Flammability Analysis of Hydrocarbon Vapors at Kittitas Terminal, Local Communities and Chicago, Milwaukee-St. Paul Railroad Tunnel

by

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I. STATEMENT OF PROBLEM

The purpose of this flammability analysis is to provide a hazard assessment of the release of fuel at the Kittitas terminal, in local communities and at the Chicago, Milwaukee-St. Paul Railroad tunnel at Snoqualmie pass where concerns for loss of life, property damage and toxicity issues are of great importance. This study is considered to be a preliminary analysis meriting further attention, as warranted by the availability of future information.

Various flammability hazards discussed herein are supported by "real world" fire data provided in video tapes. These include the following:

X Delaware Co.(Traner) outside Philadelphia - **Tosco Refinery Fire and Explosion** (Fox News, November 1998)

X Tampa, FL - **Citgo Tank Farm Fire** (American Heat, Volume 4, Program 12, June 1990)

X Great Bend, KS - **Tank Farm Fire** (American Heat, Volume 3, Program 9, March 1989)

X San Bernadino, CA - **CALNEV Pipeline Explosion and Fire** (Out of Sight, Out of Mind, American Heat, Vol. 4, Program 1, July 1989)

X Moundsview, MN - **Williams Pipeline Explosion and Fire** (Out of Sight, Out of Mind, City Video, July 8, 1998)

II. INTRODUCTION AND DISCUSSION

In any rational flammability analysis, a number of questions generally arise. These might include but not necessarily be limited to the following:

l. Under what conditions are the suspected materials flammable?

2. What are the potential ignition sources and what is the most probable ignition source?

3. What quantities of combustibles might be expected to be involved in the flammability or explosivity situation?

Using calculations based on the types of information that are required to answer the aforementioned questions one can then make explosion or flammability analyses relating the potential hazards associated with a given situation. In dealing with these types of situations which oftentimes become liability cases, one is frequently presented with a variety of possible ignition sources any of which are pre-supposed to effect ignition of a given material. The flammability characteristics of a suspected material are sometimes unknown or frequently not well defined. However, in the present situation the flammability characteristics of the various types of gasoline and distillate fuels that are proposed for pipeline transit and storage at the Kittitas terminal are well known.

Relevant flammability concepts are described in some detail in Appendix A. This report applies those concepts to the circumstances of the proposed Cross-Cascade pipeline.

III. APPLICATION OF PRINCIPLES

3.1 Electrostatic Charge Generation During Offloading from Kittitas Storage Tanks into Trucks

Electrostatic charging during flow of low-conductivity hydrocarbons through pipelines is well known in the petroleum industry. This is mentioned in Appendix A, § 6 and detailed in References 14-16. As discussed by Wagner in Reference 14, the mechanism of static charge generation is due to transport of ions present in the hydrocarbon fluids. For the assumption that negative ions are transported to the wall of the hose or pipe (the opposite situation would occur if positive ions were transported to the wall leaving behind an excess of negative ions in the flowing fluid), a net surplus of positive ions is produced in the flowing fluid. These ions can then accumulate in a receiving tank depending primarily on the electrical conductivity and flow velocity of the hydrocarbon. For low-conductivity fluids, even though the tank is grounded, little charge is lost to ground or to recombination of ions in the bulk fluid. Charge can then build up to dangerous levels in the tank and ignition can occur if the hydrocarbon is in the flammable zone and the field strength is sufficient to produce spark discharge.

Data are lacking for the electrical conductivity of the liquid fuels at Kittitas and the flow conditions are unknown, thus, an unequivocal statement about this type of an ignition mode cannot reliably be made.

3.2 Identifying and Locating the Various Sources of Ignition; Estimation of Ignition Strength

Potential ignition sources involving a heavy truck with a running diesel engine may include heated surfaces (turbocharger, heated exhaust, heated compressor surface if the truck contains an auxiliary pumping system, heating tapes used to keep the diesel fuel free flowing during cold winter days, etc.), electrical sparking (from faulty wiring, or use of truck radios and communication equipment not suitable for an environment containing combustible vapors, i.e. not approved for a Class I Group D environment) as mentioned previously. By way of example only, the following are among the numerous other possible ignition sources: striking a match; using a butane lighter; smoking a cigarette; the switching on and off of a flashlight by a truck operator; lightning in the area; static electricity generated from removing a nylon jacket; and lighting a butane torch or lamp.

Based on the energetics of comparable types of ignition sources in Table 4 it is seen that all of the aforementioned sources are capable of effecting ignition. The more energetic ignition sources can ignite gasoline and distillate type fuel/air mixtures over broader concentration ranges. However, because of the low minimum ignition energy estimated to be capable of igniting gasoline (0.7 millijoules) even static charging generated by a truck operator sliding across a seat and touching a door handle for egress could produce ignition in certain situations.

3.3 Flammability and Explosivity Considerations

It is proposed that the Kittitas terminal would ultimately have 10 above ground storage tanks: nine above ground liquid storage tanks 14.6 m (48 ft.) high and 30. 5 to 45.7 m (100 to 150 feet) in diameter and one 420,000 gallon transmix/relief tank (9.1 m [30 feet] high and 15.2 m [50 feet] in diameter would also be included with a total storage capacity of 36,120,000 gallons of product. Tank makeup includes: five large storage tanks (two regular gasoline, one premium gasoline, one LS diesel, and one HS diesel), the aforementioned transmix tank, an ethanol tank, and finally a large diesel tank, turbine fuel tank and gasoline tank to make up the total of ten tanks for the proposed site. The terminal also includes truck loading racks and parking for tanker trucks as well as other facilities and buildings as outlined in the *Draft Environmental Impact Statement* and the Project Application for the Cross Cascade Pipeline (19,20)

Because gasoline needs to satisfy requirements such as quick starts at low temperatures, freedom from stalling and rusting, eliminate knocking or detonation, good mileage and to minimize evaporative losses as well as other factors, gasoline is a blend of paraffins, olefins and aromatics. Depending on the area of the country the fuel is to be used, it may also contain methyl-tertiary-butyl ether or MTBE for short. Such formulations are referred to as "reformulated gasolines" and are in use in major metropolitan areas such as Los Angeles, Houston and other areas where high ozone and smog levels are known to be hazardous to human health. During the winter months butane (a C_4 liquefiable hydrocarbon which exists as a gas under normal atmospheric pressures) is added to gasoline to aid in ease of engine startup. Basically, gasoline is therefore a mixture of C_4 to C_{10} hydrocarbons. The mixture consists of C_4 to C_{10} saturated hydrocarbons such as butane, pentane, hexane, heptane, octane, nonane and decane. Branched saturated compounds such as iso-octane (224 trimethylpentane which has an octane rating of 100; n-heptane an octane number of 0) are also present in gasoline formulations. Aromatics include not only benzene, toluene and xylene (the so-called BTX fraction) but other aromatics such as C_9 aromatics and ethyl benzene. Unsaturated compounds include C_5 to C_7 olefins. Various locations in the United States also use ethanol (typically derived from corn but in other countries from sugar beets) because of its high octane number as a blending agent.

Other fuels to be stored at Kittitas fall under the general heading of distillate fuels. These are normally characterized by a flash point above normal storage temperature and a final boiling point limited by freezing point or by a tendency to produce soot. The major categories according to Longwell (21) are: kerosine (No. 1) turbo-jet fuel, diesel fuel (No. 2) and heating oil (No. 2). Here because the flash points are above 100 ^{o} F under normal temperature conditions, these fuels are not as hazardous as gasoline formulations for which there is always a flammable vapor/air mixture as already discussed. However, this does not mean that diesel or turbo-jet fuels are not hazardous. Heavy truck fire crashes whereby the trucks saddle tanks were ruptured and the fuel sprayed out as an aerosol cloud indeed led to many fires as witnessed by the author (22).

Cetane number is perhaps the most important descriptor used to characterize diesel fuels. It is reasonably well known that ease of starting, detonation and smoke and engine carbonization are related to cetane number. Test fuels are evaluated on the basis of cetane number whereby cetane (a normal paraffin, $C_{16}H_{34}$) is assigned a rating of 100 and alphamethylnapthalene is assigned a rating of 0. Cetane number is thus the percent of pure cetane in a mixture of cetane and alphamethylnapthalene which matches the ignition quality of the fuel sample under test.

Additives that are used in diesel formuations include stabilizers against gum and sediment formation, emulsion breakers, rust inhibitors, cetane improvers and pour depressants. Amyl nitrate is one of the better known cetane improvers. Diesel fuels are typically formulated for different regions of the United States such as Eastern, Southern, Central, Rocky Mountain and Western regions (23) and variations in cetane number, flash point and API gravity are noted.

The flammability of explosive hazards associated with storage of large quantities of gasoline because of its ease of evaporation following a large spill or a catastrophic tank failure reside in the energy stored in a given quantity of liquid. Upon evaporation this energy can be released in the form of either a deflagration or a detonation wave with devastating consequences. Such information can be expressed in terms of TNT equivalents using standard accepted approaches. For an approximation we will assume that both gasoline and distillate fuels have a stored energy content of around 20,000 BTU/lb. of liquid fuel.

A simple calculation given below will illustrate the aforementioned point for storage of 36,000,000 gallons of gasoline (the total capacity at the Kittitas tank farm):

Total Energy Stored is

$$3.6 \times 10^{7} \text{ gal } (20{,}000 \text{ BTU/lb})(45.55 \text{ lb/ft}^{3})(1 \text{ ft}^{3}/7.48 \text{ gal}) = 4.39 \times 10^{12} \text{ BTU}$$
$$\text{or } 1.11 \times 10^{15} \text{ calories } (1 \text{ BTU} = 252.16 \text{ cal}).$$

Now, the assumption of equivalence between the flammable material and TNT, factored by an explosive yield terms is used to calculate TNT amount:

$$W = \square M E_c / E_{c,TNT}$$

where

W = equivalent mass of TNT
M = mass of flammable material released
$\square$ = empirical explosion yield or efficiency
E_c = lower heat of combustion of flammable gas
$E_{c,TNT}$ = heat of combustion of TNT

Eichler and Napademsky (24) from a review of historical data conclude that the maximum expected yield is 0.2 for a symmetric cloud but could be up to 0.4 for an asymmetric vapor cloud. Thus, a value of 0.3 seems reasonable for estimation purposes. Stull (25) gives a value of 5×10^{5} calories of energy per 1 lb. of TNT. Values in the literature on a BTU basis range from 1943 to 2049 BTU/lb.

Now, 1.11 x 10^{15} calories is equivalent to 2.22 x 10^9 lb of TNT using the Stull conversion or 1.11 x 10^6 tons of TNT uncorrected for loss of efficiency of the vapor cloud versus TNT. Since 10^6 tons equal 1 Megaton, one is left with 1.11 Megatons of TNT (a common measure associated with nuclear weaponry as per the warhead size) as the uncorrected equivalent of total energy stored at Kittitas. Corrected this energy amounts to 0.333 Megatons of explosive force. Certainly, one cannot envision full vaporization of such a large quantity of gasoline before an ignition source is reached. Thus, values given in Table 5 can be better used to assess TNT equivalents for different amounts of gasoline vaporized. As seen in Table 5, the amount of energy in vaporized gasoline is very large.

The explosive effects of TNT are given in Figure 1 where the shock-wave parameters for a hemispherical TNT surface explosion at sea level are based on US Army data. Here the pressure that would be recorded on the side of a structure parallel to the blast is the side-on overpressure or P_{so}. The reflected pressure, P_r, is the pressure on a structure perpendicular to the shock wave and is at least a factor of 2 greater than the side-on overpressure. The plotting parameter, the scaled range - Z_G is defined as the distance divided by the cube root of the TNT mass (Weight units). Using information contained in Clancey (26) or in other texts dealing with explosive damage to various structures one notes the following (see Table 6) damages for overpressures as little as 2 psig - partial collapse of walls and roofs of houses; 3-4 psig rupture of oil storage tanks and 5-7 as nearly complete destruction of houses.

For illustrative purposes let us assume that an overpressure of 5 psi is equivalent to killing a significant number of people in homes due to building collapse and/or fires resulting therefrom, then one can estimate the distance for that occurring based on how many gallons of gasoline are vaporized and subsequently ignited. Let us assume, 1,000 gallon are vaporized and subsequently ignited then from Figure 1 the scaled distance Z_G to 5 psi (P_{so}) is 14 ft/lb$^{1/3}$. Converting scaled distance to real distance one arrives at

$$R_G = Z_G W^{1/3} = 14 \text{ x } (18{,}420 \text{ lb})^{1/3}$$

$$R_G = 368.5 \text{ ft.}$$

For 10,000 gallons of gasoline, taking the 1/3 power of 184,200 lbs. of TNT and multiplying by 14 gives 793 ft. Because of the 1/3 power dependence on the weight of TNT, the major damage to buildings, tanks, and various other pieces of equipment is in relatively close proximity to the vaporized fuel. This has been confirmed by actual data given for the explosions at the storage facility in Newark, NJ (27).

For other scenarios such as partial demolition of houses at an overpressure of 1 psi the distances for 1,000 gal and 10,000 gal. of gasoline exploding amount to 1,195 ft. and 2,573 ft, respectively. Glass breakage ranges at 0.15 psi overpressure extends to 5,312 ft (1 mile) and 11,436 ft (2.2 miles) for 1,000 and 10,000 gal. of vaporized gasoline, respectively.

3.4 Liquid Levels and Radiative Heat Emissions Associated with Kittitas Terminal Major Tank, Piping or Seal Failures

The NFPA text titled "Flammable and Combustible Liquids Code Handbook" (28) based on the revised 1996 edition of NFPA Codes 30 and 30 A and on the 1993 edition of NFPA 395 deals with the storage of liquid hydrocarbons such as gasoline and distillate fuels proposed for storage at Kittitas as well as other items.[1] NFPA Code 30 gives two methods for containing spills of liquids stored in tanks: 1) remote impounding, and 2) impounding around tanks by diking. It is clearly noted in **part 2-3.4.3 that "Diking is less desirable than remote impounding because it allows a ground fire to expose tanks within the diked area, ...".** It is also noted in **Figure 2.8 that "There have been many fires that have included all of the tanks in a single diked area."** It should furthermore be emphasized that **the proposed plan for Kittitas calls for diking not remote impounding. Thus, a much greater risk of a significant fire hazard is associated with the proposed diking consideration.**

With either diking or remote impounding, NFPA 30 requires that the diking area or impounding area must be large enough to contain all of the liquid from the largest tank that can drain into it. Should there be two simultaneous tank failures liquid would overflow the dike and contribute to additional fire spread and radiative heat release because of a much larger pool size. At Kittitas, the largest tank proposed is 150 ft in diameter and 48 ft. high, so the volume needed to be contained is:

[1] It should be pointed out that these NFPA Codes are consensus types based on committee members inputs. Thus, they are strongly influenced by industry representatives who have a vested interest in "minimal type" not maximum types of codes since economic considerations and other practical considerations enter into the decision making processes. The present members on NFPA 30 principally represent industries that have a vested interest in fuels, chemicals, etc. although representatives from laboratories like Underwriters Labs and insurance companies and NFPA personnel are also represented. Suffice it to say not a single representative of an environmental group nor any citizen "watchdog" type of group is represented.

$$V = \pi/4\ d^2\ h = \pi/4\ (150)^2\ (48) = 848{,}230\ ft^3\ (6{,}344{,}760\ gallons)$$

Since multiple tanks are usually contained within a single or common dike we will assume that three additional tanks of diameters 150, 100 and 100 ft. are contained within a single dike. We will furthermore assume that the dike height is restricted at the 6 ft level as stated in NFPA 30. The volume occupied by these additional tanks is therefore

$$V = \pi/4\ (6\ ft.)\ [\ (150)^2 + (100)^2 + (100)^2] = 200{,}277\ ft^3.$$

Thus, the total volume that needs to be contained within the 6 ft. high dike is 848,230 plus 200,277 cubic feet or 1,048,507 cubic feet (7,842,832 gallons). The area of a circular pool that will contain this volume is

$$A = V/6 = 1{,}048{,}507/6 = 174{,}751\ ft^2\ (16{,}243\ m^2).$$

The diameter of a circle equivalent to this area is 472 ft (143.9 m).

In addition to explosion considerations given previously for large scale liquid spills, pool fires are also commonly associated with large releases of liquid hydrocarbons that are contained within diked regions. To estimate damage effects from pool fires several types of calculations are required. Included in this analysis are estimates of: total heat released, radiant heat released, point source view factor, transmissivity, incident thermal radiation and resulting thermal effects produced by the radiation. Generally speaking these effects tend to be localized and deal more specifically with establishing employee safety zones and means for egress from the work site. However, because of the very large size required to contain a massive tank leak it is informative to investigate radiative effects for different distances from the fire source.

First, the total estimated heat released is given by

$$Q = M_b\ E_c\ A$$

where M_b = burning rate, kg/m^{2}s
E_c = heat of combustion, kJ/kg
A = pool area, m^2

According to Mudan (29), typical values for hydrocarbons lie in the range from 0.05 kg/m^{2}s for gasoline to 0.12 for liquified petroleum gas (LPG). Now assuming a heat of combustion of 40,000 kJ/kg and substituting in the above formula one obtains

$$Q = 0.05\ (40{,}000)\ (16{,}243) = 32{,}486{,}000\ kW$$

Using a radiant fraction for smoky pool fires of 0.35 (a conservative assumption since 65% of the radiant energy is assumed to be attenuated by the smoke) then the radiant heat, Q_r, is

$$Q_r = 11{,}370{,}100\ kW$$

Now the point source view factor, F_p can be estimated from

$$F_p = 1/4👌x^2$$

where x is the distance in meters from the emitting source of radiant heat.

Let us assume the distance x from the source is 200 m (656 ft. roughly two football fields in length) and calculate the view factor for that distance assuming no wind and thus no flame tilt

$$F_p = 1/4👌(200)^2 = 2.0 \text{ x } 10^{-6} \text{ m}^{-2}$$

Next, one needs to estimate the transmissivity. Pietersen and Huerta (30) give a correlation that accounts for humidity

$$☺ = 2.02 (P_w \, x)^{-0.09}$$

where ☺ = atmospheric transmissivity (fraction of energy transmitted: 0 to 1)
P_w = water partial pressure (Pascals)
x = path length, distance from flame surface to target, (m)

Let us assume 20 C and 50% relative humidity for which one has the vapor pressure of water as 2320 Pascals. Substituting into the transmissivity equation

$$☺ = 2.02 (2320 [200])^{-0.09} = 0.624$$

The thermal flux is therefore

$$Q_t = ☺ \, F_p \, Q_r = (0.624)(2.0 \text{ x } 10^{-6} \text{ m}^{-2})(11,370,100 \text{ kW})$$

$$Q_t = 14.2 \text{ kW/m}^2$$

This radiant flux is above the 12.5 kW/m^2 minimum energy required for piloted ignition of wood (see Table 7 from World Bank). Thus, for such a large pool fire that can occur from tank failure at Kittitas, one would expect the surrounding area to be engulfed in brush fires depending on the ability or lack thereof to extinguish such fires in a timely manner.

It is also informative to estimate the distance that one would experience pain and second degree burns at the threshold of 4 kW/m^2 .

$$Q_t = ☺ \, F_p \, Q_r = (0.624)(1/4👌x^2 \text{ m}^{-2})(11,370,100 \text{ kW}) = 4$$

Solving for x^2 which equals

$$x^2 = (0.624/4) (1/4👌)(11,370,100) = 141,149$$

Solving for x one obtains 376 m (1233 ft or around 1/4 of a mile). Such a distance would be expected to impede fire extinguishment of brush type fires by the average citizen who would not be wearing specialized fire fighting clothing.

It is also informative to estimate the flame height for the pool fire used in the above example. Here the correlation of Thomas (31) is given by

$$H/D = 42[M_b /(\rho_a (gD)^{0.5}]^{0.61}$$

where

H = visible flame height (m)
D = equivalent pool diameter (m)
M_b = burning rate (kg/m^2s)
ρ_a = ambient air density (typically 1.2 kg/m^3)
g = acceleration of gravity 9.81 m/s^2

Substituting 144 m for the pool diameter and 0.05 for the burning rate into the above formula one arrives at a flame height of 30.77 m (101 ft). Needless to say this is a flame height of some significance in terms of the amount of radiant heat that it can transmit.

3.5 Fire Protection at Kittitas Terminal

References 19 and 20 present limited information on the proposed fire protection for the Kittitas terminal. For example, on pg. 2.3-37 of the Cross Cascade Pipeline Project Application Number 96-1 it is stated that, “Fire suppression will include an engine-driven foam generator connected to piping to each tank. Each tank will be equipped with foam chambers. Foam and water monitors will be strategically positioned throughout the tank farm and fed from a dual loop system. Water will be supplied through a connection to the City of Kittitas public water system.” The Draft Environmental Impact Statement under **Fire** on pg. 3-319 states that “OPL would have adequate fire detection and suppression equipment onsite at the terminal to respond to a limited facility fire or storage tank fire. .... Should any single event tax the suppression system beyond its capabilities or beyond the capabilities of OPL or other local resources, OPL would have immediate access to professional fire fighting firms located in California or Texas who would have the resources and expertise to manage a large tank/facility fire. This is the same fire suppression backup resource that is available to refineries and fuel storage facilities, and provides personnel, foam, and other equipment in large quantities within 3 hours.”

It is difficult to comment on the many of the above statements since specific details are lacking. However, suffice it to say that the water supply from the City of Kittitas as detailed in Reference 33 is “woefully” inadequate for large tank fighting needs as reference to section 9 already emphasizes. There are some major issues as what is adequate for OPL concerning fire detection and suppression equipment and what concerned professionals would require for such a large tank facility. For example, it is almost implicit in the above statements that OPL doesn’t plan to be able to put out large tank fires but rely on outsiders in either California or Texas to accomplish that task. Clarification for the statement " This is the same fire suppression backup resource that is available to refineries and fuel storage facilities, and provides personnel, foam, and other equipment in large quantities within 3 hours." is required as there appears to be a missing item that needs to accompany the 3 hours (i.e., how would Olympic communicate with and mobilize and transport adequate resources and personnel from Texas or California to Kittitas in 3 hours?). This statement is believe to be **grossly overstated** relative to obtaining such capabilities at Kittitas from either California or Texas. It is furthermore meaningless as there is not adequate water nor pressure delivery capabilities planned for Kittitas. There is, furthermore, no mention of having on site personnel highly trained in large tank fire suppression. Having such personnel with the proper equipment would seem to aid early fire extinguishment rather than prolong the fire to a point where it cannot be put out.

The deficiencies in fire suppression noted above almost insure full tank farm involvement before highly skilled personnel from other parts of the country could arrive. A possible scenario could involve rupture of additional tanks due to thermal stresses and, thus, an overflowing of the diked region with burning fuel. With this situation the fire would most probably have to burn itself out.

3.6 Considerations for Chicago, Milwaukee-St. Paul Railroad Tunnel

The safety hazards that require consideration for the old Chicago, Milwaukee-St. Paul Railroad tunnel (2.5 miles) at Snoqualmie pass, which is part of the John Wayne Trail System operated by Washington State Parks and Recreation, involve toxicity, flammability and explosivity considerations due to the proposal to bury the Cross Cascade Pipeline in the tunnel floor. Toxicity considerations become more important below the lower flammability limits. From Table 4.1-20 - HUMAN EXPERIENCE: EXPOSURE TO GASOLINE VAPORS in Cross Cascade Pipeline EFSEC Application 96-1 it is noted that a concentration of gasoline vapors from 5,000 - 16,000 ppm is lethal in an exposure time of only 5 minutes. Because of such a short duration it is unlikely that anyone in center of the tunnel (i.e., 1.25 miles from an exit) including world class runners would escape considering that they will also suffer effects of dizziness and intoxication at concentration levels below that considered to be lethal. In addition, depending on the spread of gasoline along the tunnel length it is probable that certain sections of the tunnel will be within the flammability limits (1.3-1.4 to 6-7.6 % V for gasoline- Table 3). Thus, the generation of smoke and heat will further prolong egress out of the tunnel interior. To see how little fuel needs to leak into the tunnel to constitute a flammable atmosphere, calculations based on the assumption that the fuel can be treated as an ideal gas in the vapor state are given below.

First, let us address the entire tunnel volume to see what quantity of gasoline would be required for the hypothetical case of a well mixed vapor volume. (This is a very conservative approach; because gasoline is heavier than air, there probably will be preferential layering of the gas vapors close to the tunnel floor.). An estimate of the air or void volume in the tunnel using Figure 2.3-5 from EFSEC Application 96-1 for the cross-sectional tunnel layout one then has:

X Circular arc radius - 22.5 ft. - 16 ft. = 6.5 ft. The volume of 2.5 miles contained within this arc is therefore $2.5 \times 5{,}280 \times 1/2[\pi(6.5)^2] = 876{,}033\ ft^3$

X Rectangular volume - lwh = 2.5(5,280) (15.2) (16) = 3,210,240 ft^3

The total volume is therefore simply the sum of these two volumes or 4,086,273 ft^3 . Based on the tabulated values for the lower flammability limits of gasoline (1.3 - 1.4% V) and selecting the higher value for a conservative calculation one requires 57,208 ft^3 of gasoline vapor for the entire tunnel to be in the flammable zone (i.e., assuming no preferential layering). From the ideal gas law

$$PV= nRT$$

where

n= wt in grams./Molecular Weight (M.W). = moles of material

R= the universal gas constant, 0.08205 l-atm/mole K

T= absolute temperature; 20 ^{o}C is assumed or 293 ^{o}K

P= l atmosphere

one can calculate the weight in grams required to produce the 57,208 ft^3 of gasoline vapor. However, since we pointed out that gasoline is a complex mixture of various species, for illustrative purposes and for simplicity purposes, we will assume gasoline is represented by n-pentane [$C_7 H_{14}$ - M.W. equals 90]. Therefore,

(1 atmosphere) (57,208 x 28.3 liters) = Wt./90 [0.08205 l-atm/mole K] [293 ^{o}K]

solving for Wt. in grams one obtains 6,060,933 grams (13,361.8 pounds). Since the density of gasoline is 0.73 times 62.4 lb/ft^3 or 45.55 lb/ft^3 the number of gallons of gasoline corresponding to that weight is

6,060,933 g x (1 lb/453.6 g) x 45.55 lb/ft^3 x 7.48 gal/ft^3 = 2,194 gallons

From calculations in Table 8 a leak of this size can result from 0.213 inch diameter hole (i.e., a hole slightly larger than 1/64 th of an inch) in the proposed CCP pipeline in only 60 minutes

It is informative to repeat this calculation for a tunnel section of only 100 ft. in length to see how little liquid needs to be leaked to constitute a flammable atmosphere for the conservative assumption that it is uniformly mixed in this volume. That is, local pockets of flammable zones would be expected to exist for leak volumes much less that what would be given herein.

X Volume contained within the circular arc radius 100 x $1/2[\pi(6.5)^2]$ = 6,637 ft^3

X Rectangular volume - lwh = 100 (15.2) (16) = 24,320 ft^3

Total volume for a 100 foot stretch is therefore 30,957 ft^3. Now for a flammable atmosphere at

1.4% V for the assumed lower flammability limit one needs only 433.4 ft^3 of gasoline vapor. Using the ideal gas law for the same assumptions as above one then needs 45,917 grams of gasoline. Converting to gallons of gasoline at the same conversion factors as above one arrives at 16.6 gallons of gasoline. From Table 8 calculations this amounts to a leak of only 0.0184 in. in diameter (i.e., slightly larger than 1/64 th of an inch in diameter) in one hour. Larger size leaks will produce this quantity of gasoline in much shorter time periods. For example, a 3/16 inch diameter leak that produces 1,704 gal/hr will leak 16.6 gallons of gasoline in only about 1 minute. Thus, it is clearly seen that there is little hope for human survival in this tunnel for even small pipeline leaks.

This type of reasoning can easily be extended to consider lethal toxicity doses that are given as 5,000 ppm to 16,000 ppm for gasoline for a 5 minute exposure time. For the 5,000 ppm level or 0.5 % V one would only need 155 ft^3 of gasoline vapor in the 100 ft. of tunnel length for the assumed well mixed situation. This amounts to only 5.9 gallons of gasoline.

Since heavier than air vapors such as gasoline will preferentially layer on the floor of the tunnel especially under quiescent or no wind conditions it is informative to see how layering can dramatically extend the flammable zone in the tunnel. Thus, a person carrying an ignition source from hundreds of feet away from a leak in the pipeline can actually cause the ignition because of back propagation of the flame to the source. Let us assume a 10 gal. leak and layering of the gasoline vapor within 12 inches off the ground and the flammable region is that of a rectangular cross sectional area limited by the 15.2 ft. of tunnel width. So one can calculate the length of the flammable zone. Again, using the same approach we first calculate the weight in grams of 10 gallons of gasoline to be 27,622 grams. We use the ideal gas law

$$V= (27,622/90)\ (0.08205)\ (293)= 7378 \text{ liters or } 261 \text{ cu. ft.}$$

$$\text{Vol. } \%= (261/y)\ (100\%) = 1.4$$

where the lower flammability limit is again taken as l.4% by volume for gasoline. Therefore

$$y= 18,643 \text{ cu. ft.}$$

Assuming layering within 12 inches off the ground and no dilution with air, the flammable region (assuming a rectangular surface for the cross-sectional area) is

$$z\ (1 \text{ ft.})(15.2 \text{ ft.}) =18,643 \text{ cu. ft.}$$

Solving for z one obtains

$$z= 1226 \text{ ft.}$$

For a leak of 100 gallons and similar assumptions the flammable zone would spread out to 12,260 ft (2.32 miles which is almost the full length of the tunnel).

In another situation where there is no wall confinement (e.g., anywhere else on the pipeline route), a l00 gallon vaporization (using all the same assumptions) would result in a square flammable zone 432 ft. on a side:

$$z^2 \text{ (1 ft.)} = 186{,}430 \text{ cu. ft.}$$

or

$$z = 432 \text{ ft.}$$

or a circle with a radius of 243 feet (πr^2 (1 ft.) = 186,430 cu. ft.)

Beside the flammability considerations given above one must also be concerned with the prospects for an explosion since the tunnel is a confined space both vertically and in terms of its width. For a spherically propagating pressure wave that is centrally ignited, one would expect the walls of the tunnel to be contacted by the wave slightly before the ceiling and the floor of the tunnel as the distance of the width of the tunnel is 15.2 ft. versus a maximum of 22.5 feet from floor to ceiling. The length of the tunnel would provide some pressure relief such that maximum pressures in confined enclosures such as spherical bomb type test equipment wouldn't reach their limits for most hydrocarbons that typically range from around 100 to 130 psi around the stoichiometric concentrations for the various combustible vapors of interest. As with the unconfined vapor explosive forces given previously for different quantities of gasoline, one would expect similar behavior but now reflective shock interactions and much higher overpressures than that mentioned previously. The damage to personnel in the tunnel at the time of an explosion as well as from falling debris would be expected to be significant and additional calculations are not warranted at this time to show that point. One may refer to the explosion calculations in the previous section for open air situations and immediately arrive at this conclusion for a confined space. Additionally, there is more than ample information already available for methane or coal dust explosions that illustrate the effects of explosions in tunnels or drifts in the coal mining industry.

Because this tunnel is open to passage by people who might be hiking or camping, various ignition sources are conceivable especially from long distances away from an initially undiscovered pipeline leak (e.g., as far away as 1,226 feet under the assumptions stated above). These could range from smoking materials, cooking fuels, electrostatic sparking (e.g., removal of a nylon jacket), turning on or shutting off a flashlight, dropping a flashlight and breaking its bulb to even sparking resulting from degrading wiring in the AT&T or WorldCom cable systems (i.e., this assumes these cables are not approved for use in National Electrical Code (NEC) Class 1 Group D environments) similar to what is believed to occur in the fuel tanks on TWA Flight 800. Any existing lighting systems in the tunnel could also be expected ignition sources.

Having supervised pilot plant personnel (both building enclosed and completely open types of processing equipment) for several years who were involved with solvent extraction (typically with hexane a C_6H_{14} paraffin present in gasoline) of edible oilseeds and other industrial crops suffice it to say that standard NEC codes for a Class 1 Group D environment required that no ignition sources be in the fenced enclosed environment of the processing plant. This meant that all pumps, lighting systems, flashlights etc. that were needed for operation of the plant had to meet the code. Ignition sources, e.g., smoking materials and cameras, also had to be deposited in a box outside of the gate in order for visitors to enter the facility.

Suffice it to say that because of the confined space imposed by the tunnel any hydrocarbon release is considered to be of a significant consequence either from a toxicity, flammability or explosivity viewpoints (e.g., loss of life, destruction of the tunnel, destruction of the fiber optic cables in the tunnel).

3.7 Flammability Considerations for Local Communities

The calculations given previously in Section 3.4 may be applied to estimate safe distances from the pipeline for different scenarios. For example, it is already seen that for 1,000 gal. of vaporized gasoline, houses will be destroyed and, thus, people killed for a distance of 369 feet. Included within this distance are the Two Rivers High School (approximately 280 ft), the North Bend Elementary School (approximately 330 ft.) as well as other buildings that are much closer such as the North Bend Community Services building (approx. 60 ft.), Puget Sound Energy Electrical Sub-Station (on the pipeline) as well as houses that are only around 40 ft. away from the pipeline.

As previously seen in Section 3.4, fire damage to buildings and personnel is also expected to occur from pipeline leaks which are directly dependant on the pool size emanating from the leak. Unlike the previous calculations where the tank contents at the Kittitas terminal were contained by a dike of known size, one cannot accurately estimate pool diameters because the leaked gasoline will flow in an irregular shape to follow the slope of the terrain to low points (e.g., it is even possible that it will flow into the sewer system). However, based on videos of pipeline fires it is reasonable to expect direct flame involvement with houses for distances of around 100-200 feet from the pipeline.

Crocker and Napier (34) provide safe separation distances for people from pool fires estimated to be 3-5 pool diameters based on a "safe" radiant thermal impact of 4.7 kW/m^2. For an assumed burning gasoline pool diameter of only 20 ft., the safe distance ranges from 60-100 ft. Thus, for this "idealized" leak scenario, second degree burns would be expected in the range of 60-100 ft. away from a small pipeline leak that only produced a pool leak size of only 20 ft.

IV. CONCLUSIONS

Based on a comprehensive review of the literature and the flammability/explosivity/ toxicity analysis given in this report, the principal conclusions are:

X The Kittitas community around North Bend is subjected to an extreme (i.e., one that can affect many lives) flammability hazard from a large pipeline leak (e.g., around 1,000 gal. of vaporized gasoline or larger) that produces a vapor cloud explosion. The calculated distance for destruction of housing and, thus, death to occupants from a collapsing structure is estimated to be around 370 ft. At distances from 100-200 ft. from the pipeline damage including loss of life is expected from flame contact to structures from fuel runoff. Even small size pool fires (e.g., 20 ft. in diameter) can contribute to second degree burns over distances of 60-100 ft.

- X Death is expected for people inside the Chicago, Milwaukee-St. Paul railroad tunnel at Snoqualmie pass from even small amounts of gasoline either due to toxicity, flame and/or smoke poisoning (principally carbon monoxide poisoning due to incomplete fuel combustion) and explosive forces.

  + All ignition sources must be banned from the tunnel if a pipeline is to be housed therein as this combination appears to be in violation of the National Electrical Code (NEC) for a partially confined space for a Class 1 Group D classification necessary for gasoline.

- X Major damage to buildings, tanks and other items from an explosion of gasoline vapor (e.g., 10,000 gallons) is expected to be confined within a diameter of around 800 ft. Partial demolition of houses and glass breakage is expected at around 2,570 ft. and 11,435 ft. (2.2 miles), respectively. Radiant heat release from a diked pool fire 472 ft. in diameter resulting from a single 150 ft. diameter tank by 48 ft. high of gasoline is significant: wood is expected to ignite at around 650 ft. away from the fire while second degree burns are expected at around 1/4 of a mile. Brush fires are expected to occur which could spread to other occupied structures leading to additional deaths and/or property damage.

- X Grossly inadequate water supplies at the proposed Kittitas terminal and also serving the Kittitas community along with a lack of highly-trained tank fire fighting personnel preclude the extinguishment of even a single large (e.g., 150 ft. in diameter) storage tank fire. Full involvement of the remaining tanks within a diked region is probable. Structural collapse of some of the remaining tanks due to thermal stresses will overflow diked regions as the requirement is that only the content of the largest tank need be contained within the dike.

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