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NATURAL GAS PIPELINE SAFETY SETBACK

CALCULATION OF SAFETY SETBACKS FROM LARGE DIAMETER HIGH PRESSURE NATURAL GAS PIPELINES

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INTRODUCTION:
An essential element of any electric power system is reliable load following generation that can be used to match the total electricity generation to the total electricity load. From a global warming perspective the ideal load following generator is a hydroelectric dam containing a large amount of storage. However, since about 1970 the Ontario government and other governments have failed to face both the political and practical issues involved in construction of major new hydroelectric dams and their associated electricity transmission lines.

Since about 2005 the Ontario Power Authority (OPA) has chosen to use natural gas fueled combustion turbines for supplying load following generation. In order to minimize electricity transmission line right-of-way requirements the OPA chose to locate the natural gas fueled power plants close to urban areas. However, the OPA failed to adequately consider the public safety issues related to the large diameter high pressure natural gas pipelines that these combustion turbine power plants require. For public safety these pipelines should be installed in dedicated energy transmission corridors. The minimum width of these corridors is twice the minimum setback distance between the pipeline axis and the public. At present in Ontario, for natural gas pipes up to 20 inches in diameter, this minimum setback distance is municipally regulated. This web page focuses on determination of reasonable minimum setback distances, which distances are functions of both the pipeline diameter and the pipeline operating pressure.

DEDICATED ENERGY TRANSMISSION CORRIDORS:
Natural gas transmission pipelines in Canada have a relatively good safety record. There have been various explosive rupture failures with accompanying major fires, but the incidence of these failures and the related loss of life has been relatively small because most natural gas transmission lines are located in rural areas and are buried in dedicated energy transmission corridors. The use of dedicated energy transmission corridors located in rural areas reduces the incidence of both accidental impact damage and long term corrosion damage and provides distance separation between the pipeline and the public.

A major error in the Ontario Power Authority's planning has been allowing routing of large diameter high pressure natural gas pipelines under public road alowances where these pipelines are subject to a high ongoing risk of damage by third parties engaged in drainage maintenance, installation or replacement of utility poles, installation and maintenance of other buried services and road construction. Furthermore, burial of large diameter high pressure natural gas pipelines beneath public road allowances eliminates much of the distance separation that is normally achieved by pipeline burial within dedicated energy transmission corridors that run through rural areas.

COST CONSTRAINTS:
To minimize capital cost natural gas is transported in steel pipes.

Major high pressure natural gas pipelines are generally designed for a maximum working pressure that causes an operating pipe hoop stress of about 30% of the pipes Specified Minimum Yield Stress (SMYS). A further margin of safety can be introduced by reducing the working pressure. However, practical material cost considerations usually prevent a major reduction in working pressure.

There are pipeline sections that operate at 67% of SMYS. However, such pipeline sections provide little safety margin against local earth movement (earth quakes) or local weld or corrosion problems. Pipelines routed through urban areas should be restricted to a maximum allowable operating pressure that causes a hoop stress of 33% of SMYS.

CORROSION PROTECTION:
1. To prevent external corrosion steel pipes conveying natural gas pipe are coated with a layer of electrically insulating material known as dielectric. The pipe steel is electrically or galvanically biased slightly negative with respect to the surrounding ground water. This bias is usually maintained by use of sacrificial magnesium electrodes or by use of DC power supplies that are electrically bonded to the steel pipe.
2.The negative bias attracts positive hydrogen ions in ground water toward any pipe steel that is exposed by imperfections in the pipe's external dielectric coating. The corresponding negative hydroxyl ions flow toward the sacrificial positive electrode.
3.The hydroxyl ions cause corrosion of the sacrificial electrode.
4.As long as corrosion is confined to the sacrificial electrode, corrosion of the pipe steel is prevented.
5.Eventually the sacrificial electrode will corrode away or worse, it may be accidentally disconnected or may be stolen for its scrap metal value. Under these circumstances the galvanic corrosion protection mechanism is defeated and corrosion will occur anywhere that pipe steel is exposed to ground water, such as at a coating scratch that might have been inadvertently caused by a backhoe, trenching machine or utility pole auger used for work on a nearby unrelated service.
6. A relatively new threat to buried steel pipelines is electrical ground current that results from nearby grounded electrical equipment such a wind turbine transformers. Such ground current can aggravate otherwise minor corrosion problems. In extreme cases of soil over bed rock the region of accelerated pipe corrosion can extend as far as 1 km from the wind generator transformer. This issue must be considered when a wind farm and a buried steel pipeline are in close proximity.

SAFETY:
Usually large diameter high pressure natural gas pipes are buried. The functions of the soil cover are to protect the pipe and its dielectric coating from damage due to UV radiation, external impact, thermal stress and frost heaving.

There are real risks related to long term corrosion and to damage from mechanical equipment such as trenching machines, back hoes, utility pole augers and boom trucks. In the winter, when snow is piled high or during flood conditions the operators of such equipment frequently scratch or damage other buried services, in spite of their best efforts to avoid such damage.

The risks of being scratched or damaged by mechanical equipment are greatly reduced if the large diameter high pressure natural gas pipeline is buried in a dedicated energy transmission corridor. Then almost all the risks due to installation and maintenance of utility poles, buried electrical services, drainage culverts, fresh water pipes, storm sewer pipes, sanitary sewer pipes, low pressure natural gas pipes, district heating pipes, district cooling pipes, subways, telephone multipair cables, TV coaxial cables and fiber optic cables are eliminated. Frequently a natural gas transmission corridor is located adjacent to or within a high voltage electricity transmission corridor.

Another means of improving public safety is to ensure that buildings that routinely contain large numbers of people are not constructed within a specified setback distance from the axis of a large diameter high pressure natural gas pipeline. Similarly a setback distance should be maintained between the pipeline axis and outdoor locations where large groups of people routinely assemble.

A responsible organization that focuses on pipeline safety matters is the Pipeline Safety Trust. Its website is pstrust.org. Its telephone number is 360-543-5686.

RISKS:
The main risks to a large diameter high pressure natural gas pipeline are:

1.Improper engineering, fabrication or commissioning, including but not limited to inadequate:
a) Provision for hoop stress
b) Provision for thermal stress
c) Provision for sheer stress related to ground movement
d) Provision for pipe buoyancy
e) Mill testing of pipe steel
f) Weld inspection
g) Route choice (high and dry preferred to low and wet)
h) Burial depth
i) Pipe bedding and support
j) Corrosion protection
k) Hydraulic pressure testing
l) Drainage after hydraulic pressure testing
m) Nitrogen pressure testing
n) Documentation of magnesium electrode locations
o) Documentation of DC corrosin protection
p) Provision for insertion of pigs for automatic scanning of pipe wall thickness

2.Physical damage from external human activity. eg. The gas line is directly damaged by a trenching machine, backhoe, utility pole auger or boom truck leg.

3.Physical damage due to non-human activity. eg Earthquake, sinkhole, landslide or flood.

4.Minor outside surface damage in combination with loss of galvanic corrosion protection. eg Plastic coating is scratched by a trenching machine, backhoe or utility pole auger and the scratch is not promptly repaired. The magnesium electrode then rapidly corrodes away.

Alternatively a magnesium electrode may be accidentally disconnected by a backhoe or utility pole auger or may be stolen for its scrap metal value.

5.Failure of the pipeline owner to periodically check that all the magnesium electrodes are still present and connected.

6.Failure of the pipeline owner to periodically fully check the actual pipe wall thickness using a pig type electronic inspection apparatus that scans the pipe wall from the inside and measures and records the pipe wall thickness as a function of linear and angular position.

Risks #2, #4 and #5 above are greatly magnified if the pipeline is installed in a road allowance instead of in a dedicated energy transmission corridor.

Risk #6 occurs if there are pipe joints, pipe elbows, pipe fittings, valves or compressor stations that are not designed to allow insertion and axial travel of the pig type electronic equipment for measuring the pipe wall thickness as a function of linear and angular position.

Risk #6 is greatly magnified if the pipeline maintenance personnel do not have adequate time to examine the pig data and the resources to follow up risks identified via the pig data. It is essential that the pipeline owner employ sufficient staff whose first priority is pig data acquisiton, analysis and followup.

RUPTURE FAILURE MECHANISM:
If one makes a small hole with a diameter less than twice the pipe wall thickness in a high pressure natural gas pipeline the immediate result is a loud hissing noise as natural gas leaks out. The leaking high pressure natural gas will blow away soil in its path. The natural gas will mix with surrounding air and form a cloud with concentrated natural gas at its center and dilute natural gas at its edges. If the edge of this cloud with a natural gas concentration in the range 5% to 15% encounters a source of ignition such as a spark made by an electrical switch, there will be a delayed ignition explosion followed by a localized ongoing fire. However, the size of this fire will be limited by the size of the original small hole in the natural gas pipe.

However, if a hole in a high pressure natural gas pipe grows to an axial length that exceeds about four times the pipe wall thickness, a very different sequence of events takes place. At the axial ends of the hole the local hoop stress will exceed the material yield stress. The pipe will then immediately rip down its axis to form a rupture that has an open area several times the cross sectional open area of the pipe. This rupture discharges natural gas at the maximum possible flow rate from both open ends of the ruptured pipe.

PIPE RUPTURE SEQUENCE:
1.The pipe wall is thinned by corrosion, by cutting, by defective welding or by impact;
2.At the thin spot a hoop stress concentration develops that exceeds the yield stress of the pipe material;
3.The pipe wall deforms in a manner that magnifies the hoop stress concentration. This process can be observed in a stretched elastic band with a nick;
4.The pipe suddenly rips down its length causing a complete rupture. This process is similar to the sudden explosive rupture of a fully inflated child's balloon that is hit by a dart.

DAMAGE SEQUENCE:
1.The escaping high pressure natural gas explosively blows away the soil over burden,

forming a large crater in the ground;
2.The pipe rupture is fed with high pressure natural gas from both the upstream and downstream pipes.
3.The escaping gas makes a noise comparable to a large jet aircraft at takeoff;
4.The escaping gas mixes with the surrounding air. In regions where the volumetric natural gas concentration is in the range 5% to 15% the mixture is highly flammable;
5.When the flammable gas mixture finds a source of ignition such as a flame, hot surface or electric spark there is an explosive delayed ignition pressure pulse. This pressure pulse is deafeningly loud and can break windows in buildings over a kilometre from the pipe rupture location. In extreme cases the energy release during the delayed ignition explosion is comparable to the energy release of a small atom bomb.
6.Then there is a steady state flame that is fed by high pressure gas flowing out of both open ends of the ruptured pipeline. This flame is almost impossible to extinguish and continues burning until it runs out of fuel. It typically takes the pipeline company one to two hours to close valves that isolate the ruptured section of gas pipe. The natural gas flame typically burns for several more hours.

SETBACK UNCERTAINTY:
Due to uncertainty regarding wind conditions and the position of the nearest point of ignition it is impossible to specify a practical safety setback distance that will ensure no damage or personnel injury from concussion or shrapnel related to the delayed ignition explosion. However, the subsequent fire emits a quantifiable amount of thermal radiation for which a reasonable safety setback distance can be calculated.

THERMAL RADIATION:
1.The thermal radiation intensity from the steady state natural gas flame is easy to calculate and is the basis of minimum setback calculations;
2.The radiation level may be substantially larger than calculated if black smoke from burning oil, wood or asphalt is conveyed by natural convection into the natural gas flame;
3.For a clean lean natural gas flame I have derived a formula for recommended safe setback distance as a function of pipe diameter and maximum operating pressure;
4.The distance Rs corresponds to a thermal radiation intensity from the natural gas flame equal to the solar irradiance (the maximum solar energy intensity incident on the Earth).
5. At distance Rs / 2 the thermal radiation intensity from the natural gas flame is four times as large as at distance Rs.
6. Natural gas pipeline rupture accident site photographs show that due to secondary fires everything inside radius (Rs / 2) burns to a crisp. Municipal fire departments are not normally equipped to get closer than radius (Rs / 2). At (Rs / 2) the exposed surface temperature due to direct radiation from the natural gas inferno is about 200 °C. At that infrared radiation level vehicle windows crack and human flesh is quickly damaged.

PRESSURE PULSE:
The magnitude of the initial delayed ignition pressure pulse is unpredictable. The size of the delayed ignition explosion depends on the distance between the pipe rupture and the point of ignition. The larger this distance the larger the delayed ignition explosion. Depending on the location of the source of delayed ignition the pressure wave damage radius can exceed the radius of the thermal radiation damage by several fold. In extreme cases the delayed ignition explosion is comparable to the blast wave from a small tactical nuclear weapon. For this reason it is important to limit the sizes of high pressure natural gas lines in urban areas. In the Middletown, Connecticut accident the delayed ignition blast wave shattered

windows over 1.6 km away from the location of the natural gas release. At Englehart, Ontario the delayed igniton explosion pressure pulse tossed a length of 914 mm OD steel pipe with 9.1 mm wall thickness a distance of 150 m from the rupture point.

FORMULA FOR SAFE DISTANCE Rs:

In this document a formula is developed for the safe setback distance **Rs** from a natural gas pipe line required for personnel to avoid radiation related skin damage from the steady state fire that follows a high pressure natural gas pipeline rupture. It must be emphasized that the calculated safety setback **Rs** applies only to thermal radiation from lean combustion of clean natural gas.

A delayed ignition explosion can cause blast damage beyond the calculated radiation safety radius. Toxic gases such as H2S can cause loss of life beyond the calculated radiation safety radius. If the natural gas flame is over rich or if the natural gas burns in combination with other substances such as oil, coal, asphalt, wood, plastic resins, etc. soot forms. That soot can increase the thermal radiation fraction Fr as much as four fold and hence can double the required radiation safety radius Rs. Secondary fires can lead to a fire storm that causes damage far beyond safety radius Rs.

The formula developed herein assumes that only natural gas is burning and that there is sufficient combustion air to keep the burning air-gas mixture lean. The results of the formula are compared to the actual fire damage radius that occurred at Appomattox, Virginia where a 30 inch diameter buried high pressure natural gas pipeline ruptured and burned in a farm field on September 14, 2008. There have been other major natural gas pipeline ruptures, delayed ignition explosions and fires in urban areas such as at Middletown (suburb of Hartford), Connecticut on February 7, 2010 and at San Bruno (a suburb of San Francisco), California on September 9, 2010.

FORMULA DEVELOPMENT:

Consider a long straight natural gas pipeline that is subject to a sudden rupture that opens the full cross section of the pipe. To calculate the radiant heating consequences if there is a fire it is necessary to first find the natural gas mass flow rate out of the rupture. In reality there are two flows, because the pipes on both sides of the rupture discharge natural gas into the rupture. We will calculate one of these gas flows and then double the result to obtain the total mass flow rate out of the rupture.

Let **Pa** = the pressure in the pipeline distant from the rupture

Let **Pb** = the pressure at the point of rupture after the rupture. Normally **Pb** is atmospheric pressure.

Let **Dp** = pipe inside diameter

Let **Pi** = 3.14159

Let **En** = nozzle efficiency of natural gas pressure energy to kinetic energy conversion in a long straight pipe.
Generally:
0.90 < En < 0.99

The uniform pipe cross-sectional area **Ac** is given by:
Ac = Pi (Dp / 2)^2

Let **X** indicate linear position along the pipe of an element of volume **Ac dX**.

Let **Rm** = natural gas mass density as a function of linear position **X**.

Let **Rma** = natural gas density at pressure **Pa**

Let **Rmb** = gas density at pressure **Pb**

The mass of gas **dM** contained in the element of volume **Ac dX** is:
$dM = Rm\ Ac\ dX$

Let **T** = time

Then the gas linear velocity **V** is given by:
$V = (dX / dT)$

The gas linear motion kinetic energy in element of volume **Ac dX** is:
$(dM / 2) (dX / dT)^2$
$= (Rm\ Ac\ dX / 2) (dX / dT)^2$

Hence the kinetic energy density is:
$(Rm / 2) (dX / dT)^2$

Let **P** = pressure at **X**

Then the gas pressure potential energy contained in the element of volume **Ac dX** is given by:
$P\ Ac\ dX$

The pressure **P** is the gas potential energy density at **X**.

Within the pipe but near the point of rupture the gas pressure potential energy density decreases and the gas linear motion kinetic energy increases causing an increase in linear gas velocity **V**.

Let **En** be the nozzle efficiency with which gas pressure potential energy converts into gas kinetic energy of linear motion. **En** is complex to calculate but generally lies in the range:
$0.90 < En < 0.99$

Note that a small fraction **(1 - En)** of the pressure potential energy is converted into heat.

Conservation of energy along the pipe requires that:
$- dP\ En = d[(Rm / 2) (dX / dT)^2]$
or
$- 2\ En\ dP = d[Rm (dX / dT)^2]$

Let subscript **a** indicate a parameter value at a point in the pipe far from the rupture. Let subscript **b** indicate a parameter value at the rupture location. Hence the linear gas velocity at the point of rupture is **Vb**. The mass flow rate from one pipe at the point of rupture is:
$Rmb\ Ac\ Vb$

Integrating from **Pa** to **Pb** gives:
$- 2\ En\ (Pb - Pa) = [Rm (dX / dT)^2]b - [Rm (dX / dT)^2]a$

Assume that as a result of the pipe rupture the natural gas pipeline supervisory control system closes isolation valves distantly upstream and downstream from the pipe rupture.

Then the condition at the location of each of these valves is no flow, or expressed mathematically in terms of the gas stream:
[dX / dT]a = 0

Hence:
2 En (Pa - Pb) = [Rm (dX / dT)^ 2]b
or
[dX / dT]b = [2 En (Pa - Pb) / Rmb]^0.5

Fm = exiting gas mass flow rate from one pipe
= Rmb Ac [dX / dT]b
= Rmb Ac [2 En (Pa - Pb) / Rmb]^0.5
= Ac [2 En (Pa - Pb) Rmb]^0.5

Let **Ec** be the combustion heat release per unit mass of natural gas. Then the total combustion heat release **H** per unit time is given by:
H = 2 Fm Ec
where the 2 reflects the fact that the rupture is fed by two pipes.

Let **Fr** be the fraction of the combustion heat that is emitted via radiation.

Let **Rz** = radius from the center of the flame to a surface subject to radiation damage.

Assume that the radiation is evenly distributed over a sphere with radius **Rz** and surface area **4 Pi Rz^2**. Then at radius **Rz** the radiation intensity / unit area is:
Rz = (H Fr) / (4 Pi Rz^2)

Assume that to avoid skin damage the radiation intensity should be less than the most intense possible solar radiation incident on the Earth's surface (1365 W / m^2). This parameter is known as the Solar Irradiance. Hence, in terms of radiant energy, the safe distance **Rs** from the center of the flame is defined by:
(H Fr) / (4 Pi Rs^2) = 1365 watts / m^2
or
Rs = [(H Fr) / (4 Pi X 1365 watts / m^2)]^0.5
= [(2 Fm Ec Fr) / (4 Pi X 1365 watts / m^2)]^0.5
where natural gas mass flow **Fm** is given by:
Fm = Ac [2 En (Pa - Pb) Rmb]^0.5
= Pi (Dp / 2)^2 [2 En (Pa - Pb) Rmb]^0.5

Combining the formulas for **Rs** and **Fm** gives:
Rs = [(2 Fm Ec Fr) / (4 Pi X 1365 watts / m^2)]^0.5
= [(2 Pi (Dp / 2)^2 [2 En (Pa - Pb) Rmb]^0.5 Ec Fr) / (4 Pi X 1365 watts / m^2)]^0.5
= Dp [En (Pa - Pb)]^0.25 [([2 Rmb]^0.5 Ec Fr) / (8 X 1365 watts / m^2)]^0.5

The value of **Fr** can be found from a paper by J. P. Gore et al titled Structure and Radiation Properties of Large-scale Natural Gas/Air Diffusion Flames, published in Fire and Materials, Vol. 10, 161-169 (1986). These authors found that the radiation emission from a **207 MW** natural gas flame measured at ground level about **11.9 m** from the flame center was **6.37 kW / m^2**.

The surface area of that sphere was:
4 Pi (11.9 m)^2 = 1778.62 m^2
Hence the emitted radiation was:
6.37 kW / m^2 X 1778.62 m^2 = 11330 kW

= 11.330 MW
Hence:
Fr = 11.330 MW / 207 MW
= **.0547**

This **Fr** value is in good agreement with other **Fr** data for lean burn flame retention natural gas burners provided to this author by the Canadian Gas Research Institute.

NUMERICAL SIMPLIFICATION:
Pi = **3.1415928**

Rmb = 16 gm / 22.4 lit
= 16 X 10^-3 kg / 22.4 X 10^-3 m^3
= .714 kg / m^3 = density of natural gas at standard temperature-pressure

Ec = (10.4 kWh / m^3) X (1 m^3 / .714 kg) X 3600 s / h
= 52437 kJ / kg

Hence:
Rs = Dp [En (Pa - Pb)]^0.25 [([2 Rmb]^0.5 Ec Fr) / (8 X 1365 watts / m^2)]^0.5
= Dp [En (Pa - Pb)]^0.25 [([2 X .714 kg / m^3]^0.5 X 52437 kJ / kg X .0547) / (8 X 1365 watts / m^2)]^0.5
= Dp [En (Pa - Pb)]^0.25 [[1.428 kg / m^3]^0.5 X .26266 kJ m^2 / kg-watts X 1000 J / kJ]^0.5
= Dp [En (Pa - Pb)]^0.25 [1.195 kg^0.5 m^-1.5 X 262.66 J m^2 / kg-watts]^0.5
= Dp [En (Pa - Pb)]^0.25 X 17.71 kg^0.25 m^-.75 m (J / kg-watts)^0.5
= 17.71 Dp [En (Pa - Pb)]^0.25 kg^0.25 m^-.75 m (watt s / kg-watts)^0.5
= **17.71 Dp [En (Pa - Pb)]^0.25 kg^-0.25 m^.25 s ^0.5**
= **17.71 Dp [En (Pa - Pb) / Pascal]^0.25**

If pipe diameter **Dp** is in meters and if the operating pressure **(Pa - Pb)** is in Pascals this formula gives the safe setback distance **Rs** in meters.

Units Check:
(Pascal)^0.25 = (newtons / m^2)^0.25 = (kg m s^-2 m^-2)^0.25
= kg^0.25 m^-.25 s^-0.5

For practical calculations use the assumption that:
En^0.25 = 1.0.
This assumption may lead to as much as a **2.7 %** error in the calculated value of **Rs** but this assumption simplifies the formula for **Rs** sufficiently to make it suitable for practical regulatory use.

INTERPRETATION OF RESULTS:
At:
Rz = Rs
the radiation level from the natural gas inferno is equal to the solar irradiance, so human skin damage is confined to sunburn like effects.

At:
Rz = (Rs / 2)
the radiation level from the natural gas inferno is four times the solar irradiance. This is the

maximum radiation level that normally equipped municipal fire fighters can sustain. Hence in the area defined by:
Rz < (Rs / 2)
secondary fires usually burn unimpeded unless suppressed by water bombers or other comparable specialized equipment.

At:
Rz = (Rs / 4)
the radiation level from the natural gas inferno is sixteen times the solar irradiance. In the region:
Rz < (Rs / 4)
there is rapid direct ignition of almost all combustable surfaces and there is total property loss regardless of the available fire fighting capability.

SECONDARY IGNITION:
Almost immediately after the natural gas fire starts exposed combustible surfaces in the region:
Rz < (Rs / 4)
ignite. However, from a property damage perspective the bigger problem is that fires which are directly ignited within the region:
Rz < (Rs / 4)
quickly spread into the region:
(Rs / 4) < Rz < (Rs / 2)
because the thermal radiation levels in the region:
Rz < (Rs / 2)
are too high for municipal fire fighters to function in that region.

History has demonstrated that the practical way of minimizing property damage in the region:
(Rs / 4) < Rz < (Rs / 2)
is to use water bombers to minimize spread of fires via secondary ignition.

Assuming normal municipal fire fighter response not supported by water bombers, the area that will likely be destroyed by secondary fires is the ring defined by:
(Rs / 4) < Rz < (Rs / 2).
The area of this ring is about three times the area defined by:
Rz < (Rs / 4)
that burns via direct ignition.

DAMAGE MITIGATION:
Both theory and field experience indicate that the most favorable condition for mitigating of damage by a burning natural gas pipeline is a deep snow cover. The snow reflects the infrared radiation up into the sky and if the snow melts the resulting water prevents most surfaces getting hot enough to ignite.

POTENTIAL IMPACT RADIUS (PIR):
In the Province of Ontario the **Technical Standards & Safety Authority (TSSA)** has defined what **TSSA** terms **Potential Impact Radius** or **PIR**, where:
1.0 PIR ~ (Rs / 4).

A technical representative of **TSSA** readily admitted that **1.0 PIR** is not an adequate safety radius. **1.0 PIR is a compromise made by TSSA between urban pipeline corridor real estate cost and public safety.** Buildings such as secondary schools, etc. that routinely contain concentrations of healthy independently mobile people should be set back at least **2.0 PIR** from the pipeline axis. Buildings such as elementary schools, nursing homes and hospitals, that routinely contain people who are not independently mobile, should be set back at least **4.0 PIR** from the pipeline axis. However, in Ontario **the actual amount of setback from the pipeline axis is determined by the governing municipal authority**, not **TSSA**.

The practical effect of using the **TSSA PIR** as a regulatory setback is to reduce the cost of natural gas pipeline rupture failure related fire damage by about a factor of three under circumstances of no wind and good municipal fire fighting capacity. Assuming these circumstances, a regulatory setback of at least **2.0 PIR** is required to reduce the direct fire damage to close to zero. If the region in question has frequent wind or minimal fire fighting capacity, then a setback of **4.0 PIR** should be used.

EXAMPLES:

ENGLEHART, ONTARIO:
On September 12, 2009 a 914 mm OD, 9.1 mm wall natural gas transmission pipe operating at 6869 kPa ruptured about 12 km NW of Englehart, Ontario. An area of 25 hectares (250,000 m^2) was totally destroyed, indicating an average radius R of total destruction of:
R = (250,000 m^2 / Pi)^0.5
= 282 m

The fire was contained by use of water bombers. In spite of use of water bombers a rural home 320 m from the rupture point was damaged.

Assume:
En^0.25 = 1.0

Dp = .914 m

Pb = 14.7 psia = 1 bar = 101 kPa = 1.01 X 10^5 newtons / m^2

Pa = 6.869 X 10^6 newtons / m^2

Hence:
Rs = 17.71 X .914 m X (6.869 X 10^6 newtons / m^2)^0.25 kg^-0.25 m^.25 s ^0.5
= 17.71 X .914 m X 686.9^0.25 X 10 (kg m s^-2 m^-2)^0.25 kg^-0.25 m^.25 s ^0.5
= **828.5 m**
The corresponding theoretical value of **(Rs / 2)** is given by:
Rs / 2 = 414 m
and
(Rs / 4) = 207 m
Clearly the actual destruction was in good agreement with the theoretical formula.

YORK ENERGY CENTRE PIPELINE, KING TOWNSHIP, ONTARIO:
The York Energy Centre is a natural gas fueled air cooled combustion turbine based 400 MW electricity generation station located in YOrk Region, north of Toronto. This facility is served

by a dedicated **16 inch diameter 600 psi** natural gas pipeline running through a mostly rural area.

Assume:
En^0.25 = 1.0

Dp = 16 inches = .406 m

Pb = 14.7 psia = 1 bar = 101 kPa = 1.01 X 10^5 newtons / m^2

Pa = 600 psia = 40.81 bar = 4122.4 kPa = 41.22 X 10^5 newtons / m^2

Hence:
Rs = 17.71 X .406 m X (40.21 X 10^5 newtons / m^2)^0.25 kg^-0.25 m^.25 s ^0.5
= 17.71 X .406 m X 402.1^0.25 X 10 (kg m s^-2 m^-2)^0.25 kg^-0.25 m^.25 s ^0.5
= **321.97 m**

Application of this formula to the York Energy Centre pipeline gives a radiation safety distance of about:
Rs = 322 metres.
At **Rz = (Rs / 2) = 161 metres** the radiation level will be four times as high as at **Rs = 322 m**. In practice:
Rz = (Rs / 2)
is the closest that municipal fire fighters are able to approach the natural gas inferno. Hence in the area where:
Rz < (Rs / 2)
secondary fires involving both buildings and farm crops will burn unimpeded.

In the case of the York Energy Centre pipeline a minimum **161 metre setback** should be maintained from the pipeline center line to all human occupied structures and to all places of routine outdoor human assembly. This is an ongoing setback requirement that should be actively enforced by municipal authorities for the life of the pipeline. All parties should clearly understand that the radiation emitted by a pipeline rupture/fire is so intense that the only practical strategy for a municipal fire department is to let the fire burn itself out. It is also unrealistic to expect persons within radius:
Rz < (Rs / 2)
of a pipeline rupture/fire to be rescued by fire department personnel who lack equipment for working in zones of high thermal radiation.

If possible the municipality should attempt to enforce a **322 m setback** instead of a **161 m setback**. There could still easily be litigation related to injury and property damage in the ring:
161 m < Rz < 322 m
resulting from the fire simply overwhelming the capabilities of rural municipal fire department(s).

APPOMATTOX, VIRGINIA:
On September 14, 2008 a 30 inch diameter buried natural gas pipeline that normally operates at a pressure of 800 psi ruptured and burned in a farmer's field near the intersection of Highway 26 and State Route 677 just north of Appomattox, Virginia. There was a modest delayed ignition explosion. Overhead news photographs showed the area where the crop burned. The burned area was measured using distance calibrated overhead

photographs from Google maps. It was found that with reference to the pipe rupture crater the burned crop area extended **311 m** to the south-west and **275 m** to the north-east.

Assume:
En^0.25 = 1.0

Application of the formula for the radiation safety distance **Rs** gives:
Dp = 30 inch X .0254 m / inch = 0.762 m
Pa = 800 psi X 101 X 10^3 Pa / 14.7 psi = 549.66 X 10^4 Pa
Pb = 101 X 10^3 Pa = 10.1 X 10^4 Pa
Rs = 17.71 Dp (Pa - Pb)^0.25 kg^-0.25 m^.25 s ^0.5
= 17.71 X 0.763 m X (539.56 X 10^4 Pa)^0.25 kg^-0.25 m^.25 s ^0.5
= **651.25 m**
Thus the radius to which the crops spontaneously burned approximately conformed with:
Rz < (Rs / 2).

SAN BRUNO, CALIFORNIA:
On September 9, 2010 at 6:11 PM a **30 inch diameter** buried natural gas pipeline operating at a pressure of **400 psia** ruptured and burned in a single family estate home residential area in San Bruno, California. San Bruno is a southern suburb of San Francisco, about 2 miles from the San Francisco airport. The homes near the rupture location each had lot sizes in excess of one acre. San Bruno had the benefit of probably the best available municipal fire fighting capacity in North America.

There was a modest delayed ignition explosion followed by a large natural gas fire that persisted for more than two hours. Secondary fires continued for more than eight further hours. The fire scene was attended by **67 fire trucks, 4 fixed wing aerial water bombers and 1 fire fighting helicopter**.

Aerial photographs showing the area that burned were compared to distance calibrated Google maps. In spite of the large amount of immediately available fire fighting equipment **almost all the homes (38) within a 150 m radius damage circle were completely destroyed. A further 17 homes were severely damaged and a further 53 homes sustained lesser damage**. The center of the damage circle was displaced from the pipe rupture location by about 100 m. The cause of this displacement was a combination of local factors including natural gas pipeline orientation, natural gas exit velocity, wind, steep local terrain, local tree concentrations and asymetrical application of fire fighting resources.

Assume:
En^0.25 = 1.0

Application of the formula for the radiation safety distance **Rs** gives:
Dp = 30 inch X .0254 m / inch = 0.762 m
Pa = 400 psia X 101 X 10^3 Pa / 14.7 psia = 274.8 X 10^4 Pa
Pb = 101 X 10^3 Pa = 10.1 X 10^4 Pa
Rs = 17.71 Dp (Pa - Pb)^0.25 kg^-0.25 m^.25 s ^0.5
= 17.71 X 0.762 m X (264.7 X 10^4 Pa)^0.25 kg^-0.25 m^.25 s ^0.5
= **544.3 m**
Thus the calculated area of damage to or loss of homes was the area where:
Rz < (Rs / 2),
which is a circle of radius **272 m**.

It is clear from subsequent photographs and incident reports that absent the massive fire fighting resources that were immediately available close to the San Francisco Airport, including **four water bombers**, the actual area of total destruction would have closely conformed to the calculated destruction radius:
$$(Rs / 2) = 272 \text{ m.}$$

The practical experience at San Bruno indicates that there is a limit to the capabilites of urban municipal fire departments. Even when there is an army of immediately available emergency personnel and almost unlimited municipal fire fighting equipment, the municipal water mains and their pumping systems limit the municipal fire fighting capacity. Water bombers designed for fighting large forest fires are of considerable help because they can combat secondary fires in the ring:
$$(Rs / 4) < Rz < (Rs / 2)$$
which is not accessible to municipal fire fighters due to high infrared radiation levels.

However, the standby costs of maintaining a fleet of large water bombers that are available and ready to fly at a moments notice are prohibitive for most jurisdictions. In this respect the residents of San Bruno were particularly fortunate that there were four suitable water bombers immediately available and based only two miles away. Otherwise the fire damage losses would have likely at least tripled.

An important conclusion from the San Bruno NTSB accident investigation report was that the pipe section that ruptured was defective at the time of original installation and had never been subject to an as-built hydraulic pressure test to the Specified Minimum Yield Stress (SMYS) for the pipeline material.

JERSEY CITY, NEW JERSEY:

In March 2012 this author was made aware of a plan to build a **42 inch diameter 1200 psi** natural gas pipeline through a densely populated area of Jersey City, New Jersey. This author's immediate response was that this plan is stupid because that pipeline would be a long term magnet for every anti-USA terrorist in the world. This author strongly recommended that this pipeline be rerouted outside the urban area, regardless of the extra cost.

If construction of this pipeline proceeds as originally contemplated, the consequences of a rupture failure, perhaps intentionally caused, would be comparable to the air burst of a small tactical nuclear warhead. The safety radius **Rs** and the radius of probable total destruction **(Rs / 2)** can be calculated as follows:

Assume:

$En^{0.25} = 1.0$

$Dp = 42 \text{ inch} \times .0254 \text{ m / inch} = 1.0668 \text{ m}$

$Pa = 1200 \text{ psia} \times 101 \times 10^3 \text{ Pa} / 14.7 \text{ psia} = 824.5 \times 10^4 \text{ Pa}$

$Pb = 101 \times 10^3 \text{ Pa} = 10.1 \times 10^4 \text{ Pa}$

$Rs = 17.71 \, Dp \, (Pa - Pb)^{0.25} \, kg^{-0.25} \, m^{.25} \, s^{0.5}$

$= 17.71 \times 1.0668 \text{ m} \times (814.4 \times 10^4 \text{ Pa})^{0.25} \, kg^{-0.25} \, m^{.25} \, s^{0.5}$

$= 1009.2 \text{ m}$

Thus the calculated area of spontaneous combustion is an area where $Rz < (Rs / 2)$, which is a circle of radius **504.6 m**. The perimeter length of that circle, which would be the fire fighting front length, is:
$$2 \pi (504.6 \text{ m}) = 3170 \text{ m.}$$

The only way to stop a fire of that size is to make back fires to create a fire break about **3 km long** and a block wide through the center of the city. The direct and consequential damages from the natural gas fire and the back fire would be unprecedented in United States history. The fire storm and consequent loss of life and property would be comparable to the WWII fire storms in Dresden, Hamburg, Tokyo and Hiroshima.

It is the hope of this author that common sense will prevail and that senior members of the United States government will do all necessary to force rerouting of this large diameter high pressure natural gas pipeline to a longer but much safer rural route.

One practical way to force rerouting of this pipeline is to immediately enact strong legislation to require the pipeline owners to continuously carry credible third party liability insurance and reinsurance sufficient to replace everything and everyone within **500 m** of any potential pipe rupture location.

It must be emphasized that no amount of hydraulic pressure testing or pig testing will protect the public from intentional sabotage of such a pipeline passing through an urban area. The stress in the pipe walls is sufficient that even a relatively small suitably shaped fast explosive charge will cause a rupture failure.

CONCLUSIONS:

When a large diameter high pressure natural gas pipeline operating at its rated working pressure develops a crack or hole more than four pipe wall thicknesses in axial length the result is a sudden full cross section pipe rupture. The escaping high pressure gas blows away the soil overburden, forming a crater. Some time after the pipe rupture there is a large delayed ignition explosion followed by a steady state fire. This fire emits so much thermal radiation that it it is impossible to approach or extinguish the fire with conventional fire fighting equipment.

One can define a radiation safety distance **Rs** from the fire at which distance the thermal radiation level is similar to the thermal radiation level at noon in the middle of the Sahara desert on a clear cloudless day. The formula for a lean burn natural gas flame is:

$$Rs = 17.71\ Dp\ [En\ (Pa - Pb) / Pascal]^{0.25}$$

where:
Rs = radiation safety distance in metres
Dp = pipeline diameter in metres
En = nozzle efficiency ($0.90 < En < 0.99$)
Pa = pipeline absolute working pressure in Pascals
Pb = atmospheric pressure in Pascals. Normally atmospheric pressure is about 101,000 Pascals.

In highly precise scientific measurements:
$0.90 < En < 0.99$.
However, even if the nozzle efficiency **En** is as low as:
$En = 0.90$
in the formula for **Rs**:
$En^{0.25} = .974$
Hence for practical calculation purposes it is convenient to simply use the approximation that:
$En^{0.25} = 1.0$

At radii **Rz** from the rupture in the range:
$Rz < (Rs / 4)$
almost all exposed combustible materials rapidly spontaneously ignite and burn. In this

radius range there is virtually nothing that can be done to prevent 100% loss of lives and property.

At radii **Rz** from the rupture in the range:
(Rs / 4) < Rz < (Rs / 2)
secondary ignion causes exposed combustible materials to burn. In this radius range the thermal radiation level is too high for the fire to be fought by municipal fire departments. However, in this radius range damage can be mitigated through the use of water bombers if they are immediately available.

At radii **Rz** from the rupture in the range:
Rz > (Rs / 2)
absent a high wind, a well equipped and well staffed municipal fire department is usually able to prevent significant secondary ignition fire damage.

It should be emphasized that the above calculations apply to thermal radiation from steady state combustion of natural gas in a clean lean flame. There is additional danger if the natural gas flame is rich or if it triggers combustion of materials that form soot. If large amounts of soot mix with the natural gas combustion air the soot could increase the radiant heat fraction **Fr** four fold which would double the safety radius **Rs**.

The damage radius from the initial delayed ignition explosion could easily be larger than **Rs**. Based on eyewitness reports from Appomattox the sequence of events at that pipeline rupture/fire was a large delayed ignition explosion followed by steady state combustion. The same sequence of events has occurred elsewhere.

The above calculation shows that even if someone is fortunate enough to survive the initial delayed ignition explosion, the temperature within the radiation safety radius **Rs** of the flame will quickly rise past the point of human tolerance.

For large diameter high pressure natural gas pipelines passing through urban areas this author strongly recommends an initial as-built hydraulic pressure test to 100% of pipe SMYS (Specified Minimum Yield Stress) and a maximum operating pressure producing a pipe material stress of no more than 30% of SMYS. Furthermore, as long as the pipe remains in service in an urban area the pipe should be retested at least every five years with a non-combustable fluid to the larger of 50% of pipe SMYS or 150% of the maximum allowable operating pressure. These safety margins have been proven through many years of pressure vessel design, construction and use and are the basis of almost all modern pressure vessel safety codes.

In theory if the pipe could be assembled in the rigerously controlled conditions of a certified pressure vessel fabrication facility with complete material control and ideal welding, initial as-built hydraulic pressure testing to 50% of SMYS might be adequate. However, under the practical conditions that natural gas pipelines are assembled and welded in the field that degree of material and fabrication control is impossible. Hence the only solution is an initial as-built hydraulic pressure test to 100% of pipe SMYS. There is no mill test, x-ray test, pig test, spectrograph test, sampling test or inspection procedure that can replace a hydraulic pressure test to 100% of SMYS.

Given the limited resources of rural fire departments it is reasonable to assume that in the event of a large diameter high pressure natural gas pipeline rupture/fire they will simply ensure that the pipe is valved off on both sides of the rupture and then let the fire burn itself out. It is also reasonable to conclude that crops, buildings and other combustibles within a distance **Rz < (Rs / 2)** of the pipeline rupture/fire will be totally destroyed.

The principal objective of emergency services must be to immediately evacuate humans from inside the radiation safety radius **Rs**. It can safely be assumed that for:
(Rs / 2) < Rz < Rs
damage to property will be significant and for:
Rz < (Rs / 2)
almost everything will be destroyed. Most municipal fire departments are not equipped to function within the high thermal radiation levels that will occur at:
Rz < (Rs / 2).
Life and property insurance coverages should reflect this reality.

REGULATORY ISSUES:
To minimize potential damage large diameter high pressure natural gas pipelines must be installed near the center lines of available energy transmission corridors. This issue needs to be embedded in regulation.

With reference to Ontario Technical Standards & Safety Authority (**TSSA**) Fuels Safety Program, **OIL AND GAS PIPELINE SYSTEMS CODE ADOPTION DOCUMENT AMENDMENT FS-196-12** dated **November 1, 2012**, the formula for **Potential Impact Radius (PIR)** should be replaced by the formula for **(Rs / 2)** contained herein. The issue is that the formula for **PIR** contained in **AMENDMENT FS-196-12** yields a Potential Impact Radius that is only about **(Rs / 4)** whereas recent pipeline rupture fires have confirmed the validity of **(Rs / 2)** as being the actual impact radius.

Alternatively **TSSA** should modify the language in its regulations so that the general public clearly understands that the **PIR**, as defined by **TSSA**, is only about one half of the radius of 100% property loss.

The Ontario **TSSA** should be realistic with respect to the limited capability of municipal fire fighters working within high thermal radiation zones. In the event of a major natural gas pipeline rupture/fire the available fire fighters will likely attempt to save human lives but in so doing will likely sustain both personal skin damage and equipment damage. They will then be unable to fight or extinguish fires. Furthermore, the experience in San Bruno, California and elsewhere has been that the municipal fire fighting capacity is further constrained by the available hydrant water flow. The fire in San Bruno was in large measure contained through the use of water bombers that were stationed nearby for controlling forest fires. However, in much of Ontario there is no immediate water bomber availability nor viable chain of command for prompt water bomber dispatch.

In this matter I speak from personal experience. I grew up in British Columbia where during the 1960s major forest fires, and a major fire on the Vancouver waterfront, were contained using a fleet of WWII surplus giant Martin Mars flying boats. These flying boats were converted from military transports into water bombers. I believe that two of them are still in service today. When trying to control a big fire, there is nothing comparable to dropping 6000 imperial gallons of water/foam on the fire in a few seconds. The water/foam will not extinguish the main natural gas inferno but it will cool the surrounding exposed surfaces and thus minimize secondary fires in the ring:
(Rs / 4) < Rz < (Rs / 2).
This ring, which is not accessible to municipal fire fighters due to high thermal radiation from the natural gas inferno, may contain hundreds of homes.

It is a huge mistake to create a regulatory framework which has the practical effect of not allowing parties that build, own, operate and maintain large water bombers to financially prosper. There is no doubt that a fleet of large water bombers has a high ongoing cost that must be borne by the taxpayers and/or insurance industry and/or major forest companies. However, when there is a fire that overwhelms the municipal fire department/forest service, then every dollar invested in the water bomber fleet provides a hansom return. In hindsight, one of the benefits of leasing exclusive timber rights to large forest companies was that those companies, in their own self interest, paid the costs of ownership, operation and maintenance of the fleet of large water bombers.

There is a major problem related to both provincial and municipal land use planning. In Ontario both provincial and municipal planners have failed to provide sufficiently wide dedicated energy transmission corridors into major urban centers such as Toronto. The 400 series highways are located in corridors that are typically about 400 m wide, including the width allowance for the adjacent electricity transmission lines. These corridors are simply not wide enough to provide an adequate safety setback distance from a 36 inch diameter high pressure natural gas pipeline, even if the pipeline is on the corridor center line. However, in Toronto there are no other even remotely suitable corridors, so private property owners on both sides of these highways are being exposed to risk related to major pipeline rupture failures.

This problem of failed governmental planning is not unique to Toronto or Ontario. There are even worse pipeline setback problems in the New Jersey - New York City area.

There is also a new class of pipeline risks related to grounded electrical equipment located near pipeline corridors. In an effort to efficiently utilize land, in some places 3.0 MVA wind turbines are being installed in or adjacent to existing dedicated energy transmission corridors. However, wind turbine transformers can cause ground currents that lead to rapid corrosion of nearby buried steel pipelines. It is crucial that the electrical codes relating to wind turbines and other distributed power equipment address this ground current issue. Every wind turbine within a wind farm must be separately isolated from its transmission/distribution line via an ungrounded low capacitance delta type transformer connection. Every wind turbine must be fitted with ground fault detection and alarm signalling. Substation transformers need to be selected for low harmonic generation.

There needs to be new legislation that makes parties that cause ground currents financially responsible for accelerated corrosion damage to nearby buried steel pipelines. In extreme cases, especially in the proximity of large unbalanced electrical power inverters, or with subsurface bed rock, the radius of such ground current induced pipeline damage can extend more than 3 km from the electrical equipment grounding point.

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