

# Safe Purging of Natural Gas Pipelines

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**Summary.** When a newly constructed natural gas pipeline is put into service, it can be safely purged of air by injection of a slug of inert gas, such as N<sub>2</sub>. The method of sizing the required slug is based on a model of dispersion in turbulent flow in conjunction with flammability limits.

## Introduction

When a newly constructed natural gas pipeline is put into service, the initial air in the line must be purged. If natural gas is used directly to perform the purging, the air and the natural gas will mix, and flammable mixtures will form in the pipeline. The safety hazard such mixtures present is of concern. In the following discussion, the purging problem is analyzed. First, the hazards of flammable mixtures of the type that can form during purging of a natural gas line are discussed. Then it is demonstrated that inherent dangers are low and can be eliminated by introduction of an inert gas slug between the air and natural gas. A method of sizing the required slug is developed. Measurements taken during the purging of a 10-in. [25.4-cm] pipeline have been analyzed and are shown to be in good agreement with calculated performance.

Recommendations for future purging operations are presented. A step-by-step procedure for sizing of inert-gas purging slugs is given.

## Hazards of a Flame

The composition of any mixture of combustibles, inerts, and oxygen can be represented on a ternary diagram. Fig. 1 shows such a diagram divided into three regions. Compositions in the smallest region are detonable. Those in the next largest region, which includes all detonable compositions, are flammable. The balance of compositions lies in the nonflammable region.

The danger of a gas mixture in a pipeline depends on its composition. Nonflammable mixtures present no danger. Flammable mixtures, if ignited, result in propagation of a flame and attendant temperature and pressure increases. As long as operating pressures during purging are maintained at reasonable levels, the limited stresses that might be caused by ignition of a flammable (but non-detonable) mixture are tolerable. Ignition of a detonable gas mixture, on the other hand, could lead to formation of a shock wave and large pressure increases. A detonation in a pipeline would be too dangerous to be tolerated.

A simple analysis of the effects of ignition of flammable gases formed in the mixing zone during a hypothetical purging is presented below. Fig. 2 illustrates a purging operation. Assume that the gases in the flammable portion of the mixing zone (of length  $L_z$ ) are instantaneously burned and result in a flame temperature about eight times the initial absolute temperature.<sup>1</sup> The increase in temperature of the burned gases will cause a proportionate increase in pressure, which will be dissipated throughout the pipeline as gas flows away from the heated region. If no gas can escape from the pipe, the maximum final pressure in the pipeline will be approximately

$$p_f = p_i \left[ \frac{L_z}{L} (p_r - 1) + 1 \right] \dots \dots \dots (1)$$

For example, with a flammable mixing length of  $1/10$  the length of the pipeline, an initial pressure of 40 psia [276 kPa], and a ratio of flame temperature to initial temperature of eight (which gives rise to a pressure ratio of eight),

$$p_f = (40)[(0.1)(8 - 1) + 1] = 68 \text{ psia [467 kPa],}$$

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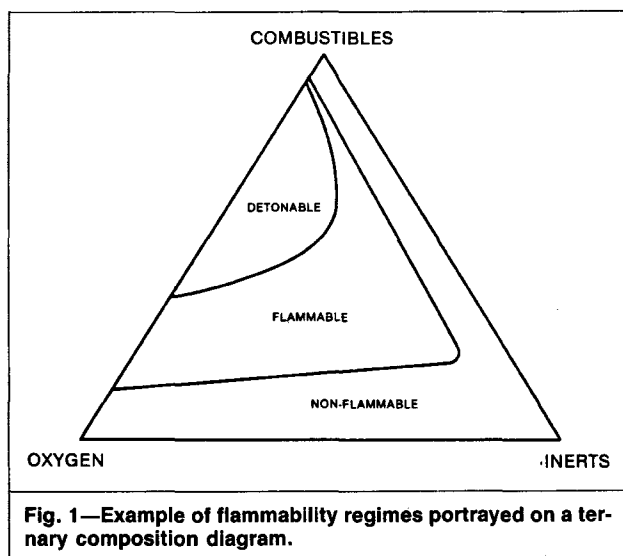
although a pressure spike of 320 psia [2.21 MPa] might be developed. Both pressures are well within the pressure rating of typical natural gas pipelines. Heat losses and the open (flow) nature of the system will cause the pressures developed in practice to be even lower. Peak temperatures are even less of a problem: if all heat is assumed to be instantaneously transferred to the pipe, calculations show that its maximum temperature increase is  $<2^\circ\text{F}$  [ $1.1^\circ\text{C}$ ] for the average pressure scenario outlined. Taken together, the pressure and temperature analyses indicate that the effects of a simple flame on a pipeline are not of concern. Detonations, on the other hand, can produce pressure increases<sup>2</sup> of greater than a factor of 40. The pressure rise occurs across a very thin zone traveling at supersonic speeds (i.e., across a shock wave sustained by the detonation). A 1,000-psig [6.9-MPa] -rated pipeline operating at an initial pressure of 40 psia [276 kPa] might not be able to sustain such a pressure pulse. The detonable region is therefore the most dangerous area for operation. Unfortunately, it is also the least well defined. Detonations can be prevented in practice, however, in several ways. For a detonation to form in a gas mixture, the mixture must be detonable, an ignition of the mixture must occur, and there must be a sufficient length of flammable gas for the flame to undergo a transition from deflagration to detonation.<sup>3</sup> If any one of these required conditions is prevented, the detonation cannot form. Each factor is discussed in detail.

First, the mixture must be detonable. This is a more restrictive requirement than flammability, as indicated in Fig. 1. Unfortunately, the detonable regime for gas mixtures is not well defined. Experimental data on the detonable range of individual combustible species are generally unavailable, and there is no well-established means of extrapolating the available data to arbitrary gas mixtures. As a general rule, hydrocarbon mixtures are not detonable in air at atmospheric pressure and temperature, but a gas high in hydrogen, hydrogen sulfide, ethane, propane, or acetylene content might be.<sup>3,4</sup>

Although the formation of detonable mixtures is improbable, prevention of detonability can be guaranteed by ensuring that the gas is nonflammable. This is a restrictive approach, but assessment of flammability is a tractable problem. Unfortunately, development of a mixing zone within which the gases are flammable is virtually guaranteed when natural gas is used directly to purge air from a pipeline. Flammable mixtures can be avoided, however, by introduction of a slug of inert gas between the air and natural gas. If the slug is of sufficient size, only limited mixing of the air and natural gas will occur, and flammable (and hence detonable) mixtures will be prevented.

The second requirement for formation of a detonation is the ignition of the flammable gas. No known ignition sources exist during a pipeline purge. Nevertheless, a static discharge or a spark resulting from impact of some particle with the pipe wall might serve as a source of ignition. This is considered unlikely and is made more so by the nature of the purging operation, which generally takes place in the turbulent flow regime where ignition is more difficult.<sup>5</sup> Nevertheless, ignition cannot be entirely ruled out.

Finally, formation of a detonation requires, in addition to ignition of a detonable mixture, sufficient travel distance in the pipe for the flame formed initially to undergo deflagration-to-detonation



transition (DDT). Typical values of the ratio of length to diameter,  $L/d$ , for DDT at atmospheric pressure are 60 to 300.<sup>2,3,6</sup> The length of the detonable mixing zone would therefore have to be greater than about 60 pipe diameters for a detonation to develop. The shock wave, once formed, would be capable of propagating in gas compositions outside the detonable regime, but it would tend to be dissipated by frictional effects.

It is clear from this discussion that the risk of having a dangerous detonation is low during the course of a pipeline purge, even if nothing is done to prevent it. Nevertheless, the uncertainty associated with detonability limits and ignition and the possibility of

exceeding run-up distances for DDT make prevention of flammable mixtures the only guaranteed form of ensuring safety in all conceivable situations.

## Nitrogen-Slug Sizing

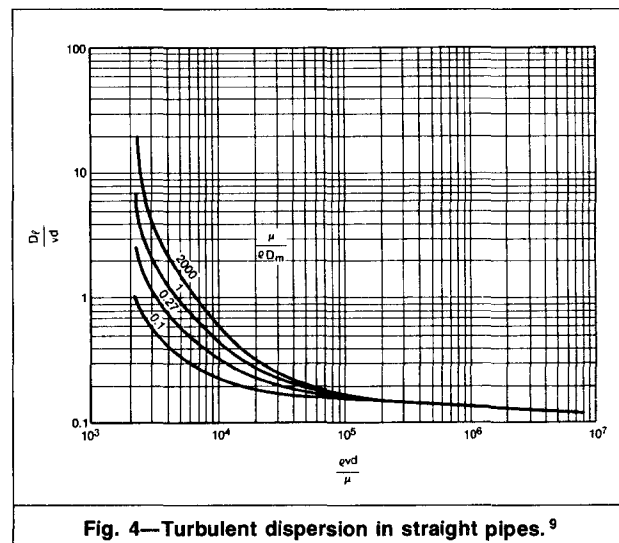
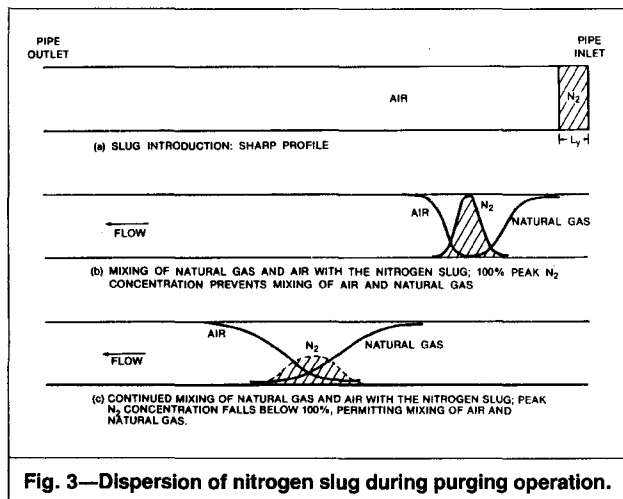
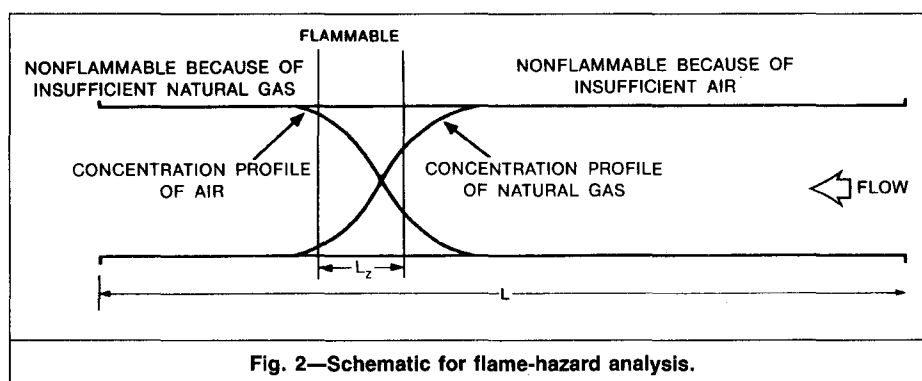
Consider a pipeline as illustrated in Fig. 3. Air in the pipeline is to be replaced with natural gas. A nitrogen slug of length  $L_y$  has been injected before the line was purged, and the slug acts as a buffer between the air and the natural gas. Mixing zones develop at both the leading and trailing edges of the slug that with time become indistinct. It is desirable to size the slug so that at no point is the composition within the flammable envelope for the combustible gases of interest.

The purging process should be designed so that flow is turbulent. If velocities are low enough to result in laminar flow, the displacement front will approach a parabolic shape,<sup>7</sup> which will lead to long transition zones and poor displacement efficiency. Under turbulent conditions, the interface between two fluids moves along the pipeline with an essentially piston-like displacement (i.e., with a relatively plane front rather than parabolic), but a transition zone develops and grows in length as the displacement increases. The S-shaped concentration profile<sup>8</sup> is given by

$$c = 0.5 \operatorname{erfc} \left[ \frac{(L_x - vt)}{2\sqrt{D_e t}} \right] + 0.5 \exp(vL_x/D_e) \operatorname{erfc} \left[ \frac{(L_x + vt)}{2\sqrt{D_e t}} \right]. \quad (2)$$

Note that  $vr$  is the position along the pipeline of the piston-like displacement.

Now consider the effective longitudinal dispersion coefficient,  $D_e$ . Dispersion occurs during flow in a straight pipe, and bends in the pipe contribute additionally to dispersion. Fig. 4<sup>9</sup> gives a



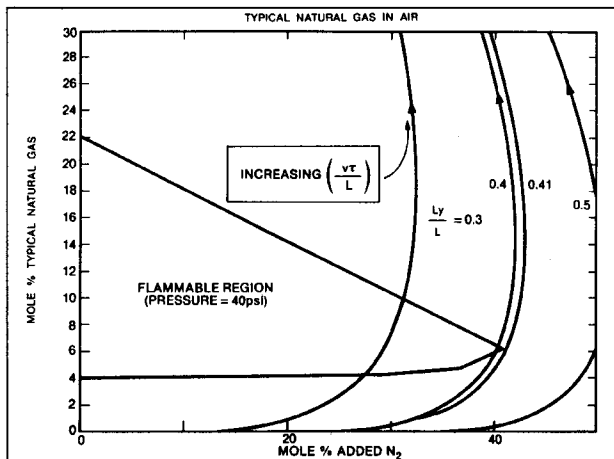


Fig. 5—Flammability envelope for typical natural gas in air and nitrogen with effluent composition curves for various slug sizes and  $(D_e/vd)(d/L) = 0.1$ .

graphical portrayal of the reciprocal of Peclet number as a function of the Reynolds number (with the Schmidt number as parameter) for turbulent flow in a straight pipe. From this figure,  $D_t$  can be determined.

Bends in the pipe can cause a significant increase in dispersion. Use of Bischoff's<sup>10</sup> method allows the effect of a number of bends in the pipe,  $n_b$ , to be combined with  $D_t$  to give the effective dispersion coefficient,  $D_e$ .

$$\frac{D_e}{vd} = \frac{D_t}{vd} \left( 1 - n_b 30 \frac{d}{L} \right) + \frac{n_b}{2} 900 \frac{d}{L} \quad \dots \dots \dots (3)$$

If a slug of nitrogen is used to separate the air and the natural gas during a purging operation, a transition zone will develop at each end of the nitrogen slug, as illustrated in Fig. 3. The length of the transition zone will depend on the distance along the pipeline, as well as on purging parameters and gas properties. If the slug is too small relative to the dispersion rate and distance traveled, it will become significantly dispersed, the peak nitrogen concentration will fall well below 100%, and air and natural gas will begin to mix in proportions that may approach flammability. The worst case occurs at the pipe exit, where the concentration of air is given by a rearrangement of Eq. 2 with  $L_x = L$ :

$$C_a = 1 - 0.5 \operatorname{erfc} \left[ \frac{0.5 \left( 1 - \frac{v\tau}{L} \right)}{\sqrt{\left( \frac{D_e}{vd} \right) \left( \frac{d}{L} \right) \left( \frac{v\tau}{L} - \frac{L_y}{L} \right)}} \right] - 0.5 \exp \left[ \left( \frac{vd}{D_e} \right) \left( \frac{L}{d} \right) \right] \operatorname{erfc} \left[ \frac{0.5 \left( 1 + \frac{v\tau}{L} \right)}{\sqrt{\left( \frac{D_e}{vd} \right) \left( \frac{d}{L} \right) \left( \frac{v\tau}{L} - \frac{L_y}{L} \right)}} \right] \quad \dots \dots (4)$$

Note that this assumes a very idealized purging operation in which the purge is assumed to begin with a flow of nitrogen that changes over instantaneously to natural gas after a slug length,  $L_y$ . The entire process is assumed to occur at a constant velocity,  $v$ .

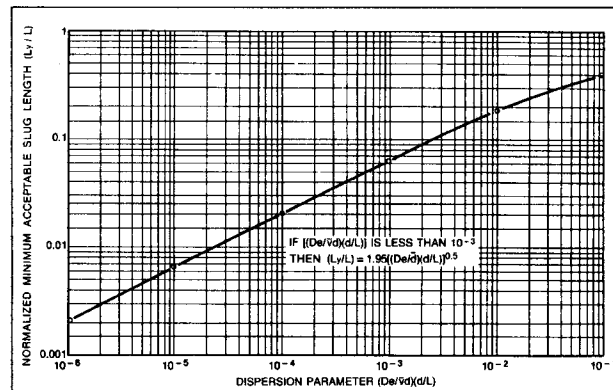


Fig. 6—Minimum acceptable slug length as a function of the dispersion parameter for Natural Gas B in air and nitrogen.

Similarly, Eq. 5 gives the concentration of natural gas at the pipe exit with  $L_x = L$  and  $t = \tau - (L_y/v)$ :

$$C_g = 0.5 \operatorname{erfc} \left\{ \frac{0.5 \left[ 1 - \left( \frac{v\tau}{L} - \frac{L_y}{L} \right) \right]}{\sqrt{\left( \frac{D_e}{vd} \right) \left( \frac{d}{L} \right) \left( \frac{v\tau}{L} - \frac{L_y}{L} \right)}} \right\} + 0.5 \exp \left[ \left( \frac{vd}{D_e} \right) \left( \frac{L}{d} \right) \right] \operatorname{erfc} \left\{ \frac{0.5 \left[ 1 + \left( \frac{v\tau}{L} - \frac{L_y}{L} \right) \right]}{\sqrt{\left( \frac{D_e}{vd} \right) \left( \frac{d}{L} \right) \left( \frac{v\tau}{L} - \frac{L_y}{L} \right)}} \right\} \quad \dots \dots \dots (5)$$

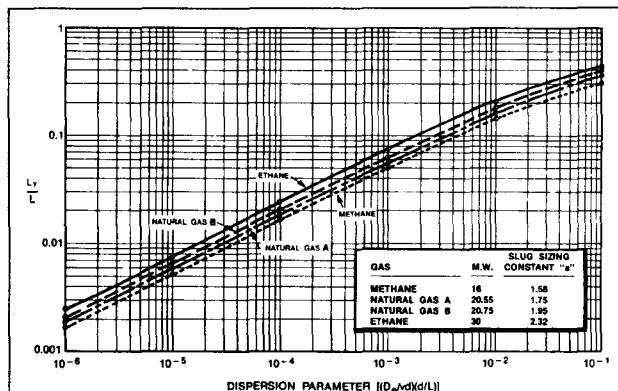
The concentration of nitrogen from the slug is given by

$$C_{N_2} = 1 - C_a - C_g \quad \dots \dots \dots (6)$$

Fig. 5 shows, for a pressure of 40 psia [276 kPa], the limits of flammability of a typical natural gas in air as a function of the inert nitrogen in the mixture (the nitrogen in addition to that in the air). Also plotted in the figure are curves giving the calculated effluent composition for a given value of  $(D_e/vd)(d/L)$  and several values of  $L_y/L$ . Movement along a curve corresponds to an increasing value of the parameter  $v\tau/L$  and hence to increasing time since initiation of the purge. The minimum acceptable slug length is defined by the effluent composition curve that is tangent to the flammability envelope. For this example of a very short pipe, a slug volume of 30% of the pipe volume is too small, and some effluent concentrations are flammable. A purge slug as large as 50% of the pipe volume is larger than needed. Fig. 5 shows that for this example a purge slug 41% as large as the pipe volume will just avoid all flammable compositions at the exit of the pipe.

Limiting values of  $L_y/L$  determined from curves like these for various values of  $(D_e/vd)(d/L)$  are plotted in Fig. 6. As indicated, the minimum acceptable slug size can be approximated by Eq. 7 for values of  $(D_e/vd)(d/L) < \sim 0.001$ :

$$\frac{L_y}{L} = a \left[ \left( \frac{D_e}{vd} \right) \left( \frac{d}{L} \right) \right]^{0.50} \quad \dots \dots \dots (7)$$



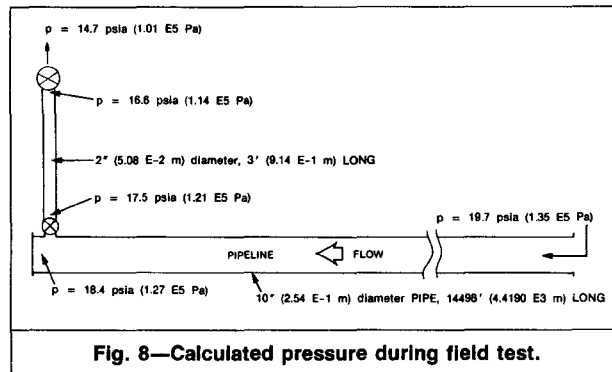
**Fig. 7—Minimum acceptable slug length as a function of the dispersion parameter for various combustible gases in air and nitrogen. (MW = molecular weight.)**

where  $a$  is determined from the log-log plot and is equal to 1.95 for this particular natural gas in air and nitrogen.

The same approach can be used with any flammability envelope to determine the associated slug-sizing function. Slug-sizing functions calculated for a different natural gas and for methane and ethane all show the same functional behavior for values of  $(D_e/vd)(d/L) < 0.001$ : the exponent in each case is 0.50, and the only varying parameter is the leading coefficient, which increases with increasing protrusion of the flammability envelope (see Fig. 7).

### Field Test Results

To obtain data in a large pipe, a field experiment was conducted during an actual purging operation. The experimental apparatus is shown in Fig. 8. A test section was installed at the pipeline vent with a bleed tap for instrument samples. The sampled gases flowed through continuous CO/CO<sub>2</sub> and oxygen meters. The concentrations were monitored simultaneously on a two-pen strip-chart recorder, and periodic measurements of pressure and temperature were made with a data logger. The natural gas contained about 1.5% CO<sub>2</sub> and no oxygen, while air contains about 20.9% oxygen and



**Fig. 8—Calculated pressure during field test.**

a negligible amount of CO<sub>2</sub> (330 ppm). The measured CO<sub>2</sub> concentration in the pipeline, normalized by its concentration in the natural gas, was used to give the percentage of natural gas in the pipeline effluent as a function of time. Similarly, the measured oxygen concentration was used to derive the concentration of air in the pipeline effluent as a function of time. The balance of the effluent gas at any point in time was assumed to be nitrogen from the nitrogen slug.

The pipeline purged for the experiment was 10 in. [25.4 cm] in diameter and 14,498 ft [4419 m] long with twenty-six 90° [1.6-rad] elbows and nineteen 45° [0.79-rad] bends along its length. Two bottles of nitrogen, each containing about 250 scf [7 std m<sup>3</sup>], were injected over a period of about 30 minutes. Fig. 8 and Table 1 summarize the calculated flow conditions and gas properties during the displacement. Effluent concentration profiles are shown in Fig. 9. The small spike of CO<sub>2</sub> contamination preceding the nitrogen slug is not believed to reflect the presence of natural gas accurately. From the length of the pipeline and the time needed for the nitrogen/natural-gas interface (defined by the 50% natural gas concentration) to reach the end of the pipe, the average velocity was determined:

$$v = \frac{(14,498 \text{ ft})}{(12.13 \text{ minutes})(60 \text{ sec/min})} = 19.9 \text{ ft/sec [6.1 m/s]}.$$

**TABLE 1—CONDITIONS AND GAS PROPERTIES DURING FIELD TEST**

Average temperature, °F [°C]	22 [-5.6]
Average pressure in 10-in. [25.4-cm] pipe, psi [Pa]	19.05 [1.313]
Average velocity in 10-in. [25.4-cm] pipe, ft/sec [m/s]	19.9 [6.07]
<b>Air properties</b>	
$\rho$ , lbm/ft <sup>3</sup> [kg/m <sup>3</sup> ]	0.107 [1.71]
$\mu$ , cp [mPa·s]	0.0165 [0.0165]
<b>Nitrogen properties</b>	
$\rho$ , lbm/ft <sup>3</sup> [kg/m <sup>3</sup> ]	0.103 [1.65]
$\mu$ , cp [mPa·s]	0.0163 [0.0163]
<b>Natural gas properties (molecular weight = 20.65)</b>	
$\rho$ , lbm/ft <sup>3</sup> [kg/m <sup>3</sup> ]	0.076 [1.22]
$\mu$ , cp [mPa·s]	0.01 [0.01]
<b>Air/nitrogen interface (use arithmetic average of <math>\rho</math> and <math>\mu</math>)</b>	
$\bar{\rho}$ , lbm/ft <sup>3</sup> [kg/m <sup>3</sup> ]	0.105 [1.68]
$\bar{\mu}$ , cp [mPa·s]	0.0164 [0.0164]
$D_{\text{air/N}_2}$ , ft <sup>2</sup> /sec [m <sup>2</sup> /s]	$1.41 \times 10^{-4}$ [ $0.131 \times 10^{-4}$ ]
$N_{\text{Re}}, \frac{\bar{\rho} v d}{\bar{\mu}} = 1.6 = 10^5$	
$N_{\text{Sc}}, \frac{\bar{\mu}}{\bar{\rho} D_{\text{air/N}_2}} = 0.74$	
<b>Nitrogen/natural-gas interface (use arithmetic average of <math>\rho</math> and <math>\mu</math>)</b>	
$\bar{\rho}$ , lbm/ft <sup>3</sup> [kg/m <sup>3</sup> ]	0.090 [1.44]
$\bar{\mu}$ , cp [mPa·s]	0.0132 [0.0132]
$D_{\text{N}_2/\text{methane}}$ , ft <sup>2</sup> /sec [m <sup>2</sup> /s]	$1.49 \times 10^{-4}$ [ $0.138 \times 10^{-4}$ ]
$N_{\text{Re}}$	$1.7 \times 10^5$
$N_{\text{Sc}}$	0.66

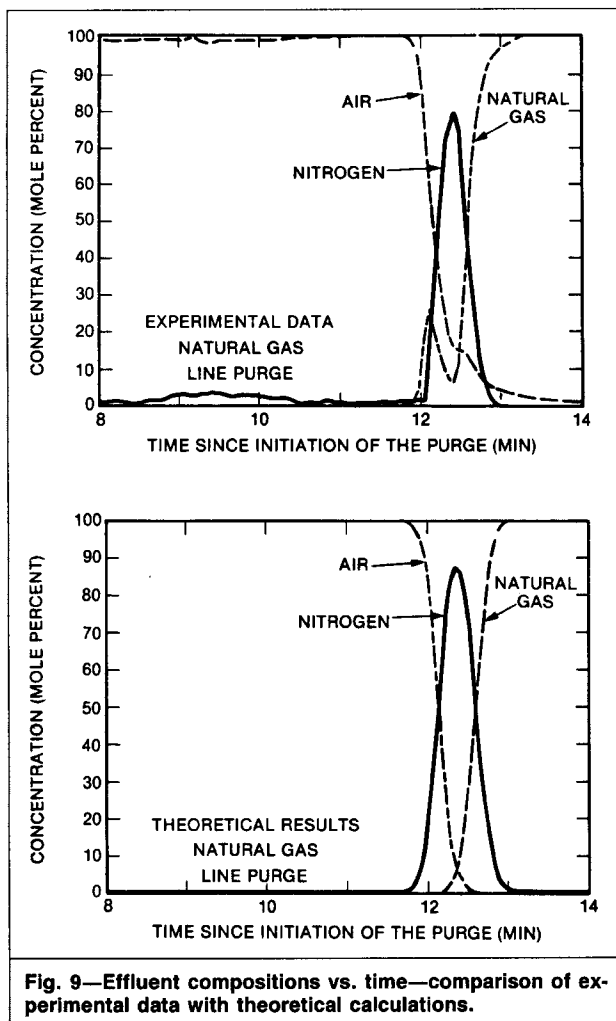


Fig. 9—Effluent compositions vs. time—comparison of experimental data with theoretical calculations.

The effective dispersion coefficient can be calculated from experimental values of the parameter

$$\lambda_x = \frac{1 - V_x/V_p}{\sqrt{V_x/V_p}}$$

The relationship between the dispersion coefficient and  $\lambda$  is<sup>11</sup>

$$\frac{D_e}{vd} = \frac{L}{d} \left( \frac{\lambda_{90} - \lambda_{10}}{3.625} \right)^2 \quad (8)$$

Experimental values of  $\lambda_{10}$  and  $\lambda_{90}$  can be determined from a plot of the concentration profiles of the air/nitrogen and nitrogen/natural-gas interface on normal probability paper (see Fig. 10). Values of  $-0.016$  and  $+0.016$ , respectively, result in a calculated value of  $(D_e/vd) = 1.35$  for the field experiment.

Values of  $D_e/vd$  for the air/nitrogen and nitrogen/natural-gas interfaces can be determined from Fig. 4 (using the data in Table 1). The most conservative value (for the lowest Reynolds number) is  $(D_e/vd) = 0.16$ .

The twenty-six  $90^\circ$  [1.6-rad] bends and nineteen  $45^\circ$  [0.79-rad] bends will significantly increase dispersion; however, Bischoff<sup>10</sup> proposed the following method to include these effects:

$$\frac{D_e}{vL} = \frac{D_t}{vL} \frac{\left( L - n_b \frac{L_b}{d} \right)}{L} + \frac{1}{2n_b} \left( \frac{n_b L_b}{L} \right)^2, \quad (9)$$

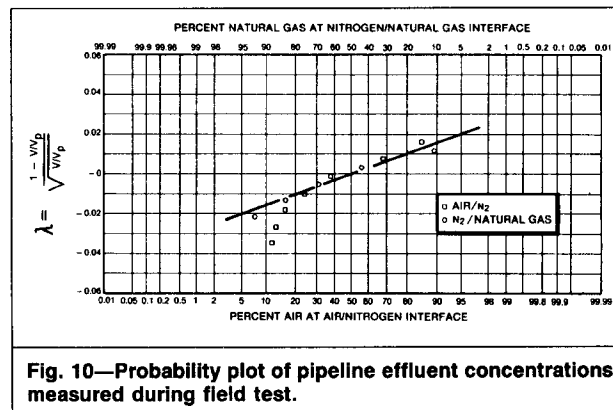


Fig. 10—Probability plot of pipeline effluent concentrations measured during field test.

which can be written as

$$\frac{D_e}{vd} = \frac{D_t}{vd} \left( 1 - n_b \frac{L_b}{d} \frac{d}{L} \right) + \left( \frac{n_b}{2} \right) \left( \frac{L_b}{d} \right)^2 \left( \frac{d}{L} \right) \quad (10)$$

Treating each of the bends equally gives the following value of  $L_b/d$  for the field experiment:

$$1.35 = 0.16 \left( 1 - 45 \frac{L_b}{d} \frac{0.833}{14,498} \right) + \frac{45}{2} \frac{0.833}{14,498} \left( \frac{L_b}{d} \right)^2$$

$$\frac{L_b}{d} = 30.$$

This value is reasonably close to the value of 26 determined by Bischoff for a different set of conditions.

The theoretical curves of pipeline effluent concentrations can be determined from Eqs. 3 through 6 and Fig. 4. These calculated curves, shown in Fig. 9, are in good agreement with concentrations measured during the field test (also shown in Fig. 9).

## Conclusions and Recommendations

1. To ensure safe operation under all circumstances, an inert gas slug can be injected as a spacer between the air to be purged from the pipeline and the natural gas used to purge it. A method for sizing inert slugs to prevent formation of flammable mixtures has been developed.

2. Slug-sizing equations should be derived for the flammability envelope for the particular natural gas of interest. In the absence of more detailed flammability data, the slug-sizing function for ethane can be used as a conservative approximation for most natural gases.

The constants in the slug-sizing equations must be recalculated if an inert other than nitrogen is to be used because the inert gas chosen affects the dimensions of the flammability envelope. ( $\text{CO}_2$  would, in fact, be preferred to nitrogen as the inerting agent because it results in a narrower flammability envelope in all cases.) Similarly, new calculations should be made for elevated pressures or temperatures because both result in a broadening of the flammability envelope.

3. To minimize dangers associated with flammable gases, the flowing pressure should be kept as low as possible, consistent with achievement of the target Reynolds numbers, for two reasons. First, the flammability envelope broadens with increased pressure. Second, initial pressures are multiplied by a constant factor if burning occurs. The peak pressure achieved is therefore strongly dependent on the initial pressure.

4. A step-by-step procedure for the sizing of inert gas slugs for the purging of natural gas pipelines is given in the Appendix.

## Nomenclature

$a$  = slug-sizing constant (see Eq. 7)

$C$  = concentration of injected gas, mol%

$C_a$  = concentration of air, mol%  
 $C_g$  = concentration of natural gas, mol%  
 $C_{N_2}$  = concentration of nitrogen, mol%  
 $d$  = pipe ID, ft [m]  
 $D_e$  = effective longitudinal turbulent dispersion coefficient, ft<sup>2</sup>/sec [m<sup>2</sup>/s]  
 $D_l$  = longitudinal turbulent dispersion coefficient, ft<sup>2</sup>/sec [m<sup>2</sup>/s]  
 $D_m$  = molecular diffusivity, ft<sup>2</sup>/sec [m<sup>2</sup>/s]  
 $F_s$  = safety factor,  $F_s > 1$   
 $L$  = pipeline length, ft  
 $L_b$  = length of pipe that would give dispersion equivalent to that occurring in a bend, ft [m]  
 $L_x$  = distance measured from pipe inlet, ft [m]  
 $L_y$  = slug length, ft [m]  
 $L_z$  = length of flammable mixing zone, ft [m]  
 $n_b$  = number of bends in the pipe  
 $n_c$  = number of cylinders of compressed gas required for minimum slug size (with safety factor included)  
 $N_{Pe}$  = Peclet number =  $vd/D_l$   
 $N_{Re}$  = Reynolds number =  $\rho vd/\mu$   
 $N_{Sc}$  = Schmidt number =  $\mu/\rho D_m$   
 $p$  = maximum pressure in the pipeline, psia [kPa]  
 $p_f$  = final pressure in pipeline after passage of flame, psia [kPa]  
 $p_i$  = initial pressure in pipeline, psia [kPa]  
 $p_r$  = ratio of pressure after burning to pressure before burning for constant-volume adiabatic system  
 $t$  = time of displacement, seconds  
 $T$  = absolute temperature, °R [K]  
 $v$  = velocity of displacement, ft/sec [m/s]  
 $V_c$  = standard volume of gas in compressed gas cylinder, scf [std m<sup>3</sup>]  
 $V_p$  = volume of the pipe, ft<sup>3</sup> [m<sup>3</sup>]  
 $V_x$  = volume of purging gas injected when x% of the purged gas is observed at the pipe outlet, ft<sup>3</sup> [m<sup>3</sup>]  
 $\lambda_x = \frac{1 - V_x/V_p}{\sqrt{V_x/V_p}}$   
 $\mu$  = viscosity, lbm/ft-sec [kg/m·s]  
 $\rho$  = gas density, lbm/ft<sup>3</sup> [kg/m<sup>3</sup>]  
 $\tau$  = time since initiation of purge (including introduction of nitrogen slug at average purging velocity), seconds

## Superscript

- = average

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## Appendix—Determination of Inert-Gas Requirements

1. Calculate the Reynolds number ( $N_{Re} = \rho vd/\mu$ ) for each fluid (natural gas, nitrogen, air) for the steady-state purging flow rate. For conservatism, use the smallest of these Reynolds numbers in further calculations. Note that operations must be designed so that this Reynolds number is  $> 2,500$  (preferably  $> 10,000$ ).

2. Calculate the Schmidt number ( $N_{Sc} = \mu/\rho D_m$ ) for each fluid interface.

3. Read  $D_l/vd$  from Fig. 4.

4. Calculate  $D_e/vd$  with Eq. 3.

5. Determine the slug-sizing function using the approach outlined in this paper.

As a conservative approximation, the ethane-slug-sizing equation [for  $(D_e/vd)(d/L) < 0.001$ ] can be used:

$$\frac{L_y}{L} = 2.32[(D_e/vd)(d/L)]^{0.50}$$

If  $(D_e/vd)(d/L) > 0.001$ , refer to Fig. 7 to determine  $L_y/L$ .

6. Calculate the number of bottles of compressed inert gas required.

These calculations use engineering correlations and are based on idealized concentration profiles. Nonideal factors, such as entrance effects and bypassing in laminar sublayers, will be encountered during actual displacements. Hence, an appropriate safety factor is recommended:

$$n_c = F_s(L_y) \left( \frac{\pi d^2}{4} \right) \left( \frac{p}{14.7} \right) \left( \frac{520}{T} \right) \left( \frac{1}{V_c} \right) \dots \dots \dots (A-1)$$

## SI Metric Conversion Factor

$$\text{psi} \times 6.894\,757 \quad \text{E}+00 = \text{kPa}$$

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