeline Rupture Foothills Pipe Lines (Sask.) Ltd. 1,067-Millimetre (42-Inch) Eastern Main Line Kilometre Post 66 + 041 Maple Creek, Saskatchewan 15 February 1994. (1995). Transportation Safety Board of Canada, Hill, Quebec, Canada.

Oenbring, P.R., and Sifferman, T.R. (May 1980). "Flare Design...Are Current Methods Too Conservative?" *Hydrocarbon Processing,* 124-129.

Pipeline Accident/Incident Summary Reports. (1986). National Transportation Safety Board, Washington, D.C.

Pipe Line Rules of Thumb Handbook. (1993). Gulf Publishing Company, Houston, TX.

SFPE Handbook of Fire Protection Engineering. (1988). National Fire Protection Association, Quincy, MA.

Safety Considerations in Siting Housing Projects. (1975). Department of Housing and Urban Development, Washington, D.C.

Texas Eastern Gas Pipeline Company Ruptures and Fires at Beaumont, Kentucky on April 27, 1985 and Lancaster, Kentucky on February 21, 1986. (1987). National Transportation Safety Board, Washington, D.C.

Texas Eastern Transmission Corporation Natural Gas Pipeline Explosion and Fire Edison, New Jersey March 23, 1994. (1995). National Transportation Safety Board, Washington, D.C.

Transcanada Pipeline Limited Line 300-1, Natural Gas Pipeline Rupture Kilometre Post MLV 302-1 + 2.849 KM Marionville, Ontario 1705 EDT, 06 June 1990. (1992). Transportation Safety Board of Canada, Hull, Quebec, Canada.

Transcanada Pipelines Limited Natural Gas Pipeline Rupture Line 100-2, 914 Millimetre (36-Inch) Mainline Kilometre Post Main Line Valve 110-2 + 22.098 Kilometres Latchford, Ontario 23 July 1994. (1995). Transportation Safety Board of Canada, Hull, Quebec, Canada.

Transcanada Pipelines Limited Natural Gas Pipeline Ruptures Main Line Valve 144-1 + 19.261 km Cardinal, Ontario 08 December 1991. (1994). Transportation Safety Board of Canada, Hull, Quebec, Canada.

United Gas Pipe Line Company 20-Inch Pipeline Rupture and Fire Cartwright, Louisiana August 9, 1976. (1977). National Transportation Safety Board, Washington, D.C.

Westcoast Energy Inc. 30-Inch Fort Nelson Main Line Natural Gas Pipeline Rupture Mile Post 102.6 Pink Mountain, British Columbia 1545 PDT, 06 October 1990. (1993). Transp. Safety Bd. of Canada, Hull, Quebec, Canada.

APPENDIX II. NOTATION

The following abbreviations and symbols are used in this paper:

AICHE	American Institute of Chemical Engineers
API	American Petroleum Institute
BR	burn radius
Btu	British Thermal Unit
D	diameter, distance from flame center to observer
F	fraction of total heat radiated
ft	foot
°F	degrees Fahrenheit
g	gauge pressure designation
H	flame height
hr	hour
in	inch
K	radiant heat flux
Mcf	thousand cubic feet
NFPA	National Fire Protection Association
NTSB	National Transportation Safety board
P	incident operating pressure
P'	gauge operating pressure
P_1	absolute pressure near the opening
PAR	Pipeline Accident Report
psi	pounds per square inch
psia	pounds per square inch absolute
psig	pounds per square inch gauge
Q	total heat content of flared gas, volumetric gas flow rate
ROW	right-of-way
scf	standard cubic feet
τ	atmospheric transmissivity
TSB	Transportation Safety Board (Canada)
V'	volumetric gas flow rate

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