# REDUCED PURGE RATES IN NATURAL GAS VENT STACKS

Grahame Y. Buss, Peter S. Tromans†
Shell Research Ltd, Thornton Research Centre, P.O. Box 1, Chester CH1 3SH, UK
†Present address Ocean Research and Development, Bel Air Technology Centre, P.O. Box 481, Houston TX7701, USA



Buoyancy driven turbulent mixing carries air into natural gas vent stacks and a concentration gradient is formed with part of the stack containing a flammable mixture. Purging with natural gas ensures that the flammable region is small A safe minimum purge rate depends on both, a reliable method for calculating the size of the flammable region as a function of purge rate and a safety criterion. We present a theory for predicting the air concentration profile in a stack. Agreement with experimental results is excellent. The criterion for determining the minimum purge rates depends on the hazard created by the region of flammable gas in the vent stack. We have conducted a series of combustion experiments in 10" and 36" diameter pipes containing stoichiometric mixtures of either propane or methane in air. The results show that the (*de facto* industry standard) Husa minimum purge rate safety criterion is unduly conservative. We recommend a ten-fold reduction in purge rates based on the Husa criterion, in all but the smallest diameter pipes.

**keywords:** vent stack, natural gas, purge rate, hazard, ignition, over pressure

## INTRODUCTION

Within Shell UK Exploration and Production operations it has been estimated that around 2 million $m^3$/year of natural gas (STP) is used as a continuous purge of vent stacks; required on the grounds of safety. Natural gas is usually lighter than air so buoyancy driven turbulent mixing carries air into the stack. The air mixes with the vented gas and a concentration gradient arises with some parts of the stack containing a flammable mixture. The aim of purging is to ensure that the flammable region is kept small. The mixing process in the stack is unsteady. Bryce and Fryer-Taylor (1993) have observed the process in small scale quartz models illuminated by a laser sheet in which one of the gas phases is dyed with smoke. They observe a flow in which air penetrates far into the stack without ostensible mixing, where time dependent flammable regions and interfaces form and where the two components become closely intertwined in thin convoluted layers. Averaged over time the stationary concentration gradient varies approximately exponentially along the stack.

The extent of the flammable region is a function of the Froude number, $F_r$,$=gd/U^2$, the density ratio , $\rho_g/\rho_o$ and the velocity ratio $U/U_w$ (where g is the acceleration due to gravity, d is the pipe diameter and U is the gas purge speed up the pipe, $\rho_g$ is the purge gas density, $\rho_o$ is the air density and $U_w$ is the wind speed). The higher the purge rate, the smaller the flammable region. The larger the pipe diameter, the larger the flammable region for a given purge rate. The heavier the gas, the shorter the flammable region. For vent gases heavier than air the flammable region is determined by the penetration of the wind into the stack alone. This general dependence is true both of the instantaneous and the stationary flows, but the propagation of a flame is fast compared to the mixing so it is the instantaneous concentration distribution that is of importance. Clearly, were the averaged, well mixed, concentration profile to exist it would present a greater hazard than the instantaneous distribution of gas, so as a convenient and conservative measure we consider the stationary flow.

Husa (1964), working for Amoco, published a safety criterion from which a safe minimum purge could be determined. This safety criterion, which has become a *de facto* industry standard, requires that there should be no more than 6 % oxygen 25' from the top of tall vent stacks. This safety criterion is based on an engineering judgement appropriate at the time, but now perhaps with an inappropriate balance between safety and atmospheric emissions. The objective of this work is to define a safety criterion on the basis of measurement, for tall vent stacks purged with natural gas.

## THE FLOW MODEL

Husa (1964, 1977) obtained empirical expressions for the time averaged penetration of air into tall purged vent stacks as a function of purge gas, pipe diameter and purge rate. Panchenko (1993) put this onto a firmer physical footing by considering the flow as pockets of air sinking and mixing into the rising purge gas. Panchenko obtains an expression with six empirical coefficients. Here, we present an analysis of the buoyancy driven turbulent penetration of air into tall vertical vent stacks and obtain an expression with one empirical coefficient. The assumption we make is that buoyancy forces dominate over inertial forces and viscosity. We obtain a one-dimensional stationary solution in which the upward flow of the lighter gas balances the turbulent diffusion of air into the stack. For this problem we take y as the co-ordinate measured positive from the top of the stack down, ρ and u as the density and velocity of the gas mixture in the stack and d as the stack diameter. We start with the continuity equation

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho u}{\partial y}=o, \qquad 1$$

and make the substitutions in terms of mean and fluctuating components;

$$\rho=\bar{\rho}(y)+\rho'(y,t) \text{ and } u=U+u'(y,t), \qquad 2$$

where $U$ is the mean velocity up the stack. The resulting equation is averaged to obtain the equation for the stationary flow,

$$U\frac{d\bar{\rho}}{dy}+\frac{d\overline{\rho' u'}}{dy}=0. \qquad 3$$

The term $\overline{\rho' u'}$ may be related to an eddy diffusion coefficient ε such that

$$\overline{\rho' u'}=\varepsilon\frac{d\bar{\rho}}{dx}, \qquad 4$$

where the eddy diffusion coefficient can be estimated from a mixing length model

$$\varepsilon=\lambda u'_{rms}. \qquad 5$$

$\lambda$ is of the order of the pipe diameter d. Furthermore, since the turbulence is generated entirely by buoyancy forces $u'_{rms}$ may be expressed in terms of a Richardson number as

$$u'_{rms} \propto \left( \frac{-1}{\bar{\rho}} \frac{d\bar{\rho}}{dy} g d^2 \right)^{1/2} . \qquad 6$$

We will also use the substitution $\eta = y/d$. Substituting for $\eta$, and equations 4, 5 and 6 in equation 3 we obtain

$$\frac{d\bar{\rho}}{d\eta} = k . \frac{g^{1/2} d^{1/2}}{U} \frac{d}{d\eta} \left[ \frac{d\bar{\rho}}{d\eta} \left[ \frac{-1}{\bar{\rho}} \frac{d\bar{\rho}}{d\eta} \right]^{1/2} \right], \qquad 7$$

where k is a constant of order 1. Writing the Froude number $F_r = gd/U^2$ and integrating once gives

$$\bar{\rho} - \rho_g = k . F_r^{1/2} \frac{d\bar{\rho}}{d\eta} \left[ \frac{-1}{\bar{\rho}} \frac{d\bar{\rho}}{d\eta} \right]^{1/2}, \qquad 8$$

where $\rho_g$ is the purge gas density and arises from the boundary condition $\bar{\rho} \to \rho_g$, as $d\bar{\rho}/d\eta \to 0$. Equations 8 is integrated by parts to give

$$\eta F_r^{-1/3} = B + 3k \sum_0^n \frac{\left(1 - \rho_g/\bar{\rho}\right)^{n+1/3}}{3n+1} . \qquad 9$$

The constant k is found by a best fit through the data given in section 4 and the constant B is found from the boundary condition $\bar{\rho} = \rho_0$ when $\eta = 0$,where $\rho_0$ is the density of air.

## EXPERIMENTAL PROGRAMME

The experimental apparatus for the first part of the work consisted of a 0.254 m diameter, 20 m long pipe supported vertically by scaffolding. Methane was vented up the pipe at various rates and the concentration along the pipe length was measured with 11 ADC ltd IR methane detectors spaced up the pipe. These detectors were located on platforms mounted up the stack to minimise the gas sample line lengths and to keep the length approximately the same for all detectors. The sample points were located 2, 4, 6, 8, 14, 16, 22, 24, 40 78 and 80 pipe diameters from the open end. The methane samples were drawn continuously from locations on the centreline of the stack at a rate no greater than 25 ml/min; chosen to be small enough so as not to interfere with the overall flow. The transit time along each sample line was approximately 2 minutes. The output from the gas detectors was collected electronically and stored on disk for later analysis. The experiment was repeated for purge rates between 0.5 mm/s and 30 mm/s at wind speeds between 0.5 m/s and 12 m/s.

In the second stage of the programme flammable mixtures were ignited in a 0.254 m diameter vent pipe, 26 m long. In this case the pipe was mounted horizontally and made up of 2 m long flanged sections. One end of the pipe was closed with a flange. Quiescent mixtures of methane (10.5%) or propane (4.5%) in air were enclosed in various lengths of the pipe and ignited either at the open end or inside the pipe (only the results for ignition sources at the open end of the vent pipe are given here). The flammable mixtures extended from the start of the open end of the pipe. The part of the vent pipe between the flammable mixture and the closed end contained air. The flammable gas was contained in the pipe by a thin plastic sheet at the open end and a thin paper sheet at the other. The plastic sheet (similar to cling film) was held lightly on by a magnetic strip that blew off at a very small over pressure. The paper ruptured at a small over pressure or in some cases, when the over pressures were very small, burned up when the flame reached it. Pressures were measured with five Kistler gauges (piezo electric type 701A) mounted flush with the wall or, in one case, in the end flange plate. The signals were recorded using the FAMOS rapid data gathering system. The ignition sources were in all cases ICI match head detonators ignited electrically.

Experiment were also done in a 36" ID pipe 8 metres in length. In this case the pipe section was closed at one end with a flange and filled with a methane/air mixture slightly rich of stoichiometric. The ignition source was at the open end of the pipe and a plastic covering was pulled free from the end of the pipe just prior to ignition. Ignition was by inductive spark.

## RESULTS AND DISCUSSION

### Concentration measurements in a vertical vent stack

Figure 1 shows the methane concentrations as a function of height for the various purge rates. The results show, as one would expect, that as the purge rate increases the methane air mixture becomes progressively more confined to the top part of the stack The top of the stack is y/d=0 and the bottom y/d=80 pipe diameters. The methane concentration at the

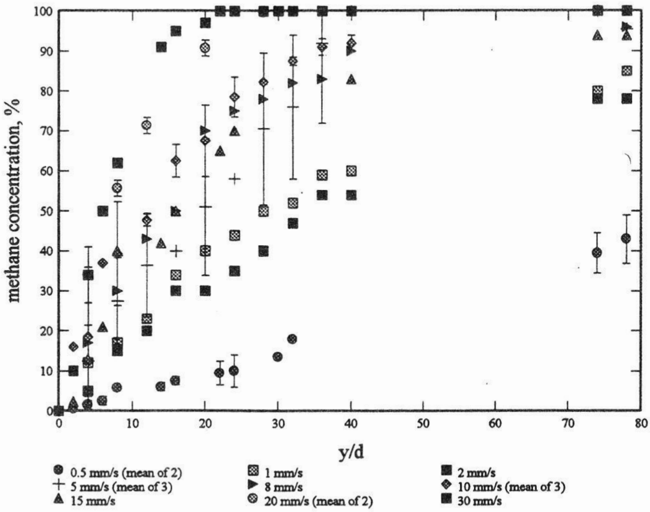


**Figure 1**. *The variation of methane concentration along a vent stack for various purge rates (shown here in mm/s). The stack has a diameter of 10" and is 80 diameters long. Error bars showing the spread of the data are included where more than one set of measurements were made for a particular purge rate. This figure shows measurements made in winds from 0.5 m/s to 12 m/s*

top of the stack, in these experiments, was always zero. This boundary condition at the top of the stack is unavoidable other than on very still days or with very high purge rates. It is extremely unusual to have a day with no wind at all; we experienced no winds less than 0.5m/s. As the wind speed was always far greater than the purge speed the methane was swept away from the stack giving to all intent and purposes zero methane concentration at the mouth.

One can show by considering the turbulent Navier-Stokes equations and assuming a Prandtl mixing length theory that the influence of the wind falls off exponentially down the pipe and will be negligible after a few diameters. For this paper we have not included the wind as an independent variable in the analysis of the data. This simplification introduces a small and negligible error of the order of the concentration change over a few pipe diameters.

Figure 2 shows results of this work together with data from Husa (1964) plotted according to equation 9 with k=0.8. The air concentration in figure 2 is related to the gas density in the pipe, $\overline{\rho}$, by the expression

$$C_{air} = \left(\overline{\rho} - \rho_g\right) / \left(\rho_o - \rho_g\right). \qquad 10$$

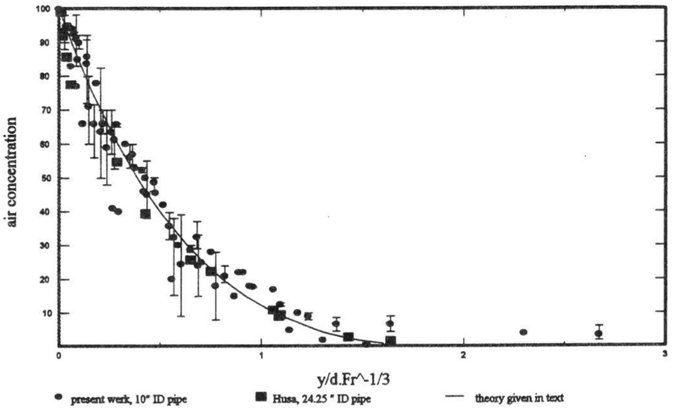


**Figure 2.** *The variation of the air concentration along the stack as a function of the non-dimensional group* $y/d.F_r^{-1/3}$ *for methane purge gas. The bars show the spread of results with the average of no more than five values in each case. The constant arising in the theory, k=0.8.*

Figure 2 demonstrates the validity of the theory for methane with pipes of the diameters shown. Figure 3 shows a comparison between the theory and experimental data taken from Husa (1964) for helium. The value of the coefficient in the fit remains 0.8.

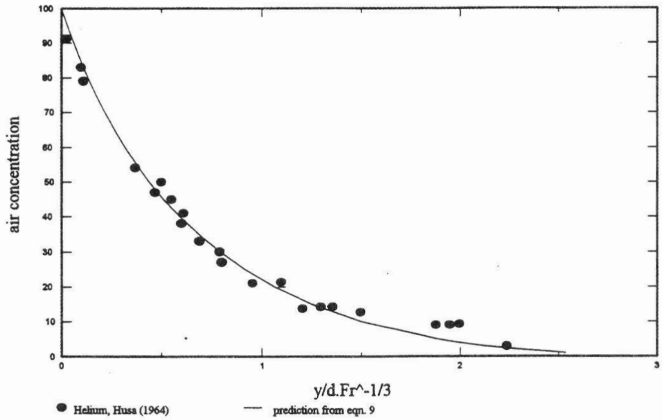


**Figure 3**. *The variation of the air concentration along the stack as a function of the non-dimensional group* $y/d.F_r^{-1/3}$ *with helium purge gas. The constant arising in the theory, k=0.8.*

One may be confident from these results that the theory is an adequate representation of the flow.

<u>The safe purge rate as a function of pipe diameter using Husa's criterion</u>

Husa (1964) states that,

> "The American Oil Co's experience indicates that tall blown stacks are safe with no more than 6% oxygen 25' from the top. This oxygen level is roughly half that required for flammable mixtures with hydrocarbons. Hence, flammable conditions would be limited to less than the top 25' of the stack. The gas rate required to establish the 6% level 25' from the stack top is therefore defined as the minimum safe purge rate."

With this safety criterion we calculate the purge rate as a function of pipe diameter using equation 9 by substituting the values given by Husa above. This gives an expression for the purge rate: $U = 0.076d^2$, where U is the purge rate up the stack in m/s and d is the stack diameter. However, if we take an oxygen level of 9% - that is, half the minimum level of oxygen required for combustion in air, we obtain

$$U = 0.044d^2. \qquad 11$$

Equation 11 is shown on figure 5 compared with purge rates from Husa (1964) and Husa (1977). At 6% oxygen the curve follows the higher purge rates given by Husa in 1964. Clearly, as the current theory is in good agreement with Husa's results it is not surprising that we obtain broadly the same purge rates when Husa's safe purge rate criterion is applied.

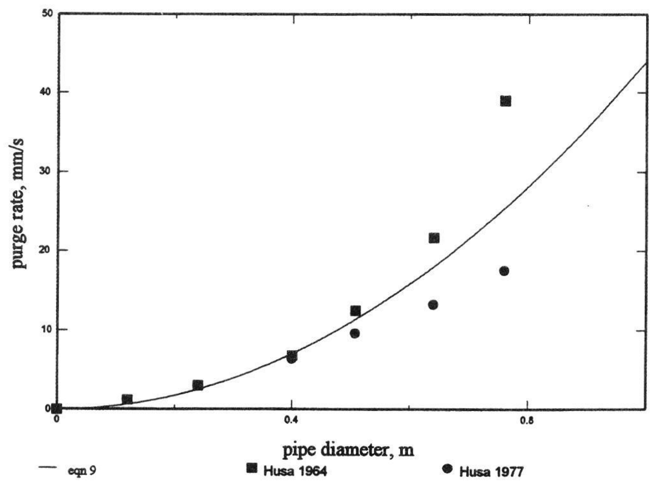


**Figure 5.** *The purge rate to satisfy the Husa safety criterion, as a function of pipe diameter.*

Low energy ignition of flammable mixtures in the vent pipe

Figure 6 shows the over and under pressures generated with ignition at the open end of the vent stack. One can see from figure 6 that the over- and under-pressures generated are slight for ignition sources at the open end of the stack. (Note that for most experiments there is an under as well as an over pressure as the pressures generated oscillate about atmospheric pressure. In many cases, where the ignition source was at the open end of the pipe, the under pressure exceeded the over pressure.) For the present study, flammable lengths up to 120 pipe diameters were investigated using methane and propane. Propane was chosen as the worst case of a natural gas mixture in terms of flame speed propagation.

The results of the present study show maximum over- and under-pressure that rises only slightly as the flammable length is increased in the 10" diameter pipe. Indeed, it is possible that the flame front propagation is stabilised at a low speed (approximately 5 m/s in this case) by the venting of the combustion products in the opposite direction to the flame front propagation. In support of this Lee (1977) states that one condition for self detonation - the condition where a flame front accelerates from a deflagration to a detonation - is that the combustion starts at a closed end. However, results from Tite *et. al.* (1989) shown on figure 6 for similar gas mixtures in a longer pipe show increasing over pressures as the flammable volume in the pipe increases.

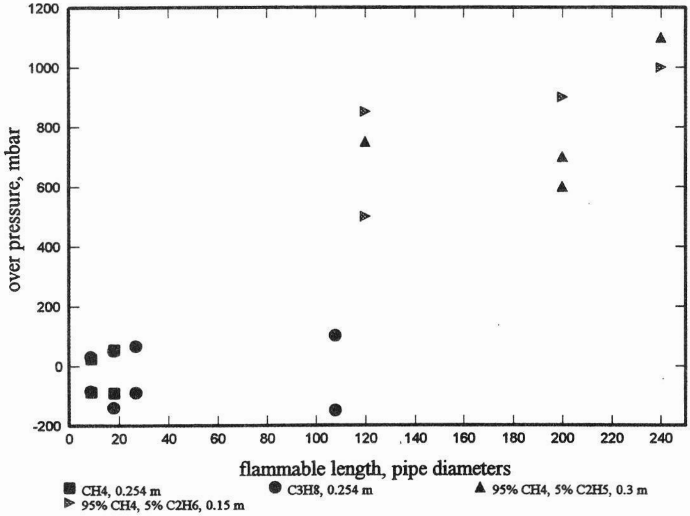


**Figure 6.** *The maximum over- (and under-) pressure generated in a straight pipe with the ignition source at the open end of the pipe. All hydrocarbons are mixed stoichiometrically with air. The pipe diameters are shown: 254 mm is the present study; 150 mm and 300 mm are taken from Tite et.al. (1989). Note that the positive and negative pressures shown are paired as the pressure trace from each event oscillates above and below atmospheric pressure.*

Tite *et. al* (1989) carried out an experimental study of the consequences of air ingress into stacks containing quiescent natural gas. In this work natural gas mixtures were ignited in pipes of 150 mm and 300 mm diameter and up to 240 diameters in length. The ignition was initiated by a low energy electrical discharge. If a comparison between the present work and that of Tite is valid then it is possible that given a long enough pipe a significant over pressure or self-detonation could result from an ignition source at the open end. However, given that most, if not all, straight vertical vent pipes will not exceed a length of 200 pipe diameters this question is not relevant to this study.

For the 36" diameter pipe we recorded no pressure greater than 1 bar.

A sufficient conclusion that may be drawn from these measurements is that the pressures measured in all cases are slight.

High energy ignition

A direct detonation may occur if the ignition energy is high enough, Lee (1977). At the open end of a vent stack the only source of energy that is a candidate for this effect is a lightning return stroke ( a number of strokes make up a flash). Taylor (1939, 1946, 1950) has addressed the questions of the propagation of constant energy blast waves and spherical detonations. Both the theories of the propagation of strong blast waves from lightning strokes (a review is given by Uman (1969)) and through detonable mixtures, e.g. Lee *et al.* (1966) or Kailasanath and Oran (1984), are based on Taylor's work. Taylor (1950) points out that an explosive charge is about a three times better radiator of energy than a point source. Lightning is a line source and therefore likely to be a poorer radiator of energy than an explosive charge. Nevertheless, to a first approximation it is legitimate to compare the energies of the two processes in terms of there efficacy in producing direct detonations.

The energy required to detonate a methane/air cloud (a spherical detonation) uniformly slightly rich of a stoichiometric mixture and of sufficient volume to produce a self-sustaining Chapman-Jouguet state (Lewis and van Elbe, 1987) is 22 Kg of tetryl explosive or $8 \times 10^7$ J, Bull *et al.*(1976). For ethane and propane in air the minimum energy is around $10^5$ J. Given the energy for a spherical detonation one can estimate the minimum energy for a cylindrical detonation using a result from Lee *et. al.* (1977). Using this we get a value of the minimum detonation energy of the order of $10^5$ J/m. For planar detonations Knystautas *et al.* (1984) give a minimum value of $2 \times 10^5$ J. Tite *et. al* (1989) found that they were able to detonate a stoichiometric natural gas/air mixture (methane containing 5.5% ethane) with 12.5 g of pentalite explosive in a 150 mm diameter pipe. In this case the detonation energy is of the order of $0.5 \times 10^5$ J. In a 300 mm diameter pipe they found $10^5$ J to be necessary. A charge of half this energy produced a deflagration comparable to that from their low energy spark ignitions.

The typical energy in a lightning stroke is estimated by Uman (1969) as of the order of $10^5$ J/m. This energy goes into dissociation, ionisation, excitation and kinetic energy. Uman and others estimate that almost all of the energy goes into the expansion of the surrounding air. A lightning stroke is made up of an initial current rise followed by a much longer decaying tail. A typical lightning stroke has a rise time of 8 μs to the peak current and has decayed back to 50% of the peak current by 25 μs. The current may flow for in excess of 300 μs. Lee et. al. (1974) and Knystautas and Lee (1976) have shown that it is the rising current wave only that initiates the direct detonation. Cornick and Greaves (1995) have produced discharges representative of the leading part of the current wave - 8 μs rise times to $3 \times 10^4$ amps across an electrode gap of 0.25 m and 25 μs to half the peak current. Measurements of the potential difference between the electrodes during the discharge enabled them to calculate the energy dissipated during the rising current portion of the current wave. They recorded a potential difference of at most 20 kV at the very start of the current wave falling to 10 kV for most of the rising current together with a peak current of $3 \times 10^4$ amps for 8 μs over a 0.25 m gap. This gives an energy of 5000 J/m. This is consistent with a total energy dissipated of something of the order of $10^5$ J/m over the complete stroke as estimated by Uman. We may conclude that the energy available in this rising current wave is 20 times too small to cause a direct detonation of a stoichiometric mixture of propane air. Peak currents greater than $3x10^4$ amps are encountered in some 10% to 25% of strokes. Peak currents as high as $11x10^4$ amps have been recorded and rise times of as long 30 μs. The energy associated with this hypothetical wave would still be just insufficient for a direct detonation of a natural gas mixture. Furthermore, Lee (1977), the energy required for a detonation increases as the time taken to deliver the energy increases.

In further support of the argument that a direct detonation will not occur, the gas mixture at the end of a vent pipe is far from the ideal conditions for a detonation. Indeed, based on the stationary flow model of minimum purge given here, the mixture surrounding the lightning stroke is not flammable over the purge rates of interest. In practice the gas mixture issuing from the end of a vent stack is composed of regions of gas of different concentrations: some are flammable and some are not, with the average concentration well below the flammable limit. For gas mixtures not at the ideal mixture ratio for detonation the energy needed for a direct detonation rises sharply. For example, Knystautas *et al.* (1984) give the direct detonation energy for 4.8 % propane in air in a pipe as $10^5$ J. With 3.4% propane in air this energy rises to $10^6$ J. At 3.2% propane it is $10^7$ J. The same effect is observed as the mixture becomes richer.

On this basis we can be confident that direct detonation from a lightning stroke and the propagation of that detonation into the vent stack, is negligible.

## PROPOSAL FOR A REDUCED MINIMUM PURGE RATE

It is clear from the measurements that an ignition at the open end of a vertical vent pipe cannot result in self detonation, other possibly than in very long pipes well in excess of 200 pipe diameters, and that over pressures are otherwise small. Furthermore, direct detonation appears extremely unlikely. Ignition of a flammable mixture at the open end of a vent pipe is the only credible location for ignition - with the possible exception of flammable mixtures extending into the knock out vessel at the base of the vent stack. Ignition further down the vent pipe is extremely unlikely as the vent pipe acts as a Faraday cage. The application of the Husa safety criterion gives flammable mixture lengths of the order of a few pipe diameters. Clearly, we can reduce the minimum purge rate. However, the precise reduction must be a matter of judgement as we have not been able to reach over-pressures hazardous to vent stacks. We propose for simplicity and ease of application a ten-fold reduction in the purge rate from the value found by the application of the Husa criterion for stacks with diameters between 10" and 36". We have chosen this range of diameters as they are covered by our experimental results. Figure 7 shows the new reduced purge rate relative to the Husa rule. For stacks with diameters less than 10" the Froude number is keep constant This ensures that the extent of the flammable region in terms of pipe diameters remains constant. The adoption of this rule for small pipe diameters is conservative and is clearly the safest case. Where this part of the curve intersects the Husa curve we apply the existing Husa rule from then on.

Using this rule a 10" diameter pipe requires a purge rate of 0.23 mm/s and a 36" diameter stack requires a purge rate of 3.5 mm/s. For stacks with diameters between 10" and 36" the flammable region extends approximately 7 metres along the pipe with the start of the flammable region 2 metres down from the open end.

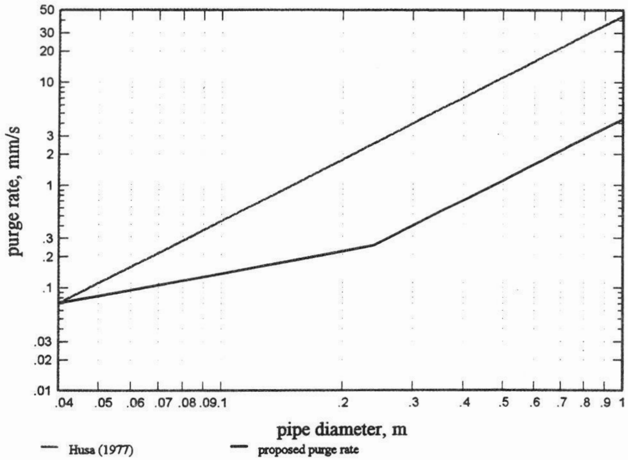


**Figure 7.** *The proposed reduction in purge rate as a function of pipe diameter compared to the purge rate given by the application of the Husa safety criterion.*

## CONCLUSIONS

We have shown that the time averaged buoyancy driven flow in a vent stack is accurately represented by a turbulent mixing length model.

We have recommended that the minimum purge be reduced to 10% of the current purge, calculated using the Husa safety criterion. We have shown that this will not entail any increased risk from dangerous over pressures arising from a low energy ignition of the flammable mixture in the vent pipe. We have also argued that the risk of a direct detonation from a high energy ignition source is negligible.

## REFERENCES

Bull D C., Elsworth J. E., Hooper G., Quinn C. P., 1976, A study of spherical detonation in a mixture of methane and oxygen diluted by nitrogen, J. Phys. London D Applied Phys. **9**, 14, 1991-2000

Bryce S. G., Fryer-Taylor, R. E. J., 1994, Reducing the purge in hydrocarbon vent stacks, J. Loss Prev. Process Ind., 7, No. 3, 249-255

Cornick, K., Greaves, D. A., 1995, Personal communication, The Electrical Engineering and Power Systems Group, UMIST

Husa H.W., 1964, How to compute safe purge rates, Hydrocarbon Processing and Petroleum Refiner, **43,** No. 5

Husa H. W., 1977, Purging requirements in large diameter pipes, presented at the Fire Safety Engineering subcommittee of the API, San Francisco

Kailasanath K., Oran E. S., 1984, in Dynamics of Shock Waves, Explosions and Detonations, **94** Progress in Astronautics and Aeronautics American, Institute of Aeronautics and Astronautics Inc, 38-54

Knystautas R., Cuirao C., Lee J. H., Sulmiistras A.,1984, in Dynamics of Shock Waves, Explosions and Detonations, **94** Progress in Astronautics and Aeronautics, American Institute of Aeronautics and Astronautics Inc, 23-37

Kynstautas, R., Lee, J. H. 1976, Combustion Flame, **27**, 221-228

Lee J. H. S., 1977, Initiation of Gaseous Detonation, Ann Rev. Phys. Chem., **28**, 75-104

Lee, J. H., Kynstautas, R., Guirao, C., 1974, 15th Symp. Int. Combust. Proc., 53-68

Lewis, B., van Elbe, G., 1987, Combustion, Flames and Explosions of Gases, Academic Press Inc

Panchenko, V. I., 1993, Determination of the safe velocity for flare stack purging, Khimicheskoe I Neftekhimicheskoe Mashinostroenie, **5**,5-7

Peraldi O., Knystautas R., Lee J. H., 1986 Criteria for transition to detonation in tubes, Twenty-first symposium (International) on Combustion , 1629-1637

Taylor, G. I., 1939, The Propagation and Decay of Blast Waves, in The Collected Papers of Sir Geoffrey Ingram Taylor, 1967, Vol III, 221-235, ed G. K. Batchelor, Cambridge University Press

Taylor, G. I., 1946, The air wave surrounding an expanding sphere, Proc. Roy. Soc., A, **86**, 273-92

Taylor G. I. 1950, The formation of a blast wave by a very intense explosion 1. Theoretical discussion, Proc. Roy. Soc., A **201**, 159-174

Tite J. P., Greening K., Sutton P., 1989, Explosion hazard of air ingress into flare stacks, Chem Eng Res Des, **67**, July.

Uman M. A., 1969, Lightning, McGraw Hill Inc.