Subject Matter Study Report

**Inadequacies of the U.S. Department of Transportation**

**PIR Equation**

January 9, 2015

(Revised November 2018 and October 2020)

By

Royce Don Deaver, P.E.

DEATECH Consulting Company

203 Sarasota Circle South

Montgomery, Texas 77356

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**PIR Equation**

**Executive Summary**

Pipeline Safety Laws of the 1990s required the U.S. Department of Transportation (U.S. DOT) to issue new regulations for pipeline integrity managements in populated or high consequence areas. After years of deadlock with the gas pipeline industry, the gas pipeline industry hired C-FER Technologies in Canada to develop a simple equation to define hazardous conditions from a gas pipeline rupture. The U.S. DOT jumped at the chance to adopt an equation offered by the pipeline industry to end the stalemate. The U.S. DOT had little if any involvement in development of the C-FER equation and apparently knew little of its development. The gas pipeline industry directed the development of the equation and assumptions used to adopt the equation. The equation was better than nothing, but was grossly inadequate for public safety.

The probable impact radius (PIR) equation in Title 49 CFR Part 192 is based on fire exposure from a pipeline guillotine rupture. The PIR is based on instantaneous ignition caused by migration of the gas cloud from the pipeline. The radiant heat exposure limit is based on second degree burns in only six (6) seconds of exposure. A much lower heat exposure level and longer exposure time should have been used for the PIR equation.

The enclosed report covers the mistakes and inadequacies of the Title 49 CFR Part 192 PIR equation and contains information on how a flammability analysis should be performed. In addition to a flammability analysis, the potential impact of an explosion of flammable gas or vapor from a ruptured pipeline should be included in both 49 CFR Parts 192 and 195. For toxic gases, Title 49 CFR Part 192 should include an analysis of the potential migration of toxic substances from a pipeline rupture.

Minimum changes in the PIR equation for a guillotine rupture should include:

1. Deletion of the 0.62 discharge coefficient and
2. Use of a heat intensity of 1,500 BTU/Hr.-Ft.2

The resulting revised PIR equation would be:

 .

If Title 49 CFR Part 192 is able to include proper criteria to prevent a guillotine rupture where the pipeline is ruptured into two pieces, a lessor PIR equation would be appropriate. However, a lower maximum allowable operating pressure (MAOP) will be required. Current MAOP limits are too high for prevention of a guillotine rupture. MAOP’s may need to be lowered by 50% to 70% depending on the fracture toughness and diameter of the line pipe.

Proper analysis of a released gas or vapor from a pipeline is more complex than appears in the PIR that appears in Title 49 CFR Part 192. However, the U.S. DOT appears to prefer simplicity rather than proper engineering analysis. When complex processes are grossly simplified, accuracy is sacrificed unless very conservative assumptions are made.

R. D. Deaver, P.E.

DEATECH Consulting Company

rddeaver.com

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**PIR Equation**

Introduction

The goal of this publication is to inform pipeline operators and government regulators on the inadequacies of the current PIR equation in Title 49 CFR Part 192 used to define a high consequence area. Title 49 CFR Part 192 includes in its title “Minimum Federal Safety Standards”. Therefore, all requirements in Title 49 CFR Part 192 prescribe minimum requirements for gas pipelines and gas pipeline operators must develop and implement safety practices that go beyond the explicitly stated requirements of Title 49 CFR Part 192. The present PIR equation does not define a safe distance from a gas pipeline rupture and fire for people. The present PIR equation defines the perimeter of the killing zone of people unable to quickly find shelter if the gas is immediately ignited.

However, natural gas from a pipeline rupture is not immediately ignited unless an ignition source is at the rupture site and the released gas is at a concentration in air above the lower flammable limit and below the upper flammable limit. Ignition also requires a minimum ignition energy of at least 0.3 milli joules.

 The more logical sequence of events is a delayed ignition resulting in migration of the released methane in air until an ignition source is found. Depending on weather conditions and locations of ignition sources, this process may take minutes to occur. The delay in ignition also creates a large fire ball of much greater heat intensity than if ignition occurs immediately.

Appropriate modeling of a pipeline release such as a natural gas rupture involves at least a three phase process to determine a potential hazardous distance or needed safety setback from a pipeline. These three phases of a pipeline release include:

1. Gas migration distance to an ignition source,
2. Fireball analysis created by the accumulated natural gas during the time between the rupture and the ignition, and
3. Thermal radiation from the sustained fire that exists after ignition and after the fire ball duration.

The hope through this publication is to assist pipeline operators and government regulators striving to increase pipeline safety rather than maintain a minimum status quo as presently provided in Title 49 CFR Parts 191, 192, and 195.

The equation developed by C-FER Technologies (C-FER) for the gas pipeline industry was adopted by the U.S. Department of Transportation for inclusion in Title 49 CFR Part 192 to define the minimum hazardous distance for determination of high consequence areas affected by a gas pipeline rupture and fire. This equation is based on a fire exposure of 5,000 BTU per hr.-ft.2 which assures second degree burns and possibly death within 30 seconds if 100% shelter from the fire is not available. This limit was based on providing 20 minutes of protection in a wood building and was therefore based on protection of property. Older, younger, and handicap people with limited mobility cannot be expected to find shelter within 60 seconds of such a fire exposure. Even younger and high mobile people in an open area are not assured of finding a fire shelter within 30 to 60 seconds.

Rather than defining a safe distance from a gas pipeline rupture and fire, the PIR defines the perimeter of the killing zone of people unable to quickly find shelter.

The subject report was prepared by C-FER Technologies (C-FER) in Edmonton, Alberta, Canada for the Gas Research Institute. The report was dated October 2000 and the report’s recommended equation for determining potential impact radius (PIR) of a natural gas pipeline rupture is included in 49 CFR 192.903. This PIR equation is given as:

  (1)

 where:

 *r* = PIR, ft.;

 *P* = pipeline pressure, psig; and

 *d* = pipeline diameter, in.

The above equation is also included in ASME B31.8S and is given for any gas as follows:

  (2)

 where:

 μ = combustion efficiency factor;

 *e* = emissivity factor;

 *Fd* = release rate decay factor;

 *Cd* = discharge coefficient;

 *Hc* = heat of combustion;

 *Ff*  = flow factor;

 ʋ*s* = speed of sound in gas;

 *I* = heat flux;

 *p* = pipeline pressure, psig; and

 *d*  = pipe diameter, in.

  (3)

 where:

 *k* = ratio of specific heats.

The velocity of sound in the gas is given by C-FER as:

  (4)

 where:

 *R* = gas constant,

 *T*  = gas temperature, and

 *m* = gas molecular weight.

Unfortunately, ASME B31.8S does include all the units in the equations, but it appears that English units are used. The recommended values of *Hc*, *Fd*, *Cd, I, Fd,* *Ff*, *e*, and *μ* are not given in ASME B31.8S.

If the recommended values for the PIR equation in the C-FER report and English units are used, the calculated PIR, *r*, using the ASME B31.8S equation for the example of 24 inch pipe at 1000 psi:

 

The above calculation is close to the calculated PIR of 524 ft. determined from equation (1), therefore, the B31.8S equation (2) requires the use of English units and psia.

Foundation for PIR Equation

A radiation heat intensity of 5000 BTU/ft.2-hr. was used as *I* for the C-FER PIR equation, based on the following stated criteria by C-FER:

1. One percent change of mortality for a person with 30 seconds of exposure to find a shelter.
2. Requires 1162 seconds (about 20 minutes) of exposure for wood shelter to ignite with piloted ignition.

The C-FER PIR model assumes that a person would take five (5) seconds after a fire to analyze the situation and run for 25 seconds at 2.5 m/s on any terrain and find long term shelter within 62.5 meters (245 feet). The running speed has to be at least 25% of the speed of an Olympic sprinter. Children, the elderly, and physically limited people will not be able to escape.

The PIR equation used a gas flow rate decay release factor (*Fd*) of 0.33 even though the report indicates the *Fd* may be as high as 0.5. This indicates that the PIR is not based on the initial flow rate when the pipeline ruptured, but a flow rate at some extended time after the rupture. This time period is not included in the calculations and will vary with different pipelines.

The discharge coefficient in the PIR equation is for an orifice meter type of discharge to indicate the restricted flow pattern downstream of a restricted opening. With a severed pipeline, you don’t have such a restricted hole. The PIR equation should not have used an orifice meter equation and a discharge coefficient of 0.62.

The PIR equation also contains the flow factor, *Ff*, defined earlier as equation (3). For a value of *k* = 1.306 for methane, as given in the report, the value of *Ff* is:



 

The speed of sound, *ʋs*, is calculated for methane at 15°C (59°F), the temperature used for PIR, with equation (4) as follows:

 

 

The Crane Technical Paper No. 410 (Crane 410) indicates that *ʋs* can also be determined for methane at 15°C (59°F) and 1000 psig as follows:

  (5)

 where:

 *pa* = gas pressure, psia and

 ρ = gas density at given pressure, lbs. per ft.3

 

At 90°F and 1000 psig, the speed of sound in methane is:

 

For methane at 59°F and 14.7 psia, the density is 0.04228 pcf and the speed of sound using equation (5) is:

 

Equation (4) used in the PIR is for low pressure gas without the effect of pressure. Equation (5) appears to be more appropriate for high pressure gas.

A temperature of 59°F is low for a gas transmission line, because significant compression heat is added at each compression station. A temperature range of 80°F to 140°F is more appropriate for gas pipelines depending on the proximity to compression facilities and geographic location.

Natural gas is not pure methane, but is usually a mixture of 95 to 99% methane with ethane and heavier fluids. The effective *k* for natural gas is often taken as 1.4 and the effective molecular weight for natural gas is higher than 16. The molecular weight of methane is 16.043, of ethane is 30.07, of propane is 44.097, and of butane is 58.123.

If a gas was composed of 92% methane, 5% ethane, 2% propane, and 1% butane, the molecular weight would be about:

 0.92 x 16.043 = 14.76

 0.05 x 30.07 = 1.50

 0.02 x 44.097 = 0.88

 0.01 x 58.12 = 0.58

 17.72

The C-FER PIR equation is based on a combustion efficiency factor, *μ*, of 0.35 and an emissivity factor, *e*, of 0.2.

The heat of combustion, *Hc*, is taken as 21,500 BTU/lb.

The heat intensity model used for the C-FER PIR equation is indicated as being the model given in the 1990 edition of API 521 and is stated as equation 2.1 in the C-FER report as follows:

  (6)

 where:

 *Qe* = effective gas flow rate, lbs. per hour;

 *n* = number of fire sources;

 *x* = distance from fire, ft.;

 *I* = 5000 BTU/ft.2-hr.;

 *μ* = 0.35;

 *e*  = 0.2;

 *n* = 1; and

 *Hc* = 21,500 BTU/lb.

For the values given above, equation (6) can be reduced to:

  (7)

For a 24 inch pipeline at 1000 psi the calculated PIR, *r* and *x*, is calculated with equation (1) as follows:

 

The effective gas flow rate that corresponds to a PIR (*r* or *x*) of 524 ft. using equation (6) is:

  (8)

For the C-FER recommended values and a PIR of 524 ft., equation (8) is calculated as follows:

 

Equation 2-4 in C-FER report indicated that the effective flow rate, *Qe*,from both ends of a ruptured pipe is to be determined as follows:

  (9)

 where:

 *2* = number of pipe ends of ruptured pipe;

 *Fd* = pipe release decay factor, 0.33; and

 *Qm* = peak release rate from the pipeline after the rupture occurs.

Therefore, in our example of *d* = 24 inches, *p* = 1000 psi, and *r* = 524 ft., the initial or peak release flow rate from each end of the 24 inch pipeline using equations (8) and (9) is:

 

When the improper use of *Cd* = 0.62 is removed from the C-FER PIR equation, *Qm* from each end of a ruptured 24-inch pipeline is:

 

Reference number ten in the C-FER report was the Technical 1988 report that included calculations for gas pipeline ruptures. Technical 1988 recommended a *Cd* =1.00, not *Cd* = 0.62 as used in the C-FER report. C-FER arbitrarily used a *Cd* of 0.62.

Crane Technical Paper No. 410

C-FER indicated that the PIR equation is based on the following equation for sonic or choked flow that is stated in Report No. GRI-00/0189 as being from Crane 410 as follows:

  (10)

 where:

 *Qm* = flow rate in unknown units and

 *Cd* = 0.62.

However, equation (10) above is not found in Crane 410. The referenced Technical 1988 report included equations from the 1981 edition of Crane.

On pages 2-15 of the 2006 edition of Crane 410, it is stated that their equation 2-24 may be used for discharge of compressible fluids through a nozzle to a downstream pressure lower than indicated by the critical pressure ratio, *rc*, by using values of:

 *Y* = minimum per page A-21,

 *C* = from page A-20,

 Δ*p* = *p1* *(1 – rc)* per page A-21, and

 *ρu* = weight density at upstream conditions.

Equation 2-24 in Crane 410 is:

  (11)

 where:

 *q* = volumetric gas flow rate at flowing conditions, ft.3 per sec.;

 *Y* = net expansion factor;

 *C* = flow coefficient (not orifice coefficient);

 *A* = pipe or orifice cross sectional area, ft.2;

 *g* = 32.2 ft. per sec.2;

 Δ*p* = differential pressure, psi; and

 *ρu* = upstream gas density, lbs. per ft.3

1. Step 1. Although a ruptured pipe does not have an orifice or nozzle restriction, an artificial value must be selected for this equation. The maximum pipe orifice or nozzle opening given on page A-21 of Crane 410 is 85% of the pipe diameter for the critical pressure determination and 75% for the expansion factor.
2. For an 85% opening (*β* = .85) and *k* = 1.31, *rc* = .633. For *pμ* = 1014.7 psia and *rc* = .633, the downstream pressure is 642.3 psia and Δ*p* is 372.4 psi. The pressure ratio, Δ*p* ÷ *pa*, is 0.367 (372.4 psi ÷ 1014.7 psia). For *k* = 1.3, Δ*p* ÷ *pa* = .367, *β* = .75, and *Y* = .70.
3. On page A-20, the value of *C* where *β* = .75 at a high Reynolds number is *C* = 1.20. A value of *C* = *Cd* only applies to square edge orifices with small openings. For a large opening the product of *C* x *Y*  approaches 1.0.

Equation 2-24 in Crane 410 (equation 11) can now be solved for methane at 1014.7 psia and 59°F where *ρu* = 3.35 lbs. per ft.3 as follows:

 

The mass flow rate, *Qm*, at *C* x *Y* = 0.84 and *ρ* = 3.35 lb. per ft.3 is 8976 lbs. per second. If *C x Y* = 1.0, *Qm* becomes 10,686 lbs. per second.

Page 3-3 in Crane 410 includes the following information on fluid specific volume or density to use in compressible flow calculations.

1. When pressure drop is greater than 10% of inlet pressure, use density or specific volume at inlet or outlet conditions.
2. When pressure drop is greater than 10%, but less than 40% of inlet pressure, use the average of density or specific volume at inlet and outlet conditions.
3. When pressure drop is greater than 40% of inlet pressure, use equation 3-20.

When flow is sonic, the limiting values of Δ*p/p1* and *Y* shown on page A-22 for the given resistance coefficients, *k*, are to be used in equation 3-20. For *k* = 1.3, the maximum value for *Y* is 0.718 and Δ*p/p1* is 0.920. For *k* = 1.4, the maximum value for *Y* is 0.710 and Δ*p/p1* is 0.926.

Equation 3-20 from Crane 410 is as follows:

  (12)

For flow inside pipe:

  (13)

 where:

 *Qm* = mass flow rate, lbs. per sec.;

*Y* = expansion factor for flow into larger area;

 Δ*p* = *p1 – p2* = pressure drop in pipe, psi;

 *ρ1* = gas density in the pipeline;

 *f* = friction factor;

 *l* = pipeline length or distance from exit, ft.; and

 *d* = pipe diameter, in.

For a very high Reynolds number above 107, the friction factor for 24 inch and larger is about 0.011 and equation (12) becomes:

 . (14)

For pipe exit conditions, *K* = 1.0 and . (See equations 31 and 32).

For pipe exit conditions where *K = 1.0*, equation (12) becomes:

  (15)

For a 24 inch pipeline at 1000 psig and 59°F where gas density is 3.35 lbs. per ft.3, equation (15) is solved as follows to calculate exit flow rate from a ruptured pipeline:

 

If the exit *K* = 1.0 is neglected and only flow in a long pipeline is considered:

  and (16)

  (17)

where:

 *t* = time after rupture, sec.

For *ʋs* = 1356 ft. per sec., 24 inch pipe and *f* = 0.015, *K* = 10.17 *t*.

Equation 1-1 in Crane 410 (also equation 3-2 in Crane 410) can be rearranged as follows to solve volumetric and mass flow rate at any point in the pipeline including exit from a ruptured pipeline:

  (18)

 where:

 *q* = volumetric flow rate, ft.3 per sec.;

 *A* = pipe cross sectional area, ft.2;

 *ʋ* = average fluid velocity in pipe, ft. per sec.; and

 *ρ* = average density in pipe, lbs. per ft.3.

Crane 410 also illustrates the analysis of equation (18) above on page 4-13 in example 4-20 as follows using equation 3-2 on page 3-2 of Crane 410.

  (19)

 where:

 *Qm* = flow rate, lbs. per sec.;

 *ʋ* = *ʋs* = fluid velocity at exit conditions, ft. per sec.; and

 *ρ* = fluid density at exit conditions, lbs. per ft.3.

Derivation of the C-FER Equation for *Qm*

Equation 9 from the C-FER report can be derived from equations (5) and (18) as follows:

1.  (Equation 18)
2.  (Equation 5)
3. At the end of the pipe, *ʋ* = *ʋs*, *A* = 0.005454 *d2*, *p* = *pe*, and *ρ* = *ρe*.
4. Equation 5 can be rearranged as follows:



1. Equation (19) can be solved as follows:



 (20)

1. C-FER added a *Ff* [see equation (3)]to the flow equation to apparently, but wronglyfully, account for the reduced pressure at the ruptured pipe outlet and:

 (21)

where:

*pe* = gas pressure at exit conditions, psia and

*p1* = gas pressure before rupture, psia.

1. A *Cd* was arbitrarily added to the flow equation by C-FER and the equation for pipeline exit mass flow rate for a severed or “full bore” ruptured pipeline wrongfully became:

 (22)

where:

*Qm* = mass exit flow rate, lbs. per sec.;

*Cd* = discharge coefficient, 0.62;

*d* = pipe diameter, inches;

*k* = ratio of specific heats, 1.307 for methane,

*Ff* = flow factor, see equation (3);

*p1* = pipeline pressure before rupture, psia; and

*ʋs* = gas sonic velocity at exit conditions, ft. per sec.

For a 24 inch pipeline at 1000 psig and 59°F where gas density is 3.35 lbs. per ft.3 and the exit sonic gas velocity is estimated at 1400 fps, the mass gas rate from equations (21) and (22) would be:

 

 

If the *Cd* is properly eliminated from equation (22) for an open ended exit area for the pipeline, *Qm* becomes 8070 lbs. per second (5003 lbs. per sec. ÷ 0.62).

AGA Pipeline Rupture Propagation Studies

Pipeline rupture studies at Battelle et al have assumed that the gas decompression process is isentropic and the decompressed pressure in the pipe is:

  (23)

 where:

 *pd* = decompressed pressure, psia;

 *p1* = initial pressure in pipe;

 *k* = ratio of specific heats;

 *ʋc* = rupture propagation velocity, ft. per sec.; and

 *ʋs* = gas sonic velocity at initial conditions, ft. per sec.

For *k* = 1.31 for methane, the equation (23) becomes:

 

For *ʋc* = 750 ft. per sec. and = 1355 ft. per sec., the equation (23) becomes:

 

When the rupture is complete and *ʋc* = 0, the ratio of *pd/p1* becomes:

  (24)

 

For one end of a rupture length of 50 feet for 24 inch pipe, the estimated time for the cracking would be 0.067 seconds (50 ft. ÷ 750 ft. per sec.) and the amount of released gas from 24 inch pipe would be:

 

 

For a 24 inch pipeline at 1000 psig, 1014.7 psia and 59°F with methane (*k* = 1.31), the exit mass flow rate using equation (19) from fracture propagation studies would be:

1. From equation (23), *pd/p1 =* 0.3 and *pd* = 0.3 x 1014.7 psi = 304.4 psia.
2. The density of methane when isentropically decompressed from 1014.7 psi and 59°F to 304.4 psia and -85°F is 1.37 lbs. per ft.3
3. The velocity of sound in isentropically decompressed methane at 304.4 psia using equation (5) is:



1. The initial exit mass methane flow rate from each end of the severed pipeline would be using equation (19) would be:



However, if the conventional critical pressure ratio [see equation (32)] is used for methane at *rc* = 0.544, the isentropic decompression of methane to 552 psia (0.544 x 1014.7 psia) will result in a methane density of about 2.17 lb. per ft.3 and velocity of sound of:

 

The initial exit mass methane flow rate from each end of a ruptured pipeline using equation (18) would be:

 

The above calculation is consistent with other calculation methods. A critical pressure ratio should also bring into question the validity of fracture propagation and arrest studies by Battelle under the “old” American Gas Association Pipeline Research Program. An arrest pressure of 0.544 times the pipeline pressure is considerably higher than the 0.300 factor assumed by AGA researchers.

Other Sources of Calculating Gas Flow Rate from a Gas Pipeline

The American Petroleum Institute “Guidance Manual for Modeling Hypothetical Accidental Releases to the Atmosphere”, Publication No. 4628 dated November 1996 contains the following guidance for modeling gas pipeline releases.

1. The second law of thermodynamics requires:

Δ*s > 0*

where:

*s* = entropy.

1. With an isentropic process Δ*s* = 0. This is an idealization which can never be attained in practice, but is a useful concept for modeling gas decompression.
2. An isenthalpic process is inappropriate for a situation in which a substantial change in kinetic energy occurs to a releasing fluid, typical of a gas or flashing liquid release from high pressure.
3. For an ideal gas,

 (25)

where:

*p* = gas pressure, psia;

*V* = gas volume;

*n* = number of moles;

*R* = gas constant; and

*T* = gas temperature, °*k*.

1. For isentropic conditions,

 (26)

where:

*T1* = upstream gas temperature, °*k*;

*T2* = downstream gas temperature, °*k*;

*p1* = upstream gas pressure, psia;

*p2* = downstream gas pressure, psia.

1. For isentropic conditions

 (27)

where:

*rc* = critical pressure ratio

1. The initial maximum flow rate during a pipeline failure is:

 (28)

 (29)

where:

*Qm* = initial flow rate through an orifice opening in the pipe;

*Cd* = discharge coefficient;

*A2* = area of discharge opening;

*p1* = upstream pressure, psia; and

*ρ1* = upstream density, lbs. per ft.3

The critical pressure ratio, *rc*, in equation (27) agrees with the equation for *rc* given in equation (8.125) of Victor L. Streeter’s Handbook of Fluid Dynamics, First Edition, 1961, McGraw-Hill.

API Publication No 4628 does not contain all the units and complete equations for calculation purposes. However, the equation can be derived from other equations in this report in the following steps.

1. Equation (18) is:



1. With a ruptured pipe the mass flow rate is based on conditions at the end of the pipe where:

 (30)

where:

*Qm* = gas mass flow rate, lbs. per sec.;

*A* = pipe cross sectional area, ft.2;

*ʋs,e* = gas velocity of sound at exit conditions, ft. per sec.; and

*ρe* = density of gas at exit conditions, lbs. per ft.3.

1. The gas velocity of sound at pipeline exit conditions from equation (5) is:



1. The exit pressure is:

 (31)

1. The critical pressure ratio according to API Publication 4628 is:

 (32)

1. The exit density is:

 (33)

1. Steps 2 – 6 can be combined as:
2. 
3.  (34)
4. 
5.  (35)
6. The pipe cross sectional area is:



1. The density, , is:

 (36)

where:

*p1* = internal pressure inside pipeline, psia.

1. Equation (34) can be changed to:

 (37)

Equation (37) is the full equation for calculation of mass exit flow rate from a ruptured pipeline based on API Publication 4628.

For a 24-inch pipeline at 1000 psig (1014.7 psia) and 59°F where methane gas density is 3.35 and *k* = 1.31, equation (37) based on API 4628 is solved as follows:



Gas Flow within a Ruptured Pipeline

Calculation of gas flow within a ruptured pipeline using equation (12) is illustrated with the following example:

1. *d*  = 24 inch;
2. *p1* = 1000 psig, 1014.7 psia;
3. *T1* = 59°F;
4. *ρ* = 3.35 lbs. per ft.3; and
5. Methane where *k* = 1.31.

The calculation steps are:

 1. Use equation (5) to calculate *ʋs* at pipeline conditions before the rupture as follows:



 2. After 1 sec., *l* = 1356 ft.

 3. Use equation (17) to determine flow resistance *K* as follows.

 .

 4. Use equation (32) to calculate the exit pressure conditions at critical

 flow:

 .

 .

 5. The differential pressure Δ*p*, in the ruptured pipe is:

 .

 6. Equation (12) can be solved as follows:

 

Since *Qm* within the pipeline is less than the exit flow rate from the pipeline, the pressure and density of the gas at the exit point will diminish with time. With isentropic conditions:

  is constant and . (38)

Comparison of Initial Ruptured Pipeline Exit Flow Equation

The initial ruptured pipeline exit flow rate equations without an orifice discharge factor can be compared for the example of a 24 inch pipeline at 59°F and 1000 psig where the initial gas density is 3.35 lbs. per ft.3

 1. C-FER PIR equation, *Qm* = 4,824 lbs. per sec.

 2. Equation 2-24 in Crane 410 = 8,976 lbs. per sec.

 3. Equation 3-20 in Crane 410 = 8,458 lbs. per sec.

 4. Corrected C-FER Technologies Equation = 7,780 lbs. per sec.

 5. AGA gas propagation studies = 5,000 lbs per sec.

 6. Corrected AGA gas propagation studies = 8,474 lbs. per sec.

 7. API 4628 equation = 8,346 lbs. per sec.

The API 4628 equation (36) without the *Cd* is recommended for use in ruptured gas pipeline modeling. For a 24 inch gas pipeline at 1000 psig and 59°F where the methane gas density is 3.35 lbs. per ft.3, *Qm* = 8,288 lbs. per second.

A ruptured pipe release decay factor, *Fd*, similar to the one used by C-FER in equation (9) can be used to calculate the effective release rate versus time. Figure 2.3 in the C-FER report contains release decay factors for an 8-inch pipeline at 580 psig and a 36-inch pipeline at 870 psig. As shown on Figure 2.3 of the C-FER report, a decay factor of 0.33 was used for the PIR equation for all pipeline diameters and pressures.

The decay factor, *Fd*, based on the C-FER report Figure 2.3 can be estimated as follows:

  (39)

 where:

 *Fd* = flow rate decay factor;

 *d* = pipe diameter, inch;

 *p* = pipeline pressure before rupture, psig; and

 *t* = time after rupture, seconds.

The C-FER report states “it follows from Figure 2-3 that a rate decay factor of 0.2 to 0.5 will likely yield a representative steady state approximation to the release rate for typical pipelines”. However, only a value of 0.33 is used for all pipelines and all times after the rupture occurs.

For a 24 inch pipeline at 1000 psig using C-FER report Figure 2.3, the following estimated decay factors are:

Table 1

Flow Rate Decay Factors

|  |  |
| --- | --- |
| Time, sec. | *Fd* |
|  0 | 1.0000 |
|  1 | 0.7100 |
|  2 | 0.5767 |
|  3 | 0.5106 |
|  4 |  0.468 |
|  5 |  0.438 |
|  6 |  0.415 |
|  7  |  0.396 |
|  8 | 0.3805 |
|  9 | 0.3673 |
|  10 | 0.3558 |
|  11  | 0.3458 |
|  12 | 0.3369 |
|  13  | 0.3289 |
|  14 | 0.3217 |
|  15 | 0.3151 |
|  20 | 0.2890 |
|  30 |  0.256 |
|  60 | 0.2079 |
|  120 | 0.1689 |
|  240 | 0.1371 |
|  480 | 0.1114 |
|  720 | 0.0986 |
| 1440 | 0.0812 |
| 3600 | 0.0686 |

For long periods after the rupture begins, the flow rate delay factor will depend on the length of the pipeline between compressor or delivery stations, compression control of the upstream station and locations of the rupture.

The decompression wave in natural gas travels at about 1300 feet per second. For a transmission line with 100 mile spacing of flow control points or stations, a mid line rupture takes about 200 seconds to travel from the rupture to a flow control station. An increase in the flow responding to a lower pressure will take some time and the recompression wave will take another 200 seconds to travel back to the rupture. Therefore, 400 to 500 seconds or longer to adjust to the new flow condition on each side of the rupture. The flow rate from the rupture will last for over an hour.

The following example illustrates the application of the above flow decay over time.

1. 24 inch, 1000 psig gas transmission.
2. Initial *Qm* from rupture is 16,700 lb./sec.
3. Calculated flow summation factors for *Qm* over time are:

Table 2

Accumulated Flow Factors

|  |  |
| --- | --- |
| Time, seconds | *Ʃ Fd* |
| 0 |  0 |
| 1 |  0.855 |
| 2 |  1.500 |
| 3 |  2.044 |
| 4 |  2.533  |
| 5 |  2.986 |
| 6 |  3.413 |
| 7 |  3.819 |
| 8 |  4.207 |
| 9 |  4.581 |
| 10 |  4.943 |
| 11 |  5.294 |
| 12 |  5.635 |
| 13 |  5.968 |
| 14 |  6.293 |
| 15 |  6.612 |
| 20 |  8.122 |
| 30 | 10.85 |
| 60 | 17.81 |
| 120 | 29.11 |
| 240 | 47.47 |
| 480 | 77.29 |
| 720 |  102.49 |

Delayed Ignition

In remote areas vapor or gas clouds are unlikely to experience an immediate ignition as assumed by the C-FER equation. Atmospheric dispersion models should be used to estimate the distance a natural gas or vapor release can travel until an adequate ignition source is encountered.

U.S. Environmental Protection Agency EPA 550-B-99-009, *Risk Management Program Guidance for Offsite Consequence Analysis*, contains vapor or gas cloud dispersion methods that can be used to evaluate atmospheric dispersion based on the following conservative atmospheric conditions.

1. Wind speed of 1.5 m/s (4.9 fps),
2. Meteorological stability Class F,
3. Ambient temperature of 25°C (77°F),
4. Relative humidity of 50%,
5. Release at ground level,
6. Temperature of released vapor or gas is 25°C (77°F), and
7. Two ground surface roughness conditions:
	1. For rural terrain and
	2. For urban terrain.

Calculations are available for 10 minute and 60 minute release durations. Tables of calculated migration distances versus vapor or gas release rate (lb./min.) ÷ by the hazardous concentration (mg/liter) of the toxic or flammable vapor or gas.

The lower flammable limits in mg/L for flammable gases and vapors are:

1. Methane – 33 mg/L.
2. Ethane – 36 mg/L.
3. Butane – 36 mg/L.
4. Propane – 36 mg/L.

For a 10 minute (600 second) release in our example, the total estimated release quantity is 1,470,880 lbs. or an average of 147,060 lbs. per minute or 2,450 lbs. per second. For a 60 minute (3600 second) release, the estimated release rate is 85,920 lbs. per minute or 1,432 lbs. per second.

For an estimated lower flammable limit of 33 mg/L for methane, the release rate ÷ endpoint in lbs./min. ÷ mg/L for determining atmosphere migration distance from the EPA report are as follow.

Table 3

Atmosphere Migration Factors

|  |  |
| --- | --- |
| Release Time | lbs./min. ÷ mg/L |
| 10 minutes | 4456 |
| 60 minutes | 2604 |

For a 10 minute release, the average distance from the rupture that the gas/vapor cloud retains a hazardous concentration of at least 33 mg/L in a rural environment is 2.55 miles, 13,460 feet. For urban conditions, the average distance from the rupture is 1.65 mile, 8710 feet.

For a 60 minute release, the average distance from the rupture that a gas/vapor cloud retains a hazardous concentration of at least 33 mg/L in a rural environment is 2.1 mile, 11,088 feet. For a 60 minute release, the average distance from the rupture that a gas/vapor cloud retains a hazardous concentration of at least 33 mg/L in an urban environment is 0.9 miles, 4752 feet.

Effects of Pipeline Length

The flow rate decay factors in the previous sections were for long gas transmission pipelines. For short pipelines the flow rate decay and duration of the rupture release will be shorter.

A 100 mile, 24-inch pipeline at a pressure of 1000 psi contains about 2,500,000 pounds of natural gas. A shorter 10 mile 24-inch pipeline at 1000 psi contains about 250,000 pounds of natural gas.

In this example, a 5,000,000 lb. release over 60 minutes cannot happen even though there may be continual flow from both ends of the pipeline during a rupture, but backflow should be low if check valves are used.

The duration of a release will also depend on the diameter of the pipeline with larger diameter pipelines having rupture release duration times.

Equations (12) and (13) indicate the flow rate through a pipeline to the rupture depends on the pipeline diameter and length as follows:

 (40)

The C-FER report did not indicate the pipeline lengths used to determine the flow rate decay. If *l* = 100 miles is used as the base of comparison the correction for pipeline length would be:

  (41)

 where:

 *Fl* = flow rate correction factor for pipeline length and

 *L* = pipeline length, miles.

The accumulated rupture quantity and average released over time is:

  (42)

 where:

  = total quantity of fluid released over a specified time, lbs.

 *Q0* = initial flow rate at rupture, lbs. per site.

The average flow rate at the rupture site over time is:

  (43)

 where:

  = average flow rate at the rupture site over time, lbs.

API RP 521

The May 2008 edition of API Standard 521, “Guide for Pressure-Relieving and Depressuring Systems”, in section 6.4.2.3.3 indicates that “The following equation by Hajek and Ludwig may be used to determine the minimum distance from a flare to an object whose exposure to thermal radiation must be limited.”

  (44)

 where:

 *x* = distance to object from center of fire, ft.;

 *Ft* = fraction of heat intensity transmitted;

 *Fr* = fraction of heat radiated;

 *H* = heat release, BTU per hr.; and

 *I* = allowable heat radiation, BTU per hr. ft.2

 (45)

 where:

 *Qm* = mass flow rate, lbs. per hr. and

 *Hc* = heating value of combusted material, BTU per lb.

  (46)

 where:

 *RH* = relative humidity, percent.

If *RH* = 25% and *x* = 2,000 ft.,

 .

The fraction of heat radiated in calculation examples for flares, *Fr*, is taken as 0.3 and *Hc* = 21,500 BTU per lb. for methane. The C-FER model includes a combustion efficiency of 0.35. The current API Standard 521 model does not include such a combustion factor. For methane, equations (7) and (44) can be rewritten as:

 (47)

 (48)

where:

*Qm* = sustained flow rate, lbs. per hr. and

*I* = thermal radiation intensity, BTU per ft.2 hr.

If *qm* = lbs. per second, equation (48) becomes

. (49)

Equation (45) calculates hazardous distances that are 1.75 times the value of the C-FER equation (7). API RP 521 contains the following recommended limits on allowable thermal radiation, *I*:

1. 5000 BTU per hr.-ft.2 in areas where workers are not likely to be performing duties and where shelter from radiant heat is available.
2. 3000 BTU per hr.-ft.2 in areas where exposure is limited to a few seconds for escape only.
3. 2000 BTU per hr.-ft.2 in areas where emergency actions up to one minute may be required without shielding, but with appropriate clothing.
4. 1500 BTU per hr.-ft.2 in areas where emergency actions lasting several minutes may be required by personnel without shielding, but with appropriate clothing.
5. 500 BTU per hr.-ft.2 in areas where personnel with appropriate clothing may be continuously exposed.

Solar radiation generally ranges from 250 to 330 BTU per hr.-ft.2. Correction for solar radiation is indicated as being proper.

In industrial locations around flares, workers normally wear fire resistant safety clothing with long sleeves and hard hats to provide protection for 90+% of the body from heat radiation.

However, in non-industrial areas people are not likely to be wearing flame retardant protective clothing and may only have about 60% of the body covered with non-fire retardant clothing. It appears at a maximum allowable heat radiation intensity of 500 to 1000 BTU per hr.-ft.2 would be appropriate for protection of the public in areas near a pipeline rupture. A heat radiation intensity of 5000 BTU per hr-ft.2, used in the C-FER report, is clearly too high for public exposure to a fire.

Frank P. Lees’ Book on Loss Prevention

Loss Prevention in the Process Industries by Frank P. Lees contains considerable information on the effects of fire exposure. Chapter 16 on fire is 318 pages in length. The effects of fire exposure depend on the radiant heat intensity and the exposure time.

The effects of fire exposure depend on exposure time and heat radiation intensity. A thermal load is used to define the effects of time and heat intensity. Heat exposure considerations create a thermal load as follows:

  (50)

 where:

 *L* = thermal load, 0.0001 (watts per meter2)1.333 sec.;

 *t* = exposure time, sec; and

 *I* = thermal radiation intensity, watts per meter2.

The effects of various thermal loads from work by Hymes are given in Table 4 as follows.

Table 4

Thermal Load Effects

|  |  |
| --- | --- |
| Thermal Load, *L* | Effects |
| 1,200 | Second degree burns |
| 1,060 | 1% mortality |
| 2,300 | 50% mortality |
| 2,600 | Third degree burn |
| 1,100- 4,000 | Piloted ignition of clothing |
| 3,000-10,000 | Unpiloted ignition of clothing |

The effects of various thermal loads from work by Lee are as follows:

Table 5

Thermal Load Effects

|  |  |
| --- | --- |
| Thermal Load, *L* | Effects |
|  850\* |  0.5% mortality\* |
|  900\* |  1.0% mortality\* |
| 1,000 |  2.5% mortality |
| 1,600 |  20% mortality |
| 2,000 |  31% mortality |
| 2,500 |  45% mortality |
| 3,000 |  59% mortality |
| 4,500 | 100% mortality |

 \* Extrapolated estimates

For an initial exposure time of 30 seconds before finding shelter, as assumed in the C-FER report on the PIR, the corresponding values of *I* for the above effects given by Lee are:

  (51)

 where:

 *Ie* = thermal radiation intensity, BTU per hr.-ft.2;

 *L* = thermal load; and

 *t* = exposure time, sec.

Table 6

Thermal Radiation Intensity for 30 Second Exposure Time

 Thermal Load*, L* Thermal Radiation Intensity

|  |  |  |  |
| --- | --- | --- | --- |
|  *L* | Wper m*2* | BTU per hr.-ft.2 | Mortality Rate |
| 1,000 | 14,230 |  4,500 |  2.5% |
| 1,600 | 20,263 |  6,415 |  20% |
| 2,000 | 23,965 |  7,585 |  31% |
| 2,500 | 28,344 |  8,970 |  45% |
| 3,000 | 32,509 | 10,290 |  59% |
| 4,500 | 44,098 | 13,960 | 100% |

The heat intensity for vegetation to ignite (from Mechlenburg) is 10-12 kW per m2 (3,165 to 3,800 BTU per hr.-ft.2). A heat intensity of 6 kW per m2 (1900 BTU per hr. ft.2) is the tolerable level for escaping personnel in an industrial location.

Lee’s book on loss prevention refers to work by Hymes on the ignition of clothing. Hymes found that clothing ignition can be predicted as follows:

  (52)

 where:

 *tc* = clothing exposure time, sec.;

 *Ic* = thermal radiation intensity, kW per m2; and

 *Dc* = clothing ignition load, (sec.-kW per m2)2.

The clothing ignition load, *Dc*, is normally 25,000 to 45,000 (sec.-kW per m2)2. For a midpoint ignition load of *Dc* = 35,000, the thermal radiation intensity vs. time is as follows.

Table 7

Thermal Radiation Intensity to Ignite Clothing

 *Ic*

|  |  |  |
| --- | --- | --- |
| Time, sec. | kW per m2 | BTU per hr. ft.2\* |
|  1 | 187 | 59,200 |
|  5 |  84 | 26,580 |
|  10 |  59 | 18,670 |
|  20 |  42 | 13,290 |
|  50 |  26.5 |  8,385 |
| 100 |  18.7 |  5,920 |
| 200 |  13.2 |  4,100 |
| 500 |  8.4 |  2,660 |

\* 0.00316 BTU per ft.2 – hr. = kW per m2

Lee’s book on loss prevention indicates that ignition of clothing has the following three effects.

1. Ignition of clothing distracts the wearer. He may stop running and try to douse the flames, which affects not only on the speed of escape, but also on the orientation of the body.
2. The other effect is the injury from burning clothing.
3. More body surfaced exposed to injury.

For mortality studies of industrial locations, the amount of skin exposed to heat radiation is typically taken to be 20% or less. For 20% exposure and burn area, the mortality rates for various age groups areas follow.

Table 8

Mortality Rates for 20% Burn Area

|  |  |
| --- | --- |
| Age | Mortality Rate, % |
|  0-44 | 0 to <10% mortality |
| 44-59 | 10% average mortality |
| 60-64 | 30% average mortality |
| 65-69 | 50% average mortality |
| 70-74 | 70% average mortality |
| 75-84 | 80% average mortality |
| 85+ | 90% average mortality |

In an industrial environment, workers probably wear protective fire retardant clothing with heavy boots, gloves and hard hat. The exposure area is probably less than 5%. When running, the hard hat is probably lost and the body exposure increases to 10%. Without gloves, the exposure would be about 15%. However, on a warm day, the public may have a body exposure of 40% or higher. With 40% exposure and burn area, the mortality rates become as follow.

Table 9

Mortality Rates for 40% Burn Area

|  |  |
| --- | --- |
| Age | Mortality Rate, % |
| 0-4 |  0 to <10% mortality |
|  5-19 |  10% average mortality |
| 20-34 |  20% average mortality |
| 35-44 |  30% average mortality |
| 45-54 |  40% average mortality |
| 55-59 |  60% average mortality |
| 60-64 |  80% average mortality |
| 65-69 |  90% average mortality |
| 70+ | 100% average mortality |

If the clothing ignites, the burn area and mortality rates increase. If clothing ignites and the burn area increases from 40% to 60% burn area, the mortality rates become as follow.

Table 10

Mortality Rates with 60% Burn Area

|  |  |
| --- | --- |
| Age | Mortality Rate, % |
| 0-4 |  30% average mortality |
|  5-14 |  40% average mortality |
| 15-24 |  50% average mortality |
| 25-34 |  60% average mortality |
| 35-44 |  70% average mortality |
| 45-49 |  80% average mortality |
| 50-59 |  90% average mortality |
| 60+ |  100% average mortality |

Normally, persons are seldom admitted to a hospital for treatment for first degree burns. Admittance for second degree burns depends on where the burns occur and percent of body affected. The thermal load for a second degree burn is 1200 s(W/m2)1.333 ÷ 10,000 and for 1% mortality is 1060 s(W/m2)1.333÷ 10,000 according to studies by Hymes.

The effects of age groups can also be evaluated by studying the effects of percent burn area versus mortality rate. For a 20-49 age group that represents workers at an industrial location, the mortality rates versus percent burn area are as follow.

Table 11

Mortality Rates vs. Burn Area and Age

 Mortality Rate vs. Age

|  |  |  |  |
| --- | --- | --- | --- |
| % Burn Area | 20 Years | 49 Years | Average |
| 10 |  0 |  < 10 |  < 10 |
| 20 |  < 10 |  10 |  < 10  |
| 30 |  10 |  20 |  15 |
| 40 |  20 |  40 |  30 |
| 50 |  30 |  60 |  45 |
| 60 |  50 |  80 |  65 |
| 70 |  70 |  90 |  80 |
| 80 |  80 | 100 |  90 |
| 85 |  90 | 100 |  95 |
| 90 | 100 | 100 | 100 |

For a 60 -79 age group, the mortality rates versus percent burn area are as follow.

Table 12

Mortality Rates vs. Burn Area and Age

 Mortality Rate vs. Age

|  |  |  |  |
| --- | --- | --- | --- |
| % Burn Area | 60 Years | 79 Years | Average |
| 10 |  10 |  40 |  25 |
| 20 |  30 |  80 |  55 |
| 30 |  50 | 100 |  75 |
| 40 |  80 | 100 |  90 |
| 50 |  90 | 100 |  95 |
| 60 | 100 | 100 | 100 |

Although I have not seen studies on the mortality rates of older people with less amounts of body coverage with clothing, it appears that the mortality rate for 60-79 years with 30% to 40% body exposure (60% to 70% body coverage) would be expected to be over 50% mortality at the heat load that causes second degree burns or *L* = 1200 sec (W/m2)1.333 ÷ 10,000. The heat radiation levels versus exposure time that corresponds to a thermal load of *L* = 1200 sec (W/m2)1.333 ÷ 10,000 are as follow.

Table 13

Heat Radiation Intensity, *I*

|  |  |  |
| --- | --- | --- |
| Time, sec. | W per m2 | BTU per hr.-ft.2 |
|  30 | 15,905 | 5,035 |
|  60 |  9,460 | 2,995 |
|  120 |  5,625 | 1,780 |
|  180 |  4,150 | 1,315 |
|  300 |  2,828 |  895 |
|  480 |  1,980 |  625 |
| 1,200 |  1,000 |  315 |

As shown above the mortality rate with 30 seconds of exposure at about 5,000 BTU per hr.-ft.2, the heat radiation intensity used in the C-FER study for 1% mortality in an industrial environment would be expected to be above a 50% mortality for persons between 60 and 80 years of age.

Other Limits and Effects of Fire Exposure

Other effects of and limits on thermal radiation appear in Table 1.1 of the Oak Ridge National Laboratory report titled “Studies for the Requirements of Automatic and Remotely Controlled Shutoff Valves on Hazardous Liquids and Natural Gas Pipelines with Respect to Public and Environmental Safety”. This report was designated as ORNL/TM-2012/411 and was dated October 31, 2012. The report is available on the U.S. DOT website.

Table 14

Effects and Limits on Thermal Radiation Intensity

|  |  |
| --- | --- |
| Effects, Consequences and Limits | Radiant Heat Flux, BTU/hr.-ft.2 |
| 1. Solar radiant heat flux on a clear surrounding (NFPA,  2011a). |  320 |
| 2. HUD limit for outdoor unprotected facilities or open spaces where people congregate. |  450 |
| 3. Common exposure limit while fire fighting. This energy  level may cause burn injuries with prolonged exposure (see NFPA, 2011a). |  800 |
| 4. Glass breakage after exposure for 30 minutes. | 1,270 |
| 5. Limit in industrial areas where emergency actions lasting 2  to 3minutes may be required by personnel without  shielding, but with appropriate clothing\* (API, 2007). | 1,500 |
| 6. Minimum energy to ignite wood with a flame, first degree burns in 10 seconds and 1% lethal in 10 minutes (NFPA, 1995). | 4,000 |
| 7. Radiant heat flux at which human skin blisters with  6 seconds of exposure with second-degree burn injury (NFPA, 2011a). | 5,000 |
| 8. Average ignition time of dry wood in 75 seconds. | 6,340 |
| 9. Steel deforms after 30 minutes (NFPA, 1995). | 7,930 |

 \*Appropriate clothing includes a hard hat, long-sleeved shirt with cuffs

 buttoned, work gloves, long-legged pants, and work shoes.

The C-FER limit of 5,000 BTU per hr.-ft.2 is clearly too high for human exposure and is borderline for protection of property. The U.S. Department of Transportation should reconsider this excessive limit and revise their PIR equation.

Fireball Models

The PIR equation in Title 49 CFR Part 192 does not include the effects of a fireball caused by a delayed ignition of a ruptured pipeline. The following relationships by Prugh for a propane fireball in Lees’ loss prevention book.

1. *x* for 1% mortality is 5.0 *M* 0.46 (53)
2. *x* for 50% mortality and third degree burns is 3.6 *M* 0.46 (54)
3. *x* for 99% mortality is 2.5 *M* 0.46 (55)
4. *x* for second degree burns is 5.3 *M* 0.46 (56)

where:

*x* = distance from the center of the fire, ft. and

*M* = amount of fuel in fireball, lbs.

For example, the distances for the above mortality rates from the center of a 50,000 pound fireball are:

 

 

 

The models of A.F. Roberts developed in the early 1980’s predict the following fireball parameters:

  for *M* < 30,000 tonnes and (57)

  for *M* > 30,000 tonnes (58)

 where:

 *td* = fireball duration, sec. and

 *M* = mass of fuel, metric tonne.

Equation (58) can be modified as follows to calculate *td* in terms of lbs.

  for *M* < 66 million lbs. (59)

 where:

 *M* = mass of fuel, lbs.

For a 50,000 pound 22.7 tonne, fireball, the estimated duration time, *td*, is:

  (Equation 57)

The distances from the fire for 1% and 50% mortality from the Roberts model are:

1*. x* for 1% mortality = 30 *t*0.366*M*0.306  (60)

2. *x* for 50% mortality = 22 *t*0.366*M*0.307 (61)

where:

*x* = distance from the fireball, meters;

*t* = exposure time, sec.;

*M* = mass of fuel (LPG), tonne.

Equations (60) and (61) can be modified as follows to calculate *x* in terms of lbs. and feet.

1*. x* for 1% mortality = 9.4 *t*0.366*M*0.306 (62)

2*. x* for 50% mortality = 6.9 *t*0.366*M*0.307 (63)

 where:

 *x* = distance, ft.;

 *M* = mass of fuel when ignition occurs, lbs.; and

 *t* = time of exposure after ignition, sec.

For a mortality rate of 99%, *x* = 4.8 *t0.366 M0.307* . (64)

For *M* = 50,000 lbs. (22.7 tonne) and *t* = *td* =12.7 seconds, values of *x* are:

1. *x* for 1% mortality = 30 (12.7)0.366 (22.7)0.306 = 198 m = 650 ft. (Equation 60)
2. *x* for 50% mortality = 22 (12.7)0.366 (22.7)0.307 = 145 m = 475 ft. (Equation 61)

The above models or equations of Robert, equations (60) and (61), apply to 10<*M*<3000 tonne (6,609,000 lbs.) and 10<*t*<300 seconds.

A model in the CCPS QRA Guidelines is:

 *x* for 50% mortality = 38.9 *M*0.432 (65)

 where:

 *x* = distance from center of the fireball, *m* and

 *M* = mass of fuel, tons.

In English units, equation (65) becomes:

  *x* for 50% mortality = 4.8 (*M)*0.432 (66)

 where:

 *x* = distance from center of fireball, ft. and

 *M* = mass of fuel in fireball, lbs.

Another model by Prugh for a propane fireball is:

 *x* for 50% mortality = 38 *M* 0.46 (67)

 where:

 *x* = distance from center of the fireball, *m* and

 *M* = mass of fuel in the fireball, tons.

For 25 tons of fuel (50,000 lbs.), *x* for 50% mortality using equation (67) is:

 *x* for 50% mortality = 38 (25)0.46 = 167 m (548 ft.)

Hardee and Lees developed the following model for a propane fireball as follows:

 *D* = 5.55 *M* 0.333 (68)

 where:

 *D* = fireball diameter, m.

 *M* = propane mass, kg.

In English units, equation (68) becomes:

  (69)

 where:

 *D =* fireball diameter, ft. and

 *M*  = propane mass, lbs.

Hardee, Lees and Benedick later in (1978) developed the following model for LNG (methane) fireballs.

 *R* = 3.12 *M* 0.333 (70)

 *D* = 6.24 *M* 0.333 (71)

 *td* = 1.11 *M* 0.167 (72)

 where:

 *R* = radius of fireball, m;

 *D* = fireball diameter, m;

 *M* = fuel mass, kg; and

 *td* = fireball duration, sec.

In English units, equation (70) becomes:

 *R* = 7.87 (*M)*0.333 (73)

 where:

 *R* = radius of fireball, ft. and

 *M* = fuel mass, lbs.

In English units, equation (72) becomes:

  (74)

 where:

 *M* = fuel mass, lbs.

Roberts developed the following model for hydrocarbon fireballs:

 *D* = 5.8 *M* 0.333 (75)

 where:

 *D* = fireball diameter, *m* and

 *M* = fuel mass, kg.

The models of Roberts [equations (58) and (62)] can be compared to the API 521 model indicated as equation (44) in this report in the following steps:

1. LPG fuel released for fireball = 50,000 lbs., 25 tons, 22.7 tonnes.
2. Distance criterion is for 50% mortality.
3. Fireball duration [equation (58)], *td*, is = 4.5 *M* 0.333 = 4.5 (22.7)0.333 = 12.7 sec.
4. For *td* = 12.7 sec. and *M* = 50,000, the average fireball fuel consumption rate, *Qm*, is 3937 lbs. per sec. = 14,170, 000 lbs. per hr.
5. For 50% mortality, the required thermal load, *L* (Table 3), is 2300, according to Hymes and Lee.
6. For *L* = 2300, equation (51) can be used to calculate the required radiation intensity, *I*, for *t* = *td* = 12.7 sec.



1. For *I* = 15,700 BTU per hr.-ft.2 using equation (49), the hazardous distance from the center of the fire is:



1. For *L* = 2600 and *t* = 12.7 sec., equation (51) is used to calculate *I* as 54,280 W per m2 = 17,185 BTU per hr.-ft.2.
2. For *I* = 17,185 BTU per hr.-ft.2 using equation (49), the hazardous distance from the center of the fire is:



1. Equation (55) can be used to calculate the distance from the center of the fire where the radiation intensity will cause a 50% mortality rate as follows:



1. Equation (62) can also be used to calculate the distance from the center of the fire where the radiation intensity and duration time will cause a 50% mortality rate as follows:



1. Two fireball models and two thermal loads and the calculated hazardous distances were within 21% of each other.

Escapability from a Pipeline Rupture and Fire

The escapability and survivability of a person from a pipeline rupture and fire depend on:

1. Escape delay time,
2. The ignition time delay,
3. Initial closeness of a person to the pipeline when ignition occurs, and
4. Speed in which a person escapes from the rupture and fire ignition.

For a 99% probability of escaping and surviving radiant heat exposure, a mortality of 1% radiant heat values should be used. Equations (53) and (62) allow calculations of the distance needed between the center of the fireball at the pipeline and person for 99% survivability/1% mortality. The distances are calculated as:

 *x* = 5 *M0.46* , ft. (Equation 53)

*x*  = 9.4 *t*0.366*M*0.307 , ft. (Equation 62)

For example, if 30,000 pounds are released in 5 seconds before ignition, the safe distances from the pipeline after 1 second of exposure are:

 *x* = 5 (30,000)0.46 = 573 ft.

After the fireball duration is ended, the pipeline will continue to feed the fire until the gas supply is free of gas. For a 1% mortality, equation (52) can be used to calculate the interrelationship between thermal radiation intensity and exposure time as follows for a thermal load of 900 from Table 5 for industrial locations.

  or (76)

  (77)

 where:

 *t* = exposure time, sec. and

 *I* = thermal radiation intensity, BTU per hr.-ft.2

The exposure time limit corresponding to various survival radiation intensities based on equations (76) and (77) are as follows.

Table 15

Exposure Time Limits

|  |  |
| --- | --- |
| Thermal Radiation IntensityBTU per hr.-ft.2 | Exposure Time Limitsec. |
|  500 | 507 |
| 1000 | 201 |
| 1500 | 117 |
| 2000 |  80 |
| 2500 |  59 |
| 3000 |  46 |
| 4000 |  32 |
| 5000 |  24 |
| 6000 |  18 |

The flow rates from the pipeline each second after the rupture for our example of *d* = 24 inch and *p* = 1000 psig for natural gas pipeline are as follow.

Table 16

Flow Rates from Ruptured Pipeline vs. Time

|  |  |
| --- | --- |
| Time after Rupture, sec. | Flow Rate from Ruptured Pipeline,lbs. per sec. |
|  0 | 16,700 |
|  1 | 11,860 |
|  2 |  9,630 |
|  3 |  8,530 |
|  4 |  7,820 |
|  5 |  7,310 |
|  6 |  6,930 |
|  7 |  6,610 |
|  8 |  6,350 |
|  9 |  6,130 |
|  10 |  5,940 |
|  11 |  5,770 |
|  12 |  5,630 |
|  13 |  5,490 |
|  14 |  5.370 |
|  15 |  5,260 |
|  20 |  4,820 |
|  30 |  4,280 |
|  60 |  3,640 |
|  120 |  2,820 |
|  240 |  2,290 |
|  480 |  1,860 |
|  720 |  1,650 |
| 1,440 |  1,360 |
| 3,600 |  1,150 |

For the previous example of 24-inch diameter at 1000 psig and 59°F where natural gas density is 3.35 and *k* = 1.31 using equation (37), the exit flow rates from both ends of a ruptured pipeline and the required distance from the pipeline for 99% survivability/1% mortality using equation (54) and fireball duration using equation (60) are as follow.

Table 17

Distances from Pipeline for 99% Survivability versus

Ignition Delay Time after Rupture

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Time after Rupture and Ignition, sec. | Ʃ *M*lbs. | Fireball Duration, sec. | 99% Survivability Distance, ft. | Survivability Escape Speed, ft./sec. |
|  1 |  16,700 |  8.8 |  438 | 438 |
|  2 |  27,000 | 10.4 |  546 | 108 |
|  3  |  35,800 | 11.4 |  622 |  76 |
|  4 |  43,900 | 12.2 |  683 |  61 |
|  5  |  51,300 | 12.9 |  734 |  51 |
|  6 |  58,000 | 13.4 |  777 |  43 |
|  7  |  65,000 | 13.9 |  818 |  41 |
|  8 |  71,300 | 14.4 |  854 |  36 |
|  9 |  77,400 | 14.8 |  888 |  34 |
| 10 |  83,700 | 15.2 |  920 |  32 |
| 11 |  89,000 | 15.5 |  950 |  30 |
| 12 |  94,600 | 15.8 |  978 |  28 |
| 13 | 100,100 | 16.1 | 1,004 |  26 |
| 14 | 105,000 | 16.4 | 1,028 |  24 |
| 15 | 110,600 | 16.7 | 1,050 |  22 |
| 16 | 115,700 | 16.9 | 1,071 |  21 |
| 17 | 120,700 | 17.1 | 1,092 |  21 |
| 18 | 125,700 | 17.3 | 1,112 |  20 |
| 19 | 130,600 | 17.5 | 1,132 |  20 |
| 20 | 135,400 | 17.7 | 1,151 |  19 |
| 25 | 158,200 | 18.7 | 1,232 |  17 |
| 30 | 179,700 | 19.5 | 1,306 |  15 |
| 50 | 257,000 | 22.0 | 1,540 |  12 |

For a 99% probability of escaping and surviving a radiant heat exposure for a mortality rate of 1% should be used for the analysis. The escape speed in which a person needs to move from the fire can be calculated from equation (62) as follows.

 (78)

where:

*ve* = velocity of escape, ft. per sec.;

*t* = fireball exposure time after ignition, sec.; and

*M* = mass of fuel, lbs.

For a 1% probability of escaping and surviving the radiant heat exposure for a mortality rate of 99% , the escape speed from the fire is:

  (79)

Another equation for a 99% probability of escaping and surviving radiant heat exposure for at a 1% mortality level using equation (53) is:

. (80)

For example if the natural gas ignition occurs 5 seconds after the rupture and the accumulated released gas in 5 seconds is 30,000 pounds, the escape speeds in 10 seconds after ignition must be:

1. For equation (78),



1. For equation (80),



The previously used example where *d* = 24 inches and *p* = 1000 psig will be used to illustrate escapability analysis using equation (78) as follows for *x* for 1% mortality.

Table 18

Required Escape Velocity from Pipeline for

99% Survivability

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Time after Rupture and Ignition, sec. | Ʃ *M* lbs. | Exposure Time after Rupture and Instant Ignition, sec. | Escape Velocity, *ve*,ft./sec.\* | Escape Distance,ft.\* |
|  1 |  16,700 |  1 | 186 |  186 |
|  2  |  27,000 |  2 | 139 |  278 |
|  3 |  35,800 |  3 | 117 |  351 |
|  4  |  43,900 |  4 | 101 |  404 |
|  5 |  51,300 |  5 |  92 |  460 |
|  6 |  58,200 |  6 |  87 |  522 |
|  7 |  65,000 |  7  |  81 |  567 |
|  8 |  71,000 |  8 |  77 |  616 |
|  9  |  77,000 |  9 |  73 |  657 |
| 10 |  83,000 | 10 |  70 |  700 |
| 11 |  89,000 | 11 |  67 |  737 |
| 12 |  94,600 | 12 |  65 |  780 |
| 13 | 100,000 | 13 |  63 |  819 |
| 14 | 105,000 | 14 |  61 |  854 |
| 15 | 110,000 | 15 |  59 |  885 |
| 16 | 115,700 | 16 |  57 |  912 |
| 17 | 120,700 | 17 |  55 |  934 |
| 18 | 125,700 | 18 |  54 |  972 |
| 19 | 130,600 | 19 |  53 | 1007 |
| 20 | 135,400 | 20 |  52 | 1048 |
| 25 | 158,200 | 25 |  48 | 1200 |
| 30 | 179,700 | 30 |  44 | 1320 |
| 50 | 257,000 | 50 |  36 | 1800 |

\* From the pipeline location

To escape with minor burns and a survivability of 99%, the person exposed to the pipeline rupture and fire must be able to escape the growth of the fireball while maintaining a safe distance from the fireball to limit the effects of the fire radiation level with time. The radius of the fireball from the pipeline without the effects of wind after the rupture and ignition using equation (73) are as follows.

Table 19

Escape from Growing Fireball

|  |  |  |  |
| --- | --- | --- | --- |
|  Time\* sec. | Ʃ *M* lbs. | Fireball Radiusft.\*\* | Fireball Radius Growth Velocity, ft./sec. |
|  1 |  16,700 | 201 | 201 |
|  2  |  27,000 | 236 |  35 |
|  3 |  35,800 | 259 |  23 |
|  4  |  43,900 | 277 |  18 |
|  5 |  51,300 | 293 |  15 |
|  6 |  58,200 | 304 |  12 |
|  7 |  65,000 | 315 |  11 |
|  8 |  71,000 | 325 |  10 |
|  9  |  77,000 | 334 |  9 |
| 10 |  83,000 | 342 |  8 |
| 11 |  89,000 | 350 |  8 |
| 12 |  94,600 | 357 |  7 |
| 13 | 100,600 | 364 |  7 |
| 14 | 105,000 | 370 |  6 |
| 15 | 110,000 | 376 |  6 |
| 16 | 115,700 | 382 |  6 |
| 17 | 120,700 | 388 |  6 |
| 18 | 125,700 | 393 |  5 |
| 19 | 130,600 | 398 |  5 |
| 20 | 135,400 | 402 |  4 |

 \* Time after rupture and ignition

 \*\* From pipeline location

The duration of the fireball, *td*, can be estimated from equation (59) and in this example is calculated as follows.

Table 20

Fireball Duration vs. Ignition Delay

|  |  |  |  |
| --- | --- | --- | --- |
| Time after Rupture, sec. | Ʃ *M* lbs. | Ignition Delay Time, sec. | Fireball Duration, sec. |
|  1 |  16,700 |  1 |  8.8 |
|  2  |  27,000 |  2 | 10.4 |
|  3 |  35,800 |  3 | 11.4 |
|  4  |  43,900 |  4 | 12.2 |
|  5 |  51,300 |  5 | 12.9 |
|  6 |  58,200 |  6 | 13.4 |
|  7 |  65,000 |  7  | 13.9 |
|  8 |  71,000 |  8 | 14.3 |
|  9  |  77,000 |  9 | 14.7 |
| 10 |  83,000 | 10 | 15.1 |
| 11 |  89,000 | 11 | 15.4 |
| 12 |  94,600 | 12 | 15.7 |
| 13 | 100,000 | 13 | 16.0 |
| 14 | 105,000 | 14 | 16.3 |
| 15 | 110,000 | 15 | 16.6 |
| 16 | 115,000 | 16 | 16.9 |
| 17 | 120,000 | 17 | 17.1 |
| 18 | 125,000 | 18 | 17.3 |
| 19 | 130,000 | 19 | 17.5 |
| 20 | 135,000 | 20 | 17.7 |
| 25 | 158,200 | 25 | 18.7 |
| 30 | 179,700 | 30 | 19.5 |
| 50 | 257,000 | 50 | 22.0 |

As an example on survivability is as follows using the previous data.

1. Data:
	1. Person is 25 and physically fit and age effects do not have to be applied,
	2. Person is 525 feet (PIR distance) from the pipeline when the rupture occurs,
	3. Ignition occurs 10 seconds after the rupture, and
	4. Person does not begin escape until ignition occurs.
2. Analysis:
	1. Ʃ*M* = 83,000 lbs.
	2. Initial fireball radius = 342 ft. (equation 73).
	3. Distance from pipeline for 1% mortality = 916 ft. (equation 53).
	4. Distance from pipeline for 50% mortality = 660 ft. (equation 54).
	5. Distance from pipeline for 99% mortality = 458 ft. (equation 55).
	6. Person is not 916 feet from the pipeline and will experience severe burns with greater than 50% mortality and may not survive.
	7. To survive with a 1% mortality, the person would have to begin the escape as soon as the pipeline ruptures and travel 391 feet (916 feet from pipeline) in 10 seconds at an average of 39 feet per second (26.6 mph).

Recommended Models for Pipeline Ruptures

The potential hazards of a pipeline rupture should be based on the following criteria:

1. Fireball from delayed ignition.
2. Heat intensity that would impede escape from the area of the fire.
3. Heat intensity that would cause clothing to ignite.
4. Heat intensity that causes buildings to ignite.
5. Heat intensity for 1% mortality.
6. Heat intensity for 50% chance of mortality.
7. Heat intensity for 100% chance of mortality.
8. Heat intensity for second degree burns.

The hazards of initial high heat intensity for short periods need to be compared to lesser sustained heat for long periods for various zones around a pipeline.

The models should also cover the effects of age groups, clothing protection, and escape mobility of the public exposed to gas pipeline ruptures.

Use of Fireball Model for Ruptured Pipelines

The fireball model should be used to consider the mass of gas lost during the initial rupture and the amount of gas initially released from each end of the pipeline until the gas is ignited. A reasonable estimate is needed for delayed ignition of the escaping gas depending on available ignition sources.

C-FER dismissed the hazard of a flash fire or fireball with the following questionable rationale:

1. 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.
2. 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.
3. If ignition occurs before the initial fireball disperses, the flammable vapor will burn as a rising and expanding fireball before it decays into a sustained jet or trench fire.
4. If ignition is slightly delayed, only a jet or trench fire will develop.
5. 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.
6. 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.
7. Impingement dissipates some of the momentum in the escaping gas and directs 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 directed and unobstructed jet.
8. 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.
9. 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 a rupture failure of the pipe, where the escaping gas is assumed to feed a sustained trench fire that ignites very soon after line failure.
10. 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 the gas release.
11. The release rate can be shown to depend on the pressure differential and the size of the hole.
12. For guillotine-type failures where the effective size of the hole is equal to the line diameter, the governing parameters are, therefore, the line diameter and the pressure at the time of failure.
13. 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.

Analyses of the above comments in the C-FER report are:

1. The buoyant nature of the natural gas vapor should not be a significant factor unless there is vertical momentum of the gas such as with a vertical flare. However, with a trench fire and two opposing jets in a trench, there should be little initial vertical momentum to the escaping gas. However, there will be significant turbulence and mixing with the air near the ground level.
2. A cloud of some shape, not necessarily “mushroom-shaped” will form and grow in size as indicated by the C-FER.
3. The C-FER report indicates that a fireball can ignite before the gas disperses, and will rise and expand as a fireball.
4. It is assumed in the C-FER report that ignition will only be slightly delayed after the rupture and only a trench or jet fire will develop.
5. The C-FER model did not overestimate the intensity of the fire to account for an initial transient fireball.
6. Although a trench fire is discussed in the C-FER report, only an unlikely vertical jet fire was modeled.
7. The C-FER model did not include the effect of a “horizontal profile”
 of the fire in their PIR model.
8. The C-FER fire model did not include the effects of the total ground area affected by a trench fire being greater than for an unobstructed jet fire. The fire was model as an unobstructed jet fire.

Recommended Fireball Model

The recommended equations or models to be used for fireball analyses of delayed ignitions of ruptured natural gas pipeline are:

 Step 1. Initial pipeline release in ruptured area:

  (81)

  (82)

 where:

 *M* = mass of gas initially released, lbs.;

 *A* = cross sectional area of pipe, ft.2;

 *l* = rupture length, ft.;

 *ρ*1 = initial gas density, lbs. per ft.3; and

 *d* = pipe diameter, inches.

 Step 2. Initial gas exit rate from each end of the rupture pipe based on

 on API Publication 4628 [equation (37)] as follows:

 

 Step 3. Gas exit rate from each end of the ruptured pipe based on

equation (37) and decay factor in equation (39).

 Step 4. Sum up the gas exit quantities determined in Steps 1 through 3

 up to the delayed ignition time.

 Step 5. Calculate the fireball duration time using equation (59) as

 follows:

 

 where:

 *td* = fireball duration time, sec. and

 *M* = gas mass in fireball, lbs.

 Step 6. Calculate the hazardous distances from the center of the fireball

 for 1%, 50% and 99% mortality using equations (53), (54) and

 (55) respectively as follows:

 a. *x* for 1% mortality = 5.0 *M* 0.46

 b. *x* for 50% mortality = 3.6 *M* 0.46

 c. *x* for 99% mortality = 2.5 *M* 0.46

 Step 7. Calculate the diameter of the fireball using equation (69) in

 English units:

 

For a 24-inch pipeline at 1000 psi and 59°F and a delayed ignition of 30 to 120 seconds, the steps in the fireball analyses are as follows:

 Step 1. 

 Step 2.  and

 

 Step 3. For two ends, initial *Qm* = 16,706 lbs. per sec.

1. At *t* = 0 sec., *Fd* = 1.0 and *Qm* = 16,706 lbs. per sec.
2. At *t* = 1 sec., *Fd* = 0.8 and *Qm* = 13,365 lbs. per sec.
3. At *t* = 2 sec., *Fd* = 0.65 and *Qm* = 10,859 lbs. per sec.
4. At *t* = 3 sec., *Fd* = 0.55 and *Qm* = 9,188 lbs. per sec.
5. At *t* = 4 sec., *Fd* = 0.50 and *Qm* = 8,353 lbs. per sec.
6. At *t* = 5 sec., *Fd* = 0.45 and *Qm* = 7,518 lbs. per sec.
7. At *t* = 10 sec., *Fd* = 0.35 and *Qm* = 5,847 lbs. per sec.
8. At *t* = 20 sec., *Fd* = 0.28 and *Qm* = 4,678 lbs. per sec.
9. At *t* = 30 sec., *Fd* = 0.24 and *Qm* = 4,009 lbs. per sec.
10. At *t* = 60 sec., *Fd* = 0.20 and *Qm* = 3,341 lbs. per sec.

 Steps 4 & 5.

|  |  |
| --- | --- |
| Accumulated Time, sec. | , lbs. |
|  0  |  631 |
|  1  |  15,661 |
|  2 |  27,779 |
|  3 |  37,803 |
|  4 |  46,574 |
|  5 |  54,510 |
|  10 |  87,923 |
|  20 | 140,548 |
|  30 | 183,983 |
|  60 | 294,233 |
| 120 | 494,233 |

 Step 6. For a 30 second delayed ignition,

 

 Step 7.

1. For a 1% mortality, *x* = 5.0 (183,983)0.46 = 1,321 ft.
2. For a 50% mortality, *x* = 3.6 (183,983)0.46 = 951 ft.
3. For a 99% mortality, *x* = 2.5 (183,983)0.46 = 660 ft.

 Step 8.

 

For a 60 second delayed ignition *M* = 294,233 lbs. and steps 6, 7 and 8 are:

 Step 6. For a 60 second delayed ignition,

 

 Step 7.

1. For a 1% mortality, *x* = 5.0 (294,233)0.46 = 1,638 ft.
2. For a 50% mortality, *x* = 3.6 (294,233)0.46 = 1,180 ft.
3. For a 99% mortality, *x* = 2.5 (294,233)0.46 = 819 ft.

 Step 8.

 

For a 120 second delayed ignition, *M* = 494,000 lbs. and steps 6, 7 and 8 are:

 Step 6.

 

 Step 7.

1. For a 1% mortality, *x* = 5.0 (494,000)0.46 = 2,080 ft.
2. For a 50% mortality, *x* = 3.6 (494,000)0.46 = 1,498 ft.
3. For a 99% mortality, *x* = 2.5 (494,000)0.46 = 1,040 ft.

 Step 8.

 

R. D. Deaver, P.E.

October 2020

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