LEAKAGE IN ETHYLENE PIPELINES

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Ethylene is transported in pipelines as a supercritical fluid. If a pipeline fails due to a small corrosion hole or mechanical damage, very low temperatures (of order –104^{o}C) will be reached at some stage, as the ethylene depressurises to atmospheric pressure. If these low temperatures are reached as the ethylene passes through the pipeline wall, the concern is that carbon steel will lose its ductile strength and a small hole will propagate into a larger, possibly full-bore, rupture. The objective of this study is to use the computer program BLOWDOWN to simulate the release of ethylene through a small hole and to determine the predicted wall temperatures in the region of the hole.

Keywords: blowdown; ethylene; pipeline; fracture

INTRODUCTION

Distribution of ethylene throughout the UK is via a series of pipeline networks. The operating pressure of the pipelines generally lies within one of two ranges:-

1. High Pressure Ethylene Pipelines (HPEP), absolute pressure 60 – 90 bar
2. Low Pressure Ethylene Pipelines (LPEP), < 45 bar

Ethylene has a critical absolute pressure of about 50 bar and a critical temperature of about 10^{o}C. Thus, a high pressure pipeline operates in the supercritical region (dense-phase) and a low pressure one in the gas region and, therefore, under normal operating conditions, both pipelines are operating in a single phase mode.

Although both types of pipeline are normally buried at typical depths of 1m, there is the risk of a small hole forming from either corrosion or accidental mechanical damage with a subsequent pressurised release of ethylene. It is certainly recognised that a release of dense phase ethylene will result in a significant temperature drop as gas-liquid equilibrium is established at lower pressures. However, an outstanding question is where does the significant cooling effect occur?

a) is it as the ethylene is exiting through the hole such that the pipeline wall bounding the hole is bathed in low temperatures, or
b) only after the ethylene has completely exited the hole?

Concerns have been expressed for a number of years that the cooling effect in case a) could be sufficient to result in brittle fracture of the pipe wall causing a small hole to develop into a much larger one (possibly full bore).

The objective of this study is to use the computer program BLOWDOWN to simulate the release of ethylene through a small hole for the two pipeline pressure regimes above and to determine the predicted wall temperatures in the region of the hole.

BLOWDOWN PROGRAM

The BLOWDOWN simulation program (Haque *et al.*, 1992a) was developed at Imperial College principally for the simulation of the depressurisation of networks of vessels and associated pipework on the topsides of offshore oil and gas platforms. It has been extensively validated for such networks (Haque *et al.*, 1990, 1992b).

It was later extended to simulate the depressurisation of pipelines (Richardson and Saville, 1991, 1992) and BLOWDOWN predictions for large scale LPG pipeline releases and showed at least adequate and often good agreement with measurements (Richardson and Saville, 1996).

Experimental evidence has shown that it is crucial to model the thermodynamics of depressurisation accurately, since failure to do so can lead to trajectories through phase (pressure – temperature - composition) space which are grossly in error. For this reason, thermodynamic, phase and transport properties of the multi-phase multi-component mixture are calculated rigorously by an extended principle of corresponding states using a proprietary computer package PREPROP. This issue is particularly important for ethylene phase trajectories passing close to the critical point and was one of the key decision drivers in choosing BLOWDOWN for this study.

METHODOLOGY

Although the ethylene transported in the pipelines is high purity, it does contain small amounts of impurities. For the purposes of this investigation, the composition was simplified to:

Component	Mole Fraction
ethylene	0.9990
methane	0.0005
ethane	0.0005

However, it was discovered that the calculations were not sensitive to the exact nature and amount of impurities present.

The main properties for a typical pipeline type are summarised in the table below:

Property	**High Pressure Ethylene Pipeline (HPEP)**	**Low Pressure Ethylene Pipeline (LPEP)**
Operating absolute pressure	60 – 90 bar	28 – 45 bar
Operating temperature*	(Ambient – 5)^{o}C	(Ambient – 5)^{o}C
Nominal bore	250mm	200mm
Nominal wall thickness	Majority is 5.65mm (some sections are 11.9mm)	8.18mm
Pipe material	API 5LX 52 (for 5.65mm wall thick) API 5LX 60 (for 11.9mm wall thick)	API 5L Grade A
Pipe coating	500 microns of fusion bonded epoxy	Coal tar epoxy
Pipe depth	Average depth ~ 1.0m backfilled with natural material.	Average depth ~ 1.0m.
Distance between block valves	16km	36km

* For all of the simulations the operating temperature was taken as 10^{o}C.

The first set of simulations investigated the flow through a small hole in the pipeline under the normal steady state operating conditions (Note: this would be the case before a pipeline leak was detected and emergency shutdown procedures initiated) For the purposes of these calculations, a steady pressure was assumed to exist in a short length of pipeline during leakage of material through a cylindrical hole in the wall of the pipe, see figure 1. Two hole sizes were chosen:

a) 10mm diameter – representative of a corrosion hole
b) 50mm diameter – representative of a hole caused by mechanical damage (digger)

The case in which the material leaving the hole could disperse freely into the atmosphere was first investigated. The model comprised the length of pipe, an acceleration region in which the slow moving ethylene was accelerated up to the speed necessary for it to enter the hole, and the hole itself, which was represented as a short cylindrical duct.

Details on the heat transfer correlations used by BLOWDOWN are give in the Appendix.

The simulations indicated that a steady state temperature distribution in the vicinity of the hole was established quite quickly, generally within 1 minute. Therefore, only the steady state variables are reported.

FLOW OF SUPERCRITICAL ETHYLENE THROUGH A HOLE IN THE HPEP

10mm diameter hole

Table 1 shows the important properties of the fluid in the vicinity of the hole, for various upstream pressures (covering the operating range of the HPEP) for flow through a 10mm diameter hole in pipe of wall thickness 11.9mm.

These results show a number of interesting points:

- Although the fluid emerging from the hole was all-liquid (VapFr=0.0), the flow through the hole was nevertheless choked (pressure at hole exit plane > atmospheric pressure) and at a relatively low speed. This was because the conditions were near critical, where the compressibility of the fluid is very large, and so the usual approximation of incompressible flow for the flow of a liquid through a hole is not applicable.

- The fluid conditions, other than those related to flow rate, were relatively insensitive to the upstream pressure.

- Most of the pressure drop, and hence also the temperature drop, took place during the acceleration of the fluid as it approached the hole. There was very little change within the hole itself.

- The fact that there was very little pressure drop through the wall of the pipe suggests that the results are insensitive to the wall thickness. This was indeed found to be the case when the wall thickness was reduced to 5.65mm (the HPEP consists of 5.65mm and 11.9mm wall sections).

The liquid emerging from the hole immediately expanded to atmospheric pressure. The energy balance indicated that the product of this expansion was at –104^{o}C, the normal boiling point of ethylene, since some 60-70% of the material was in the gas phase.

The cooled fluid passing through the hole in the wall of the pipeline generated temperature gradients in the metal around the hole. However, the fact that there was almost no change in temperature in the liquid during its passage through the hole means that there was a negligible gradient in a radial direction relative to the pipe axis, but there was a gradient in a radial direction relative to the axis of the hole. In effect, the cylindrical surface of the hole was cooled to a uniformly constant value by the cold liquid passing though it and this established a variation in the temperature field for a few hole diameters around the hole. Table 2 gives these wall temperatures as a function of distance from the surface of the hole (see figure 1, inset)

The metal temperature at the surface of the hole, not surprisingly, was essentially equal to that of the fluid passing through it, but the temperature gradient decreased quite rapidly around it.

50mm diameter hole

Tables 3 and 4 give the corresponding results for a 50mm diameter hole in the pipe wall. Calculations were performed only for the highest and lowest pressures, since as already observed, the sensitivity to pressure is small.

The pressures and temperatures are very similar to those found for the 10mm diameter hole, except that, the pressure and temperature drops through the hole were almost undetectable. All of the changes took place during the acceleration of the fluid upstream of the hole.

FLOW OF GASEOUS ETHYLENE THROUGH A HOLE IN THE LPEP

Similar calculations were performed for the LPEP, which under normal operating conditions transports ethylene in the gaseous phase. The results were calculated for two upstream absolute pressures:

a) 44 bar – representative of the maximum operating pressure for a LPEP

b) 28 bar – representative of the minimum operating pressure for a LPEP

10mm diameter hole

Tables 5 and 6 give the results for flow of gaseous ethylene through a 10mm diameter hole and at absolute pressures of 44 and 28 bar.

Again most of the pressure and temperature changes take place in accelerating the fluid up to the required speed, with only a small part of the overall changes taking place within the hole itself. However, relatively speaking, the changes within the hole were more important than they were for the supercritical fluid.

The temperature of the emerging gas is also lower than for the supercritical case, resulting in some what lower wall temperatures. At the higher upstream pressure, there is also the formation of a small amount of liquid in the acceleration into the hole and within the hole itself.

The expansion of the fluid downstream of the hole was to a temperature of –95^{o}C at both pressures. This time the phase of the fluid was all-gas.

50mm diameter hole

Tables 7 and 8 give the results for flow through a 50mm diameter hole. The results for temperature and pressures differ little from the 10mm diameter hole case.

OBSERVATIONS

1. The temperature decrease which took place before the ethylene emerged from a hole in the pipe wall was almost entirely concerned with acceleration of the fluid to the point at which sufficient mass could pass through the hole to satisfy choking conditions at its exit. The temperature drop required for fluid that was supercritical upstream was no more than 10^{o}C, but a rather larger drop was required for gas (of order 30^{o}C).

2. The predicted temperatures were relatively insensitive to hole size for the range of hole sizes studied. In these cases, the flow through the hole is not affected by the pipeline geometry which acts as a boundless reservoir for the flow. Temperatures can expected to be sensitive to the hole size if it becomes comparable with the pipeline diameter.

3. For the HPEP, the fluid flowing through and emerging from the hole was all liquid. The largest temperature change took place once the fluid left the hole when expansion to atmospheric pressure produced gas/liquid equilibrium temperatures of order –100^{o}C.

4. For the LPEP, the fluid flowing through and emerging from the hole was primarily gas, although there was a small amount of liquid. Again, the largest temperature change occurred as the gas expanded to atmospheric pressure outside the hole, and similar to the HPEP case was of order –100^{o}C.

If the pipeline is in the open where the emerging fluid can escape freely, these low temperatures would probably not affect the pipeline itself. However, in the case of a buried pipeline, one can imagine that the high momentum jet of escaping fluid might displace the soil around it, leading to a cavity* in which the pipeline would be bathed in a cloud of gas at $-100^{o}C$. This would undoubtedly cool the pipeline locally. However, its effect would be countered, to some extent, by the relatively warm fluid in the pipeline which was being fed to the leaking section from the intact parts of the line. This question is addressed in the next section where the full blowdown of an isolated HPEP is modeled.

BLOWDOWN OF HIGH PRESSURE ETHYLENE PIPELINE

When a leak is detected on a pipeline it is usual emergency response practice to stop the flow and to isolate the pipeline into discrete sections by activating *block valves*. For a pipeline running hundreds of kilometres, the block valves may be located up to tens of kilometres apart. Activation of the block valves cannot stop a leak. Their primary purpose is to reduce the maximum inventory that can be released.

The release through the hole will not be steady state as in the previous simulations. As material is released from the blocked in section of pipeline, the pipeline pressure drops, there is an associated temperature drop due to the fluid expansion, the fluid inside may undergo phase changes and the timescale of the blowdown will be sufficient for heat transfer across the pipeline walls to be of influence.

The temperature of the pipe in the vicinity of the hole will decrease to very low temperatures as the blowdown progresses. However, it is a knowledge of the trajectory followed in P-T space during the blowdown that is important.

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* Cavities are expected for relatively large holes of 50mm diameter where jet momentum is sufficient to remove the surrounding soil. However, it may be the exception for smaller hole sizes of 10mm diameter, where instead the cold release causes local freezing of the soil water content.

To investigate this, the blowdown of a blocked in section (16 km length) of the HPEP was simulated. The following assumptions were made for the simulation:-

- at time zero, the block valves were closed, isolating the leak in a 16km section;
- at time zero, the temperatures of the fluid and the walls of the pipeline were all at their normal operational ones of 10^{o}C;
- at time zero, the pressure in the closed section of the pipeline was a uniform absolute pressure of 90 bar;
- the pipeline was horizontal with free flow of liquid along the length of the line;
- the ethylene escaping from the leak created a crater that was filled with vapour around a 20m section of pipe, with the vapour conditions being atmospheric pressure and -100^{o}C.

During the majority of the pipeline depressurisation time the flow was assumed to be two-phase with stratified flow (gas above liquid) along the length of the pipeline. Similar behaviour was observed in experimental LPG pipeline releases (Richardson and Saville, 1996). Therefore, simulations have been carried out for a 50 mm diameter hole, both in the top and bottom of the pipeline.

Observations

The pressure decay curves against time for both bottom and top blowdown are shown in figure 3. and both have similar features:

- The initial sharp decay was due to the unpacking of the supercritical ethylene which was all liquid in the pipeline. During this stage both trajectories were approximately the same.

- The decay curves show a change in gradient at about 15 minutes. This corresponds with the pressure reaching the saturation boundary and the ethylene in the pipeline becoming a 2-phase mixture.

- The trajectories of the decay curves now differ after this point. For the bottom blowdown, the liquid is efficiently pushed out of the hole by the gas above it. On the other hand, if the hole was on the top, the liquid was lost by the slower process of evaporation only (50% longer overall to depressurise than bottom blowdown)

- Ultimately, all of the liquid was lost and only gas remained. This transition point is indicated by the second change in gradient of the decay curves at about 1 hr 15 minutes and 4 hrs for the bottom and top blowdown respectively.

Figure 4 shows the temperature on the wall of the hole as the pipeline depressurisation progressed for both top and bottom blowdown. The wall temperature at the transition to a 2-phase mixture is -10^{o}C.

For the bottom blowdown, the wall temperature decreases with pipeline pressure before reaching a plateau of approximately -35^{o}C in the final stages of gas depressurisation. At the end of the depressurisation there is a rapid cooling to a final wall temperature of -53^{o}C.

The trajectory has a similar profile for the top blowdown, however the plateau is at a lower temperature of -48^{o}C and reached at a lower pipeline pressure. The final wall temperature at the end of the depressurisation is -58^{o}C.

One should note that these temperatures are substantially in excess of the -100^{o}C of the gas which bathes the outside of the exposed section of pipeline. The temperature gradients in the wall and close to the hole are very similar to the ones reported earlier (see tables 2,4 etc.) although, of course, the wall temperature of the hole from which the gradient originates is following the temperature of the fluid passing through it.

It is also interesting to observe that top depressurisation by liquid evaporation produces very much lower temperatures along the entire pipeline bottom than bottom depressurisation. The lowest temperature recorded far away from the hole is $0^{o}C$ for bottom blowdown, but $-25^{o}C$ for the top blowdown.

Conclusion

It is possible with BLOWDOWN to simulate the blowdown characteristics of an ethylene pipeline instead of performing expensive large scale experiments.

A steady state release of supercritical ethylene through a small corrosion or mechanical damage hole in a flowing pipeline will remain as liquid as it passes through the hole with minimal cooling ($\sim 10^{o}C$). Flashing to a 2-phase mixture occurs outside of the hole.

The subsequent blowdown of a blocked in pipeline section containing supercritical ethylene depends on the position of the hole. The colder hole wall temperatures (at a particular pipeline pressure) are experienced during top blowdown.

Further studies which consider the material properties of a particular pipeline are required to determine the effects of the temperature regime on potential hole propagation. This should consider the pressure – temperature information given in figure 4, together with the material properties (fracture toughness) of a particular pipeline.

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Appendix – BLOWDOWN heat transfer correlations

Gas-to-wall

For natural convection, the heat transfer coefficient h is given by:

$h = 0$ for $GrPr_g < 10^4$ (1a)

$h = 0.683\ (k/D)\ (Gr/Pr_g)^{0.25}\ (Pr_g/[0.861+Pr_g])^{0.25}$ for $10^4 < GrPr_g < 10^9$ (1b)

$h = 0.138\ (k/D)\ Gr^{0.36}\ [Pr_g^{0.175}-0.55]$ for $10^9 < GrPr_g$ (1c)

where $Gr = gD^3\beta[T_w-T_g]\rho^2/\mu^2$ denotes the Grashof number, $Pr_g = c_p\mu/k$ the Prandtl number, g the gravitational acceleration, D the inside diameter of the unit, β the gas compressibility, ρ its density, μ its viscosity, c_p its isobaric heat capacity, k its thermal conductivity, T_g its temperature and T_w the wall temperature.

For forced convection, the heat transfer coefficient h is given by:

$h = 1.86\ (k/D)\ (RePr_gD/L)^{0.333}$ for $Re < 2100$ (2a)

$h = 0.116\ (k/D)\ (Re^{0.667}-125)Pr_g^{0.333}[1+(D/L)]^{0.667}$ for $2100 < Re < 10000$ (2b)

$h = 0.023\ (k/D)\ Re^{0.8}\ Pr_g^{0.333}$ for $10000 < Re$ (2c)

where $Re = \rho VD/\mu$ denotes the Reynolds number, V the axial velocity of the gas and L the length of the unit.

Liquid-to-wall

For <u>nucleate</u> boiling, the heat flux q is given by:

$$q = \mu_l (h_g-h_l) [g(\rho_l-\rho_g)/\sigma]^{0.5} [100c_{pl}(T_w-T_l)/(h_g-h_l)]^3/Pr_l^{5.1} \quad (3)$$

where subscripts l and g denote liquid and gas, respectively, h denotes specific enthalpy and σ surface tension.

For <u>film</u> boiling, the heat flux q is given by:

$$q = 0.425 [k_g^3 g\rho_g(\rho_l-\rho_g)(h_g-h_l)/\mu_g(T_w-T_l)\{\sigma/g(\rho_l-\rho_g)\})^{0.5}]^{0.25} \quad (4)$$

The maximum temperature difference ΔT_{max} for nucleate boiling is given by:

$$\Delta T_{max} = 0.01 (h_g-h_l) [Pr_l^{1.7}/c_{pl}] [0.149 \rho_g^{0.5}\sigma^{0.75}/\mu_l \{g(\rho_l-\rho_g)^{0.25}\}^{0.333} \quad (5)$$

The minimum temperature difference ΔT_{min} for film boiling is given by:

$$\Delta T_{min} = 0.127 (h_g-h_l) (\rho_g/k_g) [\sigma(\rho_l-\rho_g)/g(\rho_l+\rho_g)]^{0.667}[g/(\rho_l-\rho_g)]^{0.5} [\mu/(\rho_l-\rho_g)]^{0.333} \quad (6)$$

Soil

Transient conduction occurs in the surrounding soil and it is assumed that there is good thermal contact between the soil and the pipe. The soil is wet with assumed thermal conductivity of 1.38 W/m.K and thermal diffusivity 2.01 mm^2/s.

List of table captions

Tables

Table 1. Flow of supercritical ethylene through a 10mm diameter hole

Upstream	Hole Entry Plane				Hole Exit Plane				
P_o (bar)	P (bar)	T (K)	VapFr (molar)	Speed (m/s)	P (bara)	T (K)	VapFr (molar)	Speed (m/s)	Mass Flow (kg/s)
90.0	42.2	273	0.000	163	39.9	273	0.000	164	4.4
79.0	43.0	274	0.000	143	41.4	274	0.000	144	3.8
69.0	44.2	276	0.000	121	43.1	276	0.000	122	3.2
59.6	46.0	279	0.000	92	45.4	278	0.000	92	2.3

Table 2. Metal temperature (K) as a function of distance from hole

P_o (bar)	Upstream Radial Distance from Surface of Hole*					
	S_o (0mm)	S_1 (6mm)	S_2 (12mm)	S_3 (18mm)	S_4 (24mm)	S_5 (30mm)
90.0	273.1	278.2	280.1	281.4	282.3	283.1
79.0	274.6	279.0	280.5	281.6	282.5	283.1
69.0	276.3	279.8	281.1	281.9	282.6	283.1
59.6	278.5	280.9	281.7	282.3	282.8	283.1

* See Figure 1 for outline of measurement positions S_o to S_5

Table 3. Flow of supercritical ethylene through a 50mm diameter hole

Upstream	Hole Entry Plane				Hole Exit Plane				
P_o (bar)	P (bar)	T (K)	VapFr (molar)	Speed (m/s)	P (bar)	T (K)	VapFr (molar)	Speed (m/s)	Mass Flow (kg/s)
90.0	40.1	273	0.000	167	39.8	272	0.000	166	114
59.6	45.5	278	0.000	94	45.4	278	0.000	94	59

Table 4. Metal temperature (K) as a function of distance from hole

P_o (bar)	Upstream Radial Distance from Surface of Hole					
	S_o (0mm)	S_1 (15mm)	S_2 (30mm)	S_3 (45mm)	S_4 (60mm)	S_5 (75mm)
90.0	272.5	277.1	279.3	281.1	282.2	283.1
59.6	278.3	280.3	281.3	282.1	282.6	283.1

Table 5. Flow of gaseous ethylene through a 10mm diameter hole

Upstream	Hole Entry Plane				Hole Exit Plane				
P_o (bar)	P (bar)	T (K)	VapFr (molar)	Speed (m/s)	P (bar)	T (K)	VapFr (molar)	Speed (m/s)	Mass Flow (kg/s)
44.0	30.1	261	0.952	190	26.4	255	0.925	218	0.95
28.0	17.9	255	1.000	237	15.5	247	1.000	269	0.55

Table 6. Metal temperatures as a function of distance from hole

P_o	Upstream Radial Distance from Surface of Hole					
(bar)	S_o (0mm)	S_1 (15mm)	S_2 (30mm)	S_3 (45mm)	S_4 (60mm)	S_5 (75mm)
44.0	261.0	272.3	276.4	279.2	281.4	283.1
28.0	255.7	269.7	274.7	278.3	281.0	283.1

Table 7. Flow of gaseous ethylene through a 50mm diameter hole

Upstream	Hole Entry Plane				Hole Exit Plane				
P_o (bar)	P (bar)	T (K)	VapFr (molar)	Speed (m/s)	P (bar)	T (K)	VapFr (molar)	Speed (m/s)	Mass Flow (kg/s)
44.0	29.0	259	0.940	200	28.5	259	0.940	203	24
28.0	17.9	255	1.000	238	17.7	254	1.000	240	14

Table 8. Metal temperature (K) as a function of distance from hole

P_o	Upstream Radial Distance from Surface of Hole					
(bar)	S_o (0mm)	S_1 (15mm)	S_2 (30mm)	S_3 (45mm)	S_4 (60mm)	S_5 (75mm)
44.0	259.1	268.6	273.6	277.5	280.6	283.1
28.0	255.0	266.1	272.0	276.5	280.1	283.1

List of figure captions

Figures

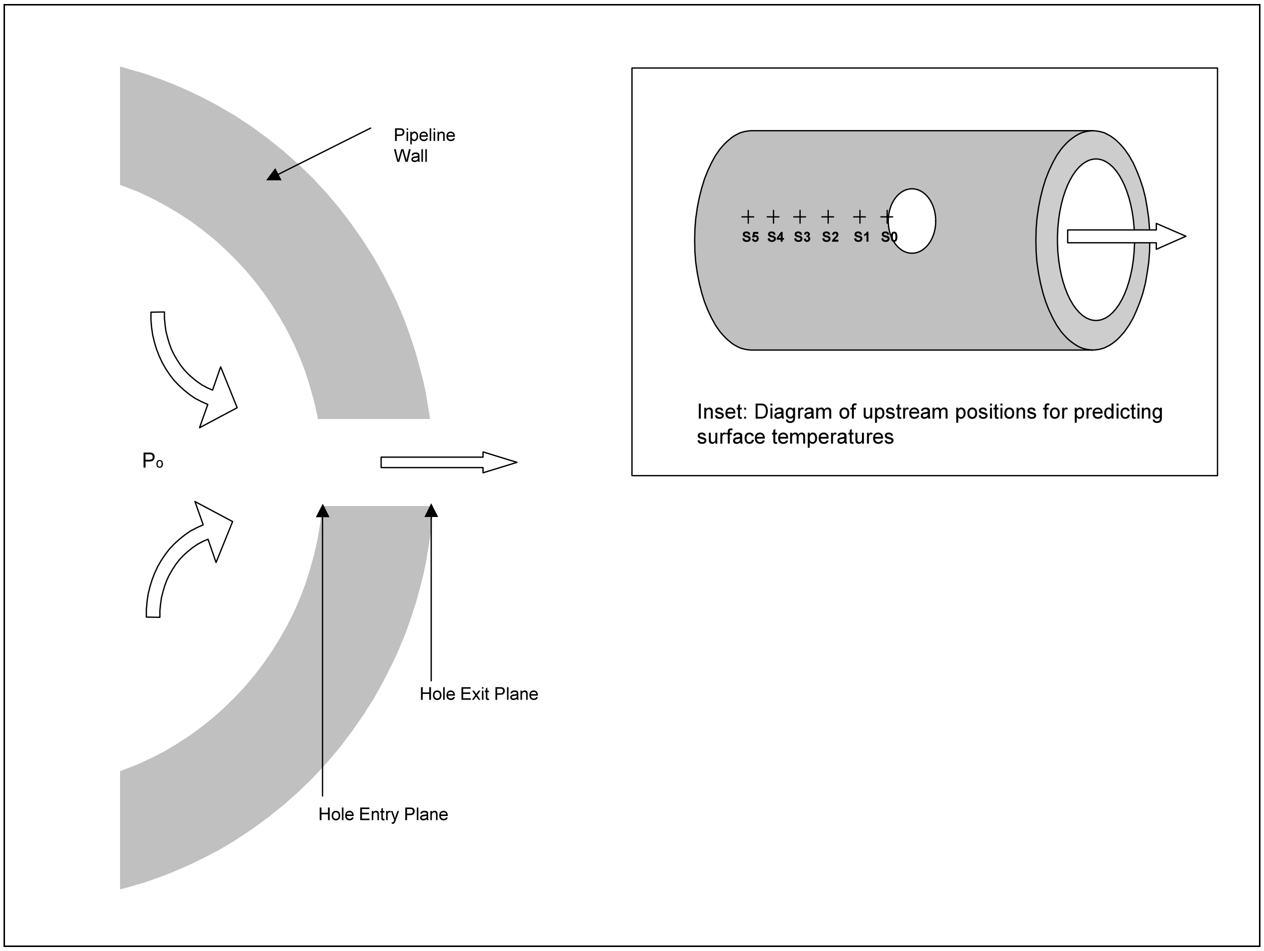

Figure 1 – Schematic of the hole geometry in the pipeline and measurement locations for parameters reported in the following tables

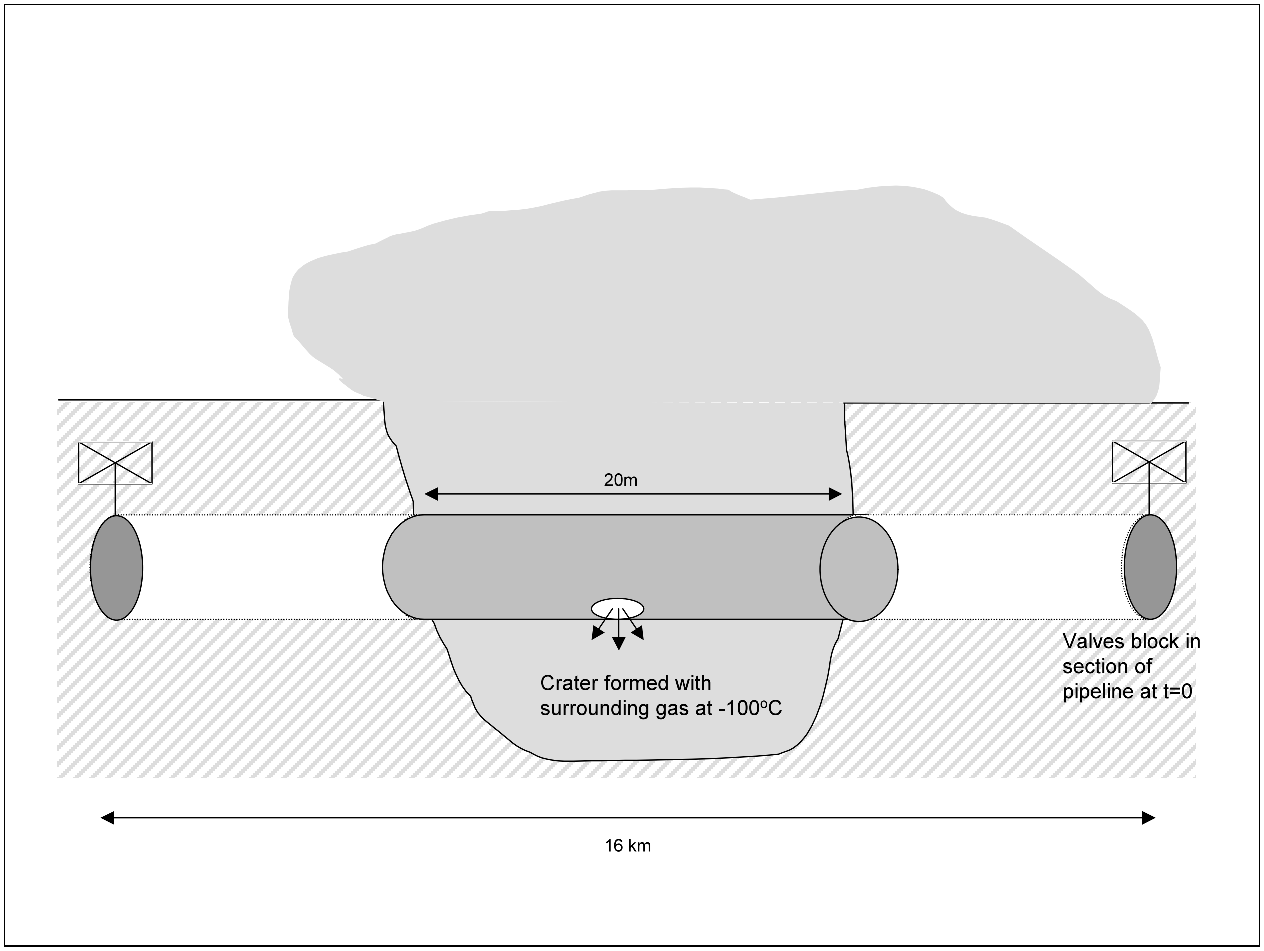

Figure 2 – Blowdown of a blocked in section of pipeline through a 50mm diameter hole

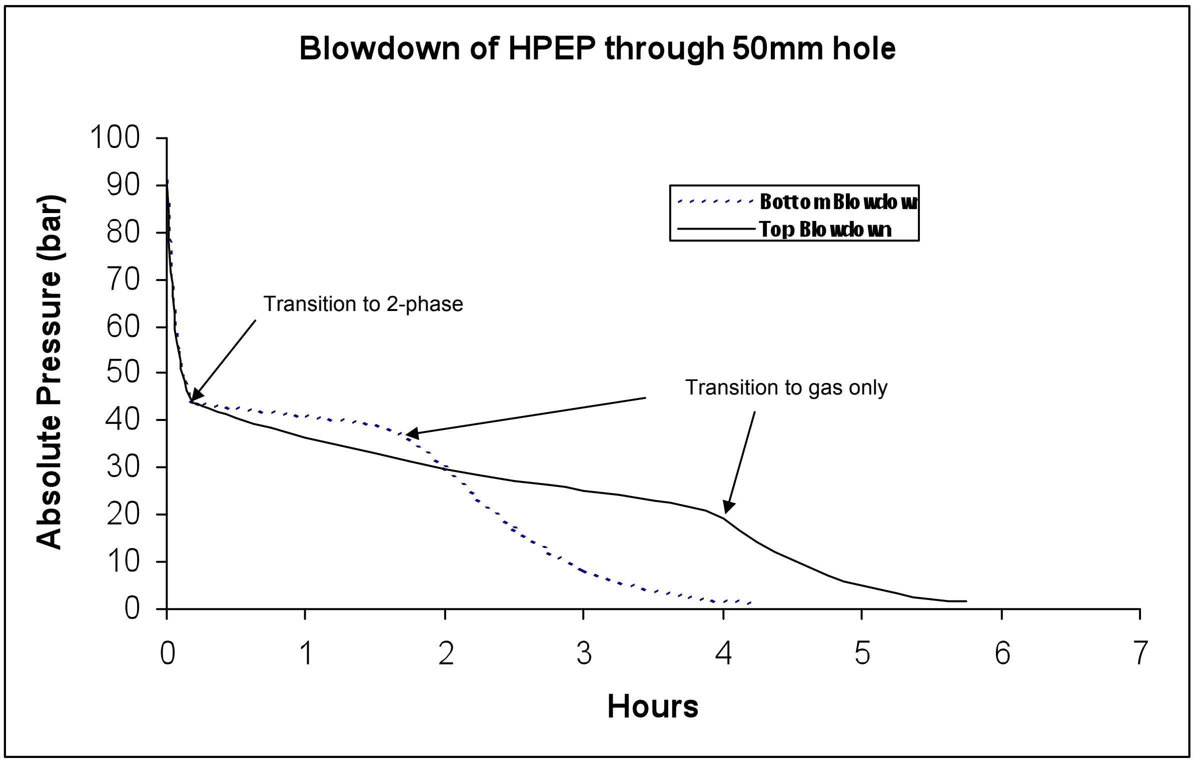

Figure 3 – Pressure decay against time for blowdown of HPEP

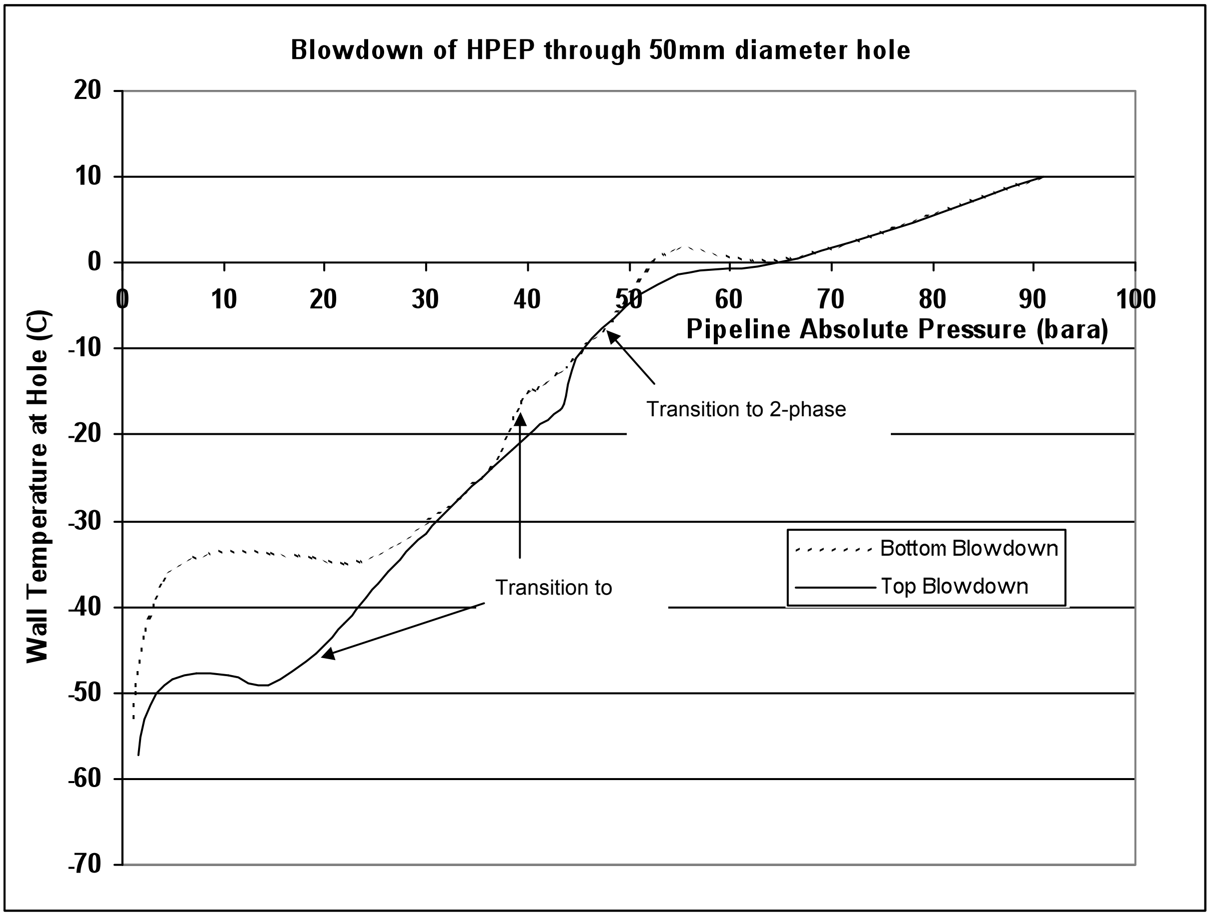

Figure 4 – Wall temperatures predicted at hole versus pipeline pressure