# MODELLING PIPELINE DECOMPRESSION DURING THE PROPAGATION OF A DUCTILE FRACTURE

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There is considerable interest world wide amongst major pipeline operators in investigating the potential for using high-strength steels for long distance gas transmission pipelines. Although pipelines that are constructed from such materials will have higher material costs, economic studies[1] have shown that overall there will be a significant capital expenditure saving on a long (greater than 1000km) transmission line if such steels are used. However, one problem associated with the introduction of pipelines made from high-strength steels is the ability to demonstrate that a propagating ductile fracture occurring in the pipeline will be arrested. That is, there is a need to show that such fractures, which are highly unlikely to occur in practice, will not propagate beyond a small number of pipe joints. The present paper focuses on one specific aspect of this, namely the prediction of the gas decompression within the pipeline as a ductile fracture propagates along the pipeline. A mathematical model is proposed that relates the pressure in the pipeline to the velocities generated in the pipeline. It is shown that if real gas thermodynamics are taken into account, rather than assuming ideal gas behaviour, then this model is in good agreement with experimental data. It is also noted how this model can be used in practice, both directly in the design of pipelines and to help design experiments to study pipeline fractures.

## INTRODUCTION

There is considerable interest world-wide amongst major pipeline operators in investigating the potential for using high-strength steels for long distance gas transmission pipelines. Although pipelines that are constructed from such materials will have higher material costs, economic studies[1] have shown that overall there will be a significant overall saving associated with their use for a long (greater than 1000km) transmission line. This is due to the reduced construction costs and the higher capacity obtained from being able to operate the pipelines at a higher pressure.

However, one concern associated with the construction of pipelines made from high-strength steel is the ability of the material to arrest a propagating ductile fracture. That is, there is a need to show that such fractures, which are highly unlikely to occur in practice, will not propagate beyond a small number of pipe joints. It is important to prevent propagating fractures as, in addition to the safety concerns associated with the release of large quantities of gas from the failure, there are also significant economic concerns, associated with the disruption to the gas supply and the cost of repair of a long length of pipeline.

There are many technical aspects involved in studying this problem. The present paper focuses on one specific aspect, namely the prediction of the gas decompression within the pipeline as a ductile fracture propagates along the pipeline. The ability to predict the decompression in the pipeline is important, for it is the pressure of the gas at the tip of the crack that provides the ‘driving’ force that, if sufficient, will lead to a continuation of the propagation.

In Section 2 of this paper, a physical description is given of some of the important fluid flow phenomena that occur whilst a ductile failure propagates along the pipeline. Section 3 contains the equations for a simplified model to determine the fluid flow and pressure decay within the pipeline. In Section 4, a comparison is presented of the model against some existing data from experiments carried out specifically to study the behaviour observed during a pipeline rupture. The practical application of the model is discussed in Section 5, where it is noted that it can be incorporated within a model to predict whether a ductile fracture of a pipeline continues to propagate[2]. It is noted that the resulting model was also used to help design a series of pipeline fracture propagation tests carried out at the BG Technology Spadeadam Test Site[3]. The conclusions of the paper are given in Section 6.

## PHYSICAL DESCRIPTION OF FLOW

When a propagating ductile fracture is initiated, gas flows rapidly out of the opening that is produced. This outflow reduces the pressure in the neighbourhood of the opening and generates a decompression front (rarefaction wave) that propagates within the pipeline, away from the point of failure. The front propagates at the speed of sound corresponding to the initial pressure and temperature of the mixture in the pipeline. Lower pressure regions are created inside the pipeline, behind the decompression front,. The pressure information in these regions moves at the speed of sound evaluated at the local pressure and temperature of the mixture. Figure 1 illustrates a typical pressure profile produced during a propagating during a propagating ductile failure of a gas pipeline.

For a steady propagating ductile fracture, there is a dependence between the pressure field and gas velocity inside, and at the opening of, the pipeline. The shape of the curve relating the pressure to the gas velocity depends on the composition, pressure and temperature of the gas in the pipeline. In particular, certain gas mixtures can enter the region in which condensation of the gas to form liquid can occur within the pipeline. This has the effect of slowing the speed with which the decompression front moves. As a result, a higher pressure exists at the crack tip than would otherwise be the case, tending to favour the continued propagation of the crack. This issue is relevant to gas mixtures containing a high percentage of higher hydrocarbons (‘rich’ gases), especially if their initial temperature in the pipeline is lower than normal ambient values. It is important to be able to model any condensation accurately, as a failure to do so may result in an optimistic prediction being made about the likelihood of a propagating ductile failure being arrested.

In the following section a model for predicting the gas decompression is presented that takes due account of the detailed thermodynamic behaviour.

## GAS DECOMPRESSION MODEL

The gas flow ahead of a propagating ductile fracture is similar to the flow in a shock tube following the rupture of a diaphragm separating a high and a low pressure region. The location of the diaphragm corresponds to the location of the crack tip in the ductile fracture propagation event. A mathematical model of this flow is now described, based on shock tube theory. To derive the mathematical model the flow is assumed to be isentropic and inviscid. It is also assumed that there is no flow in the pipeline before it fractures, that condensation occurs instantaneously at the intersection of the pressure-temperature trajectory with the phase envelope and, following condensation, that the liquid and gas mixture components are homogeneous and in thermodynamic equilibrium. These assumptions tend to apply to large diameter pipelines where heat transfer and boundary layer effects are small and separation of liquid from gas components is less likely than in smaller diameter pipes.

The isentropic assumption means that there is a unique relationship between the pressure and the gas velocity and that this relationship is independent of the axial location in the pipeline. Further, given the composition, initial pressure and temperature the local speed of sound, $v_s$, is a function of the local pressure, $P_d$, in the pipeline Under these assumptions, the local pressure wave speed, $V$, is given by the equation,

$$V = v_s - u \qquad (1)$$

where $u$ is the local gas velocity in the pipe, defined by

$$u(P_d) = \int_{P_d}^{P_0} \frac{dP}{\rho v_s} \qquad (2)$$

The integration in equation (2) is evaluated regarding all of the variables as a function of pressure, $P$. The density of the fluid (gas or two-phase mixture) in the pipeline is $\rho$, and the suffix 0 denotes a quantity that is evaluated at the initial conditions in the pipeline. Groves et al.[4] give further details. Equation (2) is derived on the assumption that the thermodynamic energy liberated by the fall in pressure is converted into kinetic energy of the flow. For later convenience, the integral equation (2) is transformed into the initial value problem,

$$\frac{du}{d\rho} = -\frac{V_s}{\rho} \qquad (3)$$

subject to

$$u(\rho_0) = 0 \qquad (4)$$

The initial condition given in equation (4) of no flow within the pipeline prior to rupture is acceptable as gas velocities in pipelines are small relative to the gas velocity once a pipeline is ruptured. It is noted that the one dimensional flow assumption is reasonable ahead of the crack tip but may not be valid in the (small) region where the pipe is deforming and gas is escaping[5].

If the gas is assumed to behave in an ideal manner, then an analytical solution can be found to equations (1) and (2), relating the local pressure $P_d$ to the local pressure wave speed $V$. This solution can be written in the form:

$$P_d = P_0 \left( \frac{2}{\gamma+1} + \left( \frac{\gamma-1}{\gamma+1} \right) \frac{V}{v_a} \right)^{2\gamma/(\gamma-1)} \qquad (5)$$

where the term $v_a$ appearing in equation (5) denotes the sound speed calculated assuming ideal gas properties for the initial pipeline temperature and $\gamma$ is the ideal specific heat ratio.

The ordinary differential equation (3) can be solved numerically to include real gas effects, by the finite difference method, as follows. For a given reduction in pressure the density and temperature are predicted by an isentropic flash calculation. The isentropic flash calculation also indicates if the pressure-temperature trajectory has entered the two phase envelope. For single phase decompression, the gas phase density is calculated using the Peng Robinson (PR) equation of state[6]. When condensation occurs the density is taken as a vapour quality weighted harmonic average of the two phase densities.

The sound speed for a single phase gaseous fluid is evaluated from the analytic expression

$$v_s^2 = \frac{P}{\rho}\frac{C_p}{C_v} \qquad (6)$$

evaluated using thermodynamic relations derived from the PR equation of state. After condensation occurs within the pipeline the analytic expression for the speed of sound can no longer be used and must be evaluated numerically using a finite difference approximation to the governing thermodynamic expression for the speed of sound.

## MODEL VALIDATION

It follows from the description given in Section 3 that to calculate the correct pressure - gas velocity dependence requires the accurate calculation of the speed of sound. Figure 2a and b shows a comparison of the measured speed of sound for methane and ethane, respectively, with values calculated using the PR equation of state, as explained in Section 3 above. The measurements for the speed of sound are taken from Stray[7] and Tsumura and Stray[8] respectively. To enable a single figure to be used for each comparison, the sound speed, plotted on the y-axis, has been made dimensionless using the speed calculated assuming ideal gas behaviour at reference conditions and the pressure, plotted on the x-axis, is shown as the reduced pressure for that material. Results are shown for a number of different temperatures, identified by the value of the reduced temperature. A reduced pressure of 6 corresponds to an actual pressure of approximately 30 MPa (300 bar) for methane and ethane. This range of species, pressures and temperatures are considered as it includes the typical range of conditions encountered during the design of transmission pipelines. The comparison for single species sound speed measurements are shown here, as little data exists for multicomponent systems. From what little data there is, Picard and Bishnoi[9] have demonstrated there is no degradation in accuracy for single-phase, multicomponent systems compared to single species systems.

It can be seen from these figures that the predicted value for the sound speed is typically within 10% of the measured value. The step changes in the predicted sound speed are an artefact of the equation of state used to describe the gases. (In detail, the root of the cubic equation for the compressibility used to calculate the sound speed is based on a minimum Gibbs free energy criterion. The root of the cubic equation in compressibility factor giving the minimum Gibbs free energy changes where the step changes occur in the solutions). More sophisticated thermodynamic models could be used to overcome this problem. However, the method is considered to be sufficiently accurate in its present form to be used in the gas decompression model.

The model for predicting the pressure - velocity dependence is considered now. The two experiments used to evaluate the model are taken from Picard and Bishnoi[10]. For each experiment, two predictions are shown, a calculation assuming ideal gas behaviour (equation (5)) and a calculation based on the numerical solution of equation (3) and the PR equation of state, assuming real gas behaviour.

The conditions in the first experiment are summarised in Table 1. Figure 3 shows a comparison between the measured and predicted pressure plotted against the pressure wave velocity. Two sets of measurements are shown. These correspond to data gathered as the fracture propagates away from the initial rupture location on either side of the pipe. The good agreement between these two sets of measurements indicate good repeatability of the experiment. The predictions obtained assuming real gas behaviour are in very good agreement with the measurements. Further detailed examination of the model output shows that the model predicts that some condensation should occur in the pipeline at a pressure of approximately 4 MPa, but there is insufficient resolution in the measurements to confirm this behaviour. The values obtained assuming ideal gas behaviour tends to underpredict the measurements, although the rate of decay is reasonable. In fact, if the initial sound speed were calculated using equation (6), the ideal curve would agree well with the measurements.

The conditions of the second experiment are summarised in Table 2. The main difference between this test and the first experiment is in the value of the initial pipeline temperature, with the second test being 24 $^oC$ colder than the first test. In Figure 4 it can be seen this change has a significant effect on the pressure - velocity curve, with a pronounced plateau occurring at a pressure of approximately 6.6 MPa. The curve showing the predictions assuming real gas behaviour is in close agreement with the measurements, showing the occurrence of the plateau. The curve showing the predictions obtained assuming ideal gas behaviour is qualitatively incorrect, as it takes no account of the condensation occurring during the depressurisation process.

The good agreement exhibited between the predictions obtained assuming real gas behaviour for both experiments in part is due to the excellent agreement in the calculated value of the initial sound speed (a relative difference of less than 0.1 %). This is consistent with the comparison of sound speeds shown earlier, as the initial reduced temperature in these cases is of the order of 1.5. The curve showing the predictions in Figure 2a) for pure methane at a reduced temperature of 1.57 is in particularly good agreement with the measured sound speed. In regions of pressure-temperature space where the sound speed prediction is not as accurate, the gas decompression model would be correspondingly less accurate. Nevertheless, the trends would be expected to be predicted correctly, provided the effects of real gas behaviour are correctly taken into account.

## APPLICATION OF THE MODEL

The gas decompression model can be combined with a model to predict the fracture velocity as described in Poynton et al[11], Eiber et al.[5] and Liu et al.[2] to provide a model to predict whether a ductile failure will continue to propagate within a pipeline. The resulting model can then be used to calculate a minimum specification for the pipeline material to prevent a propagating ductile fracture from occurring. As well as being used like this at the design stage of a pipeline project, software based on the modelling approach discussed above can also be used to analyse existing pipelines. This could be to examine proposals to increase the operating pressure or to transport a natural gas with a different composition. Output of the model can be used to investigate or demonstrate whether such proposed changes in operation would compromise the ability of the existing pipeline to arrest a propagating ductile fracture.

One further application of the model is to help in the design of experiments carried out specifically to study pipeline fractures. A key requirement in designing a pipeline fracture experiment is the determination of the length of the reservoirs, attached at each end of the pipeline test section, required to reproduce conditions that would exist in a full length pipeline. It is important that, following its initiation, the crack either propagates to the end of the test section or arrests before the reflection of the initial decompression wave travels back from the gas reservoir end cap and reaches the propagating crack tip. If the reflected wave reaches the propagating crack tip before the crack either arrests or reaches the end of the test section, the experimental data would be impaired as the subsequent pressure at the crack tip would no longer be the same as would occur in a full length pipeline.

The model has recently been used successfully in this context for a series of tests described by Johnson et al[3]. A test rig was built at full scale at the BG Technology Spadeadam Test Site to study the propagation of a ductile fracture in a pipeline. The test section consists of a buried, instrumented section of pipeline welded at either end to two gas reservoirs. The propagation of the fracture and conditions within the pipeline were recorded in the experiments. It was found that the gas decompression behaviour predicted by the model described in this paper was in good agreement with the measurements made during these tests. Figure 5 is a picture taken during one of the tests and shows the fire that was produced following the deliberate ignition of the gas released following the rupture of the pipeline. As explained further in Johnson et al.[3], the measurements that were made during these tests have been used to help demonstrate the acceptability of a specific pipeline project, proposed by Alliance Pipeline of Canada.

It is noted here that to make the application of the model as convenient as possible and to prevent inadvertent misuse, the gas decompression model and the fracture velocity models referenced above have been implemented in a computer package FRACPROP. A graphical user interface is incorporated to help the problem specification, and results are also interpreted graphically. All physical properties necessary to complete the model simulations are available as part of the computer package.

## CONCLUSION

A model for the gas decompression behaviour in a pipeline following its rupture has been presented. The thermodynamic relationships in the model are based on real gas behaviour, as opposed to ideal gas behaviour. As a result, the model can be used to analyse pipelines transporting both lean and rich natural gas over a range of operating pressures and temperatures. This is possible as the use of real gas thermodynamics means that condensation within the pipeline can be predicted. An indication of the accuracy of the model has been given, by comparing its predictions for two pipeline rupture experiments. Whilst it would be desirable to obtain comparisons of predicted gas decompression with measurements for a wider range of pipeline conditions, the agreement obtained in the two test cases is encouraging. The application of the model to practical situations, involving pipeline or experiment design, has been discussed and an example has been given in which the model was used successfully in this latter context.

A number of assumptions are required to formulate the model. Some of the assumptions, for example the isentropic flow assumption could be relaxed and a model based on the 1D Euler equations formulated. However the partial validation study presented in this paper suggests the additional complexity and computer run-time would not be balanced by the possible increase in accuracy. A better use of resources, to improve predictions of arrest or propagate of a ductile fracture in linepipe transporting natural gas, (the overall objective), would be to address deficiencies in our understanding of fracture mechanics in high strength steels such that more accurate fracture velocity models could be developed.

## NOMENCLATURE

| | |
|---|---|
| $C_p$ | Specific heat at constant pressure, J kg$^{-1}$ K$^{-1}$ |
| $C_v$ | Specific heat at constant volume, J kg$^{-1}$ K$^{-1}$ |
| $P_d$ | Pressure, Pa |
| $P_0$ | Initial pressure, Pa |
| $u$ | Gas velocity, m s$^{-1}$ |
| $V$ | Pressure wave velocity, m s$^{-1}$ |
| $v_s$ | Acoustic velocity, m s$^{-1}$ |
| $\gamma$ | Ideal ratio of specific heats |
| $\rho$ | Density, kg m$^{-3}$ |
| $\rho_0$ | Initial density, kg m$^{-3}$ |

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Table 1 - Initial conditions for Test 1

| | |
|---|---|
| **Initial Pressure (MPa)** | 7.544 |
| **Initial Temperature (C)** | 18.5 |
| **Methane** | 0.847 |
| **Ethane** | 0.082 |
| **Propane** | 0.044 |
| **Iso-Butane** | 0.002 |
| **N-Butane** | 0.002 |
| **Nitrogen** | 0.022 |

Table 2 - Initial conditions for Test 2

| | |
|---|---|
| **Initial Pressure (MPa)** | 8.786 |
| **Initial Temperature (C)** | -5.1 |
| **Methane** | 0.852 |
| **Ethane** | 0.081 |
| **Propane** | 0.044 |
| **Iso-Butane** | 0.002 |
| **N-Butane** | 0.003 |
| **Nitrogen** | 0.018 |

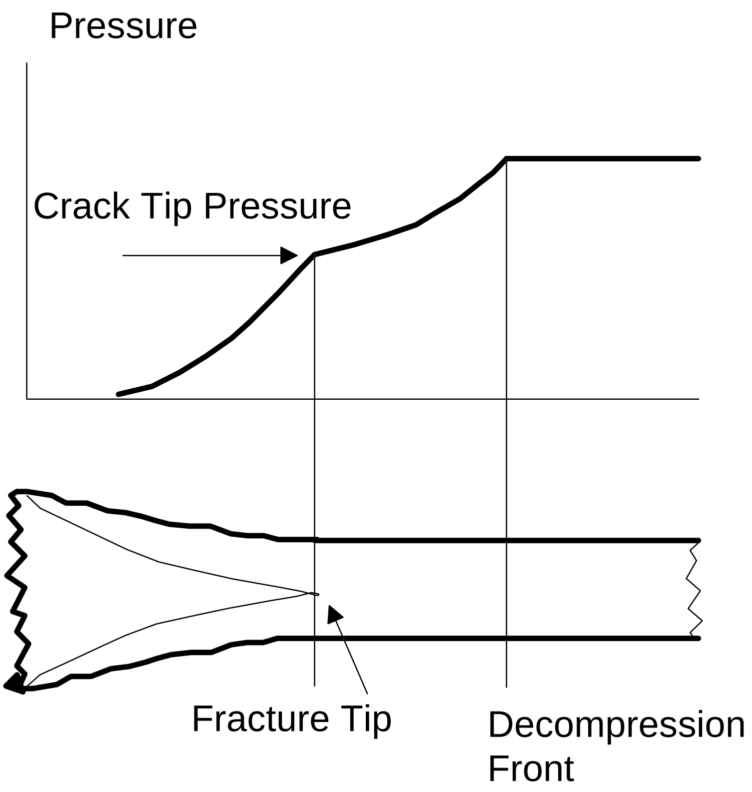
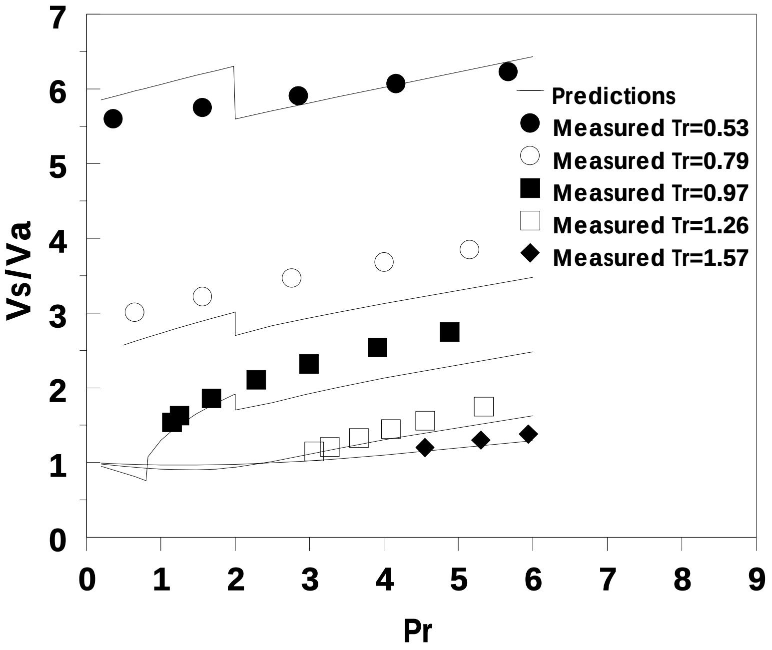
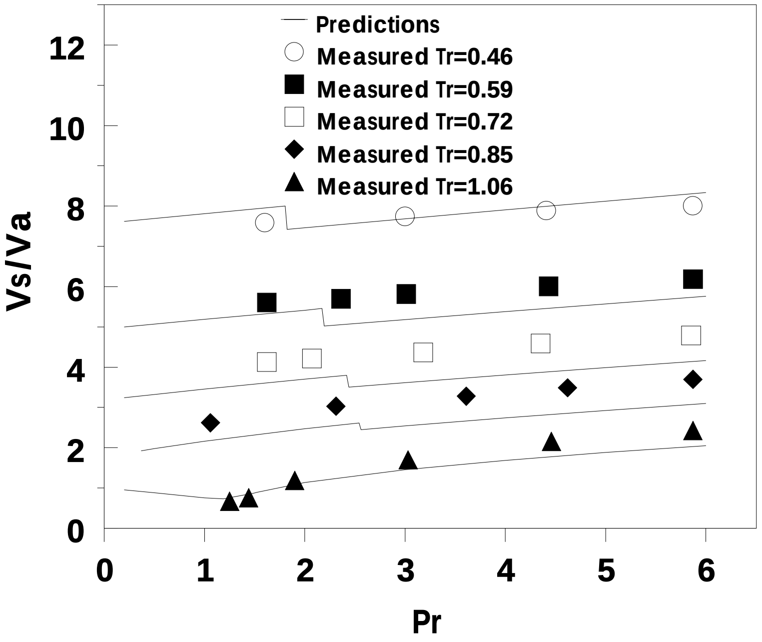


Figure 1 - Schematic diagram of a propagating ductile fracture in a pipeline.



a)



b)

Figure 2 - Predictions and measurements of sound speeds of a) methane and b) ethane.

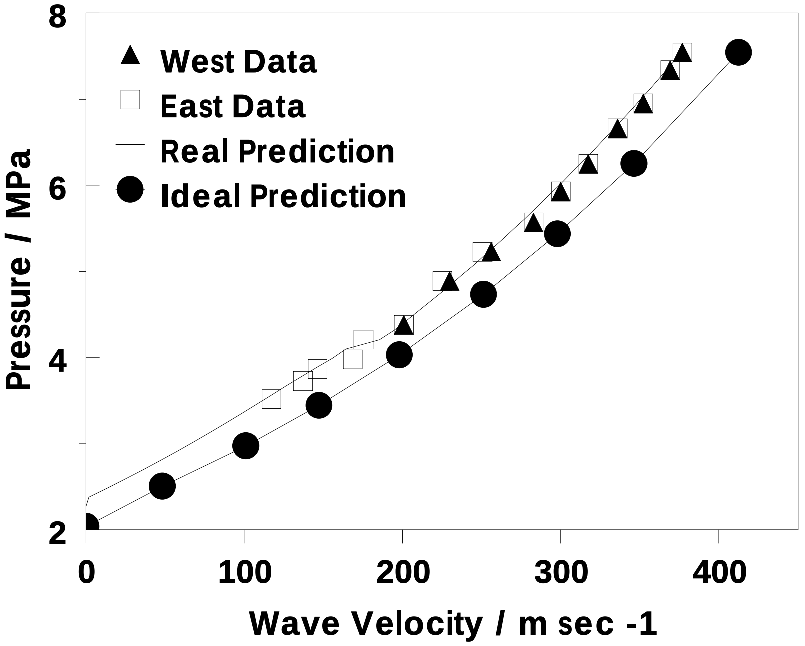


Figure 3 - Pipeline fracture experiment 1, pressure wave velocity vs. pressure.

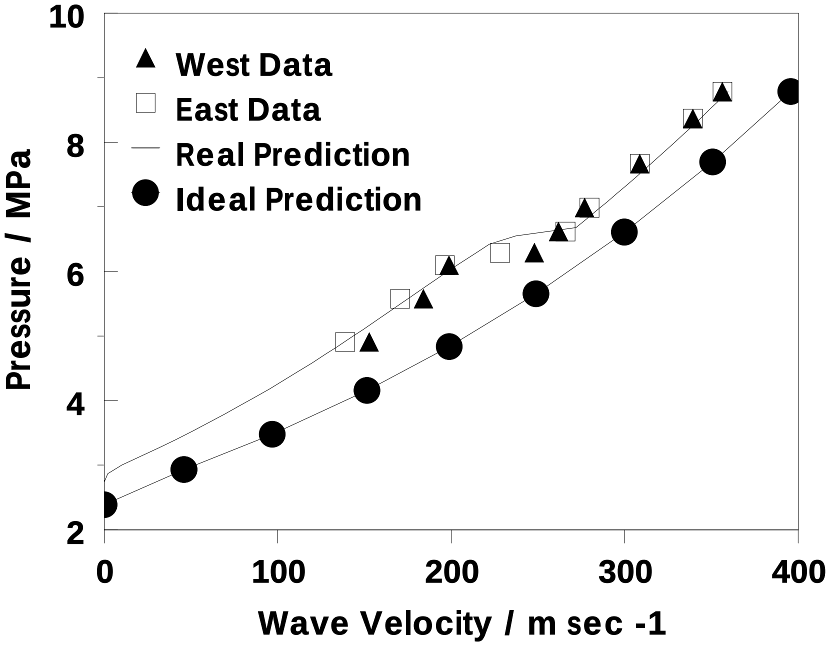


Figure 4 - Pipeline fracture experiment 2, pressure wave velocity vs. pressure.

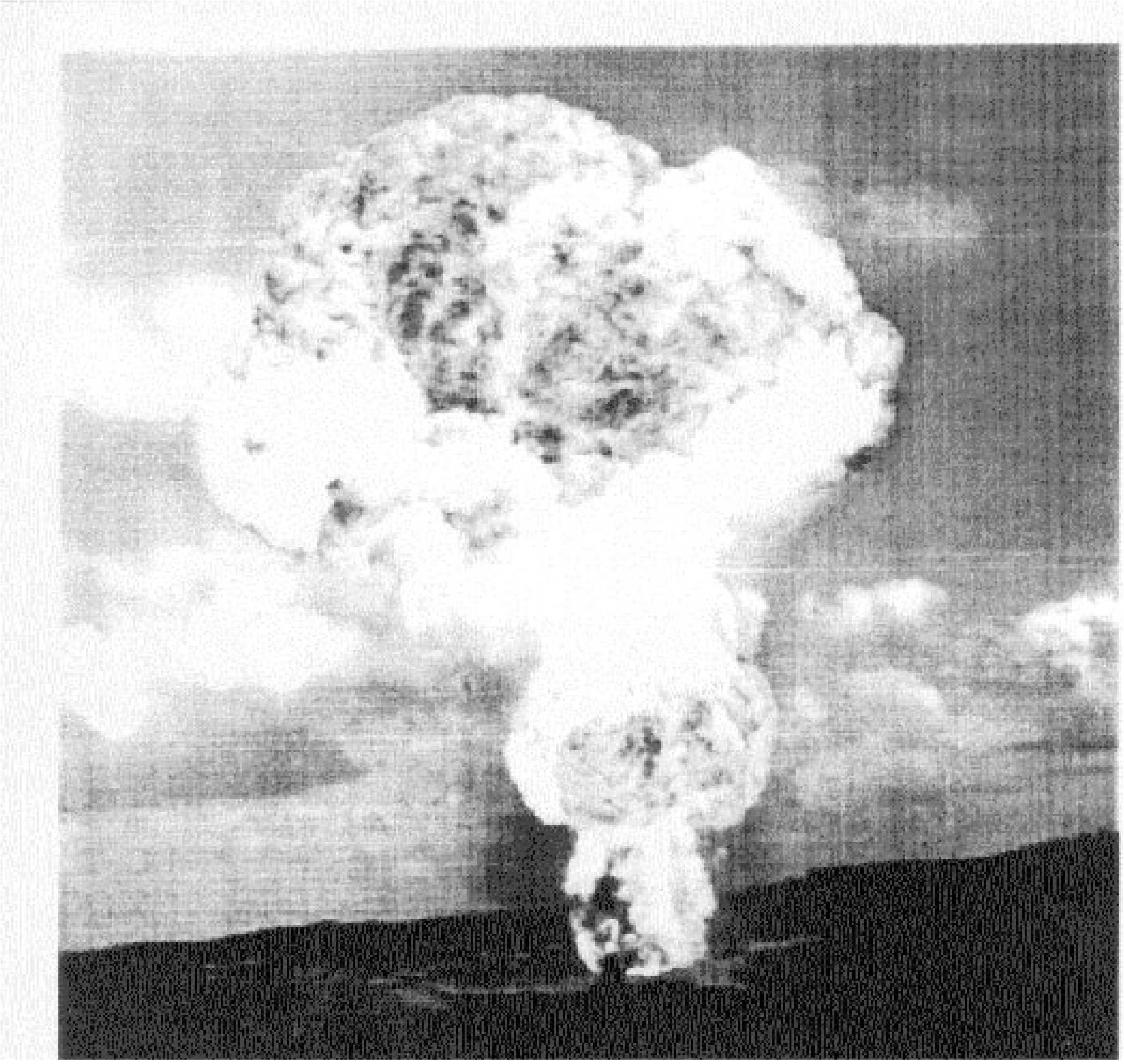


Figure 5 - Fire generated following the deliberate ignition of the released gas following a pipeline fracture.