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August 14, 2013

Susan M. Hudson, Clerk
VT Public Service Board
112 State Street, Drawer 20
Montpelier, VT 05620-2701

Re: Docket 7970

Dear Sue:

Enclosed for filing with the Board please find the original and seven copies of the Supplemental Prefiled Testimony of Stephen Pilcher on behalf of the Town of Monkton in the above docket. Also enclosed is a Certificate of Service.

Please feel free to call if you need anything further.

Sincerely,

Catherine E. Radigan

Enclosure

cc: Service List

STATE OF VERMONT
PUBLIC SERVICE BOARD

Petition of Vermont Gas Systems, Inc., requesting a Certificate of Public Good pursuant to 30 V.S.A. § 248, authorizing the construction of the **"Addison Natural Gas Project"** consisting of approximately 43 miles of new natural gas transmission pipeline in Chittenden and Addison Counties, approximately 5 miles of new distribution mainline in Addison County, together with three new gate stations in Williston, New Haven, and Middlebury, Vermont	)	Docket No. 7970

CERTIFICATE OF SERVICE

NOW COMES The Town of Monkton, by and through its attorney, Joshua R. Diamond, and hereby certifies that the Supplemental Prefiled Testimony of Stephen Pilcher and supporting exhibits have been sent via U.S. First Class Mail, postage prepaid to Michael Hurlburt, and via electronic mail to all others, on August 14, 2013 to the following:

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Dated at Montpelier, Vermont this 14th day of August, 2013.

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STATE OF VERMONT
PUBLIC SERVICE BOARD

Petition of Vermont Gas Systems, Inc., requesting a Certificate of Public Good pursuant to 30 V.S.A. § 248, authorizing the construction of the **"Addison Natural Gas Project"** consisting of approximately 43 miles of new natural gas transmission pipeline in Chittenden and Addison Counties, approximately 5 miles of new distribution mainline in Addison County, together with three new gate stations in Williston, New Haven, and Middlebury, Vermont	)	Docket No. 7970

SUPPLEMENTAL PREFILED TESTIMONY OF
STEPHEN PILCHER
ON BEHALF OF THE TOWN OF MONKTON

August 14, 2013

Stephen Pilcher's supplemental pre-filed testimony addresses the Town of Monkton's concerns about the Vermont Agency of Natural Resources' recommendation to reroute the proposed transmission pipeline that would result in the pipeline being placed close to residential homes and wells.

Exhibits

Exhibit Monkton SP-3 at p. 4.

STATE OF VERMONT
PUBLIC SERVICE BOARD

Petition of Vermont Gas Systems, Inc., requesting a Certificate of Public Good pursuant to 30 V.S.A. § 248, authorizing the construction of the **"Addison Natural Gas Project"** consisting of approximately 43 miles of new natural gas transmission pipeline in Chittenden and Addison Counties, approximately 5 miles of new distribution mainline in Addison County, together with three new gate stations in Williston, New Haven, and Middlebury, Vermont	)	Docket No. 7970

SUPPLEMENTAL PREFILED TESTIMONY OF
STEPHEN PILCHER
ON BEHALF OF THE TOWN OF MONKTON

Q1. Please state your name and address.

A1. Stephen Pilcher, Monkton, Vermont.

Q2. Do you hold a position with the Town of Monkton?

A2. Yes. Since 2009, I have been elected to and serve as a member of the Town of Monkton's Selectboard.

Q3. What is the purpose of your testimony?

A3. The purpose of my supplemental testimony, on behalf of the Town of Monkton ("Monkton"), is to address the Vermont Agency of Natural Resource's ("ANR") pre-filed testimony seeking a reroute of the proposed transmission pipeline back into municipal right of ways.

Q4. What is your understanding of ANR's position on rerouting the pipeline back into municipal right of ways in the Town of Monkton?

A.4. ANR has recommended that the transmission pipeline be rerouted 200 feet to the east at Rotax Road, from pole 218 south behind the residences to Monkton Rd. continuing on Monkton Road to pole 228 in the VELCO right of way, and into the municipal right of way along Parks Hurlburt Road. See prefiled testimony of ANR witness Eric Sorenson.

Q5. Is this a concern for the Town of Monkton?

A5. Yes. The Town of Monkton vigorously objects to these suggestions. As addressed in Vermont Gas Systems, Inc.'s ("VGS") supplemental pre-filed testimony, such rerouting is not necessary to prevent undue, adverse impacts upon significant natural communities, wetlands, and threatened and endangered species. Moreover, the rerouting will likely result in placing the transmission pipeline within close proximity to wells and residential homes located in Monkton.

Monkton negotiated the current alignment with VGS due to concerns, in part, about the potential impact to the safety of its residents, the water quality of the wells that

provide potable water to Monkton's citizens, and the use and value of the property within Monkton. Specifically, Monkton sought and largely received a routing from VGS that placed the transmission pipeline at least 300' from existing residential homes and wells. ANR's proposed rerouting would result in an alignment that brings the transmission pipeline back within 300' of many residential homes and wells.

Q.6. Is Monkton aware of any studies that support its concern over safety and the desire for 300' setbacks?

A.6. Yes. A study performed by Mark J. Stephens of C-FER technologies measured the potential impact radius caused by a breach of a transmission pipeline under various pressures and pipe diameters. For a pipe of similar diameter and maximum operating pressure as proposed by VGS, the study measured an impact radius of 330 feet resulting from a failure whereby there is a significant threat that persons and property will suffer injury and damage. A copy of this study is attached hereto as Exh. Monkton (SP-3).

Q.7. Is Monkton able to quantify the number of residences and wells that will be adversely impacted if the transmission line is rerouted as requested by ANR?

A.7. Yes. ANR's proposal will result in six (6) additional residences and three (3) or more wells that will fall within the 300' setbacks sought by the Town of Monkton. Specifically, McGuinness' well will fall within the 300' setback on Rotax Road. Depending on the precise route suggested by ANR there are three (3) houses that will fall within the 300' setback on the reroute between poles 218 and 228. These are the Alderman, Boisse and Fonte residences. In addition, the Boisse and Fonte wells will

likely fall within 300' setback. Regarding the reroute along Parks Hurlburt Road, I am aware of three (3) residences where the transmission line will fall within 300'.

Q8. Does this conclude your testimony?

A.8. Yes.

EXHIBIT
Monkton
(SP-3)
PENGAD 800-631-6989

GRI-00/0189

A MODEL FOR SIZING HIGH CONSEQUENCE AREAS ASSOCIATED WITH NATURAL GAS PIPELINES

TOPICAL REPORT

Prepared by:

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CANADA

C-FER Report 99068

Prepared for:

GAS RESEARCH INSTITUTE
Contract No. 8174

GRI Project Manager

Keith Leewis,
Pipeline Business Unit

October 2000

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1. AGENCY USE ONLY	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	October, 2000	Topical Report

4. TITLE AND SUBTITLE
A Model for Sizing High Consequence Areas Associated with Natural Gas Pipelines

5. FUNDING NUMBERS
GRI Contract 8174

6. AUTHOR(S)
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Chicago, IL 60631-3562

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
GRI-00/0189

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

12b. DISTRIBUTION CODE

13. ABSTRACT (*Maximum 200 words*)

This report developed a simple and defendable approach to sizing the ground area potentially affected by a worst-case ignited rupture of a high-pressure natural gas pipeline. Based on this model, a simple equation has been developed that relates the diameter and operating pressure of a pipeline to the size of the area likely to experience high consequences in the event of an ignited rupture failure. Pipeline incident reports, located in the public domain, were reviewed and provide the basis for evaluating the validity of the proposed affected area equation. The correlation suggests that the simple equation provides a credible estimate of affected area.

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE
$125

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)

RESEARCH SUMMARY

Title	A Model for Sizing High Consequence Areas Associated with Natural Gas Pipelines
Contractor(s)	C-FER Technologies
GRI-Contract Number	8174
Principal Investigator(s)	Mark J. Stephens
Report Type	Topical Report
Objective State	To develop a simple and defendable approach to sizing the ground area potentially affected by the failure of a high-pressure natural gas pipeline.
Technical Perspective	The rupture of a high-pressure natural gas pipeline can lead to outcomes that can pose a significant threat to people and property in the immediate vicinity of the failure location. The dominant hazard is thermal radiation from a sustained fire and an estimate of the ground area affected by a credible worst-case event can be obtained from a model that characterizes the heat intensity associated with rupture failure of the pipe where the escaping gas is assumed to feed a fire that ignites very soon after line failure.
Technical Approach	An equation has been developed that relates the diameter and operating pressure of a pipeline to the size of the affected area in the event of a credible worst-case failure event. The model upon which the hazard area equation is based consists of three parts: 1) a fire model that relates the rate of gas release to the heat intensity of the fire; 2) an effective release rate model that provides a representative steady-state approximation to the actual transient release rate; and 3) a heat intensity threshold that establishes the sustained heat intensity level above which the effects on people and property are consistent with the adopted definition of a High Consequence Area (HCA).
Results	For methane with an HCA threshold heat intensity of 5,000 Btu/hr ft^2, the hazard area equation is given by: $$r = 0.685\sqrt{p\,d^2}$$ where r is the hazard area radius (ft), d is the line diameter (in), and p is the maximum operating pressure (psi).
Project Implications	Natural gas transmission line operators will provide periodic assurances that their pipelines are safe. The Federal code 49CFR192 mandates increased wall thickness thereby reducing the corrosion and mechanical damage risks as the population density increases. The definition of High Consequence Areas is expected to require additional protection for people with limited mobility such as day care centers, old age homes, and prisons. This report suggests the definition for the HCA area of increased protection be set by two parameters, the pipe diameter and it's operating pressure.

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1. INTRODUCTION

1.1 Scope and Objective

This report summarizes the findings of a study conducted by C-FER Technologies (C-FER), under contract to the Gas Research Institute (GRI), to develop a simple and defendable approach to sizing the ground area potentially affected by the failure of a high-pressure natural gas pipeline. This work was carried out at the request of the Integrity Management and Systems Operations Technical Advisory Group (IM&SO TAG), a committee of GRI.

1.2 Technical Background

The failure of a high-pressure natural gas pipeline can lead to various outcomes, some of which can pose a significant threat to people and property in the immediate vicinity of the failure location. For a given pipeline, the type of hazard that develops, and the damage or injury potential associated with the hazard, will depend on the mode of line failure (*i.e.*, leak vs. rupture), the nature of gas discharge (*i.e.*, vertical vs. inclined jet, obstructed vs. unobstructed jet) and the time to ignition (*i.e.*, immediate vs. delayed). The various possible outcomes are summarized in Figure 1.1.

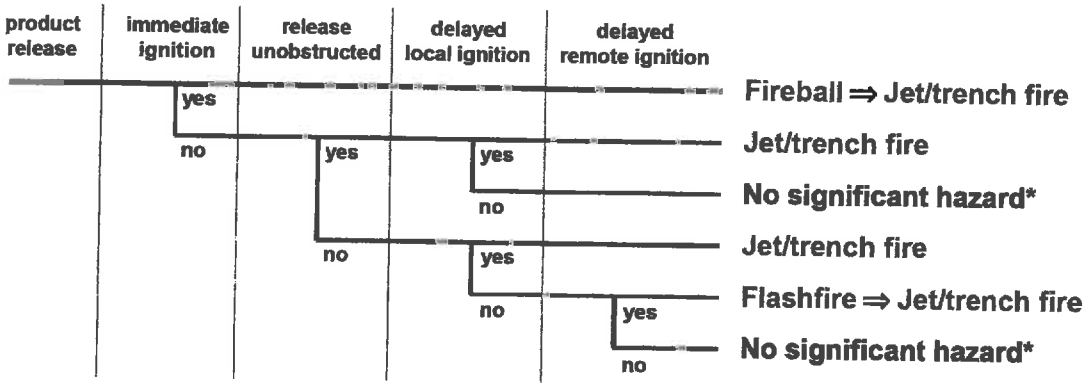

Figure 1.1 Event tree for high pressure gas pipeline failure (adapted from Bilo and Kinsman 1997).

For gas pipelines, the possibility of a significant flash fire resulting from delayed remote ignition is extremely low due to the buoyant nature of the vapor, which generally precludes the formation of a persistent flammable vapor cloud at ground level. The dominant hazard is, therefore, thermal radiation from a sustained jet or trench fire, which may be preceded by a short-lived fireball.

In the event of line rupture, a mushroom-shaped gas cloud will form and then grow in size and rise due to discharge momentum and buoyancy. This cloud will, however, disperse rapidly and a quasi-steady gas jet or plume will establish itself. If ignition occurs before the initial cloud

disperses, the flammable vapor will burn as a rising and expanding fireball before it decays into a sustained jet or trench fire. If ignition is slightly delayed, only a jet or trench fire will develop. Note that the added effect on people and property of an initial transient fireball can be accounted for by overestimating the intensity of the sustained jet or trench fire that remains following the dissipation of the fireball.

A trench fire is essentially a jet fire in which the discharging gas jet impinges upon an opposing jet and/or the side of the crater formed in the ground. Impingement dissipates some of the momentum in the escaping gas and redirects the jet upward, thereby producing a fire with a horizontal profile that is generally wider, shorter and more vertical in orientation, than would be the case for a randomly directed and unobstructed jet. The total ground area affected can, therefore, be greater for a trench fire than an unobstructed jet fire because more of the heat-radiating flame surface will typically be concentrated near the ground surface.

An estimate of the ground area affected by a credible worst-case failure event can, therefore, be obtained from a model that characterizes the heat intensity associated with rupture failure of the pipe, where the escaping gas is assumed to feed a sustained trench fire that ignites very soon after line failure.

Because the size of the fire will depend on the rate at which fuel is fed to the fire, it follows that the fire intensity and the corresponding size of the affected area will depend on the effective rate of gas release. The release rate can be shown to depend on the pressure differential and the hole size. For guillotine-type failures, where the effective hole size is equal to the line diameter, the governing parameters are, therefore, the line diameter and the pressure at the time of failure. Given the wide range of actual pipeline sizes and operating pressures, a meaningful fire hazard model should explicitly acknowledge the impact of these parameters on the area affected.

1.3 Report Organization

The hazard model developed to relate the area potentially affected by a failure to the diameter and pressure of the pipeline is described in Section 2.0. Validation of the proposed hazard area model, based on historical data from high-pressure gas pipeline failure incidents in the United States and Canada, is presented in Section 3.0.

2. HAZARD MODEL

2.1 Overview

An equation has been developed that relates the diameter and operating pressure of a pipeline to the size of the area likely to experience high consequences in the event of a credible worst-case failure event. The hazardous event considered is a guillotine-type line rupture resulting in double-ended gas release feeding a trench fire that is assumed to ignite soon after failure.

The hazard model upon which the hazard area equation is based consists of three parts: 1) a fire model that relates the rate of gas release to the heat intensity of the fire as a function of distance from the fire source; 2) an effective release rate model that provides a representative steady-state approximation to the actual transient release rate; and 3) a heat intensity threshold that establishes the sustained heat intensity level above which the effects on people and property are consistent with the definition of a high consequence area. Note that in the context of this study, an HCA is defined as the area within which the extent of property damage and the chance of serious or fatal injury would be expected to be significant in the event of a rupture failure.

The basis for each model, and any underlying assumptions, are described in Sections 2.2 through 2.4. The hazard area equation obtained by combining the model components is described in Section 2.5.

2.2 Fire Model

A jet flame can be idealized as a series of point source heat emitters spread along the length of the flame (see Figure 2.1). Each point source can be is assumed to radiate an equal fraction of the total heat with the heat flux I_i at a given location resulting from point source i being given by (Technica 1988):

$$I_i = \frac{\eta X_g Q_{eff} H_c}{4 n_p \pi x_i^2} \qquad [2.1]$$

where H_c = heat of combustion (constant for given product) ≅ 50,000 kJ/kg for methane;
η = combustion efficiency factor = 0.35;
X_g = emissivity factor = 0.2;
n_p = number of point sources;
Q_{eff} = effective gas release rate; and
x_i = radial distance from heat source i to the location of interest.

The total heat flux reaching a given point is obtained by summing the radiation received from each point source emitter.

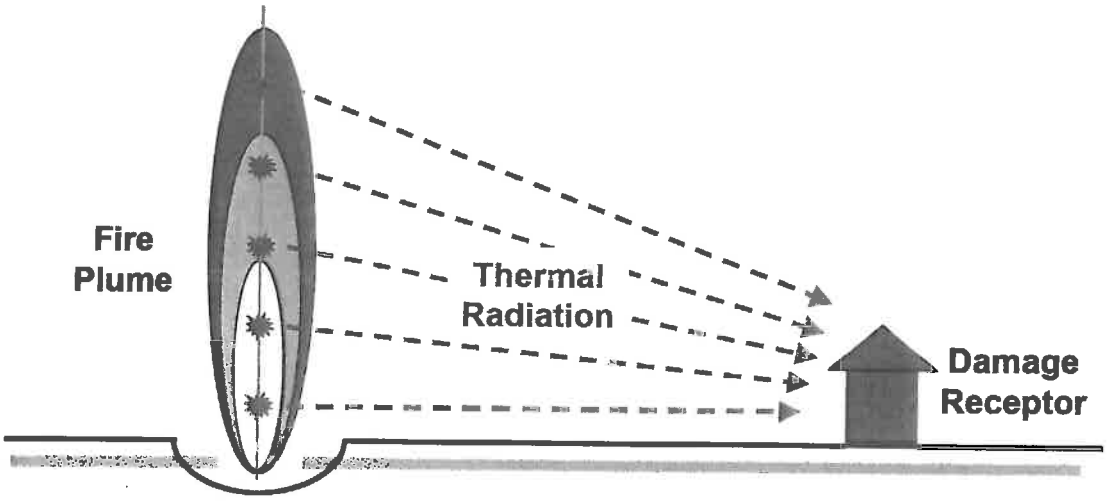

Figure 2.1 Conceptual fire hazard model.

A simplifying assumption, that generally yields a conservative estimate of the total heat flux received by ground level damage receptors, involves collapsing the set of heat emitters into a single point source emitter located at ground level (see Figure 2.2).

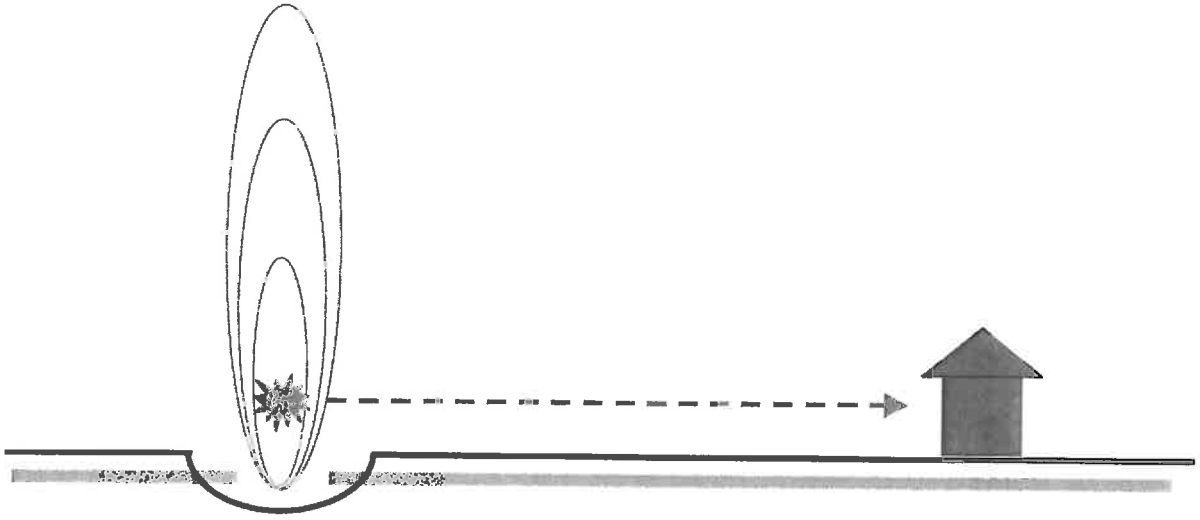

Figure 2.2 Simplified fire hazard model.

The resulting equation for the total heat flux I at a horizontal distance of r from the fire center is given by:

$$I = \frac{\eta X_g Q_{eff} H_c}{4\pi r^2} \qquad [2.2]$$

This simplification is, in some respects, more consistent with the geometry of a trench fire which, due to the jet momentum dissipation (see Section 1.2), concentrates more of the heat-radiating flame surface near ground level. Note, however, that while a ground-level point source model represents a conservative approximation to a vertically-oriented jet flame or trench fire, this conservatism is partially offset by the fact that the model does not explicitly account for the possibility of laterally-oriented jets and/or the effects of wind on the actual position of the fire center relative to the center of the pipeline.

Note, also, that for a single point source emitter located at ground level directly above the pipeline, the locus of points receiving a heat flux of I defines a circular area of radius r centered on the pipeline. Thermal radiation hazard zones of increasing impact severity are, therefore, described by concentric circles centered on the pipeline having radii that correspond to progressively higher heat fluxes.

The adopted heat flux versus distance relationship given by Equation [2.2] represents an extension of the widely recognized flare radiation model given in API RP 521 (API 1990). It can be shown to be less conservative than the API flare model (*i.e.*, it gives lower heat intensity estimates at a given distance) but this should not be considered surprising since the API model is widely recognized to be conservative (Lees 1996).

The adopted model is also preferred over some of the more generic, multi-purpose models available for industrial fire hazard analysis because it acknowledges factors, ignored by other models, that play a significant role in mitigating the intensity of real-world jet fire events. In particular, it accounts for the incomplete combustion of the escaping gas stream (through the combustion efficiency factor η), and it acknowledges (through the emissivity factor X_g) that a significant portion of the radiant heat energy will be absorbed by the atmosphere before it can reach targets at any significant distance from the flame surface.

2.3 Effective Release Rate Model

The rate of gas release from a full-bore line rupture varies with time. Within seconds of failure, the rate of release will have dropped to a fraction of the peak initial value and over time the release rate will decay even further. This tendency for rapid release rate decay is illustrated in Figure 2.3, which shows how the rate would be expected to vary with time for two representative line diameter and operating pressure combinations. The relative release rate estimates shown in the figure were calculated using a non-dimensional rate decay model presented in a study by the Netherlands Organization of Applied Scientific Research, Division of Technology for Society (TNO 1982) which is based on realistic gas flow and decompression characteristics and which acknowledges both the compressibility of the gas and the effects of pipe wall friction.

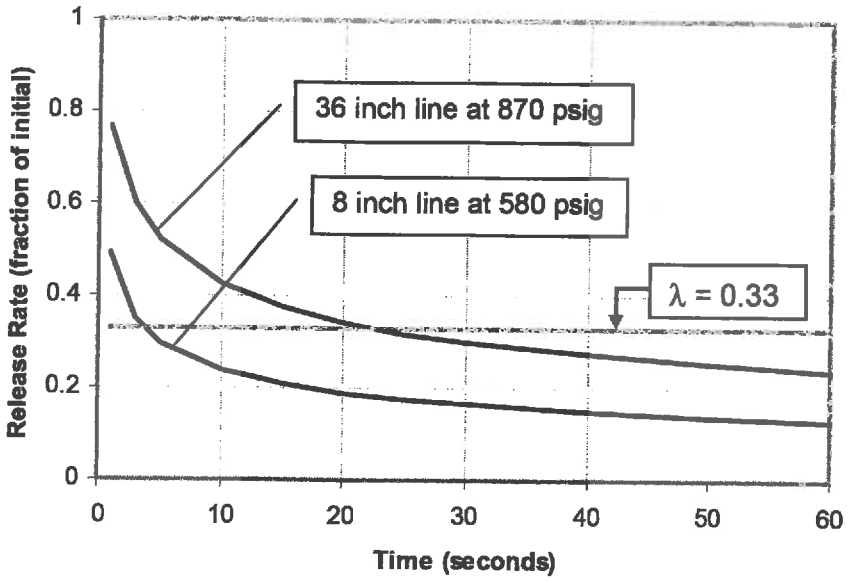

Figure 2.3 Release rate decay.

The peak initial release rate from the single end of a full-bore line rupture can be estimated using the widely recognized gas discharge equation given by the Crane Co. (1981) for sonic or choked flow through an orifice:

$$Q_{in} = C_d \frac{\pi d^2}{4} p \frac{\varphi}{a_0} \qquad [2.3a]$$

where φ = flow factor = $\gamma\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}$; [2.3b]

a_0 = sonic velocity of gas = $\sqrt{\frac{\gamma R T}{m}}$; [2.3c]

C_d = discharge coefficient ≅ 0.62;
γ = specific heat ratio of gas ≅ 1.306 for methane;
R = gas constant = 8,310 J/(kg mol)/K;
T = gas temperature ≅ 288 K or 15 C;
m = gas molecular weight ≅ 16 kg/mol for methane;
d = effective hole diameter ≅ line diameter; and
p = pressure differential ≅ line pressure.

Given that the release rate is highly variable, it follows that the size and intensity of the associated fire will also vary with time and the peak intensity of the fire will depend on exactly

when ignition occurs. The hazard model developed herein accounts for the above by approximating the transient jet or trench fire as a steady state fire that is fed by an *effective* release rate. The effective release rate is a fractional multiple of the peak initial release rate that can be used to obtain estimates of sustained heat flux that are comparable to those obtained from a more realistic transient fire model that assumes a slight delay in ignition time.

For a guillotine-type failure of a pipeline resulting in double-ended release, the effective release rate that is assumed to feed a steady-state fire is given by:

$$Q_{eff} = 2\lambda Q_{in} = 2\lambda C_d \frac{\pi d^2}{4} p \frac{\varphi}{a_0} \qquad [2.4]$$

where λ is the release rate decay factor and the factor of 2 acknowledges that gas will be escaping from both failed ends of the pipeline.

In general, the most appropriate value for the release rate decay factor will depend on the size of pipeline being considered, the pressure in the line at the time of failure, the assumed time to ignition, and the time period required to do damage to property or cause harm to people. Given that even immediate ignition will require several seconds for the establishment of the assumed radiation conditions and given further that a fatal dose of thermal radiation can be received from a pipeline fire in well under 1 minute (see Section 2.4), it follows from Figure 2.3 that a rate decay factor in the range of 0.2 to 0.5 will likely yield a representative steady state approximation to the release rate for typical pipelines.

In a study of the risks from hazardous pipelines in the United Kingdom conducted by A. D. Little Ltd. (Hill and Catmur 1995), the authors report using a release rate decay factor of 0.25. A slightly more conservative value for λ of 0.33 has been adopted herein to ensure that the sustained fire intensity associated with nearly immediate ignition of fires associated with large diameter pipelines will not be underestimated (see Figure 2.3). Given that anecdotal information on natural gas pipeline failures suggests that the time to ignition may typically be in the range of 1 to 2 minutes (as in the Edison, New Jersey incident of 1994), the adopted release rate decay factor will likely yield an effective release rate estimate that overestimates the actual rate for the full duration of a typical gas pipeline rupture fire.

2.4 Heat Intensity Threshold

For people, the degree of harm caused by thermal radiation is usually estimated using a model that relates the chance of burn injury or fatality to the thermal load received where the thermal load L_p is given by an equation of the form (Lees 1996):

$$L_p = t I^n \qquad [2.5]$$

where t is the exposure duration, I is the heat flux and n is an index.

Various recognized thermal load vs. effect models based on Equation [2.5] are summarized in Table 2.1 together with calculated estimates of the exposure times required to reach various

conditions of injury and mortality for persons exposed to specified heat intensity levels. If it is assumed that within a 30 second time period an exposed person would remain in their original position for between 1 and 5 seconds (to evaluate the situation) and then run at 5 mph (2.5 m/s) in the direction of shelter, it is estimated that within this period of time they would travel a distance of about 200 ft (60 m). On the further assumption that, under typical conditions, a person can reasonably be expected to find a sheltered location within 200 ft of their initial position, a 30 second exposure time is considered credible and is, therefore, adopted as the reference exposure time for people outdoors at the time of failure.

Radiation Intensity or Heat Flux (Btu/hr ft^2)	Radiation Intensity or Heat Flux (kW/m^2)	Time to Burn Threshold (Eisenberg et al. 1975) $t^*I^{1.15} = 195$	Time to Blister Threshold - lower[1] (Hymes 1983)[2] $t^*I^{1.33} = 210$	Time to Blister Threshold - upper[1] (Hymes 1983)[2] $t^*I^{1.33} = 700$	Time to 1% Mortality (Hymes 1983)[2] $t^*I^{1.33} = 1060$	Time to 50% Mortality (Hymes 1983)[2] $t^*I^{1.33} = 2300$	Time to 100% Mortality[3] (Bilo & Kinsman 1997) $t^*I^{1.33} = 3500$
1600	5.05	39.1	24.4	81.3	123.1	267.1	406.4
2000	6.31	23.5	18.1	60.4	91.5	198.5	302.1
3000	9.46	14.7	10.6	35.2	53.4	115.8	176.2
4000	12.62	10.6	7.2	24.0	36.4	79.0	120.2
5000	15.77	8.2	5.4	17.9	27.0	58.7	89.3
8000	25.24	4.8	2.9	9.6	14.5	31.4	47.8
10000	31.55	3.7	2.1	7.1	10.8	23.3	35.5
12000	37.85	3.0	1.7	5.6	8.4	18.3	27.9

Note:
1) Hymes gives a thermal load range (210 to 700) rather than a single value for blister formation
2) the thermal load values given by Hymes are based on a revised interpretation of the results obtained by Eisenberg et al.
3) Bilo and Kinsman assume that 100% mortality corresponds to a lower bound estimate of the thermal load associated with the spontaneous ignition of clothing

Table 2.1 Effects of thermal radiation on people.

The exposure time estimates closest to this reference time are highlighted in Table 2.1 for each different thermal load effect. Note that the onset of burn injury within the reference exposure time is associated with a heat flux in the range of 1,600 to 2,000 Btu/hr ft^2 (5 to 6.3 kW/m^2), depending on the burn injury criterion. The chance of fatal injury within the reference exposure time becomes significant at a heat flux of about 5,000 Btu/hr ft^2 (15.8 kW/m^2), if the significance threshold is taken to be a 1% chance of mortality (*i.e.,* 1 in 100 people directly exposed to this thermal load would not be expected to survive).

For property, as represented by a wooden structure, the time to both piloted ignition (*i.e.,* with a flame source present) and spontaneous ignition (*i.e.,* without a flame source present) can also be estimated as a function of the thermal load received. For buildings, the thermal load L_b is given by an equation of the form (Lees 1996):

$$L_b = (I - I_x)t^n \qquad [2.6]$$

where I_x is the heat flux threshold below which ignition will not occur.

Models based on Equation [2.6], developed from widely cited tests as re-interpreted by the UK Health and Safety Executive (Bilo and Kinsman 1997), are summarized in Table 2.2 together with calculated estimates of the exposure times required for both piloted and spontaneous ignition at selected heat intensity levels.

Radiation Intensity or Heat Flux (Btu/hr ft^2)	Radiation Intensity or Heat Flux (kW/m^2)	Time to Piloted Ignition[1] (Bilo & Kinsman 1997) $(I-14.7)*t^{0.667}=118.6$	Time to Spontaneous Ign.[1] (Bilo & Kinsman 1997) $(I-25.6)*t^{0.8}=167.6$
4000	12.62	no ignition	no ignition
5000	15.77	1162.3	no ignition
8000	25.24	37.8	no ignition
10000	31.55	18.7	65.0
12000	37.85	11.6	26.3
Note: 1) based on experiments on American whitewood			

Table 2.2 Effects of thermal radiation on wooden structures.

From Table 2.2 it can be seen that 5,000 Btu/hr ft^2 (15.8 kW/m^2), corresponds to piloted ignition after about 20 minutes (1,200 seconds) of sustained exposure. The table further shows that spontaneous ignition is not possible at this heat intensity level. It is therefore assumed that this heat intensity represents a reasonable estimate of the heat flux below which wooden structures would not be destroyed, and below which wooden structures should afford indefinite protection to occupants.

Note that the model employed for estimating the effects of thermal radiation on property explicitly considers the duration of exposure required to cause ignition. Some earlier wood ignition models, which appear to be the basis for the often cited 4,000 Btu/hr ft^2 (12.6 kW/m^2) threshold for piloted wood ignition, are in fact associated with an almost indefinite time to ignition and are, therefore, considered to be overly conservative given the transient (decaying) nature of real pipeline rupture fires.

In light of the above, if a high consequence area is defined as the area within which both the extent of property damage and the chance of serious or fatal injury would be expected to be significant, it follows that this area can reasonably be defined by a heat intensity contour corresponding to a threshold value below which:

- property, as represented by a typical wooden structure, would not be expected to ignite and burn;
- people located indoors at the time of failure would likely be afforded indefinite protection; and
- people located outdoors at the time of failure would be exposed to a finite but low chance of fatality.

The information presented on thermal load effects suggests that below 5,000 Btu/hr ft^2, a wooden structure would not be expected to burn and it, thereby, affords indefinite protection to sheltered persons. Also, this heat intensity level corresponds to approximately a 1 percent chance of fatality for persons exposed for a credible period of time before reaching shelter. A heat flux of 5,000 Btu/hr ft^2 has, therefore, been adopted as the threshold heat intensity for the purpose of sizing a high consequence area.

2.5 Hazard Area Equation

Substituting the expression developed for the effective release rate (Equation [2.4]) into the heat intensity versus distance formula (Equation [2.2]), replacing all constants and rearranging gives the following expression for the radial distance to locations where the heat flux is equal to the threshold value:

$$r = \sqrt{\frac{2348\, p\, d^2}{I_{th}}} \quad \text{(ft)} \qquad [2.7]$$

where I_{th} = threshold heat intensity (Btu/hr/ft^2);
p = line pressure (psi); and
d = line diameter (in).

For a threshold heat intensity of 5,000 Btu/hr ft^2, the above expression reduces to:

$$r = 0.685\sqrt{p\, d^2} \qquad [2.8]$$

Equation [2.8] can, therefore, be used to estimate the radius of a circular area surrounding the assumed point of line failure within which the impact on people and property would be expected to be consistent with the adopted definition of a high consequence area.

Hazard area radii, as calculated using Equation [2.8] are plotted in Figure 2.4 as a function of line diameter and operating pressure. The figure shows that, for pipelines operating at pressure levels in the range of 600 to 1,200 psi, the calculated hazard area radius ranges from under 100 ft for small diameter lines to over 1,100 ft for large diameter lines.

Note that the concept of relating the potential hazard area to the line diameter and operating pressure is not new. An approach similar to that described herein has been an integral part of the high pressure gas transmission pipeline code in the United Kingdom since 1977 (Knowles *et al.* 1978 and IGE 1993). The standard as developed in the United Kingdom incorporates the concept of a Building Proximity Distance (BPD), multiples of which serve to define development exclusion zones and establish the pipeline corridor width for the purpose of determining Location Class. The BPD is calculated directly from the line diameter and the maximum operating pressure.

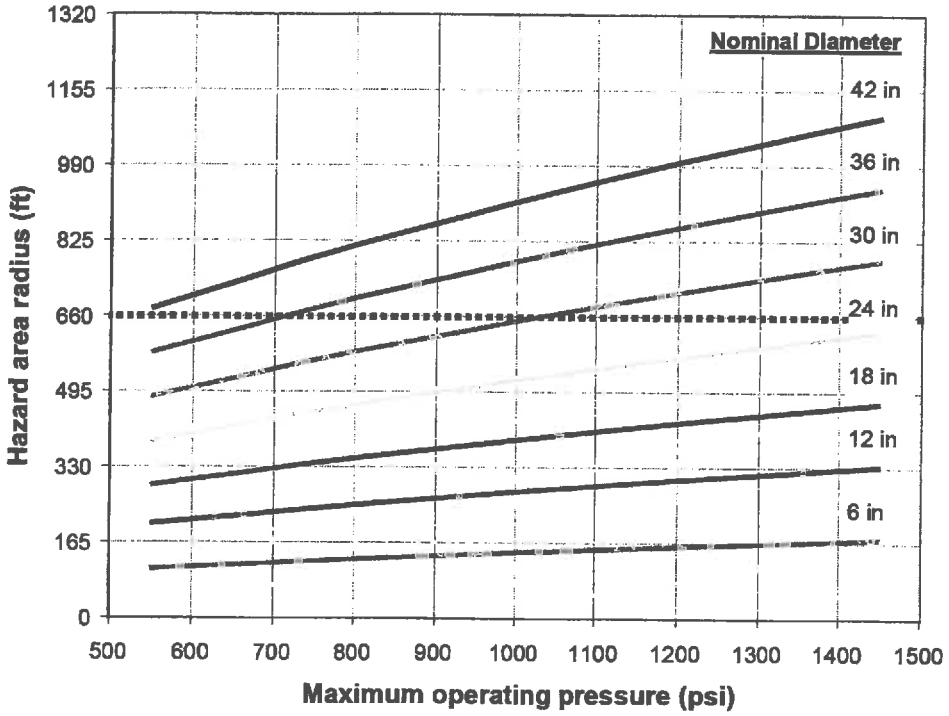

Figure 2.4 Proposed hazard area radius as a function of line diameter and pressure.

3. MODEL VALIDATION

Pipeline incident reports, located in the public domain, were reviewed to provide a basis for evaluating the validity the proposed hazard area model given by Equation [2.8]. The data sources reviewed included reports on pipeline incidents in the United States prepared by the National Transportation Safety Board (NTSB) going back to 1970, and similar reports on incidents in Canada prepared by the Transportation Safety Board (TSB) going back to 1994. Note that the information extracted from these reports required some interpretation due to differences in the way the information was reported. The processed data together with hazard area estimates obtained using Equation [2.8] are summarized in Figure 3.1. A summary of the information that forms the basis for Figure 3.1 is given in Table 3.1.

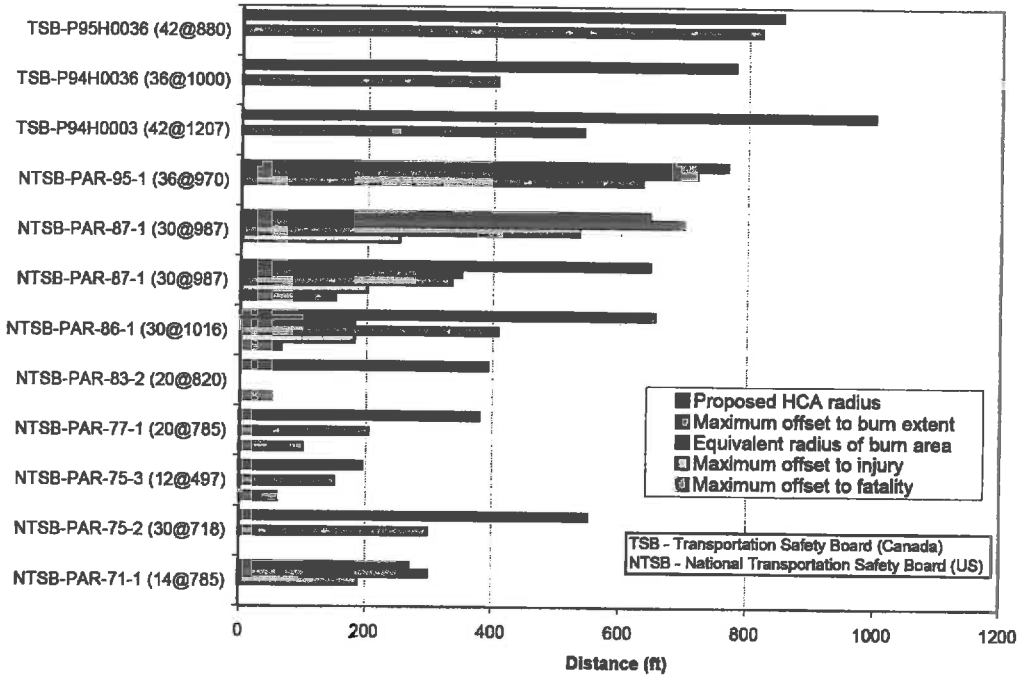

Figure 3.1 Comparison between actual incident outcomes and the proposed hazard area model.

In interpreting the incident outcomes summarized in Figure 3.1 note the following:

- the *equivalent radius of burn area* is the radius of a circle having an area equal to the reported area of burnt ground;
- the *maximum offset to burn extent* is the maximum reported of inferred lateral extent of burnt ground measured perpendicular to a line tracing the alignment of the pipeline prior to failure; and
- the *maximum offset to injury/fatality* is the maximum reported or inferred distance to an injury/fatality again measured perpendicular to a line tracing the alignment of the pipeline prior to failure.

Figure 3.1 shows that in every case the hazard area calculated using the proposed equation is greater than the actual reported area of burnt ground. In addition, with the sole exception of one of the incidents reported in NTSB-PAR-87-1, the radius obtained from the hazard area equation conservatively approximates the maximum lateral extent of the burn zone. Finally, in all cases the calculated hazard zone radius significantly exceeds the maximum reported offset distance to injury or fatality.

Note, however, that whereas the interpretation of reported burn areas and burn distances is obvious, caution should be exercised in interpreting maximum offset distances to injury and fatality. Given that most of the incidents occurred in sparsely populated areas, the reported injury and fatality offsets are more indicative of where people happened to be at the time of failure rather than being representative of the maximum possible distances to injury or fatality for the incident in question.

Acknowledging the uncertainty associated with interpreting reported offsets to injury and fatality, the balance of information still overwhelmingly indicates that the proposed hazard area radius equation provides a reasonable, if somewhat conservative, estimate of the zone of high consequence.

It is thought that one of the main reasons for the apparent conservatism in the proposed hazard area model is that it is based on an effective sustained release rate that is consistent with the assumption of almost immediate ignition. The actual time to ignition for many of the reported incidents is probably longer (see incident notes in Table 3.1) making the effective release rate approximation conservative.

Date	Report	Location	Incident	Damage	Maximum Burn Distance	Diameter (in)	Pressure (psi)
1969	NTSB-PAR-71-1	near Houston, Texas	Rupture at 3:40 p.m. on September 9th, explosive ignition 8 to 10 minutes after failure.	Burned area 370 ft long by 300 ft wide (all to one side). Houses destroyed by blast to 250 ft, heat damage to 300 ft, 106 homes damaged, 9 injuries, and 0 fatalities.	300 ft	14	789
1974	NTSB-PAR-75-2	near Bealeton, Virginia		Burned area 700 ft by 400 ft.		30	718
1974	NTSB-PAR-75-3	near Farmington, New Mexico	Rupture at 3:45 a.m. on March 15th, ignition soon after failure.	Earth charred within a 300 ft diameter circle, 3 fatal injuries (within 60 ft offset)		12.75	497
1976	NTSB-PAR-77-1	Cartwright, Louisiana	Rupture at 1:05 p.m. on August 9th, ignited within seconds	Burn area 3 acres (implies a 200 ft radius circle), 6 fatalities (within about 100 ft offset) and 1 injury.		20	770
1982	NTSB-PAR-83-2	Hudson, Iowa		5 fatalities (within 150 ft, less than 50 ft offset).		20	820
1984	NTSB-PAR-86-1	near Jackson, Louisiana	Rupture at 1:00 p.m. on November 25th, ignition soon after failure.	Burned area 1450 ft long by 360 ft wide (furthest fire extent 950 ft), 5 fatalities (within 65 ft, 0 ft offset), and 23 injuries (within 800 ft,180 ft offset).	Offset 180 ft. Distance 950 ft.	30	1016
1985	NTSB-PAR-87-1	near Beaumont, Kentucky	Rupture at 9:10 p.m. on April 27th, ignition soon after failure.	Burned area 500 ft wide by 700 ft long. 2 houses, 3 house trailers and numerous other structures and equipment destroyed. 5 fatalities due to smoke inhalation in house 318 ft from rupture (150 ft offset), 3 people burned running from house 320 ft from rupture (200 ft offset) one hospitalized with 2nd degree burns.	Offset 350 ft. Distance 500 ft.	30	990
1986	NTSB-PAR-87-1	near Lancaster Kentucky	Rupture at 2:05 a.m. on February 21st, ignition soon after failure.	Burned area 900 ft by 1000 ft. 2 houses, 1 house trailer and numerous other structures and equipment destroyed. 3 people burned running from house 280 ft from rupture (requiring hospitalization), 5 others received minor burn injuries running from dwellings between 200 and 525 ft from rupture (250 ft offset).	Offset 700 ft. Distance 800 ft.	30	987
1994	NTSB-PAR-95-1	Edison, New Jersey	Rupture at night on March 23rd, ignition within 1 to 2 minutes after failure.	Burned area 1400 ft long by 900 ft wide. Fire damage to dwelling units up to 900 ft from rupture, dwelling units at 500 ft and beyond caught fire between 7 to 10 minutes after failure, no fatalities but 58 injuries.	Offset 720 ft. Distance 960 ft.	36	970
1994	TSB Report No. P94H0003	Maple Creek, Saskatchewan	Rupture at 7:40 p.m. on February 14th, ignition soon after failure.	Fire burn area 21.0 acres (8.5 hectares).		42	1207
1994	TSB Report No. P94H0036	Latchford, Ontario	Rupture at 7:13 a.m. on July 23rd, ignition soon after failure.	Fire burn area 11.8 acres (4.77 hectares), heat-affected area 18.6 acres (7.52 hectares).		36	1000
1995	TSB Report No. P95H0036	Rapid City, Manitoba	Rupture of 42 inch line at 5:42 a.m. on July 29th, ignition soon after failure leading to rupture and fire on adjacent 36 inch line at 6:34 a.m.	Fire burn area 48.5 acres (19.6 hectares), heat-affected area 198 acres (80 hectares).		42	880

Table 3.1 Summary of relevant North American pipeline failure incident reports.

4. REFERENCES

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