TTAC Limited
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Management of Risk
and Uncertainty

Risk Assessment of Corrosion Leakage of LPG from Domestic Underground Service Pipework:

MAIN REPORT

a report produced for the Health & Safety Executive

by Matthew Hunt, Kajal Somaiya and Tony Taig

TTAC Limited

March 2010

This report has been produced by TTAC Limited under contract to the Health & Safety Executive and is intended for incorporation into a final report on the whole of the Risk Assessment project

HSE CONTRACT REFERENCE: 1.11.4.1251.

Executive Summary

This is the report of an assessment of the risks to people in their homes resulting from corrosion leaks of liquefied petroleum gas (LPG) from underground service pipework. It has been carried out by Tony Taig, Matthew Hunt and Kajal Somaiya of TTAC Limited between July and September 2009 under contract to the Health and Safety Executive (HSE), with the assistance of our project partners T8 Design Ltd (building technologists) and the Building Research Establishment (BRE), and with advice and guidance from several other organisations involved in the assessment of contaminant gas risk in buildings in the context of radon and contaminated land.

The aims of the assessment were to help HSE in a timely way to

- enhance understanding of risks at domestic installations, in particular of the impact on risk of the processes and factors involved in progressing from a leak in a pipe outside a building to harm to those inside the building, and
- provide models, data and supporting evidence to enable others (whether individual LPG users or their suppliers) to make fit for purpose assessments of risk at specific premises.

The project has involved three main research activities:

1. collection and analysis of information on LPG suppliers' experience of leaks – to understand the frequency and characteristics of relevant LPG leaks at domestic premises
2. collation and application of relevant research on the migration of contaminant gases through soil and into buildings – to understand the phenomena involved in gas leaks migrating from soil into buildings and develop models to estimate the likelihood that a given leak into soil will lead to a flammable LPG mixture inside the property, and
3. analysis of HSE's experience of LPG and natural gas incidents, based on accident, incident and investigation records – to estimate the likelihood that flammable gas mixtures in domestic properties will ignite, and the likelihood that a person present will sustain a given level of injury should they do so..

A fourth smaller research task involved the analysis of English, Scottish and Welsh Housing Condition Survey records to identify samples of domestic properties using bulk LPG as a fuel, to help understand the likely mix of properties a risk assessment needed to address and their characteristics.

The principal findings of these research tasks are

1. The average rate of initiation of corrosion leaks from underground service pipework is between 1 and 4 per 1000 properties per year. Numerous property-specific factors influence this rate but we have not been able to identify any readily useable local parameters (e.g. rainfall, age of pipework) that would provide a reliable refinement of this estimate for specific properties. The most important characteristics of such corrosion leaks for this study are that they are generally small in size, and that they develop progressively; there is no experience of sudden large leaks arising from this cause.

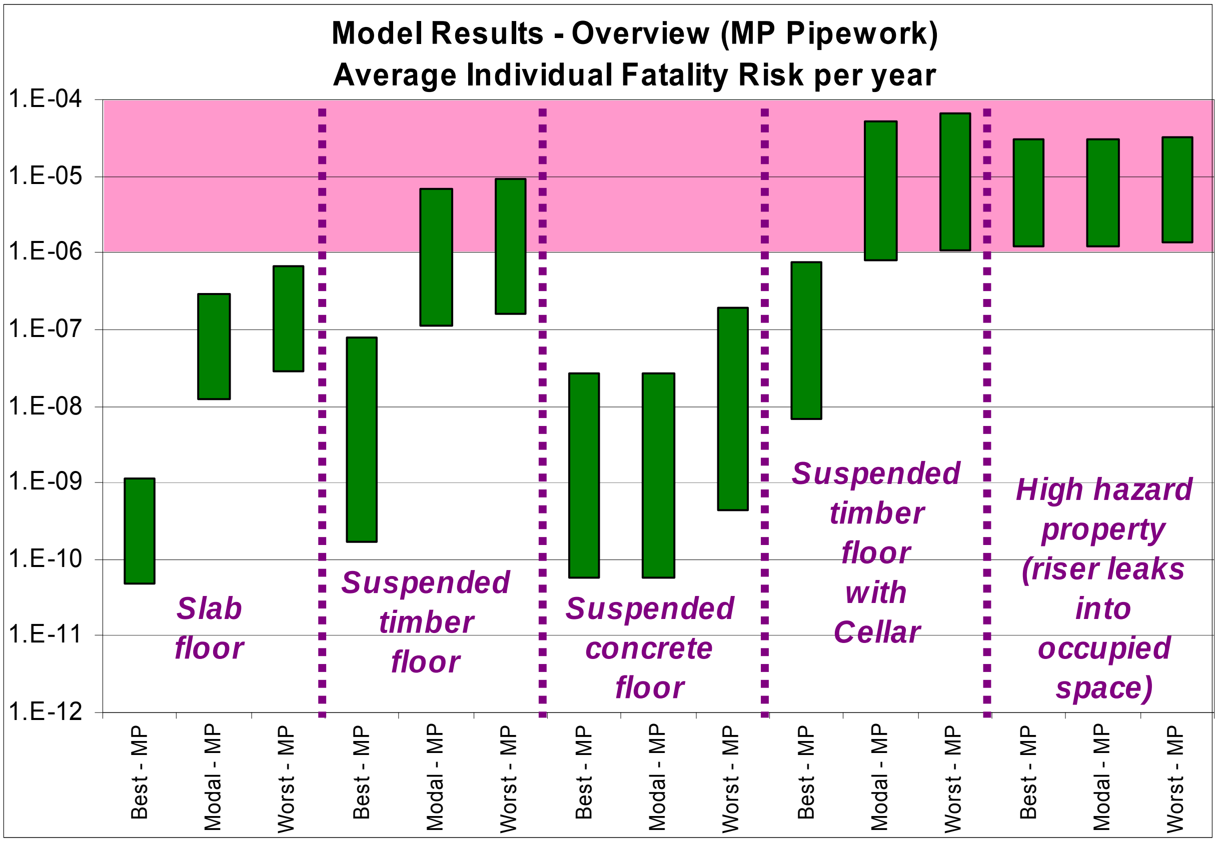
2. Migration of contaminant gases from soil into buildings over a long period of time (e.g. in the context of radon or toxic contaminant ingress) generally involves very large dilution factors, substantially greater than those required to reduce pure LPG in soil to levels indoors at or below the lower explosive limit. On shorter time scales, though, there is large variability in the dilution between soil and buildings; it is possible for gases to accumulate in soil and then be "sucked up" into buildings when conditions change. The phenomena involved are too complex to make a confident prediction of the dilution to be expected for a specific building. The key factors involved include foundation construction, the ability of leaking LPG to "track" either to the outside air or to the soil or void beneath the floor of the property, the type and condition (for which building age is a useful proxy) of the floor through which gas must migrate to enter the building, and the ventilation and dilution within under-floor voids and occupied parts of buildings.
3. A substantial proportion of major gas leakage incidents (involving natural gas as well as LPG) identifiable from HSE incident records involved the gas igniting in domestic buildings. A relatively small proportion of people present were killed or seriously injured in incidents involving gas ignition in such buildings. Use of statistics on such incidents is considered to provide a pessimistic basis for estimating risk from explosions arising from underground corrosion leaks, because

   a) the reliability of incident reporting increases with severity of incident (i.e. the proportion of incidents included in the statistics decreases in a sequence from "incidents involving serious injury", via "incidents involving explosion", to "incidents involving a flammable gas mixture in a building"), and

   b) the nature of corrosion leaks, which develop progressively, mean that there should be a high likelihood of detecting any developing accumulation of LPG in a building by smell long before a flammable concentration is reached.

A suite of event tree models to estimate the individual risk of fatality, major and minor injury to a person present in a domestic property has been developed. The inputs to the models include various property-specific factors relevant to the migration and dilution of LPG between soil and the building, and use generic estimates of the likelihood of a corrosion leak being initiated in the service pipework. The models include several major assumptions and sources of uncertainty, but are in our view consistent with established models of longer-term dilution of gas in buildings and with the available evidence on the characteristics of relevant LPG leaks.

An overview of the model findings for different properties is provided in the figures below (reproduced from Figure 13) for medium and low pressure properties respectively. The pink bars at the top of the charts indicate the areas of individual risk identified in HSE's guidance on risk tolerability as corresponding to the "ALARP" or "tolerable risk" region for members of the public. Above those bars risks would typically be regarded as intolerable; below it, they would typically be regarded as broadly acceptable.


Model Results - Overview (MP Pipework)
Average Individual Fatality Risk per year
1.E-04
1.E-05
1.E-06
1.E-07
1.E-08
1.E-09
1.E-10
1.E-11
1.E-12
Slab floor
Suspended timber floor
Suspended concrete floor
Suspended timber floor with Cellar
High hazard property (riser leaks into occupied space)
Best - MP
Modal - MP
Worst - MP
Best - MP
Modal - MP
Worst - MP
Best - MP
Modal - MP
Worst - MP
Best - MP
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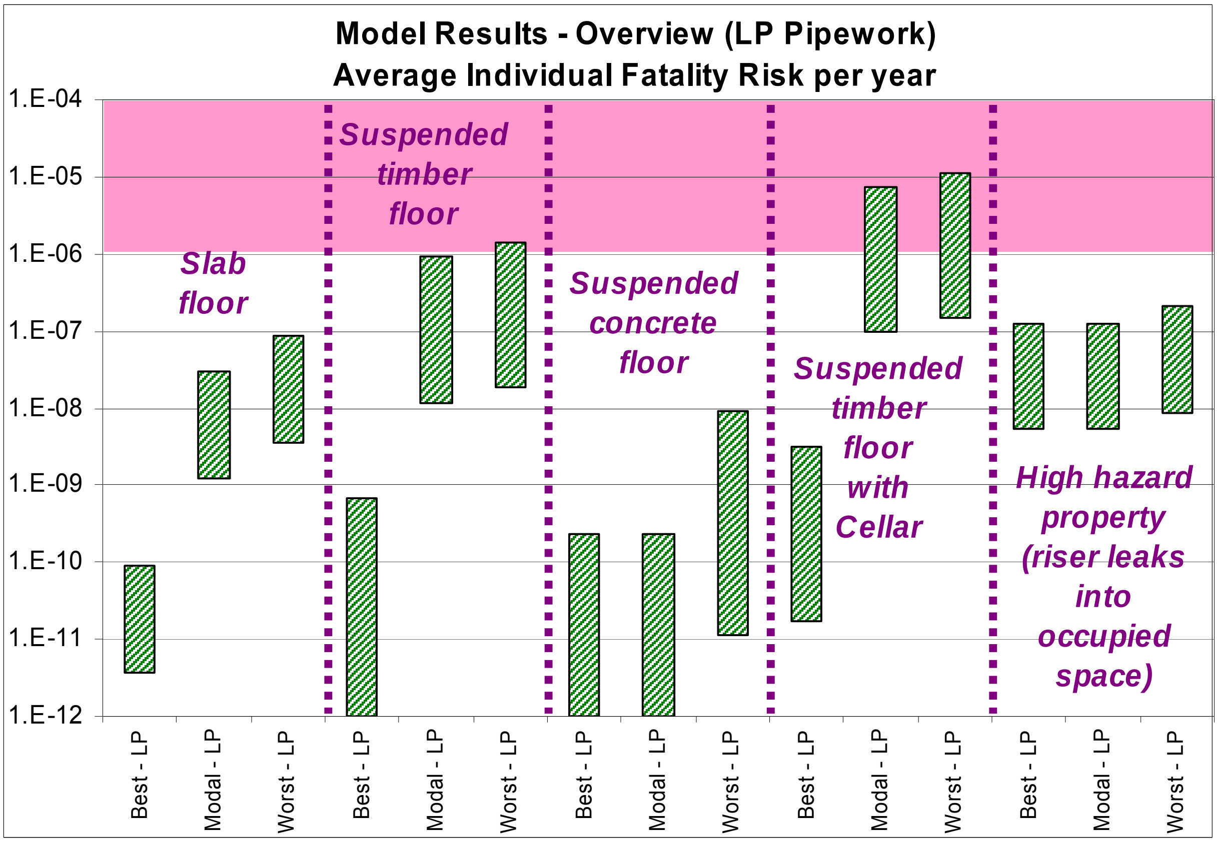
Best - MP
Modal - MP
Worst - MP


Model Results - Overview (LP Pipework)
Average Individual Fatality Risk per year
1.E-04
1.E-05
1.E-06
1.E-07
1.E-08
1.E-09
1.E-10
1.E-11
1.E-12
Slab floor
Suspended timber floor
Suspended concrete floor
Suspended timber floor with Cellar
High hazard property (riser leaks into occupied space)
Best - LP
Modal - LP
Worst - LP
Best - LP
Modal - LP
Worst - LP
Best - LP
Modal - LP
Worst - LP
Best - LP
Modal - LP
Worst - LP
Best - LP
Modal - LP
Worst - LP

Our conclusions are as follows:

1. The levels of individual fatality risk associated with corrosion leaks from underground service pipework at domestic properties are generally low. For the majority of households using LPG we would expect them to fall clearly into the “broadly acceptable” band when judged against typical risk tolerability criteria.
2. An exception to this general observation should be made for properties with cellars or basements, for which individual risk levels could extend well into the “tolerable risk” or “ALARP” region for properties with either medium or low pressure LPG pipework. Such properties are likely to constitute no more than 1-2% of domestic bulk LPG users’ homes.
3. A second important exception should be made for properties with gas installations which effectively have incorporated the service pipework and/or the riser into the fabric of the building. Individual risk levels for users with MP systems (LP systems are at substantially lower risk) may extend well up into the “tolerable risk” or “ALARP” region. Such properties are likely to constitute at most a few per cent of LPG users’ homes, and include
   - old installations with gas entering the property below ground
   - properties that have been extended over service pipework, and
   - caravans and park homes with gas-tight “skirts” built between them and the ground
4. Among properties without cellars or basements and with “normal” risers entering the property above ground through an external wall, the greatest hazard presented by corrosion leaks underground is to houses with suspended timber floors. Risks for such properties with MP gas supplies could extend into the “tolerable” or “ALARP” region; this could also be the case for particularly severe LP cases (properties with unventilated below-floor voids). Explosions in the void below the floor, as well as in the occupied parts of buildings, are important contributors to this risk.
5. Modern homes are generally at substantially lower risk from this hazard than older homes, because of the much greater attention paid both to leak-tightness of floors and to effective ventilation, both above and (where appropriate) below the floor in modern building standards.
6. LPG supply pressure is a key factor; reducing pressure from MP to LP would effectively reduce risk into the “broadly acceptable” region for all but a very small proportion of properties (those with cellars and basements, and possibly some properties with suspended timber floors with a particular propensity for gas accumulation in the below-floor void).
7. The algorithms and data used throughout our risk model are highly uncertain, as there is minimal direct evidence available on migration of LPG from soil into buildings. The models do, though, in our view provide broad consistency both with a large body of research and modelling work done on such migration in the context of contaminated land and radon, and with what limited evidence is available on relevant LPG leaks from service pipework.
8. With this said, we are confident that our models are not significantly understating the risk associated with corrosion from underground LPG service pipework at domestic premises. In particular there is good evidence that
   a) such leaks contribute only a very small proportion of the overall risk of serious LPG escapes into the interiors of domestic properties, and that
   b) our models tend to over-estimate, rather than under-estimate, the likelihood of corrosion leaks of LPG into soil leading to significant levels of LPG in buildings.

9. Of the wide range of inputs explored to our models, relatively few make a really significant difference to the predicted risk. Of those explored here, LPG pressure, building age, floor construction, ground cover and presence of the special risk factors identified in 2 and 3 above are the most important. It should be borne in mind that there is a substantial evidence base on the corrosion susceptibility of service pipework in different soil conditions, which could not be explored in this study, and which might add "susceptibility of a specific property's pipework to corrosion" to this list.

In summary, we consider that, with some important exceptions, the risk associated with this hazard at domestic premises is small in comparison with tolerability criteria and with other risks of LPG use in domestic premises. The primary focus of a tool to help users assess the risk should thus be on enabling them, as quickly and easily as possible, to identify whether their property does or does not fall into the higher risk set. A specification has been developed for such a tool based around a set of seven (7) questions/issues, which in our view should be sufficient to enable the majority of LPG users safely to make their own assessment of the risks associated with this hazard and thus help them decide what to do about it.

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5 March 2010

Contents

1. Introduction

This is the report of an assessment of the risks to people in their homes resulting from corrosion leaks of liquefied petroleum gas (LPG) from underground service pipework. It has been carried out by Tony Taig, Matthew Hunt and Kajal Somaiya of TTAC Limited between July and January 2010 under contract to the Health and Safety Executive (HSE). The aims of the assessment were to help HSE in a timely way to

1. enhance understanding of risks at domestic installations, in particular of the impact on risk of the processes and factors involved in progressing from a leak in a pipe outside a building to harm to those inside the building, and
2. provide models, data and supporting evidence to enable others (whether individual LPG users or their suppliers) to make fit for purpose assessments of risk at specific premises.

We have been assisted in this task by our partners from BRE and T8 Design (building and construction technologists), and have also received considerable assistance from the staffs of the Environment Agency (EA), the Construction Industry Research and Information Association (CIRIA), the Health Protection Agency (HPA), the British Geological Society and the Scottish Housing Condition Survey. We are extremely grateful to these organisations and individuals for their help in navigating through the large literature available on the migration of hazardous substances through soil and into buildings. The opinions expressed and conclusions drawn in this report are our own and do not represent the endorsed view of HSE, or of any of the above organisations, or of any other party.

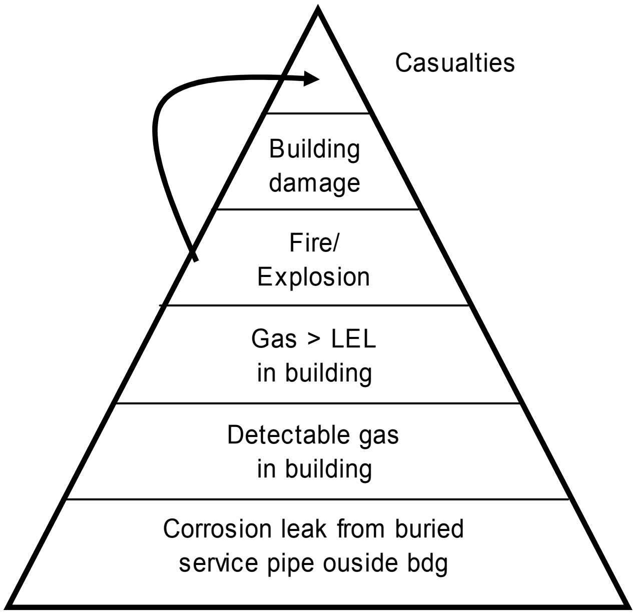
The report describes

- The approach we have adopted to the assessment (Section 2)
- The frequency and size distribution of relevant LPG leaks (Section 3)
- The likelihood of such leaks leading to concentrations of LPG at or above the lower explosive limit (LEL) in homes (Section 4)
- The likelihood that such concentrations of LPG, if they occur, will ignite/explode (Section 5)
- The likelihood of a person present being injured to different degrees if such an explosion occurs (Section 6)
- The integrated risk assessment model and sample results (Section 7)
- Observations and discussion of the results in comparison with some relevant risk benchmarks (Section 8), and
- Our conclusions and recommendations for the specification for a tool for use by householders and/or suppliers and HSE in evaluating this risk for their property (Sections 9 and 10).

2. Approach

Our approach is based on estimating the frequency of events at the base of a hazard "pyramid" as shown in Figure 1 below, and the probability that those events will then escalate up each tier of the pyramid.

Figure 1: LPG Corrosion Leakage Hazard Pyramid



The specific stages followed in assembling a risk model, the primary information sources from which these were derived, and the distribution of our report across this report and its companion reports on suppliers' leak experience and the migration of LPG from soil into buildings, are shown in Figure 2.

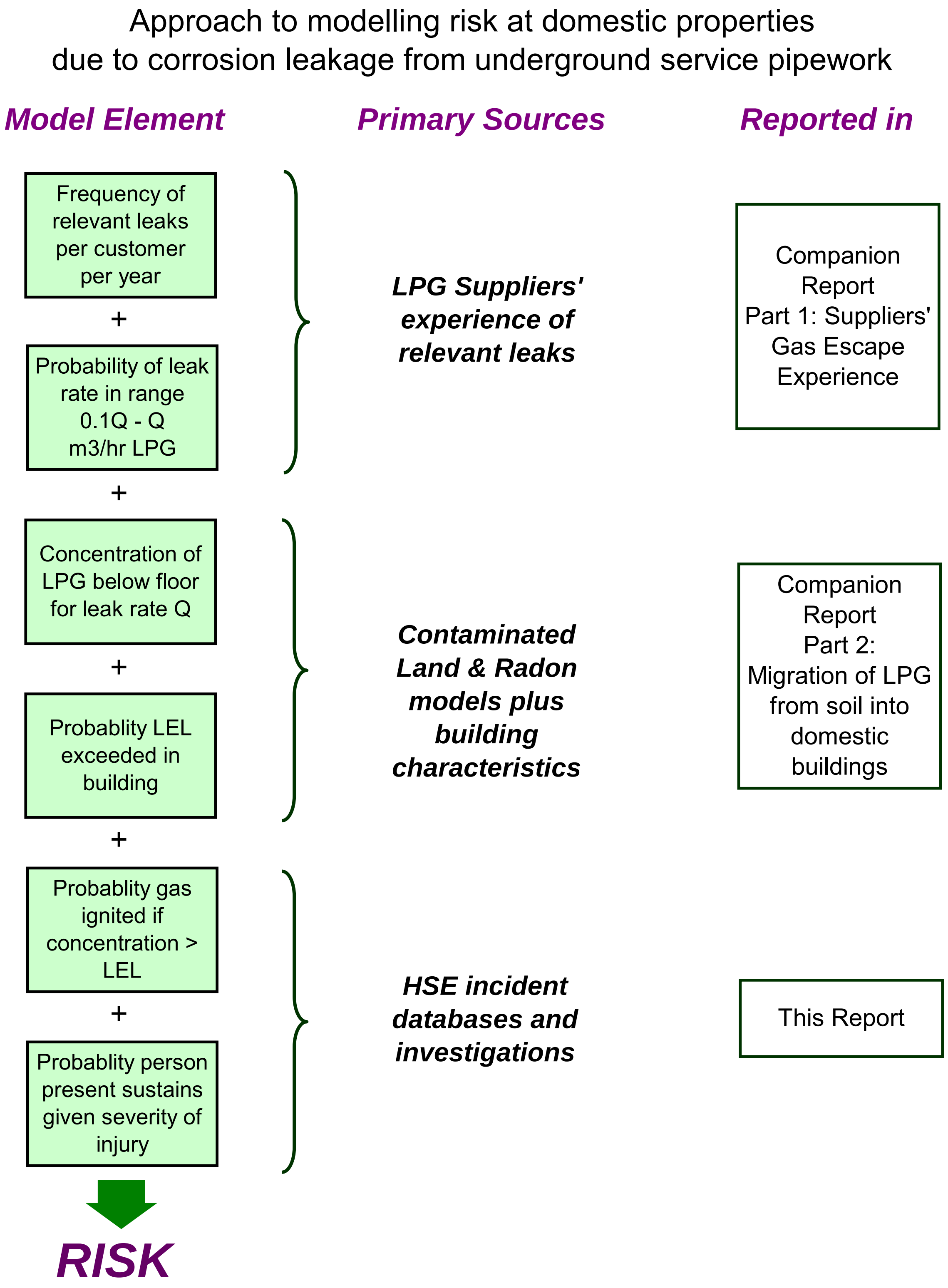
This report provides a summary of the findings from the companion reports as regards the first four elements of the model shown in Figure 2, and an explanation of the elements derived from HSE data towards the bottom of Figure 2 (Sections 3-6).

The findings of the work are incorporated into a companion spreadsheet containing event tree risk assessment models for

- Properties with concrete slab floors
- Void spaces below suspended floors (including cellars)
- Occupied spaces in properties with suspended timber floors, and
- Special cases where a gas leak could be forced directly into the occupied part of the property.

The models and their results are described in Section 7 and are discussed and compared with some relevant benchmarks in Section 8.

Figure 2: Model Approach, Sources and Report Structure



3. Frequency and Nature of Relevant LPG Leaks

Our research in this area involved collaboration with four leading suppliers of LPG (BP, Calor, Flogas and Shell). We held a workshop with experienced engineers and managers from each supplier to elicit and discuss their experience of relevant leaks. Each supplier also provided us with samples of records of relevant gas escape incidents, which we then reclassified and analysed. The total body of corrosion leak experience collected via the workshops and records is summarised in Table 1 below.

Table 1: Suppliers' Experience Collected in this Study

(a) Collected Personal Experience of Workshop Participants

Person-Years LPG engineering experience attending customer emergency calls	350-400$^{(1)}$
Total domestic underground service pipework corrosion leaks attended by workshop participants	240-500

(b) Documented gas escape records provided

Total records provided by suppliers	~ 50,000
of which domestic underground service pipework (USPW) leaks approx	500 - 1000
of which domestic USPW leaks due to corrosion approx	15 - 200

(1) Excludes experience, via staff reporting directly to them, of Engineering Managers who attended 3 of the 4 workshops

The work is described in full in our companion report[1]. Its main findings are described here in terms of what we learned about

a) the frequency of relevant leaks per customer,

b) the nature and size distribution (gas escape rate) of relevant leaks, and
the likelihood of such leaks escalating to give significant gas in buildings.

NOTE: Throughout this report we refer to domestic LPG systems as being either "medium" or "low" pressure (MP and LP respectively). These typically correspond to excess pressures (above atmospheric) in service pipework of 750 mbar and 37 mbar respectively; these pressures are used throughout as representative of MP and LP service pipework systems.

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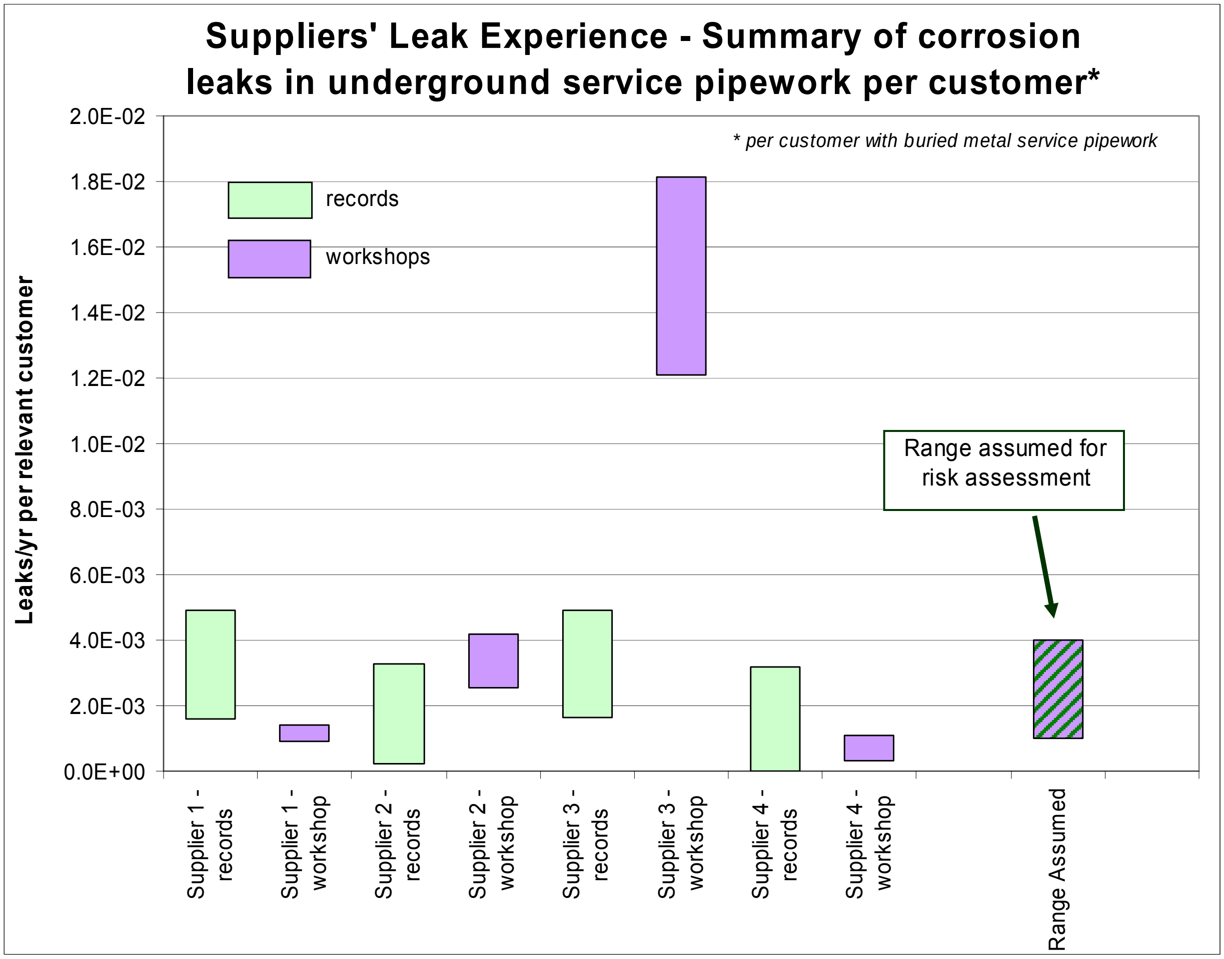
[1] Risk Assessment of Corrosion Leakage of LPG from Domestic Underground service Pipework: Part 1 – Suppliers' Gas Escape Experience (DRAFT), TTAC Ltd, November 2009

3.1 Frequency of Corrosion Leaks from Underground Service Pipework

Figure 3 shows the range of leak rates derived from our work with the four suppliers.

Figure 3: Leak Rates per Customer and Variability



There is considerable variability from supplier to supplier and between values estimated from experience in workshops and those estimated from documented records of escapes. The provenance of the workshop estimates relies on how accurately the experience of attendees is recollected and how well it represents their organisation's general experience. The provenance of the estimates based on documented records depends on how well they can be classified from the available text contained in them in terms of whether they involved leaks due to corrosion from underground domestic service pipework.

The lower bounds of the pale green bars represent incident records that clearly and definitely DID involve such leaks; the upper bounds of the bars represent all incidents that MIGHT have involved such leaks. We met the individuals involved in running the emergency desks and call logging, and are confident both a) that emergency calls are generally reliably logged, and b) that our classification of all incidents that might have been attributable to corrosion of underground service pipework erred significantly on the side of caution. We are therefore confident that the upper end of the average leak rates per customer is below the upper end of the green boxes on the chart.

Based on our considerations of the relative strengths and limitations of each data source, we have adopted a range from 1 to 4 corrosion leak incidents per thousand relevant customers (ones with underground service pipework containing some metal components) per year. As explained in the Part 1 companion report, the workshop with Supplier 3 provided high quality qualitative information about corrosion leaks, but there were particular difficulties in extrapolating the experience of workshop participants up to the whole company's experience (for all other workshops it was possible, in effect, to calibrate this extrapolation against company-wide records during the workshop). The significantly higher purple bar in the figure for the Supplier 3 workshop is thus considered to be an anomaly in terms of average risk experience.

When asked about the key factors making such leaks more or less likely, every supplier workshop immediately mentioned moisture as a key issue. Some of the suppliers provided us with leak records linked to customer postcode districts, and we purchased rainfall data from the Meteorological Office to explore whether there might be a significant correlation with leak rates. We subsequently obtained data on pipe material & estimated soil corrosivity and relative vulnerability of underground pipework to corrosion for sample LPG users' properties via HSE, based on a survey carried out by UKLPG and related calculations carried out for HSE by Germanische Lloyd. We were not able to obtain reliable information on property-specific LPG service pipe parameters (such as age, location, moisture around riser, specific soil type around riser, depth of pipe, ground covering around riser and length of underground service pipe).

We re-analysed our database of corrosion leaks and possible corrosion leaks and explored possible correlations between the frequency of initiation of leaks in relevant service pipe work, and the local rainfall, soil corrosivity and other factors. We found no such correlations, which is unsurprising in view of the long list of unknown potential confounding factors (those in parentheses in the previous paragraph). We did, though, find a good correlation between rainfall and the frequency of above-ground service pipework leaks due to corrosion, suggesting that if there were a strong correlation to be found we might reasonably have hoped to find it.

3.2 Nature of Corrosion Leaks from Underground Service Pipework

Some important aspects of corrosion leaks were identified from this work, in particular

a) they occur predominantly at the property, rather than the tank, end of the service pipework

b) a majority occur at or around the base of the riser, a significant minority occur where the riser enters the ground, particularly where this is in concrete

c) they are progressive in nature; there are no known instances of full fractures of LPG service pipework due to corrosion (in contrast with cast iron natural gas pipes, for which this is an important potential failure mechanism).

We have made the assumption that ALL of the underground service pipework corrosion leaks considered in Section 3.1 will take place from the base of the riser, close to the property, and at a depth of 60 cm (the industry standard depth for service pipework). This is pessimistic not only in respect of ignoring the percentage of leaks not at this location (as in (a) and (b) above), but also in that many leaks occur at shallower depths than this. An important aspect of our model of gas migration in soils is that it assumes LPG is trapped in a layer extending from 60cm depth down to the water table; 60 cm of soil can provide a potentially very effective barrier to LPG escaping into the surrounding air via the soil surface.

The other very important feature of corrosion leaks identified in our workshops and corroborated (in the minority of cases where a leak rate is mentioned) in suppliers' incident records is that they are generally quite slow. Typical pressure drop rates reported for medium pressure (MP) pipework are of order a few mbar to several 10's of mbar per minute, and correspondingly lower for low pressure (LP) pipework. Instances of rapid pressure drop are rare, and when they do occur are likely to have been preceded by considerable periods with lower leak rates.

The information provided by the suppliers on pressure drop experience has been translated into typical gas leak rates and then fitted to a log-normal probability distribution to provide a model enabling the likelihood of "rare but large" leaks to be estimated. The resulting distribution of probabilities by pressure band is shown in Figure 4, and is fully consistent both with the generality of observations made by suppliers, and with the more remote possibility of very large leaks (greater than 1 m^3/hr) occurring occasionally.

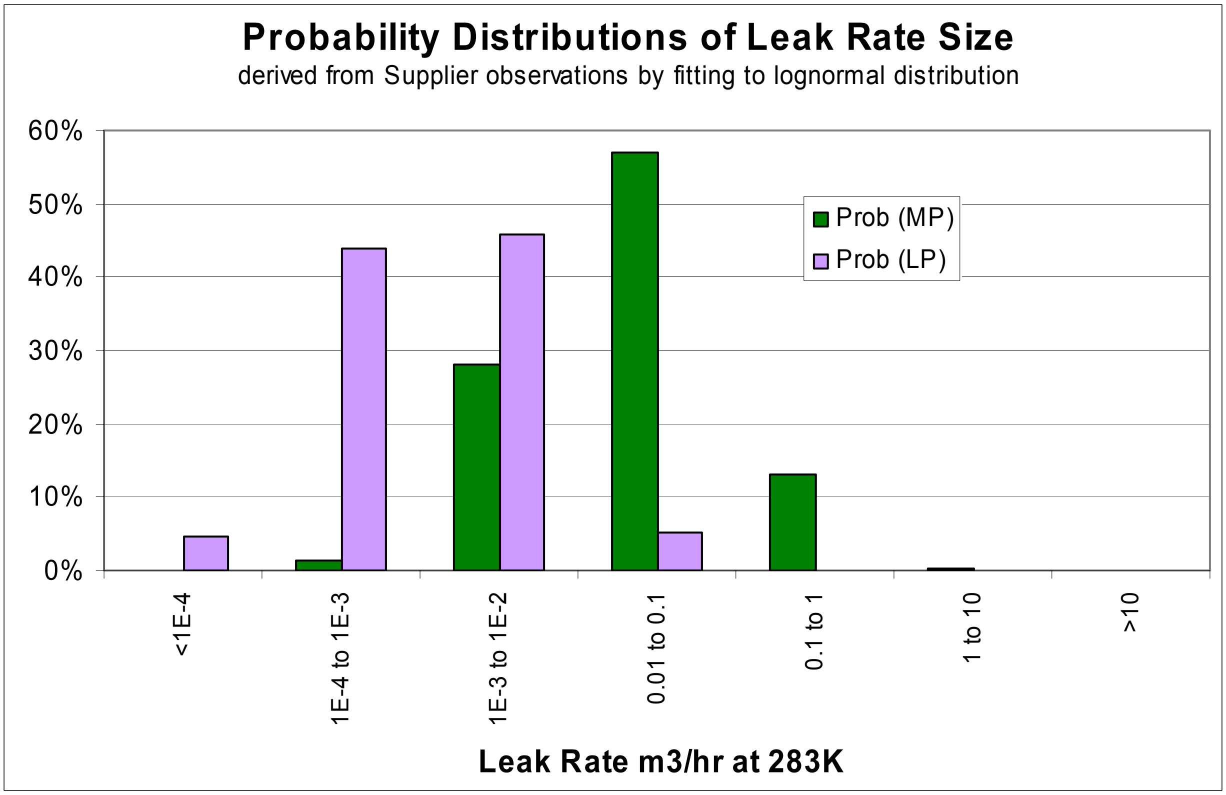
The basis of the distributions shown in the figure is to translate supplier observations that

- typical MP pressure drop rates are of order 1 mbar per second, times or divide by 5-ish (Supplier 2), or
- pressure drop in relevant MP leaks is in range 1-100 mbar over a 15 second observation period (Supplier 4)

into corresponding gas escape rates in m^3/hr at soil temperature. This is done based on simple Gas Law formulae, using an average domestic supply pipe length of 18m (the average found in a large survey of such pipework systems reported by Calor to the ICL Inquiry). The observed range of pressure drop rates cited by Supplier 4 are then treated as the 5th and 95th percentiles of a log-normal distribution.

A corresponding distribution for LP systems is then obtained by scaling down the MP parameters pro rata to the difference in excess pressure (37 mbar LP vs typical 750 mbar MP). The assumption here is that soil corrosion is independent of pressure in the pipe, so that the rate of development of corrosion and of any holes or penetrations should be the same whatever the system pressure. Our assumption is that the rate of gas escape is limited by diffusion through corrosion products and into the soil outside, not by free gas flow through the holes in pipework. On this basis, the gas escape rate should be directly proportional to the pressure difference between the gas in the pipe and that in the surrounding soil. We have assumed that soil gas is effectively at atmospheric pressure and hence that the escape rate is proportional to the excess pressure in the supply pipework. Thus escape rates for LP systems are set equal to (37/750) times the corresponding escape rates for MP systems.

Figure 4: Distribution of Leak Rate Sizes – TTAC Model



This model is applied to broad bands of leak rate (as shown in the figure), each of which is then assumed in subsequent assessment to be characterised by the maximum leak rate within the band. For example, the band from 0.01 to 0.1 m^3/hr is treated as a leak of 0.1 m^3/hr. We are confident that this approach does not understate the likelihood of substantial leaks – we are in effect assuming that well over 10% of MP system corrosion leaks underground lead to gas escape rates of 1 m^3/hour or higher.

3.3 Escalation of Relevant Leaks to Produce Significant Gas in Buildings

Our work with the suppliers also identified some important characteristics of corrosion leaks from underground service pipework which helped steer our development of models for migration through soil and into buildings, as well as providing “reality checks” for our model outputs. These were:

1. Most corrosion leaks, when excavated, are well-contained by the surrounding soil. It is rare to find a void around the leak. Even when the condition of the leaking area is very poor (e.g. liable to disintegrate when excavated) it is common to find that the soil has held the pipe together with only modest leakage.
2. LPG often “tracks” along the service pipework to find a channel to the ground surface. This can happen over long distances; in one example a leak was detected by smell on the other side of a road from the source having tracked along the service pipework.

3. Of the 200+ corrosion leakage incidents of which our workshop participants had direct personal experience, none had involved concentrations of LPG inside a building detectable by smell, EXCEPT when gas had entered from outside air via a window or door.
4. Some suppliers were aware of a proportion of incidents in which a customer had reported a smell of gas in the house, and where traces were subsequently found indoors at ppm up to few 10's of ppm levels, using a Gasco meter on a wand to "sniff" for gas around skirtings and cupboards.
5. A high proportion of those incidents identified from one supplier's records had involved cases where the riser was effectively within the boundary of the property. The workshops identified this as a specially hazardous situation with examples including
   - extensions, porches, garages or decking built over the riser
   - old installations with risers entering the property below ground
   - caravans or park homes with leak-tight "skirts" built around the base to reduce drafts.
6. As a contributor to the incidence of significant gas escapes into buildings, underground service pipework leaks are a very distant "second fiddle" to leaks inside the property, which are a) orders of magnitude more frequent, and b) often involve mechanisms capable of generating a substantial leak without prior warning, in contrast with corrosion leaks.

To this information relevant to LPG migration through soils and into buildings we can add information gleaned from HSE's various accident and incident records and investigations, and described in our companion report[2] on gas migration through soil and into buildings:

7. Little can be learned directly from HSE incident records about the proportion of underground service pipework leaks that lead to significant gas in buildings, as these are generally not reportable or reported unless gas in a building, or a particularly large external leak, results.
8. Based on analysis of significant gas escape incidents reported to HSE under the GSM(R) regulations, we indirectly inferred a highly pessimistic estimate of the proportion of service pipework leaks generally that might lead to significant gas in buildings of 0.2 to 2%.
9. The one known instance of a relevant corrosion leak leading to an explosion in a building took place in Scotland in 2006, and was extensively investigated by HSE[3]. This involved a very large leak, estimated at about 4 m^3/hr in subsequent tests, leading to an explosion of LPG in the void under the floor of the property. The precise means by which the gas tracked into the void could not be determined; the ground outside was paved which may have helped trap the LPG below the surface.

We now move on to consider the migration of LPG from soil into buildings.

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[2] Risk Assessment of Corrosion Leakage of LPG from Domestic Underground service Pipework - Part 2: Migration of LPG from soil into domestic buildings, Issue 01, TTAC Ltd, January 2010

[3] Personal communication, B Fullam, HSE

4. Likelihood of LPG ≥LEL in Homes

The migration of contaminant gases through soils and into buildings has been much studied in the context of contaminated land and radon. We have been fortunate to be guided through the extensive relevant research by our partners in BRE, and by the staff of the Environment Agency, CIRIA, HPA and BGS. We have made particular use of the Environment Agency's CLEA model[4] (based on slab floors), of the VOLASOIL model[5] (for suspended floors) developed by their Dutch counterparts, and of the Johnson and Ettinger model[6] on which both are based. A paper by one of the authors of this model providing guidance on how to avoid the (very easy) pitfalls of using incompatible input assumptions for predicting gas dilution between soil and building air was especially useful[7].

We have adopted a two-stage approach to estimating the likelihood that a given LPG leak will lead to the LEL for LPG being reached or exceeded inside a property:

1. we estimate the concentration of LPG that could result under the floor, and then
2. estimate the probability of sufficiently low dilution of gas migrating up through the floor into the building for the LEL to be reached or exceeded inside the property.

After consideration of UK patterns of housing construction and their significance for LPG migration into buildings, we have developed two different models for step 1, and three for step 2:

Scenario	Model for Concentration of LPG under floor	Model for Migration and Dilution of LPG into building
Slab (concrete) floor	Based on diffusion of LPG trapped underground	Based on probability distributions devised to be consistent with age & characteristics of UK buildings with slab floors
Suspended floor	Based on migration into and ventilation/dilution in void	As above, with parameters appropriate to UK suspended timber or concrete floors
High hazard (riser incorporated into building)	N/A (gas assumed to leak directly into occupied space)	As above, with parameters appropriate to ventilation in occupied space of homes

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[4] "CLEA Software (Version 1.04) Handbook", Environment Agency Science Report SC050021/SR4, 2009.

[5] "The VOLASOIL risk assessment model based on CSOIL for soils contaminated with volatile compounds", M.F.W. Waitz et al, Netherlands National Institute of Public Health and the Environment, RIVM Report 715810014, 1996.

[6] Originally presented in "Heuristic Model for Predicting the Intrusion Rate of Contaminant Vapours into Buildings", P.C.Johnson & R.A.Ettinger, Environmental Science & Technology **25**, pp 1445-1452, 1991

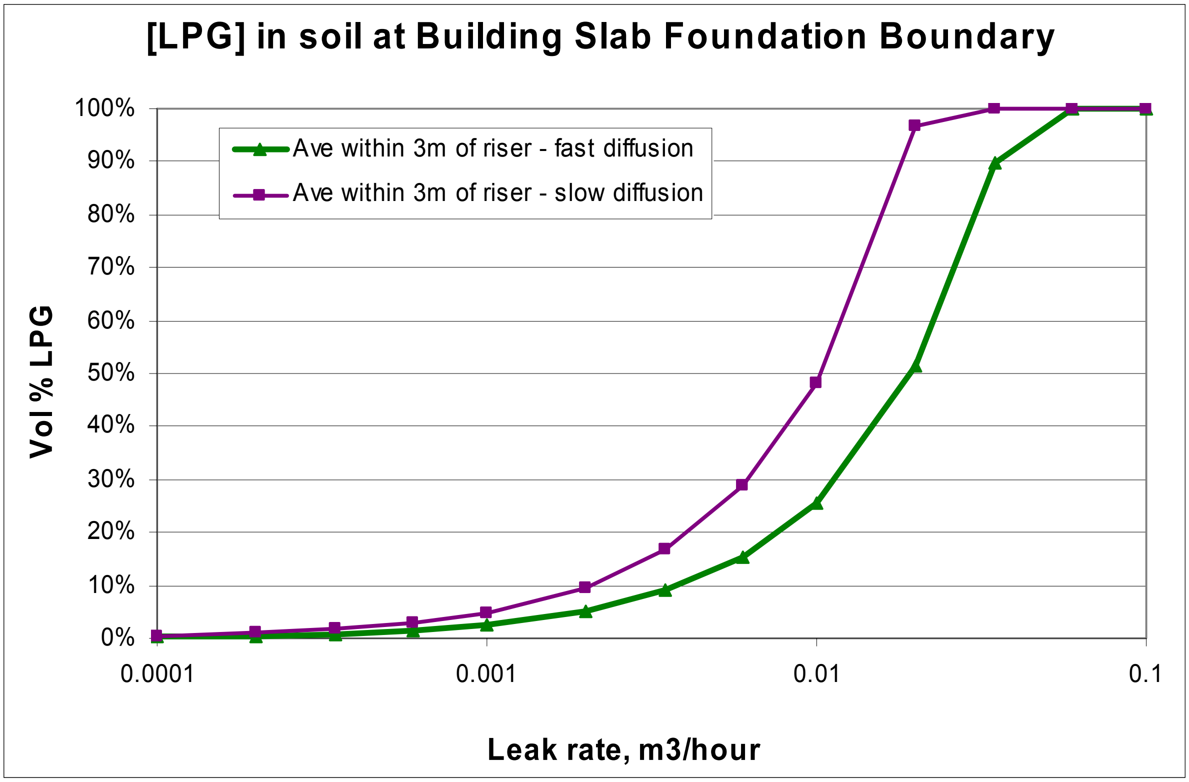
[7] "Identification of Critical Parameters for the Johnson & Ettinger (1991) Vapor Intrusion Model", P.C.Johnson, American Petroleum Institute Bulletin no. 17, May 2002

The main features of the models we have adopted are explained in the following sections

4.1 LPG Migration through Soil and Concentration Beneath the Floor

For slab floors, we use a diffusion model to estimate the migration of LPG from the immediate location of the leak (assumed always to be at 60 cm depth) both under and away from the house. The LPG is assumed to be trapped in a layer of soil extending from 60cm depth down to the water table. The edge of the foundation slab, which is considered the most likely point at which gas might enter the property through such a floor, is assumed to be in contact with the top of this layer. LPG diffusion and/or tracking up through the soil to the outside air can be turned on or off in the model. The results for a range of soil diffusion conditions are shown in Figure 5.

Figure 5: Average LPG Concentration within 3m of Riser after 1 Week



The key observation from this model is that LPG, even at quite low leak rates, can build up to relatively high concentrations in soil close to the riser. The concentration, though, falls off quite quickly with distance, so that rooms further from the riser would be at much lower risk than that immediately next to it. Our model thus considers only the possibility of an LPG explosion in the room closest to the riser.

Because diffusion is a slow process, the effect of enabling or disabling diffusion to the surface is minimal in this model. So long as a high vapour pressure of LPG is maintained close to the source, the concentration gradient will still exist to produce curves virtually indistinguishable from those shown in Figure 5. Tracking to the surface makes a bigger difference, but has been switched off for all risk calculations in this report – that is, we assume that ALL the LPG released is available to diffuse under the building, and none escapes via tracking into the air outside.

For suspended floors our model considers both the proportion of the leak that migrates into the void, and its subsequent dilution by ventilation in the void below the floor. Our model includes the possibility that different proportions of the escaping LPG will enter the void as opposed to tracking up to the surface or migrating elsewhere outside the property. In general, we would consider it at least as likely that LPG would track up the riser to the outside air as that it would track through the soil and foundations and into the void. But there must be a significant possibility, particularly for older properties with less robust foundations, of LPG tracking through into the void. We therefore consider two possibilities:

a) that a high percentage (10-100%, treated as 100%) of LPG will migrate into the void, and

b) that a lower percentage (<10%, treated as 10%) of LPG will migrate into the void.

We would expect the likelihood of encountering (a) rather than (b) at a particular property to depend strongly on the age of the property concerned. Houses built in the last 40 years or so should have foundations, typically of poured concrete or of brickwork, extending to a depth of about 1m (or 700mm for some soils), and we would consider scenario (a) unlikely in such a case. Older properties, though, have a wide variety of below-ground structures (ranging down to virtually nothing) and would be expected on average to be of higher permeability to LPG. We have used lower, central and upper estimates for the probability of encountering scenario (a) as shown below to quantify these expectations.

Building Age	Probability of 10-100% escaped gas migrating into void		
	lower	central	upper
post-1980	0.02	0.05	0.1
1965-1980	0.05	0.2	0.3
1945-1964	0.2	0.3	0.5
1919-1944	0.3	0.5	0.9
pre-1919	0.4	0.5	0.9

We would expect that our assumptions as to the proportion of escaping gas migrating into the void below a property, or available for diffusion into the soil below a property, are such as to err significantly on the side of caution (i.e. will tend to overstate, rather than understate, risk in homes). We discuss the possible extent of over/underestimation in Section 8.1.

Having estimated the net flow rate of LPG into the void, we then work out, assuming the gas in the void is well-mixed, the ventilation rate in air changes per hour (ACH) that would be needed to produce a defined concentration of LPG (somewhere between the LEL and pure LPG, or 50x the LEL of 2%) in the void. We then estimate the likelihood of that concentration arising by deriving a probability distribution for void ventilation, taking into account current NBS Building Regulations, relevant Dutch research, and the qualitative differences we anticipate between properties of different ages (generally the older the property the higher the likelihood of poor ventilation). An example of the application of this model to a small floor area (= higher risk in this respect) house to estimate the likelihood of reaching or exceeding the LEL in the void is shown in Figure 6 below.

The notable feature of this chart is that, for virtually any property, there is a relatively high probability that a large leak of LPG will lead to gas at or above the LEL in the below-floor void. For older buildings, this drops off relatively gradually, with a 10% probability of reaching the LEL for leaks in the 0.001 to 0.01 m3/hour range. Following the upper curve in the graph, even a low pressure LPG leak might have the potential to exceed the LEL in the void with a few % probability. For newer properties the curves fall away much more quickly with reducing leak rate. This is considered entirely plausible, as ventilation standards are much clearer for newer buildings, and less likely to have been compromised by subsequent accidental or deliberate interference that reduces ventilation in the void.

This model has been applied to the incident in Scotland in 2006 where gas exploded in the void beneath a house. Based on

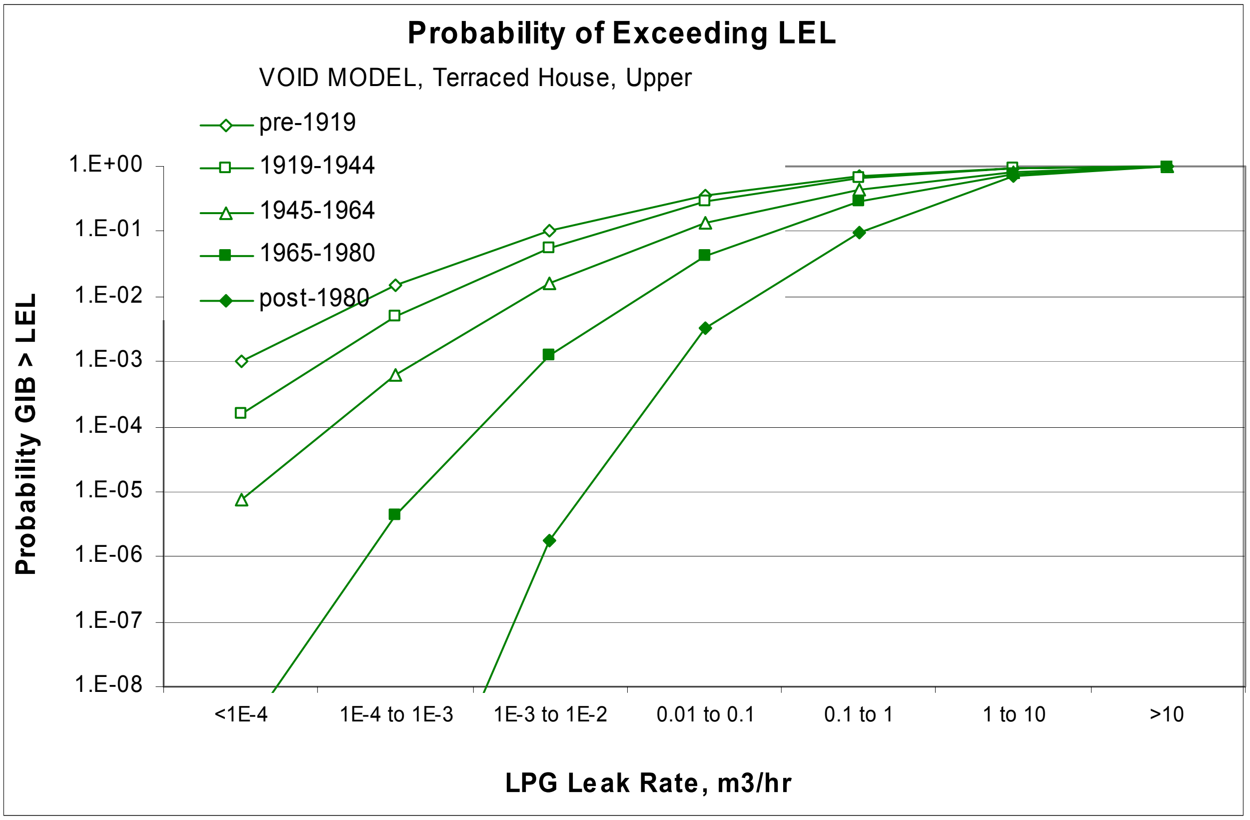
a) the floor layout and area of the house, with an assumed crawl space depth of 60 cm,

b) the leak rate of LPG estimated by HSL in their investigation of the incident for HSE, and

c) the standard minimum ventilation specified in Building Regulations,

the concentration of LPG in the void under the floor can be calculated. The resulting estimate is in the middle of the range of flammable concentrations for LPG in air.

Figure 6: Probability of Exceeding LEL in Below-Floor Void



This model is used both to provide a direct assessment of the hazard of LPG exploding in the void beneath the house, and (like the slab floor model) to provide a "source term" of LPG concentrations below the floor to be used in the subsequent model of LPG migration into and dilution in buildings.

4.2 LPG Migration through Floors and Dilution in Buildings

We spent considerable time and effort attempting detailed calculations of LPG migration and dilution in buildings using the Johnson & Ettinger equation and variants thereof. All of this work corroborated the advice we had received from all the agencies involved in radon and contaminated land work that realistic dilution factors for contaminant gases between soil and buildings were likely to be of order 1,000-10,000x or more. To achieve the LEL of LPG in a building we need a dilution factor of 50 or less; anymore would dilute even pure LPG below the floor to concentrations less than the LEL of about 2%.

We therefore developed our own probabilistic interpretation of the guidance on realistic ranges for dilution between gas below and above the floor of houses that was provided by one of the authors of the Johnson & Ettinger model (ref 7). He recommended a range of long-term time-averaged dilution factors from 100 to 10,000, and noted a single experimental measurement in one instance of a dilution factor of about 10.

We wished to allow for the variability of dilution with time – the explosion incident in Scotland (where traces of gas had been smelt off and on for months before the explosion happened), and all the radon and contaminated land evidence, is clear that migration and dilution in buildings is highly time-dependent. It is credible that LPG might build up for days or weeks below a floor and then be "sucked up" into the property following a change in atmospheric conditions or householder activity. We also wanted to allow for substantial variability between properties, and to take into account the qualitative factors we knew were likely to affect migration through floors for different properties, the most important being age (modern building standards require much greater attention to leak-tightness of floors than did standards pre-war or even up to the 1960's and 70's).

We developed three related probabilistic models of dilution of gas entering the occupied space of a building (described in greater detail in Section 7.1):

1. for slab floors, using Johnson's 100-10,000 range as a starting point and treating these values as percentiles of a probability distribution that becomes progressively broader for older buildings
2. for suspended timber floors, using this same range for modern buildings but a wider range for older buildings, and again assuming for older buildings that the percentiles represented by the range would decrease as age increased (i.e. both the range of values considered, and the proportion of buildings expected to have values outside that range, are treated as increasing with age)
3. for the "high hazard" scenario where a leak is assumed to occur directly into the occupied space of a property – here we adopted what we considered to be suitably cautious probability

distributions[8] for the ventilation rates applicable in homes taking into account that even the most "fresh air" oriented householder is likely to have considerable periods where ventilation is low.

These models are then used in conjunction with the models described in Section 4.1 to estimate the overall likelihood of a given LPG leak into soil translating into LPG at or above the LEL in the building. Examples of the resulting probabilities of exceeding the LEL for a small house of various ages are shown in Figure 7 (a), (b) and (c), where the letters (a) to (c) correspond to the three models listed above.

Notable points of the charts include

- The slab model results plateau beyond leaks in the range 0.01 to 0.1 m^3/hr, corresponding to the point beyond which the soil below the slab is saturated with LPG vapour.
- The suspended floor model predicts probabilities of exceeding the LEL mostly somewhat larger than those predicted by the slab floor model (generally within a factor of 10); the exceptions are for newer properties assumed to have good, effective below-floor ventilation.
- For both slab and suspended floor models, the probability of exceeding the LEL increases rapidly with age of the property. This effect is particularly pronounced for suspended floors, where it is necessary to make fairly extreme assumptions about poor ventilation below the floor to arrive at significant probabilities of exceeding the LEL above it.
- The very simple model for leaks directly into the occupied space predicts probabilities of exceeding the LEL that are independent of house age and rise rapidly with leak size, reaching 100% for leaks in the range 0.1 to 1 m^3/hr or bigger.

We are aware that these models are very simplistic, and are not directly evidence-based. A log-normal probability distribution of parameters was chosen because there is extensive evidence that radon measurements in buildings display a log-normal distribution (see e.g.[9]), and because this provides a good starting point for estimating variability in output parameters known to have a wide range of values depending on a wide range of varied inputs. The other attractive feature of the log-normal distribution is that in all the examples used here, it provides a way of estimating the likelihood of unlikely circumstances for which we have no direct evidence as to likelihood, in such a way as to provide plausible results that are consistent with known evidence, when we interpret that evidence in a cautious way. Our judgment is that these models are likely to over, rather than understate the likelihood of LPG concentrations above the LEL arising in buildings.

We recognise, though, that this is a difficult judgment to defend, given the many uncertainties involved. We have therefore developed a version of our model which calculates as its end point the likelihood of encountering LPG concentrations in a building which would be above the threshold of detection by smell. This is based on:

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[8] The probability distribution is fitted to the assumptions that 10% of such homes would experience ventilation rates of less than 0.1 air changes per hour, and 90% would experience ventilation rates less than 0.3 ACH.

[9] "Factors affecting indoor radon concentrations in the United Kingdom", J A Gunby et al, Health Physics, 1993, **64**

Figure 7(a) Probability of Exceeding LEL – Slab Floor

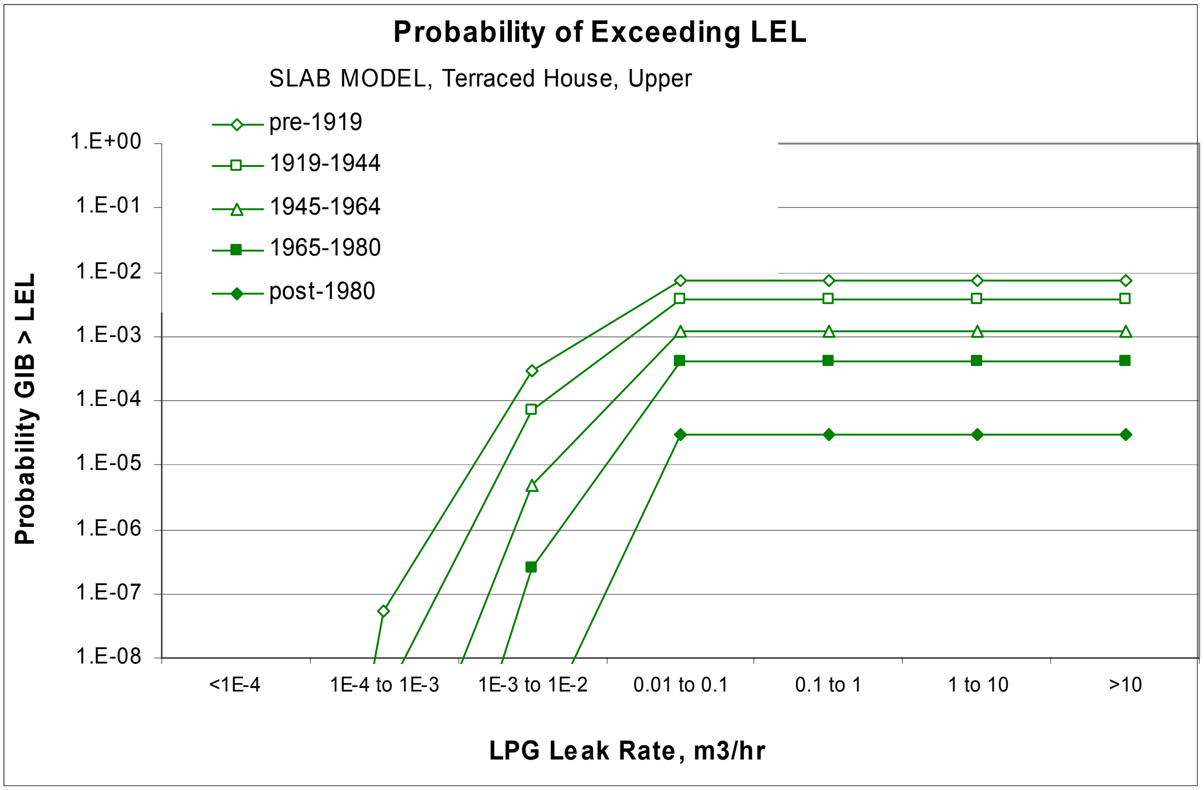


Figure 7(b) Probability of Exceeding LEL – Living Space above Suspended Timber Floor

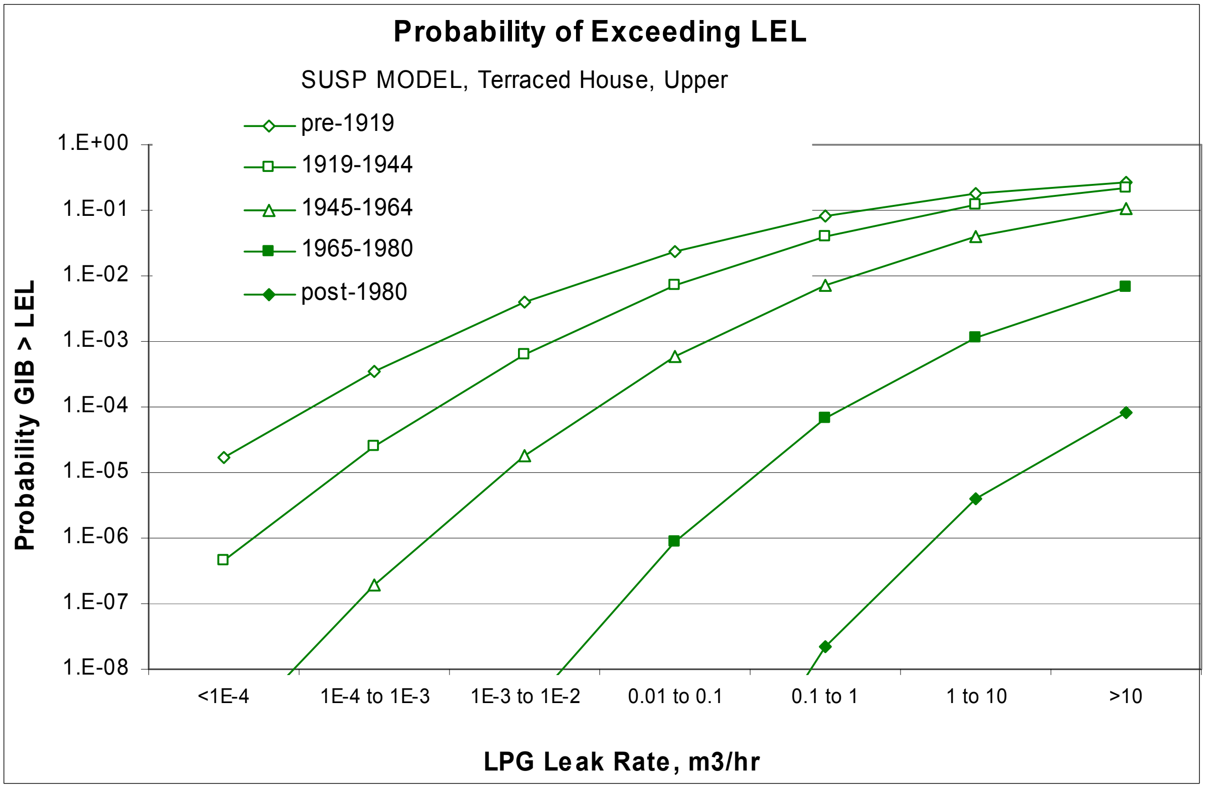
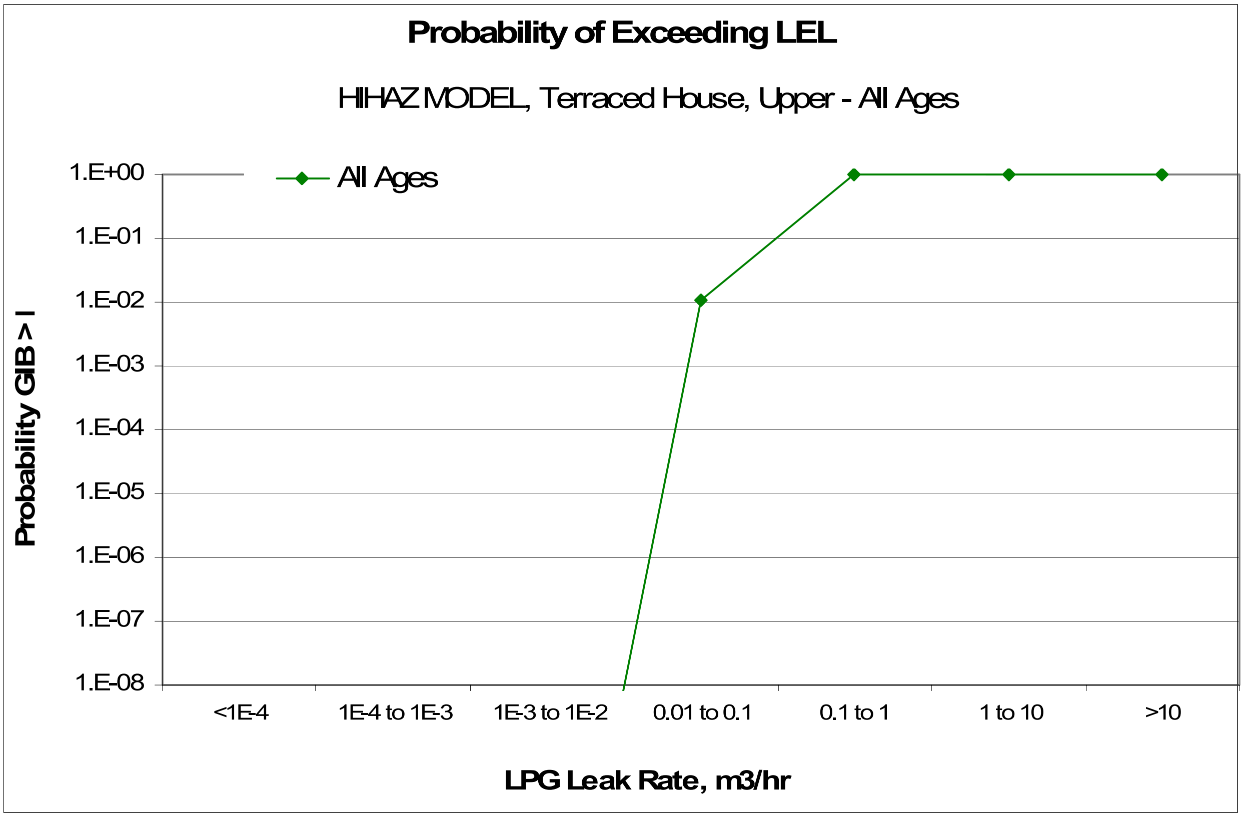


Figure 7(c) Probability of Exceeding LEL – High Hazard (leak into occupied space)



a) The same models as described above to estimate the concentration (or probability of encountering a given concentration) of LPG in the soil or void below the property, and

b) The same probability distributions to characterise the likelihood of encountering a given multiple of the concentration below the floor in the occupied space above it, along with

c) An estimate of the concentration of LPG in air that would be detectable by smell of 0.005% by volume[10].

This version of the model has been run for the same combinations of circumstances as the first to provide a range of outputs as to the proportion of LPG leaks into soil that should be detectable by smell inside houses. The results, presented in Section 7.4, suggest that a substantial proportion of such leaks should be detectable by smell inside homes. The observation from the suppliers that this is a very rare circumstance provides substantial confidence that our assumptions and models of LPG transport into and dilution in buildings are tending significantly to over, rather than under-state the likelihood of encountering significant concentrations of LPG in buildings via this route.

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[10] Based on the stanching agent, typically ethyl mercaptan, being present in LPG at 20ppm, and being detectable by smell at 1ppb, hence being capable of dilution 20,000 times and still being detectable by smell. Actual levels present in LPG are typically 25-50ppm, whilst ethyl mercaptan is detectable by most people at 1 part per 2-3 billion, so it is possible LPG might be detectable at an order of magnitude lower concentration. On the other hand, it has been argued that stanching agents may be absorbed to some extent in some soils; we consider 0.005% a reasonable, cautious estimate

5. Likelihood of LPG ignition

Our assessment of the likelihood of a flammable gas mixture being ignited in a domestic building, if present, is based on analysis of a large sample of HSE records of gas escape incidents, the majority of which involved natural gas rather than LPG. The data obtained from HSE and the analysis carried out on it are described in Appendix 1. The results and our conclusions in terms of probabilities of ignition in the occupied space of homes and in the voids below floors are presented in Sections 5.1 and 5.2 respectively

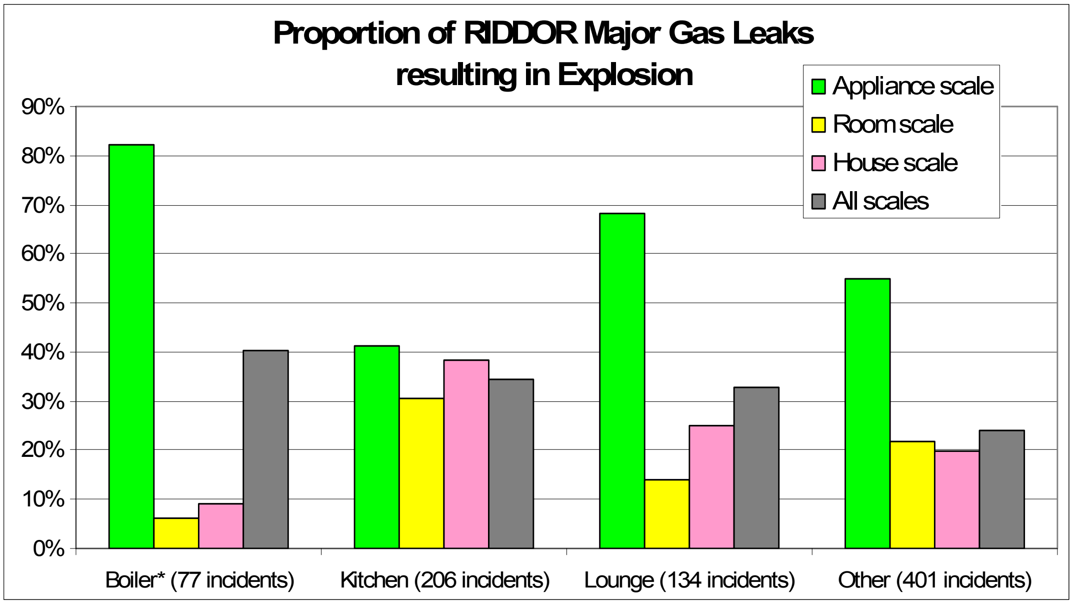
5.1 Ignition in the Occupied Space of Homes

Over 2000 RIDDOR incidents suspected (based on filters and keyword searches) to involve large gas leaks into homes were extracted into Excel and reanalysed in terms of the scale of the leak involved, whether the property was actually a domestic building, and whether a flammable gas mixture (if present) was ignited. Over 800 incidents were identified in which there had been gas present above the LEL; these were classified in terms of the scale of the gas release in terms of

- Appliance scale (flammable mixture sufficient to fill some or all of an appliance such as a boiler, cooker or fire)
- Room scale (flammable mixture filling a whole room or substantial portion thereof), or
- House scale (flammable mixture filling more than one room).

The results are summarised in Figure 8 below.

Figure 8: Proportion of Major Leaks leading to Explosion



Once the more minor appliance scale events are stripped out, the resulting proportions of incidents involving ignition appear intuitively self-consistent. In kitchens and lounges, house scale incidents are more likely to result in ignition than room scale incidents (note – we consider the appliance scale incidents are only likely to be reported if ignition occurs; the ignition probabilities are thus likely to be highly overstated). And ignition is more likely in a kitchen than in other major rooms of a house, consistent with the generally higher likelihood of finding time switches and other ignition sources in kitchens. (Note that in the "other" category almost all the "house scale" events involved external or outdoor leaks and thus are of limited relevance to ignition inside a building).

We have adopted values based on those in Figure 8 in our risk assessment as shown below.

Leak Enters:	**Room scale P(ignition)**	**House scale P(ignition)**
Kitchen	0.33	0.4
Other	0.2	0.25

As discussed in Appendix 1, we are confident that any systematic error in these values is likely to be in the direction of overstating rather than understating the likelihood of ignition,

a) because we (and the HSE providers of the relevant incident data) consider reporting is likely to be more reliable for incidents that involved ignition/explosion, and

b) because the nature of corrosion leaks is progressive, there should be a high likelihood of detection of the leak via smell well before flammable concentrations can develop (though this will not apply to unoccupied or rarely occupied parts of buildings such as cellars or voids below floors).

5.2 Ignition in Voids Below Floors

We were not able to estimate the probability of ignition of a flammable mixture in a void below the floor directly from HSE data. We have estimated a range of values for this probability for the most typical case, of a crawl space below a suspended timber floor, on the following basis:

1. We would expect (see Figure 6 above) a significant proportion of underground leaks to generate gas > LEL below suspended floors, BUT
2. Explosions below floors are rare; in the one well-investigated recent LPG example in Scotland in 2006 the source of ignition was thought to have been via traces of flammable gas in the occupied space above the floor.
3. The other significant feature of the Scottish incident is that there had been several call-outs over previous months relating to a smell of gas in the occupied parts of the house. We consider it overwhelmingly likely that flammable concentrations of LPG had been present in the void below the house for weeks or months prior to the explosion, but had not ignited in the absence of any ignition source.
4. Relevant to the hazard of interest, corrosion leaks of LPG into soil would ALWAYS be expected to be progressive events with the leak rate increasingly gradually with time. This makes it much more likely that a leak will be detected by smell before a flammable mixture develops, effectively reducing the likelihood of a flammable mixture developing undetected.

Our conclusion from all the above is that ignition in the void below floorboards is a rare event, while the presence of flammable gas below floorboards is a relatively frequent event. Our judgment is that such ignition might occur in at most a few % of cases, and possibly very much less. The probability would clearly be significantly higher if there were exposed electrical wiring or switches (the RIDDOR records do include examples of explosions in voids elsewhere in houses linked to electrical ignition sources). We would also expect this probability to be higher for LPG than for natural gas, not because of any difference in the energy required to ignite mixtures of gases, but because natural gas, being lighter than air, is unlikely to accumulate and persist in below-floor voids, whereas LPG being heavier than air is prone to do the opposite.

In the absence of relevant direct evidence, we have assumed the following values in our risk assessment for the probability of ignition below a suspended timber floor (the significance of upper, lower and central values is explained in Section 7).

• Upper value	0.05	(5.0%)
• Central value	0.01	(1.0%)
• Lower value	0.002	(0.2%)

We now need to consider two other cases: first, the more modern version of a suspended floor, the "beam and block" concrete block arrangement, and second the possibility of gas accumulation in a larger space (a cellar or basement) below the ground floor.

Beam and block floors differ significantly from timber floors in that, once laid, they are generally covered with a screed which effectively permanently isolates them from the occupied space of the house. It is very unusual for any electrical wiring (other than the incoming, armoured electricity supply cable) to run through the space beneath a beam and block floor, which is in most cases likely to be as close to an "ignition source free zone" as one is likely to find in domestic dwellings. We have adopted probabilities of ignition in a void below such a floor 10 times lower than those above for the void below a suspended timber floor.

Cellars and basements are another matter. From the RIDDOR large leaks analysis described in Appendix 1 we were able to identify 10 large leaks into cellars, of which none had ignited. We would expect that the natural gas explosions identified will have included a significant proportion where gas entered the property below the floor, but this is not identifiable from any of the incident descriptions. We would be surprised if there were not 100's or more of natural gas escapes annually in which gas enters a property via the cellar, and would be unsurprised if some of the explosions in our dataset had not resulted from gas initially entering homes below ground via cellars or voids.

Generally, we would expect the likelihood of ignition for LPG present in a cellar or basement as the result of a corrosion leak to be relatively high, as

a) the act of entering such spaces generally involves switching on a light, providing possible ignition sources, and

b) the likelihood of earlier detection of the leak by smell in the house could be relatively low, as gas may accumulate undetected while the cellar or basement is unoccupied.

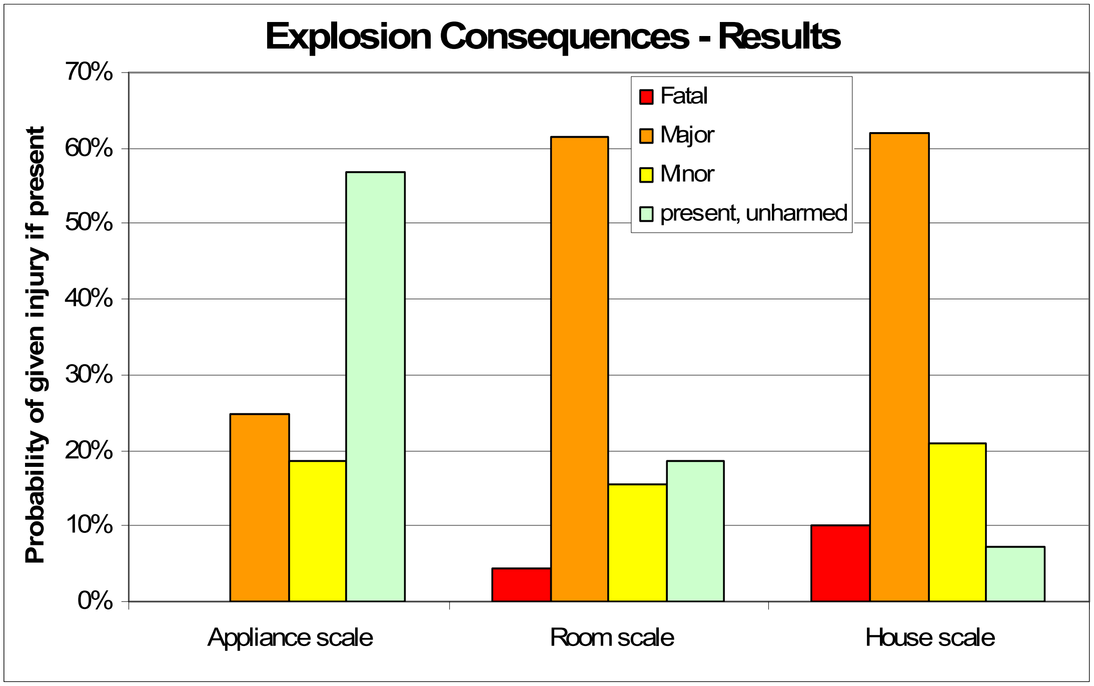
We have assumed for cellars and basements is that there is at least a 10% chance of a flammable LPG mixture generated via a corrosion leak into soil outside being ignited, if present. For an upper estimate we have assumed ignition could be 10 times more likely than for the void below a suspended timber floor, i.e. 50% chance. We have taken the average of these two values (30%) as a central estimate for this probability.

6. Likelihood of Persons Present being Injured

As in the previous section, our assessment of the consequences of domestic gas explosions (in terms of the probability that a person present is killed or suffers a major or minor injury) is based on analysis of a large sample of relevant HSE incident records. The selection of the dataset used, and the re-classification and analysis of the information carried out, are described in Appendix 1.

The results are summarised in Figure 9 for explosions of different scales.

Figure 9: Explosion Consequences – Probability of Injury



The key figures carried forward into our risk assessment are that for a room-scale explosion (taken to be the consequence of any explosion arising in a slab-floored building, or of an explosion below the floor) the probability of fatal injury is about 4% for a person present in the room, while for a house scale explosion the corresponding probability is about 10%.

The other important issue for our model is the choice of the scale of explosion to be applied in different circumstances. The key issues here are the quantity of any flammable mixture present, and the potential for structural damage to the building (which is the primary source of serious harm to people; far more people are killed and seriously injured in explosions in buildings via the structural damage done to the property than by the direct effects of blast overpressure and heat). These considerations lead us to the following assumptions:

For explosions in occupied space:

- for slab floors, the explosion is treated as room scale, as the range over which LPG could diffuse under the slab to develop high concentrations in soil is limited to a few metres from the riser, whereas
- for suspended floors, the explosion is treated as house scale, as for most voids below floors there is (by intention) good mixing across the whole of the below-floor space under houses, meaning that any concentration of LPG in the void will in most cases be available across the whole of the ground floor.

For explosions in voids below floors:

- for any property where the “void” is a cellar or basement, an explosion is treated as house scale based on the substantial quantity of gas and potential for major structural damage demonstrated by such explosions involving natural gas,
- for properties with a suspended concrete (“beam and block”) floor, an explosion is treated as house scale, because there is plenty of energy available but very limited potential for pressure relief – so although we consider explosions under such floors to be improbable (see 5.2 above), we consider their consequences, should they occur, could be severe in terms of structural damage and harm to building occupants, while
- for properties with a suspended timber floor and a crawl space beneath it, an explosion is treated as room scale, as although there could be considerable energy released in such an explosion, timber floors readily flex and break to relieve overpressure, thus limiting the damaging effects on both structures and people (this view is corroborated by the LPG explosion in Scotland in 2006 below a timber suspended floor[5] – people in the rooms above that floor were hurt but not killed; windows were blown out and smashed but there was no major structural damage to or collapse of the building).

7. Integrated Risk Assessment Model

The models described in previous sections of this report have been assembled into a set of spreadsheet-based event trees, which are provided in the form of a working spreadsheet model including all necessary supporting calculations, as a companion to this report. Please note that TTAC Ltd is not an accredited software supplier and offers no warranties as to the accuracy or otherwise of this model; it is provided in good faith to HSE as a means of demonstrating the integration of all the models described in this report into the risk assessment process, of illustrating the calculational approaches used throughout the model, and to provide indicative results.

Separate event tree models are provided for explosions as follows (our working titles for the relevant models are in square brackets at the end of each):

a) in the room closest to the riser in a property with a concrete slab floor [SLAB]

b) in the void below a suspended floor (either timber or concrete) [VOID]

c) in the occupied space above a suspended floor (timber or concrete) [SUSP], and

d) in a property subject to direct ingress of leaking LPG into occupied space [HIHAZ].

Section 7.1 provides a general overview of the model, the phenomena it considers and the assumptions used in key stages along the calculational route. Section 7.2 presents the actual event tree structure used in the spreadsheet implementation of the model. Section 7.3 presents results in terms of individual risk to building occupants, and Section 7.4 the equivalent sample results in terms of likelihood of LPG being detectable by smell in buildings as a result of relevant leaks into the soil outside. The significance of these results is discussed in Section 8.

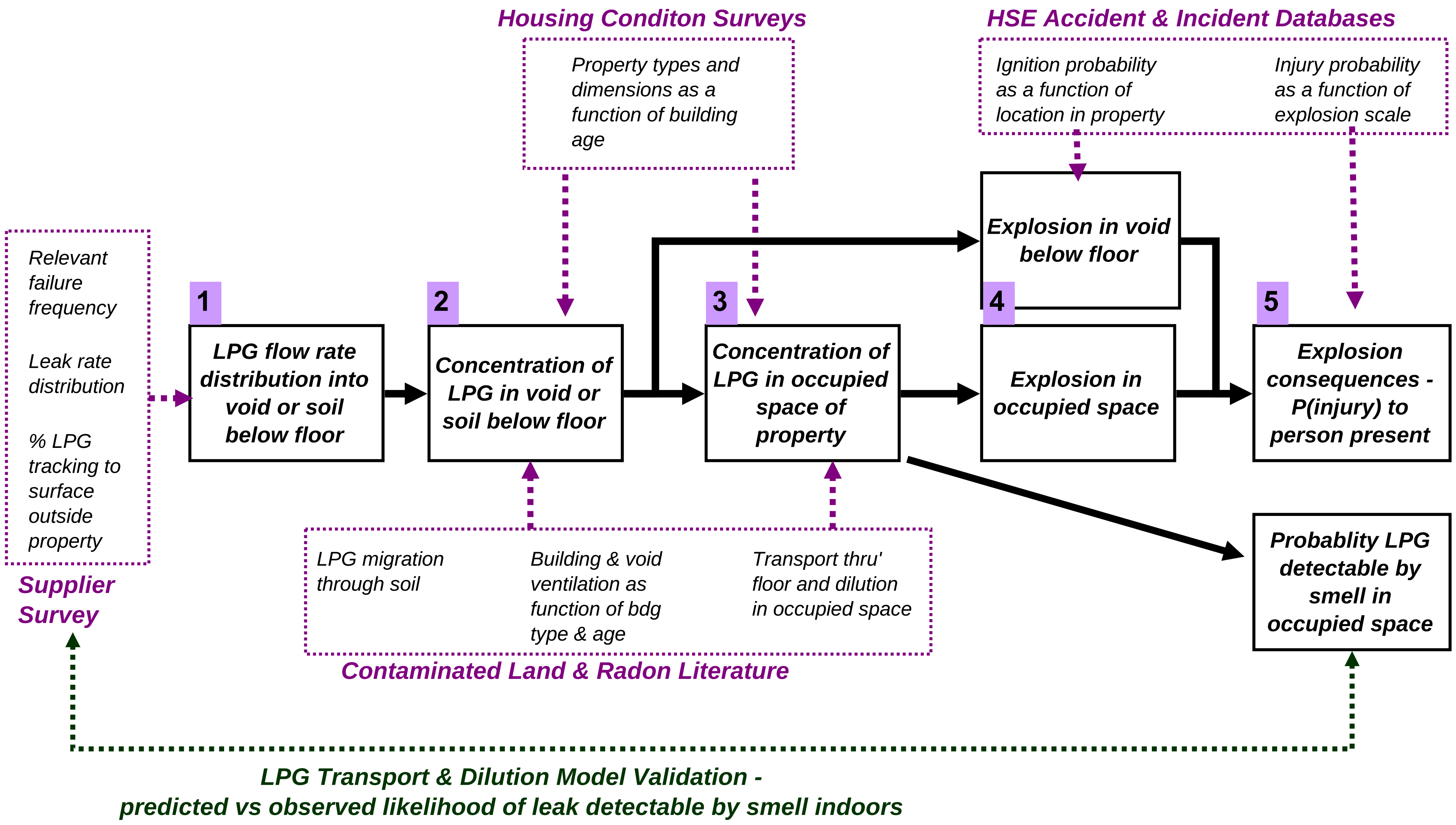
7.1 Model Description

The general processes modelled and sources of information introduced at each stage are illustrated in Figure 10, which divides the calculation into five stages:

1. Dividing the spectrum of possible LPG escape rates into soil into a set of discrete bands of flow rates, and estimating for each both the probability of that band arising in the event of a relevant leak, and the effective flow rate of LPG into the space below the property
2. For each escape rate band, estimating the concentration of LPG that would result in the space below the floor of the property, and thus
3. Estimating the probability that LPG above the LEL would result in the occupied space above the floor, given the concentration below it
4. Estimating the probabilities that an explosion would result either in the void below the floor or in the occupied space of the property, and
5. Estimating the outcomes in terms of probability of a given severity of injury to people present, or that LPG would be detectable by smell in the property.

These five stages are described in turn.

Figure 10: Risk Model Flowchart



An important general aspect of the model which applies throughout all stages is that we have recognised from the outset that the uncertainties associated with this modelling process are large. We have therefore set up the model to propagate a range of lower, central and upper estimates throughout the entire calculational route, rather than to provide a single, "point estimate" of risk. The results are presented in terms of a band of values rather than as single values. The plausibility of these bands of values and the degree of caution inherent in adopting the upper end of the bands can then be gauged by comparing the results with the evidence available to us on the frequency of relevant escapes and of resulting LPG concentrations in domestic properties.

Stage 1: LPG Flow Rate Distribution

The information here is derived entirely from the Suppliers' evidence on relevant LPG escapes, as discussed in Section 3 above. The key assumptions used in the model are:

a) There is a fixed likelihood of a corrosion leak developing in underground LPG service pipework in the range 1 to 4 per thousand properties with metallic underground pipework components per year. This is not dependent on LPG system pressure, nor on any characteristics of the property such as soil type or rainfall/moisture levels.

b) The possibility of different scales of release rate from the pipework is modelled by dividing the full spectrum of possible release rates into discrete bands of values, each spanning a factor of ten. The lowest band is "releases $< 10^{-4}$ m^3/hr"; the highest is "releases $>$ 10m^3/hr". The probability of each band is dependent on the LPG supply pressure, and is calculated by fitting a log-normal probability distribution to the observed values of leak rates as described in Section 3.2 and Figure 4 above.

c) The model includes probabilities that different proportions of the released gas will track to the surface outside the house and thus be unavailable for developing LPG concentrations below it. For all calculations in this report such tracking is effectively "switched off" by setting the probability that 0% LPG tracks to the surface (and thus that 100% of released LPG is available to migrate below the house) to 1.

d) For slab floored properties, 100% of the escaped LPG not tracking to the surface is assumed to be available to migrate into the soil under the house. For properties with a void below a suspended floor, two scenarios are considered: first that 100% of the available gas will enter the void, and second that 10% of the gas will enter the void. The weight given (i.e. the probability assigned) to each scenario depends on property age as described in Section 4.1 above, with the probability of the higher (100% escape into void) scenario being set in the range 0.4 to 0.9 (40% to 90%) for older properties, and 0.02 to 0.1 (2% to 10%) for newer ones.

Stage 2: Concentration of LPG Below Floor

The information here is derived from simple models of diffusion into soil (for slab floors) and of ventilation and mixing (for suspended floors).

Slab floors:

a) It is assumed that all the available LPG is trapped in a layer of soil whose upper boundary is 60cm below the ground surface and whose lower boundary is a water table at 150cm below the ground surface.

b) LPG can diffuse under and away from the building, and to the ground surface outside if the user chooses to allow this (for all calculations in this report, diffusion to the surface was not allowed).

c) This 90cm layer of soil containing the trapped LPG is assumed to be well-mixed vertically, and a 2-D numerical Fickian diffusion model is used to estimate the concentration build-up of LPG in the soil below the building as a function of time.

d) The average concentration estimated in this fixed depth layer within 3 metres of the riser is then assumed to be the concentration of LPG in the soil in contact with the underside of the foundation slab for the most at-risk room in the house (i.e. that nearest the riser).

e) The effect of foundations in impeding the flow of LPG laterally under the building is simulated by adding a lateral distance the LPG must migrate to reach the underside of the slab, of 50 cm for older and 100 cm for newer buildings.

f) The model was originally set up to derive effective diffusion coefficients in soil for coarse, medium and finer (clay type) soils, but the results were not sensitive to this parameter so worst case diffusion parameters are used throughout.

g) The net effect of this model is to predict relatively high concentrations of LPG below the room nearest to the riser even for quite small release rates into soil.

Suspended Floors:

a) LPG leaking from soil into the void below a suspended floor is assumed quickly to become well mixed across the whole of the space below the ground floor of the house

b) Default average floor areas are provided depending on the house type input by the user, based on information derived from the English, Welsh and Scottish Housing Condition Surveys (a property-specific value can be input if desired); the values used for terraced and detached houses for which results are shown in Sections 7.3 and 7.4 are 35 and 60m^2 respectively.

c) Default heights are provided for occupied rooms (2.4m) crawl spaces (60 cm), cellars (1.6m) and basements (2.2m) ; again property-specific values can be input if desired.

d) The possibility is now considered that a whole range of concentrations of LPG in the void might result, with the range of interest lying from the LEL up to pure LPG (any concentration below the LEL in the void cannot lead to an explosion either in the void or in the occupied space of the building).

e) This range of interest is divided into discrete bands of multiples of the LEL (1-2x the LEL, 2-3x the LEL …. up to 49-50x the LEL or pure LPG). For each band, the range of ventilation rates in the void (in air changes per hour or ACH) is calculated that would lead to a concentration of LPG in that band.

f) The probability of each band arising is then estimated from a probability distribution of different air changes per hour arising, developed as described in Section 4.1 above. The probability distributions assume that poor ventilation (thus higher probabilities of high concentrations of LPG) is more likely in older than in newer properties.

g) The net effect of this model and the assumptions involved is to predict relatively high likelihoods of flammable mixtures of LPG resulting in voids, even for relatively modest escape rates of LPG into soil.

Stage 3: Concentration of LPG in Occupied Space

The approach used here starts from the concentration of LPG below the floor, and estimates the probability that the ratio of the concentration above to that below the floor will be such as to lead to a concentration above the floor greater than or equal to the LEL. This is done by translating guidance on the range of dilution to be expected in such circumstances in the context of contaminated land into probability distributions for buildings with different floor types and of different ages, as described in Section 4.2 above. The model originally included probability distributions taking account of householders' ventilation preferences, with lower probabilities of high LPG concentrations being accorded to households who preferred a well-ventilated as opposed to a "cosy" atmosphere. After discussion with HSE this feature was removed in favour of generally cautious assumptions (corresponding to a preference for lower ventilation in the occupied space of homes and thus lesser dilution of LPG above the floor).

a) For slab floors, a single estimate of the concentration below the floor was derived during Stage 2, and a single calculation is made of the probability of the LEL being exceeded above the floor, given that estimate of LPG concentration in the soil below it.

b) For suspended floors, probabilities of each of fifty different concentration bands below the floor (ranging from the LEL up to 50x the LEL, or pure LPG) were estimated in Stage 2. For each of these, a probability of exceeding the LEL above the floor is derived, and the overall probability of exceeding the LEL above the floor is obtained by summing over all possible concentrations above the LEL below the floor.

c) The net effect is that in all cases, the likelihood of achieving sufficiently low dilution to exceed the LEL in the occupied space is low. The likelihood of low dilution (i.e. high concentrations in the occupied space) follows the general order
suspended timber > suspended concrete > slab floors.

d) The model in this area is based on plausible assumptions that are reasonably consistent with a cautious interpretation of available evidence, rather than on any direct evidence. The model and assumptions are intended to provide a conservative (erring on the side of overestimating rather than underestimating the likelihood of explosive mixtures developing in homes). We recognise that the uncertainties here are thus particularly high and have developed additional outputs from this part of the model (see Stage 5 below) to provide the possibility of comparing model predictions of the likelihood of encountering particular concentrations of LPG with the actual incidence of such concentrations identified in the Supplier workshops.

Stage 4: Explosion Probability

The calculation here is straightforward, using the probabilities of ignition explained in Section 5 to estimate the probability that flammable LPG mixtures will ignite as a function of scale and location of the mixture in the home.

Stage 5: Explosion Consequences

The calculation here is again straightforward, using the probabilities of a given level of injury severity explained in Section 6 to estimate the probability that a person present will suffer minor, major or fatal injury, depending on the scale of the explosion. Only the fatality risk results are presented in the report to facilitate comparison with established benchmarks for individual risk. Individual risk is calculated by summing over all gas escape scenarios (as per Stage 1 above), on the assumption that the person at risk is present for 100% of the time in the at-risk location.

Additional model outputs are also calculated, using the identical models and assumptions, to estimate for each case the probability and frequency of encountering, as a result of a corrosion leak in underground service pipework,

- An LPG explosion
- LPG at levels at or above the LEL, and
- LPG at levels detectable by smell.

7.2 Event Tree Implementation of Model

The assembled event tree risk models are illustrated conceptually in Figures 11 (a) to (d) for slab floors, the void below suspended floors, the occupied space above suspended floors, and a "high hazard" scenario with leakage direct into the occupied space of a house. Each diagram shows a single path through the event tree for simplicity of illustration. The shaded boxes correspond to deterministic steps in the calculation and do not have probabilities associated with them. The boxes whose frequency and probability values multiply together to give the risk contribution for each path through the tree are indicated in each diagram.

Some additional general points about the event tree models used to make the calculations below are worth noting:

1. Upper, lower and central estimates are propagated through each event tree pathway. The upper output is the product of all upper values, the lower output that of all lower values.
2. Results are presented as ranges of values (from lower to upper), and are shown beneath the model inputs for ease of exploring sensitivity of results to inputs.
3. Risk is calculated in terms of annual expected individual fatality risk; major injury and minor injury risks can also be calculated.
4. For suspended floors, the risk is the sum of that associated with explosions below the floor (VOID event tree model) and that with explosions in the occupied space (SUSP model).
5. The model does not at present include occupancy – that is, it assumes the exposed person is present 100% of the time. This is reasonable for all models except SLAB, where only one room is at particular risk (usually the kitchen) and it might be worth including a user-input "how many hours per day do you/the max user spend in that room?" This would be expected to reduce all the results for the SLAB model by a factor of perhaps 4 or 5 or more.

The models were implemented into an Excel spreadsheet model which has been provided to HSE to enable the calculational route used to be documented and recorded.

Figure 11 (a): SLAB Event Tree Risk Model

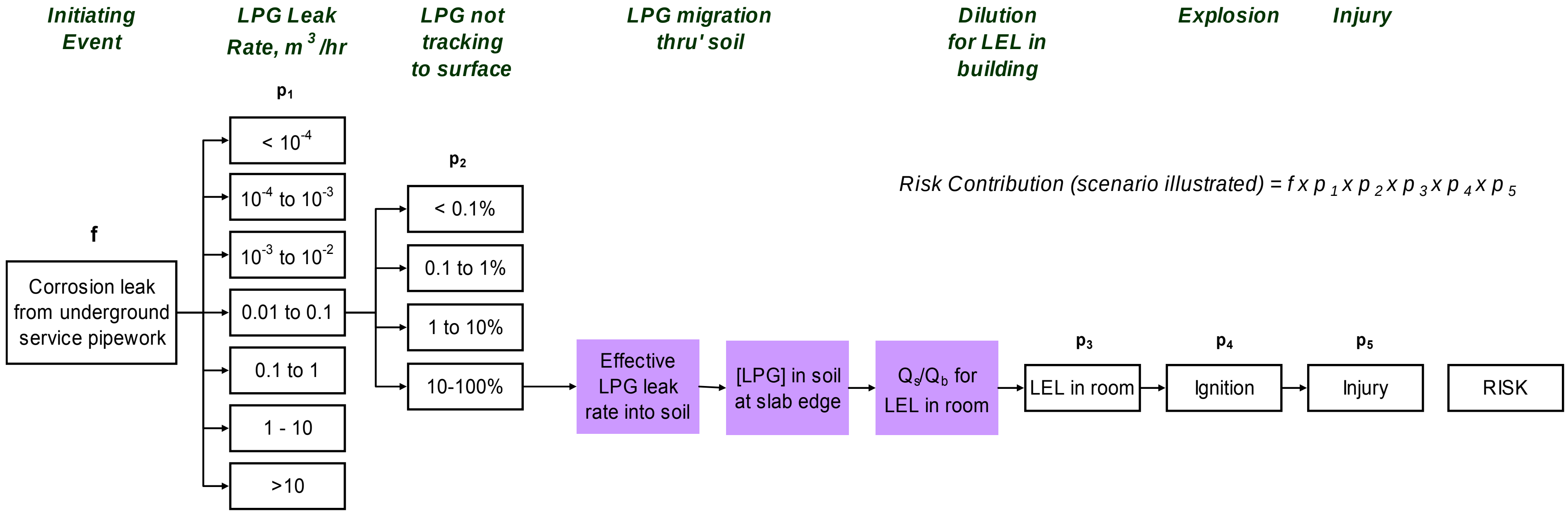
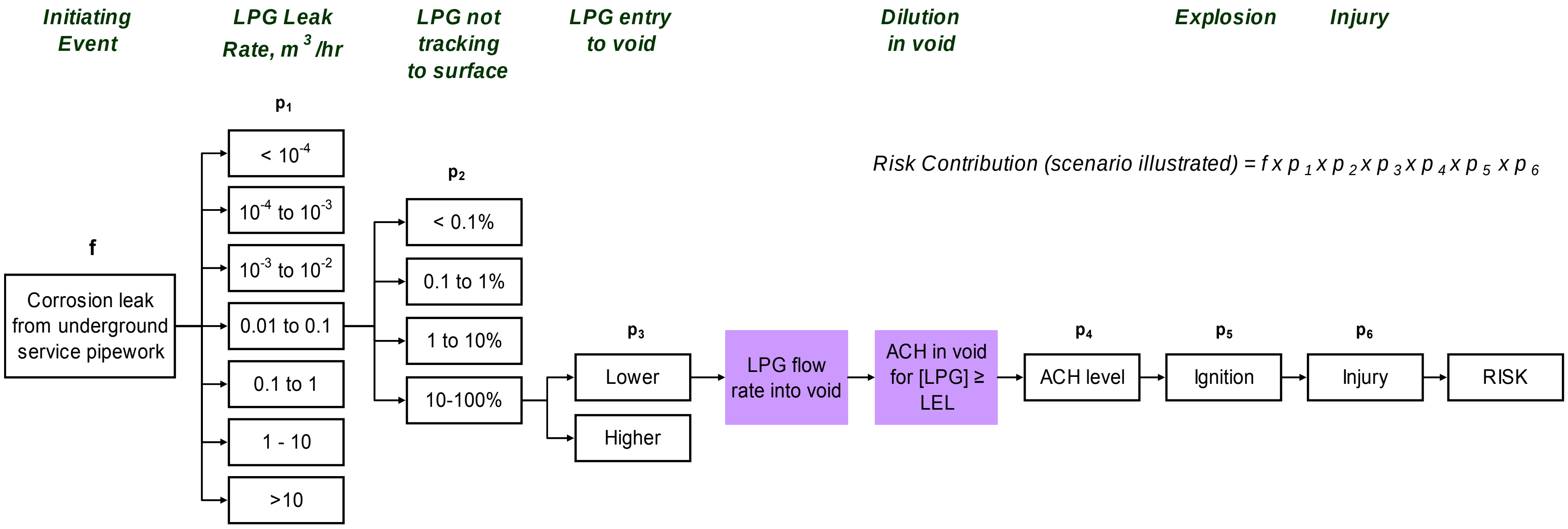


Figure 11 (b): VOID Event Tree Risk Model



Risk Contribution (scenario illustrated) = $f \times p_1 \times p_2 \times p_3 \times p_4 \times p_5 \times p_6$

Figure 11 (c): SUSP Event Tree Risk Model

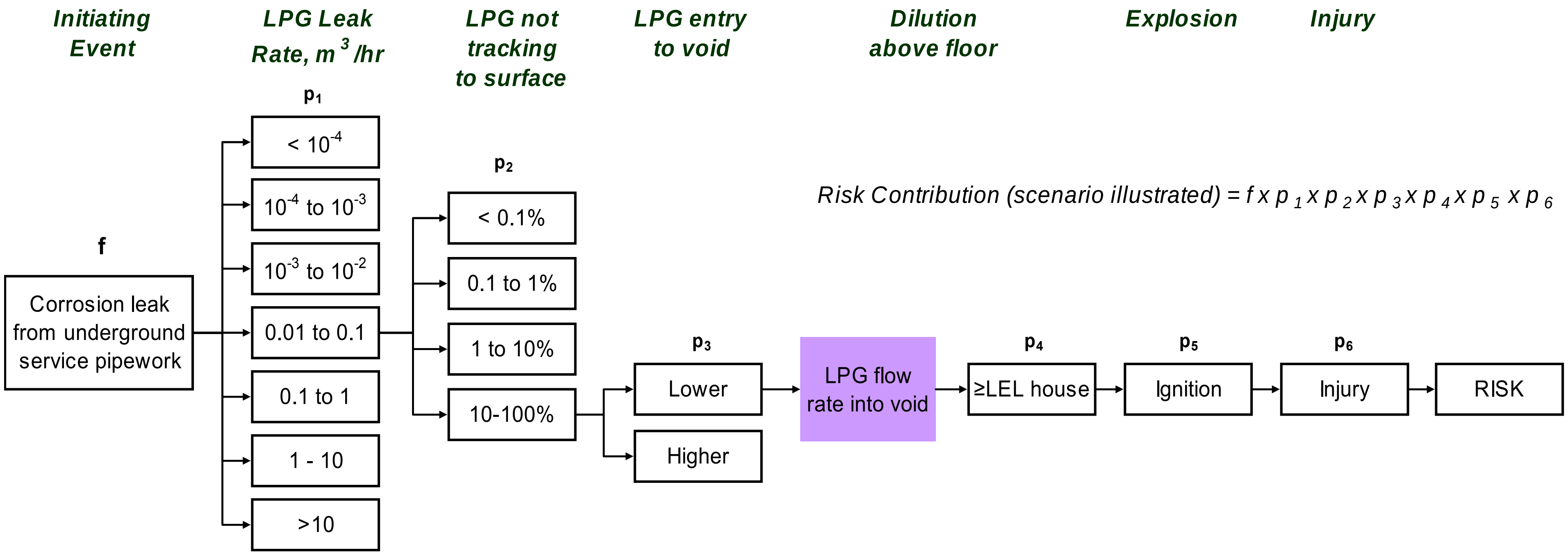
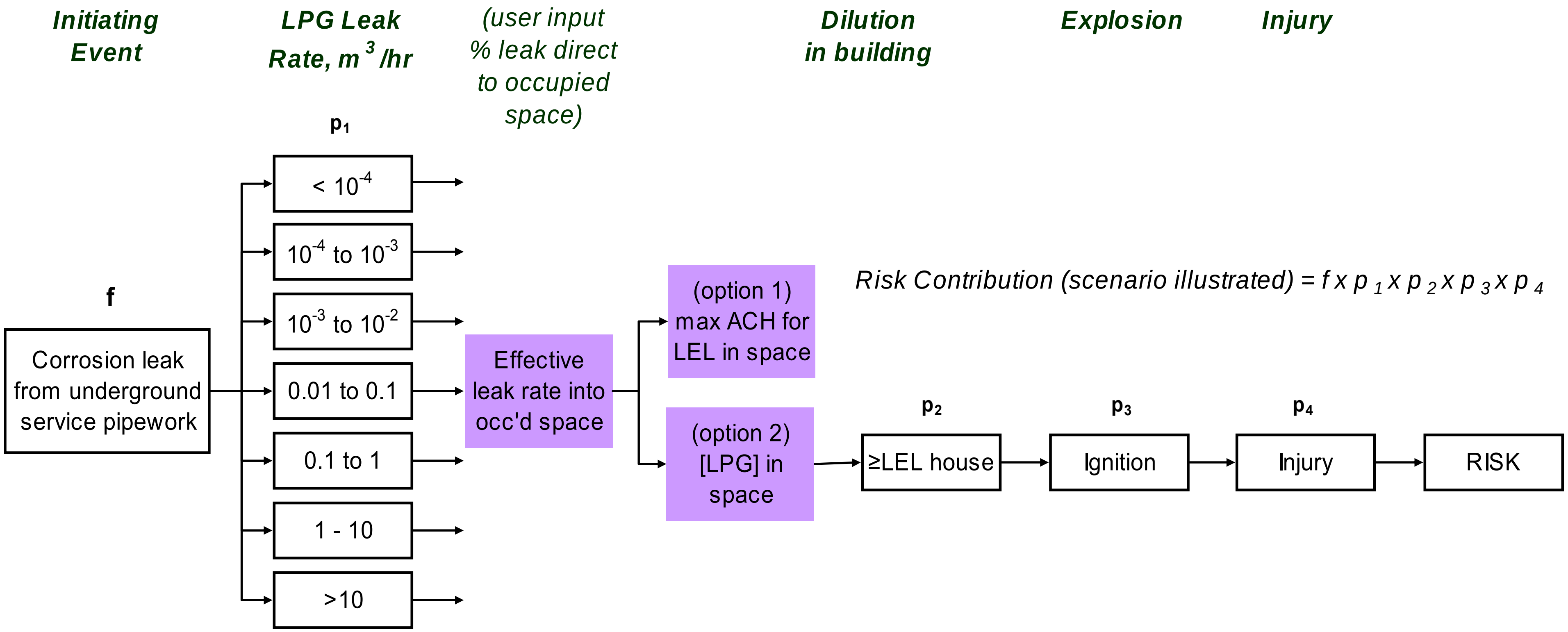


Figure 11 (d): HIHAZ Event Tree Risk Model



Risk Contribution (scenario illustrated) = $f \times p_1 \times p_2 \times p_3 \times p_4$

7.3 Sample results

Figures 12 (a) to (e) provide a sample of results of the models, representing

(a) Slab floored properties
(b) Suspended timber floored properties with crawl space
(c) Suspended concrete floored properties with crawl space
(d) Suspended timber floored properties with a cellar/basement
(e) HIHAZ properties with gas escape direct into the occupied space.

Each figure shows results for a “lower risk”, a “higher risk” and a “modal risk” property. The mode is taken from the analysis of English, Scottish and Welsh Housing Condition Surveys described in our Part 2 companion report (Section 5.2), which identified “Detached” as the most common building type for LPG users and “pre-1919” as the most common age of LPG users’ homes. “Worst” properties are the oldest and smallest floor area; “Best” are the newest and largest floor area (design & construction more effectively limiting gas ingress from soil; more dilution of LPG once into the property).

Each chart shows results for the three property types for both medium (solid) and low pressure (diagonally hatched) LPG pipework systems.

Interesting observations on these results include

1. For concrete floored properties (whether slab or suspended floors) the worst case risk even for MP pipework is estimated at less than 10^{-6} per year, for a person present 100% of the time in the at-risk location.
2. The worst case and modal cases for suspended timber floors extend well above 10^{-6} per year for MP, and marginally above this value for LP systems.
3. The HIHAZ case (for a property in which a corrosion leak would be forced directly into the occupied space) predicts values of individual risk extending above 10^{-5} per year even for larger and better ventilated buildings with MP systems, but does not predict values above 10^{-6} per year for even a worst case LP system.
4. The estimates of risk for leaks into cellars are higher again than the HIHAZ case, with even LP leak risk zones extending up to about 10^{-5} per year. While it may seem counter-intuitive that risks for cellars are even higher than for leaks direct into occupied space, there are two features of the model that explain this; both are in our view conceptually correct. These are
   a) our model includes a much higher probability that voids below floors (of which cellars are an example) will experience very low ventilation rates, and thus be able to generate significant probabilities of flammable LPG mixtures for even modest leak rates, in comparison with occupied rooms, and
   b) we consider the probability of ignition of a flammable mixture in a cellar to be potentially considerably higher than that in an occupied room, because in the latter there would be strong prior warning of gas via smell, whereas in a cellar gas may accumulate un-noticed until the sudden event (e.g. of switching on a light to enter the cellar) triggers an explosion.
5. LP systems are predicted, as would be expected, to be substantially lower risk than MP systems across all categories. The contrast between MP and LP systems is illustrated

particularly sharply in the HIHAZ case; for low pressure, none of the individual risk bands extends above 10^{-6} per year.

6. The suspended timber floor models predict a particularly large gap between the "best" buildings and others. While we genuinely consider there to be a very large difference between newer and older buildings, we believe this very large gap may be to some extent an artefact of the numerical model used to estimate the probability of encountering low ventilation rates in below-floor voids in combination with high gas transfer rates through floors.
7. The modes (most likely buildings to have bulk LPG supplies) are very close to the worst case. This is because building age is an important driver of the likelihood of developing a flammable gas mixture in voids or occupied spaces, and bulk LPG users on average live in considerably older properties than natural gas users.
8. The "best" properties (large modern ones) show ranges of individual risk in the occupied space of normal users' buildings (i.e. for slab and suspended floor properties) that are orders of magnitude lower than the ranges for modal and worst case properties. This reflects our genuine belief that homes built to modern building standards (which have evolved particularly in recent years to place far greater emphasis on leak-tightness of floors in combination with effective ventilation both above and below floors where appropriate) are effectively not at risk from flammable vapours of any sort migrating into the building from the ground.

With the model as it is presently configured, a significant percentage of LPG users' properties (i.e. pre-1919 buildings with suspended timber floors and MP supplies) are likely to emerge with ranges of individual fatality risk extending up above 10^{-6} per year. These relatively high upper values are driven by the assumptions that

a) extremely low ventilation rates are reasonably likely below the floor in older homes, and

b) the assumed ignition probability below floors could be up to 2% (which we consider could be a very pessimistic value, but which is difficult to estimate from the evidence available to us) and above floors could be up to 40% (which we consider highly pessimistic in that it takes no account of the likelihood that corrosion-related leaks will be progressive in nature, and will be detected by smell well before a flammable concentration is reached).

A small percentage of LPG users' buildings (perhaps a few per cent where the supply is effectively incorporated into occupied parts of the building, plus 1-2% with cellars or basements) may be anticipated as emerging as being at particular risk, in some cases for LP as well as MP gas supplies.

Figure 12(a) Sample Results – Slab Floors

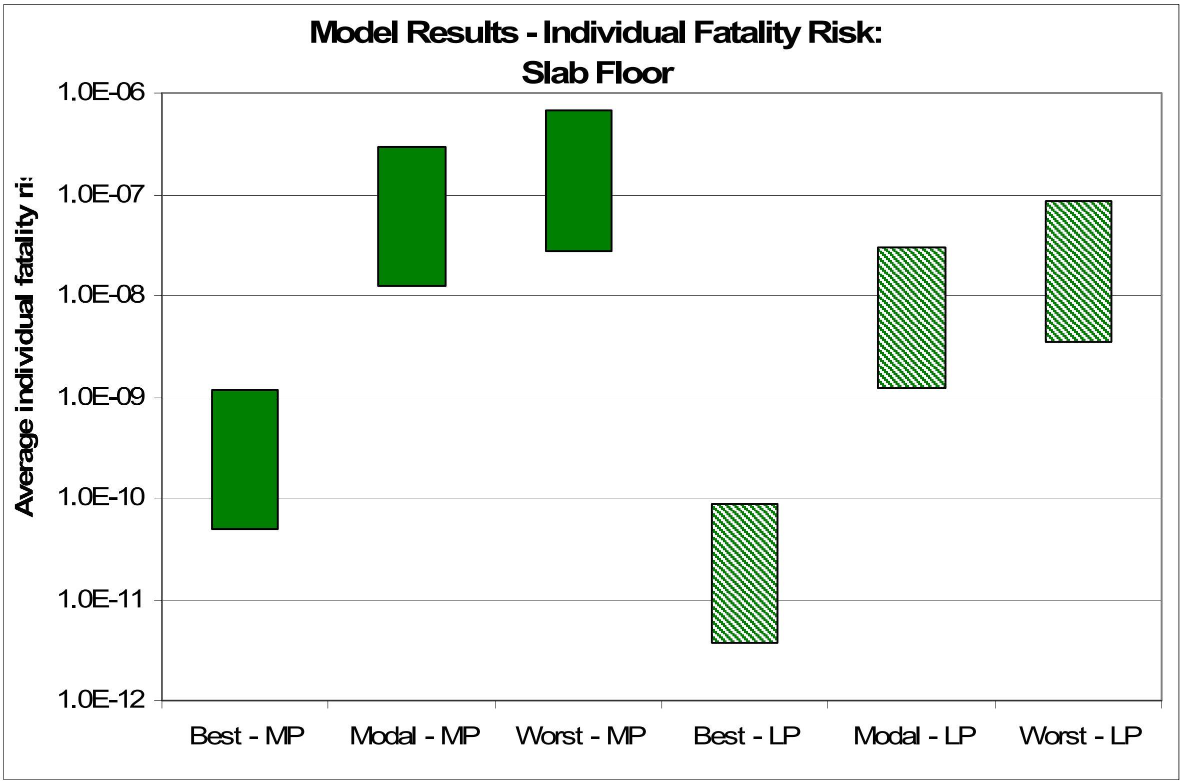


Figure 12(b) Sample Results – Suspended Timber Floors (no cellar)

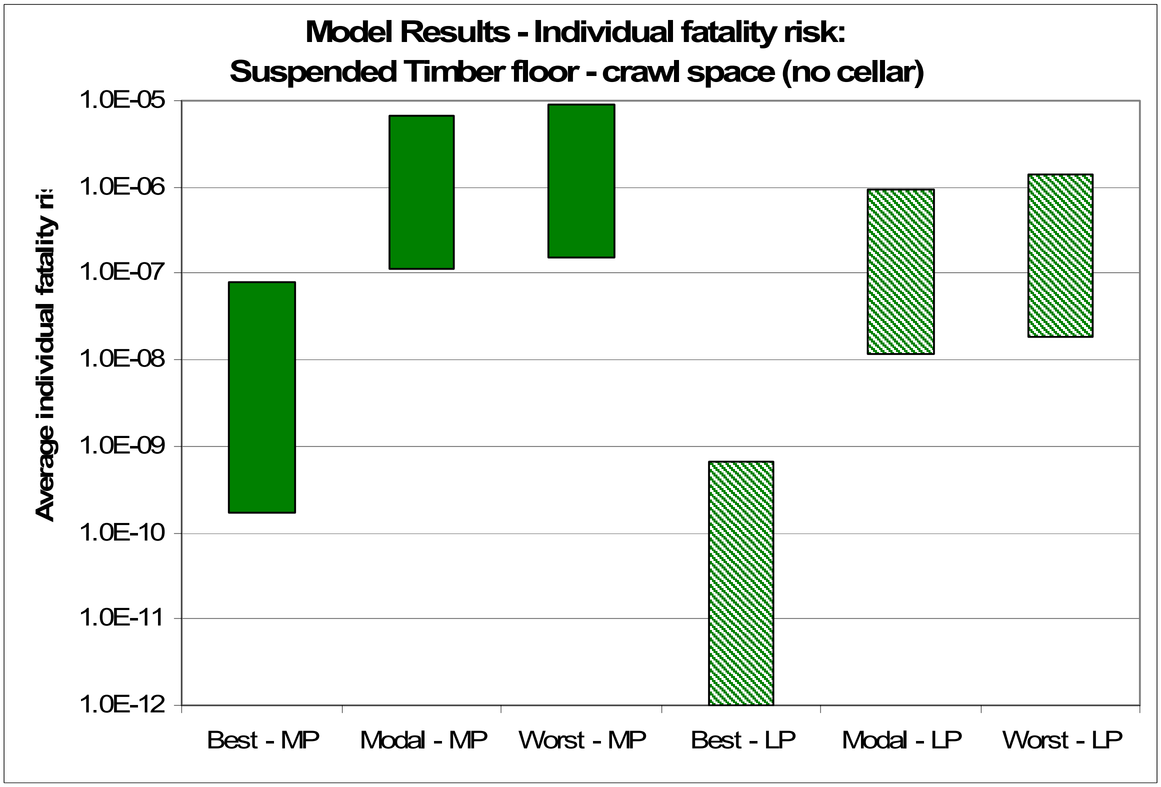


Figure 12(c) Sample Results – Suspended Concrete Floors (no cellar)

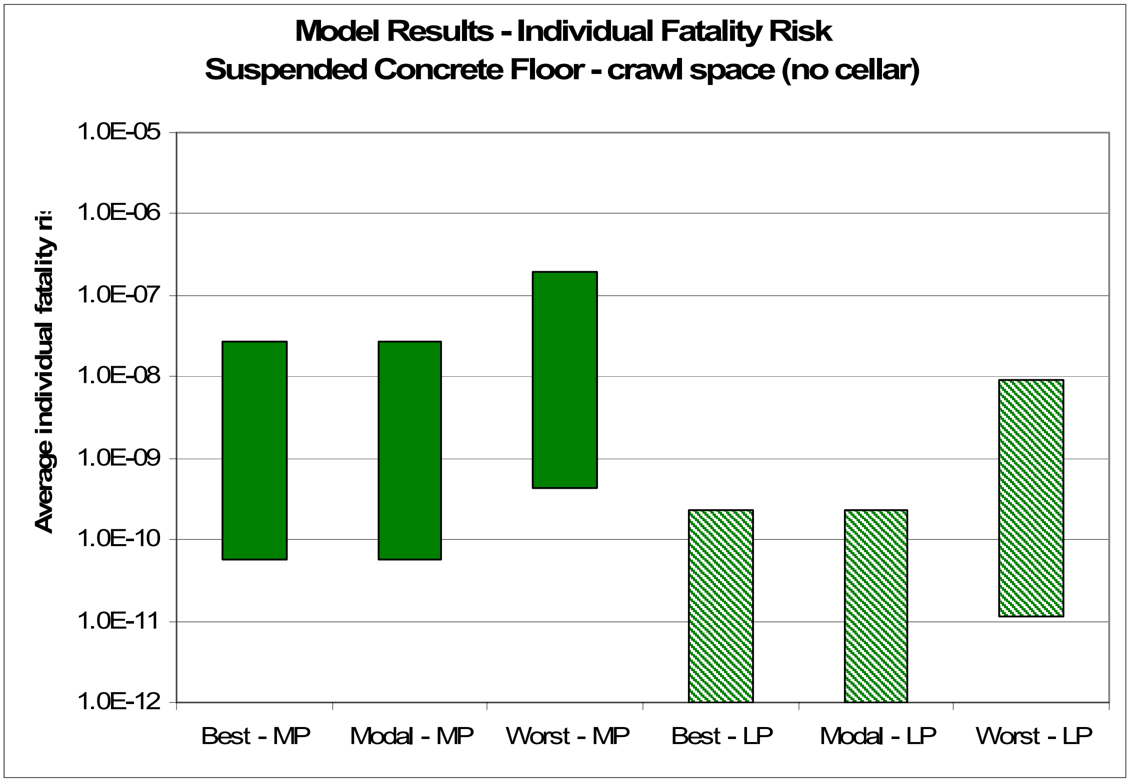


Figure 12(d) Sample Results – Suspended Timber Floors, with Cellar/Basement

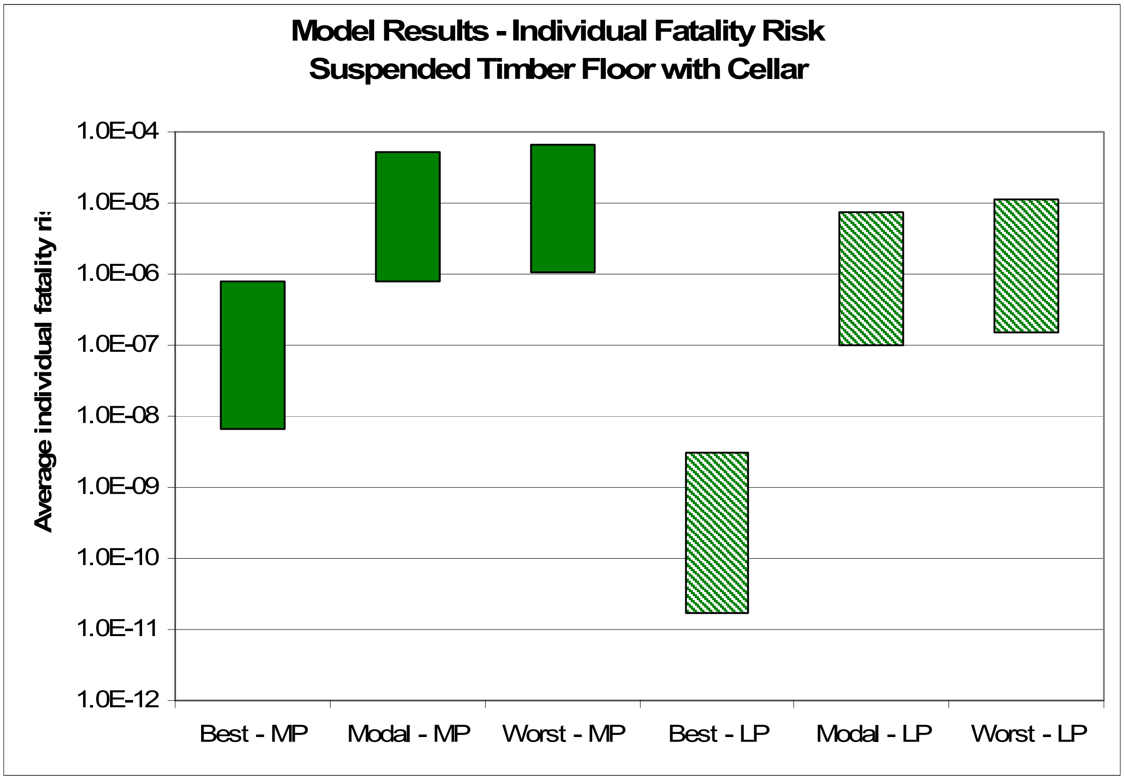
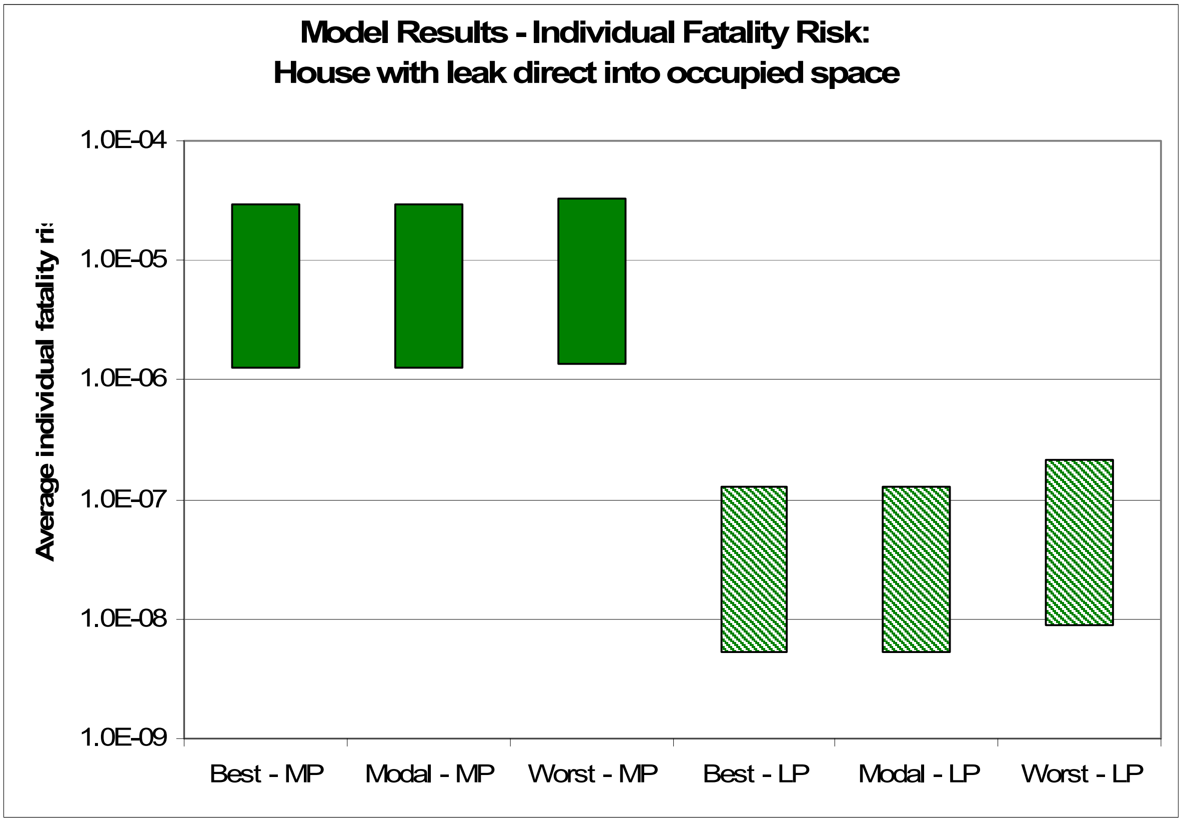


Figure 12(e) Sample Results – HIHAZ Model (LPG Escape Direct into Occupied Space)



7.4 Intermediate Model Outputs

To the best of our knowledge, nobody has ever died as the result of a corrosion leak of LPG from underground domestic service pipework, so there is clearly no direct way of comparing the risk predictions from the model with historical statistics. We have therefore generated a number of "intermediate outputs" of the model in addition to the final individual risk estimates, to facilitate the comparison of model predictions (particularly for the highly uncertain elements of the model relating to LPG migration into and dilution in buildings) with experience. Figure 13 shows such outputs for older detached properties (the prototypic domestic bulk LPG user home) for

(a) the frequency of explosions, whether fatal or not,

(b) the frequency of encountering LPG in the occupied part of a building at or above the LEL, and

(c) the frequency of encountering LPG in the occupied part of a building at levels that would be detectable by smell (probabilities per corrosion incident are also marked on this chart).

Our conclusion from these charts is that explosions are too infrequent to provide a reliable comparator between model predictions and statistics, though we note that the statistic of one relevant explosion known in the past 10-20 years is compatible with Figure 13(a). The predicted frequencies of encountering flammable and smell-detectable mixtures in buildings are, though, much higher than those implied by Suppliers' experience (Section 3).

Figure 13(a) Frequency of Explosions

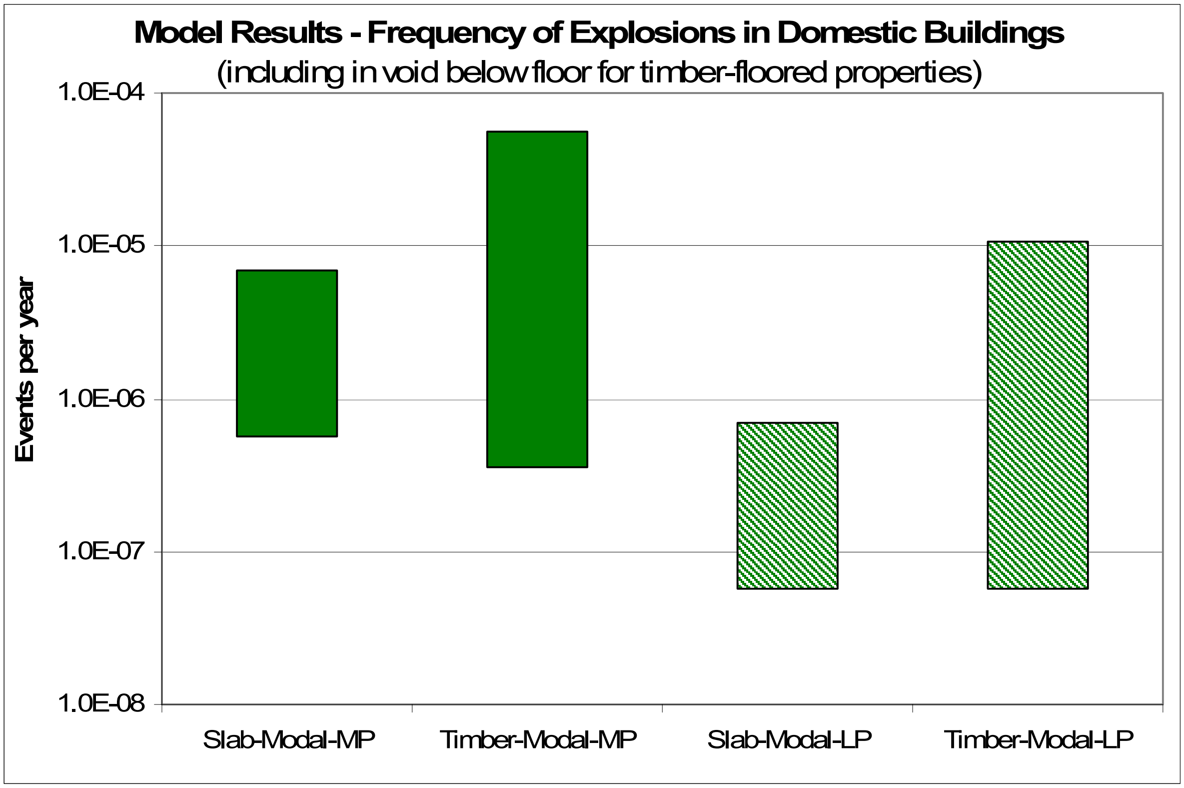


Figure 13(b) Frequency of LPG at or above the LEL in Occupied Parts of Buildings

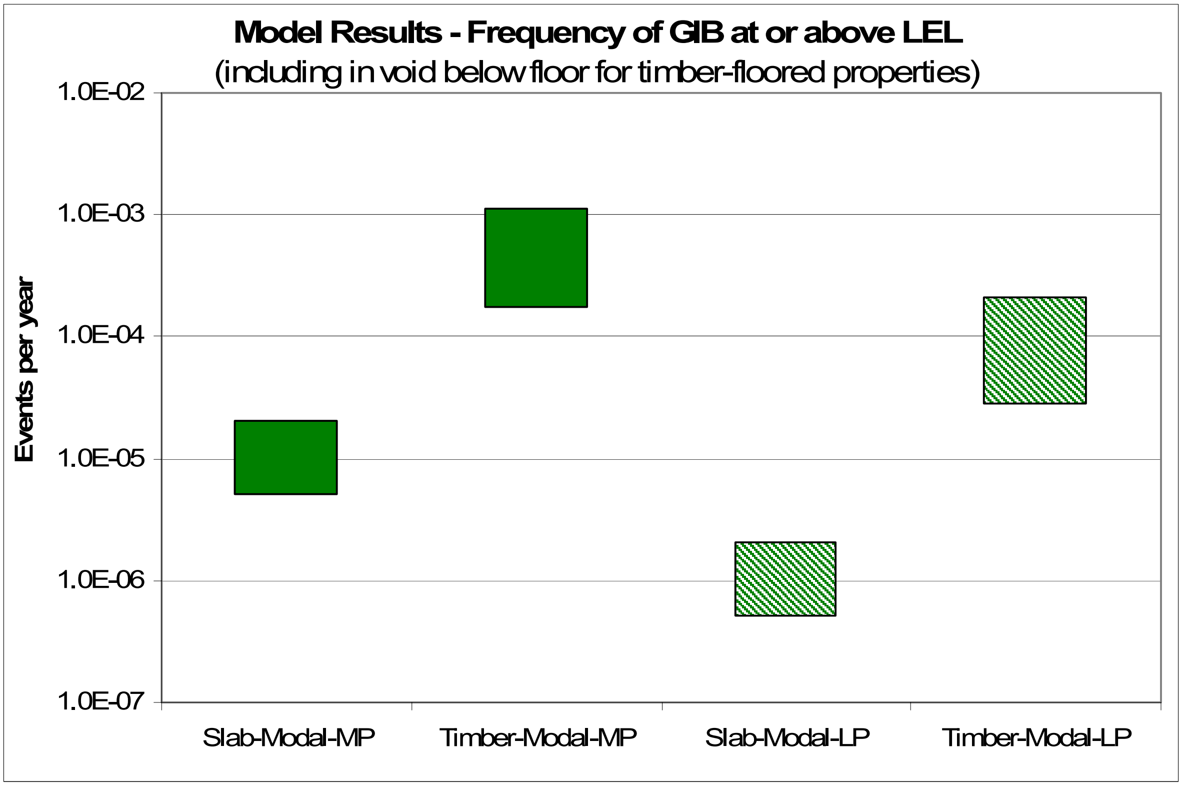
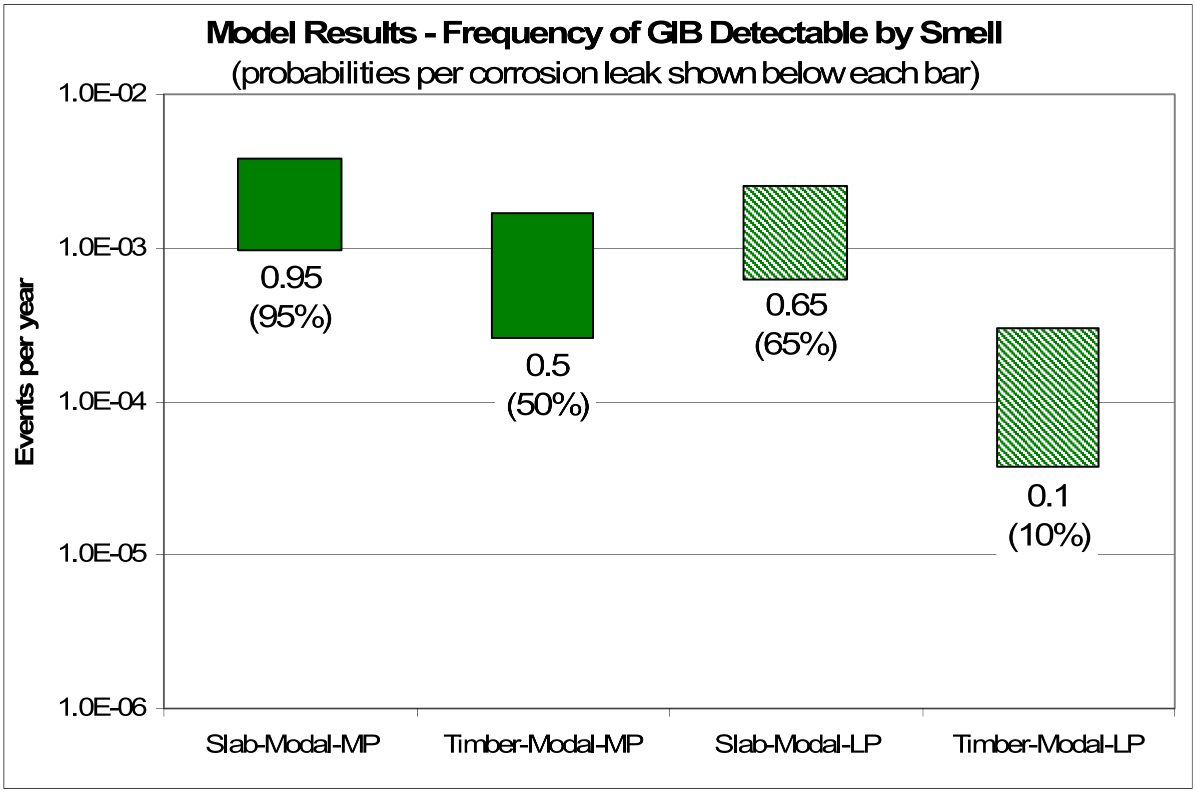


Figure 13(c) Frequency of LPG Detectable by Smell in Occupied Parts of Buildings



It should be noted that Figure 13(c) is predicated (as explained in Section 4.2) on stanching agent (typically ethyl mercaptan) being added at the lowest level mandated by current standards of 20 ppm (typical added concentrations are 40-50 ppm), and being detectable by smell at 1 part per billion (most people can detect ethyl mercaptan at 2-3 times lower levels than this). Even if a large percentage of the stanching agent were to be lost via adsorption onto soil particles, these results suggest that the models used here predict a generally substantial likelihood that corrosion leaks into soil should be detectable by smell inside domestic properties.

This contrasts with the finding of our workshops with Suppliers (Section 3) that, out of their collected experience of an estimated 200-500 such incidents, none had involved LPG detectable by smell in the occupied space of a building (other than in traces around skirtings, cupboards etc). This suggests that our model is substantially over-predicting, rather than under-predicting, the likelihood of significant concentrations of LPG developing in buildings. This point is developed further in Section 8.

8. Discussion

We discuss here

- The provenance of our risk model, in terms of its consistency with the evidence available to us about LPG corrosion leaks and their effects (8.1) and then
- The significance of its results in comparison with other possibly useful risk benchmarks, in particular
  a) HSE's risk tolerability benchmarks established in the R2P2 document[11] (8.2) and
  b) other risks associated with LPG use in domestic premises (8.3).

8.1 Comparison with LPG Corrosion Leak Evidence

HSE estimate that the number of domestic properties using bulk LPG that have some form of buried metal pipework, based on returns from suppliers who surveyed their customers during the first half of 2009, is up to 60,000. Based on our discussions with suppliers, we estimate that roughly 1/3 of these involve MP and 2/3 LP systems.

From our exploration of the English, Welsh and Scottish Housing Condition Surveys (companion report Part 2, Section 5.2) we know that roughly equal proportions of bulk LPG users have suspended and solid concrete floors, and that only 1-2% have cellars or basements. We further know via our research with suppliers that perhaps 1-2% of properties fall into the "High Hazard" category, which suggests that, with the scale of risk revealed in figures 12 (a) to (e), the main contribution to the aggregate risk to all homes in Great Britain from this hazard is likely to come from suspended floor properties, including those with cellars.

To provide a rough and ready comparison between our results and what we know about GB-wide experience of LPG corrosion leaks, we have therefore scaled up both the individual fatality risk results as shown in Figure 12, and the intermediate outputs shown in Figure 13 for

a) relevant incidents involving LPG in a domestic property at or above the LEL,
b) relevant incidents involving an LPG explosion at a domestic property, and
c) relevant incidents involving LPG at levels detectable by smell in domestic properties.

The scaling is based on the assumptions that

- there are 40,000 domestic bulk LPG users with LP and 20,000 with MP systems,
- 1% have cellars; of the remainder
- half have slab and half suspended timber floors, and
- our "modal property" (a pre-1919 detached house) provides a reasonable basis from which to scale up for a national average.

The results and underlying parameter values are shown in Table 2 overleaf.

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[11] "Reducing Risks, Protecting People – HSE's Decision Making Process", HSE, 2001

Table 2: Scaling from Model Outputs for Modal Property to UK National Expected Risk

Frequency of	per household				All GB total	
	MP Pipework		LP Pipework			
	Lower	Upper	Lower	Upper	Lower	Upper
Fatalities	1.8E-08	2.1E-06	2.2E-09	3.4E-07	0.0005	0.06
Explosions	5.6E-07	3.5E-05	7.0E-08	6.1E-06	0.01	0.94
GIB at or above LEL	9.1E-05	5.8E-04	1.4E-05	1.1E-04	2.4	15.8
GIB detectable by smell	6.1E-04	2.8E-03	3.3E-04	1.4E-03	25	111

The predicted annual fatalities per year are too low to provide any meaningful comparison with experience (which is zero in recent years via this hazard for domestic properties). We note that there are approximately 15 major injuries estimated per fatality in our "explosion consequences" model (see Figure 9 above and Appendix 1, Table A1.1). On this basis the predicted roughly $5x10^{-4}$ to $6x10^{-2}$ expected GB fatalities per year corresponds to about $7.5x10^{-3}$ to 0.9 major injuries per year. While the data is too sparse to draw any comfort from statistical comparisons, this appears broadly compatible with the experience of 2 major injuries known in the past 5 years via the explosion at Scotland in 2006.

The predicted explosion rates are also too small to permit meaningful comparison with direct experience, but again are broadly compatible with the experience of 1 known domestic explosion via this hazard in the past 5 years. The model also predicts that this frequency should have a substantial component from explosions in voids below suspended floors, which is again consistent with what very limited experience we have.

The predictions of expected frequency of LPG concentrations in the occupied parts of buildings at or above the LEL are of between 2 and 16 incidents of LPG at or above the LEL due to this hazard per year. This contrasts with the observation from our Suppliers' workshops (Section 3) of zero such incidents (or one including the Scottish explosion in 2006) from between 200 and 500 incidents attended or investigated in person by workshop participants.

Finally, the prediction of between 25 and 111 incidents per year in which corrosion leaks would be detectable by smell in buildings contrasts even more strongly with the workshop observations that none of the external corrosion leak incidents attended (the 2006 explosion in Scotland excepted) had involved LPG levels detectable by smell in the building.

Our overall conclusion from the above is that our model is tending significantly to over-predict the likelihood of significant concentrations of LPG developing in buildings.

8.2 Tolerability of Risk

Figure 14(a) provides a comparison between the outputs provided by this model for MP pipework across the four models we have developed and a range of properties in each. The "tolerable risk" or "ALARP region" for members of the general public having a risk imposed on them (as articulated in HSE's R2P2 document[8]) is shown in pink at the top of the figure. Figure 14(b) provides the equivalent predictions for LP pipework.

Figure 14(a): Medium Pressure Risk Model Predictions

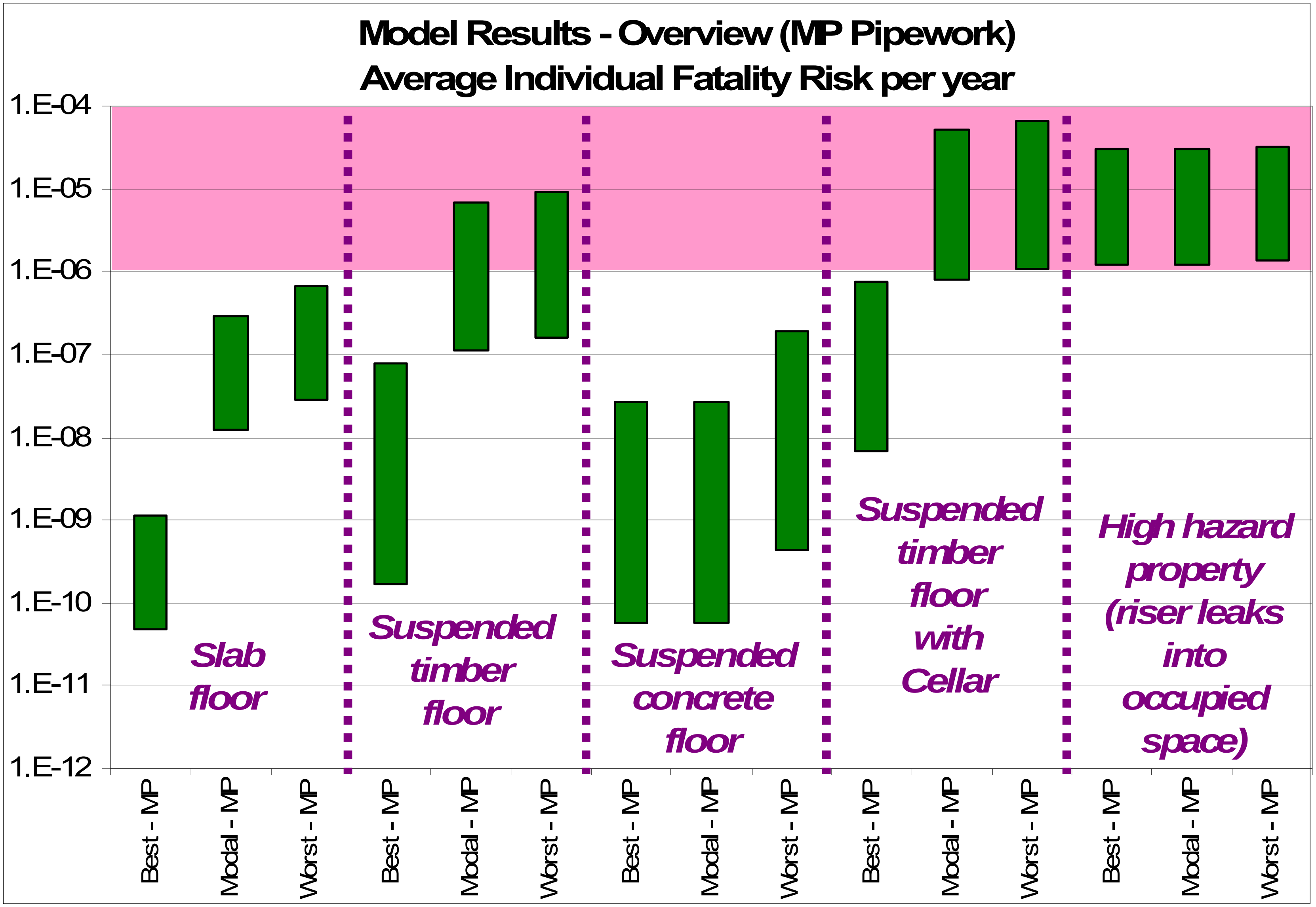
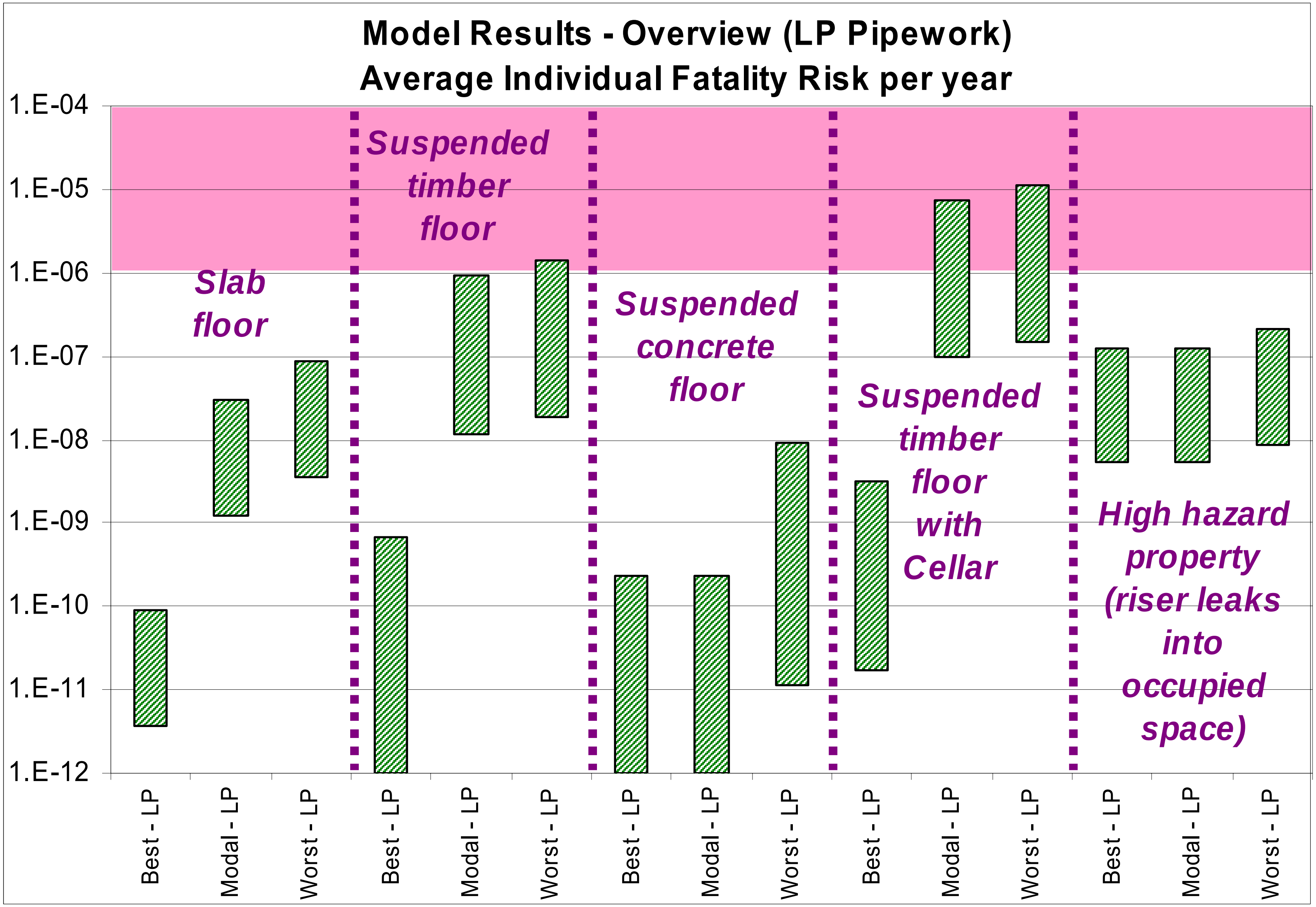


Figure 14(b): Low Pressure Risk Model Predictions



In interpreting these figures it should be borne in mind that we have intentionally aimed to "err on the safe side" in developing our model. The comparisons of predicted vs observed frequencies of encountering lower levels of LPG in houses via relevant leaks in Section 8.1 suggest that our model results are likely to be pessimistic in predicting the likelihood of encountering significant gas in buildings via such leaks. Thus the upper ends of the bars shown in Figure 14 represent, in our view, potentially quite pessimistic estimates of risk; it should not be assumed that because a green bar extends up into the pink region that there is high confidence the risk could be above 10^{-6} per year

For the bulk of properties with LP pipework (i.e. those with slab or suspended floors and no cellar or basement), the risk is estimated, even with the most cautious of assumptions we have used, to be below the 10^{-6} per year "broadly acceptable" level (i.e. below the pink bar). The same applies to slab floored and suspended concrete floored properties (without cellars) with MP pipework.

The properties where our model predictions do include some or all of the output range extending above 10^{-6} per year are

a) those with cellars or basements, whether low or medium pressure pipework,

b) those with the LPG supply riser effectively incorporated into the property, and

c) those with MP pipework and suspended timber floors.

Based on the sample of bulk LPG users identifiable from the Housing Condition Surveys we have analysed, properties of type (a) with cellars or basements are likely to constitute no more than 1 or 2% of all bulk LPG users' homes.

Based on the judgments expressed in our supplier workshops, properties of type (b) with the riser effectively incorporated into the residential part of the property are again likely to constitute no more than 1 or 2% of domestic bulk LPG users.

Of greater possible practical significance are the risk estimates for properties of type (c) - older buildings with suspended timber floors, which could easily constitute several 10's of % of LPG users based on the information available on LPG users via the Housing Condition Surveys.

None of the models developed here, even with the widest possible range of buildings analysed, predict risks extending into the intolerable region. For LP systems, the only types of properties with risks extending above the "broadly acceptable" region are those with cellars and basements.

8.3 Comparison with Other Risks of Significant LPG in Buildings

Whatever the uncertainties associated with our model outputs, we can estimate where corrosion leaks from underground service pipework sit in a hierarchy of risks due to gas use in the home with some confidence.

For both natural gas and LPG, incidents involving serious leaks, explosions and casualties all show a similar order of importance of different causes of gas incidents:

a) leaks due to technical failures are infrequent in relation to leaks due to human error or action, and

b) external service pipework leaks are a small contributor to the overall frequency of leaks due to technical failures.

As regards this second point, it is worth noting that from LPG suppliers' experience, the overall rate of external service pipework leaks (of which a large majority involve cut-throughs and other mechanisms other than corrosion) is small in comparison with the rate of occurrence of leaks from appliances and pipework inside properties. It is useful to set the expected incidence and severity of gas in building incidents due to corrosion leaks in underground service pipework in context against such leaks:

i) significant gas in buildings is anticipated from a small fraction, of order 1% or less, from all corrosion leaks from underground service pipework, which in turn constitute

ii) a small proportion of all underground service pipework leaks, which in turn are

iii) relatively infrequent compared with internal pipework and appliance failures in buildings, which in turn are

iv) infrequent relative to human errors and behavioural causes of leaks inside buildings, and

v) all of the leaks in (iii) and (iv) involve leaks directly into the occupied space of buildings, and

vi) a substantial proportion of them involve mechanisms creating a relatively sudden, large escape of gas, in contrast with external underground corrosion leaks, which are progressive by nature.

Putting all this together we would be astonished if the contribution of underground corrosion leaks in service pipework to the overall risk of LPG explosions in domestic buildings was more than a few per cent, and would be unsurprised if it were significantly lower.

The discussion in this section reinforces our view from the outset of this study that significant care would need to be taken in implementing measures to control the risk from corrosion leaks in underground service pipework so as to ensure that

a) the relatively rare high risk properties were targeted, whilst

b) the large majority of low risk properties were not subjected to inappropriate requirements to upgrade underground service pipework, and in general

c) attention were not diverted from more significant and controllable risks associated with gas use in domestic properties onto underground service pipework corrosion.

9. Conclusions

Our conclusions are

1. The levels of individual fatality risk associated with corrosion leaks from underground service pipework at domestic properties are generally low. For the majority of households using LPG we would expect them to fall clearly into the "broadly acceptable" band when judged against typical risk tolerability criteria.
2. An exception to this general observation should be made for properties with cellars or basements, for which individual risk levels could extend well into the "tolerable risk" or "ALARP" region for properties with either medium or low pressure LPG pipework. Such properties are likely to constitute no more than 1-2% of domestic bulk LPG users' homes.
3. A second important exception should be made for properties with gas installations which effectively have incorporated the service pipework and/or the riser into the fabric of the building. Individual risk levels for users with MP systems (LP systems are at substantially lower risk) may extend well up into the "tolerable risk" or "ALARP" region. Such properties are likely to constitute at most a few per cent of LPG users' homes, and include
   - old installations with gas entering the property below ground
   - properties that have been extended over service pipework, and
   - caravans and park homes with gas-tight "skirts" built between them and the ground
4. Among properties without cellars or basements and with "normal" risers entering the property above ground through an external wall, the greatest risk presented by corrosion leaks underground is to houses with suspended timber floors. Risks for such properties with MP gas supplies could extend into the "tolerable" or "ALARP" region; this could also be the case for particularly severe LP cases (properties with unventilated below-floor voids). Explosions in the void below the floor, as well as in the occupied parts of buildings, are important contributors to this risk.
5. Modern homes are generally at substantially lower risk from this hazard than older homes, because of the much greater attention paid both to leak-tightness of floors and to effective ventilation, both above and (where appropriate) below the floor in modern building standards.
6. LPG supply pressure is a key factor; reducing pressure from MP to LP would effectively reduce risk into the "broadly acceptable" region for all but a very small proportion of properties (those with cellars and basements, and possibly some properties with suspended timber floors with a particular propensity for gas accumulation in the below-floor void).
7. The algorithms and data used throughout our risk model are highly uncertain, as there is minimal direct evidence available on migration of LPG from soil into buildings. The models do, though, in our view provide broad consistency both with a large body of research and modelling work done on such migration in the context of contaminated land and radon, and with what limited evidence is available on relevant LPG leaks from service pipework.
8. With this said, we are confident that our models are not significantly understating the risk associated with corrosion from underground LPG service pipework at domestic premises. In particular there is good evidence that
   a) such leaks contribute only a very small proportion of the overall risk of serious LPG

escapes into the interiors of domestic properties, and that
b) our models tend to over-estimate, rather than under-estimate, the likelihood of corrosion leaks of LPG into soil leading to significant levels of LPG in buildings.

9. Of the wide range of inputs explored to our models, relatively few make a really significant difference to the predicted risk. Of those explored here, LPG pressure, building age, floor construction, ground cover and presence of the special risk factors identified in 2 and 3 above are the most important. It should be borne in mind that there is a substantial evidence base on the corrosion susceptibility of service pipework in different soil conditions, which could not be explored in this study, and which might add "susceptibility of a specific property's pipework to corrosion" to this list.

10. Recommendation: Specification for Risk Assessment Tool

We are sufficiently confident in our risk assessment model to recommend that, following appropriate peer review and discussion with HSE and the industry as to the appropriate assumptions that should be incorporated into it, a tool could be developed from it that householders can use to assess their own risks from this hazard with a relatively low risk of receiving false assurances from that assessment.

The specification we propose for this tool is as follows:

1. The minimum question set to be answered by an LPG user should be that summarised in Table 3 below and presented in flowchart form in Figure 15.
2. Detailed risk calculations are unlikely to be warranted in developing advice for individual LPG users; we would regard it as preferable to use the findings of this study to support the development of general advice as to the priority warranted for addressing this hazard at different properties.
3. The advice to be offered based on the risk estimates developed in this report is a matter for discussion between HSE, LPG suppliers and other interested parties, not least the LPG users who are potentially exposed to this risk and who would in most cases have to pay for any upgrade to their service pipework.

Matthew Hunt
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TTAC Ltd
5 March 2010

Figure 15: Proposed Risk Assessment Tool – Input Issues Flowchart

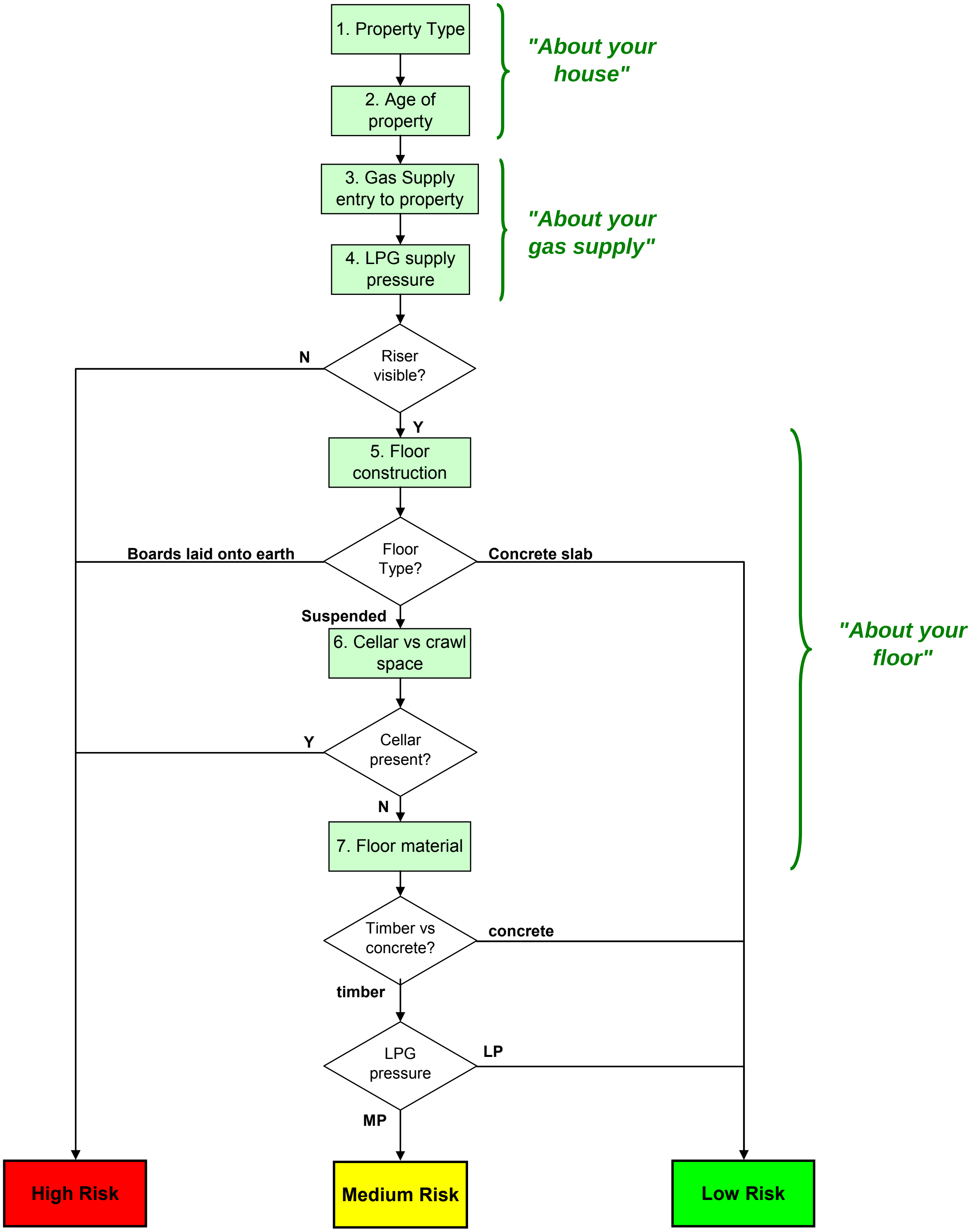

Table 3: Question Set for Proposed Risk Assessment Tool

No.	Issue	Key Question / User Action	Notes
1	Property Type	Selection of property type from list provided (see spreadsheet)	e.g. Detached, semi-detached, terraced, bungalow etc
2	Age of property	Select from age bands provided (pre-1919, 1919-1944, 1945-1964, 1965-1980, post-1980)	Important parameter; may need to provide guidance for users unsure or around the boundaries of the age bands
3	Gas Supply Entry to Property	Does the gas supply pipe emerge from the ground and enter the building through an external wall above ground level?	Presupposes suppliers have definitively identified customers with underground service pipework with some metal components. If not, further questions may be required to clarify whether user is/is not in scope.
4	LPG Supply Pressure	Select MP or LP	Provide guidance on how to identify MP from presence of regulator on riser.
5	Floor construction	Is the floor of your house a) boards laid direct onto earth, b) a concrete slab, or c) suspended? (the latter should be able to be determined reliably by looking for ventilation outside the property if the householder is not sure whether there is a void below the floor or not)	May be useful to include sub-question on whether the property has effective anti-radon ingress measures in place (which would default to "low risk" for this hazard).
6	Cellar vs crawl space	[for suspended floors only] Select type of space below floor from list (crawl space, cellar, basement)	No distinction in model between cellar and basement, though latter (designed for occupation) may have better ventilation.
7	Floor material	[for suspended floors only] Is suspended floor made of wood or of concrete? ("beam & block" construction)	May require significant guidance; pre-1970 virtually certain to be wood.

Appendix 1: HSE Incident and Investigation Analysis

This appendix explains the information we obtained from HSE, and the analysis carried out using it. The primary uses made of this information in our risk assessment model are to derive probabilities

a) that gas in domestic buildings will ignite if present in flammable concentrations, and

b) that a person present in a building when a gas explosion occurred will sustain minor, major, fatal or no injuries.

The appendix is presented in sections covering

- the databases and sources to which we were given access and the records extracted from them for our study
- the re-classification of incidents we carried out to enable them to be re-analysed for issues of interest in our assessment, and
- the results of the subsequent analysis

A1.1 Data Sources and Extracts

A1.1.1 RIDDOR

The Reporting of Injuries, Diseases and Dangerous Occurrences Regulations 1995 (RIDDOR), place a legal duty on employers, self-employed people and people in control of premises; to report work-related deaths, major injuries or over-three-day injuries, work related diseases, and dangerous occurrences (near miss accidents). These incidents are reported to HSE via the ICC (Incident Contact Centre) and HSE maintains a database of these reported incidents. Gas incidents are recorded on forms F2508G1/2 for those involving injuries or as dangerous occurrences (DOs) which appear on form F2508 or with no specified form. It was possible to distinguish between fatal and major injury incidents in the data available as form F2508 was split into a file for fatalities and a file for major injuries.

There are two different ways to get at RIDDOR incident data. The first involves going to the ICC (Incident Contact Centre) part of the HSE intranet and using a very simple search facility to select a sub-set of the RIDDOR. This allows access to the latest incidents, but a limited number of fields. The second involves a major download from the ICC which goes to HSE at Bootle every 6 months. This provides comprehensive access to all the RIDDOR fields (many of which may not consistently filled in), including useful gas incident-specific fields such as building type, room type and gas incident cause, but can be missing the last 6 months of incidents.

The second RIDDOR data access route gave us two datasets, one containing all incidents on forms F2508G1/2 (13,058 incidents), and one containing all DOs (23,270 incidents). Incident records acquired through this source covered all relevant gas incident fields, but the key description field was truncated to 255 characters as a result of the storage/access methods. The first access route allowed us to access the full description fields for 34,287 incidents (a significant proportion of which do not overlap with the data from the second access method). This data could then be combined into one source which, as it contains personal details in many records, was stored fully encrypted on laptops.

As there are so many records it was impractical to anonymise them all so for data exploration relevant subsets were extracted and anonymised before being classified and analysed.

A1.1.2 COIN

COIN is the HSE database containing all details of incident investigations; it replaced its predecessor FOCUS in the early 2000's. We were provided with a dataset of all COIN records for all RIDDOR/RGAS/REGD & RIDDOR/RGAS/REGM Cases with dated between 01/04/05 and 31/03/09. This contains 5,706 records (Excel rows) of 4,683 incidents investigated over this 4-year period and included carbon monoxide, asbestos and dangerous appliance incidents amongst others which were out of the scope of this work. Many of the description fields contained significant amounts of personal data which was removed from all incidents within the scope of this project before the classification and analysis was undertaken.

A1.1.3 GSMR Data

The Gas Safety Management Regulations (GSMR), require operators to investigate any incident which leads to gas in building at concentration > 20% of the Lower Explosive Limit (LEL) (or any outdoor leak involving > 500kg gas escape) and send HSE a copy of the investigation. These investigation reports are received by the Pipelines Unit at Sheffield, where they are reviewed and entered into a simple Excel spreadsheet database (containing no names or other particularly sensitive information). We have had access to a full copy of the GSMR database which contains incidents covering each year back to 2003, though as this is not a formal database it is quite possible that there are a number of incidents not contained within it.

We were also granted access to a portion of the operators' investigation reports from which we extracted additional information of interest such as postcode, leak characteristics and consequences. We also found quite a lot of the operators' reports weren't in the database, affirming that the database was not complete. Having added these extra details and incidents the final dataset contained 1,724 incident records.

The MAJOR value of this database is that it provides us with a dataset of upstream (on the external side of the emergency control valve) incidents that have involved significant gas in buildings. There are no incidents in which corrosion failure of service pipework, whether for natural gas or LPG, has led to an explosion inside a building.

A1.1.4 Domestic Gas Fatalities Database

We were given access to a database maintained by HSE Utilities' Division of all fatal accidents involving gas in domestic buildings extending back over a decade. This provided valuable high level information early in the study to set LPG hazards in context against other risks of gas use. It provided no information not contained in the other datasets obtained from HSE and was not used directly in the analyses on which we rely in sections 5 and 6 of our main report.

A1.2 Data Classification and Analysis

A1.2.1 Explosion incidents

A dataset of explosion incidents was identified by selecting those incidents from the RIDDOR and GSMR datasets which contained the phrase “explo” in their description fields. The resulting set of incidents was then annonymised and manually separated into explosion and none explosion incidents resulting in a database of explosion incidents containing 423 records. Where there it was possible to identify a corresponding COIN record for each of these records the relevant COIN data was added to the database.

Each record was next classified as the size of the explosion and the number of persons present and the degree of injury they each sustained. Explosion size was derived by estimating the minimum and maximum possible explosion sizes on the scale; Appliance full, Room full, House full, > House full based on the description of the damage and location. This was converted to a scale as given in Table A1.1 below:

Table A1.1 Characterisation of Explosion Scale

Min size	Max size	Scale
appliance full	appliance full	Appliance Scale
room full	room full	Room Scale
appliance full	room full	Room Scale
appliance full	house full	Room Scale
room full	house full	House Scale
house full	house full	House Scale
house full	> house full	House Scale

Injuries and persons present were inferred from the description fields. If no mention was made of injuries then if the RIDDOR data was from a F2508G1 from then it was assumed to involve a death or major injury based on original source file (as detailed in A1.1).

With all records classified the probability of a person present when an explosion occurred sustaining a given severity of injury was calculated directly from the incident statistics, as shown in Table A1.2.

Table A1.2 Probability of Injury for Persons Present at Domestic Explosions

	Expected injury type given explosion scale			
Gas Explosion Scale Description	**Fatal**	**Major**	**Minor**	**unharmed**
Appliance scale	0.0%	24.7%	18.5%	56.8%
Room scale	4.3%	61.5%	15.5%	18.7%
House scale	10.1%	61.9%	20.9%	7.2%

The likelihood and severity of injury increase with the scale of the explosion as would be anticipated. In our view these figures are likely significantly to overstate the likelihood of injury in explosions, as many incident reports do not make mention of persons present but uninjured.

A1.2.2 Likelihood of Ignition of Flammable Gas Mixtures

Both the GSMR and RIDDOR data were used to extract relevant datasets for analysis. In both cases we considered estimates derived from this data of the likelihood of flammable gas mixtures igniting to be significant overestimates, as the reliability of reporting and recording is likely to be greater (in the view of the HSE staff supplying the data as well as in our own judgment) for incidents where ignition occurred than for those where it did not.

Using the GSMR Data simple text searches for “explo”, “fire” or “ignite” in the description field followed by a manual check all those incidents which involved an explosion or ignition of the gas were identified and flagged.

This classification in combination with the GSMR field stating whether or not there was Gas In Building (GIB) > 20% of the LEL gives an estimate that between 7 and 20% of GIB incidents result in explosion.

A significant limitation in interpretation of this data is that the incident descriptions in the database are very terse. Our judgement is that this dataset is likely to overstate the % involving explosion, as

a) occurrence of an explosion is very likely to be noted in the description, and

b) reporting is more likely if an explosion resulted than if it did not.

A parallel analysis was carried out based on RIDDOR data. Using the full set of RIDDOR data provided to us, records were selected using text searching methods on the key description fields to

a) include incidents with words "explo", "evac", "ignit", "full drop", “evac" and any LEL-like term (LEL, L.E.K, "lower explo") and any variations and similar phrases.

b) and exclude incidents with words “asbestos”, “carbon mono”, “ CO ” and “no evac”

This dataset of 2034 incidents was then classified, where possible, in terms of:

a) Whether there was significant gas in the building

b) Building Type (domestic or not)

c) Room in which leak occurred (or "external")

d) Scale of leak (appliance, room, house) - min, max and range just as for A1.1

e) Whether ignition/explosion occurred, and if so

f) Cause/source of ignition if identifiable

This selection and classification process almost certainly understates population of "external leaks with no GIB" as

a) these are less likely to be reported and/or recorded,

b) there is a large % of "can't tell" in classifying a-f above and

c) in classification we have tended to treat virtually any indication of significant GIB as equivalent to "flammable gas mix present in building".

Between 23 and 30% of gas in building incidents analysed resulted in ignition and/or explosion. The proportion varies significantly with scale of explosion; if we exclude appliance scale explosions (which we have done in applying this analysis in our risk assessment) then the proportion falls to 19%. The proportions of incidents involving different explosion scales in different rooms is shown in Table A1.3.

Table A1.3 Proportion of Major Leaks leading to Explosion

Explosion size → Location ↓	**Appliance scale**	**Room scale**	**House scale**	**All scales**
Boiler* (77 incidents)	82.4%	6.3%	9.1%	40.3%
Kitchen (206 incidents)	41.3%	30.6%	38.5%	34.5%
Lounge (134 incidents)	68.2%	14.1%	25.0%	32.8%
Other (401 incidents)	55.0%	21.8%	19.8%	23.9%

The likelihood of ignition appears somewhat higher for incidents involving kitchens as opposed to other rooms in the house, and on this basis we have adopted a higher value in our assessment if the room into which gas enters the house (which is likely to be the kitchen for a majority of LPG users' homes if gas migrates through soil to the room nearest the riser) is the kitchen.

[Appendix ends]

TTAC Limited
For More Effective Management of Risk and Uncertainty

Risk Assessment of Corrosion Leakage of LPG from Domestic Underground Service Pipework:

Part 1: Suppliers' Gas Escape Experience

a report produced for the Health & Safety Executive

by Matthew Hunt, Kajal Somaiya and Tony Taig

TTAC Limited

March 2010

This report has been produced by TTAC Limited under contract to the Health & Safety Executive as a companion document to the final report on the whole of the Risk Assessment project

Executive Summary

This report presents the findings of research carried out by TTAC Ltd on behalf of HSE and the UK LPG industry during the summer of 2009 to collate major LPG suppliers' experience of corrosion leaks from underground service pipework (USPW) at domestic properties. This is part of a larger risk assessment carried out by TTAC Ltd to help inform LPG users' and suppliers' decisions on the priority that should be attached to replacement of metal underground service pipework at domestic premises.

The report draws together the analysis of gas escape records provided by BP, Calor, Flogas and Shell, along with the findings of workshops held with engineers, engineering managers and emergency desk managers from each company. The experience collected covers some 350-400 person years of engineering experience dealing with LPG escapes at domestic properties, including some 240-500 domestic USPW leaks due to corrosion.

Our conclusions are:

1. The average frequency of domestic leaks from underground service pipework due to corrosion is between 1 and 4 per thousand customers with metal service pipework per year.
2. Such corrosion leaks typically occur at or near the base of the riser adjacent to the property, though a significant percentage may occur at or near the ground surface, particularly where the riser is set in concrete.
3. There is a strong association of corrosion leaks from underground service pipework with
   a) the moisture levels local to the riser into the property, and
   b) the quality of corrosion protection (galvanisation and wrapping) when the pipework was installed.
4. Typical leak rates due to corrosion are small in comparison with many other gas escape mechanisms and can remain small even when corrosion is far advanced so long as the surrounding soil holds the pipework/corrosion products together.
5. Corrosion leaks from underground service pipework develop progressively over a period of time; there are no known instances of leaks developing suddenly to a large size.
6. Most corrosion leaks from underground service pipework involve low rates of gas escape and pressure drop during tightness testing. Typical pressure drop rates are of the order of mbar or 10's of mbar per minute from MP pipework, and correspondingly lower from LP pipework.
7. Rapid gas escapes ("full drop" type leaks) from underground service pipework due to corrosion are very rare, occurring in less than 1% of cases.
8. A modest percentage of underground service pipework leaks due to corrosion lead to traces of LPG inside the property at ppm (part per million) levels around floors and skirtings close to the leak location.

9. With the exception of the explosion at a domestic property in Scotland in 2006, no participant in any of our workshops was aware of they, or any of their colleagues, ever having been able to detect LPG by smell inside a house as a result of gas from an underground service pipework leak migrating into the property via the soil.

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Tony Taig

TTAC Limited
5 March 2010

Contents

1. Introduction

This report provides a summary of four major LPG suppliers' (BP, Calor, Flogas, Shell) experience of gas escapes, and what can be inferred from this experience about the frequency and characteristics of leaks from underground metal service pipework (USPW)[12]due to corrosion at domestic properties. It has been prepared by TTAC Ltd as part of a larger project funded by the Health & Safety Executive (HSE) to develop methods and supporting evidence and data to assess risks to domestic LPG users from such leaks. It is based on records of gas escape incidents provided by the suppliers, and workshops held with their engineering staff, during August and September 2009.

The report describes

- The approach adopted and experience collected in the course of this work (Section 2)
- Suppliers' processes for responding to suspected gas escapes (Section 3)
- The frequency of corrosion leaks from underground service pipework (Section 4)
- The characteristics of such leaks (Section 5)
- Observations on other leaks capable of generating gas in buildings (Section 6), and
- The conclusions drawn from this collected experience and adopted in the risk assessment process (Section 7).

We are extremely grateful to Alan Caldwell of BP, Terry Ritter of Calor, Tony Humphreys, Alan Kirk and Andy Mackie of Flogas and Ian McCluskey, Sheila Martin and Daniel Koseoglu of Shell for their considerable efforts in arranging the workshops and the extraction of data from company systems (which in several cases has involved considerable IT effort), and to all their colleagues who have participated in workshops and in providing data.

The suppliers have participated openly in this exercise on the basis that no information would be attributed to any individual or supplier by name, and that the suppliers would have the opportunity to review the analysis of and conclusions drawn from their input prior to its publication. Individual workshops have been documented and reviewed by the participants at each supplier to confirm our understanding of what they told us. This report has been circulated to the suppliers in draft to fulfil our commitment to allowing them to review our analysis and conclusions prior to publication.

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[12] Throughout this report, the abbreviation USPW refers to underground service pipework at domestic properties.

2. Approach and Collected Experience

Experience was collected via suppliers' documented records of reported gas escapes, and via workshops (one for each supplier) held with engineers experienced in "front line" response to gas escapes at customers' premises.

2.1 Workshops with Engineers

The workshops were all slightly different in character, involving different mixes of managerial, front-line and "emergency desk" staff with experience from different parts of England, Scotland and Wales. The common theme was that suppliers co-operated enthusiastically in making staff available at short notice, and in encouraging them to speak freely and openly. Important "ground rules" of the workshops to enable free and frank discussion were

1. individuals participating would remain anonymous

2. no remark would be attributed to a specific individual (or named organisation without that organisation's prior consent)

3. no material would be included in any shared report that would allow sensitive customer information to be deduced for the participating suppliers (e.g. numbers of customers, or gross annual numbers of leaks); data to be shared would be normalised per customer

4. organisations would have the opportunity to review the findings from our work with them prior to issue of a report to HSE or of publication of the TTAC work.

The workshops each followed the same process, discussing in turn:

1. the relevant experience of the participants in terms of years of relevant "front line" experience and numbers of relevant gas escapes attended

2. the organisation's process for responding to reported gas emergencies, including both
   a) initial telephone response and decisions to dispatch engineers to site
   b) the engineers' approach on-site to diagnose and repair leaks, and
   c) the recording of associated incident details

3. frequency of emergency calls, focusing down from total annual calls received to
   - actual leaks as opposed to false alarms
   - leaks from service pipework and elsewhere, and
   - the sub-set of underground service pipework leaks due to corrosion

4. characteristics of underground service pipework leaks (and the proportions of incidents with different characteristics), and corrosion leaks in particular, including
   - pipework failure mechanisms
   - leak location

  - leakage rate and/or pressure drop rates observed in tightness testing
  - factors associated with corrosion leaks in particular

5. factors relevant to the escalation of a leak from underground service pipework to generate significant gas inside a building, including
   - incidence of larger scale leaks and/or voids in soil around corrosion leaks
   - incidence of detectable (or higher) concentrations of gas in buildings due to external underground service pipework corrosion leaks

6. other leaks with potential to generate gas in buildings (in particular leaks taking place from pipework or appliances internal to buildings), and concluding in each case with

7. an open "is there anything else you can think of relevant to any aspect of the risks presented by this hazard to domestic householders?" question addressed to the group.

The workshops were extremely informative and we are most grateful to all who took part for their time and openness in discussion.

4.2 Documented Gas Escape Records

Following the scoping study carried out in May 2009 prior to this work we had anticipated that the useful information available from documented records of gas escapes would be very limited. This was because, while records are kept of EVERY emergency call by each of the suppliers, those records are not classified in terms of the location, cause or characteristics of leaks that would be of interest for this study.

In our initial discussions with suppliers during this study, we met the individuals running the emergency desks in each of the supplier organisations and were allowed to see at first hand the records being produced for calls from customers. In every case, there were useful text fields in the relevant databases which in many cases permitted leak location and cause to be deduced. Each supplier had to do some considerable work to assemble and link information from various customer and incident systems in order to provide us with leak records, and we are very grateful to the relevant managerial and IT staff whose ingenuity enabled this to be done.

While all suppliers' customer incident databases contained basic information for each incident (e.g. date, time, customer name, address & unique identifier, some form of text description), there were numerous differences which related to the process by which the information was collected and recorded. One supplier had a well-established process by which engineers on site would use PDAs to record incident causes and locations using a standardised classification system. The others combined information from the engineer on site with initial records made by the emergency desk largely via telephone communication between the engineer and the emergency desk dispatcher.

Unsurprisingly, none of the supplier records had individual incidents neatly classified in terms of customer type (e.g. domestic vs other), leak location (i.e. underground service pipework vs other) and leak cause (i.e. corrosion vs other) in readiness for this project. We therefore carried out our own analysis of each suppliers' data, using primarily the free text descriptions (plus any other information where available e.g. on leak location, customer type, where gas could be smelt) to classify incidents in terms of

- customer type (domestic vs other)
- whether the leak was from a underground service pipework or not, and if so,
- whether its cause was corrosion or something else.

The classified records were then analysed to determine the range of possible values for the number of domestic underground service pipework corrosion leaks for each supplier. This was then divided by the average number of domestic customers and time period (in years) for each supplier's data, to provide an estimate of the average annual frequency of underground service pipework leaks per customer per year.

4.3 Summary of the Quantum of Experience Collected

Table 1 provides a summary of the total volume (a) of experience of the participants in the workshops and (b) of reported leak incident records provided by the suppliers.

Table 1: Suppliers' Experience Collected in this Study

(a) Collected Personal Experience of Workshop Participants

Person-Years LPG engineering experience attending customer emergency calls	350-400(1)
Total domestic underground service pipework corrosion leaks attended by workshop participants	240-500

(b) Documented gas escape records provided

Total records provided by suppliers	~ 50,000
of which domestic underground service pipework (USPW) leaks approx	500 - 1000
of which domestic USPW leaks due to corrosion approx	15 - 200

(1) Excludes experience, via staff reporting directly to them, of Engineering Managers who attended 3 of the 4 workshops

Table 2 shows the overall range of numbers of relevant corrosion leak incidents collected from the data. The minimum number of incidents is the top right figure in the table (certainly underground service pipework, corrosion-caused, and domestic), and the maximum number is the left hand figure in the table (all possible incidents that could have involved a corrosion-caused leak from domestic underground service pipework).

Table 2: Suppliers' Aggregate Documented Relevant Leaks Experience

	Count	Underground Service Pipe?	count	Corrosion?	count	Domestic?	count
ALL Potential Domestic Buried Service Pipe Leak Records	**149**	Y	98	Y	14	Y	**14**
		Y		Y		Can't tell	0
		Y		Can't tell	84	Y	30
		Y		Can't tell		Can't tell	54
		Can't tell	51	Y	8	Y	6
		Can't tell		Y		Can't tell	2
		Can't tell		Can't tell	43	Y	28
		Can't tell		Can't tell		Can't tell	15

As can be seen from the table, the provenance of this data in terms of our ability to distinguish between leak incidents is relatively weak, with about an order of magnitude difference between the lower and upper ends of the range of incident numbers.

In arriving at our overall judgment as to the expected frequency of relevant leak incidents per customer per year we have therefore combined this information with estimates derived from the personal experience of engineers at the workshops, as described in subsequent sections.

Information on the characteristics of domestic underground service pipework (USPW) leaks, and of corrosion USPW leaks in particular, has been derived largely from the information provided in the workshops. Whilst this is of course largely anecdotal, there are several important areas in which there is very good correspondence between the estimates offered by different suppliers. We are confident that the picture of corrosion leaks assembled in this report, and the estimated quantitative estimates of leak frequencies, represent an overall picture with a high degree of consistency across the range of inputs collected (with one or two exceptions which are highlighted as they arise).

3. Suppliers' Response to Reported Gas Escapes

The suppliers follow similar processes in response to a customer call reporting a gas escape:

1. Identify and locate the caller on the customer database, and log details of the incident.
2. Advise the customer what to do:
   - close the emergency control valve (ECV)
   - isolate the gas supply at the tank
   - (if there is any smell of gas in the house) open windows and
   - take precautions to avoid introducing sources of ignition anywhere near the leak.
3. Log the customer's response to this advice, and in particular clarify whether the leak has been controlled (tank isolated) or not.
4. Despatch an engineer to site and pass to them (via telephone or PDA) details of the incident as provided by the customer. (Note – there used to be significant differences in practice historically; some suppliers would not attend if it was clear that the leak was on customer appliances or systems inside the house but would instead refer the customer to a local registered firm for help. This situation has changed and the general practice now is to attend all suspected leak calls unless the telephone conversation with the emergency desk identifies with certainty that there is not a gas escape involved.)
5. On arriving at site the engineer will then trace the leak:
   - starting by talking to the customer
   - then using smell, visual inspection and sometimes hearing to trace the leak
   - if the leak persists when the ECV is closed but cannot be traced to the tank or above-ground components, a pressure drop test will then be carried out on the service pipework between the tank isolation valve and the ECV.
6. If the leak is in the underground service pipework and this can easily be accessed (e.g. if the leak results from a gardening implement or digger having cut through the pipework) the engineer may effect a repair on the spot. If excavation is likely to be required then the customer may be asked to excavate the pipework (or in some cases a quotation may be offered to do this for the customer), and an appointment made for the supplier to return, make a repair and restore the supply.

There are some differences between suppliers, for example in terms of:

a) the equipment used for leak-tightness testing (most suppliers are moving or have already moved to using digital manometers while some engineers sometimes use water manometers; some suppliers equip all engineers with gas concentration meters whilst others do not)

b) practice in dealing with leaks that prove to be internal to the house (3 suppliers will trace the leak, of whom 2 will then usually refer the customer to a local Gas Safe firm for repairs while the third will usually offer a quotation to carry out the work. One supplier advises its engineers not to enter customer properties and always to refer the customer to a local Gas Safe firm for works inside the premises)

c) the mix of staff used to attend leaks (most suppliers preferentially use in-house engineers to attend reported escapes, but use contractors if this enables a more rapid response to be made. Specialist contractors may then be used to effect repairs once the leak has been traced) and

d) what information and how is transmitted back to the supplier's HQ, and in what form. All the suppliers are careful to log details of any work required or carried out to repair leaks and of likely gas lost from the tank, as this is an important determinant of their costs, and may be the subject of discussion with customers over payment for repair works or compensation for lost gas. Recording details of the cause and characteristics of leaks is of secondary importance, so practice here can vary considerably both within and between suppliers, though location of the leak is usually recorded fairly reliably.

These differences meant that some of the engineers in our workshops were able to provide information (e.g. on rates of pressure drop for slower leaks, or on gas concentrations measurable in and around buildings, or on the nature of leaks internal to properties in comparison with external leaks) that others could not.

These differences also account for significant differences in records available from suppliers. Those whose most detailed records of incidents derive from engineers on site (e.g. via PDA[13]s) have the most accurate classification of leak location, but are less directly linked to customer databases (hence are more difficult to distinguish between domestic and commercial customers). It is also notable that incident records derived from a telephone conversation between an emergency desk operator and an engineer more often include mention of the cause of the incident than do those derived direct via an on-site engineer's PDA.

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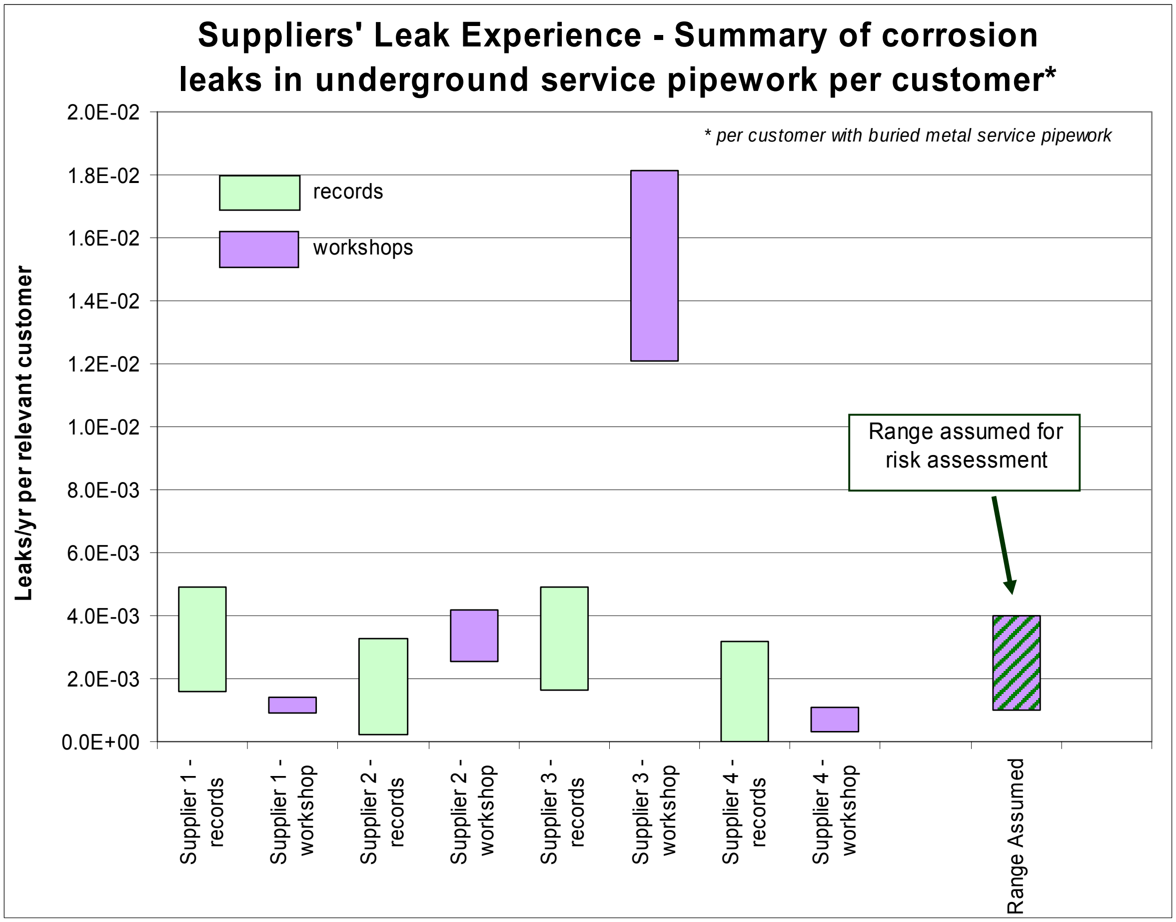
[13] Personal Digital Assistant (PDA) – a hand held data collection/storage device.

4. Frequency of USPW Corrosion Leaks

4.1 Suppliers' Collected Experience and Discussion

Figure 1 below provides an overview of the rates of occurrence of underground service pipework corrosion leaks per relevant customer (i.e. customers with some form of underground metal in their service pipework system) per year. It should be noted that the number of such customers, as well as the number of relevant leaks, is not known with precision; suppliers have estimated these numbers via surveys and records available to them, but there are significant numbers of cases in which it is difficult to determine what is in place below the ground. The bars show the range of rates per customer per year (from max leaks / min customers at the top down to min leaks / max customers at the bottom of the bar). The diagonally hatched bar on the right shows the range which we propose adopting in our risk modelling work for HSE, as explained below.

Figure 1: Summary of Suppliers' Experience of Relevant Incidents



We had anticipated considerable variability in what we would find via workshops and documented records across the different suppliers, and were not disappointed in this respect. Some significant points are worth making, first in general, and then about individual suppliers and bars on the chart:

1. The estimates from workshops are based on anecdotal recollections from a small fraction of each suppliers' relevant workforce, so may vary significantly based on the different geographic ranges covered, the numbers of leakage incidents attended, the likelihood of individuals being despatched to particular types of calls, and individuals' different judgements as to both the number of incidents and the time frame within which they were experienced. We had anticipated there might be order of magnitude variations from supplier to supplier and this was indeed the case.
2. That said, engineers at all workshops considered that corrosion leaks from underground supply pipework were generally highly memorable, as they tended to be among the most difficult to trace and also to require the greatest effort to remedy (because of the need to excavate the pipework or dig a new trench). We are confident that individual engineers' recollections of numbers of relevant incidents attended were broadly correct, though it is of course possible/likely that more recent experience will weigh more strongly in the memory than that earlier in a full working life.
3. There may be systemic and potentially predictable differences between different suppliers' customer bases and individual engineers' customer bases, arising from differences in soil type, moisture levels and other factors influencing corrosion rates.
4. Corrosion is a minority cause of leaks from underground service pipework, with cut-throughs a substantially larger cause. Other mechanisms such as penetration by sharp stones or other objects placed in contact with pipework can also be important.
5. While our ability to classify emergency calls in terms of whether they involved:
   - domestic
   - service pipework
   - underground, and/or
   - corrosion

   was variable, we met and spoke to the emergency calls desk managers in each of the suppliers, and are confident that in all four suppliers, 100% of emergency calls are being reliably recorded.
6. **Supplier 1**: In our view the consistency of the average leak rates inferred from records and from engineers' experience via the workshop is good. The records covered a limited period during which we identified 4 incidents that were clearly identifiable as corrosion-related leaks from domestic underground service pipework, and a further 10 incidents that were possibly of this set. That is, the number of relevant records for the period sampled was small and the statistical significance of the green bar for Supplier 1 is thus limited. The workshop was attended by 5 engineers, each with decades of relevant experience, whose experience of relevant incidents (domestic underground service pipework leaks due to corrosion) varied from 0.03 to 0.2 per year (i.e. quite high variability across individuals). The proportion of gas escapes attended by in-house staff as opposed to contractors is high, making extrapolation from the sample of engineers at the workshop to the whole company relatively straightforward.
7. **Supplier 2**: The workshop here involved three engineers with front-line experience of variable durations from a few years to a few decades, two of them with a significant proportion of customers on or near the coast within their geographic areas covered. Their recollections of the frequency with which relevant incidents (domestic underground service

pipework leaks due to corrosion) was quite consistent, and we are confident that their purple bar in Figure 1 represents a reasonable range of leak rates for the customer mix of the engineers at the workshop. It may, though, overstate the whole-company average in view of the observation at this workshop that corrosion leaks in underground pipework occurred preferentially near the coast.

8. **Supplier 3**: This supplier has the largest difference between leak rates derived from incident records and those derived from engineers' experience at the workshop (some 4-5x the rate derived from the records). The workshop was attended by 5 engineers with over 100 years of industry experience between them (and some 50 years with this supplier), one of whom was the engineering manager with a good overview of the past 10 years' company experience. All had considerable experience of relevant leaks. We were aware at the time of the workshop that extrapolation from these levels would produce a higher rate of leaks than that derived from other suppliers, so took pains to test with the participants the scope and accuracy of their recollections. We are confident that both the engineers' recollections and the analysis from records are reasonably accurate. We consider the most likely reason for the difference is that we had 2-3 people at the workshop with particularly high experience of such leaks, associated with local factors (customers transferring in from other suppliers, high moisture levels, corrosive soils, different histories of quality of installation – see Section 5.1) leading to large geographic variability in the rate of such incidents.
9. **Supplier 4**: The records provided by Supplier 4 were particularly useful in that they included
   a) initial comments on the nature of the leak and where gas could be smelt (derived from the telephone conversation between emergency desk and customer),
   b) classification of leaks by location, with "underground MP" and "underground LP" clearly itemised (derived from engineers' records made on-site), and
   c) in several cases where the customer had reported smelling gas in the property there were notes on what was found indoors using a Gasco meter.

   On the other hand, these records did not classify customers by type (domestic vs commercial), or make mention of the causes of underground escapes (corrosion vs other). It was possible definitively to classify about 30% of incidents in terms of domestic vs commercial, 85% in terms of underground service pipework vs other, and 60% in terms of corrosion vs other. Because very few incidents emerged as definitively classified as (domestic + underground service pipework + corrosion), the lower bound in the green bar is very low. On the other hand, the upper bar, while almost certainly excessive (in that it includes all "maybe domestic, maybe underground service pipework and maybe corrosion" incidents), provides in our view a reliable upper estimate of relevant leak rates because we are confident that the full set of "underground service pipework leaks" had been quite accurately identified and classified as such in the supplier records.

   As regards the Supplier 4 workshop, this produced the lowest estimated leak rates per customer of all the workshops. The workshop attendees had the lowest number of recent front-line engineer-years' experience of dealing with leaks present. On the other hand, the attendees included the managers responsible:
   a) for a substantial proportion of the company's engineers who attend leaks
   b) for virtually the entirety of the company's work to repair leaks in service pipework in which excavation is required, and

c) for health & safety.

Our view is that the estimated annual rate of relevant incidents (domestic underground service pipework corrosion leaks) at the workshop should be broadly reliable, and that differences between this suppliers' and others' experience probably derive largely from genuine differences in the mix of customers and service pipework materials, installation, soil type, moisture etc.

4.2 Further Exploration

The likelihood of an underground service pipework leak at a specific property will depend on many local and property-specific factors, such as the age and material of the pipe, and the corrosivity of and moisture level in the surrounding soil. Since completing our earlier study we have obtained further information on

a) rainfall for different UK postcode districts (data purchased from the Met Office), and

b) pipe material & estimated soil corrosivity for sample LPG users' properties (via HSE, based on calculations made by Germanischer Lloyd (GL)).

We were not able to obtain reliable information on

c) property-specific LPG service pipe parameters such as age, location, moisture around riser, specific soil type around riser, depth of pipe, ground covering around riser and length of underground service pipe.

We re-analysed our database of corrosion leaks and possible corrosion leaks and explored possible correlations between the frequency of initiation of leaks in relevant service pipe work, and the local rainfall, soil corrosivity and other factors. We found no such correlations. We did, though, find a strong correlation between rainfall and the frequency of above-ground service pipework leaks due to corrosion, suggesting that if there were a strong correlation to be found (i.e. one strong enough to emerge despite all the confounding factors in (c) above) we might reasonably have hoped to find it.

4.3 Conclusions

Having taken all the above factors into account we recommend that a sensible range for the average frequency of the initiating event "Corrosion leak from underground service pipework" for domestic bulk LPG users in Great Britain would be:

Between 1 and 4 per 1000 relevant customers per year.

Relevant customers are those with some element of metallic underground pipework. It would be sensible to explore a range of uncertainty of about a factor of 3 in either direction around this range.

There may be large differences between individual premises, based on age and quality of installation of pipework, soil type, soil moisture, temperature etc, but these cannot be predicted based on available data.

5. Characteristics of USPW Corrosion Leaks

The information in this section is derived largely from the workshops held with supplier engineers, except where indicated otherwise. As mentioned in Section 4, it is fortunate for this project that corrosion leaks in underground pipework tend to be quite memorable for engineers, as a) they are among the most difficult to trace, and b) they tend to require particular arrangements to be made to excavate a new trench (or the old pipework).

5.1 Factors associated with corrosion leaks

An important factor identified unprompted in the workshops was soil moisture. Typical answers to the question "What sort of places do you tend to find corrosion?" were broadly along the lines "Where it's wet." Observations included associations of underground corrosion leaks with:

a) Visible moisture or water in the soil around the corroded area of pipework/risers

b) Presence of downpipes, drains, gutters or other local sources of particular soil wetness

c) Coastal locations (one supplier).

In view of the importance attached by all of the workshops to moisture we have procured a dataset from the Met Office providing long-term rainfall data for the UK in 5km grid squares, and the postal datasets enabling us to link post codes to that data set. Some of the suppliers provided us with postcodes attached to leak incidents and we are using this data to explore the possibility of a significant correlation between rainfall and frequency of corrosion leaks. We would expect, though, that local factors either exacerbating moisture close to houses (gutters, downpipes, drains, shade, ground topography etc) or mitigating it (e.g. trees, topography) would be capable of making a bigger difference than average rainfall in the area. This work will be reported in our main report for HSE.

A second general factor identified was the quality of installation of the pipework. Properly wrapped, galvanised steel pipework should be reasonably well protected. A large proportion of corrosion leaks occur when either:

- the wrapping has not been properly applied, or
- in parts of the system not reached by the wrapping, of which the ground/air interface was identified as an important area

5.2 Location of corrosion leaks

The general experience was that a large majority of corrosion leaks occurred at the property, rather than the tank end of underground service pipework. This was attributed in two workshops to the generally wetter soil conditions next to walls, under gutters etc. Some individual engineers had experienced similar numbers of leaks at the tank and property ends of service pipework, but the numbers of incidents experienced in each such case was small. The general view was that 90-95% or more of leaks would occur at the property end.

As regards whereabouts on the system these "property end" leaks occur, there were two important main locations:

a) at the surface of the ground, particularly where moisture can collect around the pipework; this is particularly an issue where the riser is surrounded by concrete, which is both corrosive in its own right and can tend to trap moisture next to the pipework, and

b) at the bottom of the riser and/or the transition joint and/or the bend (if metal) between riser and the horizontal underground pipework run.

The former of these is less hazardous as a high proportion of leaks will be able to dissipate into the air rather than being forced underground. Two workshops independently estimated that corrosion leaks in underground service pipework occur roughly 1/3 at the top of the underground section where the riser passes through the ground, particularly when concreted around, and 2/3 at or around the base of the riser.

We have assumed in our risk model that service pipework where the riser is surrounded by concrete is equally likely to experience leaks underground as are other pipes. We have assumed that the leaks identified in Section 4 all correspond to "occurring underground at or around the base of the riser next to the property", and that none correspond to the (less hazardous) "leak from pipework at the ground/air interface" or "leaks from service pipework at distance from the property" categories.

5.3 Corrosion characteristics

When pipework that has experienced a detectable corrosion leak is excavated, it is not uncommon to find it in poor condition, but having been held together by the soil around it. Some pipework sections will look reasonable until rubbed or wire brushed when corrosion products may flake off and the pipework fall apart. Others may disintegrate when removed from the ground. Some examples had been found where pipework had corroded to the point where no metal remained at all, yet gas had continued to flow almost normally, with the corrosion products (and gas) retained by surrounding (generally clay rich) soil.

The general mechanism by which corrosion develops to produce a leak is via surface corrosion and pitting. None of the workshop participants had ever come across an example of an underground service pipework being weakened by corrosion and then suffering a full circumferential fracture (as happens sometimes to iron natural gas mains and service pipes).

The two important conclusions drawn from discussions of corrosion characteristics were:

a) corrosion leaks from underground LPG service pipework are likely to develop over a long period of time; sudden or "catastrophic" failure (if it can occur at all) is extremely rare, and

b) underground pipework can retain its functionality to carry gas even when very seriously corroded, so long as the soil around it holds the corrosion products in place.

5.4 Size of corrosion leaks

All workshop participants agreed that an important general feature of corrosion leaks is that they involve low rates of gas escape.

The participants in two of the workshops did not feel able to be more specific about how slow; their aim when carrying out pressure tightness testing was to distinguish between “no drop” and “any drop” rather than to note how rapidly the pressure drop occurred. In these two workshops, though, participants agreed that rapid pressure drops from corrosion leaks were rare, and that situations involving a significant void building up around an underground corrosion leak, followed by escalation of the escape up to a rapid rate (such as that encountered in the explosion at a domestic property in Scotland in 2006) were very rare. In the hundreds of years of experience of the engineers at these two workshops, three instances had been encountered of rapid pressure drops in underground service pipework leaks due to corrosion. All had involved medium pressure pipework and none involved a simple supply to an individual domestic property (1 pub, 1 school, 1 bulk supply to a pub plus 5 houses). None had been traced to the primary location of leaks for domestic premises (at the base of the riser next to the property).

The other two workshops were attended by engineers who routinely used digital manometers for pressure drop testing and who had a better idea of the range of leak rates involved with corrosion leaks from service pipework. Digital manometers would generally be set to a sensitive setting (0.01 or 0.1 mbar scale) during tightness testing, so that even a very small leak would be revealed fairly quickly and produce a noticeable rate of pressure drop. Typical pressure drop rates were described as noted in the table below

Service Pressure	**Workshop A**	**Workshop B**
Medium pressure	Typical pressure drop of order 1 mbar/second (give or take a factor of maybe 3 or 5)	Typical drop of 10 mbar over test period. Get larger drops occasionally; >100mbar would be exceptional. Lower drops e.g. 1 mbar would not be unusual.
Low pressure	Substantially lower, more like 1 mbar per minute (better to work from MP estimate and scale down pro rata to pressure)	Scale down/ pro-rata to pressure. Many low-pressure corrosion leaks are very slow, giving around or less than 0.25 mbar drop over the test period.

Our conclusions are that most corrosion leaks are slow, which is consistent with the engineer’s observations that soil remains packed around pipework in the vast majority of cases. In our main report for HSE we compare these leak rates with the gas escape rates that can be migrated away from the leak site by diffusion and show that there is a rough correspondence between the maximum rate at which gas could be diffused away from a leak site (i.e. without significant overpressure being required to force the creation of new pathways and channels through the soil) and the maximum observed pressure drop rates from corrosion leaks.

In our risk model for these gas escapes we consider the possibility that the gas escape rate following a corrosion leak from underground service pipework (USPW) could fall into any of the following bands:

- <10^{-4} m^3/hr at NTP (≡ about 0.2 mbar/minute for an average domestic service pipework[14])
- 10^{-4} to 10^{-3} m^3/hour (up to about 2 mbar/minute)
- 10^{-3} to 10^{-2} m^3/hour (up to about 20 mbar/minute)
- 10^{-2} to 0.1 m^3/hour (up to about 200 mbar/minute)
- 0.1 to 1 m^3/hour (up to about 30 mbar/second)
- 1 to 10 m^3/hour (effectively rapid full pressure drop/unlikely to be able to pressurise system)
- > 10 m^3/hour (full drop).

The probabilities of a corrosion leak from USPW falling into each band are estimated in our risk model by assuming that the probability of the leak rate exceeding a given size follows a log-normal distribution as a function of leak rate, with the parameters of that distribution estimated from the information above, in particular:

a) that a large majority of MP corrosion leaks from average length pipework systems would fall in the range 1 to 100 mbar pressure drop in the period of observation under test, with 5% > 100mbar and 5% < 1 mbar, and
b) a fraction of 1 per cent of MP leaks might exceed 1 m^3/hr based on the observations across all workshops of no very rapid pressure drop corrosion leaks in 2-500 corrosion leaks from USPW experience sampled in the workshops (see Table 1).

5.5 Gas in building experience

An important finding from every workshop was that with one notable exception, no individual participant had ever, or was aware of a colleague who had ever, been able to detect LPG by smell indoors that had migrated into the house via a leak outside into the soil. The one notable exception was the incident at a domestic property in Scotland in 2006, in which an explosion occurred under the floor of a house where a large corrosion leak from the service pipework outside had gone undetected for many months, despite several reports from the householder of a smell of gas in the house, and several attempts by the supplier to trace the leak. There are other situations in which gas has been smelt indoors and attributed by customers to an external underground leak, but these are generally the result either of gas in the air outside (from the leak or from appliance fumes) entering the house through an open window or door.

As mentioned in Section 4, one of the suppliers did include in the incident records supplied to us a field noting (from the initial gas emergency call from the customer) whether gas could be smelt inside the property. In a significant percentage of these cases, the engineer's notes provided to us

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[14] The research carried out into underground service pipework and presented by Calor to the ICL Inquiry measured the lengths of service pipework in 500 domestic systems, and found an average length of 18m. This statistic has been applied industry-wide here. The majority of the pipe run is assumed to be 25mm inside diameter polyethylene pipe, with metal transition joints and/or risers at tank and property ends of the system.

then described what had been found when using a gasco meter inside the property to explore for traces of gas. Of the incidents (domestic and commercial) mentioning "gas detectable by smell in building" from the initial call, 35% were confirmed by engineers to have involved detection of gas inside the property, of which the worst case was one in which gas had been detected at 2% of the lower explosive limit (LEL) – i.e. gas concentration 2% of the LEL (itself 2%), or 0.04%.

We were keen to learn all we could from this experience and discussed it at some length with the supplier during our workshop with them. The supplier emphasised that these measurements involved taking a gasco meter on a "wand" and exploring areas around skirtings, inside kitchen cupboards etc for traces of gas. The meters would typically be set at PPM levels, and a record by an engineer of "detectable gas" means that "some trace was discovered, somewhere, that would register on the meter" and NOT that "average concentration in the room was at PPM levels".

The detectable concentration of the stenching agent (ethyl mercaptan) in LPG is of order 1 in 2-3 parts per billion for most people, and it is added to LPG typically at levels of 20-50 parts per million. Assuming 0.3 to 1 ppb of ethyl mercaptan would be readily detectable by smell, this means that LPG should be readily detectable at levels of around 1 part in 20-100,000, or 0.001% to 0.005%. The finding from the workshops is that traces of LPG at PPM levels are detectable in a modest percentage of houses as a result of underground service pipework leaks outside. This is consistent with the observed extreme rarity of being able to smell LPG that has migrated into houses via soil in such cases.

It is unsurprising that traces of LPG should be detectable leaking into buildings from the soil. Workshop participants noted the propensity of LPG to "track" along pipework, and one workshop noted an example of an underground leak being detected on the other side of the road from where it had happened for this reason. If a leak takes place at the bottom of a riser, typically at a depth of 60cm and very close to the foundations of a house, it is easy to envisage circumstances in which either LPG vapour could build up in soil around the foundations, or (if the house has a suspended floor) there may well be a shorter and easier pathway to "track" through to the void under the floor than to the surface of the outside soil. Our companion Part 2 report to this study demonstrates the feasibility of substantial concentrations of LPG developing in soil or voids immediately below the floors of buildings.

The mechanics of LPG transport from soil to buildings are examined in greater depth in our main report for HSE and in our Part 2 companion report. A key issue which is difficult to quantify with any reliability is the proportion of leaks close to houses in which the gas would track up the riser and find a low-resistance pathway to the outside air. We infer from the suppliers' experience collected here that such situations probably make up a large proportion of relevant leaks, but have used cautious assumptions in our risk model in the absence of any reliable general or property-specific direct evidence.

Our conclusion from the workshops, plus the leak records from Supplier 4, is that

- traces of LPG entering buildings may be detectable at PPM levels seeping in through cracks, floors etc in a modest percentage of domestic properties, but

- none of the 200-500 corrosion-related USPW leaks within the experience of our workshop participants had led to detectable (of order 0.005% or more) levels of LPG inside the occupied rooms of the house.

These findings have been used to help calibrate a model of gas entry into buildings which is described in our main report for HSE.

5.6 Special risk factors

A key point identified in each supplier workshop was that there is a small sub-set of customers who would be expected to be exceptions to the general rule (from 5.5 above) that an underground service pipework leak into soil would only very rarely lead to detectable gas in a building. These are situations where the gas service pipework runs directly into a property below ground (e.g. into a cellar or basement), or where the property has been extended to cover part of the service pipework. Examples cited in the workshops included:

- extensions, garages and porches built out over the riser and service pipework
- decking being built over riser and pipework, providing a "trap" for any LPG leak
- older properties with pipework entering the cellar or basement (all suppliers insist that these are brought up to modern standards with above-ground entry to building whenever an instance is discovered)
- caravans or residential park homes where the occupants have built up structures around the lower frame to suppress drafts.

It is interesting to note that of the cases described in Section 5.5 where gas in buildings was measured following a customer report that gas had been smelt in a building where the leak was underground, about half involved leaks effectively into the building or into an extension built over the supply, and a fifth involved leakage into a cellar. Only just over a fifth involved traces of gas being detectable in "normal" gas supply situations.

In all such cases we have assumed in our risk modeling that 100% of any gas leak would find its way into the cellar and/or occupied space of a building. Such cases represent a particularly high risk from this hazard; estimates of the proportion of properties with such characteristics ranged from about 1% at the most optimistic workshop, to somewhere in the region of 2-5% at the most pessimistic.

6. Other Leaks Internal to Buildings

LPG suppliers' engineers' familiarity with leaks internal to buildings is in most cases less than that with external leaks, as the supplier is not responsible for internal pipework and appliances.

However, all suppliers keep records of every emergency call from which it is usually possible to distinguish internal and external leaks, and most engineers have some considerable experience of tracing faults internal to buildings if not in repairing them.

From the records provided to us by suppliers and our discussions with them at the workshop some simple comparisons can be drawn that enable the risk from USPW leaks due to corrosion to be put in context relative to the risk of leaks internal to domestic properties:

1. The frequency of internal leaks reported to suppliers is of order 10-100x higher than the frequency of USPW leaks due to corrosion into the soil outside.

2. The greatest risk from internal leaks arises from user errors (e.g. leaving appliances turned on but unlit), which are generally unreported unless they have some unpleasant consequence; the actual frequency of hazardous internal gas escapes may be significantly greater than that implied in (1).

3. The typical causes of internal leaks (cookers unlit or leaking, pilot lights going out, re-entry of flue gases, service valves/elbows on gas fires, nails through pipework etc) typically lead to substantially larger rates of pressure drop and gas release than do typical corrosion USPW leaks into soil.

4. The proportion of such internal leaks entering the occupied space of buildings is generally 100%, whereas for corrosion USPW leaks into soil the proportion is typically tiny or non-existent.

Without carrying out any sophisticated calculations, it appears to us that the risk to householders from USPW corrosion leaks must be 3-4 orders of magnitude (or more) lower than that from internal leaks because:

a) the frequency of initiating events is 1-2 orders of magnitude lower

b) the average scale of leaks and gas escape rates is substantially lower, and

c) the proportion of escaped gas entering the occupied space of the building is likely to be orders of magnitude lower than that for internal leaks.

This provides another useful reference point against which to calibrate our risk assessment model for USPW corrosion leaks

7. Conclusions

Our conclusions are:

1. The average frequency of domestic leaks from underground service pipework due to corrosion is between 1 and 4 per thousand customers with metal service pipework per year.

2. Such corrosion leaks typically occur at or near the base of the riser adjacent to the property, though a significant percentage may occur at or near the ground surface, particularly where the riser is set in concrete.

3. There is a strong association of corrosion leaks from underground service pipework with
   a) the moisture levels local to the riser into the property, and
   b) the quality of corrosion protection (galvanisation and wrapping) when the pipework was installed.

4. Typical leak rates due to corrosion are small in comparison with many other gas escape mechanisms and can remain small even when corrosion is far advanced so long as the surrounding soil holds the pipework/corrosion products together.

5. Corrosion leaks from underground service pipework develop progressively over a period of time; there are no known instances of leaks developing suddenly to a large size.

6. Most corrosion leaks from underground service pipework involve low rates of gas escape and pressure drop during tightness testing. Typical pressure drop rates are of the order of mbar or 10's of mbar per minute from MP pipework, and correspondingly lower from LP pipework.

7. Rapid gas escapes ("full drop" type leaks) from underground service pipework due to corrosion are very rare, occurring in less than 1% of cases.

8. A modest percentage of underground service pipework leaks due to corrosion lead to traces of LPG inside the property at ppm (part per million) levels around floors and skirtings close to the leak location.

9. With the exception of the explosion at a domestic property in Scotland in 2006, no participant in any of our workshops was aware of they, or any of their colleagues, ever having been able to detect LPG by smell inside a house as a result of gas from an underground service pipework leak migrating into the property via the soil.

Matthew Hunt
Kajal Somaiya
Tony Taig

TTAC Ltd
5 March 2010

TTAC Limited

For More Effective
Management of Risk
and Uncertainty

Risk Assessment of Corrosion Leakage of LPG from Domestic Underground Service Pipework:

Part 2: Migration of LPG from soil into domestic buildings

a report produced for the Health & Safety Executive

by Matthew Hunt, Kajal Somaiya and Tony Taig

TTAC Limited
March 2010

This report has been produced by TTAC Limited under contract to the Health & Safety Executive as a companion document to the final report on the whole of the Risk Assessment project

Executive Summary

This report provides an overview of the phenomena involved in the transport of LPG leaking from underground service pipework into domestic buildings, and of the approach adopted to assessing the likelihood that LPG will accumulate at levels at or above the Lower Explosive Limit (LEL) in such buildings. It has been prepared by TTAC Ltd as part of a larger project funded by the Health & Safety Executive (HSE) to develop methods and supporting evidence and data to assess risks to domestic LPG users from corrosion leaks from underground LPG service pipework, and should be read in conjunction with the Main Report of this study[15].

The report covers:

- The approach adopted and building types considered (Section 2)
- Evidence available from gas escape incidents (Section 3)
- Migration of LPG through soil (Section 4)
- Characteristics of UK buildings (Section 5)
- Modelling LPG concentrations below building floors (Section 6)
- Modelling LPG migration through floors and dilution in buildings (Section 7), and
- A summary of the models, sample results and discussion of their consistency with available evidence (Section 8).

Our conclusions are:

1. The factors determining migration of LPG through soil and its entry into and dilution in buildings are complex, and defy accurate calculation of the resulting concentration of LPG in the building for any specific domestic building.
2. In the event of a significant corrosion leak of LPG from underground service pipework it is entirely plausible for high concentrations of LPG to develop below the floors of buildings, either in the soil below slab floors or in the void below suspended floors.
3. If pure LPG were present below the floor of a building, it would have to be diluted no more than 50x in order for the LEL to be reached inside the building (LEL = 2%). Typical long-term average dilutions of ground gases on entry to buildings are in the range 100-10,000x or more.
4. Time-average dilution factors do not provide a safe way of estimating the risk of LPG accumulation in buildings, as migration from soil and dilution in buildings vary considerably with factors such as weather and householder activities. It is entirely plausible that high concentrations of LPG could be present for long periods of time below a floor without leading to detectable LPG in the building, but that a change in conditions could then lead to significant concentrations of LPG being developed in the building.

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[15] "Risk Assessment of Corrosion Leakage of LPG from Domestic Underground Service Pipework: MAIN REPORT, Issue 01", TTAC Ltd, January 2010

5. Insights from actual observations on LPG leaks, and relevant elements of the various models developed by the Environment Agency and its US and Dutch counterparts to predict migration of contaminant soil gases into buildings, have been used along with our own judgment and interpretation to develop simple probabilistic models of the likelihood of encountering:
   a) different LPG concentrations below a building floor, and
   b) concentrations in excess of the LEL in the occupied space of buildings,
   as a function of leak rate size, for properties of different ages and dimensions.
6. Application of these models to individual properties will involve considerable uncertainty, but we are confident that the model predictions are consistent with actual observations of LPG and other gas behaviour, and that they provide on average a pessimistic basis for assessing the risk to householders from this hazard.
7. The general order of hazard (in terms of likelihood of exceeding the LEL for a given leak rate into soil) predicted by the models for a given leak rate into soil is:

Highest:	Void under suspended wooden or concrete floor
Next highest:	High hazard house (riser incorporated into building)
Lower:	Occupied space in timber suspended floor house
Lower still:	Occupied space in concrete (slab or suspended) floor house.

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5 March 2010

Contents

1. Introduction

This report provides an overview of the phenomena involved in the transport of LPG leaking from underground service pipework into domestic buildings, and of the approach adopted to assessing the likelihood that LPG will accumulate at levels at or above the Lower Explosive Limit (LEL) in such buildings. It has been prepared by TTAC Ltd as part of a larger project funded by the Health & Safety Executive (HSE) to develop methods and supporting evidence and data to assess risks to domestic LPG users from corrosion leaks from underground LPG service pipework, and should be read in conjunction with the Main Report of this study[16].

We have been assisted in this task by our partners from BRE and T8 Design (building and construction technologists), and have also received considerable assistance from the staffs of the Environment Agency (EA), the Construction Industry Research and Information Association (CIRIA), the Health Protection Agency (HPA), the British Geological Society and the Scottish Housing Condition Survey. We are extremely grateful to all of them for their help in navigating through the large literature available on the migration of hazardous substances through soil and into buildings. The opinions expressed and conclusions drawn in this report are our own and do not represent the endorsed view of HSE, or of any of the above organisations, or of any other party.

The report describes

- The approach adopted and building types considered (Section 2)
- Evidence available from gas escape incidents (Section 3)
- Migration of LPG through soil (Section 4)
- Characteristics of UK buildings (Section 5)
- Modelling LPG concentrations below building floors (Section 6)
- Modelling LPG migration through floors and dilution in buildings (Section 7)

before providing

- A summary of the models, sample results and discussion of their consistency with available evidence (Section 8), and
- Our conclusions (Section 9).

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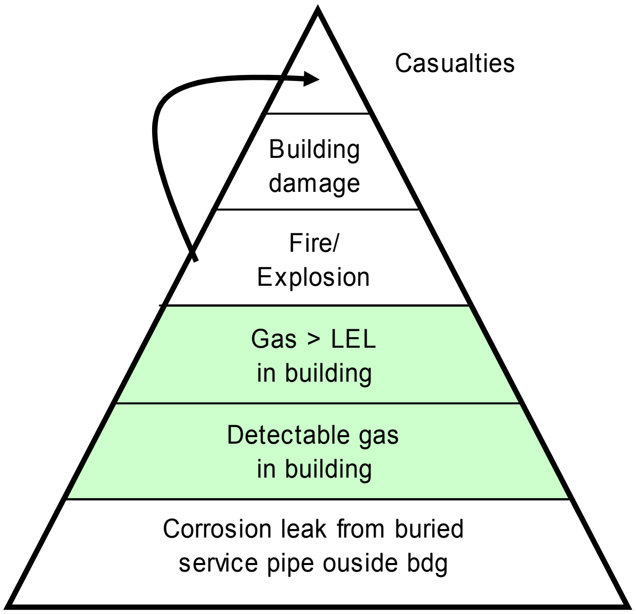
[16] "Risk Assessment of Corrosion Leakage of LPG from Domestic Underground Service Pipework: MAIN REPORT, DRAFT 2009-09-30", TTAC Ltd, September 2009

2. Approach

2.1 Scope

Our overall approach to assessing the risk associated with corrosion leaks from domestic underground LPG service pipework is illustrated in Figure 1 below, in terms of a "hazard triangle" up which an incident must escalate in order to harm the occupant of a building.

Figure 1: Hazard Triangle for Domestic LPG Leaks into Soil



This report is concerned with the pale shaded portion of the escalation process. That is, given a defined leak into the ground outside a dwelling, what phenomena are involved in gas migrating into the building and diluting or accumulating in it? In particular, how likely is it that a given leak will lead to concentrations of LPG in the building at or in excess of the LEL?

2.2 Process

Our approach to tackling this question is as follows:

a) First, we consider what we know about the nature of LPG leaks due to corrosion in underground service pipework and about their escalation into gas in buildings. This both informs the starting assumptions for this report, and provides observations on the incidence of events involving some form of detectable migration of gas into buildings against which to test our model predictions (section 3).

b) Second, we describe the general phenomena and issues involved in migration of gases from soil into buildings, and in determining the dilution of gases between soil and building air (section 4).

c) Third, we describe the range of commonly encountered building design and construction types in the UK, with a particular focus on the factors of most relevance for gas migration into and dilution in buildings, and on floor construction in particular (Section 5).

d) Fourth, we consider migration of LPG through soil and the implications for its concentration at or around the foundations of UK domestic buildings (Section 6), and

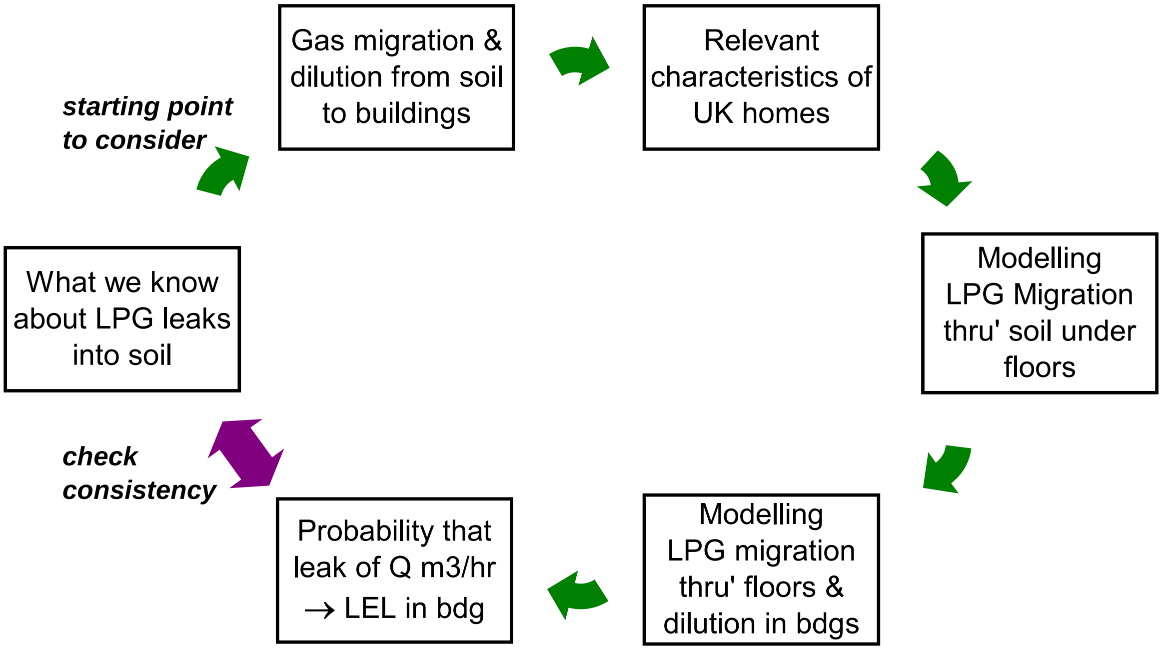
e) Fifth, we address the migration of gases through floors and dilution in UK domestic buildings (Section 7), and describe our proposed approach to deriving the probability of the key output from this report:

   The probability that a given leak rate from a service pipe into soil at the base of the riser will lead to a concentration of LPG at or above the LEL in the relevant part of the building.

f) Finally, we present our conclusions in terms of the model predictions of this probability for different leak rates into soil and building types (Section 8).

The whole process adopted in this report is illustrated in Figure 2 below.

Figure 2: Understanding the Likelihood of [LPG in soil] ➔ [LPG ≥ LEL in building]



2.3 General Principles

The general principle we have followed throughout this work is to use available, validated models of gas behaviour in the ground and entering buildings so far as they are relevant. In general, models established to estimate long-term time average concentrations of soil gases in buildings predict dilution too great for LPG ever to attain the LEL in buildings. We have replaced relatively complex deterministic models of dilution in buildings by relatively simple probabilistic models, designed to yield outputs consistent with the available evidence. These simple probabilistic models allow for the possibility both:

a) that short-term concentrations of LPG in a building may be considerably in excess of the long-term averages, and

b) that the large variability in gas migration into and dilution in buildings may mean that a small proportion of buildings could exhibit dilution considerably less (and thus LPG concentrations considerably higher) than the average.

It is important to note that these models generally consider only a limited sub-set of the features of a property that will determine the actual concentration of LPG inside it for a given leak into soil outside. With substantial effort it might be possible, based on detailed surveys of a specific site and property, to arrive at a more property-specific estimate of such dilution, but any such estimate would always be highly uncertain.

We have sought to err on the side of caution throughout our modelling. For example, when estimating the parameters of a probability distribution to represent the likelihood of experiencing different ventilation rates, or of different dilution factors across a floor boundary, we have tended to use broad distributions (large standard deviations) so as to overstate rather than understate the likelihood of experiencing the more extreme and potentially hazardous circumstances involved.

Finally, when the information from this report is combined with the rest of our work into the overall risk model (see main report) we have propagated upper, central and lower estimates of frequencies and probabilities throughout the model. Our aim in doing this is to ensure that the possibility of combinations of circumstances such as to maximise the probability of LPG developing concentrations at or above the LEL in buildings is captured and recognised. The results are presented as a broad band of values rather than as a point value.

3. Gas Escapes from Underground Service Pipework

We consider here both:

- the characteristics of LPG due to corrosion of service pipework that should provide the starting point for our assessment of the probability of developing concentrations at or above the LEL in buildings (3.1), and
- what we have been able to learn about the likelihood of LPG escapes into soil escalating to give high concentrations of LPG in buildings, both
  a) via LPG suppliers' experience of relevant gas escapes (3.2), and
  b) via HSE's collected records of gas escape incidents and investigation reports (3.3).

3.1 Key Characteristics of Relevant Gas Escapes

Our starting point for this assessment was to consider the characteristics of LPG leaks due to corrosion of service pipework, as developed from our work with LPG suppliers and described in our companion report[17]. The key conclusions relevant to migration of LPG into buildings were

1. There are between 1 and 4 leaks due to corrosion from underground service pipework per 1000 relevant customers per year. There are estimated to be 25-30,000 customers with underground service pipework containing metallic components, so that this multiplies up to an estimated 25 to 120 corrosion leaks per year from underground LPG service pipework.
2. Most corrosion leaks in underground service pipework occur close to the property using the gas, rather than near the tank or along the bulk of its length.
3. Of those corrosion leaks, about 2/3 occur at the base of the riser, at or around the bend or transition from vertical riser to horizontal pipe run. The other 1/3 occur mostly around the point where the riser emerges from the ground.
4. When excavated, it appears that even very seriously corroded pipework is often held in place by the soil packed around it. It is very unusual to find a corrosion leak taking place into a void or gap in the soil.
5. The development of such leaks is generally progressive. That is, they involve gradual development of corrosion and pitting, leading initially to a small penetration of the pipe which may then grow with time – there is no known experience of sudden large scale pipe failures. It is possible, though, in light of (4) above that a seriously corroded pipe might suddenly disintegrate under mechanical forces exerted on it or the surrounding soil, leading to a sudden change in the ability of gas to escape from perforations in the pipe.
6. Householders are unlikely to detect leaks in the early stages, because
   a) the surrounding soil may effectively contain gas and reduce the escape rate, and

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[17] Risk Assessment of Corrosion Leakage of LPG from Domestic Underground Service Pipework: Part 1: Suppliers' Gas Escape Experience, TTAC Report U107/part 1, Issue 01, January 2010

b) concentrations of gas in the outside air above and around the leak may be too small to be detectable.

The key assumption from all of the above that is taken forward throughout this report as a starting point for estimation of the probability that a given leak will lead to gas in the building at or above the LEL is that ***corrosion leaks from underground service pipework will take place at the base of the riser, at or around its transition to a horizontal pipe. We assume that this will be at a depth of 600mm in the soil.***

3.2 From LPG in Soil to LPG in Buildings – Suppliers' Experience

Some important insights into the likelihood of corrosion leaks of LPG into soil leading to significant gas in buildings emerged from our workshops with LPG suppliers:

a) Of the several hundred corrosion leakage incidents from underground service pipework attended personally by the participants in our workshops with suppliers, none had ever involved detectable (by smell) levels of LPG in the occupied parts of a domestic property resulting from migration through soil.

b) Some examples had been encountered within that body of experience of i) detectable LPG odour in a house arising from leaks into outside air getting into houses via doors/windows, and ii) traces of LPG being detectable around skirtings or cupboards using a Gasco meter on a "wand".

c) A single example was known of by the workshop participants in which an explosion had resulted in a building following a corrosion leak from outside underground service pipework (see 3.3 below).

Asked to identify special cases of potentially high risk of a leak into soil leading to gas in buildings, the workshop attendees consistently identified scenarios in which, for a variety of reasons, the riser had effectively been incorporated into the occupied space of the building. Example scenarios included:

- caravans or park homes with poorly ventilated "skirts" built around the base
- patios or decking erected over the riser, placing it in an enclosed space
- houses being extended over the riser, or
- old LPG systems where the riser entered the house below ground (all suppliers insist on these being updated to the modern standard of above-ground gas entry to the house whenever such cases are found).

Estimates of the proportion of LPG users falling into one or more of these categories varied from about 1% up to a few %.

The records of LPG leaks provided by suppliers generally contained little information about what (if anything) was found inside the property. One supplier's records did, though, in some cases include the attending engineer's notes on what was found on investigating householders' reports of suspected gas odours inside the property. Several records (out of a few hundred) mentioned traces of gas having been found using a Gasco meter as per 3.2 b) above. On examining these records in more detail, it transpired that the majority of such cases involved exactly the kinds of high-risk scenarios identified by the workshop participants.

The one known example of an explosion in a building due to LPG entry from an underground corrosion leak of a service pipe (the incident in Scotland in 2006 – see also 3.3 below) had involved an explosion in the void below the floor, apparently initiated by some ignition source above the floor. It was not clear how the gas had tracked into the space below the house; what was clear was that the leak had progressed to being a very large one, and that there had been several previous attempts made to diagnose the source of a suspected leak following reports from the householders of a smell of gas.

3.3 From Gas in Soil to Gas in Buildings – HSE Experience

We have reviewed data on gas leak incidents obtained from HSE with the aim of

- Identifying incidents involving leaks into the ground outside buildings.
- Characterising the scale of such leaks in terms of gas escape rate, and
- Characterising whether and to what extent gas migrated into buildings (based on detectable gas in buildings or "GIB")

This approach may provide us with some insight into the approximate overall incidence of GIB incidents due to corrosion leaks from service pipes (for natural gas as well as LPG). But any information it provides on the proportion of such leaks that lead to GIB is likely to be highly conservative (i.e. greatly overstate the proportion of such leaks that lead to GIB). This is because the recording and reporting of GIB incidents is much more likely than that of more minor service pipe leaks that do not lead to GIB.

Three sources of information were analysed:

a) a database of incidents for which HSE's Hazardous Installations Directorate received operators' reports under the GSM(R) Regulations. Reportable incidents are those involving >20% LEL of gas in a building, or >500 kg escape outside
b) the RIDDOR database, from which gas incidents were extracted based on all injury incidents and dangerous occurrences recorded on the relevant gas incident forms (F2508G1 and G2), and on a wider trawl of dangerous occurrences otherwise recorded, and
c) HSE's investigation reports into the one known incident involving the explosion of LPG within a domestic property resulting from a corrosion leak into the ground outside (in Scotland in 2006).

The GSM(R) incidents provide a dataset of more serious leaks. It includes 77 identifiable records of corrosion leaks from service pipes in just over 4 years, of which 68 are recorded as involving GIB > 20% LEL. This dataset is of some use in providing a rough estimate of the total annual incidence of such leaks leading to GIB (approx 16 GIB incidents from this cause annually, all involving natural gas rather than LPG). But it is of no use in estimating the proportion of such leaks that progress to giving significant GIB, because the vast majority of such leaks do not do so, and if they are detected at all, are not reportable under GSM(R).

For the RIDDOR analysis, 858 incidents were selected from the RIDDOR gas escapes dataset of 15,575 incidents supplied to us by HSE covering the 4-year period from 1/4/2005 to 31/3/2009, based on searches of the free text incident description for terms indicative of possible leaks into soil outside buildings. These were then classified in terms of:

- The location/cause of the leak (External, Internal, Due to works near pipe, Unclear, No leak), and (for External and Unclear only)
- Whether the leak had involved detectable gas in the building (Yes, No, Unclear), and
- Whether GIB had reached or exceeded the LEL (Yes, No, Unclear).

The results are shown in Table 1 below.

Table 1: Analysis of RIDDOR Suspected External Gas Leaks

External?	Count	GIB?	Count	> LEL?	Count
Yes	174	Yes	39	Yes	14
Yes		Yes		Unclear	25
Yes		Unclear	21	Yes	0
Yes		Unclear		Unclear	21
Yes		No	114		
Unclear	26	Yes	18	Yes	8
Unclear		Yes		Unclear	10
Unclear		Unclear	6	Yes	0
Unclear		Unclear		Unclear	6
Unclear		No	2		
N	658				

For incidents that were clearly external leaks, the proportion involving gas above the LEL in the building was between 8% and 35% (a clear “Yes” vs “Yes + Unclear” for >LEL column). For incidents that were possibly external leaks the proportion involving gas above the LEL was between 11% and 42%.

The incidents shown in Table 1 comprise largely natural gas incidents. Of the total of 858, just 8 involved LPG, of which 3 were external and none involved any suggestion of gas being detectable in a building. Interestingly there are approximately 100x as many homes with natural gas as there are using bulk LPG as a fuel, so the ratio of 8 LPG to 850 natural gas incidents is close to what would be expected if the overall rates of external leaks per customer were similar for the two fuels.

It should also be noted that the incidents in Table 1 include all external leak causes, not just corrosion of underground service pipework. A small proportion of incidents could be identified as corrosion-related (all involving natural gas). Of 15 such incidents, 5 clearly involved GIB at or above the LEL (about 33%).

We regard these percentages of incidents leading to GIB at or above the LEL as extremely conservative and unsuitable for application in this risk assessment, as

a) the reporting and recording of minor leaks from service pipes is clearly much less likely than that of more substantial leaks that lead to GIB, and

b) for natural gas service pipes, which were mostly cast iron, the dominant corrosion failure mechanism is a circumferential break of a cast iron pipe leading to a sudden large escape of gas (a mechanism not relevant to LPG service pipework).

An alternative possible approach to using this information to derive an approximate general estimate of the proportion of corrosion leaks from underground service pipes that lead to significant GIB is as follows:

a) derive annual incidence of ALL GIB incidents due to corrosion in service pipes (approx 16/yr for all gas types, from GSM data as above)

b) apply a multiplication factor (perhaps 2 or 3) to allow for limitations in reporting and recording [➔ 30-50 GIB incidents per year, LPG & natural gas combined]

c) estimate the proportion of the resulting leaks expected to involve LPG pro-rata to number of users (approx 1% of all gas users)

d) combine (a-c) to estimate annual frequency of LPG GIB incidents via such leaks [➔ 0.3 – 0.5/year GIB incidents for LPG leaks due to corroded service pipes]

e) estimate total number of LPG leaks from corroded, underground service pipes via supplier information (approx 25 to 120 per year) , and

f) combine (d-e) to estimate proportion of such leaks that lead to significant GIB [➔ 0.25% to 2%] (i.e. between 0.3/120 and 0.5/25)

The resulting estimate, while more realistic than that derived direct from the RIDDOR data, should be highly conservative (i.e. overstating proportion of relevant leaks leading to significant GIB). This is not only because of limitations in recording and reporting, but also because the GSM dataset of "service pipe corrosion incidents leading to significant GIB" all involved natural gas. Natural gas data is likely to be pessimistic for application to LPG for two reasons:

i) A substantial proportion of these incidents may have involved a leak from a service pipe INSIDE the property, as it is still the case that many properties have the Emergency Control Valve for natural gas inside a basement, cellar or other part of the property, and thus have sections of service pipe within the building space – whereas this is rare for LPG – and

ii) Natural gas service pipe corrosion incidents include a large proportion involving a sudden large break of the pipe (as noted above), which is not the case for LPG.

The conclusion of this analysis of GSM(R) and RIDDOR incident records is that a highly pessimistic estimate of the proportion of underground LPG service pipe leaks leading to significant gas in buildings is of order 0.25% to 2%.

Finally, we have reviewed in some depth HSE's investigation reports into the one known explosion of LPG vapour in a domestic property due to an external underground service pipe corrosion leak. This took place in Scotland in 2006 and was intensively investigated by the Health & Safety Laboratory (HSL) on behalf of HSE[18]. Nobody was killed but two people sustained major injuries in the explosion.

Important aspects of this incident in terms of its implications for understanding gas migration from soil to buildings include:

1. The rate of leakage of LPG from the pipe was very large – estimated at about 4 m^3/hour in subsequent tests of the pipework at HSL.
2. The leaking pipe was underneath paving, providing at least partially impermeable ground cover.
3. The explosion took place in the void below the floorboards; the centre of the explosion was under a room some distance from the wall where the riser entered the house.
4. There had been several previous reports of a smell of gas in the months prior to the incident; it appears likely that the leak had persisted, with occasional episodes of gas detectable in the house, for at least several months.
5. The route by which the gas entered the house could not be definitively established; there were redundant pipes present that could not be ruled out as a possible alternative source of gas entering the void below the floor of the house.
6. The explosion appears to have been ignited from within the occupied space of the building, presumably via some wisp of LPG above the LEL within that occupied space acting as a "fuse" to transmit the flame down into the void below the floor.

While we consider the combination of circumstances leading to this incident would be very unlikely to recur, it provides a valuable reference point against which to test the realism of our various models and assumptions, and is referred to in several parts of this report and our main study report.

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[18] Private communication, B Fullam HSE.

4. Gas Migration in Soils and Entry to Buildings

Our thinking in this area developed rapidly in the course of this project. In this section we describe

- How we arrived at the approach we chose to adopt for modelling these phenomena, and
- The pathways from soil gas into buildings, the dilution that can be expected between contaminants in soil gas and in building air, and the factors that determine that dilution.

4.1 Evolution of Modelling Approach

To begin exploring the state of knowledge in this area, we held an initial review of the issue with BRE, the notes of which are attached as Appendix 1. They directed us towards, and we have explored, two main sources of evidence in relation to modelling migration of gas from soil into buildings:

- radon, and
- work on contaminated land and its implications for health.

Our initial thinking as to how to approach these issues was that we might apply models and information developed in the contaminated land and radon areas to produce a deterministic model to calculate the concentration of LPG in a building that would result from a given leak into soil outside, based on the specific characteristics of the building in question.

We have explored the radon and contaminated land literature, guided by discussions with the Health Protection Agency (HPA) and British Geological Society (BGS), who are the leading UK authorities on radon in buildings and in soil respectively, and with the Environment Agency (EA), on the contaminated land evidence base. We have found particularly useful the EA's CLEA (Contaminate Land Exposure Assessment) model[19], and its Dutch counterpart VOLASOIL[20] and supporting references towards which the EA directed us. This exploration led us to some important conclusions that caused us to change our thinking and approach.

Our first conclusion was that our initial aspiration, to develop a deterministic model of gas migration into and dilution in buildings, tailored to the properties of a specific building, is simply not feasible. This is because the dilution between soil and buildings depends on so many parameters (of the building, the surrounding environment, and of the building usage) that it is effectively impossible to predict it reliably for a given building. Measurements of radon in air in a row of identical buildings built over an apparently homogeneous geological unit can show variations of several orders of magnitude.

Our second conclusion was that the dilution that occurs between contaminant gases in the soil and the occupied space of buildings is substantial. Typical measurements of radon in air in buildings are 3-4 orders of magnitude lower than corresponding measurements in soil air.

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[19] "CLEA Software (Version 1.04) Handbook", Environment Agency Science Report SC050021/SR4, 2009.

[20] "The VOLASOIL risk assessment model based on CSOIL for soils contaminated with volatile compounds", M.F.W. Waitz et al, Netherlands National Institute of Public Health and the Environment, RIVM Report 715810014, 1996.

Typical dilution factors calculated using the CLEA model are of order 1,000-10,000, entirely consistent with the radon work. We were initially concerned that such factors might not apply to LPG present in potentially large concentrations in soil below a building, given its denser than air nature and that much of the radon and contaminated land literature is based on very dilute gases in soil. But the CLEA model has been validated[21] against experiments using hydrocarbons such as benzene and toluene which are heavier than LPG, and at vapour pressures in soil up to around 0.1 bar, which significantly alleviated this concern.

Our third conclusion was that a simple steady state model (of gas leaking into a space below a building, a proportion of the leak getting into occupied space and diluting there), could well be overly simplistic. In practice, transfer of gas from soil into buildings is a highly time-dependent and non-uniform process, driven by the pressure differential between soil and building. Key possible contributors to this pressure differential include

- Any positive excess pressure in the soil generated by escaping gas
- The stack effect (pressure in building < in soil because of temperature differences), leading to wide variations in extent of "sucking" gas up from soil in the building e.g. night >> day, and
- Weather conditions, particularly wind and its interaction with the building can "suck up" gas from soil into the building to extents that vary significantly with time.

While it would not be possible to make a reliable deterministic estimate of the dilution between soil and building to be anticipated at a specific property, the agencies involved agree that it would reasonable to try and develop a probabilistic model of the likelihood of dilution insufficient to prevent the LEL being exceeded. This is accordingly the approach we have pursued.

4.2 Pathways and Dilution from Soil to Building Air

The pathways by which soil gas can migrate into buildings have been well described elsewhere. Figure 3, adapted from the CIRIA guide to assessing risks posed by hazardous ground gases to buildings[22], provides a summary of the main pathways and of possible gas accumulation locations in domestic buildings.

The key factors affecting migration into and dilution in buildings are:

- Soil characteristics and boundary conditions around the leak location (water table below, ground cover above)
- Diffusion and advection through soil to the building boundary below-ground
- Foundation and floor/below-floor building characteristics affecting transport of gas via cracks and voids from the soil beneath the building into it, and
- Ventilation characteristics of the building and its use that affect subsequent transport of gas through, and dilution in, the rest of the building.

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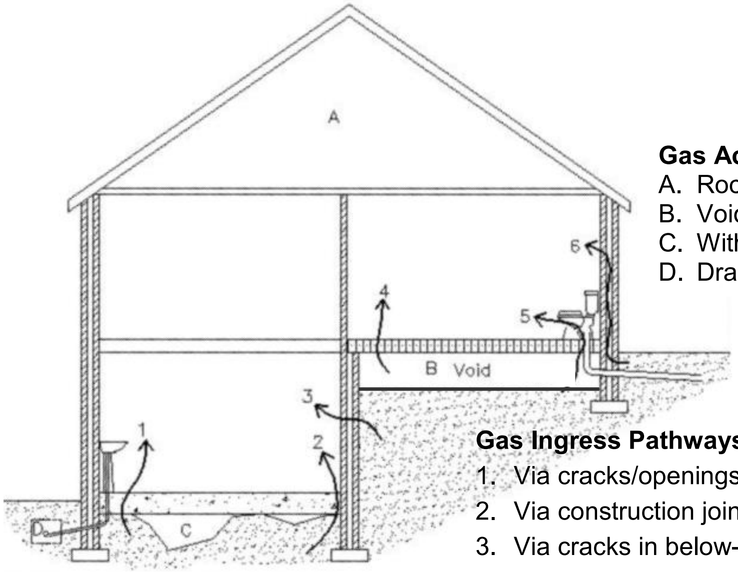
[21] "Vapour Transfer of Soil Contaminants", D Evans et al, Environment Agency Science Report P5-018, 2002

[22] "Assessing risks posed by hazardous ground gases to buildings", S Wilson et al, CIRIA report C665, 2007

Figure 3: Gas Ingress Routes to Buildings



Gas Accumulation Locations

A. Roof voids
B. Voids below suspended floors
C. Within settlement voids
D. Drains & soakaways

Gas Ingress Pathways

1. Via cracks/openings in concrete ground floor slabs
2. Via construction joints/cracks where wall meets floor slab
3. Via cracks in below-ground walls
4. Via gaps & openings in suspended concrete/timber floors
5. Via gaps around service pipes, ducts, drains etc
6. Via cavity walls

Floor type in particular is an important determinant of gas entry from soil to buildings. Suspended wooden floors will generally experience larger gas flow rates through the floor than will slab concrete floors, but will also typically have some effective ventilation below them to dilute any LPG in the void beneath the floor before it can migrate into the building. There is no simple “slab floors are better than suspended floors” rule, though it is clear that the combination of “leaky floor” with “no effective ventilation beneath” represents the worst case scenario for developing high concentrations of gases in buildings from gas in the soil beneath.

In the context of contaminated land, there is a strong focus on estimating an effective dilution factor α between gas in soil air and that in a building as a long-term time average. Typical values of α are in the range 10^{-3} to 10^{-4} or less (i.e. the average concentration of gas in the building air is 1,000-10,000 or more x less than the concentration in the soil). Note that these values apply to long-term average ratios of concentration in building air to that in soil gas. Throughout the radon and contaminated land field, the focus is generally on estimating long-term time-averaged concentrations of hazardous gases in buildings in the context of estimating long-term exposure to toxic substances, rather than short-term build up of flammable or explosive hazards.

When we began exploring this field, we were advised by BRE, HPA and the EA that dilution by as little as 50x from gas in soil to that in building air (the factor required to reduce pure LPG in the soil to the LEL in a building) would be very unusual. We applied the CLEA and VOLASOIL models to estimate dilution factors from soil to buildings for a range of typical UK domestic buildings with slab concrete and suspended wooden floors respectively. These models are intended to provide a rough and generally pessimistic (i.e. erring on the side of safety by over- rather than under-estimating concentrations in buildings) estimate of long-term soil contaminant vapour concentrations in buildings.

In every case we were unable to find realistic values of input parameters to yield a dilution factor α in the range necessary to reach or exceed the LEL of LPG in the building. The critical value of α is 0.02; any lower values will dilute even pure LPG in the soil to volume concentrations < 2% (i.e. below the LEL) in the building.

While reassured by this corroboration of the relevant organisations' advice that generating explosive levels of LPG in buildings via migration from soil was clearly unlikely, we did not feel able to use these results in any direct way to assess the risk of interest in this study, because

a) the values of α generated by the models are long-term averages; given the strong time variability of gas concentrations in buildings for a given concentration in soil we considered it entirely plausible that a long-term LPG concentration average less than the LEL could result from intermittent periods above and below the LEL, and

b) the known large variability of relevant factors from building to building means that while it might be safe to assume that average or typical dilutions were well above 50x, there might still be a proportion of buildings at the "tail" of a distribution of α factors with dilution factors of 50 or less ($\alpha > 0.02$).

We have therefore used several elements of the models developed for contaminated land in this work, but have in several cases adapted them and developed semi-empirical probability distributions of relevant parameters to enable us to estimate an approximate likelihood of the relatively unusual parameters occurring that would give rise to LPG at or above the LEL in a building. The approach throughout this modelling work is in two stages:

1. Estimating the concentration of LPG that will arise immediately below the floor of the dwelling space for a given LPG leak rate from the riser, and
2. Estimating the probability that the LEL will be reached or exceeded in the building for that given leak rate.

Whereas the parts of the model considered elsewhere are reasonably generic for different types of property, there are clear and significant potential differences in the areas covered in this report for different types of building floor construction in particular. The range of floor construction scenarios this report needs to address is discussed in the next section. This is then followed (Section 6) by a description of the modelling approach adopted for each floor construction scenario.

5. Relevant Characteristics of UK Homes

This section describes first the general characteristics of the floor construction types commonly used in the UK insofar as they would be expected to affect ingress and dilution of LPG from soil (Section 5.1). There then follows a brief overview of the relative incidents of significant building characteristics for homes using bulk LPG as a primary fuel, based on analysis of the English, Welsh and Scottish Housing Condition Surveys (Section 5.2), and our conclusions as to the floor types requiring separate consideration in our modelling approach (Section 5.3).

5.1 Floor Construction Types for UK Homes

Figure 4 shows the three main types of floor construction in widespread use in the UK, plus a fourth example with a basement or cellar (effectively a special case of a suspended floor, with a particularly deep space – which may or may not be occupied/inhabited – below the floor). These four examples are discussed below in terms of the characteristics that will influence the migration of LPG into, and dilution in, different parts of the building, covering in each case

- Migration of LPG towards and accumulation beneath the floor
- Transport through the floor, and
- Ventilation and dilution.

5.1.1 Suspended Timber Floor

This is the traditional “floorboards on wooden beams” floor type, which may have anything from a shallow crawl space to a deep cellar or basement beneath.

Migration into below-floor space: A significant feature is that the path length for gas to travel from a leak location near the bottom of the riser into the void below the floor may be quite short – a few cm of soil up to the foundations, plus the foundation thickness. In older houses in particular, foundations were often of limited depth and/or would have provided little barrier to the admission of gas (e.g. using overlapping “honeycombed” bricks to save money). A sensible general assumption would be that, for older homes in particular, LPG would not have to track far to find routes into the below-floor void. Modern floors of this type are more likely to have some sort of seal over the earth below the floor, in the form of a layer of concrete and/or some form of moisture-impermeable membrane, as well as more substantial and gas-proof foundations acting as a vapour barrier between the leak and the void below the floor.

Dilution in below-floor space: The purpose of the void is to allow free circulation of air beneath the timbers, among other things to prevent damp and rot. All homes with such floors will therefore have been designed (and usually built) with good ventilation of the below-floor space. It is not uncommon in older homes, though, to find that the ventilation has been rendered ineffective, whether accidentally (e.g. by raised ground height outside, or just by dirt blocking the vents) or deliberately (to suppress drafts). Again reflecting the purpose of the void, most below-floor spaces will permit free movement of gas between different parts of the space; properties with effective gas-proof partitioning of the void below floors (other than those with habitable basement rooms) make up a small minority of the total. Modern building standards set a minimum effective ventilation area of 500 mm^2 per m^2 of building floor area[23]. This is intended to provide a minimum 0.3 litres/sec of ventilation per m^2 of floor area; the average ventilation rate would generally be significantly higher. In a crawl space of height 60 cm this minimum ventilation rate would correspond to just under two air changes per hour (ACH), which, assuming LPG entering the void were well mixed within it, would be sufficient to dilute all but very large leaks of LPG to levels below the LEL.

Note 1: the property involved in the 2006 Scottish explosion discussed in Section 3.3 above had a ground floor area of about 110 m^2. Assuming the void below the floor was 60cm deep, and that the whole of the estimated 4 m3/hr leak rate was directed into the void, the above minimum ventilation rate would have diluted the gas in the void to an average concentration of about 3.4 vol %, which is within the flammable range. Clearly, gas might also have been present in the flammable range as a result of lower leakage rate into the void in combination with a lower ventilation rate.

Note 2: We are alert throughout this report to the possibility that LPG, being denser than air, might be more hazardous than neutrally buoyant gases, for which many of our assumptions and formulae were originally developed. In this case, it is conceivable that a significant leak of LPG into a below-floor void might lead to a "puddle" of more concentrated LPG vapour on the floor of the void, with more dilute LPG at the top of the void. In general this would be less hazardous in terms of transfer of LPG through the floor into the house, as the concentration immediately below the floor would be reduced by any dense gas behaviour of LPG. It might, though, possibly mean that parts of the void could contain flammable mixtures in situations where a well-mixed assumption would lead to the conclusion that LPG in the void was not flammable.

Migration of LPG Through Floors: Wooden floors would generally permit larger flows of gas into the occupied space of the building for a given pressure differential than would solid slab or beam and block types of construction. This is because

a) they are much thinner, so the path through which gas has to travel is shorter, and

b) they typically contain more gaps.

In older buildings in particular, shrinkage of timbers may lead to significant gaps. Some older properties may use straight sided floorboards rather than tongue and groove. And, unlike slab and beam and block floors, there is no screed or other smooth covering applied over the floorboards to provide a seal against moisture or gas rising from beneath.

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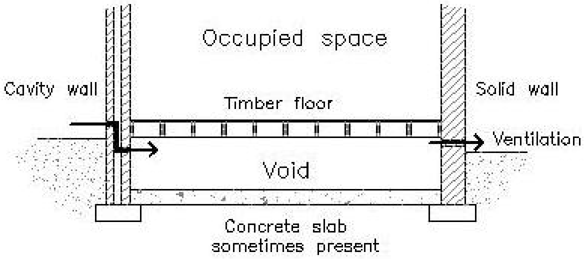
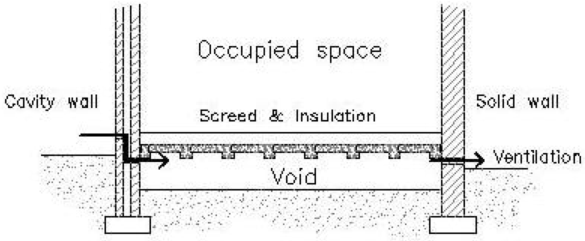
[23] NBS Building Regulations Approved Document Part C Section 4 (2004 Edition)

Figure 4: Widespread UK Floor Construction Types

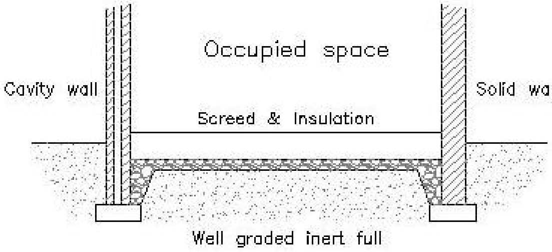
a) Suspended Timber



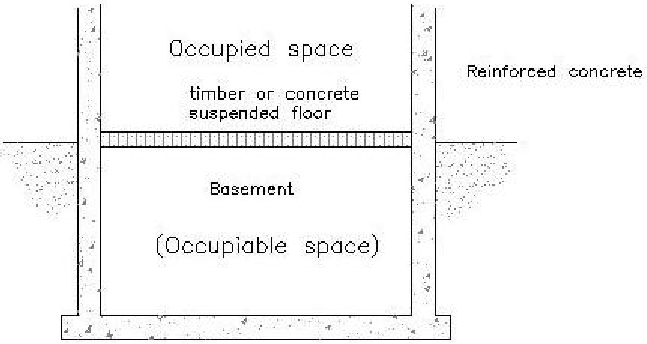
b) Suspended slab
(beam & block)



c) Ground bearing slab



d) Basement



Dilution in Building: Once LPG has entered a building we assume that it will mix fairly quickly and achieve a steady-state concentration in which the flow in through the floor is matched by the flow out with ventilation air. We ignore any dense gas behaviour – for any reasonable rates of flow through floors this is very unlikely to be an issue. The key determining parameter of concentration for a given flow up from below the floor is thus the ventilation rate of the building. Minimum requirements for modern domestic buildings are to provide 0.3 litres/sec of ventilation per m2 of floor[24], which for a typical building with 2.4 m ceilings corresponds to a minimum of about 0.45 air changes per hour (ACH). In practice, "normal" ventilation rates in buildings are around 1 ACH or higher; above about 3 ACH would tend to feel fresh, whilst less than about 0.5 ACH would tend to feel stuffy. We have assumed that the ventilation characteristics of a property are independent of floor type. Ventilation characteristics will depend strongly on the habits and preferences of the occupants as well as on building design and construction, though older buildings may well experience a wider range of ventilation characteristics than do newer ones (the width of range resulting from older and draftier situations at one extreme, through to buildings that have been subject to determined draft-proofing without regard to maintaining adequate ventilation at the other).

5.1.2 Suspended Slab (Beam & Block) Floors

This is the modern version of suspended flooring, using reinforced concrete beams with an inverted "T" cross section to support concrete blocks. Typical beam thickness is 150mm, with 100mm blocks between the beams. The typical void beneath the beams is shallower than in traditional suspended timber floors, typically with around 150mm space rather than a "crawl space".

Migration into below-floor space: Broadly similar to suspended wooden floors, EXCEPT that in floors with this more modern construction there is more likely to be both a) good quality solid surrounding walls or foundations around the perimeter providing considerable resistance to gas flow, and b) some form of membrane or slab beneath the void to prevent moisture ingress from the soil (both are requirements of current building regulations).

Dilution in below-floor space: As for suspended timber floors, current building regulations require an effective 500mm^2 of ventilation flow area per m^2 of floor area, designed to provide a minimum 0.3 litres/sec of ventilation flow per m^2 of floor area. Though the volume is typically smaller than that of the void below a suspended timber floor, the ACH are correspondingly higher and similar observations regarding the likelihood of developing concentrations above the LEL in the void would apply.

Migration of LPG through floor: This would be expected to be significantly less than for a timber suspended floor, because

a) the floor is considerably thicker, so migration paths would be longer.

b) significant gaps between blocks are unlikely (minimal shrinkage, for example), and perhaps most importantly

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[24] NBS Building Regulations, Approved Document Part F: Ventilation (2006 Edition)

c) normal practice is to cover the blocks with insulation and a screed (sometimes also with a damp-proof membrane beneath the insulation), which could be expected to provide a reasonably leak-tight floor.

Dilution in building: As for suspended timber floors.

5.1.3 Concrete Slab Floors

These range from (for some older houses) a thin layer of concrete poured directly onto the ground with little or no supporting structure underneath, to (for modern houses) a well-laid perimeter foundation extending to 700-1000 mm below ground, with a reinforced slab typically 150 mm thick laid within that perimeter and for approx 1 brick's thickness above it out to the lower level of the wall built on the foundation, all supported on a thick bed of compacted hard core material, with a damp-proof membrane laid between the hard core and the concrete. Insulation and a screed may then be laid on top of the slab.

Migration into below-floor space: The "space below the floor" in this case is the soil. To gain access to the house, LPG would first need to migrate to the location of any cracks or gaps in or around the slab, and then migrate up through those cracks into the building. Diffusion in soils is very slow compare with mixing in air, so there is likely to be a significant difference from suspended floors in that a considerable concentration gradient of LPG in the soil gas could build up under the house. Risk would be expected to be considerably lower for rooms further away from the riser than for those close to it.

Dilution in below-floor space: Dilution will occur as LPG migrates through the soil; for lower leak rates of LPG that can be dispersed in soil via diffusion, the concentration of LPG will fall off with distance in line with the concentration gradient required to maintain a flux of LPG vapour sufficient to disperse the leak. For larger leaks, any leak in excess of that which can be dispersed via diffusion will have to find some form of flow channel or pathway via the path of least resistance (which might be either away from or towards and into the building).

Migration of LPG through floor: The most likely general location to find gaps through which LPG could migrate would be between the slab and the surrounding foundations and perimeter wall, where shrinkage will typically lead to the development of small pores and cracks. The other significant possibility is that penetrations will be made in the floor after it is laid, and then not be properly sealed. Modern floors of this type would be expected to perform significantly better in impeding gas flow than older floors, because

a) typical design and construction standards include more effective barriers to gas, and

b) it is less likely (simply because the buildings are younger) that someone at some stage will have perforated the floor in the course of work on drains, utility services etc.

Dilution in building: As for suspended wooden floors.

5.1.4 Basements and Cellars

Basements and cellars represent special cases of the suspended floor situation, with a deeper space below the main building floor. The distinction often made between basements and cellars, which we will adopt here, is that

- a ***cellar*** is a space below the floor that is not designed to be occupied in normal use, whereas
- a ***basement*** is such a space that is designed and built for normal occupation.

Migration into below-floor space: Similar observations to those made for suspended timber floors would apply also to cellars. For basements, there should be a significantly better barrier to the ingress of gases through the walls as a) the walls should be of solid construction throughout, and b) they should (particularly for more modern buildings) contain some form of effective moisture ingress barrier.

Dilution in below-floor space: Building regulations require similar ventilation provisions for a cellar to those for any under-floor void. For basements, particular provisions are required to ensure sufficient and effective ventilation. Cellars may simply be treated as a rather taller type of below-floor void. Basements should on average be significantly lower risk than cellars in light of their superior moisture-proofing and ventilation.

Migration of LPG through floor & dilution in building: As for relevant suspended floor type.

5.2 Characteristics of Domestic LPG Users' Properties

The housing condition surveys carried out annually in England, Wales, Scotland and Northern Ireland from time to time include questions as to the primary fuel used in the house. This enables households using bulk or bottled LPG as their primary fuel to be distinguished from other properties.

With the assistance of BRE (Enland and Wales) and the Scottish Office (Scotland), we have analysed the similarities and differences between LPG users' properties and those of natural gas users. These are summarized in Figure 5 for key characteristics that can be discerned from the survey data as follows:

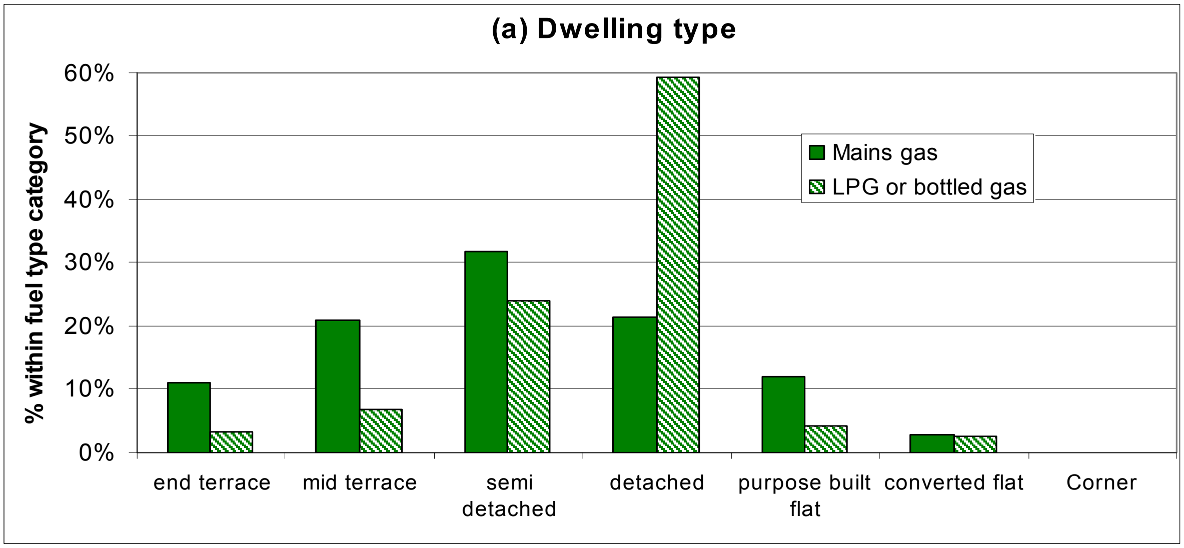
(a) Types of house
(b) Age of house
(c) Floor type
(d) Presence of cellar or basement.

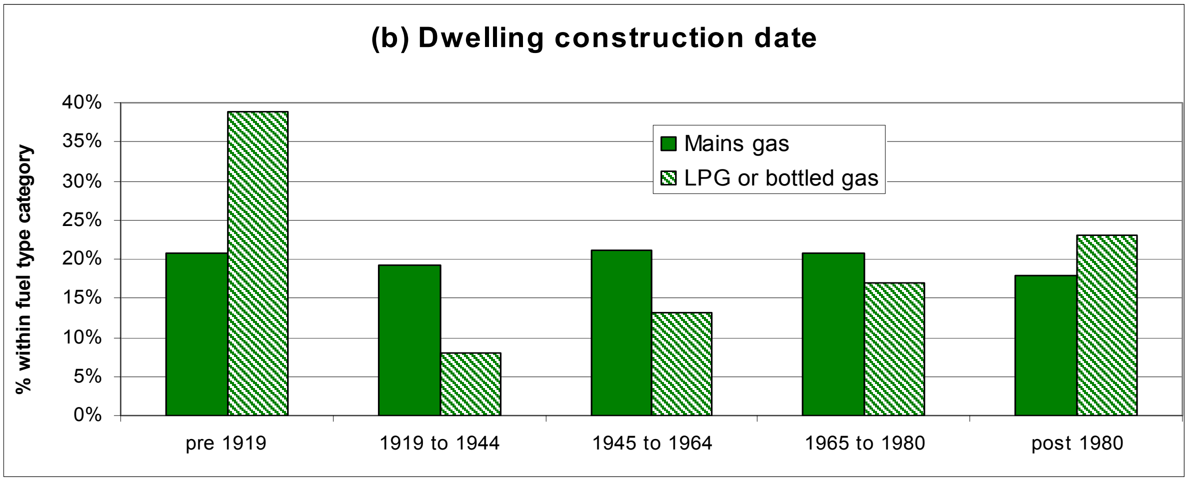
The key points emerging from this analysis are

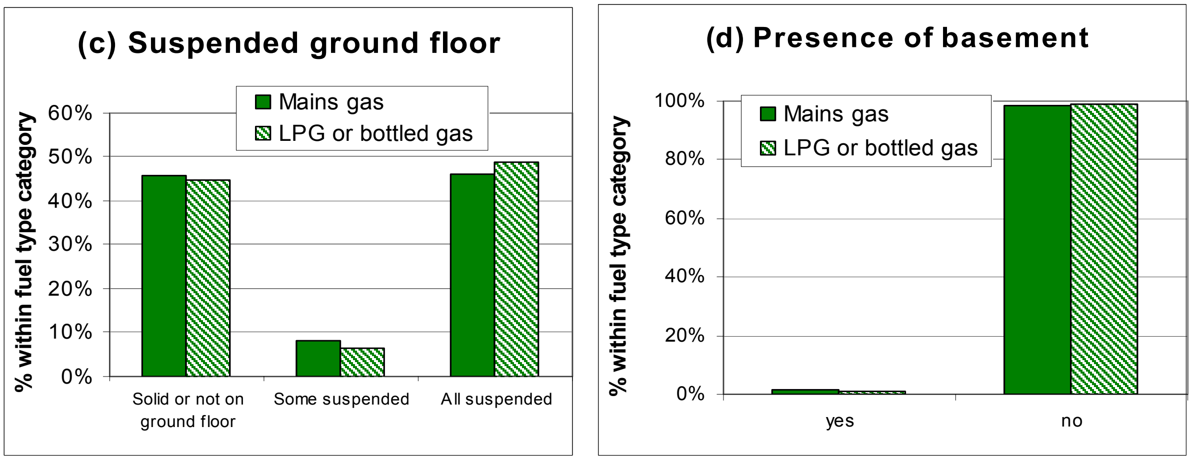
- LPG users on average have larger and older houses than natural gas users.
- Both LPG and natural gas users have roughly equal numbers of suspended (no distinction between timber and block & beam is possible) and solid floors.

- Less than 2% of properties (in either case) have cellars or basements.

Figure 5: Characteristics of LPG vs Natural Gas User Properties


(a) Dwelling type


(b) Dwelling construction date


(c) Suspended ground floor

(d) Presence of basement

5.3 Floor Scenarios to be Modelled

In light of the above discussion (Sections 3, 4 and 5.1) on LPG leak characteristics, factors influencing LPG migration into buildings and the characteristics of commonly encountered UK floor types, we considered it important to give separate consideration to three types of scenario representing significant potential differences in risk. The three scenarios correspond to the different possible routes for LPG ingress from soil to the building and are as follows:

Scenario 1: LPG flow from leak ➔ soil ➔ occupied part of building

Scenario 2: LPG flow from leak ➔ soil ➔ void below floor ➔ occupied part of building

Scenario 3: LPG flow from leak ➔ occupied part of building.

The first scenario corresponds to the slab floor situation, the second to a suspended floor situation, and the third to the “high hazard” situation identified in our work with suppliers, in which for whatever reason the riser has effectively been incorporated into the property.

Note that for the second scenario, there are two hazards to be considered:

a) explosion in the void below the floor (a special case of which would be a cellar or basement), and

b) explosion in the occupied part of the building.

The modelling approach is now discussed for each of these scenarios, considering first the transport of LPG through soil to arrive at a location from which it can migrate through a floor and into the occupied part of a building, and second the migration of LPG through floors and its dilution in the occupied part of buildings.

6. Modelling LPG Migration through Soil

We consider first the general mobility of LPG in soil and the limits placed on its movement by diffusion (6.1). This is important in understanding the boundary between situations in which leaking LPG is able to disperse via diffusion, and those in which it must find some sort of tracking pathway. We then consider in turn the migration of LPG through soil under slab floors (6.2), and its migration and dilution in voids below suspended floors (6.3). The special "high hazard" case in which LPG migrates direct from a leak into the occupied part of a building is assumed not to involve any leak mitigation via transport through soil, so is not considered here.

Throughout this section the primary mechanism for LPG transport through soil that we consider is diffusion. This is in line with the Johnson and Ettinger model[25] (J&E) for soil gas migration into buildings, which is incorporated into the CLEA and VOLASOIL models developed for slab and suspended floors respectively by the Environment Agency and their Dutch counterparts. We have found particularly helpful a paper by Paul Johnson (of Johnson & Ettinger) explaining the pitfalls associated with indiscriminate use of wide ranges of input parameters to the J&E model[26], and advising on appropriate ranges of various parameters and groups of parameters. We have used his advice in several parts of this and the following section to help us understand realistic plausible ranges of various parameters and groups of parameters.

While the basic migration process we consider thus mirrors exactly the J&E and CLEA models, the boundary conditions we are considering are very different (they are focused on a long-term source some depth below or distance away from the building, where as we are considering shorter-term leaks immediately next to the building and at a depth of just 60 cm). We have therefore used our own models to make predictions and as a foundation for our risk assessment model – based on the same phenomena and similar assumptions to those used in CLEA and VOLASOIL but adapted for this problem.

6.1 LPG Mobility in Soil – General Considerations

A contaminant gas may move through soil by diffusion (migration down a concentration gradient in the soil air), or advection (flow down a pressure gradient with the soil air with which it is mixed). Diffusion is a slow process. Advection can also be slow if soil air movement is impeded by low porosity of the soil (e.g. fine grains, high moisture content), but can rise by orders of magnitude if the soil gas is able to open up channels/pathways of larger radius through the soil.

To illustrate the limiting effect such processes can have on gas movement, Figure 6 shows the maximum rate of gas leakage into a hollow void in soil that can be dispersed by diffusion.

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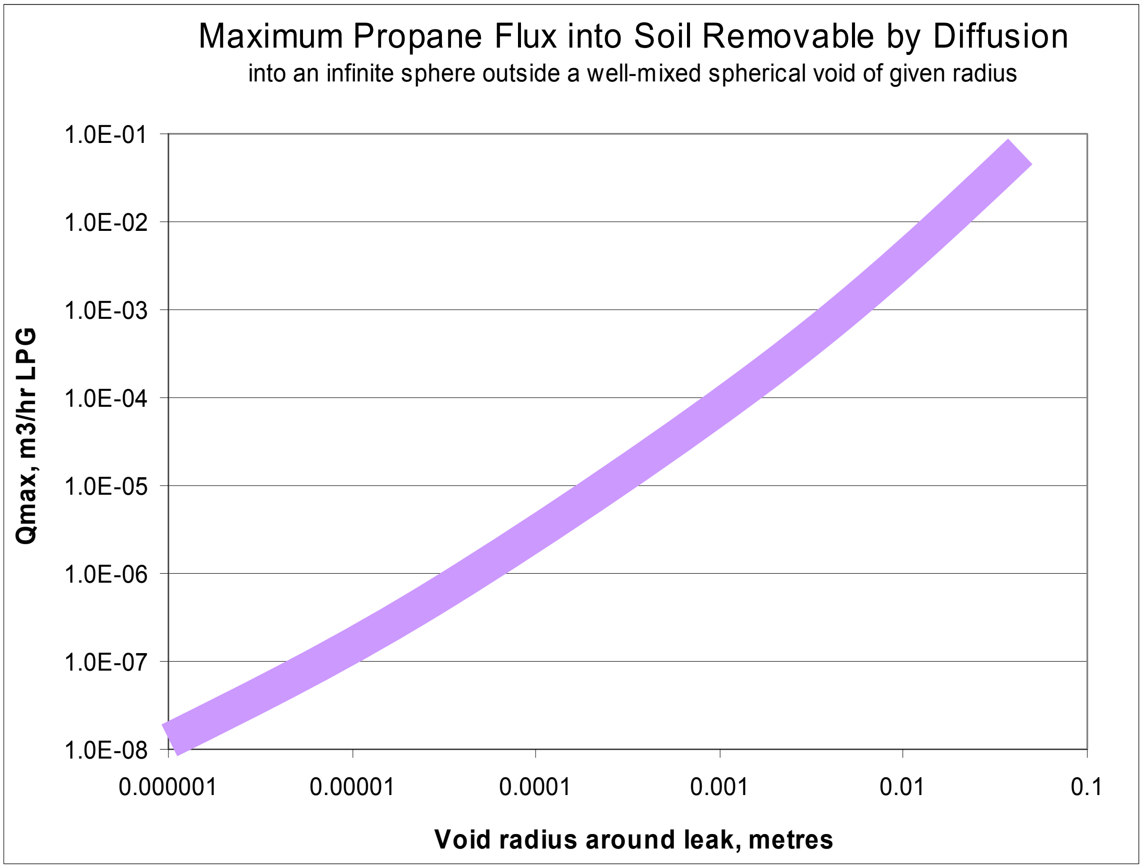
[25] Originally presented in "Heuristic Model for Predicting the Intrusion Rate of Contaminant Vapours into Buildings", P.C.Johnson & R.A.Ettinger, Environmental Science & Technology **25**, pp 1445-1452, 1991

[26] "Identification of Critical Parameters for the Johnson & Ettinger (1991) Vapor Intrusion Model", P.C.Johnson, American Petroleum Institute Bulletin no. 17, May 2002

Figure 6: Maximum Diffusion Rate of Propane through Soil



The derivation of the relevant equations and diffusion parameters for propane in soil are provided in Appendix 2.

The main point we note from this figure is that the scale of maximum diffusion rates from particles in the 0.1 to few mm range (broadly 10^{-6} to 10^{-3} m^3/hr) overlaps substantially with the range of typical LPG leak rates into soil observed by LPG suppliers for corrosion leaks (1 mbar per minute pressure drop – typical of LP leaks – would correspond to 10^{-4} to 10^{-3} m^3/hr for most domestic supply pipework systems). We strongly suspect that what we are seeing here is corrosion leakage rates being limited in some cases by the rate at which gas can migrate away into soil, rather than by the condition of the service pipe and/or the size of the perforations in it.

For larger leaks to occur into soil, some process other than diffusion needs to be involved, and for really substantial leak rates into soil, the gas would need to open up channels and pathways of an effective diameter larger than soil particle scale. In our view the supplier observations

a) that there is only very rarely a significant void around corrosion leaks when excavated, and

b) that corrosion leak rates from underground service pipework are generally low,

are closely related.

6.2 Modelling Approach - Transport to Slab Foundation Boundary

Our aim here is to estimate the concentration of LPG in soil below a slab floor at the point(s) from which gas might be able to leach upward through cracks in that floor and into the property. In principle, we consider it plausible that even quite low leak rates into soil could lead to high concentrations of LPG around the foundations and edges of the slab floor, if

a) LPG is trapped below the ground and has plenty of time to diffuse under the edge of the house without being removed by suction up into the building, and

b) There is subsequently a change in conditions in the house (e.g. people returning from holiday, sudden shift in atmospheric pressure) that causes the house to "inhale" substantial gas from the ground over a short period of time.

To simulate this scenario, we developed a 2-D model of diffusion of LPG into soil around and below a domestic property. The main assumptions of the model are:

1. The LPG is trapped in a layer of soil below ground of thickness a few 10's of cm and upper boundary 60cm below ground level.
2. LPG can be assumed to escape to the soil surface outside the house via diffusion upwards from the trapped layer at 60cm depth and below (or this phenomenon can be switched off).
3. The LPG migrates via diffusion both towards and away from the house.
4. LPG = propane (generally the case, and diffuses better in soil than butane).

The model calculates the concentration of LPG in the soil, in terms of volume % of LPG in the soil gas, as a function of distance both perpendicular to the wall next to the riser, and laterally along that wall from the riser. The processes considered are illustrated in Figure 7.

The diffusion equations are solved numerically to calculate the time evolution of the concentration of LPG in the soil at different locations. The detail of the equations is provided in Appendix 3. Typical results for the most rapid (dry, coarse sandy) and slowest (moist clay) soils are shown in Figure 8 at one week from the start of the leak (the longest period that could be easily modelled in a single Excel workbook while maintaining numerical stability). Figure 9 shows the variation of concentration of LPG in the soil with distance both in/out from the wall (along the X axis) and at different lateral distances along the wall from the leak (different curves).

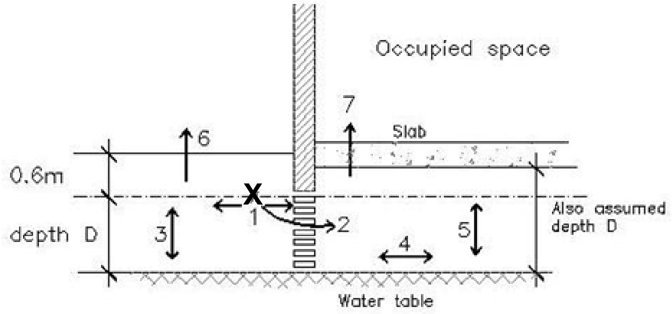
The main points of note in the Figures are:

1. For both slow and rapid diffusion, the average concentration at the slab edge along a reasonable length of the wall next to the riser reaches 100% (i.e. pure LPG) at leak rates in the range 0.01 to 0.1 m3/hour.
2. The effect of different soil diffusion rates for propane is not large in comparison with other uncertainties in this risk assessment – the two diffusion scenarios shown differ by a factor of 10 in effective diffusion coefficient (based on advice as to realistic ranges of effective diffusion coefficients from ref. 11), but only by about a factor of 2 in the leak rate at which saturation of the soil is reached within a few metres of the riser.

3. Slower diffusion increases the concentrations nearer the riser (the LPG is more effectively "trapped" in the region close to the riser)
4. The rate of decrease of LPG concentration with distance is quite marked (Figure 9); the risk for rooms not adjacent to the riser would be much less than for that adjacent to the riser.

Figure 7: Slab Floor LPG Migration in Soil Model

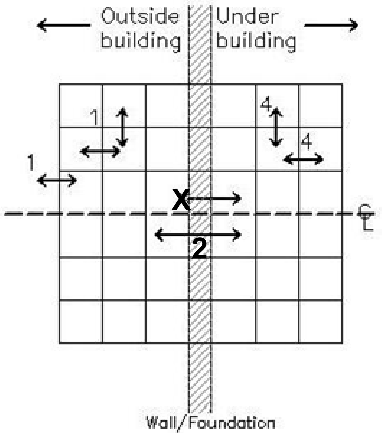
Section View



Key:

X Leak Location
1. Lateral diffusion in soil outside building
2. Migration into soil below building
3. Vertical diffusion in soil outside building
4. Lateral diffusion in soil below building
5. Vertical diffusion in soil below building
6. Migration to surface outside building
7. Migration through slab into occupied space

Plan View



A final important observation based on this model is that switching on or off the ability for LPG to diffuse to the surface outside the building makes little difference to the results. This is because, in relation to the rate at which LPG can diffuse through soils, the soil surface at 60cm above the LPG is a long way away. The slow process of diffusion to it does little to reduce the effective vapour pressure of LPG immediately around the riser, which is what provides the driving force for LPG diffusion under the house and to the slab/foundation boundary. Our assumptions here are clearly pessimistic, as they ignore the significant possibility of LPG "tracking" along the riser and finding a relatively low-resistance path to the surface.

Further results and discussion of the model is provided in Appendix 3. The results of this model have been used to develop simple correlations used in our overall risk assessment model to enable the concentration of LPG in soil at the foundation/slab edge to be estimated for a given leak rate of LPG and building age. Building age is assumed to make a modest difference to the distance LPG has to diffuse to reach the foundation slab boundary – around 1 metre for newer buildings and 0.5m for older ones – so that the concentration at the slab/foundation boundary would be somewhat higher for older and lower for new buildings.

Figure 8: LPG Concentration in Soil at the Slab/Foundation Boundary

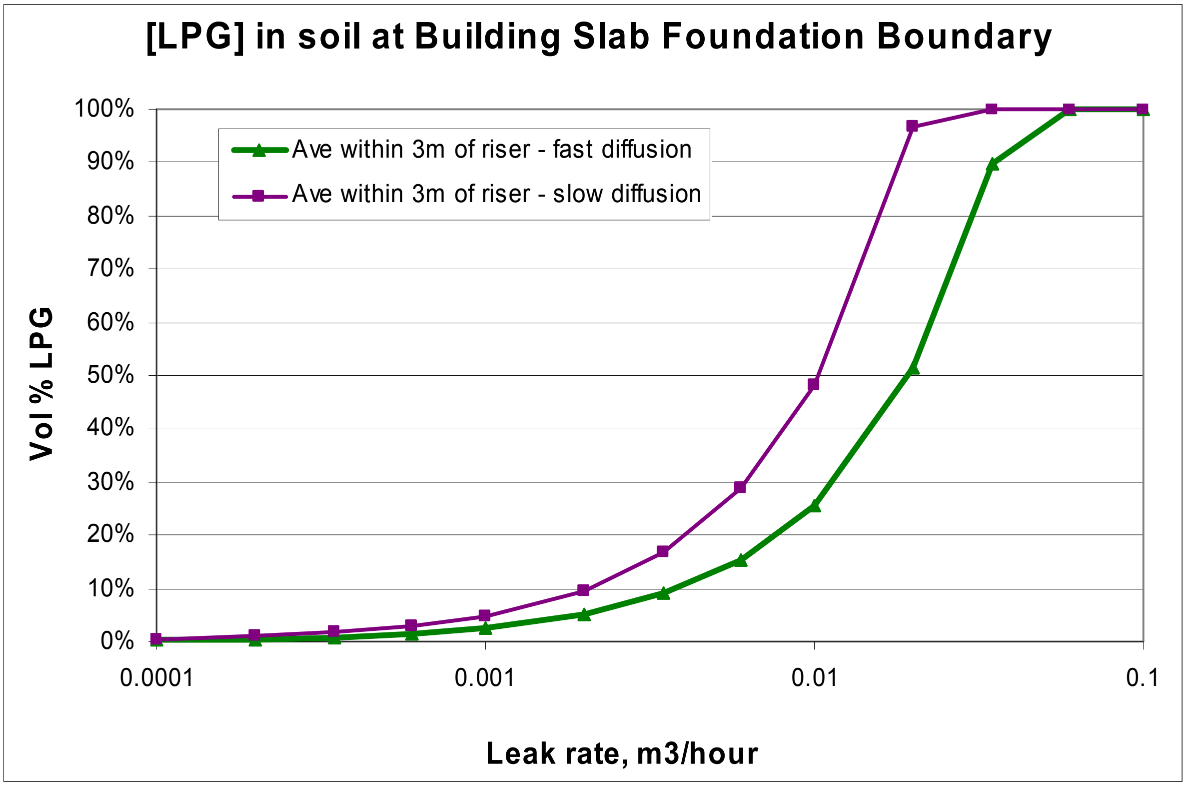
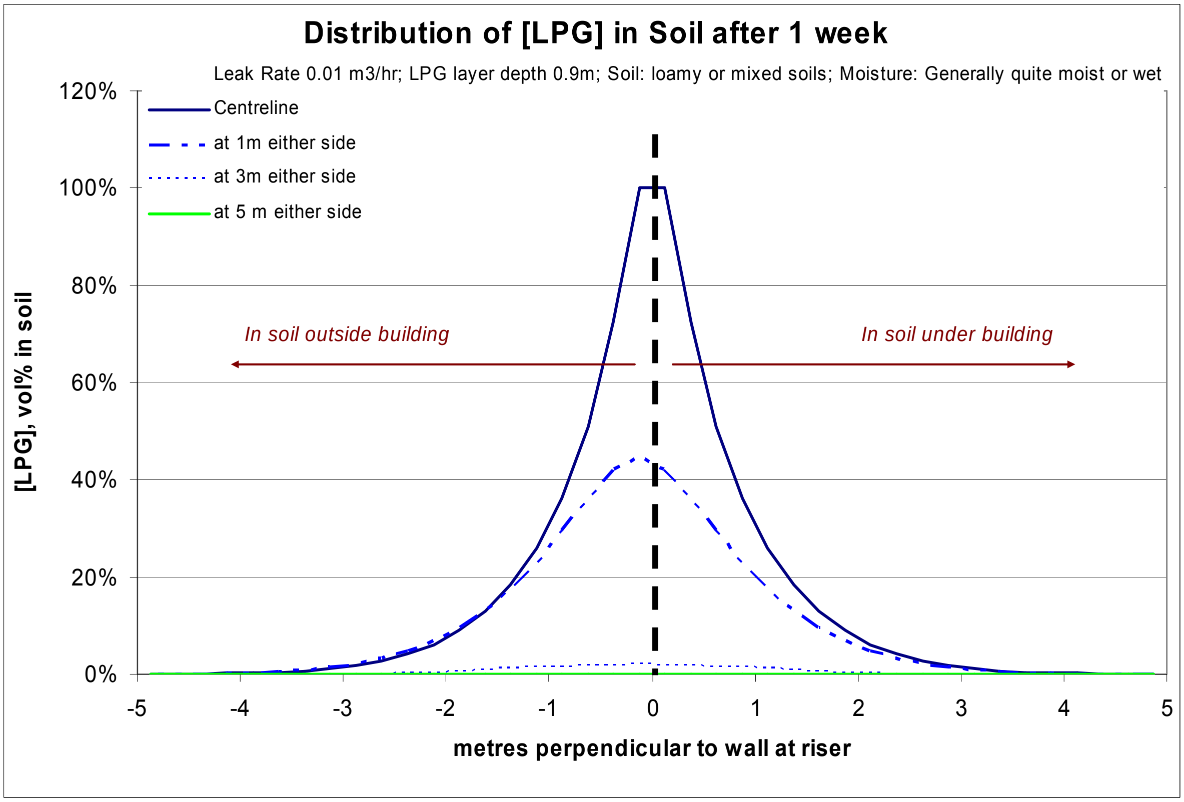


Figure 9: LPG Concentration in Soil vs Distance from Riser



6.3 Modelling Approach - Transport and Dilution into Below-Floor Voids

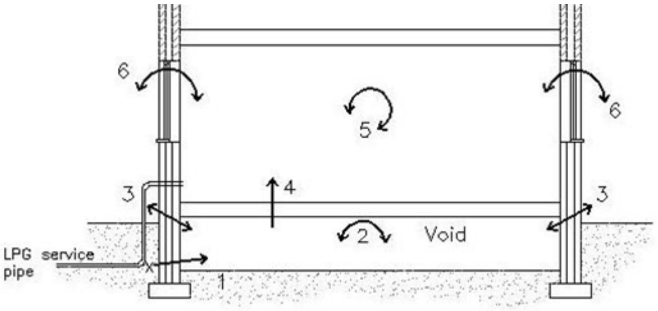
To estimate the concentration of LPG below a suspended floor we need to consider both

a) the ingress of gas into the void below the floor, and

b) the mixing and dilution of gas in that void as a result of ventilation.

The processes involved in modelling suspended floors are illustrated in Figure 10; we are concerned here with nos. 1-3 and in Section 7.3 with nos. 4-6.

Figure 10: Modelling Gas Migration – Suspended Floor



X Leak Location
1. Migration into below-floor space
2. Mixing in below-floor space
3. Ventilation of below-floor space
4. Migration through floor into occupied space
5. Mixing in occupied space
6. Ventilation of occupied space

The first issue to be considered is the proportion of the leaking gas that enters the void. We used the diffusion models described in Section 6.2 above to explore the proportion of gas that would migrate towards the building given various assumptions about the permeability of the foundations next to the leak in comparison with that of the soil and ground cover above it. Because the potential path length into the void is so short (a few cm of soil at most plus a few 10's cm of brick/concrete of difficult provenance to assess, and/or of soil around the bottom of the foundations) in comparison with that to the surface (maintaining our assumption that all leaks are at a depth of 60cm), our conclusion was that, barring the development of pathways for LPG to track upwards to the outdoor ground surface, it was entirely plausible that the majority of the leak might find its way into the void.

This is clearly a pessimistic assumption, not only because of the "barring tracking to the outdoor surface" assumption, but also because it ignores the potentially substantial barrier effects of well-built foundations and any impermeable membranes or other arrangements built in to prevent moisture ingress via the walls around and the soil beneath the void. We have included in our risk assessment model an event tree branch for "proportion of escaped gas entering void", and use default assumptions of 100% probability of the whole leak entering the void if the ground cover is impermeable outside the property. For permeable ground cover, we consider tracking to the surface much more likely than tracking into the void, and assume a 90% probability that the proportion of the leak entering the void would be reduced by a factor of 10.

Our next consideration is then how likely it is, given a specified gas ingress rate to the void, that LPG will accumulated in it at concentrations at or above the LEL. We assess this as follows:

a) For a given leak rate of LPG into the void (= leak rate from pipe x fraction entering void) we work out from the volume of the void space the ventilation rate, in air changes per hour (ACH) that would be necessary to yield a given multiple of the LEL in the void.

b) We then estimate the likelihood of encountering such a ventilation rate using a purely empirical probability distribution of ACH, based on providing a plausible explanation of the realistic range of ACH that might be encountered in buildings of different ages.

As regards (a), the ACH required is given by the equation:

$$Q = C . V . ACH$$

where Q is the flow rate of LPG into the void, m3/hr

C is the concentration in the void at steady-state (vol %), and

V is the volume of the void.

As regards ventilation rates in the below-floor void, the Dutch VOLASOIL cites Netherlands research into a sample of over 100 domestic properties which found an average ACH per hour of just over 1. As mentioned in Section 4, UK building regulations require a minimum effective ventilation capability sized to provide at least 0.3 litres/second of ventilation per m2 of floor, which translates into about 1.8 ACH for a 60cm deep crawl space. Average ventilation rates should generally be higher for modern properties built to this standard, but may be much lower for older properties if the vents have been covered or blocked for any reason.

We have developed probability distributions for ACH on the following basis:

1. Assume below-floor space ventilation is log-normally distributed as a function of ACH (a typical assumption for a variable with a range of potential values spanning orders of magnitude).
2. Assume the mean of this distribution for properties in the 1945-1964 band is around 1 ACH (i.e. not as good as required under modern standards; about same as Dutch average).
3. Assume mean is 1.5x this for the newest category of properties and 0.5 x this for the oldest.
4. Assume the LN(standard deviation) is narrow for the newest properties (1) and wide for the oldest (2.5)[27]

These assumptions give the values for the parameters of a log-normal distribution of the probability of encountering less than or equal to a given ACH as shown in Table 2 below. The effect of these assumptions on the assumed probability of encountering a given ventilation rate (in ACH) is shown in Figure 11. The age categories of buildings are those used in the English, Welsh and Scottish Housing Condition Surveys described in Section 5.2.

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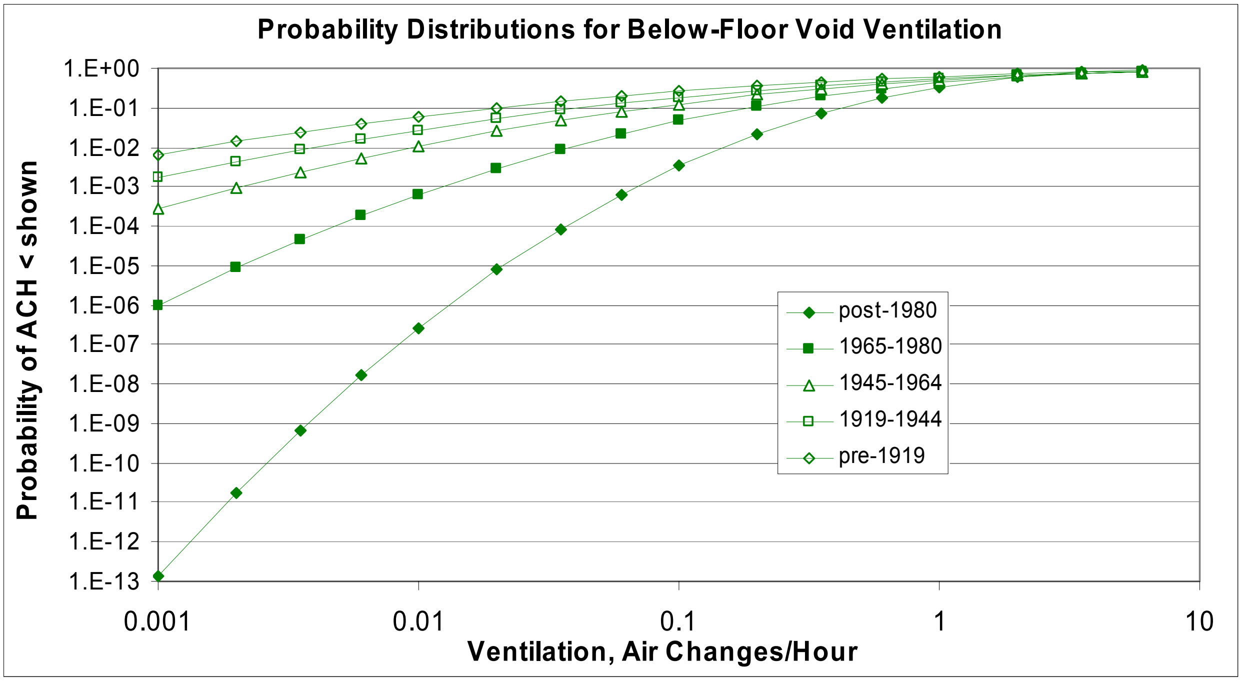
[27] The value of a geometric SD of 2.5 in a log-normal distribution is used as a radon "rule of thumb" for the variability of indoor radon concentrations in buildings as a result of a very wide variety of factors. It gives what we considered to be a suitably wide range of plausible ventilation characteristics, from very drafty down to virtually none-existent, for older buildings.

Table 2: Probability Distribution Parameters for Ventilation (ACH) in Void

Building Age	Log-normal distrib parameters	
	mean	LN(SD)
post-1980	1.5	1
1965-1980	1.25	1.5
1945-1964	1	2
1919-1944	0.75	2.25
pre-1919	0.5	2.5

Figure 11: Probability Distributions for Ventilation (ACH) in Void



The net effect of these assumptions is that for modern buildings, the assumed probability of ACH less than 0.1 per hour (a low value) is of order 1% to a few %. For older buildings the probability of ACH at or below this level is over 10%, along with several % likelihood of < 0.01 ACH (effectively stagnant). While clearly we have no direct evidence on which to base these distributions, they appear to us to provide a feasible and suitably cautious (i.e. pessimistic) way to estimate the likelihood of encountering particularly low ventilation rates in below floor voids. The parameters of the model can readily be modified in the spreadsheet version provided in conjunction with this report.

This model is used directly to estimate the likelihood of exceeding the LEL in the below-floor void, and in combination with other factors to estimate the probability of exceeding the LEL above the floor in a suspended floor building (as described in Section 7.3 below).

7. Modelling Migration & Dilution in Buildings

Section 6 described our modelling approach to estimate the concentration of LPG below the floor of buildings, and/or (in the case of voids below suspended floors) the probability of a given concentration being attained below the floor. In this section we address the migration of LPG through floors and its dilution in buildings, with the aim of estimating the likelihood that the LEL will be exceeded in the occupied space for a given concentration of LPG immediately below the floor. We describe in turn

- The general factors determining dilution of LPG between under-floor and above-floor spaces (7.1), and our approach to modelling, in turn, such dilution for
- slab floor properties (7.2)
- suspended floor (timber or concrete beam and block) properties (7.3) and
- "special case" high hazard properties in which the LPG riser has effectively been incorporated into or close to the occupied space of a building (7.4).

7.1 Transport into and Dilution in Dwellings – General Considerations

The concentration of a contaminant gas entering a building through the floor is determined by the balance between the rate at which it enters through the floor, and the rate at which it is cleared from the building.

Our focus here is on a key ratio, of the concentration C_b of LPG in the occupied space of a building, to the concentration C_s in the soil or void gas immediately below the floor. Assuming the gas in the occupied space of the building is well mixed, then the ratio of C_b:C_s is determined by the ratio of the overall flow rate of gas (LPG + air) Q_s up through the floor, and the ventilation rate Q_b of the building (both in m3/hr), as at steady state

Rate of flow of LPG into occupied space, $= C_s \, . \, Q_s$

= Rate of loss of LPG from occupied space, $= C_b \, . \, Q_b$

So $C_b / C_s = Q_s / Q_b$.

Our modelling approach is based on generating estimates that a ratio Q_s/Q_b will be encountered which is sufficient to give LPG concentrations in the building at or above the LEL for a given concentration beneath the floor. Clearly it is impossible for concentrations below the LEL under the floor to give rise to concentrations above the LEL above it. At the other extreme, the concentration below the floor cannot be higher than 100% (in volume % terms), or pure LPG, which is roughly 50x the LEL. The range of dilution factors C_b/C_s (or Q_s/Q_b) in which we are interested is thus from 0.02 to 1.

The Johnson & Ettinger, CLEA and VOLASOIL models all incorporate estimates of Qs based on Darcy's Law relating flow through small orifices to their diameter, gas viscosity and pressure drop per unit length along the flow pathway. They then combine these with estimates of Q_b to produce, in effect, an overall value for Q_s/Q_b which determines the dilution experienced between under-floor space and above-floor space.

We have explored a wide range of plausible parameters to use with the J&E models and estimate separate values for Q_s and Q_b. It is easy to generate values of Q_s/Q_b in excess of 0.02 (i.e. in the range where concentrations above the LEL in the building might be feasible), but these generally involve a combination of

a) a very large flow rate of gas up through the floor, in conjunction with

b) a very low ventilation rate within the building.

This combination seems intuitively implausible, and we turned to Johnson's paper providing practical advice on realistic inputs for the J&E model (ref. 11, as described in Section 6.1) for advice on the realistic range of Q_s/Q_b to be anticipated for domestic buildings. He describes the ratios of Q_s/Q_b that have been measured experimentally, and recommends a general range of 10^{-4} to 10^{-2}. The values of interest for us (0.02 to 1) are outside this range.

However, Johnson does mention a single experimental measurement of Q_s/Q_b as high as 0.1. We are also mindful that the ratios he is discussing are of long-term, time-averaged concentration ratios, and that it may well be possible for values outside the range he recommends to apply over a shorter term. As the incident in Scotland (Section 3.3) illustrates, it may well be possible for a significant gas escape to persist for a long period without gas above the LEL being present in the building, and then for a dangerous concentration to arise for a short time sufficient for an explosion to take place.

We have therefore re-interpreted Johnson's advice from
- range of values applying to the long-term average ratio of Q_s/Q_b, into
- percentiles of a probability distribution for Q_s/Q_b.

We have assumed that the ratio Q_s/Q_b could have any of a wide range of values, characterised by a log-normal probability distribution. We have further incorporated our judgment as to the characteristics of this probability distribution based on what we know to be the key determinants of Q_s/Q_b, in particular

- leakier floors, in combination with
- poor ventilation in the occupied space of the building,

will tend to produce higher values of this ratio, and thus higher average concentrations of LPG in the occupied space. Buildings with a wider range of these characteristics will be characterised by probability distributions with larger standard deviations and wider ranges e.g. from 10-90%-iles than will buildings which tend to have narrower ranges for these factors.

As in Section 6.3 where we used a similar approach for estimating the likelihood of encountering ventilation rates in below-floor voids less than a given value, we have no direct evidence on which to base this assumption. But, as in Section 6.3, we consider that it provides plausible results which are broadly consistent with, and generally pessimistic in relation to, the available evidence on the proportion of LPG corrosion leaks into soil that generate significant gas concentrations in buildings. The test of this is provided in the discussion of the results of our models in comparison with the available evidence in Section 8 below.

7.2 Modelling Approach – Concrete Slab Floor

As discussed above, for real buildings, Johnson (ref. 11) advises that a sensible range of values for Q_s/Q_b would be 10^{-4} to 10^{-2} (0.0001 to 0.01); the maximum ever measured is about 0.1. The upper end of his proposed sensible range is still too small to enable the LEL for LPG to be generated in a building.

For most UK slab-floored homes we consider it is genuinely the case that the house could be sitting on ground saturated with LPG yet never experience even a short-duration episode of concentration inside the building at or above the LEL. This would particularly be the case for more modern homes with reasonably leak-tight floors.

However, we do consider it plausible, given a rare combination of building factors (large cracks/penetrations in floor) and ventilation circumstances (e.g. period of low ventilation for LPG to build up in soil followed by period of rapid "inhalation" of soil gas by house) that Q_s/Q_b could in principle rise above the value of 0.02 necessary to generate the LEL. The likelihood of this happening would be significantly higher for older houses where

a) there is less likely to be an effective moisture barrier limiting gas ingress through the slab,

b) slab shrinkage may have generated more and larger cracks in the floor,

c) more time has elapsed in which people may have made larger penetrations in the floor for drains, utilities etc, and

d) building practice was less likely to include measures (such as membranes below and screed above the slab) that would improve leak-tightness of the floor.

In order to estimate probabilities of exceeding a Q_s/Q_b ratio of 0.02 for a given property, we have interpreted Johnson's "realistic range" of 0.0001 to 0.01 as representing the percentiles of a log-normal distribution, and have gone on to re-distribute the percentiles of that distribution across newer/older buildings, as shown in Table 3 below.

Table 3: Probabilistic Interpretation of Q_s/Q_b Ratio – Slab Floor

Building Age	Range of Qs/Qb		% buildings with Qs/Qb		Log-normal distrib parameters		Prob of Qs/Qb > 0.02
	lower	upper	< lower	< upper	mean	SD	
post-1980	1.00E-04	1.00E-02	0.10%	99.90%	-6.91	0.75	2.90E-05
1965-1980	1.00E-04	1.00E-02	0.50%	99.50%	-6.91	0.89	4.02E-04
1945-1964	1.00E-04	1.00E-02	1.00%	99.00%	-6.91	0.99	1.24E-03
1919-1944	1.00E-04	1.00E-02	2.00%	98.00%	-6.91	1.12	3.77E-03
pre-1919	1.00E-04	1.00E-02	3.00%	97.00%	-6.91	1.22	7.20E-03

The table assumes that Johnson's range applies to all domestic buildings with slab floors, BUT that it represents progressively widening distributions (in terms of the percentiles outside that range) for increasingly older buildings. The translation of assumed distribution percentiles to log-normal distribution parameters, and thus into the likelihood of encountering Qs/Qb > 0.02 (i.e. sufficient in the worst case of pure LPG below the floor to produce LPG above the LEL in the building), is shown on the right-hand side of the table.

This model has been used in combination with the estimated concentration of LPG in soil below a slab floor in the room nearest the riser (as described in Section 6.2) to estimate the likelihood of achieving gas in the building at or above the LEL for a given leak rate of LPG into soil at the base of the riser.

7.3 Modelling Approach – Suspended Floors

We assume that the hazard here will apply to the whole of the ground floor of the property (in practice, as in the Scottish incident in 2006, the most likely outcome would be that gas would preferentially infiltrate one room or another, and that any explosion in the occupied space would be at less than "whole houseful of gas" scale, possibly in combination with an explosion of gas in the space below the floor - as in the Scottish incident). But for this model we assume gas below the floor is well mixed and that any infiltration into the property at or above the LEL would result, if ignited, in a "whole houseful of gas" scale explosion. This is significant as our integrated risk model includes different estimates of the likelihood of people being injured for room-scale as opposed to house-scale explosions.

To develop a concentration of LPG in the house at or above the LEL we need the combination of

a) Gas in the below-floor space at some multiple M (≥1) of the LEL, and

b) Corresponding dilution by less than or equal to that factor M in the occupied space of the house.

(a) is straightforward, as we can work out the ACH necessary to get M x LEL below the floor, then use the lognormal distribution derived in Section 6.3 above to estimate the probability of a property experiencing that ACH or fewer.

(b) requires a means of estimating the likelihood that gas will be diluted by less than or equal to a given factor between under-floor space and occupied space. We address this in a similar way to that used in the slab floor model. For slab floors Johnson (ref. 11) advised a reasonable range for the ratio Q_s/Q_b from 1E-4 to 1E-2, but noted an extreme experimental measurement of 0.1 in a single instance.

Suspended timber floors should generally have larger values of Q_s/Q_b than slab floors, as

a) the flow area potentially available may be much greater (mm scale gaps between each pair of floorboards, as opposed to one shrinkage gap around the outer perimeter of the property, plus any penetrations in either case), and in particular

b) the path length to be travelled by gas to get through the floor will typically be much less (20-25mm of floorboard thickness, as opposed to typically 10-30 cm of concrete).

Suspended concrete floors, in contrast, would be expected to have low values of Qs/Qb, and to be rather unlikely to have higher values, as

a) the path length for gas to flow through the floor into the building is significantly longer than for a wooden floor (typically 10cm+ around the beam/block edge)

b) the gaps between beams and blocks are small, are much less likely to increase with age due to shrinkage, and are typically fairly well filled up with dust, dirt or screed particles during construction

c) any service pipework, utilities etc installed or modified after construction of the building is likely to be routed above floor level into the house rather than requiring new penetrations in the floor, as it would be very difficult working in the (typically very shallow, concrete-surrounded) space below the floor, and finally

d) the floor is covered with a screed providing an additional layer through which gas would have to travel to reach the occupied space. Screeds do crack significantly, but the compound effect of migration through the beam/block gaps and then through the screed should in the vast majority of cases greatly increase dilution between below-floor and above-floor spaces.

As for slab floors, we have explored making direct calculations of Q_s and Q_b for different property characteristics and assumptions, but do not feel able to make sensible property-specific estimates. We have therefore adopted a similar approach to that in the slab model, of fitting a probability distribution to the ratio Q_s/Q_b and using that distribution to estimate the likelihood of encountering ratios that would be of interest in terms of generating gas at or above the LEL in the occupied space of the building, for a given concentration of LPG in the void below the floor.

As for slab floors, Q_s/Q_b should typically increase significantly with age of the property (except for beam and block floors, which we treat as a special case), as

a) different standards of floor construction were used in times past (e.g. sometimes using straight edge rather than tongue & groove floor timbers)

b) timbers would be expected to shrink and warp over time, increasing the potential for gaps and cracks to develop, and

c) ventilation standards in dwellings have also evolved considerably; modern houses are designed and built to achieve minimum ventilation levels; older houses may sometimes be draftier (better ventilated) but are more likely to have been subject to ad hoc solutions to reduce drafts which do not provide compensating additional ventilation.

Our assumptions in generating a probability distribution for dilution across a suspended floor are

1. The probability of encountering a ratio of Q_s/Q_b follows a log-normal distribution.
2. Consideration of the floor-related factors (a) and (b) above suggests that average Q_s/Q_b values are likely to increase with age of property.

3. Consideration of the ventilation factors in (c) above suggests the distribution of Q_s/Q_b values is likely to widen with age (older properties may be either "draftier & more well ventilated", or "drafts solved but less well ventilated" than their modern peers).
4. For any given age of property, the ratio Q_s/Q_b may be an order of magnitude or so higher than for a corresponding slab-floored property
5. For beam and block floors, the ratio Q_s/Q_b is unlikely to vary much with age of property. It is assumed that only a fraction of 1% of properties would lie outside a range of Q_s/Q_b from 10^{-4} to 10^{-2}.

These assumptions lead us to values assumed for the key parameters of the probability distribution for Qs/Qb as shown in Table 4 below.

Table 4: Probabilistic Interpretation of Q_s/Q_b Ratio – Suspended Floor

Building Age	Range of Qs/Qb		% buildings with Qs/Qb		Log-normal distrib parameters		P(Qs/Qb) ≥ 0.1
	lower	upper	< lower	< upper	mean	SD	
post-1980	1.00E-04	1.00E-02	1.00%	99.00%	-6.91	0.99	1.64E-06
1965-1980	3.00E-04	3.00E-02	1.00%	99.00%	-5.81	0.99	1.98E-04
1945-1964	1.00E-03	1.00E-01	1.00%	99.00%	-4.61	0.99	1.00E-02
1919-1944	1.00E-03	1.00E-01	5.00%	95.00%	-4.61	1.40	5.00E-02
pre-1919	1.00E-03	1.00E-01	10.00%	90.00%	-4.61	1.80	1.00E-01
beam & block (all ages)	1.00E-04	1.00E-02	0.30%	99.70%	-6.91	0.84	1.95E-08

For suspended wooden floors, the probability of encountering dilution less than 50x (i.e. concentration of LPG above floor > 0.02x that below floor) based on this model is much greater than that for slab floors in table 3 – up to tens of % for older buildings, around a fraction of 1% even for the newest buildings, and a few per cent for buildings in the 1965-1980 age range. For suspended concrete (beam and block) floors, the model leads to lower probabilities of encountering dilution less than 50x than for a concrete slab floor.

This model is combined in our integrated risk model with the below-floor concentration model described in Section 6.2 as follows:

- The below-floor model is used in isolation to estimate the probability of encountering LPG in the below-floor void at or above the LEL for a given leak rate of LPG into the void, and
- The below floor model and this model are used in combination to estimate the probability of encountering the combination of concentration of LPG in below-floor void in range 1-50x LEL with dilution through floor insufficient to prevent LEL forming above floor[28].

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[28] This combination probability is evaluated as the integral of the product of the probabilities (a) of generating gas in the void at M x LEL and (b) of dilution above the floor by less than or equal to a factor of M, over all values of M capable in principle of generating gas at or above the LEL above the floor (i.e. 1 to 50)

Sample results are presented and discussed in Section 8.

7.4 Modelling Approach – High Hazard Scenario

For the high hazard scenario, LPG is assumed to leak directly into the occupied space of a building. The only parameter to be varied is a simple user input percentage of the leak that is assumed directly to enter the occupied space (default set to 100%).

To estimate the likelihood of exceeding the LEL given a specified gas flow rate into the property, we need once again to estimate first the necessary maximum ventilation rate (in ACH) that would still enable LPG to remain at or above the LEL, and then estimate the probability of encountering a ventilation rate at or below that level.

Estimation of the necessary ventilation rate is obtained using the equation

$$Q = C \,.\, V.\, ACH$$

Where Q is the LPG ingress rate in m^3/hr, C the volume % concentration in the occupied space, and V the volume of that space in m^3.

Setting $C \geq$ LEL (2%) gives

$$ACH \leq 50\, Q / V.$$

Estimating the likelihood of encountering a sufficiently low ACH to produce LPG at or above the LEL is again carried out by fitting a log-normal probability distribution to the ventilation rates anticipated in the occupied space of buildings. These in turn are presumed to depend critically on the way the householder likes to ventilate the building when at home (how the building is ventilated when the householder is out is not an issue, as the risk is experienced only when in the house), as shown in Table 5 below.

Table 5: Probabilistic Interpretation of Ventilation Preferences

Ventilation preference	Ventilation - range of ACH values		representing percentiles of distribution		Log-normal distribn parameters	
					Ln (Mean)	Ln (SD)
Cosy	0.1	0.3	10%	90%	-1.75	0.43
Fresh	0.5	1.5	10%	90%	-0.14	0.43
In-between	0.3	1	10%	90%	-0.60	0.47

An alternative, simpler model providing upper, lower and central fixed values of ACH is also included in the integrated risk model. The two give broadly similar results but that represented by the distributions in Table 5 generally gives higher probabilities of reaching the LEL (because of the greater weight it gives to low values of ACH) and is therefore incorporated as the default choice in the model.

8. Models, Results and Discussion

8.1 Models and Results

The models described in sections 6 and 7 have been incorporated into our risk assessment event tree models to estimate individual fatality or injury risk at a given property. There are four event tree models referred to as follows:

- SLAB for solid concrete slab floors
- VOID for LPG concentration > LEL in the void below any suspended floor
- SUSP for LPG concentration > LEL in a house with suspended timber or concrete floor, and
- HIHAZ for LPG concentration > LEL in a dwelling that has incorporated the riser into the occupied space of the building

The sections of the event tree derived from this report are those which estimate the probability of LPG exceeding the LEL in a building for a given leak rate into soil.

Figures 12 (a) to (e) show the resulting probabilities of exceeding the LEL in a domestic building as a function of leak rate into the soil, for buildings of different ages. All of these figures are based on a worst case default house type (terraced; this has the smallest average floor area) and on the upper end of the uncertainty ranges used in our models (we have incorporated lower and central estimates into the VOID and SUSP models, which make a modest difference to the results in comparison with the variation with pressure and age).

Important points of note include:

1. In the SLAB model, the probability of exceeding the LEL in the building is always quite low. For any given building age it rises to a maximum (corresponding to the soil below the foundation becoming saturated with pure LPG vapour) and then remains constant. The maximum is higher for older and considerably lower for newer buildings, and is reached at leak rates into soil in the range 0.01 to 0.1 m3/hr.
2. In the VOID model, the probability of exceeding the LEL is considerably higher, rising to virtual certainty for all house ages at the highest leak rates. The probability falls off quickly with decreasing leak rate for newer houses because of the greater assumed availability of effective ventilation of the void, but tapers off more slowly for older houses.
3. In the SUSP model for a timber suspended floor, the probability of exceeding the LEL is of similar order to that in the SLAB model, though falls off more gradually as leak size decreases because of the assumed still significant probability of generating high concentrations of LPG in the void below the floor. For beam and block floors, the probability of exceeding the LEL in the occupied part of the building is significantly lower than for any other floor type.
4. In the HIHAZ model, the probability of exceeding the LEL for houses of ANY age rises rapidly with leak rate, reaching 100% in the leak rate range 0.1 to 1 m3/hr.

Figure 12(a): Probability of GIB ≥ LEL, SLAB model

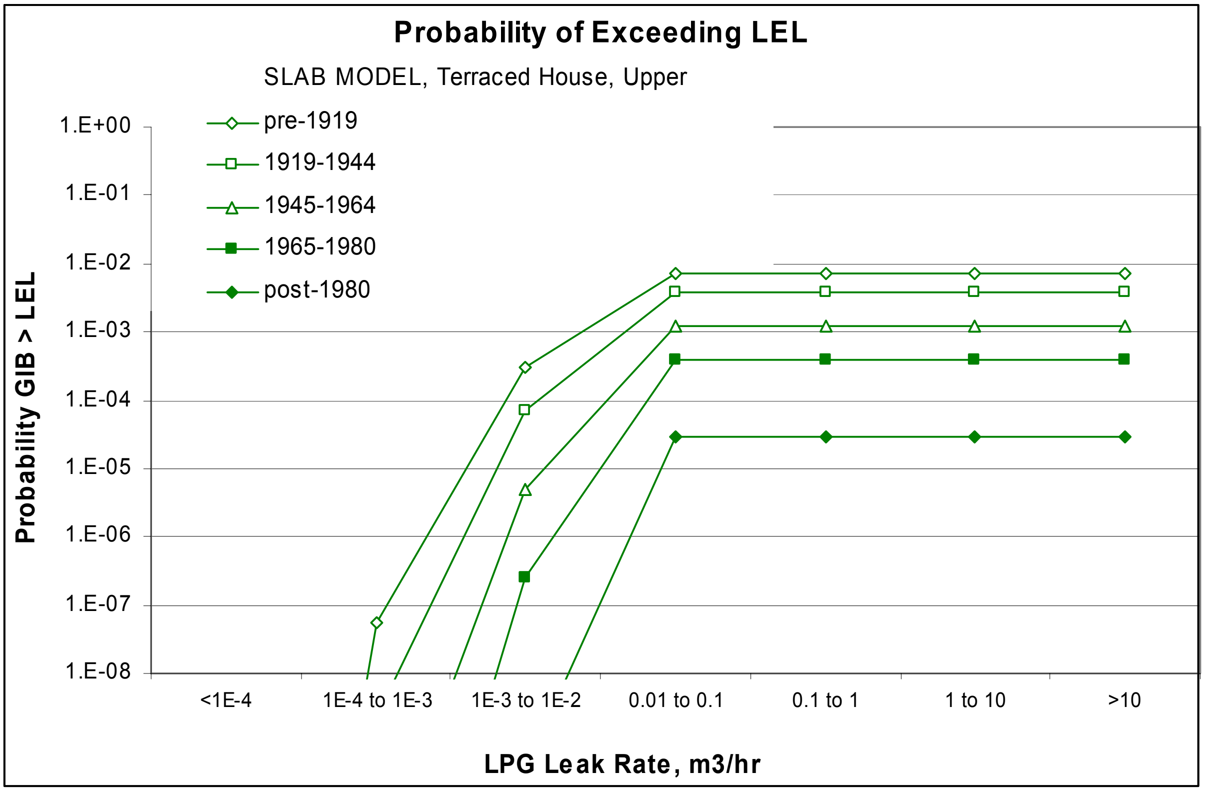


Figure 12(b): Probability of GIB ≥ LEL, VOID model

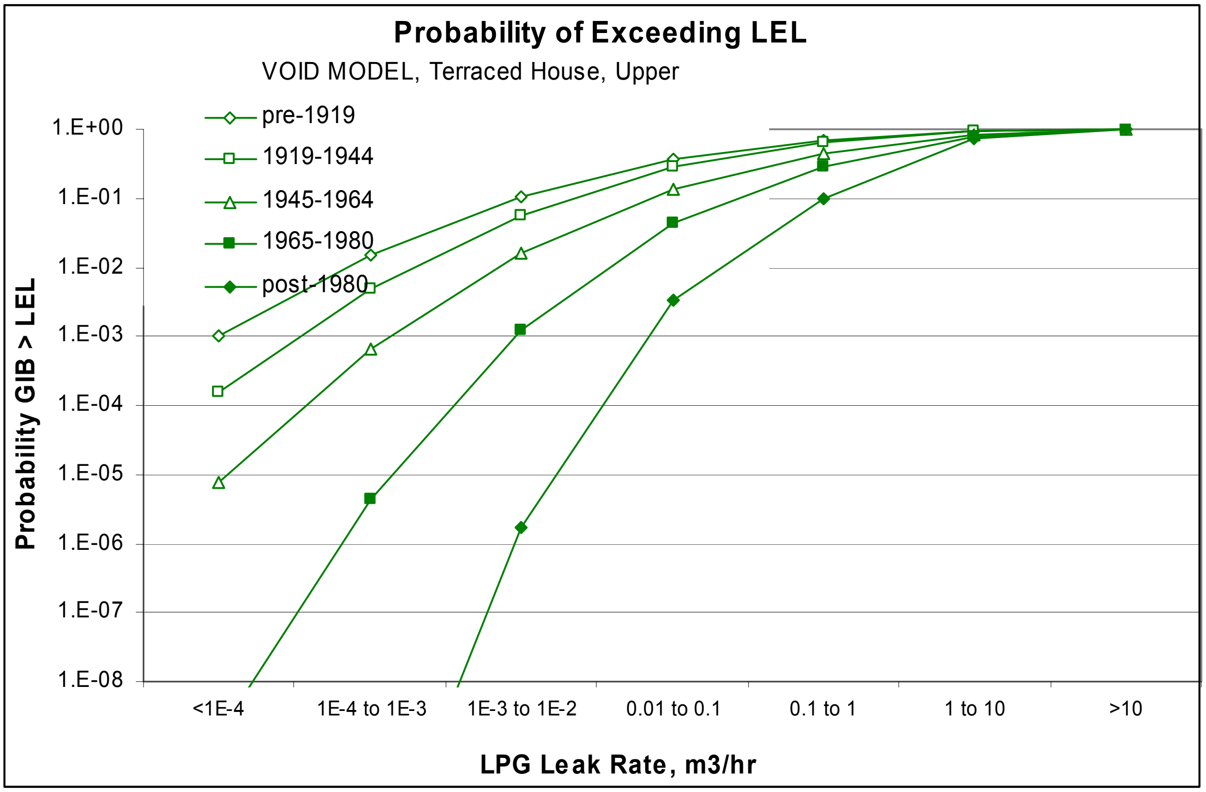


Figure 12(c): Probability of GIB ≥ LEL, SUSP model (timber floor)

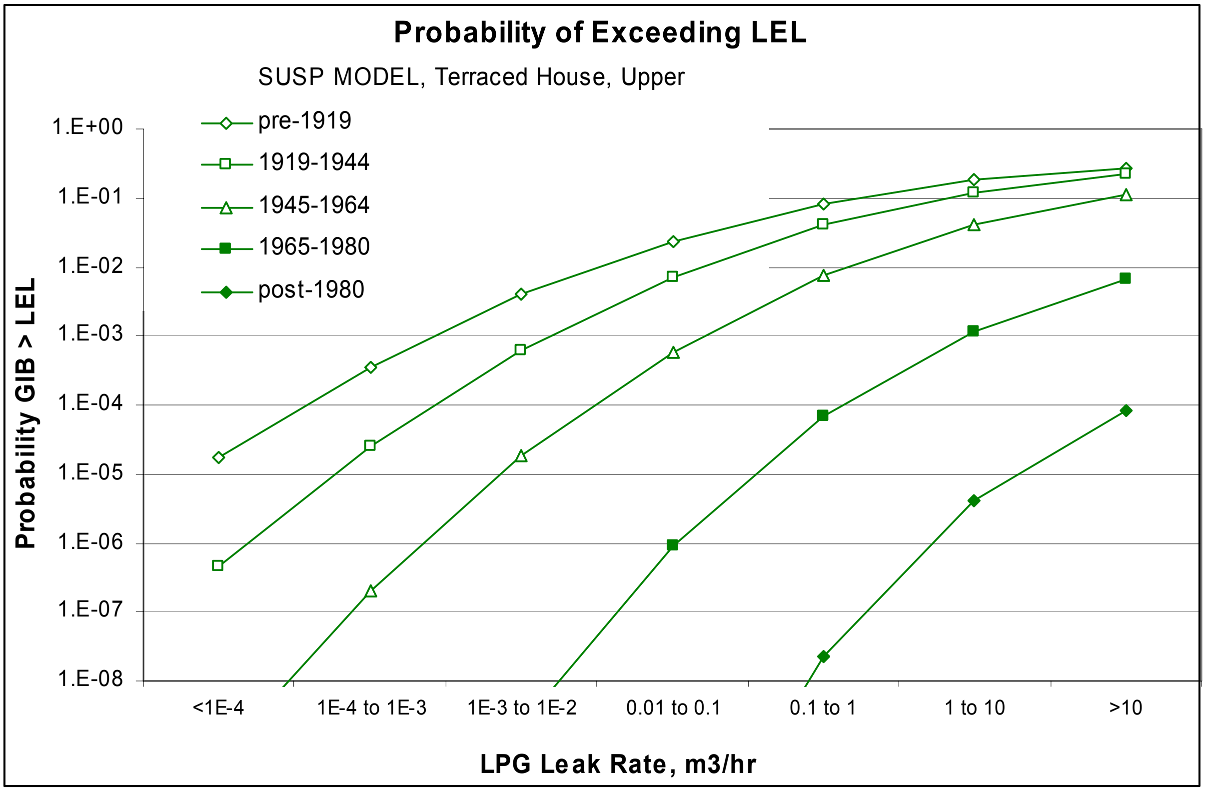


Figure 12(d): Probability of GIB ≥ LEL, SUSP model (concrete “beam & block” floor)

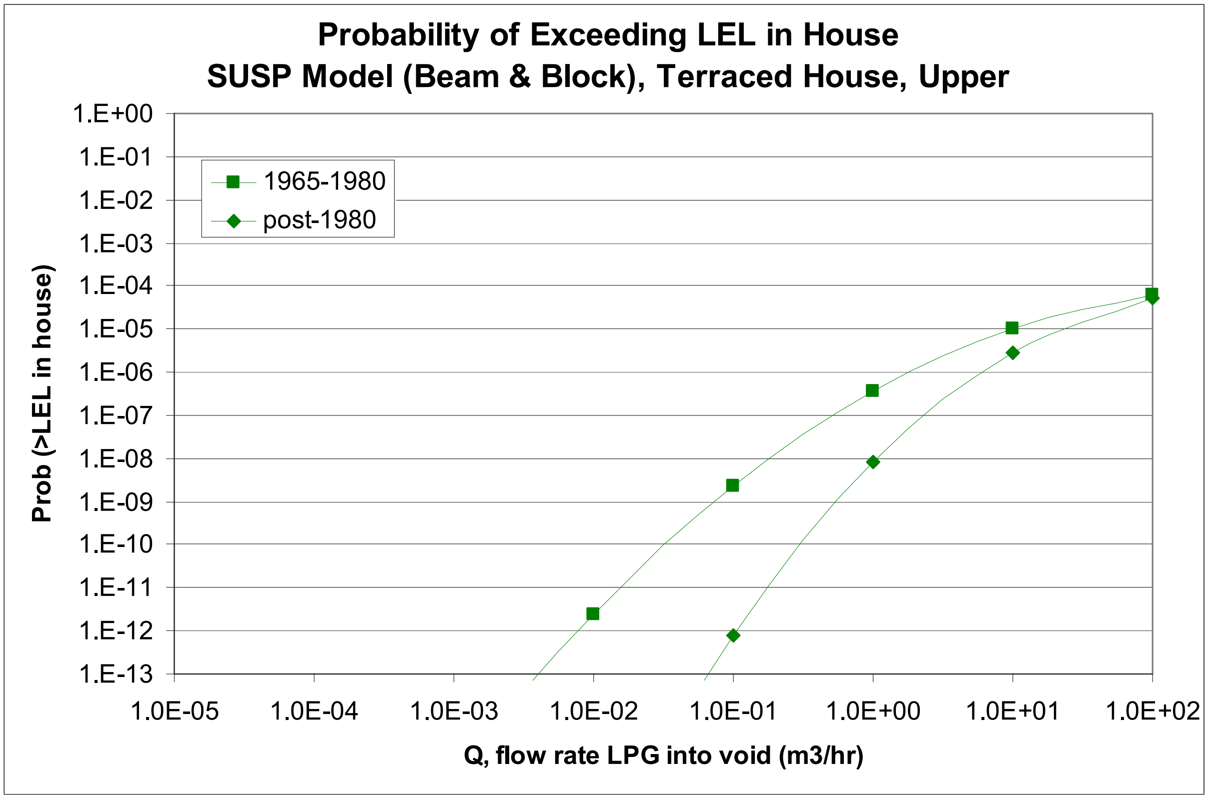
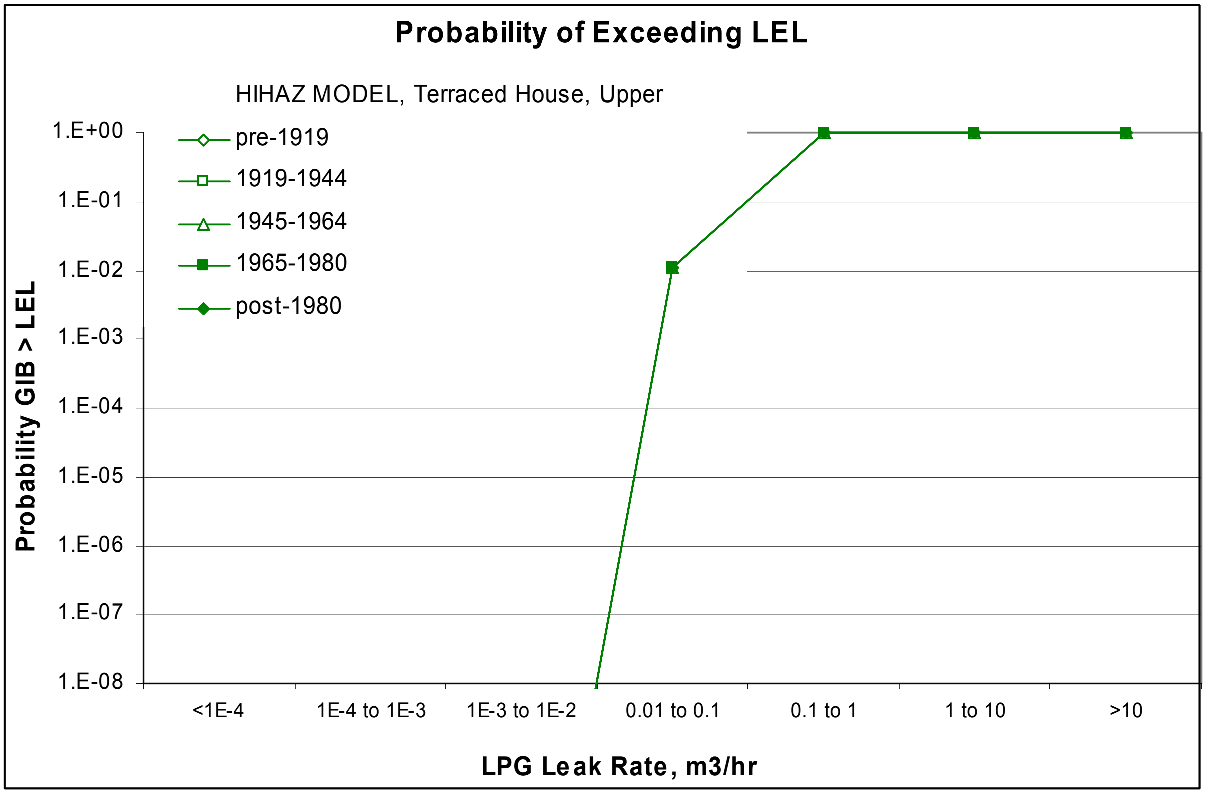


Figure 12(e): Probability of GIB ≥ LEL, HIHAZ model



Peer review of the draft of these reports commented on the high uncertainty associated with these models of gas migration from soil to buildings. The high uncertainty is recognised. To provide additional confidence that the results of the models are not understating risk in domestic properties, we added capability to the model to predict the probability of developing a gas concentration in occupied parts of the building that should be detectable by smell (a much lower threshold than the LEL, of order 0.002 to 0.005 % LPG in air[29]). This uses exactly the same processes to estimate the likelihood of different concentrations of LPG below the floor (in soil or void) arising as described above. It then uses identical probability distributions for Q_s/Q_b used to estimate the likelihood of exceeding the LEL above the floor, to estimate the likelihood of exceeding this lower concentration threshold inside the property as an average over all possible leak rates from buried pipework.

The results of this model, for a range of properties with both concrete slab and suspended timber floors, are shown in Figure 13 below. The key observation for slab floors is that, according to our models of LPG transport through soil and into buildings, MP leaks should almost always be detectable by smell in buildings, and LP leaks should commonly be detectable (in 10’s of % of cases). For suspended wooden floors, detectability would depend critically on the ventilation below the floor, but for median or higher properties, 10’s of % of MP leaks and several % of LP leaks should be detectable by smell inside the building.

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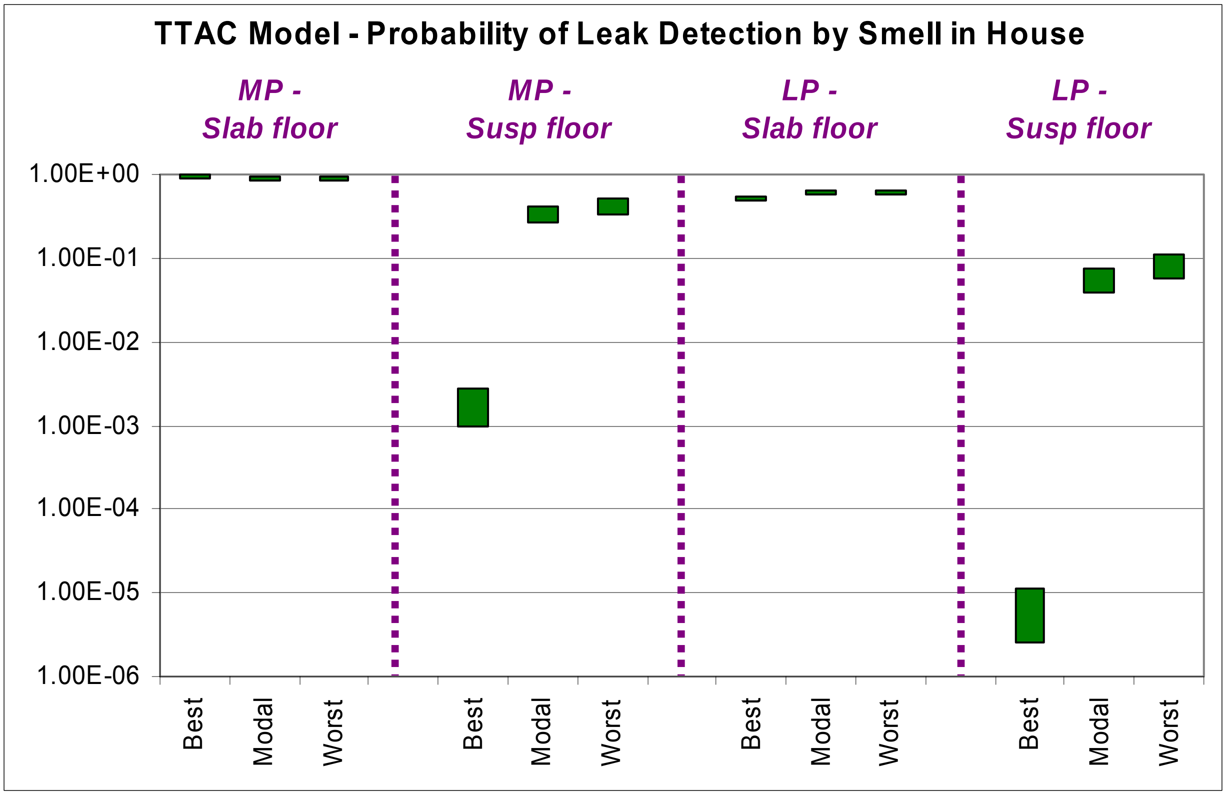
[29] Based on the most common stanching agent, ethyl mercaptan, being detectable at 1 ppb (for most people it is detectable at 1 part per 2-3 billion), and being added to LPG at concentrations of 20-50 ppm (i.e. 1 ppb corresponding to dilution of the LPG in air by 20,000 to 50,000x).

Figure 13: Probability of Exceeding Threshold of Detection by Smell



8.2 Discussion

The models developed and used to estimate the likelihood of a given leak into soil leading to LPG at or above the LEL in a building are all highly simplistic and empirical. While designed to replicate reasonable, cautious assumptions as to the probabilities that can be anticipated for various factors modelled (in particular ventilation rates and gas migration rates through floors), they are not based on direct evidence. It is therefore particularly important to cross-check the credibility of their results against what we know about the likelihood of relevant LPG leak incidents leading to gas in buildings. The key findings of our work with suppliers and HSE on the feasibility and likelihood of corrosion leaks into soil leading to significant gas in buildings were:

1. Of the several hundred relevant leakage incidents from underground service pipework attended personally by the supplier staff consulted, none had ever involved detectable (by smell) levels of LPG in the occupied parts of a domestic property resulting from migration through soil.
2. Some examples had been encountered within that body of experience of traces of LPG being detectable around skirtings or cupboards using a Gasco meter on a “wand”.
3. A single example is known in the past 10 years in which a relevant leak resulted in an explosion in the void below the floor of a domestic building; this example involved a large leak rate of LPG (estimated to be of order 4 m3/hr).

4. Buildings where the riser has been effectively been incorporated into the occupied space or a void whose only exit is via the occupied space are likely to be particularly at risk of accumulation of LPG at or above the LEL in the occupied space.

Our model results presented in Figures 12 (a) to (e) and Figure 13 appear to be producing results which are broadly consistent with or pessimistic in relation to these four findings.

1. **Detectable LPG in building**: Figure 13 suggests that several 10's of % of LPG leaks into soil outside LPG-users' properties should, based on our model, lead to gas levels detectable by smell in the bulk indoor air of the building. The suppliers' observation of there being no such incidents from a population of several hundred such leaks attended suggests that our model is substantially pessimistic in terms of estimating the likelihood of significant LPG transfer from soil into buildings.

2. **Traces of Gasco-detectable gas**: The relevant comparison here is with the concentrations of gas that our models predict BELOW the floors of houses, as what is detected with a meter around cupboards and skirtings may be much closer to the concentration of LPG in gas migrating up from below the floor than to the concentration of LPG in the bulk space of the room. These concentrations as a function of leak rate and house age are shown in Figure 8 (for slab floors) and figure 12(b) (for suspended timber floors). The key prediction of both models is that even relatively modest leaks can lead to significant concentrations of LPG below either a slab or a suspended floor. The model predictions are entirely consistent with measurable (typical ppm to 10's of ppm) LPG traces being found close to the areas where gas may migrate up into houses from below the floor.

3. **Feasibility of large leak leading to explosion in void below floor**: Figure 12(b) predicts that it is relatively easy for quite a wide range of LPG leak rates into soil to build up flammable mixtures in the void below a suspended floor. Calculations carried out for the Scottish incident in 2006 (see 3.3. above) show that the estimated gas escape rate for that incident plus the assumptions in this model for an average ventilation rate in a domestic void space would have produced an LPG concentration in the void within the flammable range.

4. **High hazard properties**: The model results in Figure 12(e) corroborate the engineers' view that the likelihood of reaching or exceeding the LEL in a property where a substantial proportion of any underground pipe leak would be forced into the occupied space of the building would be substantial.

Overall we are conscious that the results produced by this model represent extremely crude averages for houses, and that individual properties may differ considerably from the predictions of the models. But as a basis for estimating an average risk for properties of a given type associated with this hazard, we consider the models provide a reasonably pessimistic way of estimating the risk of a given leak escalating to give LPG at or above the LEL in a domestic building, and of differentiating between properties of different floor construction and age.

9. Conclusions

Our conclusions are:

1. The factors determining migration of LPG through soil and its entry into and dilution in buildings are complex, and defy accurate calculation of the resulting concentration of LPG in the building for any specific domestic building.
2. In the event of a significant corrosion leak of LPG from underground service pipework it is entirely plausible for high concentrations of LPG to develop below the floors of buildings, either in the soil below slab floors or in the void below suspended floors.
3. If pure LPG were present below the floor of a building, it would have to be diluted no more than 50x in order for the LEL to be reached inside the building (LEL = 2%). Typical long-term average dilutions of ground gases on entry to buildings are in the range 100-10,000x or more.
4. Time-average dilution factors do not provide a safe way of estimating the risk of LPG accumulation in buildings, as migration from soil and dilution in buildings vary considerably with factors such as weather and householder activities. It is entirely plausible that high concentrations of LPG could be present for long periods of time below a floor without leading to detectable LPG in the building, but that a change in conditions could then lead to significant concentrations of LPG being developed in the building.
5. Insights from actual observations on LPG leaks, and relevant elements of the various models developed by the Environment Agency and its US and Dutch counterparts to predict migration of contaminant soil gases into buildings, have been used along with our own judgment and interpretation to develop simple probabilistic models of the likelihood of encountering
   a) different LPG concentrations below a building floor, and
   b) concentrations in excess of the LEL in the occupied space of buildings,
   as a function of leak rate size, for properties of different ages and dimensions.
6. Application of these models to individual properties will involve considerable uncertainty, but we are confident that the model predictions are consistent with actual observations of LPG and other gas behaviour, and that they provide on average a pessimistic basis for assessing the risk to householders from this hazard.
7. The general order of hazard (in terms of likelihood of exceeding the LEL for a given leak rate into soil) predicted by the models for a given leak rate into soil is:
   Highest: Void under suspended wooden or concrete floor
   Next highest: High hazard house (riser incorporated into building)
   Lower: Occupied space in timber suspended floor house
   Lower still: Occupied space in concrete (slab or suspended) floor house.

Matthew Hunt, Kajal Somaiya and Tony Taig
TTAC Ltd
5 March 2010

Appendix 1: Note for the Record

Discussion with BRE, Wednesday 8 July 2009

Present

Steve Curwell, T8 Phil Hargreaves, T8 Matt Hunt, TTAC Kajal Somaiya, TTAC Tony Taig, TTAC	Chris Scivyer, Principal Consultant, BRE Richard Hartless, Associate Director, BRE Dr Andrew Dengel, Associate Director - Environmental Evaluation, BRE

Introduction

Tony explained the background to the risk assessment of leaks from underground LPG pipes that TTAC is carrying out for HSE. Chris has particular background in radon, whose dilution and mixing in buildings has clear parallels. Richard works closely with the team who produce the English Housing Survey and has broad relevant experience, including landfill gas behaviour in buildings. Andrew also has broad experience, with particular relevant expertise in air quality standards, which involves considerable assessment of the factors leading to dilution and mixing of externally sourced contaminants in buildings.

The notes below summarise key issues discussed in approximate order from "seepage through ground into building" up to "escalation of leaks in buildings to explosions". These notes are followed by a summary of next steps with respect to high value evidence sources for the HSE project, and of key conclusions for the TTAC risk modelling project.

LPG Entry to Building from Soil

1. We should NOT assume that "solid concrete floor" means "no LPG seepage hazard". Levels of gas ingress (via cracks, seepage at boundaries with walls etc) are likely to be much less for homes with well sealed, leaktight floors than for those with more "leaky" floors. We might make sensible estimates of rates of gas flow up through solid floors by
   a) estimating upper bound leakage area for flows up from below (e.g. assume a 1mm gap along the whole length of both internal and external walls) and/or
   b) comparing contaminant dilutions (e.g. radon) in buildings with solid/suspended floors, if such data were available.

2. BRE confirmed that it may not be desirable to place reliance for mitigation of gas entry into a building on below-ground foundations, structures or damp-proof courses, as a) if present they cannot be relied upon for effectiveness, and b) their presence would be difficult for a householder or LPG supplier to assess. (An exception to this would be any buildings with modern radon protection, which would be expected to be very effective in mitigating the LPG hazard).

3. We identified different forms of below-floor structure of interest which may have significantly different characteristics of relevance to LPG entry & dilution:

a) full height basement (occupied space below ground level)
b) full height cellar/other unoccupied below-floor space (150cm+)
c) suspended floors with voids beneath (critical dependence on leaktightness of floor and ventilation of void)
e) boards laid directly onto earth (not uncommon in SW England), and
f) solid concrete pad floor.

4. Presence of a basement is a clear risk factor in terms of potential for flammable concentrations to develop in an occupied space. This would be mitigated to some extent by ventilation (better than in a cellar – in modern times minimum occupied space standards/building regs would apply just as for other occupied rooms) and measures to isolate the basement from the ground (damp proofing, leak-tightness). But there are always likely to be some pathways for gas to get from soil into a basement; we could make estimates of the effects of gas seepage into and dilution in basements as in (1) above – either from physical modelling or from empirical data on dilution of contaminants between soil and basements.

5. Presence of a ground floor bathroom may be associated with an increased rate of gas flow into the occupied space of a dwelling as where there is a bath there is usually a large, unsealed hole in the floor structure below it for pipework. Kitchens, toilets and service cupboards may present comparable problems.

6. Rate of gas flow up through floor should correlate with rate of seepage of gas from soil into below-floor space. Key driver is pressure differential between soil gas and occupied part of building. Major factors here include atmospheric conditions (e.g. rainfall and changing atmospheric pressure as in the Loscoe example), stack effect (temperature difference), wind speed and direction, height of building (taller buildings generally create a stronger stack effect which has a noticeable effect on radon levels in otherwise similar buildings) and ventilation habits in building (e.g. leaving upstairs windows open creates effective chimney effect; leaving downstairs windows open can create more “closed loop” circulation in occupied rooms with lesser suction up through floor & from soil). Other important factors are the level of floor space ventilation and the leak tightness of the suspended floor.

7. Much work has been done to investigate and develop models for seepage from soil, dilution & mixing in buildings in the contexts of radon, contaminated land and indoor air quality (see key evidence sources below), as well as in the direct context of flammable gases (e.g. via BG Research, now GL). This is an area of considerable complexity and the actual extent of dilution from concentration of gas in soil to that in the occupied part of a building will depend on many environmental, situational, weather and “pattern of use of the building” factors as well as on the physical characteristics of the building. We would need to explore a wide range of sensitivities to arrive at reasonable ranges/uncertainty bounds on such dilution. Making a reliable prediction from simple building features assessable by a building owner is unlikely to be feasible, though may enable the range of uncertainty to be narrowed considerably.

8. Various physical models of gas entry to and dilution in buildings are available, e.g. the Environment Agency’s CLEA model for contaminated land. A particularly useful document is CIRIA Report C665 “Assessing risks posed by hazardous ground gases to buildings”,

which is the updated version of the work done post-Loscoe, with the benefit of the CLEA model and supporting evidence. Also mentioned was the "Johnson and Ettinger model" which is referenced in many gas entry models and is used as the core of the CLEA model.

9. We had a useful discussion of what me might be able to learn from the English Housing Survey (EHS) and its Scottish, Welsh and Northern Ireland counterparts (note from subsequent discussion with Julian Delic at HSE – Northern Ireland need not be specifically addressed within the scope of our current project). BRE carry out the EHS for the Department for Communities & Local Government, and have accumulated a database of some 20-30,000 dwellings in England, all strictly anonymised. This will include features of interest for us such as
   a) age of building
   b) number of basement rooms
   c) main fuel used.
   d) floor type and condition (indicative of ventilation levels)
   Mentioned using Kevin White (whitekj@bre.co.uk) as a point of contact for questions on the EHS.

10. With roughly 1 in 1000 homes using LPG as their main fuel, it may be possible to extract a subset of data on perhaps a few hundred LPG users' buildings. We would NOT be able to have their addresses as the surveys are strictly confidential. Next steps to developing this as an information source will be to get hold of the publicly available data and explore what we can extract from it ourselves, then to talk further to Richard's team about what we would most like to learn and how to extract it.

11. Andy explained the work done on indoor air quality, which covers a wide range of contaminant sources including seepage from the ground. As in other areas of BRE's work there is a natural tendency for the majority of buildings they see to be those experiencing some sort of problem. A survey of 900 homes was carried out in 1999 which has proved very useful in providing a balanced picture of relative incidence of particular features/issues across the UK.

12. Cavity walls are not likely to lead to major gas seepage into the occupied space as external walls will typically be leakier than internal walls. Cavity walls can result in larger radon concentrations in roof spaces than in the rest of the house; this may also apply to LPG concentrations.

Evidence Sources and Next Steps

- **Radon**: Contact HPA, who offer a free service to measure radon in homes, to explore what data may be available on measured concentrations in soil and in occupied rooms for UK homes. TT to progress.
- **Contaminated Land/Landfill gas**: First step to obtain CIRIA report C665 (TT – in hand via HSE library). May then be worth contacting Environment Agency to explore particular aspects and/or supporting evidence
- **Indoor air quality**: Probably not a priority at present; start with CIRIA C665 and CLEA.

- **English Housing Survey**: Explore publicly available data (MH) then revert to BRE (TT/MH) to discuss what we can learn on LPG users' buildings from this.

Conclusions for Risk Model and HSE Project

The idea that a householder may be able to answer a small number of easy questions on the basis of which a good percentage could be classified as "zero risk" is probably illusory, as gas behaviour in soil/buildings is too complex to make such statements without considerable detailed assessment of local building features, environment and use.

There should be a good chance, though, of being able to estimate the dilution factor from LPG in the ground to LPG in the occupied rooms of a building using physical models of the building and the gas transport and mixing processes in it. The preferred approach is likely to involve using simple models of gas transport and mixing, along with broad exploration of sensitivity to the various parameters that could make a significant difference. The result for any building would be a broad band of plausible values of dilution factors, which could then hopefully be validated against such empirical evidence as was available – radon measurements in soils and buildings appears the most promising avenue in terms of direct comparison with measured dilution factors, while the CIRIA report C665 is the most promising avenue in terms of collected assessment models based on other evidence.

The other key area to emerge from this discussion was the potential for use of the English Housing Survey (and its Scottish & Welsh counterparts) to provide a database of a few hundred properties using bulk LPG. We should explore this vigorously as it may provide us with a "backstop" option if for any reason our proposed "mini survey" of LPG users' homes cannot be carried out.

Tony Taig
TTAC Ltd
10 July 2009

Appendix 2: Steady State Diffusion into an Infinite Sphere of Soil

A2.1 Assumptions

Leak takes place at rate	Q	m^3/hr
into a well-mixed spherical void of radius	r_0	m
within which average [LPG] at steady-state =	C_0	vol %
Effective diffusion coefficient =	D	m^2/hr

A2.2 Method

(a) Calculation of C(r)

At steady state, flux F through any radius r greater than r_0 is equal to Q

But

$F = D.A.dC/dr = Q$ (Fick's Law)

and

$A = 4\pi r^2$

So

$$F = \frac{4 \pi D}{r^2} . \frac{dC}{dr} = Q$$

So

$$\int (4\pi D/Q)\, dC = \int dr/r^2$$

which gives

$C = C_0 - (Q/4\pi D) (1/r_0 - 1/r)$

BUT at $r = \infty$, $C = 0$, so

$C_0 = Q/(4\pi D r_0)$

(b) Calculation of Q_{max}

Qmax, the maximum flux that can be removed by diffusion, is obtained when $C_0 = 1$ (pure LPG).

Hence $Q_{max} = 4 \pi D r_0$

(c) Footnote: Effective Diffusion Coefficient of Propane in Soils

D (free air)	0.13	cm^2/s

D (free air) 0.0468 m^2/hr

From Johnson (API 2002, ref 12 of main report), range of D_{eff}/D is from
0.1-0.2x (coarse sandy soils), down to
0.02-0.04x (moist clay soils), where D_{eff} is effective diffusion coefficient in soil

====> range of D_{eff} of 0.02 to 0.2 x D(free air) = 0.000936 to 0.00936 m^2/hr

A2.3 Results

(a) C_0 falls off as soil particle size rises

Table A2.1: Calculated C_0

Q = 0.001 m3/hr

D = 0.01 0.001

r	Sandy Soil	Wet Clay Soil
0.5	0.015915	0.159155
1	0.007958	0.079577
2	0.003979	0.039789
3	0.002653	0.026526
4	0.001989	0.019894
5	0.001592	0.015915
6	0.001326	0.013263
7	0.001137	0.011368
8	0.000995	0.009947
9	0.000884	0.008842
10	0.000796	0.007958

(b) Q_{max} rises as soil particle size rises (see also Figure 6 in report main body)

Table A2.2 Calculated Q_{max}

	r_0, metres	Sandy Soil	Wet Clay Soil	*Typical % sand (% air from 2mm up)*	Typical Qmax
(clay)	1.00E-06	1.26E-07	1.26E-08	*0*	1.26E-08
	2.00E-06	2.51E-07	2.51E-08	*0*	2.51E-08
(silt)	4.00E-06	5.03E-07	5.03E-08	*0*	5.03E-08
	8.00E-06	1.01E-06	1.01E-07	*0*	1.01E-07
	1.60E-05	2.01E-06	2.01E-07	*4.76837E-07*	2.01E-07
	3.20E-05	4.02E-06	4.02E-07	*1.43051E-06*	4.02E-07
(sand)	6.40E-05	8.04E-06	8.04E-07	*3.33786E-06*	8.04E-07
	1.28E-04	1.61E-05	1.61E-06	*7.15256E-06*	1.61E-06
	2.56E-04	3.22E-05	3.22E-06	*1.4782E-05*	3.22E-06
	5.12E-04	6.43E-05	6.43E-06	*3.00408E-05*	6.44E-06
	1.02E-03	0.000129	1.29E-05	*6.05583E-05*	1.29E-05
(grit+)	2.05E-03	0.000257	2.57E-05	*0.000121594*	2.58E-05
	4.10E-03	0.000515	5.15E-05	*0.000243664*	5.16E-05

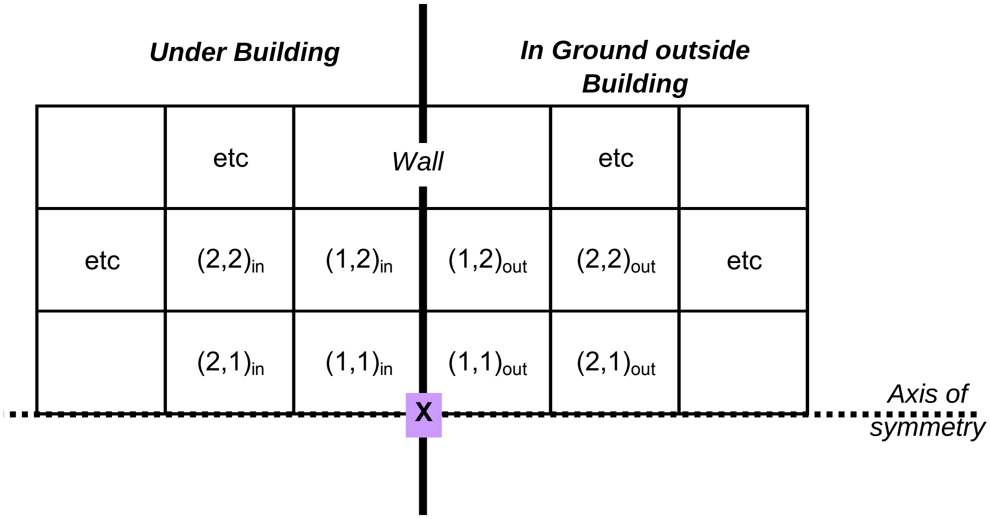
[end of App 2]

Appendix 3: 2-D Diffusion Model under Slab

A3.1 Assumptions

1. LPG is assumed to be trapped in a layer of soil extending from the source depth H_s down to an impermeable barrier (e.g. a ground water layer) at depth H_w.
2. LPG is transported in the X (perpendicular to wall) and Y (along wall) directions by Fickian diffusion through soil.
3. This is modelled via a series of square cross-section cells (i.e. equal x,y lengths of each cell) of uniform thickness.
4. LPG is released from a source at point (0,0) at a steady rate Q units/hr (e.g. kg, g mol).
5. The system is symmetric around the X axis (the line perpendicular to the wall passing through the source point).
6. Underneath the building, LPG can transfer ONLY between adjacent cells and cannot escape from the LPG layer.
7. Outside the building, the user has an option either
   a) to treat LPG as trapped in the same layer as that under the building, or
   b) to allow LPG also to diffuse to the soil surface whence it is lost to air.

The situation is illustrated schematically in the plan view below.



A3.2 Method

The net flux into a given cell within the LPG layer over a short interval of time is modelled as the sum of

- Net flux in from X direction (flux in from cell nearer to source – flux out to cell further away)

plus

- Net flux in from Y direction (flux in from cell nearer to source – flux out to cell further away).

From Fick's Law, this flux δq_{ij} into element $(i,j)_{in}$ in time δt is given by

$$\delta q_{ij} = (D.\delta t.A_X)\ .\ \{(c_{i-1,j} - c_{i,j}) - (c_{i,j} - c_{i+1,j}) + (c_{i,j-1} - c_{i,j}) - (c_{i,j} - c_{i,j+1})\} / \delta x$$

$$- D.\delta t.A_z.c_{i,j} / H_s$$ (outside building only; can be switched off by user)

where terms are defined as follows:

		Units
δq_{ij}	is the net flux of LPG into cell (i,j) over time interval δt	mass or gmol
D	is the effective diffusion coefficient of LPG in soil	m^2/hr
A_x	is the flow area between cells (= height x width)	M^2
c_{ij}	is the concentration of LPG in cell (i,j) at time t	flux units/m^3
A_z	is the x-sectional area of a cell for vertical transport	M^2
H_s	is the depth of the source below the soil surface	M
δx	is the distance between centre points of adjacent cells	M
	(special case: $\delta x(1,1) = \delta x / \sqrt{2}$)	

Then

$\delta c_{ij} =$ $\delta q_{ij} / (A_z . (H_w - H_s))$

where H_w = depth of impermeable boundary below layer of LPG

Special cases apply at the boundary cells as follows:

(1,1)	$Q_{in} = 0.5 \times Q$	(either side of the axis of symmetry perpendicular to the wall
(i,1)	$Q_{in,y} = 0$	(concentrations equal either side of axis of symmetry)
(1,j), j=2,N-1	$Q_{in,x} \equiv C_{(1,\ j)out} - C_{(1,\ j)in}$	Where N is the outermost cell modelled
(i,N)	$C_{out,y} = 0$	
(N,j)	$C_{out,\ x} = 0$	

After some exploration of alternative ways of solving the equations for 2NxN cells (modelling cells outside the building separately from those under it), the equations were set up in Excel to solve for N=20 and up to just over 500 time steps. (This combination enabled time steps to be modelled as successive columns over 2 sheets within Excel, and 800 cells to be modelled in 800 rows). The following parameters were adjustable by user input:

- The source depth H_s, impermeable lower layer depth Hw and cell length/width δx
- Soil type (coarse/sandy, loamy/mixed or clay/silt) and moisture (generally dry, modest moisture or moist/wet)
- The LPG ingress rate Q m3/hr at NTP and time step δt for the calculation, and
- A "toggle" to turn diffusion up to the surface outside the building on or off.

A3.3 Results

The figures below show results for more rapid diffusion (dry sandy soils) and slower diffusion (wet clay soils) for a leak rate of 0.01 m3 LPG per hour, in terms of

- Build-up of LPG concentration in soil air below the building over a period of 1 week (it is considered unlikely that steady conditions would persist for longer periods), with a series of concentration/time curves shown for different average distances from the leak source (Figure A3.1)
- Concentration of LPG as a function of distance under the building or out from it, at different lateral distances (along the wall) from the leak source, after one week (Figure A3.2), and
- Concentration of LPG in soil at the wall or foundation of the building, as a function of distance along the wall (Figure A3.3).

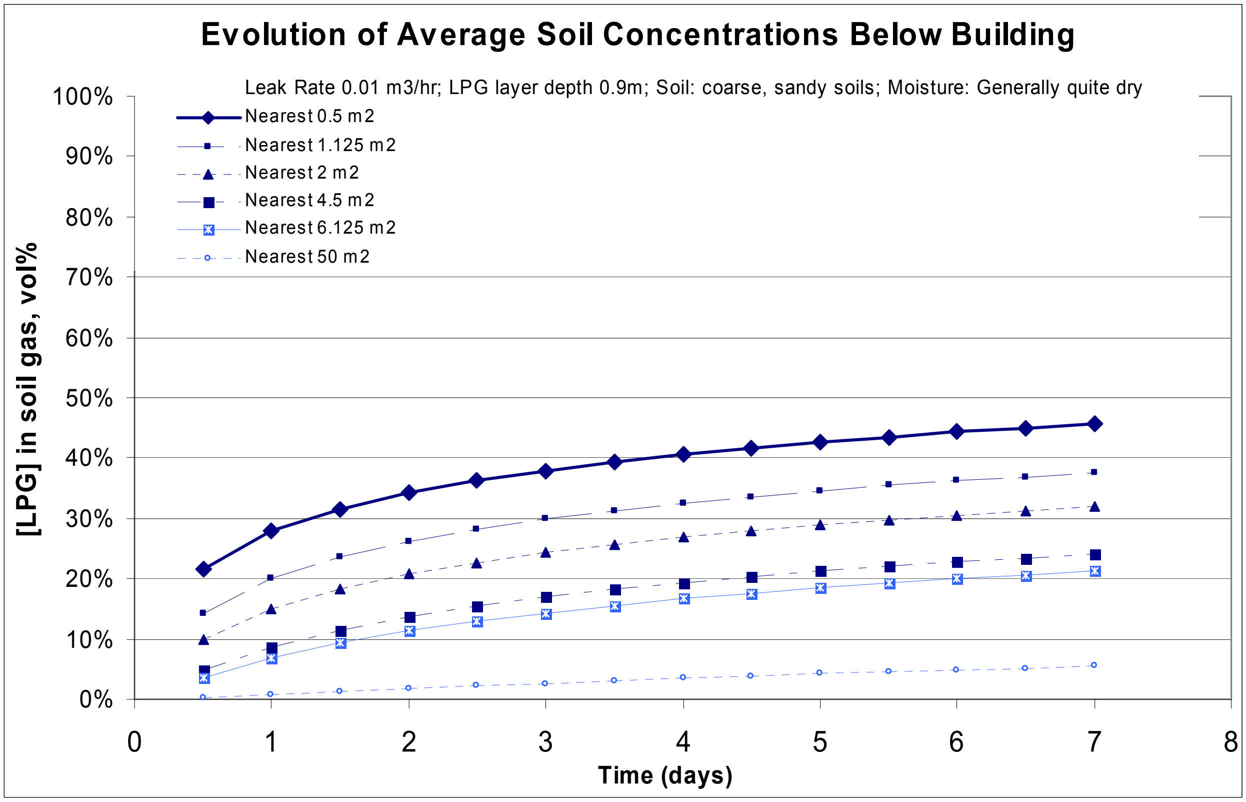
Significant observations from these figures include:

1. Diffusion is a slow process; even in the more rapid cases (upper figures) it takes many days to build up LPG concentrations under a building, and a steady state is not reached within a week.
2. As would be expected, more rapid diffusion leads to higher concentrations of LPG at some distance from the leak source after a given period of time, but the general observation (which is robust to a wide variety of input parameters) is that concentrations in soil fall off rapidly with distance from the source. [Note – this is with the assumption that the LPG is 100% trapped within a layer of soil below the house – introduction of mechanisms for LPG to be lost either further below ground or upwards into the building or outside it would further increase the rate of fall-off of soil concentration with distance from the source].
3. Slow diffusion represents the most pessimistic circumstance in terms of creating the potential to build up high concentrations of LPG in soil close to the leak source, with leaks of reasonable, modest sizes (well below the m3/hour levels of the Scottish incident in 2006) able to build up LPG concentrations of 100% (i.e. pure LPG) in soil close to the leak source.

These figures all have the toggle to permit LPG diffusion up to the soil surface outside the building switched off, and thus represent completely impermeable outside surfaces. Figure A3.4 shows the effect of switching this toggle on, i.e. switching to a permeable surface, for the most rapid diffusion case. The difference is small; for less rapid diffusion the difference is not detectable. Our conclusion from this is NOT that permeability of the outside soil surface does not matter (we know that it does), but that the mechanism by which LPG escapes through permeable surfaces outdoors is almost certainly via tracking along pathways in the soil (e.g. along the outside of the riser). We know that tracking is important; it will generally tend to reduce the estimates of soil concentration of LPG below buildings generated by this model.

[end of Appendix 3 text]

Figure A3.1: Build-up of LPG Concentrations with Time



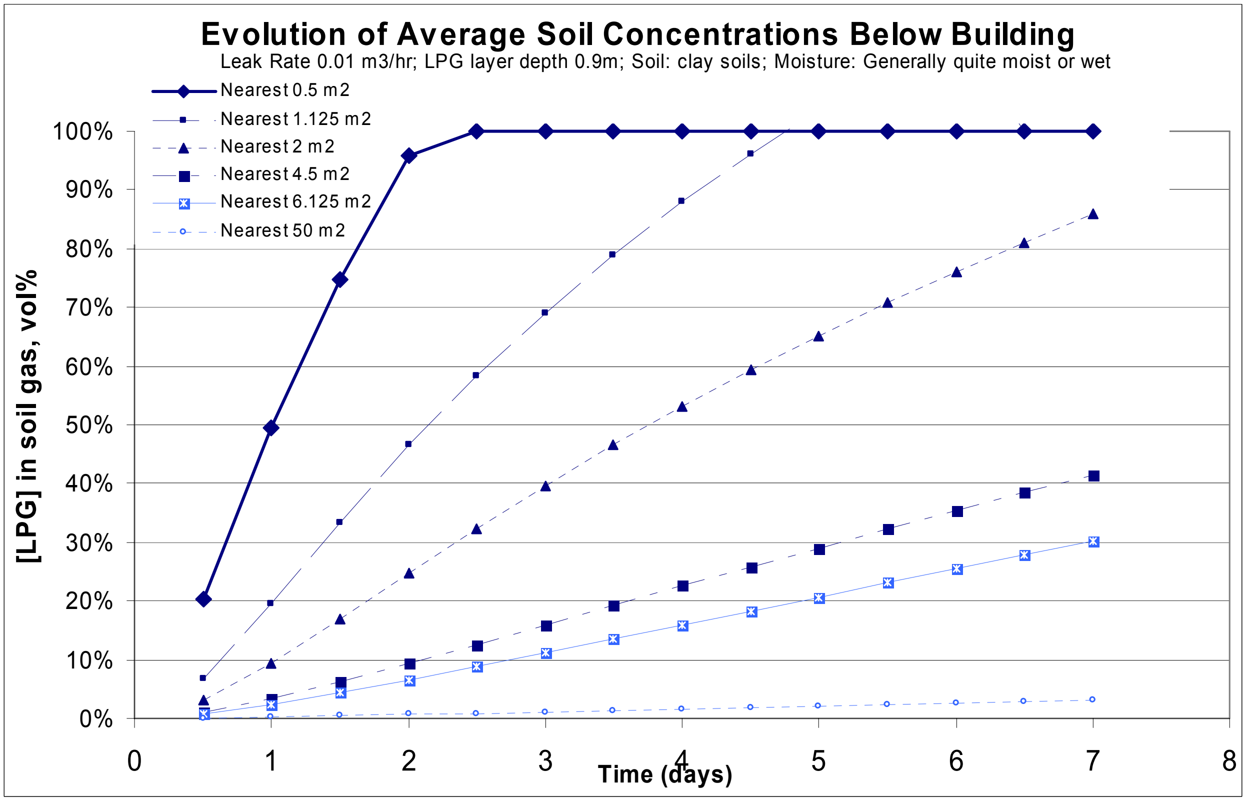
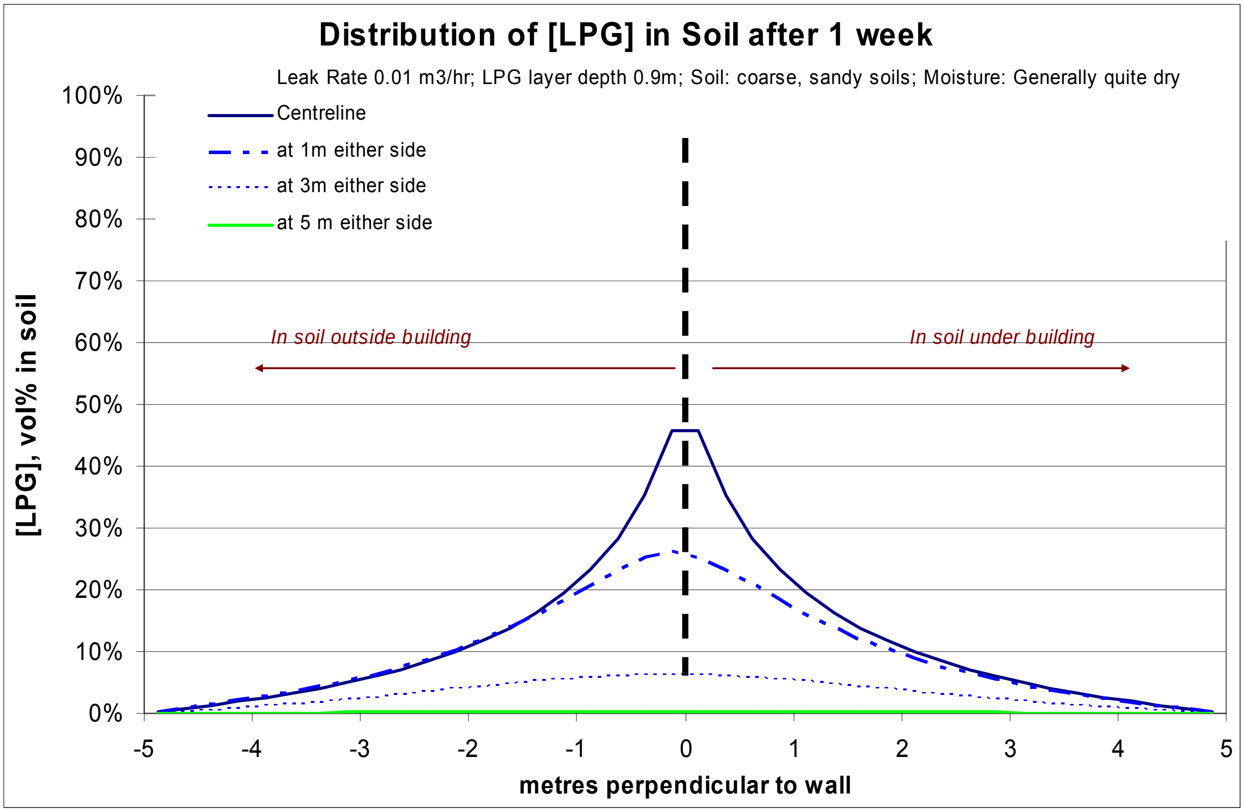


Figure A3.2 LPG Concentration in Soil Perpendicular to Wall after 1 Week



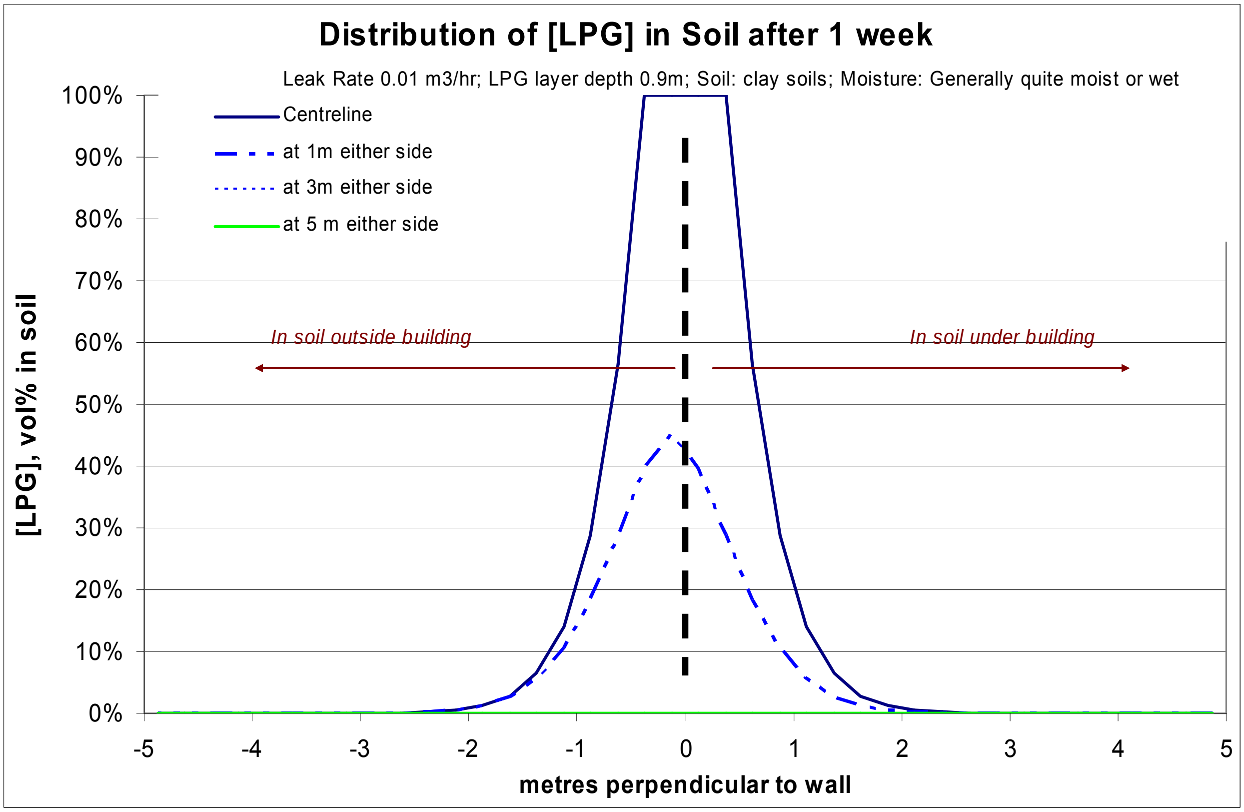
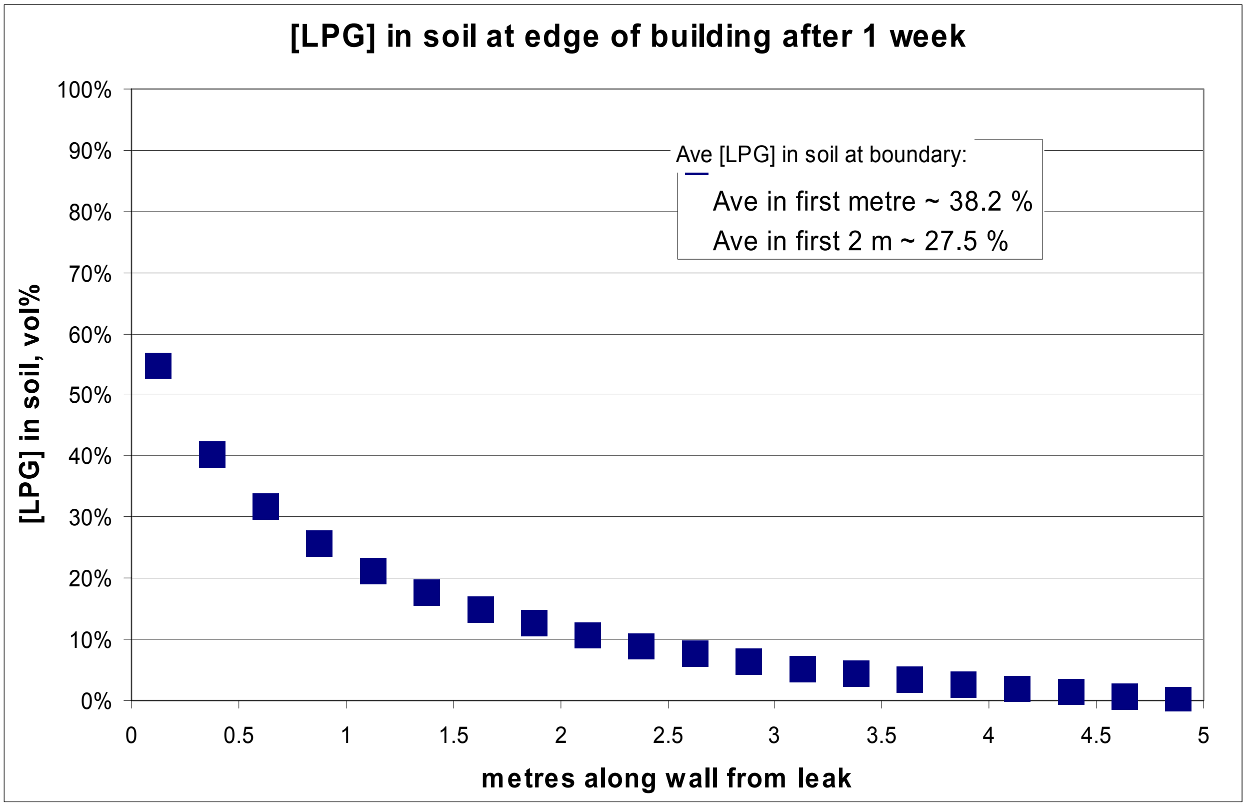


Figure A3.3 LPG Concentration in Soil Along Wall after 1 Week



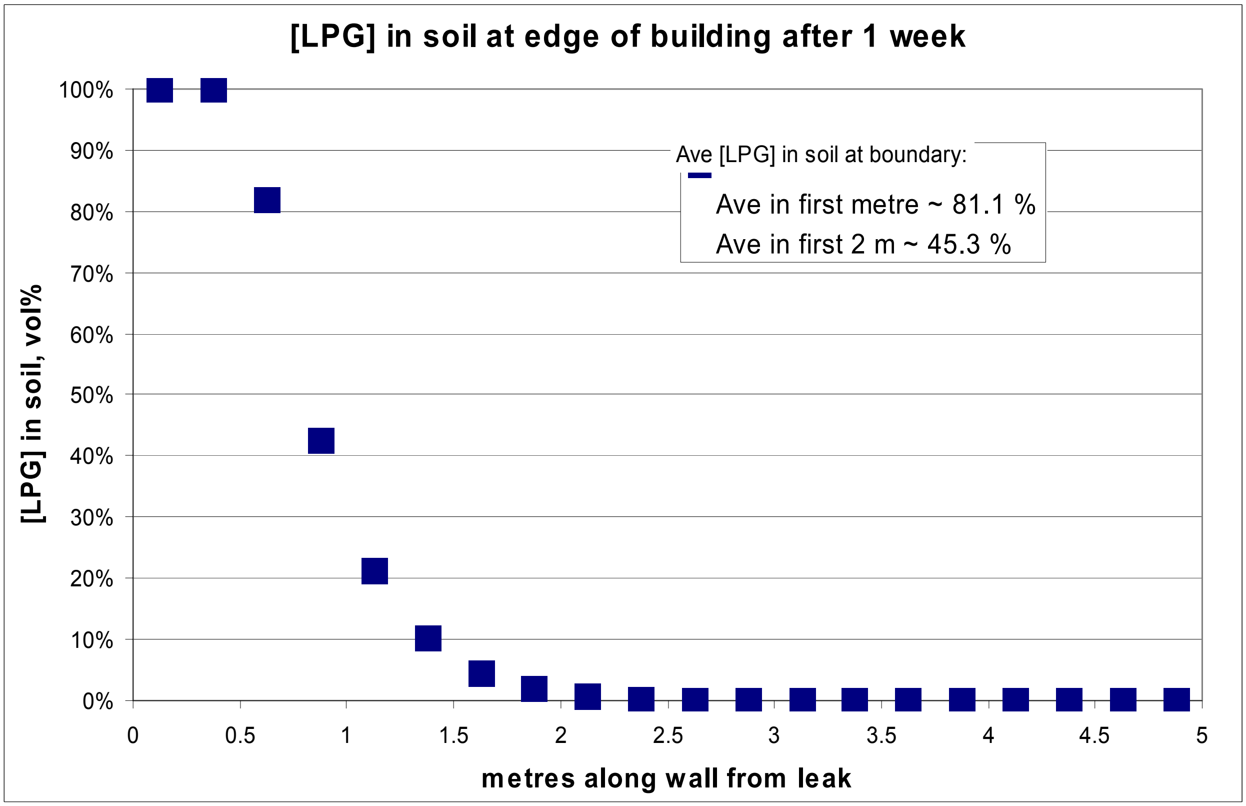
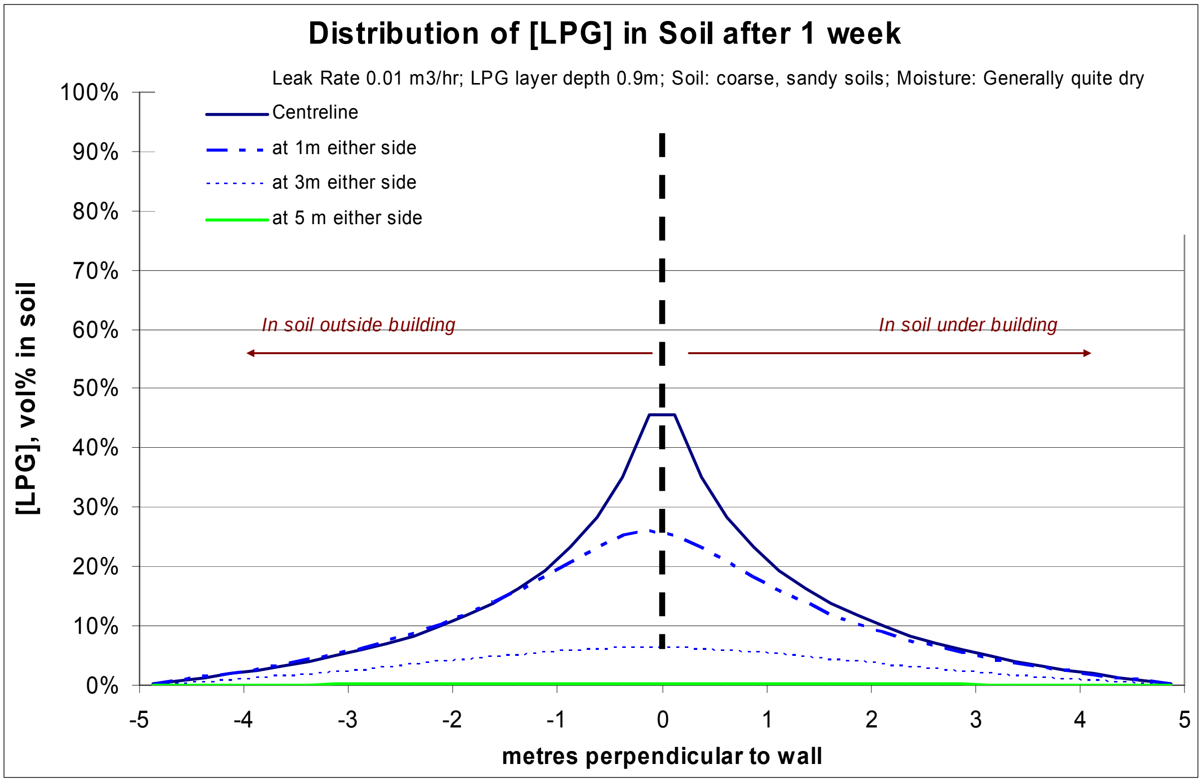


Figure A3.4 Effect of LPG Diffusion to Outside Air

(a) No diffusion (Impermeable)



(b) With diffusion (Permeable)