FULL-SCALE FRACTURE PROPAGATION EXPERIMENTS: A RECENT APPLICATION AND FUTURE USE FOR THE PIPELINE INDUSTRY

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ABSTRACT

A full scale fracture propagation test facility has been developed to validate the design, in terms of the ability of the material to avert a propagating fracture, of a major new pipeline to transport gas 1800 miles from British Columbia in Canada to Chicago in the USA. The pipeline, being built by Alliance Pipeline Ltd, will transport rich natural gas, i.e. gas with a higher than normal proportion of heavier hydrocarbons, at a maximum operating pressure of 12,000 kPa. This gas mixture and pressure combination imposes a more severe requirement on the pipe steel toughness than the traditional operating conditions of North American pipelines. As these conditions were outside the validated range of models, two full-scale experiments were conducted to prove the design. This paper will provide details of the construction of the 367m long experimental facility at the BG Technology Spadeadam test site along with the key data obtained from the experiments. Evaluation of this data showed that the test program had validated Alliance’s fracture control design. The decompression data obtained in the experiments will be compared against predictions from a new decompression model developed by BG Technology. The use of the experimental facility and the model to support future developments in the pipeline industry, particularly in relation to the use of high strength steels, will also be discussed.

INTRODUCTION

Alliance Pipeline is in the process of constructing a US$3.0 billion (Canadian $4.5 billion) natural gas pipeline system from north-eastern British Columbia to Chicago, Illinois, where it will interconnect with the North American pipeline grid. The Alliance pipeline will be approximately 3000km long and will carry a rich natural gas (with elevated ethane, propane and butane concentrations) at pressures of up to 120bar (12,000kPa). The pipeline will be mainly 36" in diameter, but will include some 42" diameter sections and is designed for an initial throughput volume of 37.5 million cubic meters per day.

One important factor in the design of such a pipeline is to ensure that the selected pipeline material will arrest any fracture that might occur in the pipeline. The Battelle two-curve model, which calculates the toughness required to arrest a ductile fracture, was used by Alliance in setting pipe toughness specifications. However, the mixture composition and pressure to be used in the Alliance pipeline is beyond the experimentally validated range of this model. This issue was raised in public hearings concerning the construction of the pipeline. Therefore, Alliance Pipeline contracted BG Technology to carry out two full scale fracture propagation experiments at the Spadeadam Test Site. These tests were designed to verify that their pipe was sufficiently tough to arrest a running fracture and to validate the Battelle two curve model for the range of conditions pertinent to their pipeline.

The experiments were carried out with a mixture composition and pressure relevant to the operational pipeline. The tests involved initiating a fracture at the centre of a 100m long test section constructed from the selected pipeline material and monitoring the distance of propagation of the fracture and the decompression of the gas within the experimental facility. Other scientific measurements were also made during the tests.

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1 Previous burst tests were carried out using rich gas with a heating value in the 1135 BTU/ce (42.3 MJ/m3) range and a gas pressure of 1260 psig (8688 kPa). The Alliance ultimate gas mix has a heating value of 1188 BTU/ce (44.3 MJ/m3) and a maximum pressure of 1740 psig (12,000 kPa).
including studies of the effect of the pipeline failure on the surrounding ground, the far field air pressures and the thermal radiation characteristics resulting from ignition of the released gas. A summary of the test conditions and measurements are given below, with a more detailed description being given in Johnson et al [1].

A key requirement of any fracture model is to be able to predict the decompression of the pipeline. Following the experiments, therefore, comparison has been made between the gas decompression measurements and predictions from a gas decompression model developed by BG Technology.

**TEST FACILITY**

**Design of the Test Facility**

When a fracture is initiated in a transmission pipe, a decompression wave travels through the high pressure gas in the pipe. In the test facility, this decompression wave will reflect from the closed ends and the reflected wave will travel back along the pipe. For the experiments to produce the same fracture behaviour as the actual transmission pipeline, it is important to ensure that while a fracture is propagating through the section of pipe under test, the decompression of the gas in the pipe is also the same as would occur in the actual pipeline. Essentially this requires that the fracture travelling along the pipe must not intersect the reflection of the decompression wave returning from the ends of the test facility. In order to achieve this, gas reservoirs, comprising pipe of the same diameter as the pipe under test, were placed either side of the test section.

In order to determine the required length of the gas reservoirs, the speed of the decompression and reflected waves and the slowest speed of a propagating fracture were estimated. The speed of the initial decompression wave and the reflected waves were conservatively taken as the acoustic velocity in the gas at the test temperature and pressure. Once initiated, a fracture will generally accelerate to speeds of up to 300 ms⁻¹ and then slow down after about one pipe length, as the gas pressure falls, to a speed commensurate with the pipe toughness. The speed of the fracture when it is on the point of arresting (i.e. at its slowest) was predicted, using DUCTOUGH [2]. Again, to be conservative, the fracture speed was taken as this slowest value throughout its propagation along the pipe.

Given that the length of the test section would be approximately 100m, the speeds of the gas decompression wave and the fracture indicated that the gas reservoirs should each be at least 122m in length.

**General Description of the Test Facility**

The test facility is shown schematically in Figure 1 (not to scale) and comprised a 367m long, 36" diameter buried pipeline and a 12" diameter recirculation loop. The central part of the 36" diameter pipeline formed the test section, where the pipe lengths to be tested were located. This test section was approximately 100m in length.

As shown in Figure 1, the ends of the reservoirs were connected by a 12" diameter pipe loop. This loop was used to recirculate the gas to ensure uniform gas mixing and temperature. The pipe loop incorporated fans to move the pressurized gas around the loop and a heat exchanger to enable...
the gas inside the test facility to be heated. The test facility was located in the central part of the BG Technology Spadeadam Test Site, with the facility being aligned approximately in the east-west direction (the alignment of the 36” diameter pipe was actually 94° with respect to true north). The terms ‘east’ and ‘west’ will be used to indicate direction along the 36” diameter pipe from the point where the fracture was initiated.

The pipe used for the reservoirs comprised 22mm (7/8") wall thickness, 914mm (36") nominal bore pipe, X60 grade. Following completion of the welding of these pipes, three large concrete anchors were cast around each reservoir to prevent their movement during the test. In addition, the ends of the reservoirs were cast into concrete thrust blocks to prevent longitudinal movement.

In order to protect the reservoirs in the event that a fracture initiated in the test section failed to arrest, the open ends of the reservoirs were wrapped with 18mm diameter wire rope to form crack arrestors which would prevent a fracture propagating from the test section into the fixed gas reservoirs.

Natural gas was injected into the test facility at two points located near to the closed ends of the gas reservoirs. The natural gas was supplied via the site 32mm (1.1/4") diameter charge line feeding from the high pressure gas site storage reservoirs and the Liquified Natural Gas (LNG) vaporisation facility at Spadeadam.

In order to obtain the gas composition required for the experiments, additional quantities of ethane, propane, butane and, for the second test, CO₂ were admitted to the test facility through special fill points located on the recirculation loop, as shown in Figure 1.

**Test Section**

The pipe lengths used for the test section were made from X70 material and of two types, Welland seam welded pipe and IPSCO spirally welded pipe. For both tests, the fracture was initiated at the central girth weld between two relatively low toughness pipes (1E/1W) to ensure generation of high speed propagating fractures. All pipes were supplied with unique identifying numbers stamped onto the pipes and the toughness of the pipeline material at each end of the pipe length had been measured. For the purposes of the tests, the pipes were given a label consisting of a number and a letter. The number indicated their order from the central weld in the test section and the letter indicated the east or west direction. Thus, pipe 2W was the second pipe length from the central weld in the west direction.

The experimental facility was operated from a blast proof control room located approximately 500m to the west of the central point of the test section. The control of the main test rig functions was provided by a SCADA system. The SCADA system was also used to monitor signals from the pressure, temperature and strain gauge sensors on the test facility.

### Table 1 Arrangement of Pipes in Test Section

<table>
<thead>
<tr>
<th>Pipe Number</th>
<th>Type</th>
<th>Length (m)</th>
<th>Toughness (Joules)</th>
<th>Type</th>
<th>Length (m)</th>
<th>Toughness (Joules)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>East End</td>
<td>West End</td>
<td>West End</td>
<td></td>
</tr>
<tr>
<td>1E</td>
<td>Welland</td>
<td>8.97</td>
<td>185</td>
<td>184</td>
<td>Welland</td>
<td>10.95</td>
</tr>
<tr>
<td>2E</td>
<td>IPSCO</td>
<td>11.21</td>
<td>231</td>
<td>223</td>
<td>IPSCO</td>
<td>10.89</td>
</tr>
<tr>
<td>3E</td>
<td>IPSCO</td>
<td>10.618</td>
<td>329</td>
<td>254</td>
<td>IPSCO</td>
<td>10.62</td>
</tr>
<tr>
<td>4E</td>
<td>IPSCO</td>
<td>11.21</td>
<td>344</td>
<td>339</td>
<td>IPSCO</td>
<td>11.15</td>
</tr>
<tr>
<td>5E</td>
<td>Welland</td>
<td>6.98</td>
<td>-</td>
<td>276</td>
<td>Welland</td>
<td>4.87</td>
</tr>
<tr>
<td>1W</td>
<td>Welland</td>
<td>10.918</td>
<td>178</td>
<td>181</td>
<td>Welland</td>
<td>10.9</td>
</tr>
<tr>
<td>2W</td>
<td>Welland</td>
<td>10.945</td>
<td>237</td>
<td>253</td>
<td>Welland</td>
<td>10.93</td>
</tr>
<tr>
<td>3W</td>
<td>Welland</td>
<td>10.39</td>
<td>242</td>
<td>259</td>
<td>Welland</td>
<td>10.87</td>
</tr>
<tr>
<td>4W</td>
<td>Welland</td>
<td>10.5</td>
<td>211</td>
<td>205</td>
<td>Welland</td>
<td>10.54</td>
</tr>
<tr>
<td>5W</td>
<td>Welland</td>
<td>3.95</td>
<td>227</td>
<td>-</td>
<td>Welland</td>
<td>3.94</td>
</tr>
</tbody>
</table>

Pipe 4W, had a greater wall thickness of 15.6mm compared to the rest of the test section, which had a wall thickness of 14.2mm, in both tests. Thus its hoop stress was lower.
Sequential operation or synchronisation of data logging systems and cameras during the period immediately prior to initiation of each experiment, was achieved automatically by a computer controlled, sequence/timer unit. The sequence controller triggered devices such as transient recorders, tape recorders and the exploder, which fired the linear shaped charge, with an accuracy of better than 1 millisecond.

INSTRUMENTATION

The primary instrumentation on the test facility comprised:

- Thermometers, for both pipe wall and gas temperatures.
- Strain gauges.
- Pressure transducers, to monitor the pressure prior to the test and to measure the gas decompression during the test.
- Timing wires, to measure propagation of the fracture.
- Gas sampling, to monitor the composition of the gas in the test facility.

In addition to this primary instrumentation, strain gauges were also used to measure strain in the wall of the test section. Instrumentation was also deployed in the vicinity of the test pipe to monitor:

- The pressure generated in the soil close to the test section.
- Ground accelerations.
- The overpressure wave generated in the air as a result of the pipeline rupture.
- The thermal characteristics of the fireball produced following deliberate ignition of the gas inventory released from the pipeline.
- The prevailing meteorological conditions.

Primary Instrumentation

The gas composition measurements were carried out using a gas chromatograph. Five gas sample streams were provided from locations along the 36” diameter pipe and at various depths within the pipe (to confirm that there was no stratification of the gas components). As a final check on the composition of the mixture, high pressure bottle samples were taken from the test facility on the day of each test. These samples were then analysed on an independent chromatograph.

Two transducers measured the gas pressure inside the test facility. As a final calibration of the pressure transducers, on the day of each test, the pressure in the test facility was measured using a dead-weight pressure gauge with an accuracy of ±0.035 bar. Sixteen pressure transducers were used to measure the decompression of the gas within the pipe following initiation of the test.

Gas and pipe wall temperatures were measured using platinum wire resistance sensors at six locations each.

The propagation of the fracture in the test section was measured using timing wires fitted around the external surface of the pipe. In general the timing wires were located at 1 m intervals in each direction from the centre of the test section. Details of other instrumentation are given in Johnson et al [1].

TEST PROCEDURE

Gas Filling

The first stage in the preparations for an experiment was filling the test facility with the required gas mixture. This process began approximately one week before the test was carried out. The main component to be used to fill the test facility was natural gas, transported to the Spadeadam site as LNG.

Using the target concentration ranges for the C₂ to C₄ and CO₂ components, the masses of each of these components were determined by employing a BG Technology gas properties code to calculate the mixture density, along with the test facility volume. Given the known composition of the natural gas, this enabled the calculation of the additional mass of ethane, propane, butane and (for Test 2) CO₂ that needed to be added to the test facility. Trace amounts of Pentane, Hexane and Nitrogen were also present in the base LNG mixture.

The bulk of the gas components were added to the facility to take the test facility close to the test pressure and temperature. The gas properties code was then used, along with the measured gas composition in the test facility, to determine the additional masses of ethane, propane and butane components that needed to be added to achieve the mixture composition targets.

Explosive Charge and Incendiary Devices

The explosive charge was designed to make a cut along the top dead centre of the pipe. The charge was placed on the test section such that it evenly straddled the 1W/1E girth weld.

To ensure ignition of the released gas following pipeline rupture, incendiary devices were located close to the test initiation point. The sequence controller fired these devices a few seconds prior to the fracture being initiated.

Once the explosives had been fitted and connected, the steam to the heat exchanger was turned off. The gas
temperatures on the gas reservoirs and the test section were then monitored until they reached the target range. At this point, the recirculation fans were turned off, the 12" recirculation loop isolated from the 36" pipe and the final countdown sequence was carried out with the test being initiated using the sequence timer.

EXPERIMENTS CONDUCTED

The experimental conditions in the two tests conducted are defined by the details of the pipes in the test section and the gas pressure, temperature and composition at the time of initiation. The details of the pipes used in Tests 1 and 2 are given in Table 1. The pressure of the gas inside the test facility was 120.2 bar and 120.1 bar in Tests 1 and 2 respectively. The gas temperature measured in the test section at the time of initiation was 23.9°C and 16.5°C in Tests 1 and 2 respectively. The final composition of the gas mixture is given in Table 2 for both experiments.

<table>
<thead>
<tr>
<th>Table 2 Gas Compositions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Component</td>
</tr>
<tr>
<td>Methane</td>
</tr>
<tr>
<td>Ethane</td>
</tr>
<tr>
<td>Propane</td>
</tr>
<tr>
<td>n-Butane</td>
</tr>
<tr>
<td>i-Butane</td>
</tr>
<tr>
<td>i-Pentane</td>
</tr>
<tr>
<td>n-Pentane</td>
</tr>
<tr>
<td>C6</td>
</tr>
<tr>
<td>Nitrogen</td>
</tr>
<tr>
<td>CO₂</td>
</tr>
</tbody>
</table>

It can be seen that in addition to the changes to the pipe arrangement, the main variations from Test 1 to Test 2 were in the gas temperature and gas composition. Test 1 was designed to provide validation for fracture arrest in the main NPS 36 pipeline. Test 2 was designed to provide validation for fracture arrest in the NPS 42 portion of the pipeline, which requires a higher pipe toughness to achieve arrest. This is due to possible operation of the NPS 42 system at lower gas temperatures than the NPS 36 system. The reduction in gas temperature, in Test 2, provided the same predicted pipe toughness to achieve arrest in the 36" diameter test pipe as that calculated to achieve arrest in the operational NPS 42 pipe.

RESULTS FROM PRIMARY INSTRUMENTATION

Fracture Arrest

In Test 1, the fracture initially accelerated in both directions at speeds of up to 330 ms⁻¹ and then decelerated. The fractures arrested after propagating 14.9 m to the east and 14.3 m to the west of the point of initiation. The path of the fracture along the pipe is shown in Figure 3 as a thick line (in this drawing, the pipe has been opened up flat with the centre line being top dead centre of the pipe, the drawing also shows the location of samples taken from the pipe after the tests and the position of timing wires). The fracture arrested on the east side in a spiral weld pipe with a toughness of 223 J and on the west side in a straight seam pipe with a toughness of 237 J. To the east, in the spiral weld pipe, the fracture turned into a helical path just after entering pipe 2E and continued in a helical path approximately perpendicular to the spiral weld seam and encircled the pipe four times. To the west, the fracture encircled the pipe and arrested in pipe 2W.

In Test 2, the fractures again accelerated, reaching high speeds, then slowed and arrested. To the west, this arrest took place 12.9 m from the point of initiation, as shown in Figure 4. To the east, the fracture propagated a total distance of approximately 20.9 m. However, the fracture had actually encircled the pipe after propagating approximately 16.7 m from the point of initiation. The additional 4.2 m the fracture
propagated to the east appears to have been caused by movement of the pipe in the trench. In fact, this section of pipe along with part of the adjacent IPSCO pipe 3E were subsequently broken off by this movement and ejected from the trench. The fracture arrested on the east in a pipe with a toughness of 226 J and on the west in a pipe with a toughness of 217 J.

**Gas Decompression**

An example of the decompression measured by one of the pressure transducers is given in Figure 5. The curve illustrates two aspects of the decompression. Firstly there is an inflection in the decompression curve at a pressure of 60 to 65 bar. This inflection is caused by the production of liquid droplets as the temperature of the gas in the pipe reduces. This behaviour is particular to the ‘rich’ natural gas composition under the test conditions. No inflection would have been present had the gas in the pipe been the more typical ‘lean’ natural gas. The presence of the inflection makes the prediction of the gas decompression process more complicated, and this is discussed in more detail in the following section.

The second aspect of this curve is the sudden change in gradient about 900ms after the test was initiated. This change in gradient indicates that the reflection of the decompression wave from the ends of the gas reservoir passed the transducer at this point in time.

**MODELLING OF GAS DECOMPRESSION**

**Model Description**

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 as pressure waves.

For a steady propagating ductile fracture, there is a dependence between the pressure field and the pressure waves inside, and at the opening of the pipeline. The shape of the curve relating pressure to the velocity of the pressure wave depends on the composition, pressure and temperature of the gas in the pipeline. In particular, certain gas mixtures can enter the region of pressure-temperature space in which condensation of the gas to form liquid can occur within the pipeline. This has the effect of slowing the speed of sound and therefore the speed with which the decompression front moves, resulting in the inflection in the decompression curve shown in Figure 5. As a consequence, a higher pressure exists at the crack tip than would otherwise have been the case had the gas not condensed to form liquid, 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), such as in the tests described above. 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.
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 regions of high and a low pressure. 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, Picard and Bishnoi [3].

The isentropic assumption means that there is a unique relationship between the pressure and the velocity of the pressure wave 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, \( P \), in the pipeline. Under these assumptions, the local pressure wave speed, \( V \), is given by the equation,

\[
V = v_s - u
\]  

where \( u \) is the local gas velocity in the pipe, defined by:

\[
u(P_d) = \int_{P_d}^{P_0} \frac{dP}{P_{v_s}} \tag{2}
\]

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 \( \rho \). The density of a two-phase mixture is taken to be the harmonic mean of the gas and liquid phase densities weighted by the vapour quality,

\[
\rho = \frac{1}{(1 - \chi_{v})/\rho_{eq} + \chi_{v}/\rho_{gas}} \tag{3}
\]

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,

\[
\frac{du}{d\rho} = -\frac{V_s}{\rho} \tag{4}
\]

subject to

\[
u(\rho_0) = 0 \tag{5}
\]

The initial condition given in equation (5) 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, Eiber et al. [2].

The ordinary differential equation (4) can be solved numerically by the finite difference method. The thermodynamic quantities necessary to solve the initial value problem are calculated with a cubic equation of state (EOS) described by Gibbons and Laughton [5], labelled as GL for convenience. This equation of state has a similar form to the Soave variant of the Redlich Kwong (RKS) equation of state, Reid et al. [6], but unlike the RKS EOS, can predict the vapour pressure accurately for the full temperature range from the triple point to the critical point. For the fracture propagation experiments considered, the GL EOS tends to reproduce the slope of the velocity of the pressure wave vs. pressure curve more accurately than the Peng Robinson EOS, Reid et al. [6], a popular choice of EOS for fracture propagation modelling. However the PR EOS is superior at predicting the initial sound speed. Therefore the model predictions of the velocity of the pressure wave vs. pressure curve have been improved by laterally translating the predicted curve to agree with the PR prediction of initial sound speed.

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

\[
V_s^2 = \frac{P}{\rho} \frac{C_p}{C_v} \tag{6}
\]

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 Evaluation

To illustrate the predictive capability of the gas decompression model, its application to the first fracture propagation experiment is considered. Three predictions of the velocity of the pressure wave vs. pressure curve are shown in Figure 6 together with the curve deduced from the experimental measurements. The curve labelled Hybrid EOS has been calculated using the methodology described above, whereas the other two predictions have been calculated with the Peng Robinson EOS and the computer program GASDECOM which uses a variant of the Benedict, Webb, Rubin and Starling EOS, Reid et al. [6].

Comparing the three predictions the curve calculated using the Hybrid EOS is the closest to the curve representing the measurements. The difference between the pressure wave velocity vs. pressure curve using the Peng Robinson EOS and the Hybrid EOS are small, with a difference in wave velocity
Figure 6 Measured and Predicted Gas Decompression/Wave Velocity Curves

at the dew pressure of the order of 4%. Considering the GASDECOM prediction of gas decompression, the model agrees well with the measured curve except when condensation initially occurs, as the measured dew pressure is underpredicted by approximately 11%. This is important as this stage of the decompression can have a significant influence on the predicted pipe toughness required for arrest.

The data from the Alliance fracture control tests provides a severe challenge for the gas decompression model, as a number of assumptions used in the basis of the model are questionable for such a 'rich' natural gas. For example, using equation (3) to evaluate the two-phase density is only accurate for high vapour quality mixtures. Picard and Bisnoi [7] reported good agreement using this equation with vapour qualities down to 0.9 for natural gas. However, in the simulation of gas decompression during the Alliance fracture control experiment, the lowest vapour quality predicted using the Hybrid EOS is of the order of 0.84. The good agreement between the experimental results and the model indicates that extension to this lower vapour quality is valid.

FUTURE APPLICATION

As has been shown, the full scale experiments have provided a validation for both the Alliance pipeline design and a decompression model that can closely represent the two-phase stage of the decompression process. Looking to the future needs of the pipeline industry, the experimental facility and the decompression model can provide important benefits in the study of high strength steels.

High strength steels corresponding to grades around X100 offer attractive options for the construction of low-cost high-capacity pipelines. Conceptual and feasibility studies by several major international pipeline operators have highlighted advantages of 10% or more in installed cost resulting from the use of X100 to increase the operating pressure or reduce the diameter of long distance pipelines.

However, there is no data available on which to base fracture control plans for X100 pipelines and without them a robust overall pipeline design cannot be developed. In addition, high strength steel pipelines are likely to be operated at high pressures. At these pressures, the two-phase effect seen in the Alliance 'rich' natural gas mixture will also occur with leaner natural gas mixtures.

It is therefore proposed to develop a joint industry project that will generate data from a series of four full-scale fracture propagation tests containing standard and rich natural gas, incorporating around 30 pipe lengths from four suppliers, together with data from state-of-the art laboratory-scale tests. These experiments will provide the pipeline industry with guidelines for developing fracture control plans for X100 pipelines based on expert interpretation of the information obtained.

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, MPa
\[ P_0 \] Initial pressure, MPa
\[ u \] Gas velocity, m s\(^{-1}\)
\[ V \] Pressure wave velocity, m s\(^{-1}\)
\[ v_s \] Acoustic velocity, m s\(^{-1}\)
\[ x_q \] Vapour quality
\[ \rho \] Density, kg m\(^{-3}\)
\[ \rho_0 \] Initial density, kg m\(^{-3}\)

REFERENCES