

COMPARISON OF THE SUBSURFACE MIGRATION OF LPG AND NATURAL GAS[†]

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Incidents have shown the serious potential consequences when underground pipes carrying flammable gases begin to leak and gases migrate through the soil into nearby buildings. This applies to underground pipework supplying LPG as well as natural gas. However, data on how gas migrates through a range of typical soil types is only available for natural gas. Adaptation of this knowledge to LPG migration would be a useful short cut in addressing some of the risks associated with LPG installations.

The paper describes a programme of experimental work commissioned by the Health & Safety Executive to assess any major differences between LPG and natural gas movement through the ground, looking at two extremes of soil type. The results of the tests are presented and the significance of the findings is discussed.

INTRODUCTION

Liquefied Petroleum Gas (LPG) is often used in commercial and domestic premises, supplied from a storage tank in the open air, with underground pipework connecting the tank to the building. Modern standards recommend that low-pressure underground pipes are made of polyethylene but previously carbon steel pipework was used, often with a water-resistant tape cover.

Underground pipework has a limited lifetime, and older pipes in service in the UK may be reaching the point where they need to be replaced. In May 2004, LPG leaking from a corroded underground pipe entered the premises of ICL at Maryhill, Glasgow. A gas explosion in the basement led to the collapse of the building, killing 9 people and injuring 33 more. This incident highlighted the potential consequences of leaking LPG. This has led to the suggestion of a systematic replacement programme for all metallic underground LPG pipes. There are many thousands of LPG installations that may need replacement pipework, and a replacement programme may take several years to complete. To reduce the likelihood of further incidents, it may be appropriate to prioritise the replacement of those pipes at most risk. Such prioritisation will depend on three factors:

- the likely age of the installation – with older pipes having higher priority,
- the likely speed of corrosion – with those areas where the soil type might give faster corrosion rates having higher priority
- the likelihood that a leak might lead to serious consequences – with those areas where gas escapes might be difficult to detect or could quickly travel into buildings having higher priority.

When similar issues were recognised with natural gas distribution pipework, significant effort was put into understanding corrosion of pipes in different environments and the way in which natural gas migrates through different soil types. When the knowledge gained from this work

was combined with data on local soil types and local pipe-work history, it allowed the relative risk of a hazardous leak from different sections of pipe to be assessed. This was then used in prioritising the natural gas pipework replacement programme.

The external corrosion effects will be the same for pipe made from similar materials, irrespective of the gas being transported. Data obtained for corrosion of ferrous natural gas pipework will be relevant to ferrous LPG pipes, although the actual failure mechanisms of iron and steel pipes may need to be addressed differently.

Should a leak occur, migration through soils would have different characteristics for different gases. Work for the earlier studies used natural gas, as that was the direct concern. Factors such as gas density, viscosity and diffusion rates will affect the movement of gas and change between different gases. Table 1 shows these properties for methane and propane – the primary constituents of natural gas and LPG, respectively. This shows that there could be significant differences between natural gas and LPG behaviour.

A proprietary model for natural gas movement through the ground had previously been developed to assist with risk assessment for mains gas. In order to understand whether this model could be used as the basis for a migration model within a risk assessment tool for LPG pipe, HSE commissioned a series of experiments to compare the actual behaviour of propane and methane released in underground leaks. In order to minimise the number of experiments, a limited number of circumstances were examined. These included just two soil types, two types of ground cover and a single gas flow rate. LPG and natural gas are mixtures with a wide range of potential components. To guarantee consistent gas composition throughout the experiments, pure propane and methane were used.

EXPERIMENTAL

The two different soils selected for test were each contained in identical, open-topped boxes, constructed from reinforced

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Table 1. Some properties of methane and propane

	Density at NTP (kg/m ³)	Viscosity at ~20°C (mPa.s)	Diffusion velocity in air at NTP (mm/s)
Methane	0.717	0.011	5.1
Propane	1.868	0.008	3.4

Reference: Matheson, Gas Data Book, 6th Ed., 1980 & <http://wps.com/LPG/WVU-review.html>

plywood. The internal dimensions were 2000 mm long × 800 mm wide × 1100 mm deep.

One box was filled with yellow builders ‘sharp’ sand and the second with a commercially supplied topsoil mixture. Both were filled with approximately 1.5–2 tons of substrate to a depth of 750 mm for sand and 820 mm for soil.

The sand would give a relatively uniform distribution of small voids through which gas could pass. In the topsoil, voids would be larger and irregularly spaced with dense lumps of soil between them.

Gas was released into the substrate via a length of 3/8” diameter pipe, capped at one end and with a slot cut into the side. The pipe was pushed vertically downwards into the substrate close to one end of the box with the leak position facing away from the nearest wall. Gas was released symmetrically along the centre line of the box from a depth of 250 mm and at a distance of 100 mm from a solid box wall.

The schematic drawing in Figure 1 shows the position of the release point within the box while Figure 2 shows the release pipe and cut slot. The propane or methane test gas was regulated from a cylinder to 275 kPa (40 psi) and the release rate controlled using a rotameter control valve. A flow rate of 0.25 m³.hr⁻¹ (4.2 l.min⁻¹) was used in each test.

Within each box, gas sampling points were set at 300 mm and 600 mm distance from the release point along the centre line of the box and at nominal depths of 40 mm, 250 mm and 500 mm (see Figure 1).

Gas sampling at up to six points in the substrate was achieved by inserting rigid plastic sampling pipes with 6 mm outside diameter vertically into the substrate at the required depth and distance from the release point. Each pipe fed into a gas analyser with a built in sampling pump, via 1 m of flexible tube with a built-in filter. ATEX certified landfill gas analysers were used. These were portable, battery powered devices able to be used in flammable or explosive atmospheres and capable of measuring hydrocarbon (methane) concentrations from 0 to 100% CH₄. They operate over two ranges, continuously displaying both the gas concentration as % gas and as % LEL (lower explosive limit, 5% for methane). The analysers used held valid calibration for methane, with a worst-case accuracy cited as 3% at the 100% gas level. When testing propane it was necessary to apply a correction factor to the measurements obtained. This factor was measured by running a propane span gas through each analyser.

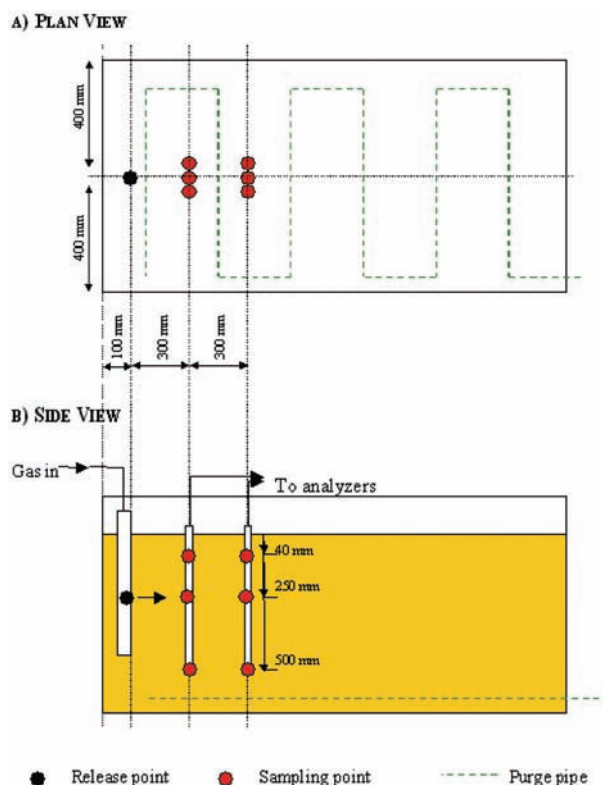


Figure 1. Relative positions of the release point and sampling points

Different types of ground cover were provided for by either covering the substrate surface with plywood sheet (equivalent to a non-porous covering such as asphalt) or leaving uncovered (a porous covering such as soil beds or turf). In practice, the cover was made from several sheets of plywood that could be placed on the surface while allowing the gas sample lines to remaining position. The cover therefore allowed limited leakage, both between the separate sheets at certain distances along the box, and at the very edges of the box. In this respect the cover is more like paving slabs than an asphalt or poured concrete surface. Nonetheless, it would be expected that a significant degree of cover would have a marked effect of the progress of gas through the ground.

The base of each box was fitted with a series of perforated pipes. This enabled compressed air to be used to purge residual gas contamination after each test. The entire system of both boxes and sampling system were contained in a large IP rated flammable store whose doors were closed during testing. To facilitate measurement of concentrations, the six analysers were arranged close to each other and a video camera used to allow remote observation of the analyser displays. The camera image was recorded to a remote recording device allowing post-test evaluation and recording of gas concentration readings.



Figure 2. Photograph of the release point

Tests were run for two hours or until all analysers were reading a steady, stable gas concentration. One test was performed per day and the system allowed to purge overnight. A typical test set up is shown in the photographs in Figure 3.

To assess the effects of variability in the soil, tests were carried out at an alternative location in the box – the release point and sampling points were moved, as whole, 200 mm from the centreline towards one long edge.

RESULTS

Tests were carried out across a full matrix of the controlled variables (i.e. propane or methane gas, open or covered surface, sand or top soil substrate). For the tests in topsoil with an open surface, tests were also carried out with the instrumentation at the alternative location.

Figures 4 to 13 show the results from each of these tests. Each graph shows time histories of the samples from each test point. The darker shades show the samples at 300 mm along from the release point, while the lighter shades show samples at 600 mm. The black/grey traces are near the surface, red/pink at the release depth and blue/cyan at twice the depth of the release. These are shown in the legends. For example, in Figure 4 the legend 300/250 indicates the sample point at a distance of 300 mm from the release point and at the nominal release depth of 250 mm. All the results are shown as a volume percentage concentration of gas. In interpreting the graphs with respect to a hazardous situation, it should be recalled that the lower flammable limits are 5% for methane and 2.2% for propane.

The results are summarised in Table 2, which gives a general overview of the behaviour in each test condition:

A number of other observations were made:

- In all the propane tests there was a noticeable smell of gas within a short time of the release starting. (The methane used was not stench and so had no detectable smell).
- A single test was carried out with sampling at several points across the surface of the soil filled box. This showed that the concentration rose to the highest levels close to the edges of the box.

DISCUSSION

TIME TO REACH LOWER FLAMMABLE LIMIT

The lower flammable limit (LFL) is the lowest concentration of gas at which an ignition source can start the gas burning. For an explosion to occur, the gas must be present at a concentration above LFL. For methane this limit is 5% concentration of gas in air, while for propane it is lower at 2.2%.

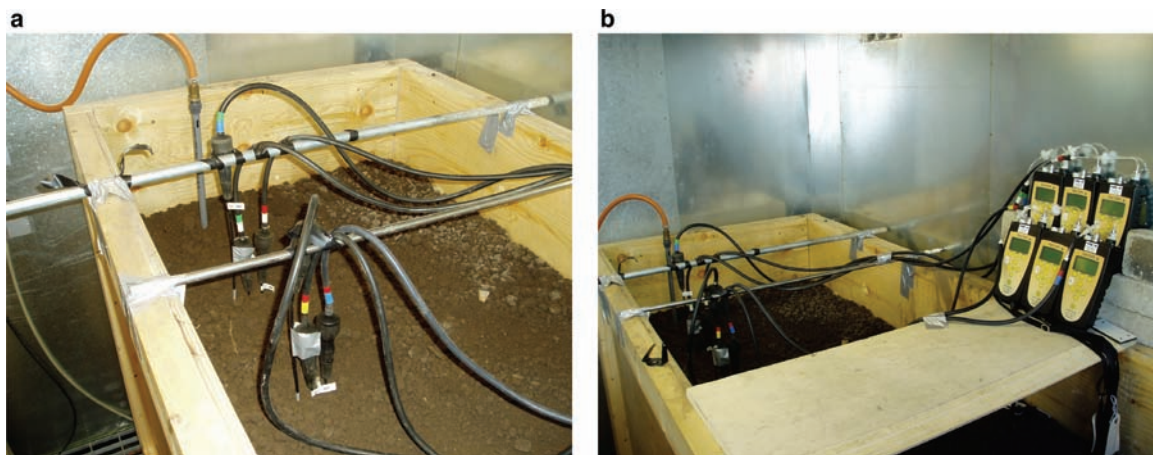


Figure 3. Photographs of experimental set-up for uncovered soil tests

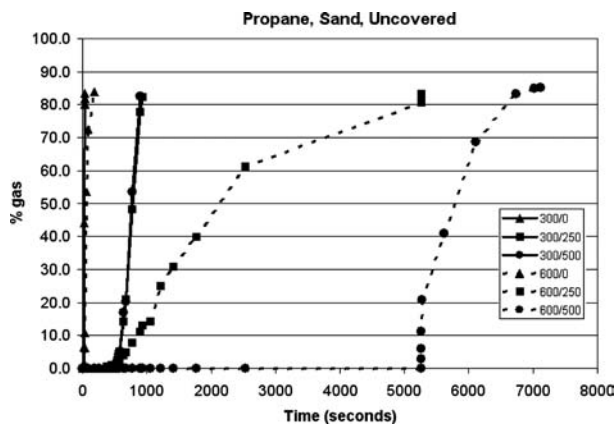


Figure 4. Propane release in open sand

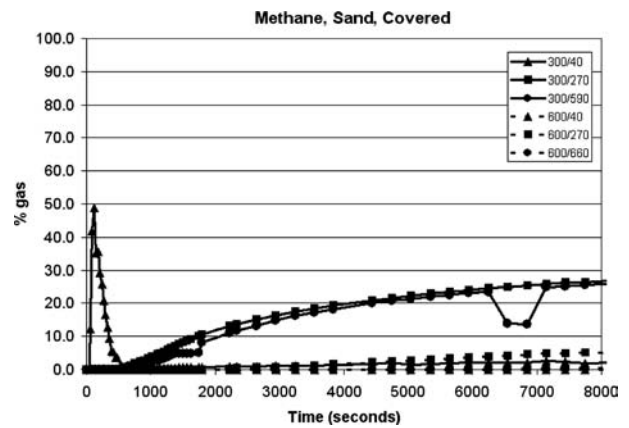


Figure 7. Methane release in covered sand

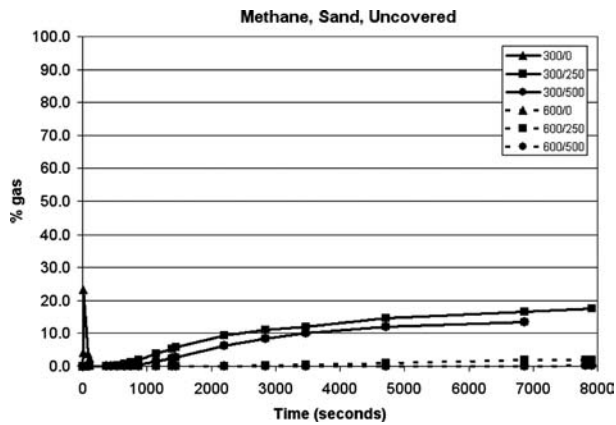


Figure 5. Methane release in open sand

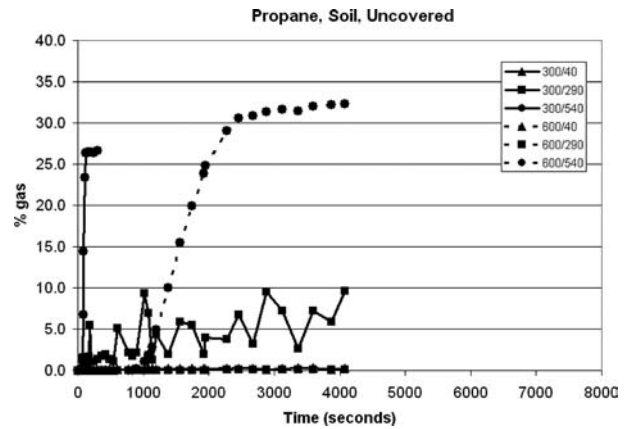


Figure 8. Propane release in open soil

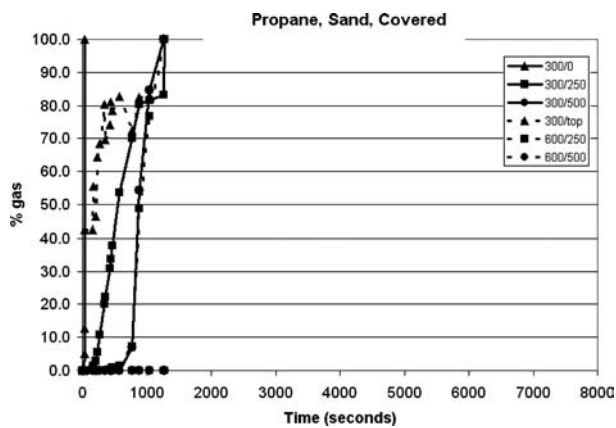


Figure 6. Propane release in covered sand

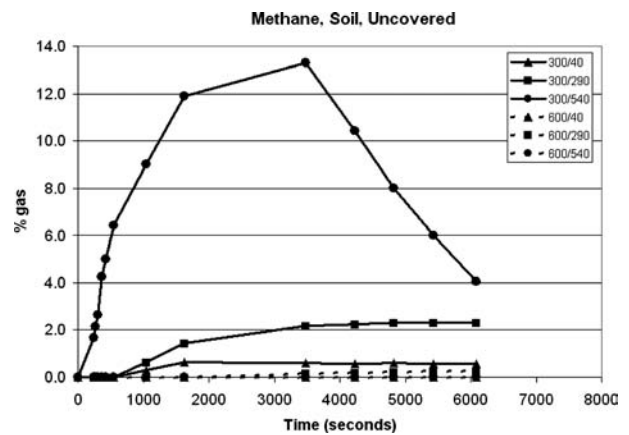


Figure 9. Methane release in open soil

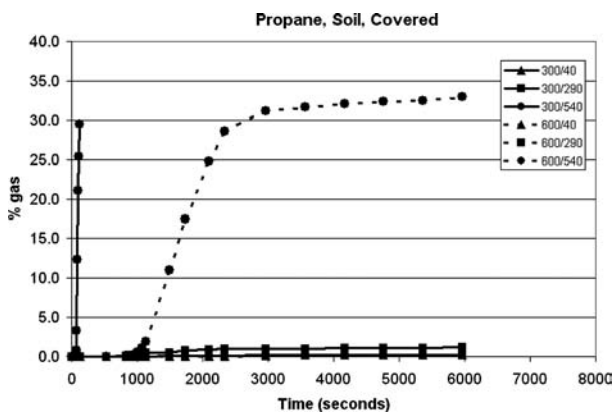


Figure 10. Propane release in covered soil

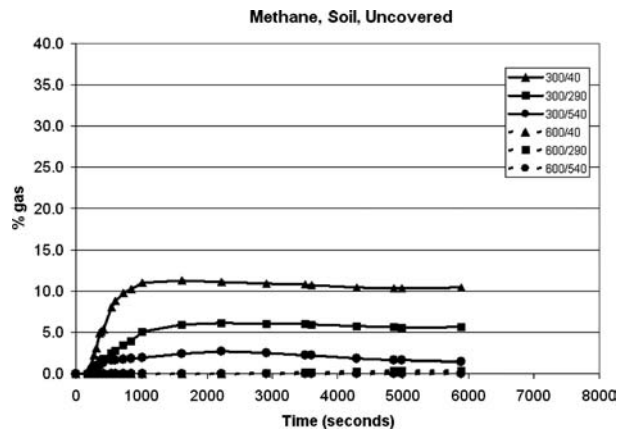


Figure 13. Methane release in uncovered soil (Alternative location)

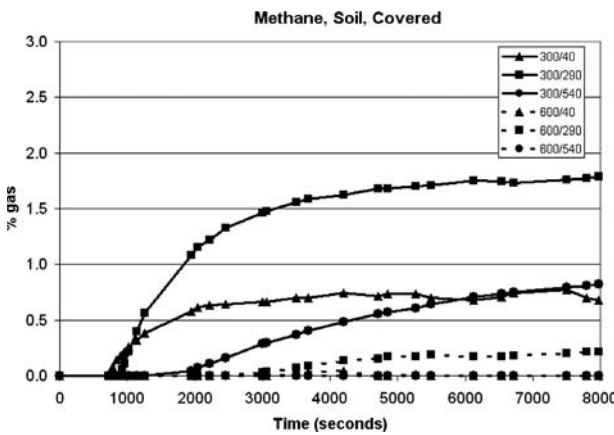


Figure 11. Methane release in covered soil

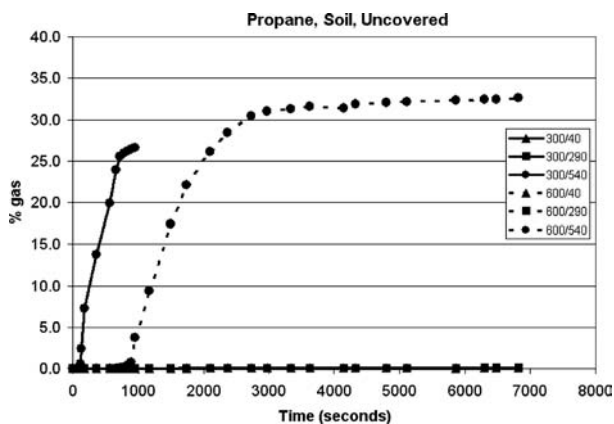


Figure 12. Propane release in uncovered soil (Alternative location)

Tables 3, 4 and 5 show the time at which LFL was reached at three depths at the near location (300 mm from the release point). The time to LFL is shown in seconds, with “<LFL” indicating that concentrations did not rise to LFL at that point at any time during that experiment.

These results show that LFL is typically reached very much faster for propane than methane, more so than can be accounted for by the higher LFL concentration of methane alone. In the most extreme case, it took nearly five times longer to reach LFL with methane compared to propane.

DIFFERENCES IN SOIL TYPE

Because of the differences in void structure, it would be expected that the flows in sand would be more uniform and repeatable, while in soil the flows are more likely to vary between different points and to be more sensitive to small changes in structure. This is reflected in the results. In particular, the results for tests carried out at the alternative position in the soil bed differ significantly from otherwise identical tests at the primary position.

This could well be a significant issue for buried pipes, which will be located at the bottom of refilled trenches. The ground along the length of the pipe and above it is likely to be less compacted than the ground to either side and below. Gas is therefore likely to track preferentially along the pipe run and to the surface. Easier flow to the surface may be advantageous, as the gas may be detected more quickly. However, easier flow along the length of the pipe may be more problematic, as it will encourage gas to move back towards the source (such as an LPG tank) and towards the point of use.

IMPLICATIONS FOR MODELLING FLOWS

The proprietary model presumes that there are two drivers for gas flow through porous ground: buoyancy and pressure

Table 2. Summary of test results

Ground type	Covering	Distance from release	Comments on behaviour
Sand	Covered	300 mm	Propane concentration high at all depths. Methane only rose to 25% max.
		600 mm	Propane concentrations high towards surface. Methane only at 5% after 2 h 15 m
	Open Surface	300 mm	Propane high at all levels. Methane only rose to 15% max.
		600 mm	Propane rose to high levels but slowly (1 h 30 m at 500 mm depth) Methane only 5% after 2 h 15 m (i.e. as covered)
Soil	Covered	300 mm	Propane high below release depth, low elsewhere Methane only rose to 1.5% at release depth
		600 mm	Propane rose to 30% at lower depth after 20 min. Methane below 1% even after 2 h 15 m.
	Open	300 mm	Propane high below release depth, low elsewhere. Methane peaked at ~45 min (13% at lower depth) then concentrations fell again.
		600 mm	Propane rose to 30% at lower depth after 45 min. Methane below 1% even after 2 h 15 m.
	Open (alternate location)	300 mm	Propane 25% below release depth, low elsewhere. Methane peaked at ~45 min (3% at lower depth) then concentrations fell slightly.
		600 mm	Propane rose to 30% at lower depth after 45 min. Methane rose to 1% after 2 h 15 m.

Table 3. Time to reach LFL at positions near the surface (seconds)

	Propane		Methane	
	Sand	Soil	Sand	Soil
Open surface	25	<LFL, <LFL (alt.loc)	14	<LFL, 375 (alt.loc)
Covered surface	30	<LFL	55	<LFL

Table 4. Time to reach LFL at positions at the release depth (seconds)

	Propane		Methane	
	Sand	Soil	Sand	Soil
Open surface	510	180, <LFL (alt.loc)	1300	<LFL, 1000 (alt.loc)
Covered surface	185	<LFL	1170	<LFL

Table 5. Time to reach LFL at position below the release depth (seconds)

	Propane		Methane	
	Sand	Soil	Sand	Soil
Open surface	540	73, 128 (alt.loc)	2650	419, <LFL (alt.loc)
Covered surface	635	70	1700	<LFL

differences. It is likely that any other model would also include these drivers.

The results clearly show that there is a difference in behaviour between methane and propane, with methane reaching a given concentration more quickly above the release point and propane reaching a given concentration more quickly at lower levels. This indicates that buoyancy is affecting the flow through the ground. It is also clear that this difference is more pronounced in the topsoil where there are larger, less uniform voids. During the tests at the alternative location in the topsoil, the propane concentration never rose to LFL near the surface while the methane concentration did not reach LFL at the lowest position.

The results also show that buoyancy is not the sole driver – if this were the case then methane would not have sunk below the release point. Equally, propane would not have risen above the release point until all the space in the lower part of the box had filled with gas.

The observed behaviour was that propane was quickly detected at the surface. In the sand tests there was sufficient propane to be measured by the instruments. In the soil tests there were lower concentrations at the surface, but there was still sufficient propane escaping from the surface for the stenching agent to be detected. Methane was also seen at the lower measuring points, below the release point.

This shows that pressure is also affecting the subsurface flow. The overall effect of pressure differences is to drive gas towards the surface, the air pressure being lower than the gas pressures. However, more locally the effect is to drive the gas in all directions away from the initial release point. Pressure differences also enhance the effects of channelling along the path of least pressure drop. This is clearly seen in the observation that surface propane concentrations appear highest at the box walls. The impervious walls and floor of the boxes serve as a total blockage to further lateral flow and pressure can only drive the gas upward to the surface.

The results indicate that both pressure and density effects have a role in the migration of gas through the ground. Both effects need to be included in any predictive model of behaviour.

It is also clear that the practical results will be more variable in more broken ground. Any modelling also needs to reflect this and either err on the side of caution or clearly indicate a lower level of confidence in the margin of error around an “average” result. Where results are used to predict the likelihood of flammable gas entering a building through the ground, the conservative assumption is for the fastest movement of gas.

CONCLUSIONS

The proprietary model for natural gas behaviour incorporates the two driving effects, buoyancy and pressure difference, both of which have been seen in this experimental study. As such it could form the basis of an LPG-specific model.

Any modelling of gas movement should recognise the differences in behaviour and physical properties of LPG when compared with natural gas. For the existing knowledge gained from natural gas to be useful in assessing the risks for LPG installations, care needs to be taken to include appropriate factors for the faster movement of LPG through the ground, as well as its lower LFL.

Such a model can compare the risk from one situation with that from another. However, to produce a model capable of detailed prediction of the specific behaviour of LPG in particular circumstances, further work would be needed to quantify the effect of the mechanisms that have been indicated in this study.

In broken ground or where other spaces exist which might channel gas, it should be recognised that it is likely that gas movement (whether LPG or natural gas) will be dominated by flow along such channels. In such soils, prediction of an average migration rate will provide an accurate input into prediction of average risk, but to predict the highest risk then the highest migration rate needs to be calculated.