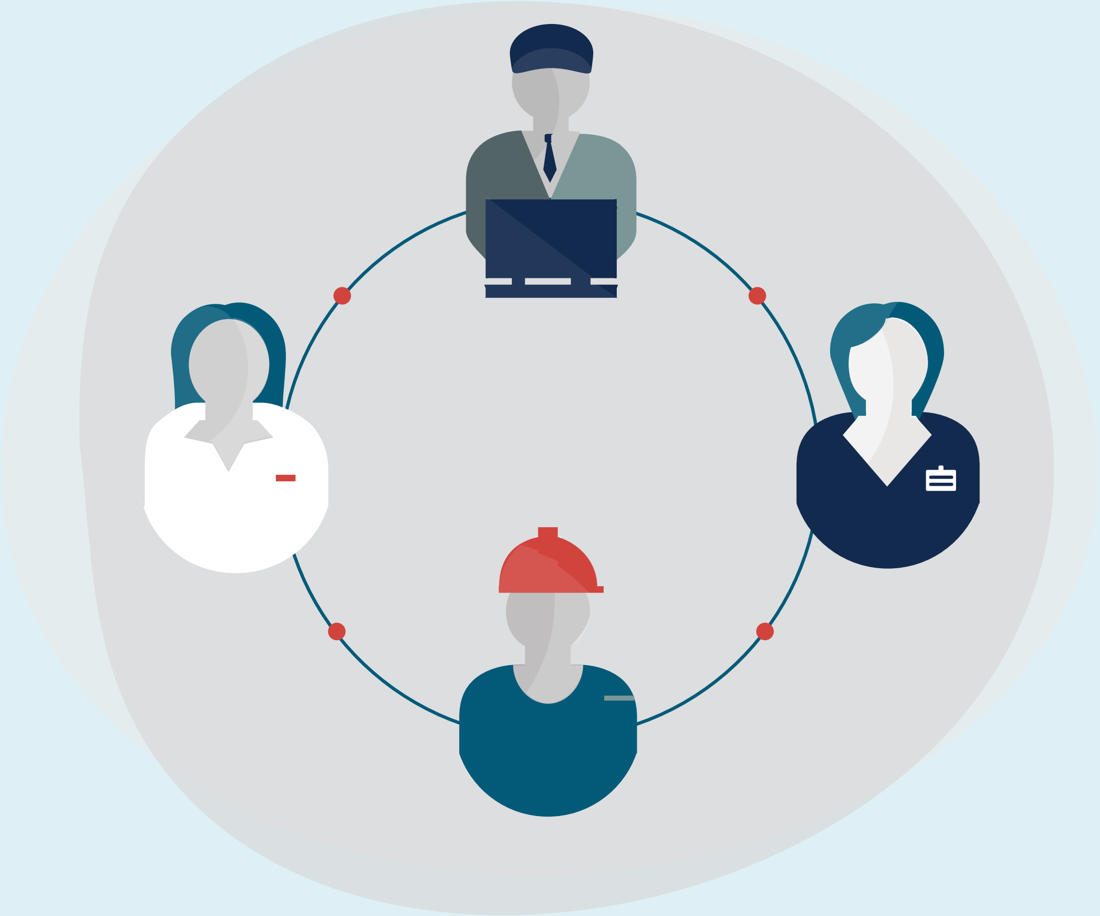
Hy4Heat
demonstrating
hydrogen for heat

Department for
Business, Energy
& Industrial Strategy

WORK PACKAGE 7

Safety Assessment:

Gas Escape Frequency and Magnitude Assessment



WP7 SAFETY ASSESSMENT

The Hy4Heat Safety Assessment has focused on assessing the safe use of hydrogen gas in certain types of domestic properties and buildings. The evidence collected is presented in the reports listed below, all of which have been reviewed by the HSE.

The summary reports (the Precis and the Safety Assessment Conclusions Report) bring together all the findings of the work and should be looked to for context by all readers. The technical reports should be read in conjunction with the summary reports. While the summary reports are made as accessible as possible for general readers, the technical reports may be most accessible for readers with a degree of technical subject matter understanding.

Safety Assessment:

Precis

An overview of the Safety Assessment work undertaken as part of the Hy4Heat programme.

Safety Assessment:

Conclusions Report

(incorporating Quantitative Risk Assessment)

A comparative risk assessment of natural gas versus hydrogen gas, including a quantitative risk assessment; and identification of control measures to reduce risk and manage hydrogen gas safety for a community demonstration.

Safety Assessment:

Consequence Modelling Assessment

A comparative modelling assessment of the consequences in the event of a gas leak and ignition event for natural gas and hydrogen gas.

Safety Assessment:

Gas Ignition and Explosion Data Analysis

A review of experimental data focusing on natural gas and hydrogen gas ignition behaviour and a comparison of observed methane and hydrogen deflagrations.

Safety Assessment:

Gas Dispersion Modelling Assessment

A modelling assessment of how natural gas and hydrogen gas disperses and accumulates within an enclosure (e.g. in the event of a gas leak in a building).

Safety Assessment:

Gas Dispersion Data Analysis

A review of experimental data focusing on how natural gas and hydrogen gas disperses and accumulates within an enclosure (e.g. in the event of a gas leak in a building).

Safety Assessment:

Gas Escape Frequency and Magnitude Assessment

An assessment of the different causes of existing natural gas leaks and the frequency of such events; and a review of the relevance of this to a hydrogen gas network.

Safety Assessment:

Experimental Testing - Domestic Pipework Leakage

Comparison of leak rates for hydrogen and methane gas from various domestic gas joints and fittings seen in typical domestic gas installations

WP7 SAFETY ASSESSMENT

Safety Assessment:

Experimental Testing – Commercial Pipework Leakage

Comparison of hydrogen and methane leak rates on a commercial gas pipework system, specifically the gas meter and equipment contained within the Plant Room of a MOD site.

Safety Assessment:

Experimental Testing - Cupboard Level Leakage and Accumulation

Comparison of the movement and accumulation of leaked hydrogen vs. methane gas within cupboard spaces in a typical domestic property.

Safety Assessment:

Experimental Testing - Property Level Leakage and Accumulation

Comparison of the movement and accumulation of leaked hydrogen vs. methane gas within a typical domestic property.

Safety Assessment:

Experimental Testing - Ignition Potential

Investigation of the ignition potential of hydrogen-air mixtures by household electrical items and a comparison with the ignition potential of methane-air mixtures.

Hy4Heat

Gas Escape Frequency and Magnitude Assessment

1.0 | 1 May 2021

Department for Business, Energy & Industrial Strategy

Hy4Heat

Gas Escape Frequency and Magnitude Assessment

KIW-WP7-HSE-REP-0001

1.0 | 1 May 2021

Document verification

Role	Name	Company
Prepared by	Paul McLaughlin James Thomas Sam Cottrill	Kiwa Gastec
Checked by	Iain Summerfield Sophie Brown	Kiwa Gastec Arup
Approved by	Mark Crowther Albert Law	Kiwa Gastec Arup
Programme Technical Review	Mark Crowther	Kiwa Gastec
Programme Management Review	Heidi Genoni	Arup
Approval to publish	David Cormie	Arup

Contact:

Paul McLaughlin

Senior Consultant

t: 01242677877

e: Paul.McLaughlin@kiwa.com

Kiwa Gastec
Kiwa House
Malvern View Business Park
Cheltenham
GL52 7DQ
United Kingdom

kiwa.co.uk

Contents

1 Executive summary

This gas escape frequency and magnitude assessment report is part of the Hy4Heat Safety Assessment suite of reports. Within the existing natural gas system, downstream of the emergency control valve (ECV), the gas escape (leak) causes and frequency has been captured and analysed. Understanding the frequency and causes of the leaks is critical to informing the overall safety assessment and Hy4Heat QRA. In order to capture the data a survey questionnaire was developed and completed by the First Call Operatives (FCOs) of the GDNOs who attended callouts of reported natural gas leaks. Key information that the survey gathered included for example the escape location, mechanism and cause.

This report sets out the work undertaken to inform the frequencies of gas escapes, for different types of escape, which informs the initiating events within the QRA. This work has assessed the differences between natural gas as is currently supplied and hydrogen, considering the differing fluid mechanics describing the escape scenarios.

Literature was reviewed to determine the existing body of knowledge on gas escape rates and frequencies. Whilst various figures are reported in national statistics and other publications, there was insufficient data to allow full construction of the QRA and therefore new primary research was required. This research took two main strands:

Firstly, a survey was built for gas company employees known as First Call Operatives (FCOs) to complete when responding to calls made to the Gas Emergency number to understand how many investigations are associated with escapes of unburnt gas, and to determine what mechanisms lead to such escapes. This survey was completed by FCOs from all four gas distribution network operators covering Great Britain, and 1,303 surveys were completed and the results analysed, identifying 911 relevant gas leaks with known causes.

As a result of this survey, an observation has been made that the gas smart meter implementation programme has resulted in a significant increase in the number of gas leaks associated with meter replacements. BEIS is aware of this issue, and it is associated with the number of meter replacements rather than an inherent issue with the type of meter.

Secondly, an extensive test programme was conducted assessing real failure mechanisms of gas pipework and fittings to understand the rates of gas escape that would occur for natural gas and hydrogen. These results demonstrate consistency with theoretical expectations for escapes equivalent to small cracks or large holes, or transitional sizes between. Significantly, this shows that a low-pressure system that is gas tight with natural gas is gas tight with hydrogen.

By combining the survey results database with the failure test programme results, an understanding of the likely frequencies of different gas escape rates for natural gas and hydrogen can then be drawn. These frequencies will be used in the QRA, with the consequences of such leaks assessed through other work within Work Package 7, to understand the dispersion of gas within domestic properties, and then to understand the potential for fires or explosions from such dispersed gas atmospheres.

The shape of the ensuing curve i.e. physical leak rate vs frequency of occurrence is a key element of the QRA.

Out of ~900 data points, only a few leaks (about 3%) are considered large enough to generate a flammable atmosphere in a simple model room with either hydrogen or natural gas. It is not possible to generically relate leak size to concentration (as the latter is a function of room size and ventilation) and this is discussed at length within the dispersion modelling report. But by way of exemplar, data is reported (see Appendix 8 & Figure 14) pertaining to the concentration level expected if these leaks had occurred in the kitchen at DNV GL Spadeadam.

If the gas was methane there would have been 22 off giving a concentration in excess of 8%, and if it were hydrogen there would have been 5 off between 8% and 15% and 17 off over 15%.

Having presented these apparently large numbers it must be noted that the occurrence of spontaneous large leaks is tiny. Internal gas pipes (operating at 20 mbarg) almost never suffer major structural failure without external stimulus, for example a DIYer with a drill or a builder with a saw. In the case of such human driven damage, the FCO data shows that most people follow the correct response i.e. open a window, turn the gas off and phone the gas leak hot-line. Possibly surprisingly this level of correct response is higher than often found in industry; most likely due to the relative simplicity of the situation. A person causing damage to a pipe will hear and/or smell gas and take action; industrial sites involve levels of responsibilities and the complexity of control rooms.

2 Introduction

A fundamental part of the work to develop a representative gas system quantitative risk assessment is determining the frequency at which hazardous base events are likely to occur, and to quantify the kind of consequences that would follow for such events. This section of the work considers gas escapes as found within the existing gas system where there is the potential for such gas to build up within a domestic property.

The information that is required can be described as follows:

- How often do escapes occur?
- What is the distribution of escape sizes?
- How would hydrogen differ from natural gas?

It is a key aspect of this work that it considers build-up in domestic properties. Releases of gas due to escapes from the distribution system are being considered as part of the Ofgem Network Innovation Competition (NIC) funded H21 programme and are outside the scope of the Hy4Heat project. Conversely, the scope of H21 research ends at the Emergency Control Valve, therefore escapes from downstream need to be considered here.

In this work, the words “leak” and “escape” are both used to describe both intentional (malicious) and unintentional (accidental) releases of unburnt gas. Incident reporting by the HSE uses the former, while the gas industry uses the latter within its procedures. Some of the literature uses both interchangeably. No attempt has been made to differentiate between the terms as the difference in usage between them is not consistent.

This work is associated with Lot 1 of WP7 and the Integrity / Leak Scenarios segment of the Hy4Heat QRA – Non-site-specific work as shown in Figure 1.

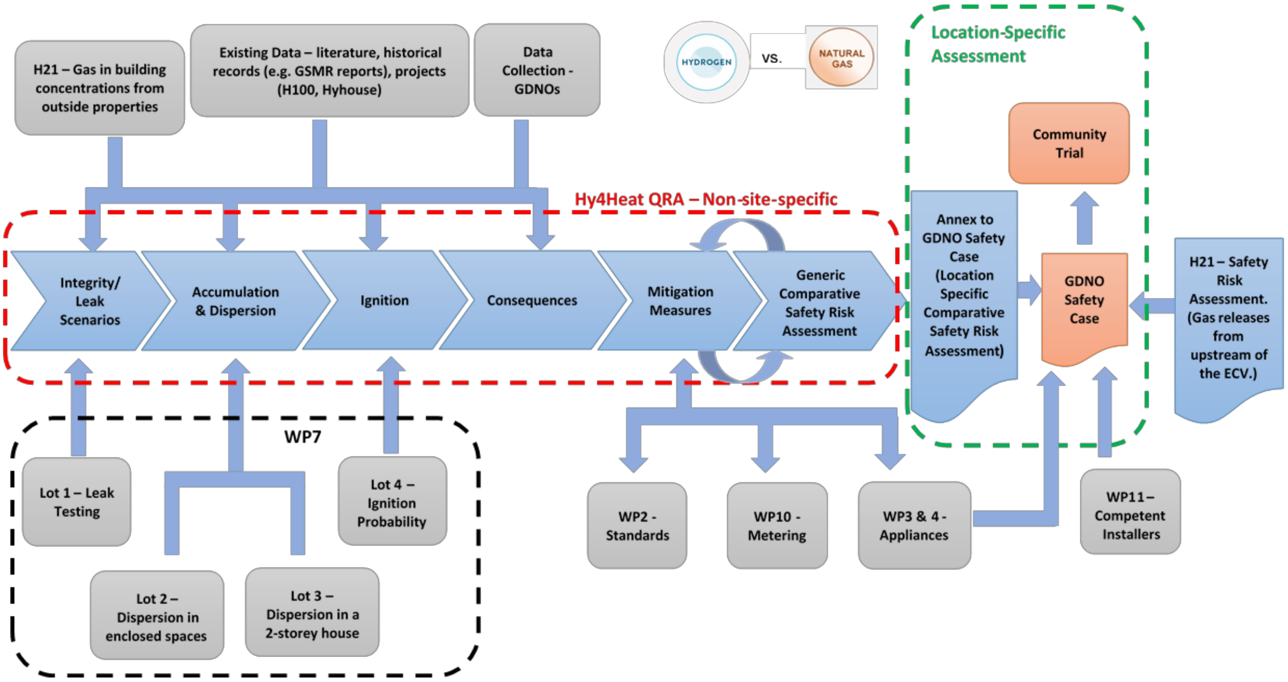


Figure 1: WP7 safety assessment – illustrative approach

3 Literature review

There is a longstanding interest in understanding the causes, frequencies, and magnitudes of flammable gas leaks, from various parties and for various applications. This has driven theoretical and experimental work which has been published in a range of literature. It is important to ensure that the literature is appropriate to the scope of Hy4Heat, namely domestic scale systems consisting of low diameter pipework containing low pressure gas.

Whilst large amounts of failure data are published for conducting risk assessments in the chemical and oil and gas industries, high hazard installations do not align closely to the domestic scale. Therefore, this section focuses on the literature that is relevant to the domestic scale, which are primarily related to investigations into incidents that have occurred.

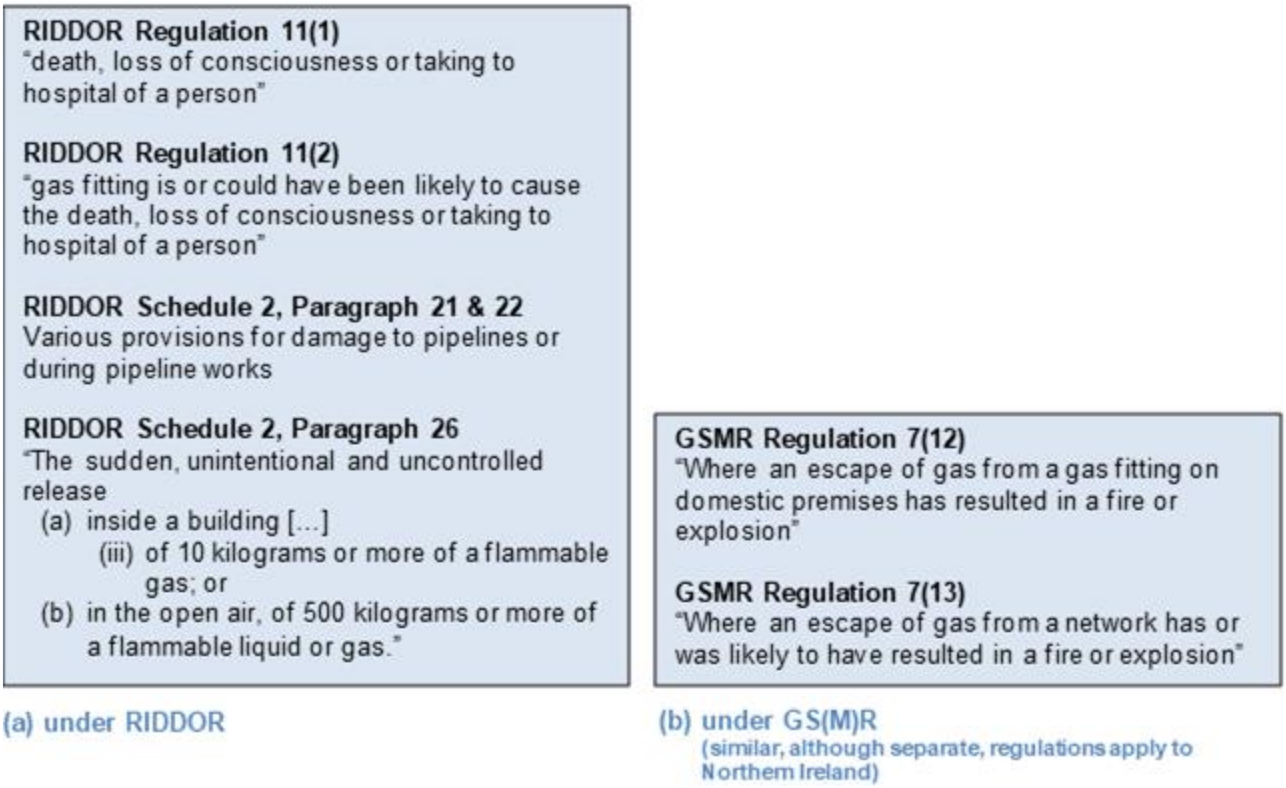
A series of high-profile fires and explosions in the 1970s led the former Department of Energy to commission an inquiry into their circumstances [1]. This inquiry aimed to determine whether there was any common cause between explosions. Moreover, the five-year long time period that the inquiry covered included both natural gas and hydrogen-containing town gas as was used historically. The inquiry concluded that there was no change in the numbers of explosions or the number giving rise to fatalities when comparing the two gases, despite their physical properties differing.

Over the period from 1972 to 1977, the causes of explosions that occurred were attributed to locations as shown in Table 1. This table allows an understanding of the relative likelihood of leakages to occur from different places in the gas system, as reported in this time period in the 1970s.

Table 1: Summary of analysis of explosions known to be due to gas, by cause, 1972-1977

Location	Total explosions	Percentage of total
Mains	123	23%
Services	49	9%
Meter area	83	15%
Installation piping	110	20%
Appliances	162	30%
Cause not known	10	2%
Total	**537**	

Current practice requires the reporting of various categories of dangerous occurrences to be made to the Health and Safety Executive under the Reporting of Injuries, Diseases and Dangerous Occurrences Regulations (RIDDOR) [2]. The reasons for reporting are defined directly within RIDDOR, with addition reasons contained within the Gas Safety (Management) Regulations [3] as summarised in Figure 2.



RIDDOR Regulation 11(1)
"death, loss of consciousness or taking to hospital of a person"

RIDDOR Regulation 11(2)
"gas fitting is or could have been likely to cause the death, loss of consciousness or taking to hospital of a person"

RIDDOR Schedule 2, Paragraph 21 & 22
Various provisions for damage to pipelines or during pipeline works

RIDDOR Schedule 2, Paragraph 26
"The sudden, unintentional and uncontrolled release
(a) inside a building […]
(iii) of 10 kilograms or more of a flammable gas; or
(b) in the open air, of 500 kilograms or more of a flammable liquid or gas."

(a) under RIDDOR

GSMR Regulation 7(12)
"Where an escape of gas from a gas fitting on domestic premises has resulted in a fire or explosion"

GSMR Regulation 7(13)
"Where an escape of gas from a network has or was likely to have resulted in a fire or explosion"

(b) under GS(M)R
(similar, although separate, regulations apply to Northern Ireland)

Figure 2: Reportable gas escapes

This set of statistics is designated as a National Statistic according to the UK Statistics Authority, and published on the HSE website [4], and updated annually. Within this data set, the tables designated as RIDGAS (Gas-related incidents reported in Great Britain) contain details of incidents associated with natural gas and LPG systems over the previous five-year period.

It is informative to compare the reported incidents over the five-year period from 1972-1977 with the five-year period from 2014-2019 using these two sources. Table 2 of the inquiry report reports the number of explosions causing severe damage, while Table 1 of RIDGAS reports the number of fire/explosion incidents that give rise to injuries. Over the period in the 1970s, a total of 144 such incidents occurred, whereas 132 incidents occurred in the period in the 2010s. Given that there were differences in definitions and the underlying increase in Great Britain population over this period, the numbers appear similar, and are not suggestive of significant changes in the number of incidents over this approximately thirty-year interval.

More importantly, these two data sources also include the number of fatalities due to gas explosions. These figures show a marked difference. Over the period from 1972-1977, a total of 57 fatalities due to explosions were reported i.e. (<12/yr), whereas over the period from 2014-2019, the total reported was 3 (<0.5/yr). It is not possible to determine how much of this near 20-fold reduction is due to improvements in gas systems and how much is due to improved medical treatment or other extrinsic reasons.

Further details of fatalities associated with gas are reported by HSE, within the workplace fatality data [5] with 2016-2017 being the last year where data for fatalities have been published. These figures are consistent with RIDGAS, with one fatality due to fires or explosions within the common time period of coverage. Where they differ is in the number of carbon monoxide fatalities, due to some of these cases resulting from use of LPG. Combustion of hydrogen does not carry the potential to produce carbon monoxide.

Further analysis of reporting to specifically understand the impact of piped gas rather than bottled gas required unclassified but unpublished information obtained under a Freedom of

Information Request directly from the HSE [6]. The data supplied describes incidents reported under the requirements of the Gas Safety (Management) Regulations (GS(M)R) [3] (Figure 2), associated with piped natural gas. This excludes bottled gas supplies but covers a narrower time frame. Table 2 summarises the incidents described in this report, showing that between 6% and 10% of reported incidents result in injuries.

Table 2: GS(M)R data, 2016-2019

Gas year	GS(M)R reported incidents	Incidents with injuries	Percentage of GS(M)R incidents with injuries
2016-2017	287	28	10%
2017-2018	263	17	6%
2018-2019	230	13	6%
Total	**780**	**58**	**7%**

3.1 Literature conclusions

Overall, reviewing the information in the literature showed that whilst there is an understanding of what has caused each RIDDOR reportable gas incident [6], these are events that have been allowed to escalate beyond the initial point at which gas started to leak from the system. A full understanding of the characteristics of gas leaks requires consideration of occurrences that have not developed to such a level that RIDDOR reporting requirements are activated.

To address the gaps in knowledge as to how large gas leaks that occur are, and how frequently such leaks happen, a survey of gas First Call Operatives (FCOs) was envisaged. FCOs are the specialist gas engineers dispatched by gas distribution network operators to investigate reports made by members of the public to the Gas Emergency Number (0800 111 999). These engineers are trained to respond to emergency reports and make them safe. Due to their experience of gas work and following existing procedures to record their work, they were deemed to be the most appropriate people to request further information from.

4 Research methodology

Figure 3 shows the overall flow of work carried out to develop an empirical evidence base to understand the potential for flammable gas leaks to give rise to flammable atmospheres in buildings.

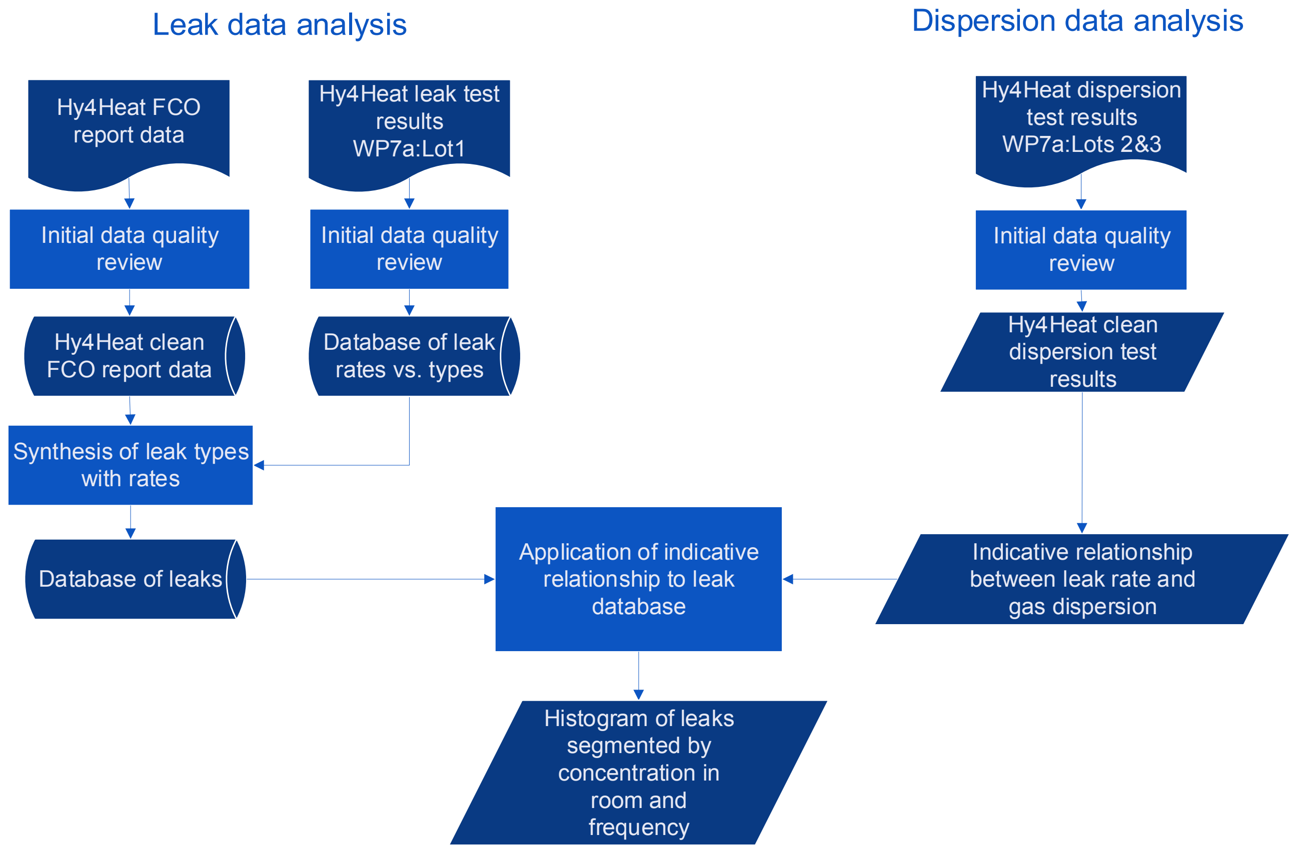


Figure 3: Process flow diagram

A survey to collect information from the FCOs investigating emergency calls was developed as the first part of this work implemented in an electronic format to allow efficient completion by FCOs.

This was followed with attribution of leak rates based on research undertaken under Hy4Heat WP7 to investigate what quantity of gas would be reasonably expected to develop from different leak causes. This was then used to produce a database of leaks, describing the key expected frequency of different gas escape rates, to be used in the quantitative risk assessment.

A screening assessment comparing hydrogen and natural gas atmospheres that would be foreseen following different leak rates was conducted based on one model room size. This was informative only to allow sanity checking as to the impact of a change between the two gases and does not include the full range of layers of protection that the QRA will consider. This is described in Appendix 8.

4.1 Escape data collection

The collection and analysis of gas escape survey data was to provide a dataset representative of natural gas escapes, from consumers who are supplied with gas from the mains, in the following scenarios:

Escapes within the scope of the data collection were:

1. Downstream of (i.e. not including) the emergency control valve (ECV)

2. Upstream of the ECV, but located inside a building
3. Upstream of the ECV and not inside a building, but where gas tracked into a building.

This approach was chosen to ensure that the data is most comparable to hydrogen gas supplied via mains in the future. This dataset was designed to give an indicative understanding of the gas leak cause and potential gas build up parameters / scenarios in the home environment to a level detail not recorded in any existing GDNO or HSE databases.

This survey of escapes was then combined with information on the gas flow regimes and flow rates involved in various types of escape as described in section 4.2 below to produce a dataset of anticipated annual escapes and their flow rates for both natural gas and hydrogen.

The data collection and analysis process can be divided into four parts:

- Sources of data
- Constraints
- Survey development
- Sample size

- Training sessions
- Pilot session
- Expand to other locations
- Roll-out with email & video briefings

- Regular updates for stakeholders
- Check progress
- Maintain buy-in
- Check response quality

- Select responses in scope
- Categorise location, escape mechanism and cause
- Correct mislabelled responses
- QA testing of analysis accuracy

(* presented in the next section)

Figure 4: Data collection and analysis process

4.1.1 Design & build

4.1.1.1 Sources of data

Before the survey was designed, existing data collected by two GDNOs was examined and it was determined that further information would be needed. This additional data was then sourced through surveys of FCOs. The existing data primarily comprised:

- Compliance data, e.g.:
    - details of the FCO
    - arrival and departure time
- Work that was carried out, e.g.:
    - was work carried out on the meter?
    - is follow-up work required?
    - what gas concentrations were detected? (including measuring equipment details)
    - was a safety notice issued?

- Confirmation system was left in a safe state, e.g.:
    - was a CO survey completed?
    - was a final tightness test conducted?
    - was the gas supply isolated?

This existing suite of data was not deemed sufficient for Hy4Heat purposes and therefore in order to attribute flow rates of gas to each escape, further information was required, specifically:

- Escape location – where inside/outside the property and at what point in the gas system, e.g.:
    - hole in interior pipework
    - valve on gas hob appliance
    - fitting on meter
- Escape mechanism – the means of escape of gas, including an estimate of the flow rate of the escaping gas, e.g.:
    - a hole or cut in a pipe (including details of hole size)
    - through a threaded fitting
    - up a valve stem
- Leak cause – in the opinion of the FCO, e.g.:
    - corrosion or degradation
    - appliance left on but unlit
    - third-party damage

A full list of classifications is given in Appendix 2 – Escape classifications.

4.1.1.2 Constraints

In order to gather the required data, Hy4Heat designed a survey for FCOs to complete during call-outs involving gas escapes. The following constraints were identified:

1. **The survey could not interfere with the normal safety duties of the FCO.** It had to be carried out after the completion of work and not delay travel to their next call-out, so as not to affect the FCOs' emergency and investigation response times. It could not require a special device and had to comply with the GDNOs' security policies. As such, a mobile-friendly survey was selected, and the completed survey was tested to ensure completion times were less than five minutes.
2. **The survey had to be simple.** For the dataset to be representative, the survey would have to be rolled out across a number of FCOs and locations, with minimal training requirements and without affecting normal work pattern of FCOs. As such, only relevant questions were asked in the survey, dependent on the previous answers given; many options were via a dropdown box with an 'other' option allowing for more unusual occurrences to be entered manually.
3. **Some information would have to be inferred.** Whilst some information could be gathered by means of a direct question (e.g. size of the hole in the pipe), other information could only be gathered by proxy. As such, a number of supporting questions were asked that would later allow these determination to be made (e.g. the flow rate of a gas escape up a valve stem could be estimated using the results of a tightness test and assumption made based on the property type).

4. **Limited information on gas concentrations was available.** Although FCOs take measurements of gas concentrations, and the survey asked them to record these, it was recognised that householders would be asked to ventilate areas if safe to do so, so the measurements of gas concentrations in rooms would usually be lower than prior to the call-out.

4.1.1.3 Survey development for Hy4Heat

Hy4Heat devised an initial question list and survey logic. The survey used a web-based data collection tool. A mobile-friendly option was chosen to ensure FCOs could complete this easily on their existing mobile devices without the need to install any additional software. Screenshots are provided in Appendix 3 – Screenshots of Hy4Heat data collection tool.

Each question was included to provide a potential source of information (either direct or inferred), and detailed survey logic was set-up to ensure questions were only displayed if a relevant set of previous response was given. This initial survey went through several revisions, involving comment and review by Kiwa's Gas Safe training staff, GDNOs, FCOs and Arup.

The final version of the survey was tested using a group of trainee gas engineers at Kiwa's training centre, in a workshop that allowed for different scenarios to be created. Although they were not trained as FCOs, after a short briefing they were able to complete the survey to an acceptable level in an average of 4.4 minutes (the full range of response times was 3.5 to 5.0 minutes).

The final version of the Hy4Heat survey question list, along with background on the purpose of each question and survey logic are provided in Appendix 4 – Question list & survey logic.

4.1.1.4 Sample size

Of the total approximately 2.4 million annual calls to the Gas Emergency Number, approximatively 400,000 of these are confirmed by an attending FCO as being related to an escape of natural gas. As discussed in the literature review, each year around 200-300 of these natural gas escapes result in a GS(M)R report [6]. These will be the most serious of escapes, that caused or had the potential to cause a serious injury.[1]

It is useful to use these 200-300 most serious escapes as a means of calibrating the desired sample size. Assuming these serious escapes are randomly and uniformly distributed amongst the annual total, a simple statistical model predicts a sample size of 10,000 would likely lead to around six of these serious escapes being included in the sample.[2]

Whilst it is not necessary to include these serious escapes within the sample (as they are reported elsewhere), seeing them in the sample would provide a useful indication that the sample size was large enough to capture at least some of the rarest of escapes, and thus provide confidence in its representativeness.

Reflecting on this and the above constraints on the practicable disruption to FCOs, a minimum sample size of 1,000 survey responses was chosen, with a desire to collect somewhere between 1,000-10,000 responses in total. The 1,000 minimum size would result in an approximately 50% chance of a GS(M)R reportable incident being found in the

---

[1] A full list of notification requirements is shown in Figure 2.

[2] There is a 95% probability of being 2-11 serious escapes in the sample. A statistical treatment is given in Appendix 5 – Simple statistical model of serious gas escapes.

sample set. As these incidents are already investigated to a greater degree than other gas escapes, it was deemed to be more important to ensure that escapes of a smaller than GS(M)R reportable size were characterised. By applying the assumption that small escapes will be more common than large escapes, the minimum sample size of 1,000 would result in an expectation of revealing more information than was known before undertaking the survey.

4.1.2 Deployment

4.1.2.1 Training sessions

A training session was developed for FCOs and FCO team leaders. Two to three hours in duration, each session consisted of:

- an introduction to hydrogen as an energy vector, its properties and the potential for using it in the gas network;
- an introduction to the Hy4Heat programme, particularly the value in collecting this data for the QRA in Work Package 7;
- a walkthrough of the survey, including setting the survey up on FCO mobile devices and practices on a test version of the system;
- feedback from FCOs and team leaders.

The first training session was, as a pilot, held with one group of FCOs who were part of a single GDNO depot. From the FCO feedback, minor modifications to the survey were made after this session, including adding additional options to dropdown selection boxes.

After a review of response rates and the data collected, the survey training session was rolled out to additional depots at that GDNO, and then to other GDNOs. To provide an even wider group of FCOs collecting data, email and video briefing options were also developed as an alternative to in-person briefings and were used at the later stages of data collection. Survey responses from these training cohorts did not show significant differences, indicated by consistency between them and the other areas.

4.1.3 Collection

Survey data was regularly downloaded, grouped by GDNO and depot, and collated by week received. The data was then reviewed to check response levels from each area, and an initial analysis was performed to show the distribution of escape locations that were being collected.

The data was summarised and conveyed weekly to stakeholders via a set of dashboards,[3] an example of which is provided in Appendix 6 – Stakeholder dashboard.

Stakeholders included:

- **The Hy4Heat team**, who received dashboards with total and weekly response rates per GDNO, and combined (anonymised) escape classifications from each of the GDNOs.
- **Each of the four GDNOs**, who received dashboards with total and weekly response rates for each of their depots, and escape classifications from each of their own responses.

The dashboard served several purposes:

---

[3] Data processing in Python [12] using NumPy [13] and pandas [14]; additionally dashboards created using Matplotlib [15], seaborn [16], Jinja2 [17], WeasyPrint [18].

- To show progress to the stakeholders, maintaining buy-in with management and enabling additional resource to be targeted at areas with fewer responses.
- To allow the Hy4Heat team to check for unexpected differences or disparities between GDNOs or areas.
- To feed back to GDNOs on the quality of responses that were being received, including any themes observed.

Data was collected from June 2019 (the pilot phase) and then from October 2019 (the main phase) until January 2020.

4.2 Hy4Heat leak test results

A known limitation of the FCO survey data is that the survey had to be non-disruptive to the FCOs' emergency and investigation response times. Consequently, it became clear that only a small minority of leak rates would be determined by use of a pressure gauge to conduct a tightness test following the method contained in IGEM standard UP/1 [7]. It is therefore necessary to process the survey data and establish reasonable estimates of the level of tightness in all of the survey visits where there is sufficient information to allow inferences to be drawn.

A number of methods are used to estimate the leak rate that is to be expected based on the location and mechanism of the leak, and the physical properties of the gases. These methods have been determined based on fundamental fluid mechanics where appropriate, and experimental results from "Hy4Heat Work Package 7 – Lot 1" as conducted by Steer Energy [8].

There are three main categories of leak types with regards to the calculations:

1. **Turbulent leaks**, which are large leaks where the release rate is proportional to the square root of gas pressure. Bernoulli's equation determines that hydrogen should be released at a volumetric rate 2.8 times that of methane, through the standard orifice equation derived from an energy balance. There is a constant of proportionality for each type of hole, which takes hole area into consideration if it is known.
2. **Laminar leaks**, which are smaller leaks. In these cases, the release rate is directly proportional to the gas pressure, and the Hagen-Poiseuille equation determines that that hydrogen should be released at a volumetric rate 1.2 times that of methane, based on relative viscosities. For these leaks, the cross-sectional area of the hole is extremely low, and so the proportionality constant cannot take it into consideration.
3. **Appliances left on**, where it is assumed that the release rate is the full appliance heat input rating, and conversion from natural gas to hydrogen would maintain the energy release rate. For these cases, to maintain energy output rates the volumetric release rate of hydrogen is 3.1 times that of methane. It should be noted that any such releases should become progressively less likely over time as appliances without flame failure devices become replaced.

4.3 Volumetric and energy leak rates

A full exploration of the impact of different sizes of gas escapes forms the gas dispersion report [9].

There is no easily comparable quantitative metric that can be applied to allow wholly applicable comparisons between the two gases before considering dispersion analysis. Instead, the existing industry concept of a Maximum Permissible Leak Rate (MPLR) can be used to make an initial comparison between the gases.

4.3.1 Low release rates

At low release rates, the MPLR of gas can be used as a metric to determine whether or not a gas installation would pass or fail a tightness test [7]. There is currently no officially defined MPLR for hydrogen, with work ongoing to determine an appropriate value. Based on the similarity between the lower flammable limits of hydrogen and natural gas, it appears likely that the current volumetric MPLR for natural gas will also be applied for hydrogen as a conservative value. This assumption has been used in this report.

Two values of MPLR are then used to subcategorise low release rates, a most conservative value for new build installations, and a higher value for existing installations in well ventilated areas. Table 3 shows the values of MPLR, in volumetric and energy flow rates. Note that as the release rates are low, the energy values are in watts.

Table 3: Maximum permissible leak rates

Situation	Volumetric MPLR (m^3/h)	Natural gas gross energy MPLR (W)	Hydrogen gross energy MPLR (W)
New installation or extension	0.0014	14.7	4.7
Existing installation, adequately ventilated internal area, volume 60 m^3 or greater	0.0300	315.0	101.0

The MPLR rates shown in Table 3 show that the energy release rate of a maximally permissible leak of hydrogen would be lower than that of natural gas, consistent with the energy density differences.

5 Results & analysis

5.1 Escape data analysis

Data was collected from June 2019 (the pilot phase) and then from October 2019 (the main phase) until January 2020. In total 1,303 responses were received from approximately 170 FCOs. 1,134 of the responses were related to escapes of natural gas, and 915 of these were within the scope defined in Section 4.1. Data collection continued after January 2020, however this has not been analysed as part of this work.

To analyse the data, developed an expert system[4] was developed due to the initially small sample size (from the point-of-view of machine learning training set sizes). Figures 5–7 show the results of the classifications at the end of January 2020. The full processed dataset is available separately.

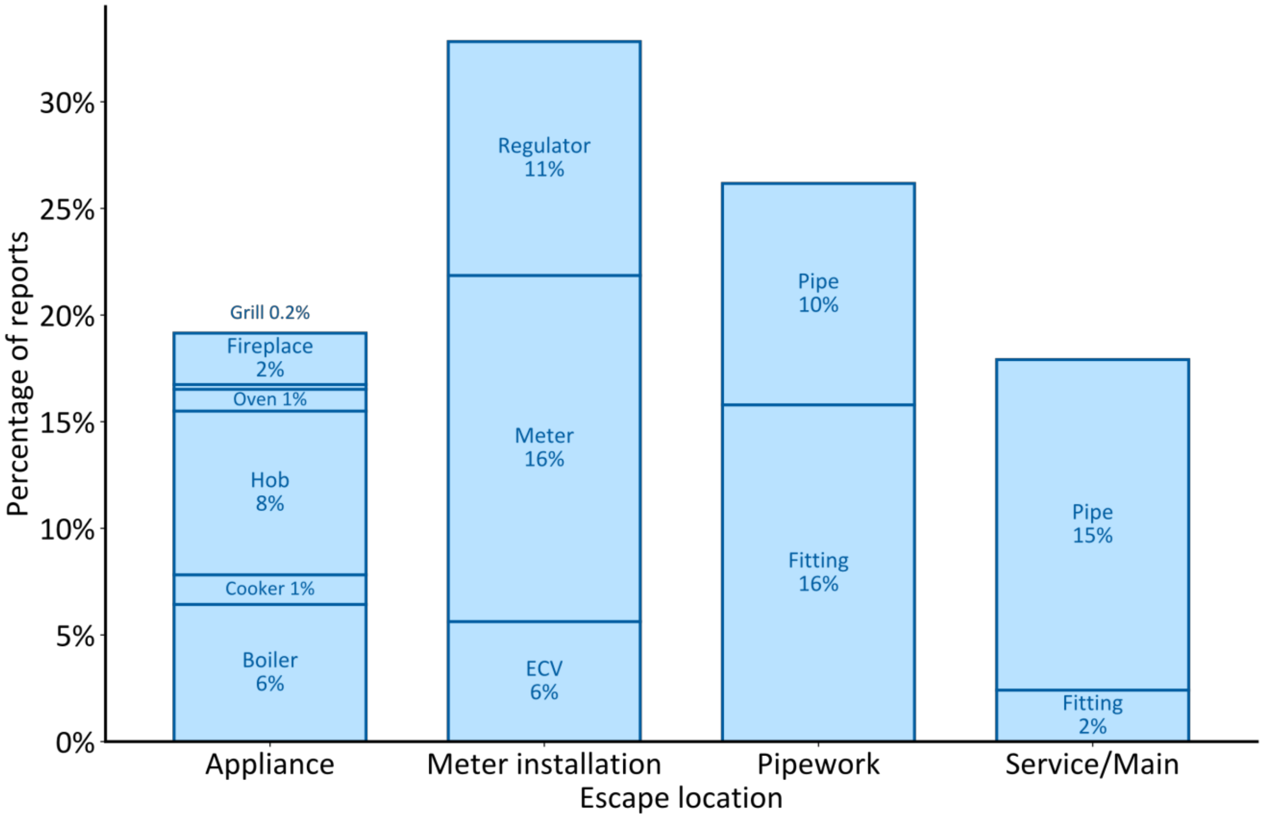


Figure 5: Locations of escapes from FCO survey

---

[4] Expert system developed in Python [12] using NumPy [13] and pandas [14].

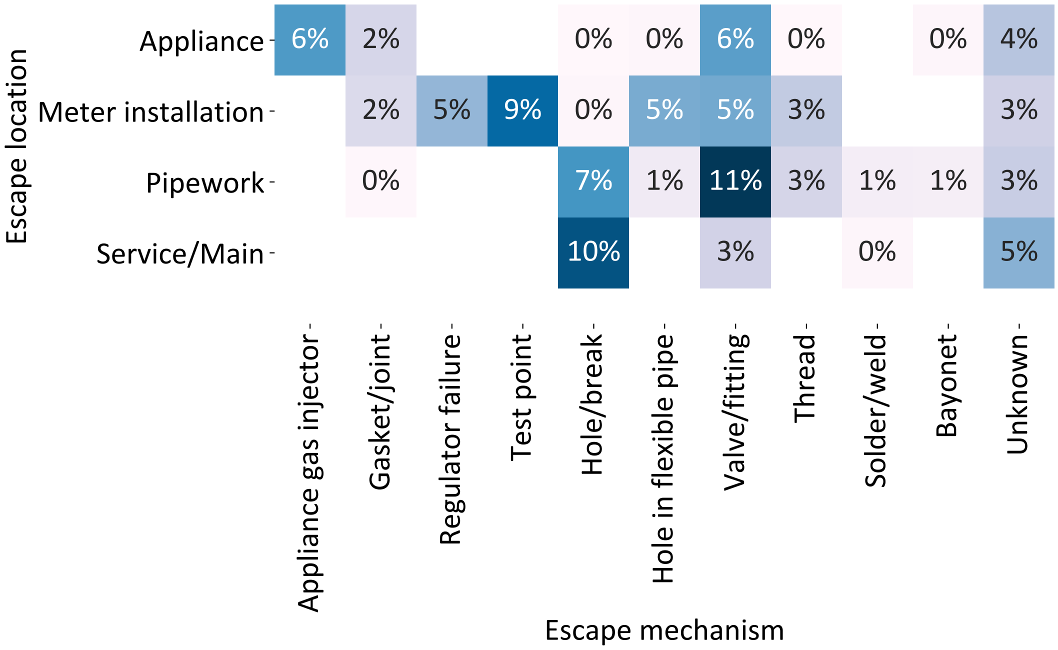


Figure 6: Escape mechanisms by escape location from the FCO survey

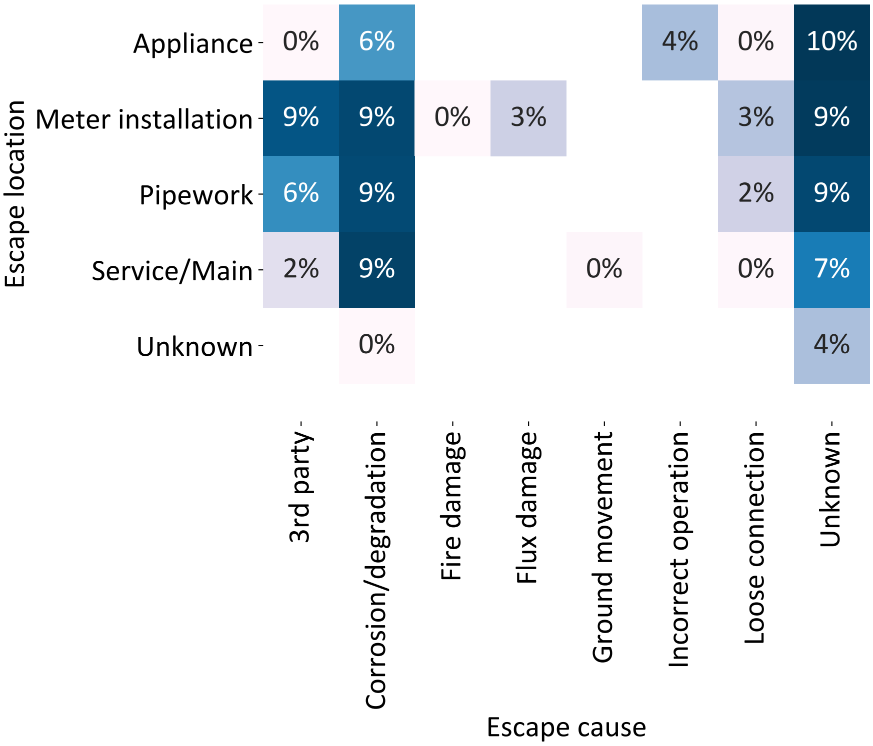


Figure 7: Escape causes by escape location from the FCO survey

5.1.1 Pre-processing of the data

Initial pre-processing steps included:

- **Removal of duplicates** – in limited cases an FCO completed a report with preliminary information then added more information later. These were counted together as one response.
- **Rewriting “other” options** – in many of the questions, FCOs were able to select an “other” option and then enter a free-text response. Similar entries were gathered together and assigned to a consistent option if one has been later added.

5.1.2 Determination of escape classifications

The main analysis continued with:

- **Classification of responses** – each escape was classified by assigning it five categories in each of the following areas: location, mechanism and cause. If the escape was external, it was also categorised based on whether the gas had tracked into a building. If there was insufficient information to assign a category in an area, the generic category “unknown” was used. This is not necessary a failure of the classification system, as in some cases the FCO was unable to determine e.g. the cause of the escape. A full list of classifications is given in Appendix 2 – Escape classifications.
- **Determination of scope** – based on the classifications, escapes were categorized as either in or out of scope (defined in Section 4.1). This was more straightforward than educating the FCOs about the detailed scope of the QRA and collecting a wider group of escapes reduced the risk of missing escapes that should have been in scope.

To determine the location of escapes, a combination of two approaches was used. Firstly, the multiple-choice options selected by the FCOs were examined; and secondly, sets of keywords were searched for within the text entries made by the FCO, particularly those in the “any other details” box. For example, to determine exactly where in a meter installation the escape occurred, the keywords search for included: meter, regulator, ECV, anaconda. A similar process was followed for escapes located in the service pipe/main, pipework, fittings and in appliances.

This process was then repeated to determine the escape mechanism and escape cause, although at this stage more emphasis was placed on the keywords entered by FCO. Scenarios were considered in the following order: appliance misuse, degradation, meters, ECVs, anaconda, regulator, service/main damage, corrosion or holes in pipework, degradation of fittings, loose connections.

5.1.3 Robustness of data analysis

As more data was collected, the outputs of the expert system were checked against human-determined classifications. There were four cycles of human-checking – including 146, 200, 270 and 77 responses (respectively). The first two cycles checked randomly selected responses, whereas in the final two cycles the responses were sampled predominantly from the least-correctly classified groups.

The first three cycles of checking were used to make adjustments to the expert system, before the final round of checking. Table 4 shows the expert system’s accuracy scores, defined to be the percentage of correctly assigned classifications. The (later) selection of a gas escape flow rate was most strongly influenced by the three escapes locations, which showed the greatest accuracy. The most common misclassifications in escape mechanism and escape cause tended to be between categories that did not greatly affect the estimated flow rate (e.g. escape through a soldered fitting and through a threaded fitting).

After the first 1,000 responses, a machine learning model was developed and trained using the human-determined classifications as ground-truths. Five support vector machine models were created – one to determine each of the five categories for every escape. A one-vs-all approach was used, with features synthesised using a bag-of-words model (with up to size 3 n-grams) on the combined text from all the entries in each response.[5] A train-test split of 75%/25% was used to determine the accuracy scores, which were similar to the existing expert system (Table 4).

Table 4: Accuracies of the expert system approach (used for the final analysis) and the machine learning approach

	Escape location			Escape mechanism	Escape cause	External escape tracking inside
	Part 1	Part 2	Part 3			
Expert system	94.6%	91.8%	**89.4%**	**79.2%**	81.0%	**97.8%**
Machine learning model	**95.7%**	**93.4%**	89.0%	70.5%	**81.5%**	Not tested

The final dataset has been processed using the expert system, with any corrections identified during the final round human-checking applied. Up to a sample of this size, this approach is still appropriate and practicable, however now that a large enough dataset for training has been collected, if the data collection is continued at a larger scale, it is recommended that the machine learning approach is adopted and developed further.

---

[5] Machine learning model developed in Python [12] using with scikit-learn [19] and NLTK [20].

5.1.4 Comparison of leak locations to existing literature

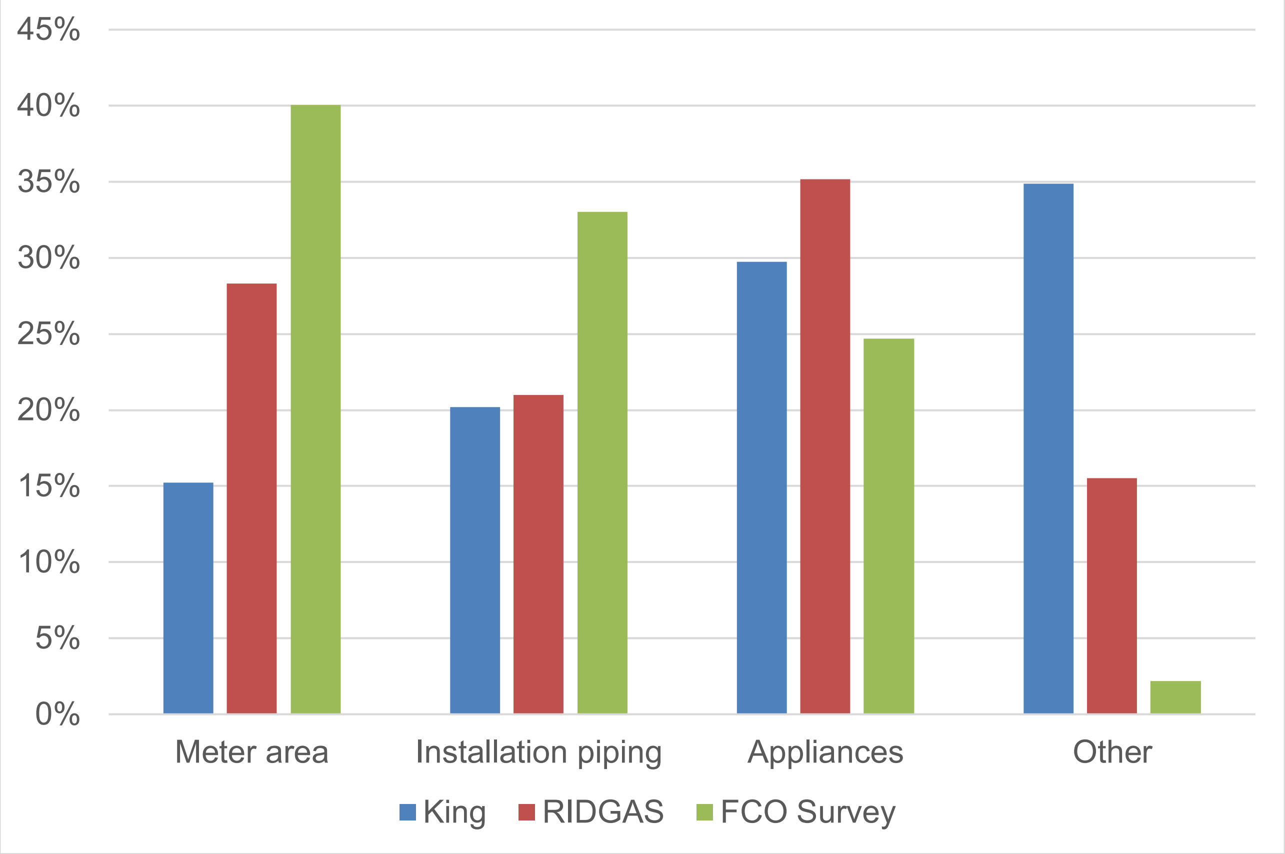


Figure 8: Leak location comparison

Figure 8 compares the locations where leaks were reported from two of the historical literature sources, the King Inquiry [1] and the RIDGAS report [4], with the results of the FCO survey. To allow comparison between the data sets, mains and service leaks are included within "Other" as the RIDGAS data does not explicitly include them.

These data sources are not entirely comparable as they cover differing time periods and differing bases of reporting. The King data covers the period 1972-1977 and is based on investigations of explosions. The RIDGAS data covers the period 2014-19 and is based on RIDDOR reportable dangerous gas fittings. The FCO survey data covers the period in 2019-20 discussed above and considers all gas-related in-scope FCO call-outs by the operatives undertaking reporting.

The FCO data shows a significantly higher proportion of leaks associated with meter areas. This can be attributed to the number of leaks associated with the installation of new smart gas meters, and can be seen in the latest figures within the RIDGAS data where there has been an upward trend in meter area leaks since 2014. During discussions with a member of the BEIS smart metering team, it was established that BEIS is already aware of this issue, and it is attributable to the increased number of meter replacements associated with that programme rather than inherent to the type of meter itself.

There is an increased proportion of installation piping leaks in the FCO data, which can be explained as small leaks of gas from deteriorating fittings can make themselves known (through odour) at rates below that which would give rise to a RIDDOR-reportable leak rate.

The majority of the large peak of "Other" causes in the King data are attributable to mains leaks that tracked into properties. The Iron Mains Replacement Programme that is in progress was established specifically to reduce this risk.

Overall, the proportions of leak causes as established in the FCO survey do not give rise to concern about representativeness for the purposes of this review.

5.2 Database of leak rates for different types of leaks

For a minority of leaks, the FCOs were able to conduct tightness tests using gas to determine a pressure drop rate. For these cases, a first-order decay model has been used to calculate the leak rate from the pressure drop rate – in a simplified form this is the method used by the IGEM standard [7] for tightness tests. For a system that is sufficiently tight that the tightness test can be reasonably used, a laminar leak is assumed and used to calculate the leak rate of hydrogen by ratio of hydrogen to natural gas:

Volume escape ratio = 1.2 : 1

Energy escape ratio = 0.38 : 1

For the majority of leaks, the leak rate had to be estimated based on data. For a very small minority, no cause could be reasonably attributed and hence no leak rate determined.

In practice, the Lot 1 data [8][6] revealed that in most cases gas flow is not always entirely laminar or turbulent and thus the relationship between methane and hydrogen release rates results in a ratio between the values of 1.2 and 2.8. For some of the release types downstream of the meter where the pressure can be treated as relatively constant, a constant value is used.

When calculating release rates upstream of the meter regulator, a pressure of 50 mbar has been assumed. Whilst low pressure mains can be operated at up to 75 mbar, this is not common practice – mains are operated at as low a pressure as possible to minimise any leakage from cracks or other imperfections in the mains or service pipes. The intention of this work is to understand the likely real-world implications of leaks, rather than the worst-case implications.

For leaks downstream of the meter regulator, a pressure of 20 mbar has been used as this is the nominal inlet pressure at operating appliances.

Table 5 lists the calculation types used in the analysis code, with leak flow regimes determined based on the release characteristics determined from the Lot 1 data.

Table 5: Calculation type basis

Calculation type	Pressure range (mbar)	Leak location (vs meter)	Leak flow regime
Hole	20 – 75	Either	Turbulent
Emergency control valve	25 – 75	Upstream	Laminar
Meter regulator inlet anaconda	25 – 75	Upstream	Turbulent
Meter regulator diaphragm	25 – 75	Upstream	Turbulent
Loose fitting	20 – 75	Either	Laminar
Meter test point open	20	Downstream	Turbulent
Incorrect appliance operation	20	Downstream	Fixed energy rate

---

[6] It is recommended that this section should be read in conjunction with this reference, “Hy4Heat Work Package 7 – Lot 1 - Safety Assessments for the Suitability of Hydrogen in Existing Buildings - Final Report”

Calculation type	Pressure range (mbar)	Leak location (vs meter)	Leak flow regime
Pipe damage	20	Downstream	Fixed rate
Soldered fitting	20 – 75	Either	Laminar
Compression fitting	20	Downstream	Fixed rate
Bayonet fitting	20	Downstream	Fixed rate
Valve	20	Downstream	Fixed rate
Pipework full bore failure	See below	Downstream	Fixed rate
Meter connections not tight	20	Either	Fixed rate

Leak rates for each of these calculation types are detailed in Table 8 within Appendix 1, with the values used in that table used in the results processing code to attribute an escape rate to each relevant FCO visit report. For each calculation type, the ratio of escape rates is summarised below on a volumetric and energy basis.

5.2.1 Hole

Holes can conceptually be found anywhere on a gas system. The tests described in Appendix 1 of Lot 1 cover releases from holes, and the release rates determined are consistent with the theoretical values predicted in the main Lot 1 report and illustrated in its Figure 4 for 6 mm diameter holes.

Regression of leak rates against hole areas at a pressure of 20 mbar as shown in Figure 38 of Appendix 1, has been carried out, knowing that the release is already turbulent by that pressure.

Volume escape ratio = 2.6 : 1

Energy escape ratio = 0.83 : 1

5.2.2 Emergency control valve

This refers to a release from an emergency control valve to the air around it, rather than a passing valve. The emergency control valve will contain gas at the service line pressure, between 25 and 75 mbar, so the pressure driving force and therefore the release rate will be higher than it would be downstream of the meter regulator, with the ratio between gases remaining constant.

Of the Lot 1 data, Appendix 7 contains the results of the valve tests. Valve 7 was a 1” brass meter control cock, and test 9 assessed leak rates following removal of the plug, wiping off the grease, and replacing it loosely. The test results showed that the leak with methane and hydrogen was laminar to above 20 mbar.

Baseline leak rates of 0.013 m^3/h of methane and 0.016 m^3/h of hydrogen have been used at 20 mbar, with the estimated leak rates being proportional to the pressure available when upstream of the meter. Assuming a pressure of 50 mbar upstream of the meter, these rates scale up to 0.033 m^3/h of methane and 0.040 m^3/h of hydrogen.

Volume escape ratio = 1.2 : 1

Energy escape ratio = 0.39 : 1

5.2.3 Meter regulator inlet anaconda

“Anaconda” is the term used in the gas industry to refer to the corrugated metallic flexible hose used to connect the emergency control valve to the meter regulator. As with the emergency control valve, this normally operates at the service line pressure.

Analysis of survey results shows that anaconda leaks are commonly pinholes resulting from long term deterioration from corrosion due to the presence of trace amounts of flux on the outer surface. With this gradual deterioration, leaks are reported early. This can be modelled using the smallest hole sizes reported in Lot 1 Appendix 1. Rather than using the line of best fit as used in the “Hole” section above, the measured leak rates for the smallest (0.3 mm diameter) holes are used.

Volume escape ratio = 2.6 : 1

Energy escape ratio = 0.83 : 1

5.2.4 Meter regulator diaphragm

Meter regulator diaphragm failures were not assessed as part of the work undertaken in Lot 1. However, previous work undertaken in SGN’s H100 project involved the release of gas from a meter regulator, from which the diaphragm had been entirely removed, allowing the gas to vent from the breather hole with no other restriction. A pressure of 75 mbar was used for this testing, and this would very much represent a worst case.

Volume escape ratio = 2.7 : 1

Energy escape ratio = 0.86 : 1

5.2.5 Loose fitting

Lot 1 Appendix 4 describes tests conducted using various screwed fittings. Screw01 investigated the leak of gas possible from a ½” brass BSPT fitting that was made up hand tight with no sealant. This would represent a loose fitting that might pass cursory inspection and could be downstream of the meter or on the anaconda. Based on leak rates of 0.033 and 0.050 at 20 mbar, a near-laminar flow relationship is used.

Volume escape ratio = 1.5 : 1

Energy escape ratio = 0.49 : 1

5.2.6 Meter test point left open

Appendix 7 of Lot 1 describes the leak rates associated with valve problems. None of these cases accurately describe a meter test point leak, due to the presence of an orifice much smaller than the apparent diameter of the test point, as shown in Figure 9.

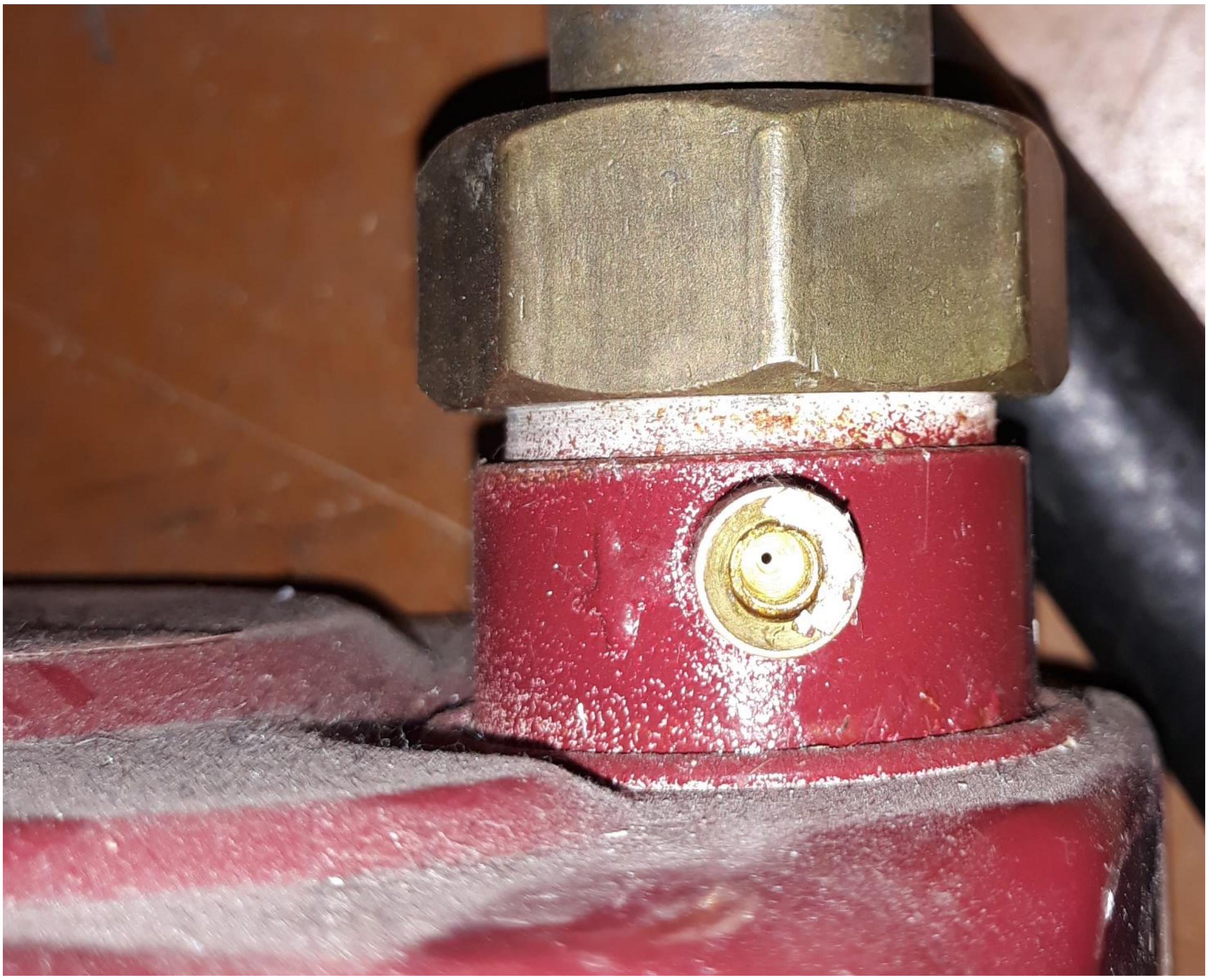


Figure 9: Meter test point, with small orifice visible

As with the inlet anaconda, the measured leak rates for the smallest (0.3 mm diameter) holes are used.

Volume escape ratio = 2.6 : 1

Energy escape ratio = 0.83 : 1

5.2.7 Incorrect appliance operation

Three types of appliances are used as indicative of those to be found in homes.

Hobs operate at 2 kW of gross heat input.

Grills and ovens operate at 3 kW of gross heat input.

Gas fires operate at 6 kW of gross heat input.

Volume escape ratio = 3.1 : 1

Energy escape ratio = 1 : 1

Boilers are not included in the same way, as they are controlled by sophisticated management systems, have doubly redundant gas valves, and do not vent unburnt gas into an occupied space. Instead, the incorrect operation of a boiler is to be treated as if it had a leaking valve, as described in section 5.2.12.

Boiler volume escape ratio = 1.5 : 1

Boiler energy escape ratio = 0.5 : 1

5.2.8 Pipe damage

Pipe damage can describe a wide range of situations. Appendix 8 of Lot 1 is the relevant data set for this category of leaks. The tests carried out in this set of work consisted of a variety of nails or screws being hammered or screwed through pipes to differing levels of penetration.

Tests 3, 8 and 10 result in leaks that are so small that they are not included in this analysis, and neither is test 5 which used an extremely large roofing nail with a helical shank – this is not a common piece of hardware that would be foreseen to be in use for tasks that would place gas pipes at risk of damage.

Table 6: Pipe damage leak rates

Test	Methane leak rate (m^3/h)	Hydrogen leak rate (m^3/h)
1	0.082	0.170
2	0.028	0.066
4	0.140	0.355
6	0.017	0.039
7	0.012	0.027
9	0.015	0.028
Average	**0.049**	**0.110**

These averages are used for pipe damage.

Volume escape ratio = 2.2 : 1

Energy escape ratio = 0.73 : 1

5.2.9 Soldered fitting

Lot 1 Appendix 5 details the tests conducted to look at leak rates from a variety of poorly made soldered joints. Tests 4, 5, 6 and 7 gave measurable results that can be averaged as shown below in Table 7.

Table 7: Soldered fitting leak rates

Test	Methane leak rate (m^3/h)	Hydrogen leak rate (m^3/h)
4	0.085	0.124
5	0.089	0.118
6	0.050	0.062
7	0.128	0.161
Average	**0.049**	**0.110**

These averages are used for soldered joints. As these joints could be upstream of the meter, the calculation includes the release point pressure.

Volume escape ratio = 1.4 : 1

Energy escape ratio = 0.73 : 1

5.2.10 Compression fitting

The results of tests documented in Appendix 3 with hand-tight compression fittings and fittings that were tightened without an olive present were used to represent two foreseeable cases of poorly made compression fittings. At 20 mbar these resulted in methane leak rates of 0.108 and 0.075, and hydrogen leak rates of 0.194 and 0.100 respectively. The averages of these readings are used.

Volume escape ratio = 1.6 : 1

Energy escape ratio = 0.52 : 1

5.2.11 Bayonet fitting

A bayonet fitting is the type of fitting used to connect a domestic cooker to the wall via a hose. This was tested as part of the work in Appendix 6, by crushing the brass connection on the fitting with a hammer while it was held in a vice. The leak rates from this damaged fitting at 20 mbar are used.

Volume escape ratio = 1.3 : 1

Energy escape ratio = 0.41 : 1

5.2.12 Valve

Valves other than the ECV were also tested in the work documented in Lot 1 Appendix 7. The large majority of tests resulted in very low release rates, so instead the largest reasonably foreseeable leak rate of a split O-ring within a disc-on-seat valve is recommended for use. This is also deemed to be conservative as an appliance gas valve leak rate.

Volume escape ratio = 1.5 : 1

Energy escape ratio = 0.5 : 1

5.2.13 Pipework full bore failure

A full-bore failure of the gas pipework in a property represents the worst case that could be experienced other than tracking of gross amounts of gas following an external service or mains failure. Following an unmitigated failure, the gas flow will be bottlenecked at some point from the service top tee to the point of failure.

Unlike the other internal releases, the flow in this case can be a function of the service pipe pressure. The work in Lot 1, as documented in section 4.8.4 of its final report shows how a regulator and meter connected together will limit the gas flows. The flow can be fit to the data using the following relationships:

Methane leak rate (full bore) = 4.0 x √ (Service pipe pressure)

Hydrogen leak rate (full bore) = 10.3 x √ (Service pipe pressure)

This relationship must be used very cautiously. The flow calculated in this way is the absolute maximum that could be delivered by the regulator and meter in series; in reality at high flow rates there will be large pressure drops along the service pipe and any length of installation pipework between the meter and the failure point. It would be unlikely that any feasible gas distribution network would be designed in such a way that the pressure at the inlet to the regulator would be above 30 mbar when the regulator and meter are delivering gas at their full rates. At 30 mbar regulator inlet pressure, the rates would be:

Methane leak rate (full bore, reasonably foreseeable maximum) = 22 m^3/h

Hydrogen leak rate (full bore, reasonably foreseeable maximum) = 56 m^3/h

These rates are very large and should reinforce the importance of excess flow valves as layers of protection for the provision of hydrogen to buildings.

Volume escape ratio = 2.5 : 1

Energy escape ratio = 0.82 : 1

Some work has been conducted at Spadeadam by DNV-GL [10] as part of the gas dispersion test work undertaken within WP7. This considers flows up to approximately 70 m³/h of hydrogen, representing a full bore failure with a regulator inlet pressure of about 50 mbar. The flows for those cases have not be used in this report, as they would be very unlikely to be seen in practice. Regardless of whether a pressure of 30 mbar or 50 mbar is assumed at the regulator inlet, a very high gas release rate would ensue following a full bore failure.

5.2.14 Meter connections not tight

Loose meter connections represent one known failure mode, seemingly due to poorly performed meter replacements, where the leak rate has not been explicitly examined. It is however possible to establish an estimate by reference to the hand-tight loose fittings as already described from Lot 1 Appendix 4. Whereas ½" fittings were used for that testing, a meter is equipped with two 1" fittings. With the area of a leak path being proportional to the circumference, it is reasonable to use a rate four times that of the loose fittings, with the meter always being after the regulator by definition. On that basis, the following estimated leak rates should be used:

Methane leak rate (meter connections not tight) = 0.13 m³/h

Hydrogen leak rate (meter connection not tight) = 0.20 m³/h

Giving release ratios of:

Volume escape ratio = 1.5 : 1

Energy escape ratio = 0.48 : 1

5.3 Database of leaks

From the total reports, the data can be filtered to look at the reports which are relevant leaks with explained causes as follows:

Total reports = 1303

Number deemed not relevant = 388

Number deemed relevant but without explained cause = 4

Therefore, number deemed relevant and with explained cause = 911

The cumulative distributions of leak rates are detailed in Appendix 7. This is illustrated in Figure 10 and Figure 11. These are displayed with logarithmic x-axes as the majority of leaks are very small, with far fewer large outliers.

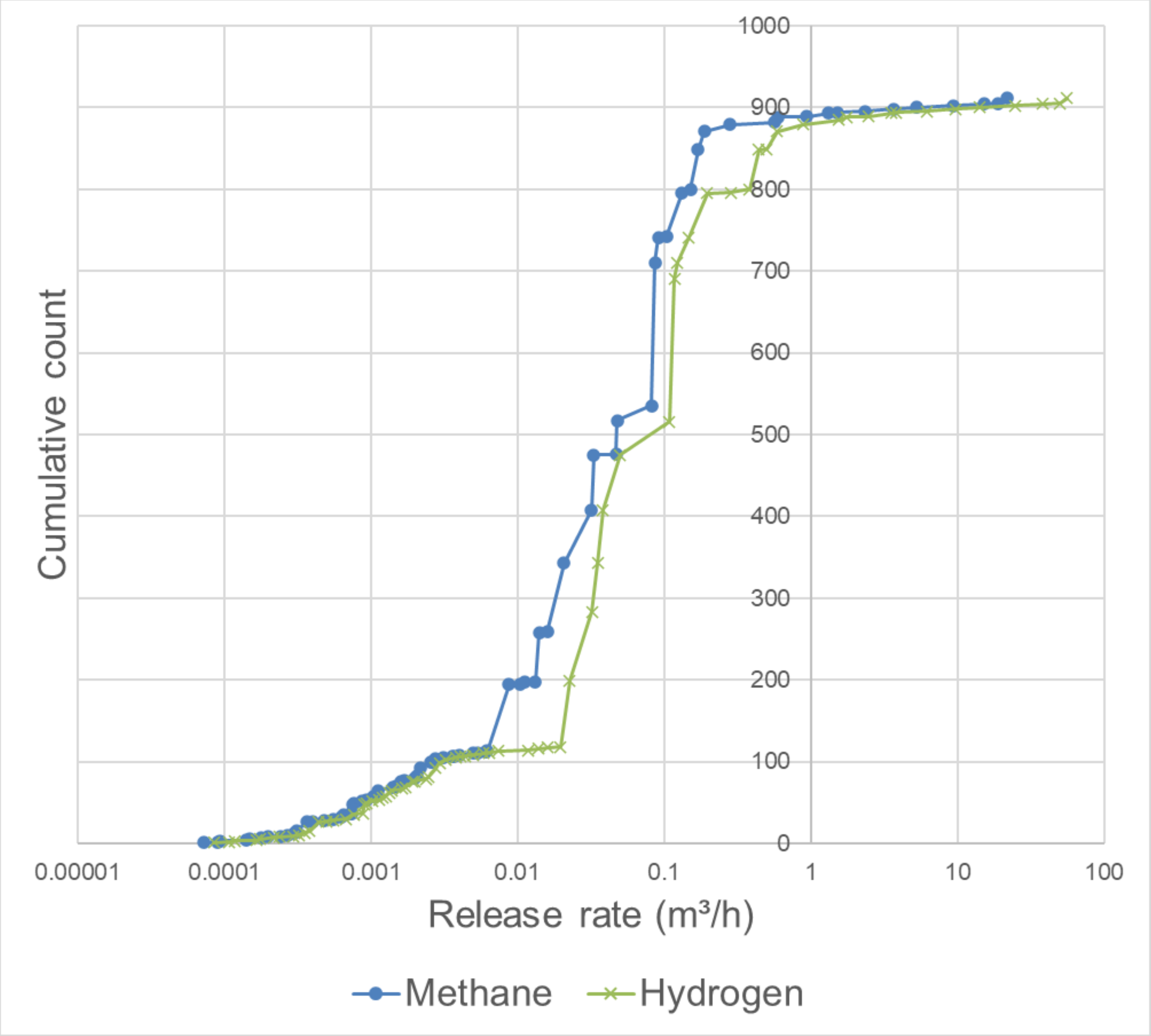


Figure 10: Cumulative counts of volume-basis gas release rated

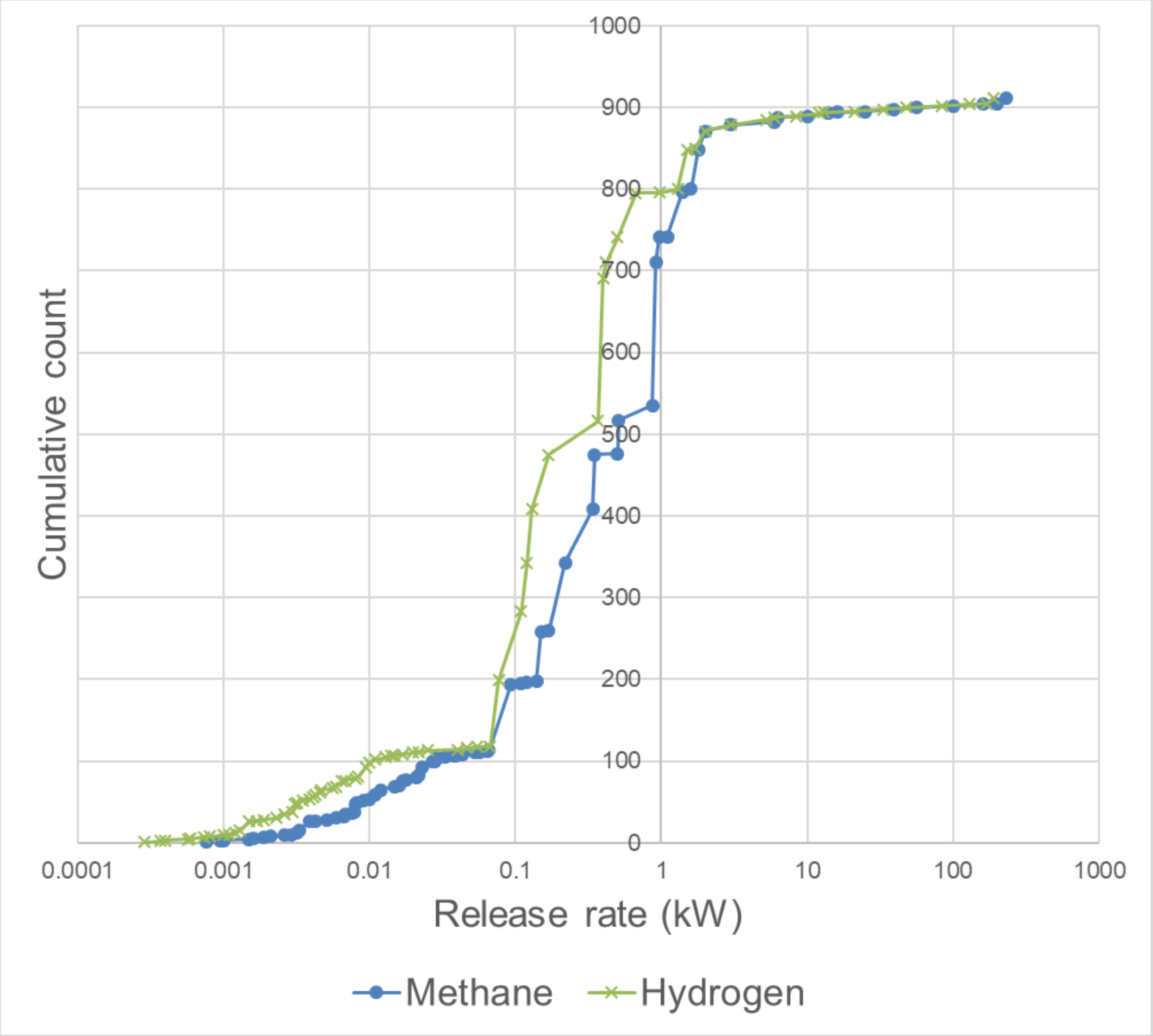


Figure 11: Cumulative counts of energy-basis gas release rates

6 Conclusions

Existing literature has been considered to understand the extent of knowledge about the causes of gas leaks. There is information about historical leaks following incident investigations, but information gaps led to the need to undertake new research through a survey of First Call Operatives (FCOs) who respond to relevant calls made to the Gas Emergency Line.

The locations of leaks that were observed by the FCO surveys were compared to the literature values. Whilst the proportions of leaks reported were not identical to those in the existing knowledge, the differences were understandable based on differences in reporting criteria and changes over time.

Having observed the types of leaks found during surveys, research work carried out under Hy4Heat assessing the rates at which gases leak for different types was applied to this data. This assessment used reasonable worst-case estimates for leak types to be conservative. The conclusions of this review are:

- A large number of leaks reported would be below the maximum permissible leak rate on natural gas. Some of these leaks would be above the MPLR if hydrogen were to be conveyed.
- For the leaks that would not pass a tightness test with hydrogen when they would with methane, they would not fail to such an extent that a flammable atmosphere would be created.
- The curves of leakage rate versus frequency of occurrence can have been validated (as much a possible) by reference to historical data.
- Out of ~900 data points, only a few leaks (about 3%) are large enough to generate a flammable atmosphere in a simple model room with either hydrogen or natural gas. This is considered further in a separate gas dispersion report.

The number of spontaneous large leaks is tiny. Internal gas pipes (operating at 20 mbarg) almost never suffer major structural failure without external stimulus. In the case of human driven damage, the FCO data shows that most people follow the correct response. This analysis is conservative, as the leak rates used for each type of leak would not generally be reached immediately following a failure. Gradual deterioration over time means that the leak rates have the potential to be much lower than assumed.

The large majority of leaks responded to by FCOs are well below the level at which there would be potential for a flammable atmosphere to be generated. This is a feature of the effectiveness of odorisation of gas, which allows small gas leaks to be investigated and resolved early.

The most significant cases are by definition associated with the largest release rates. These cases are primarily related to full bore failures, or though appliances allowing unburnt gas to pass into a room through the lack of a flame failure device. Straightforward layers of protection such as excess flow valves or effective flame failure protection in hydrogen-fired gas appliances have the potential to mitigate changes to the risk potential. This will be quantified in the QRA.

Finally, a large proportion of leaks investigated by FCOs were attributable to the installation of smart gas meters. BEIS is already aware of this issue.

7 References

[1] P. J. King, G. T. Clegg and W. J. Walters, “Report of the Inquiry into serious gas explosions,” Her Majesty's Stationery Office, London, 1977.

[2] “The Reporting of Injuries, Diseases and Dangerous Occurrences Regulations 2013,” UK Statutory Instruments, 2013 No. 1471.

[3] “Gas Safety (Management) Regulations 1996,” UK Statutory Instruments, 1996 No. 551.

[4] Health and Safety Executive, “RIDGAS - Gas-related incidents reported in Great Britain,” October 2019. [Online]. Available: https://www.hse.gov.uk/statistics/tables/ridgas.xlsx. [Accessed 06 March 2020].

[5] Health and Safety Executive, “In-year workplace deaths where HSE is the relevant enforcing authority,” [Online]. Available: https://www.hse.gov.uk/foi/fatalities/in-year-names.htm. [Accessed 06 March 2020].

[6] Health and Safety Executive, “GSMR Report Data 2016-19 (Obtained under Freedom of Information Request Reference No. 201907285),” 2019.

[7] The Institution of Gas Engineers and Managers, IGE/UP/1 - Strength testing, tightness testing and direct purging of industrial and commercial gas installations, 2nd ed., Loughborough, 2005.

[8] N. Ryan and S. Roberts, “Hy4Heat Work Package 7 – Lot 1 - Safety Assessments for the Suitability of Hydrogen in Existing Buildings - Final Report,” Steer Energy, 2019.

[9] E. Kotrotsou and S. Dogruel, “Hy4Heat Work Package 7 - Gas Dispersion Modelling,” 2020.

[10] G. Simpson and D. Allason, “Hy4Heat WP7 Lot2 Cupboard Level Leakage and Accumulation Data Report,” DNV-GL, 2020.

[11] K. Miller, “Quantifying Risk and How It All Goes Wrong,” in *Hazards 28*, 2018.

[12] Python Software Foundation, “Python 3.7,” URL: https://python.org.

[13] T. E. Oliphant, A guide to NumPy, USA: Trelgol Publishing, 2006.

[14] W. McKinney, “Data structures for statistical computing in python,” in *Proceedings of the 9th Python in Science Conference*, Vol. 445, pp. 51-56, 2010.

[15] J. D. Hunter, “Matplotlib: A 2D Graphics Environment,” *Computing in Science & Engineering,* vol. 9, pp. 90-95, 2007, DOI: https://doi.org/10.1109/MCSE.2007.55.

[16] M. Waskom et al, “seaborn: statistical data visualization,” Version 0.9.0, July 2018, DOI: https://doi.org/10.5281/zenodo.592845.

[17] A. Ronacher, “Jinja2 Documentation,” 2008, URL: http://mitsuhiko.pocoo.org/jinja2docs/Jinja2.pdf.

[18] S. Sapin and G. Ayoub, “WeasyPrint: The Awesome Document Factory,” 2019, URL: https://weasyprint.org.

[19] F. Pedregosa, et al, “Scikit-learn: Machine learning in Python,” *Journal of machine learning research,* vol. 12, pp. 2825-2830, Oct 2011.

[20] S. Bird, E. Loper and E. Klein, Natural Language Processing with Python, O’Reilly Media Inc., 2009.

Appendix 1 – Leak rates

All leak rates are expressed to two significant figures to avoid giving any unrealistic impression of the accuracy of data.

Table 8: Leak rates

Leak type	Methane leak rate (m^3/h)	Methane leak rate (kW)	Hydrogen leak rate (m^3/h)	Hydrogen leak rate (kW)
Hole	$0.19\ A\ \sqrt{(P / 20)}$	$2.0\ A\ \sqrt{(P / 20)}$	$0.50\ A\ \sqrt{(P / 20)}$	$1.7\ A\ \sqrt{(P / 20)}$
Emergency control valve	0.013 (P / 20)	0.14 (P / 20)	0.016 (P / 20)	0.054 (P / 20)
Meter regulator inlet anaconda	$0.0089\ \sqrt{(P / 20)}$	$0.093\ \sqrt{(P / 20)}$	$0.023\ \sqrt{(P / 20)}$	$0.077\ \sqrt{(P / 20)}$
Meter regulator diaphragm	$0.21\ \sqrt{(P / 75)}$	$2.2\ \sqrt{(P / 75)}$	$0.56\ \sqrt{(P / 75)}$	$1.9\ \sqrt{(P / 75)}$
Loose fitting	0.033 (P / 20)	0.35 (P / 20)	0.050 (P / 20)	0.17 (P / 20)
Meter test point open	$0.0089\ \sqrt{(P / 20)}$	$0.093\ \sqrt{(P / 20)}$	$0.023\ \sqrt{(P / 20)}$	$0.077\ \sqrt{(P / 20)}$
Incorrect appliance operation (hob)	0.19	2.0	0.60	2.0
Incorrect appliance operation (grill or oven)	0.29	3.0	0.89	3.0
Incorrect appliance operation (gas fire)	0.57	6.0	1.8	6.0
Incorrect appliance operation (boiler)	0.021	0.22	0.032	0.11
Pipe damage	0.049	0.51	0.11	0.37
Soldered fitting	0.088 (P / 20)	0.92 (P / 20)	0.12 (P / 20)	0.40 (P / 20)
Compression fitting	0.092	0.97	0.15	0.50
Bayonet fitting	0.0022	0.023	0.0028	0.0094
Valve	0.021	0.22	0.032	0.11
Pipework full bore failure	22	230	56	188
Meter connections not tight	0.13	1.4	0.20	0.67

Nomenclature

A	Hole area	mm^2
P	Gas pressure	mbar (gauge)

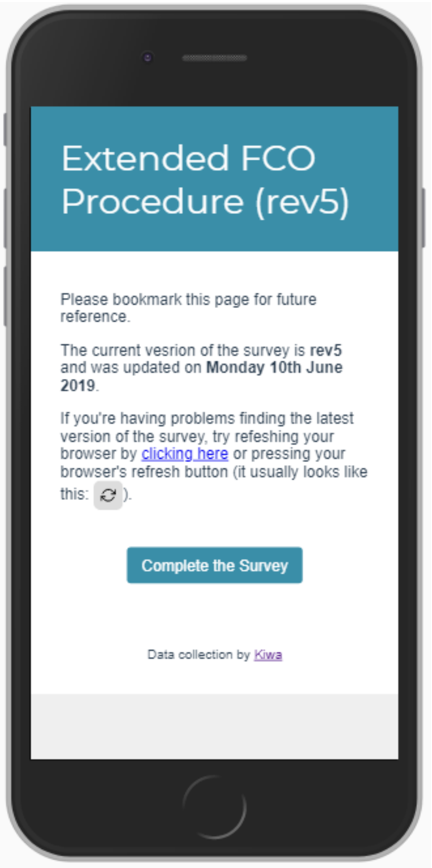
Appendix 2 – Escape classifications

Each escape was classified by assigning it five categories in each of the following areas. If the escape was external, it was also categorised based on whether the gas had tracked into a building. If there was insufficient information to assign a category in an area, the generic category “unknown” was used. This is not necessary a failure of the classification system, as in some cases the FCO was unable to determine, e.g. the cause of the escape.

Table 9: Escape classifications

Escape location			Escape mechanism	Escape cause
Part 1	Part 2	Part 3		
Internal or External	Pipework or Service/Main	Fitting or Pipe	Full-bore failure	Corrosion/degradation or Loose connection or 3rd party or Ground movement or Fire damage or Flux damage (for regulators) or Incorrect operation (of an appliance)
			Hole/break	
			Hole in flexible pipe	
			Solder/weld	
			Gasket/joint	
			Thread	
			Valve/fitting	
			Bayonet	
	Meter installation	ECV	Gasket/joint	
			Thread	
			Valve/fitting	
		Meter	Full-bore failure	
			Hole/break	
			Meter seal	
			Gasket/joint	
			Thread	
			Test point	
		Regulator	Regulator failure	
			Hole/break	
			Hole in flexible pipe	
			Gasket/joint	
			Thread	
			Valve/fitting	
Internal only	Appliance	Boiler or Fireplace or Oven/Grill/Hob or Cooker	Appliance gas injector	
			Hole/break	
			Hole in flexible pipe	
			Gasket/joint	
			Thread	
			Valve/fitting	
			Bayonet	

Appendix 3 – Screenshots of Hy4Heat data collection tool

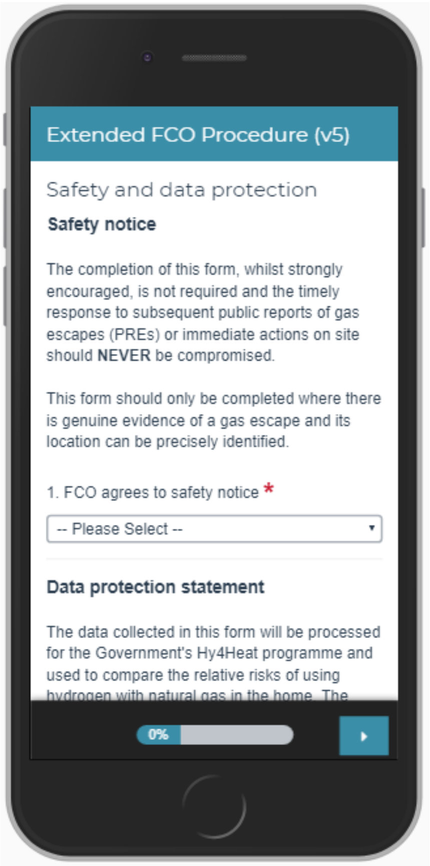


Extended FCO Procedure (rev5)

Please bookmark this page for future reference.

The current vesrion of the survey is **rev5** and was updated on **Monday 10th June 2019**.

If you're having problems finding the latest version of the survey, try refeshing your browser by clicking here or pressing your browser's refresh button (it usually looks like this: ⟳).



Extended FCO Procedure (v5)

Safety and data protection

Safety notice

The completion of this form, whilst strongly encouraged, is not required and the timely response to subsequent public reports of gas escapes (PREs) or immediate actions on site should **NEVER** be compromised.

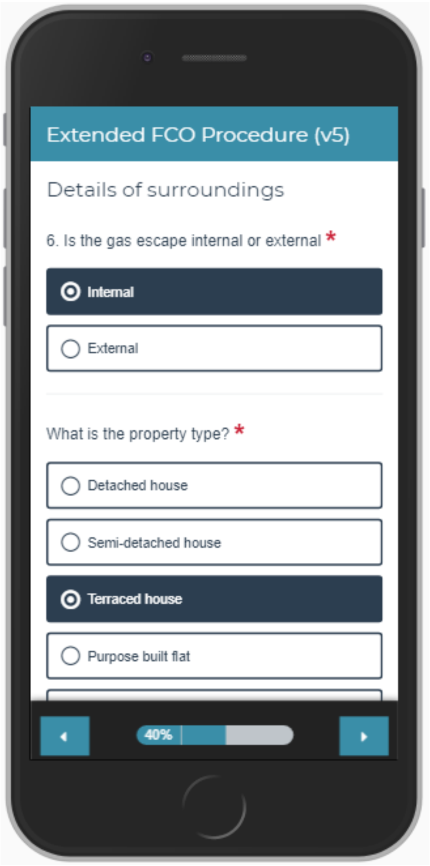
This form should only be completed where there is genuine evidence of a gas escape and its location can be precisely identified.

1. FCO agrees to safety notice *

-- Please Select --

Data protection statement

The data collected in this form will be processed for the Government's Hy4Heat programme and used to compare the relative risks of using hydrogen with natural gas in the home. The



Extended FCO Procedure (v5)

Details of surroundings

6. Is the gas escape internal or external *

● Internal

○ External

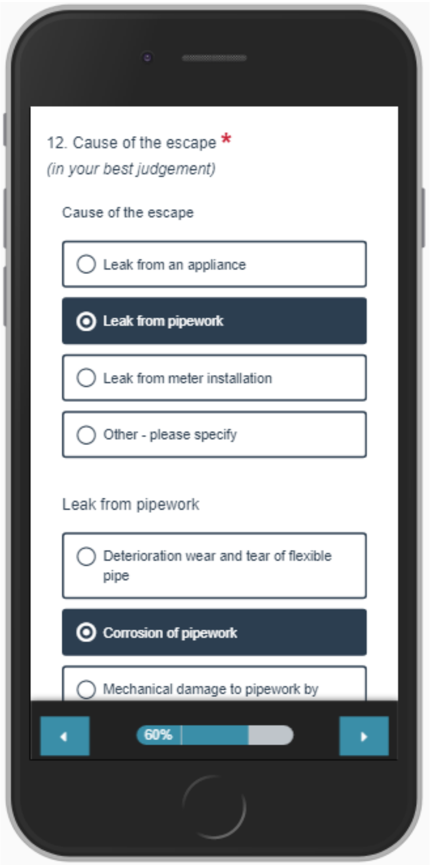
What is the property type? *

○ Detached house

○ Semi-detached house

● Terraced house

○ Purpose built flat



12. Cause of the escape *

(in your best judgement)

Cause of the escape

○ Leak from an appliance

● Leak from pipework

○ Leak from meter installation

○ Other - please specify

Leak from pipework

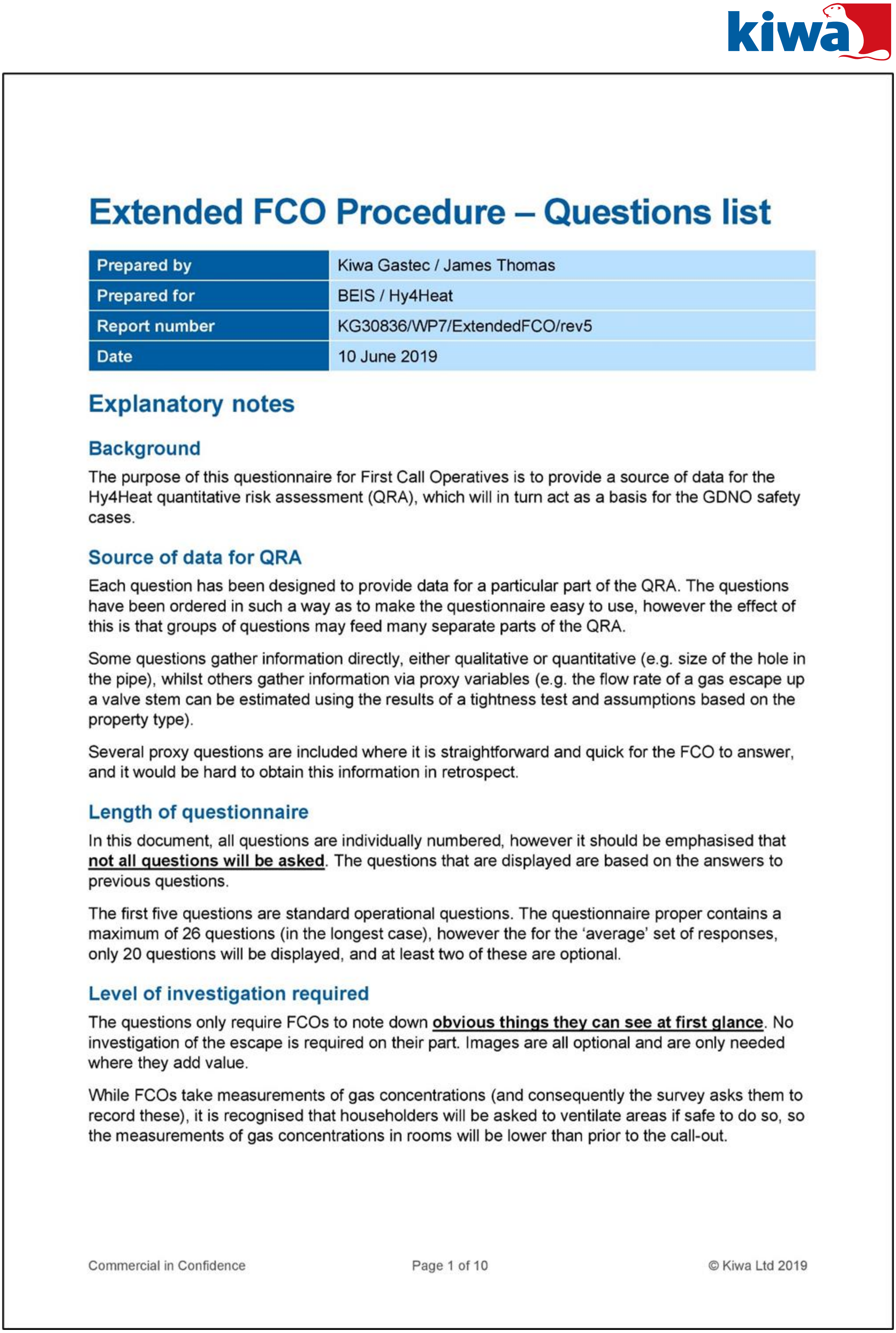
○ Deterioration wear and tear of flexible pipe

● Corrosion of pipework

○ Mechanical damage to pipework by

Appendix 4 – Question list & survey logic

The following pages show the questions asked in the FCO survey, and the logic pathway followed by the survey to ask them.



Extended FCO Procedure – Questions list

Prepared by	Kiwa Gastec / James Thomas
Prepared for	BEIS / Hy4Heat
Report number	KG30836/WP7/ExtendedFCO/rev5
Date	10 June 2019

Explanatory notes

Background

The purpose of this questionnaire for First Call Operatives is to provide a source of data for the Hy4Heat quantitative risk assessment (QRA), which will in turn act as a basis for the GDNO safety cases.

Source of data for QRA

Each question has been designed to provide data for a particular part of the QRA. The questions have been ordered in such a way as to make the questionnaire easy to use, however the effect of this is that groups of questions may feed many separate parts of the QRA.

Some questions gather information directly, either qualitative or quantitative (e.g. size of the hole in the pipe), whilst others gather information via proxy variables (e.g. the flow rate of a gas escape up a valve stem can be estimated using the results of a tightness test and assumptions based on the property type).

Several proxy questions are included where it is straightforward and quick for the FCO to answer, and it would be hard to obtain this information in retrospect.

Length of questionnaire

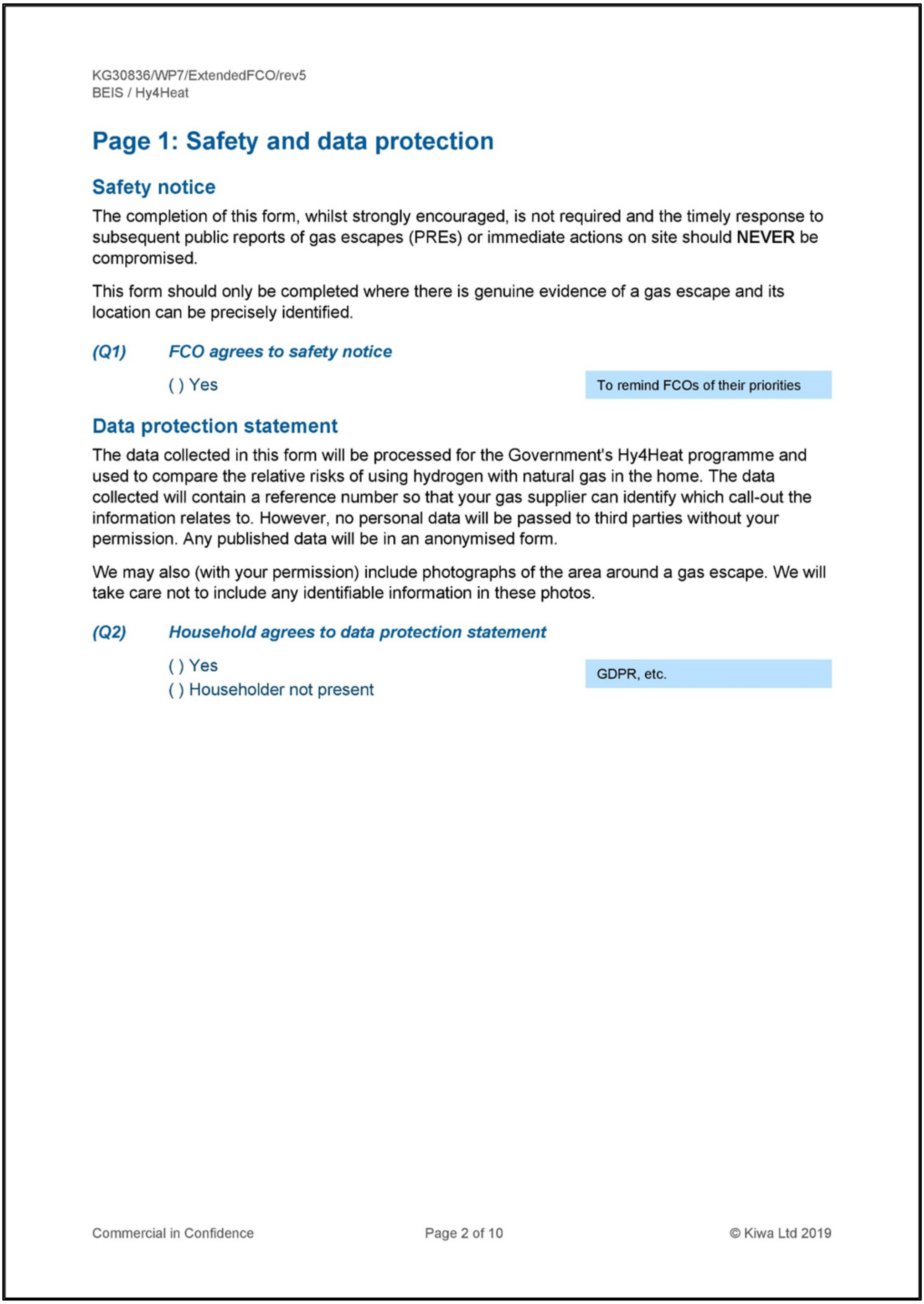
In this document, all questions are individually numbered, however it should be emphasised that **not all questions will be asked**. The questions that are displayed are based on the answers to previous questions.

The first five questions are standard operational questions. The questionnaire proper contains a maximum of 26 questions (in the longest case), however the for the ‘average’ set of responses, only 20 questions will be displayed, and at least two of these are optional.

Level of investigation required

The questions only require FCOs to note down **obvious things they can see at first glance**. No investigation of the escape is required on their part. Images are all optional and are only needed where they add value.

While FCOs take measurements of gas concentrations (and consequently the survey asks them to record these), it is recognised that householders will be asked to ventilate areas if safe to do so, so the measurements of gas concentrations in rooms will be lower than prior to the call-out.



KG30836/WP7/ExtendedFCO/rev5
BEIS / Hy4Heat

Page 1: Safety and data protection

Safety notice

The completion of this form, whilst strongly encouraged, is not required and the timely response to subsequent public reports of gas escapes (PREs) or immediate actions on site should **NEVER** be compromised.

This form should only be completed where there is genuine evidence of a gas escape and its location can be precisely identified.

(Q1) FCO agrees to safety notice

( ) Yes

To remind FCOs of their priorities

Data protection statement

The data collected in this form will be processed for the Government's Hy4Heat programme and used to compare the relative risks of using hydrogen with natural gas in the home. The data collected will contain a reference number so that your gas supplier can identify which call-out the information relates to. However, no personal data will be passed to third parties without your permission. Any published data will be in an anonymised form.

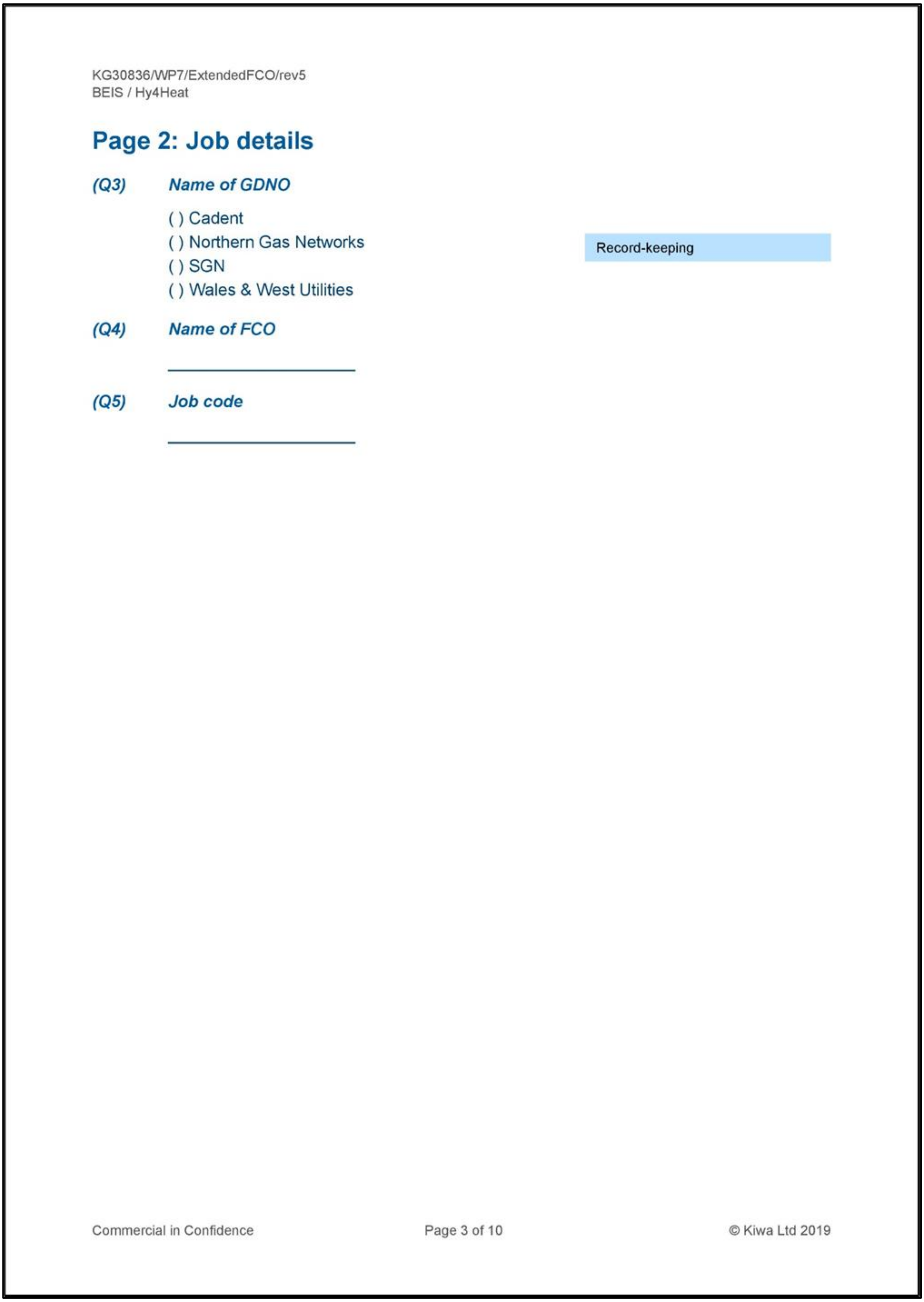
We may also (with your permission) include photographs of the area around a gas escape. We will take care not to include any identifiable information in these photos.

(Q2) Household agrees to data protection statement

( ) Yes
( ) Householder not present

GDPR, etc.

Commercial in Confidence Page 2 of 10 © Kiwa Ltd 2019



KG30836/WP7/ExtendedFCO/rev5
BEIS / Hy4Heat

Page 2: Job details

Record-keeping

(Q3) ***Name of GDNO***

( ) Cadent
( ) Northern Gas Networks
( ) SGN
( ) Wales & West Utilities

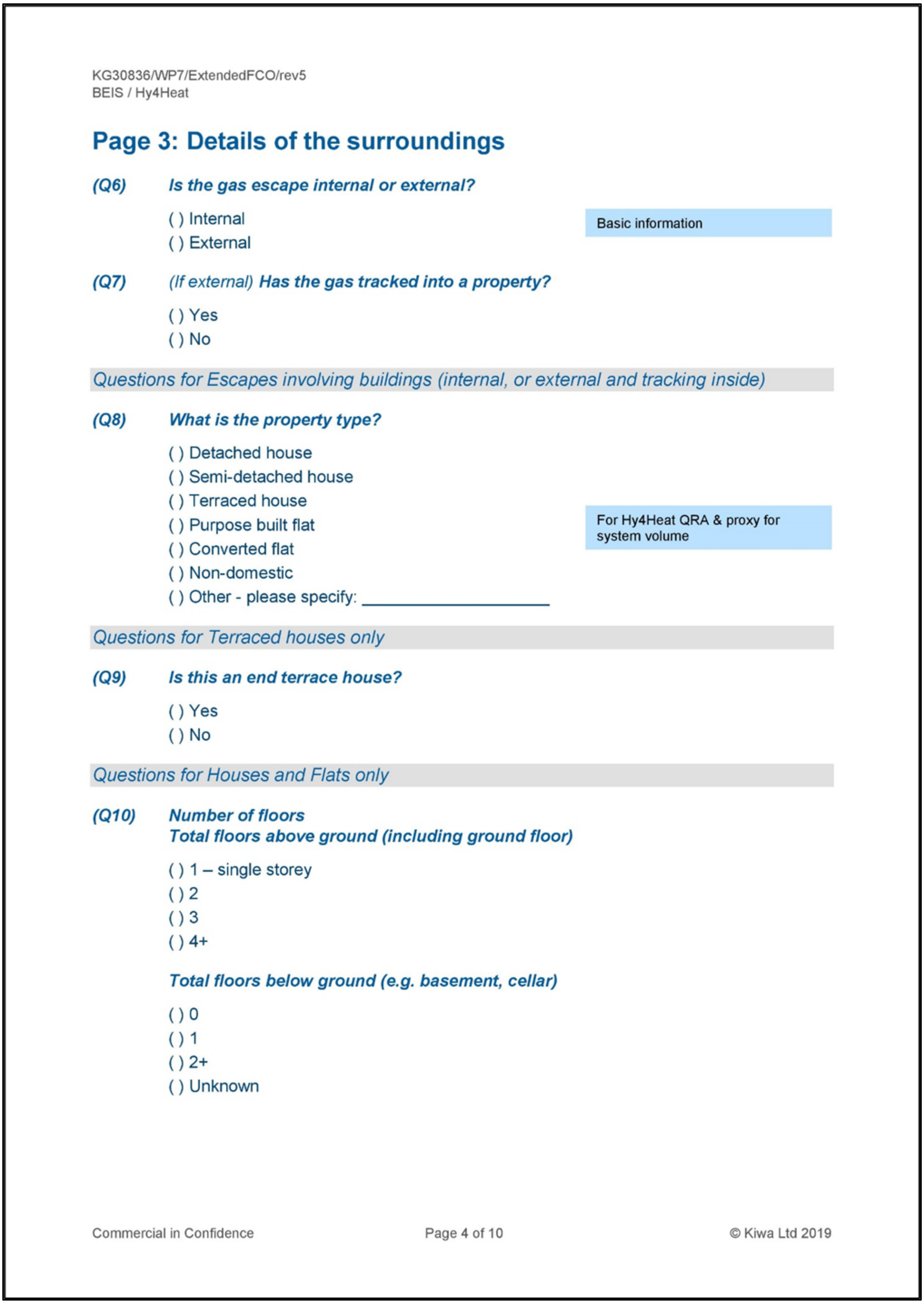
(Q4) ***Name of FCO***

____

(Q5) ***Job code***

____

Commercial in Confidence Page 3 of 10 © Kiwa Ltd 2019



Page 3: Details of the surroundings

(Q6) ***Is the gas escape internal or external?***

( ) Internal
( ) External

Basic information

(Q7) *(If external)* ***Has the gas tracked into a property?***

( ) Yes
( ) No

Questions for Escapes involving buildings (internal, or external and tracking inside)

(Q8) ***What is the property type?***

( ) Detached house
( ) Semi-detached house
( ) Terraced house
( ) Purpose built flat
( ) Converted flat
( ) Non-domestic
( ) Other - please specify: ____________________

For Hy4Heat QRA & proxy for system volume

Questions for Terraced houses only

(Q9) ***Is this an end terrace house?***

( ) Yes
( ) No

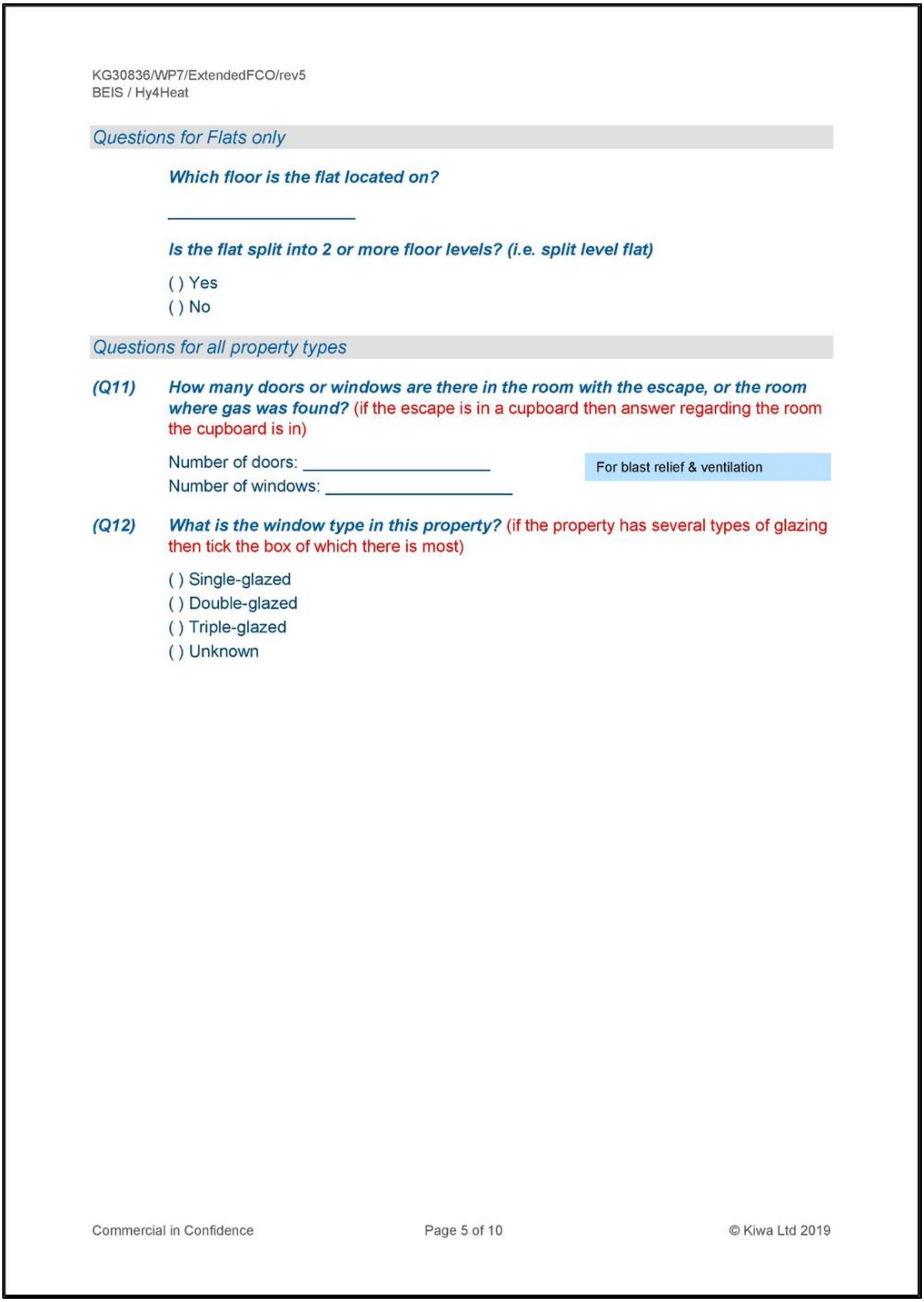
Questions for Houses and Flats only

(Q10) ***Number of floors***
Total floors above ground (including ground floor)

( ) 1 – single storey
( ) 2
( ) 3
( ) 4+

Total floors below ground (e.g. basement, cellar)

( ) 0
( ) 1
( ) 2+
( ) Unknown



Questions for Flats only

Which floor is the flat located on?

____

Is the flat split into 2 or more floor levels? (i.e. split level flat)

( ) Yes
( ) No

Questions for all property types

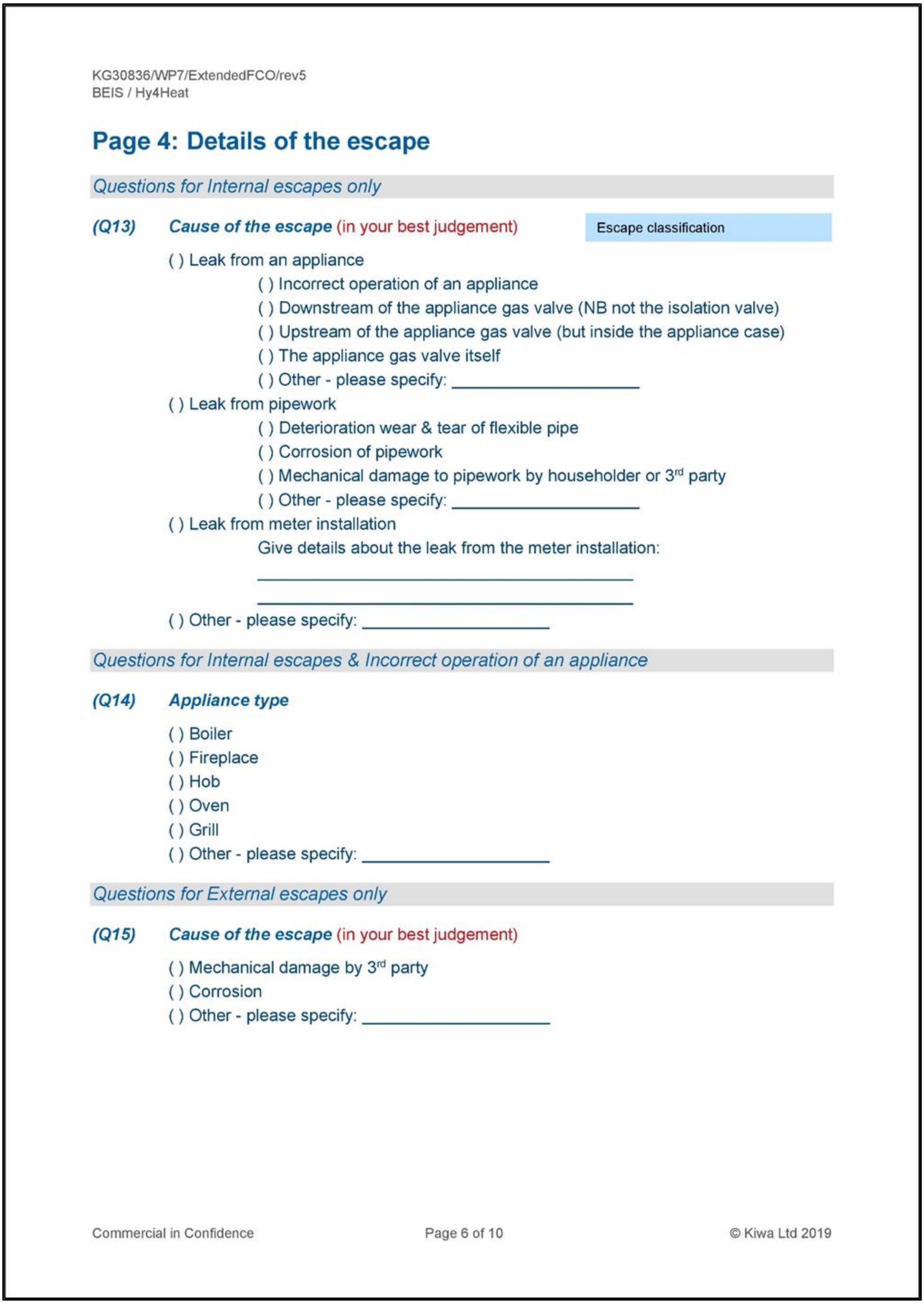
(Q11) **How many doors or windows are there in the room with the escape, or the room where gas was found?** (if the escape is in a cupboard then answer regarding the room the cupboard is in)

Number of doors: ____________________
Number of windows: ____________________

For blast relief & ventilation

(Q12) **What is the window type in this property?** (if the property has several types of glazing then tick the box of which there is most)

( ) Single-glazed
( ) Double-glazed
( ) Triple-glazed
( ) Unknown



Page 4: Details of the escape

Questions for Internal escapes only

(Q13) ***Cause of the escape*** (in your best judgement)

Escape classification

- ( ) Leak from an appliance
    - ( ) Incorrect operation of an appliance
    - ( ) Downstream of the appliance gas valve (NB not the isolation valve)
    - ( ) Upstream of the appliance gas valve (but inside the appliance case)
    - ( ) The appliance gas valve itself
    - ( ) Other - please specify: ____________________
- ( ) Leak from pipework
    - ( ) Deterioration wear & tear of flexible pipe
    - ( ) Corrosion of pipework
    - ( ) Mechanical damage to pipework by householder or 3rd party
    - ( ) Other - please specify: ____________________
- ( ) Leak from meter installation
    - Give details about the leak from the meter installation:
    - ____
    - ____
- ( ) Other - please specify: ____________________

Questions for Internal escapes & Incorrect operation of an appliance

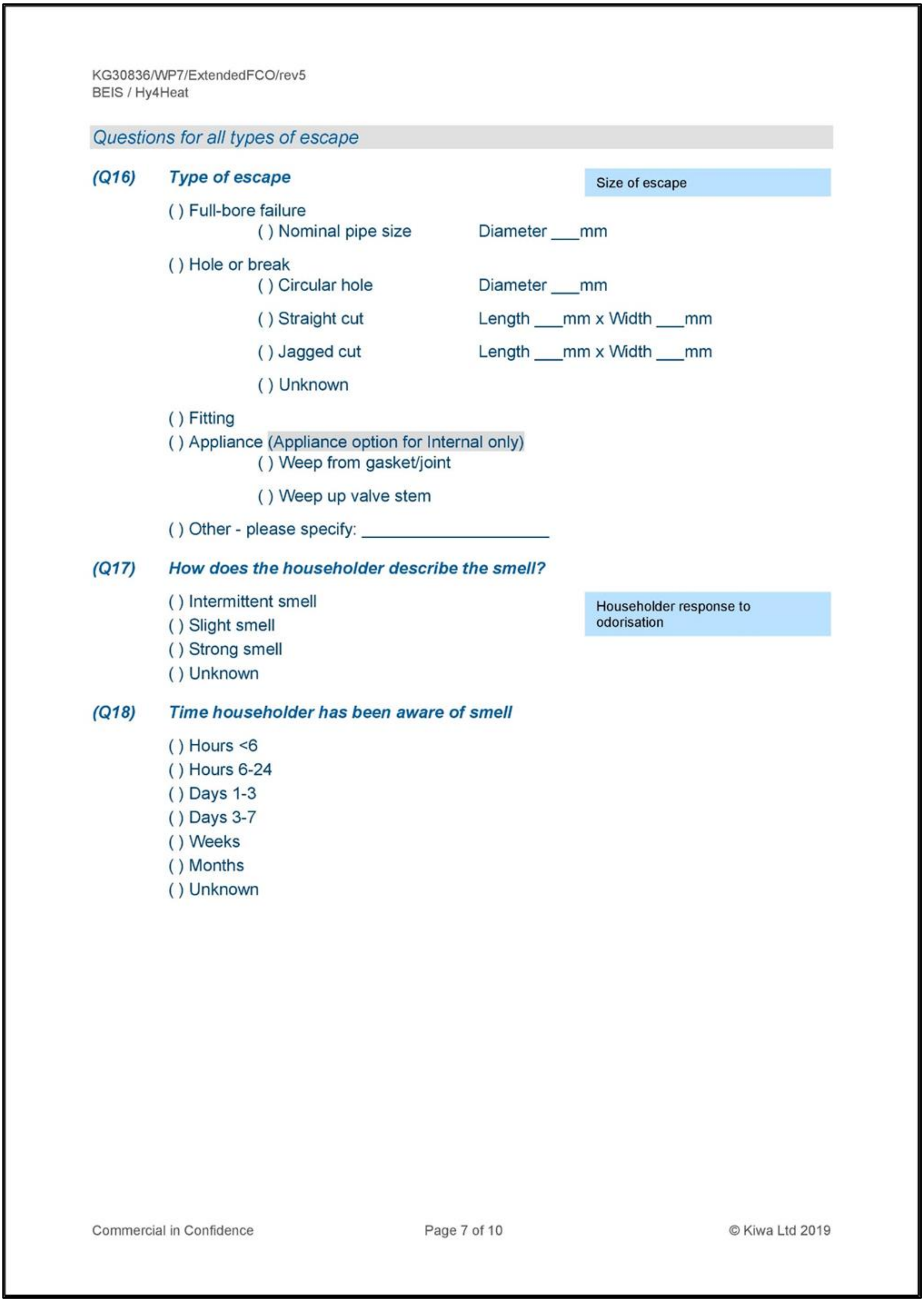
(Q14) ***Appliance type***

- ( ) Boiler
- ( ) Fireplace
- ( ) Hob
- ( ) Oven
- ( ) Grill
- ( ) Other - please specify: ____________________

Questions for External escapes only

(Q15) ***Cause of the escape*** (in your best judgement)

- ( ) Mechanical damage by 3rd party
- ( ) Corrosion
- ( ) Other - please specify: ____________________



KG30836/WP7/ExtendedFCO/rev5
BEIS / Hy4Heat

Questions for all types of escape

(Q16) ***Type of escape***

Size of escape

( ) Full-bore failure
    ( ) Nominal pipe size — Diameter ___mm

( ) Hole or break
    ( ) Circular hole — Diameter ___mm
    ( ) Straight cut — Length ___mm x Width ___mm
    ( ) Jagged cut — Length ___mm x Width ___mm
    ( ) Unknown

( ) Fitting
( ) Appliance (Appliance option for Internal only)
    ( ) Weep from gasket/joint
    ( ) Weep up valve stem

( ) Other - please specify: ____________________

(Q17) ***How does the householder describe the smell?***

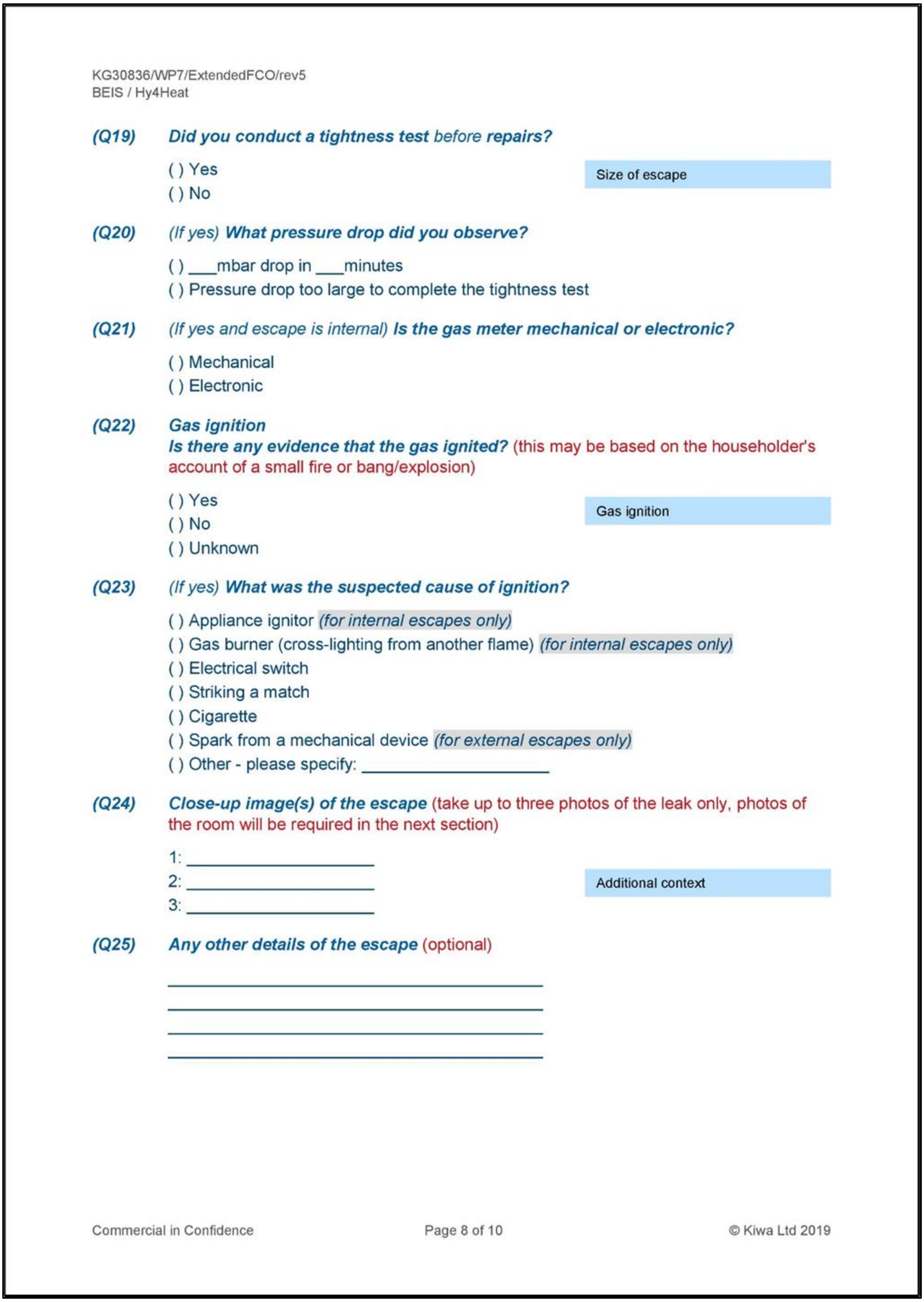
Householder response to odorisation

( ) Intermittent smell
( ) Slight smell
( ) Strong smell
( ) Unknown

(Q18) ***Time householder has been aware of smell***

( ) Hours <6
( ) Hours 6-24
( ) Days 1-3
( ) Days 3-7
( ) Weeks
( ) Months
( ) Unknown

Commercial in Confidence — Page 7 of 10 — © Kiwa Ltd 2019



KG30836/WP7/ExtendedFCO/rev5
BEIS / Hy4Heat

(Q19) ***Did you conduct a tightness test** before **repairs?***

( ) Yes
( ) No

Size of escape

(Q20) *(If yes)* ***What pressure drop did you observe?***

( ) ___mbar drop in ___minutes
( ) Pressure drop too large to complete the tightness test

(Q21) *(If yes and escape is internal)* ***Is the gas meter mechanical or electronic?***

( ) Mechanical
( ) Electronic

(Q22) ***Gas ignition***
Is there any evidence that the gas ignited? (this may be based on the householder's account of a small fire or bang/explosion)

( ) Yes
( ) No
( ) Unknown

Gas ignition

(Q23) *(If yes)* ***What was the suspected cause of ignition?***

( ) Appliance ignitor *(for internal escapes only)*
( ) Gas burner (cross-lighting from another flame) *(for internal escapes only)*
( ) Electrical switch
( ) Striking a match
( ) Cigarette
( ) Spark from a mechanical device *(for external escapes only)*
( ) Other - please specify: ____________________

(Q24) ***Close-up image(s) of the escape*** (take up to three photos of the leak only, photos of the room will be required in the next section)

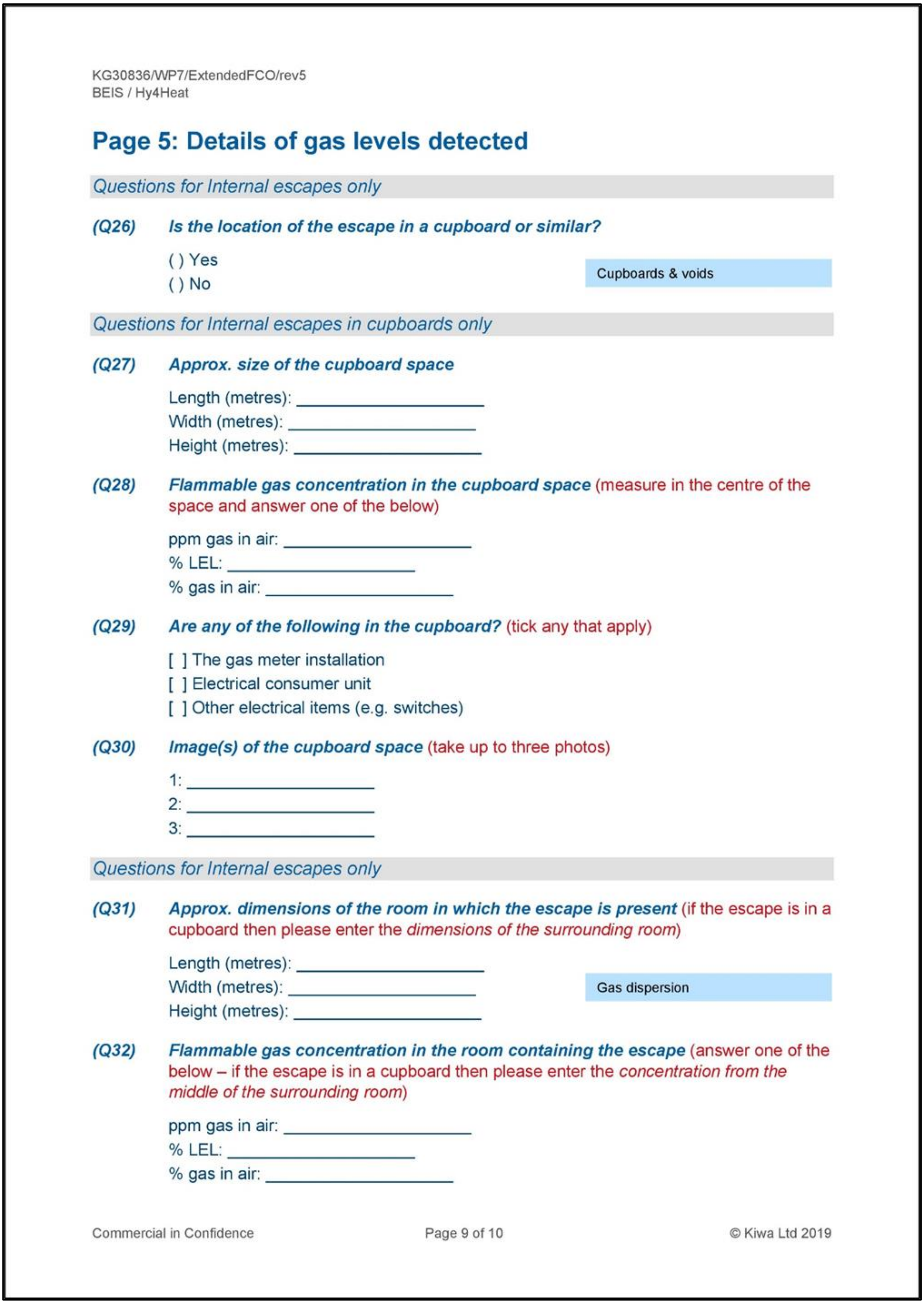
1: ____________________
2: ____________________
3: ____________________

Additional context

(Q25) ***Any other details of the escape*** (optional)

____
____
____
____

Commercial in Confidence　Page 8 of 10　© Kiwa Ltd 2019



Page 5: Details of gas levels detected

Questions for Internal escapes only

(Q26) ***Is the location of the escape in a cupboard or similar?***

( ) Yes
( ) No

Cupboards & voids

Questions for Internal escapes in cupboards only

(Q27) ***Approx. size of the cupboard space***

Length (metres): ____________________
Width (metres): ____________________
Height (metres): ____________________

(Q28) ***Flammable gas concentration in the cupboard space*** (measure in the centre of the space and answer one of the below)

ppm gas in air: ____________________
% LEL: ____________________
% gas in air: ____________________

(Q29) ***Are any of the following in the cupboard?*** (tick any that apply)

[ ] The gas meter installation
[ ] Electrical consumer unit
[ ] Other electrical items (e.g. switches)

(Q30) ***Image(s) of the cupboard space*** (take up to three photos)

1: ____________________
2: ____________________
3: ____________________

Questions for Internal escapes only

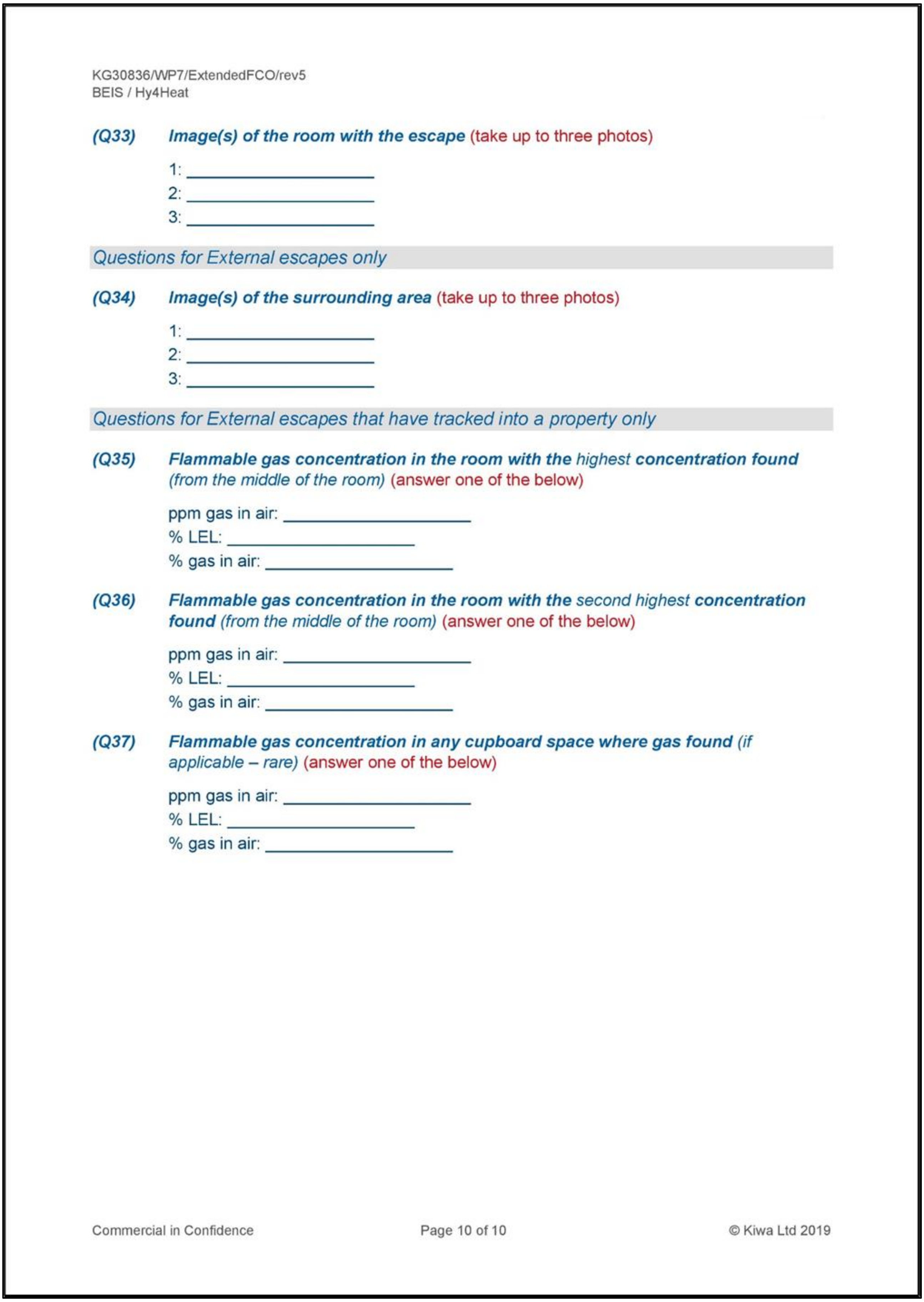
(Q31) ***Approx. dimensions of the room in which the escape is present*** (if the escape is in a cupboard then please enter the *dimensions of the surrounding room*)

Length (metres): ____________________
Width (metres): ____________________
Height (metres): ____________________

Gas dispersion

(Q32) ***Flammable gas concentration in the room containing the escape*** (answer one of the below – if the escape is in a cupboard then please enter the *concentration from the middle of the surrounding room*)

ppm gas in air: ____________________
% LEL: ____________________
% gas in air: ____________________



(Q33) ***Image(s) of the room with the escape*** (take up to three photos)

1: ____________________
2: ____________________
3: ____________________

Questions for External escapes only

(Q34) ***Image(s) of the surrounding area*** (take up to three photos)

1: ____________________
2: ____________________
3: ____________________

Questions for External escapes that have tracked into a property only

(Q35) ***Flammable gas concentration in the room with the*** *highest* ***concentration found*** *(from the middle of the room)* (answer one of the below)

ppm gas in air: ____________________
% LEL: ____________________
% gas in air: ____________________

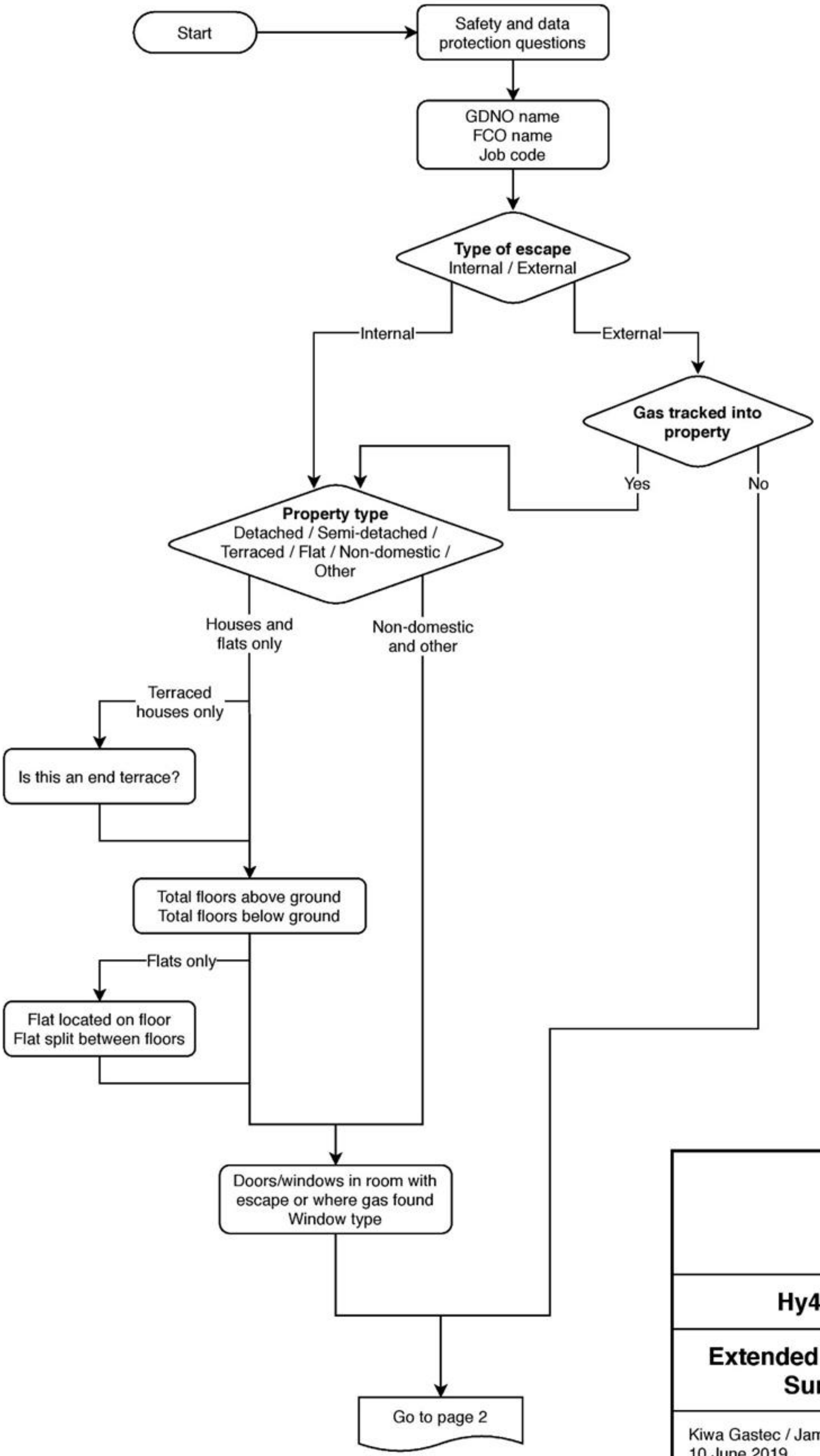
(Q36) ***Flammable gas concentration in the room with the*** *second highest* ***concentration found*** *(from the middle of the room)* (answer one of the below)

ppm gas in air: ____________________
% LEL: ____________________
% gas in air: ____________________

(Q37) ***Flammable gas concentration in any cupboard space where gas found*** *(if applicable – rare)* (answer one of the below)

ppm gas in air: ____________________
% LEL: ____________________
% gas in air: ____________________

Page 1 / 2



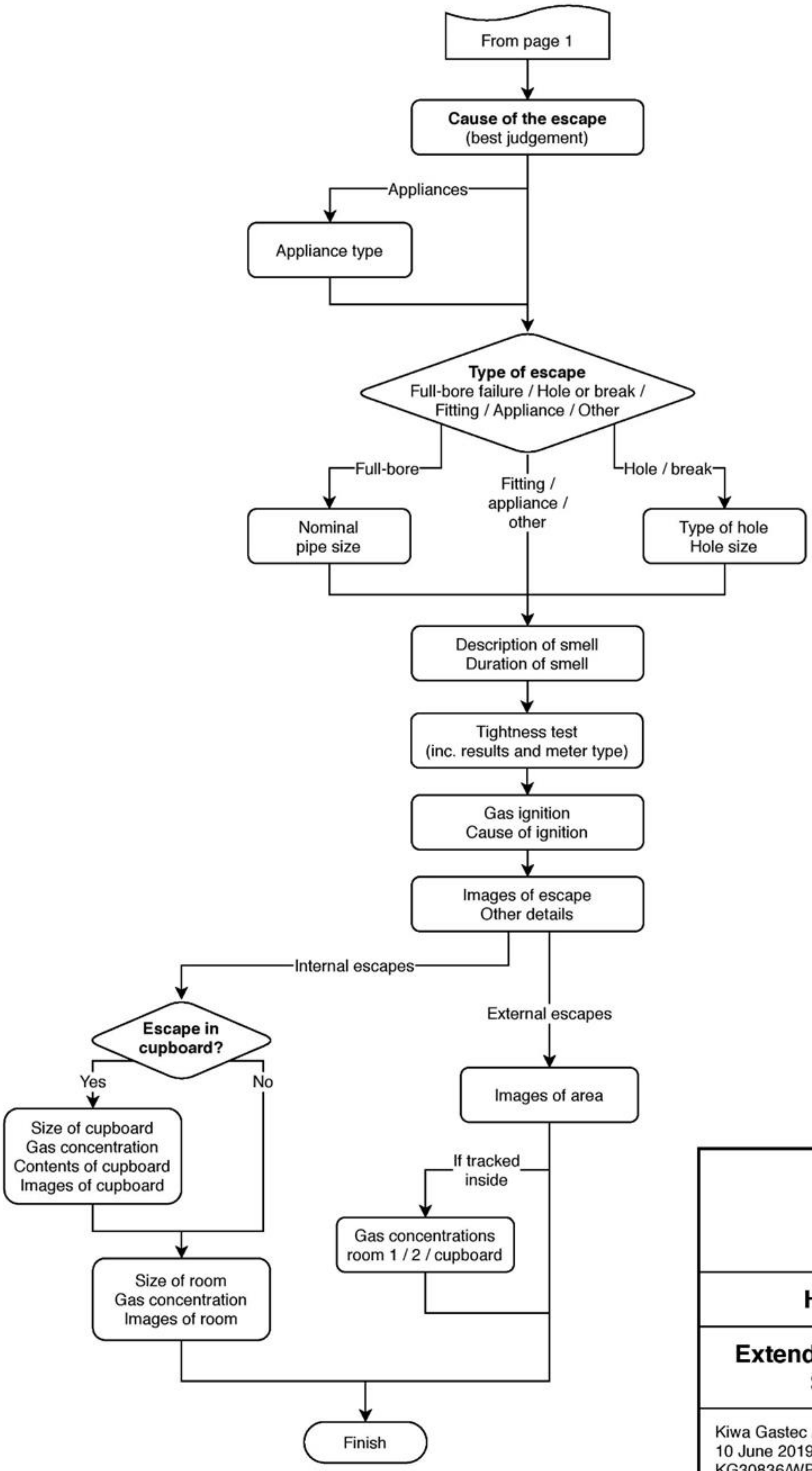
Hy4Heat WP7

Extended FCO Procedure Survey logic

Kiwa Gastec / James Thomas
10 June 2019
KG30836/WP7/ExtendedFCOLogic/rev5

Commercial in Confidence

Page 2 / 2



Hy4Heat WP7

Extended FCO Procedure Survey logic

Kiwa Gastec / James Thomas
10 June 2019
KG30836/WP7/ExtendedFCOLogic/rev5

Appendix 5 – Simple statistical model of serious gas escapes

The following page shows the calculation used to assess the likelihood of encountering a reportable escape during FCO surveys.

Client	Hy4Heat
Client Ref	WP7
Kiwa Project No.	30836
Calculation No.	1
Sheet	1 of 1

Statistical analysis of likely number of reportable escapes to be observed during Extended FCO Procedure

Calculation Sheet

There are around 400,000 FCO call-outs due to gas escapes per year, of which 200-300 are reportable. For this exercise, it is assumed that this equates 1:1 to 400,000 escapes per year, 250 of which are reportable:

Total escapes 400,000 escapes/y
Reportable escapes 250 escapes/y (under GS(M)R)

A survey has been designed that will cover up to 10,000 FCO call-outs, or 3 months elapsed time (whichever is greater). This will start Q3 2019, on order to cover most of the heating season.

Sample size 10,000 escapes

Assuming reportable escapes are randomly and uniformly distributed amongst the population of total escapes, this is equivalent to sampling coloured balls from a bag, without replacement:

Non-notifiable 'balls' 399,750 escapes
Notifiable 'balls' 250 escapes

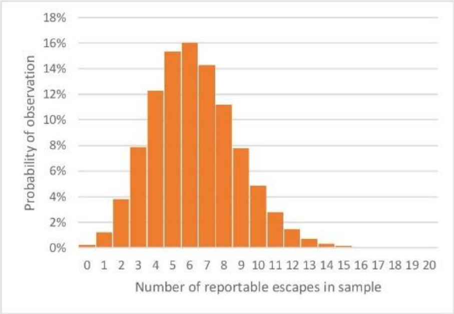
We require the minimum number of reportable escapes that we expect to see 95% of the time. This can be worked out by considering the propabilities of observing different numbers of reportable escapes, e.g.

$$p(1\ \text{notifiable}) = \frac{250}{400{,}000} \times \frac{399{,}750}{399{,}999} \times \frac{399{,}749}{399{,}998} \times \frac{\ldots}{\ldots} \times 10{,}000\ \text{choose}\ 1$$

As the population size is large, this is approximately a Binomial distribution ~ B(n, p) with:

n = 10,000 escapes
p = 0.000625

No. reportable escapes	Probability of finding	Cumulative Probability	Cumulative Inverse Probability
0	0.2%	0.2%	
1	1.2%	1.4%	99.8%
2	3.8%	5.2%	98.6%
3	7.9%	13.0%	94.8%
4	12.3%	25.3%	87.0%
5	15.3%	40.6%	74.7%
6	16.0%	56.6%	59.4%
7	14.3%	70.9%	43.4%
8	11.2%	82.0%	29.1%
9	7.7%	89.8%	18.0%
10	4.8%	94.6%	10.2%
11	2.7%	97.4%	5.4%
12	1.4%	98.8%	2.6%
13	0.7%	99.5%	1.2%
14	0.3%	99.8%	0.5%
15	0.1%	99.9%	0.2%
16	0.0%	100.0%	0.1%
17	0.0%	100.0%	0.0%
18	0.0%	100.0%	0.0%
19	0.0%	100.0%	0.0%
20	0.0%	100.0%	0.0%



The expected number of reportable escapes in the sample is np =

Expected 6 reportable escapes

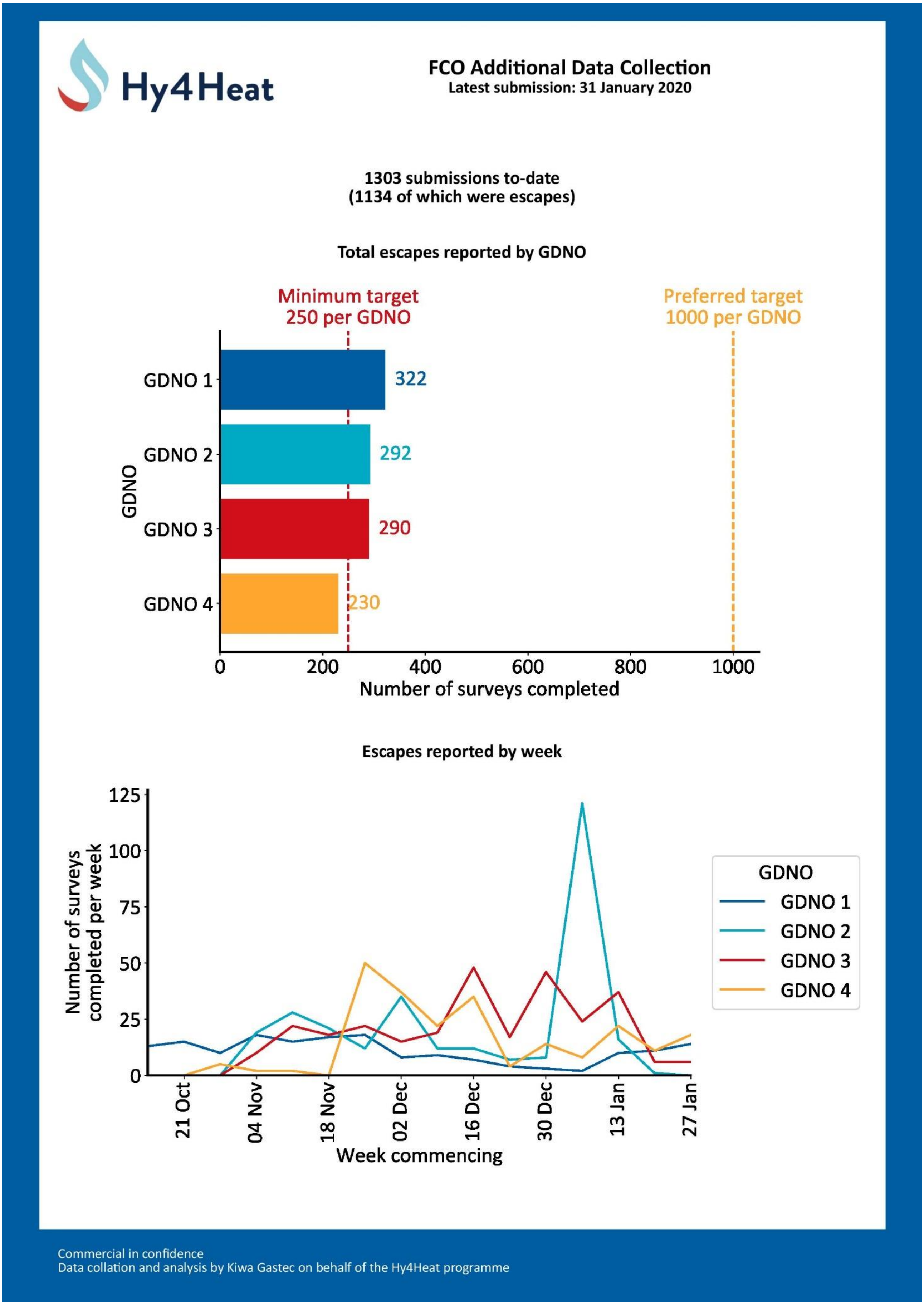
and there is an approx 95% proability of finding at least:

At least 2 reportable escapes

Revision	A	B	C	D	E	F
Date	14/01/2019	05/03/2020				
Preparer	James Thomas	James Thomas				
Checker		Paul McLaughlin				
Approver		Paul McLaughlin				

Appendix 6 – Stakeholder dashboard

The following pages show the dashboard pages generated to report on the results of FCO surveys.



FCO Additional Data Collection

Latest submission: 31 January 2020

1303 submissions to-date
(1134 of which were escapes)

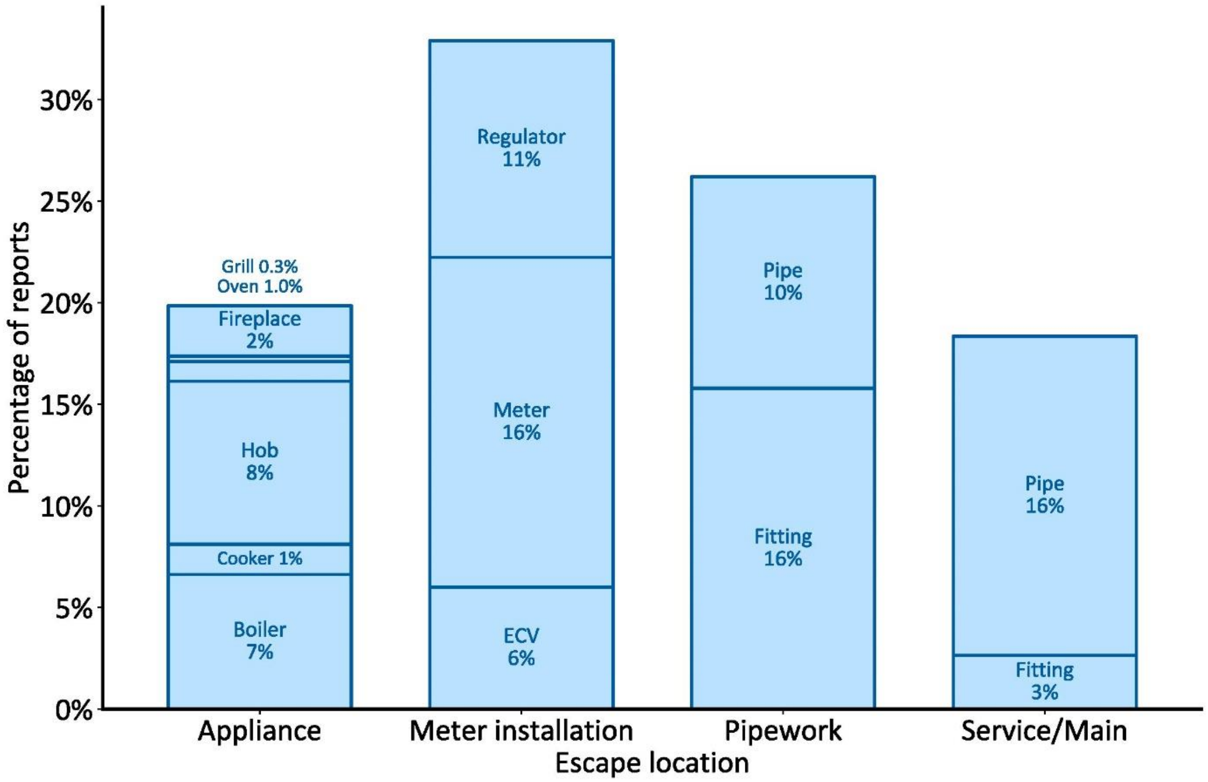
Total escapes reported by GDNO

Escapes reported by week

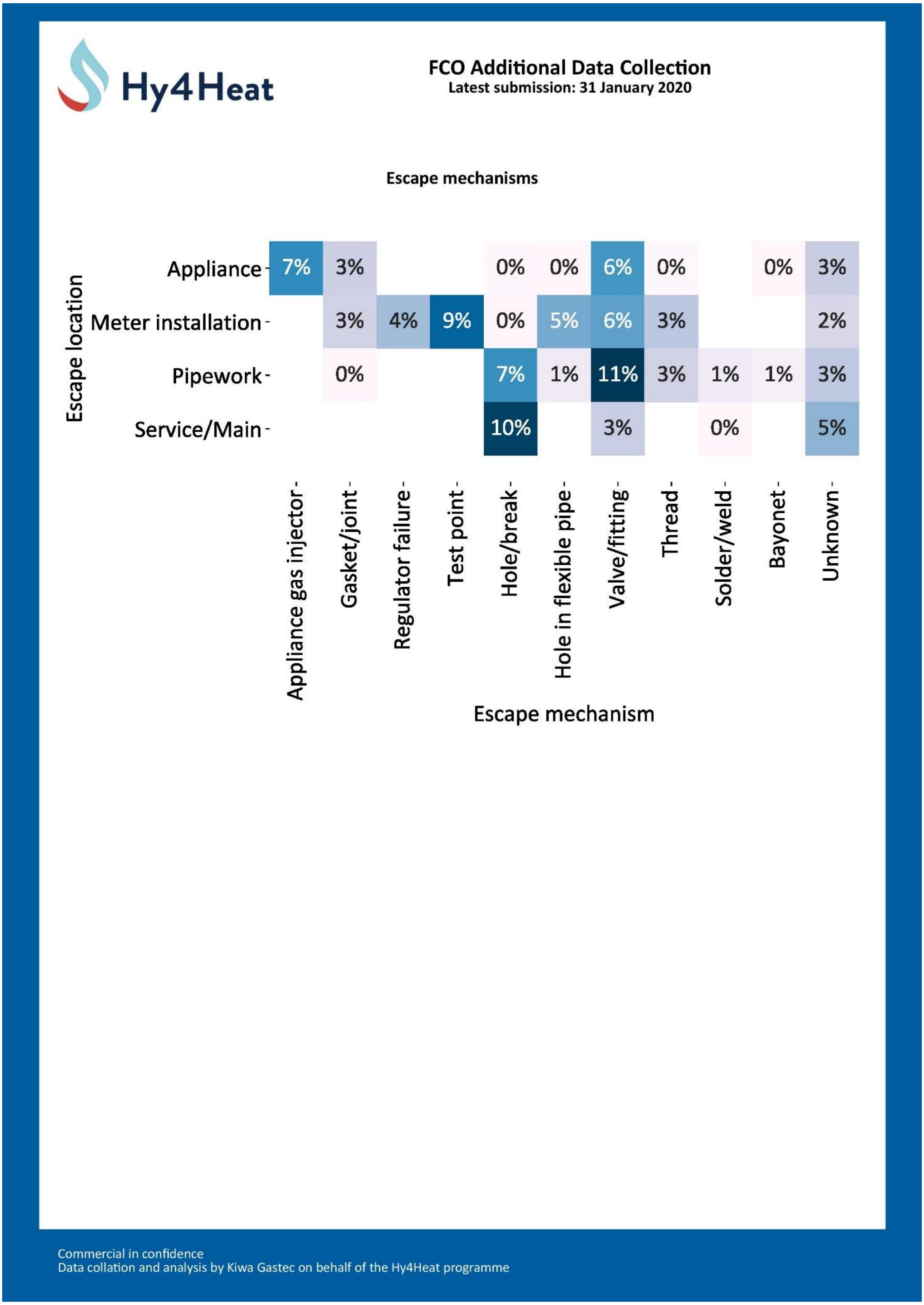
Commercial in confidence
Data collation and analysis by Kiwa Gastec on behalf of the Hy4Heat programme

FCO Additional Data Collection

Latest submission: 31 January 2020



Commercial in confidence
Data collation and analysis by Kiwa Gastec on behalf of the Hy4Heat programme



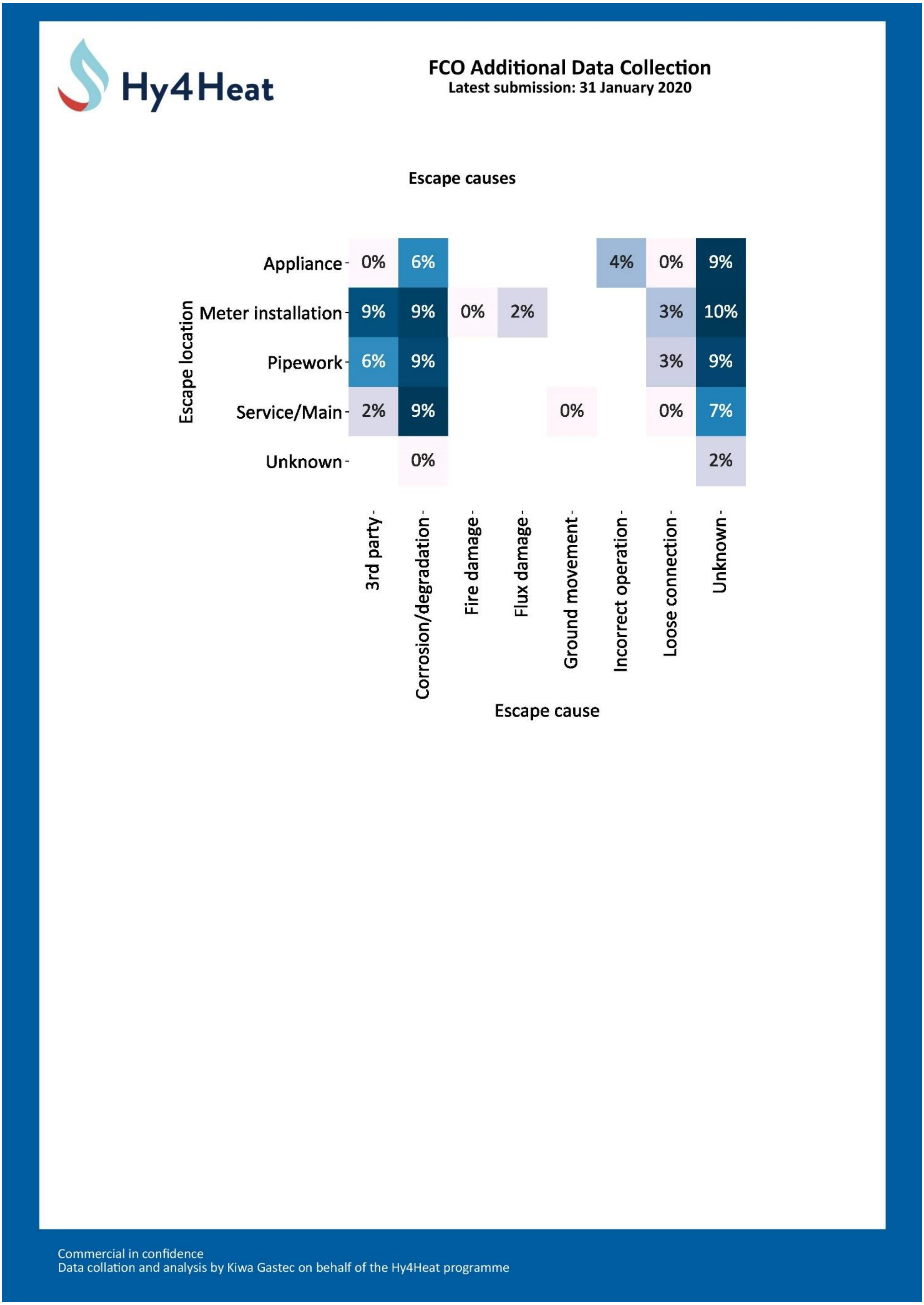
Hy4Heat

FCO Additional Data Collection
Latest submission: 31 January 2020

Escape mechanisms

Escape location	Appliance gas injector	Gasket/joint	Regulator failure	Test point	Hole/break	Hole in flexible pipe	Valve/fitting	Thread	Solder/weld	Bayonet	Unknown
Appliance	7%	3%			0%	0%	6%	0%		0%	3%
Meter installation		3%	4%	9%	0%	5%	6%	3%			2%
Pipework		0%			7%	1%	11%	3%	1%	1%	3%
Service/Main					10%		3%		0%		5%

Commercial in confidence
Data collation and analysis by Kiwa Gastec on behalf of the Hy4Heat programme



FCO Additional Data Collection

Latest submission: 31 January 2020

Escape causes

Escape location	3rd party	Corrosion/degradation	Fire damage	Flux damage	Ground movement	Incorrect operation	Loose connection	Unknown
Appliance	0%	6%				4%	0%	9%
Meter installation	9%	9%	0%	2%			3%	10%
Pipework	6%	9%					3%	9%
Service/Main	2%	9%			0%		0%	7%
Unknown		0%						2%

Escape cause

Commercial in confidence
Data collation and analysis by Kiwa Gastec on behalf of the Hy4Heat programme

Appendix 7 – Leak rate distribution data

Table 10: Methane leak rate

Methane leak rate (kW)	Count	Cumulative count
0.00077	1	1
0.00096	1	2
0.001	1	3
0.0015	1	4
0.0016	1	5
0.0019	2	7
0.0021	1	8
0.0026	1	9
0.0029	1	10
0.0032	3	13
0.0033	2	15
0.0039	11	26
0.0043	1	27
0.0051	1	28
0.0059	2	30
0.0067	2	32
0.0069	3	35
0.0077	1	36
0.0079	1	37
0.008	11	48
0.0082	1	49
0.0092	3	52
0.01	1	53
0.011	5	58
0.012	7	65
0.015	4	69
0.016	1	70
0.017	6	76
0.018	1	77
0.021	3	80
0.022	2	82
0.023	11	93
0.027	6	99
0.028	1	100
0.029	3	103
0.033	2	105
0.038	1	106
0.039	1	107
0.043	1	108
0.053	2	110
0.057	1	111
0.065	1	112
0.066	1	113
0.093	81	194
0.11	1	195
0.12	2	197
0.14	1	198
0.15	60	258
0.17	1	259
0.22	84	343
0.34	65	408
0.35	67	475
0.5	1	476
0.51	41	517
0.87	18	535
0.92	175	710
0.97	31	741
1.1	1	742
1.4	54	796
1.6	4	800
1.8	48	848
2	23	871
3	8	879
6	3	882
6.3	6	888
10	1	889
14	4	893
16	1	894
25	1	895
39	3	898
56	2	900
100	2	902
160	2	904
200	1	905
230	6	911

Table 11: Hydrogen leak rate

Hydrogen leak rate (kW)	Count	Cumulative count
0.00077	1	1
0.00096	1	2
0.001	1	3
0.0015	1	4
0.0016	1	5
0.0019	2	7
0.0021	1	8
0.0026	1	9
0.0029	1	10
0.0032	3	13
0.0033	2	15
0.0039	11	26
0.0043	1	27
0.0051	1	28
0.0059	2	30
0.0067	2	32
0.0069	3	35
0.0077	1	36
0.0079	1	37
0.008	11	48
0.0082	1	49
0.0092	3	52
0.01	1	53
0.011	5	58
0.012	7	65
0.015	4	69
0.016	1	70
0.017	6	76
0.018	1	77
0.021	3	80
0.022	2	82
0.023	11	93
0.027	6	99
0.028	1	100
0.029	3	103
0.033	2	105
0.038	1	106
0.039	1	107
0.043	1	108
0.053	2	110
0.057	1	111
0.065	1	112
0.066	1	113
0.093	81	194
0.11	1	195
0.12	2	197
0.14	1	198
0.15	60	258
0.17	1	259
0.22	84	343
0.34	65	408
0.35	67	475
0.5	1	476
0.51	41	517
0.87	18	535
0.92	175	710
0.97	31	741
1.1	1	742
1.4	54	796
1.6	4	800
1.8	48	848
2	23	871
3	8	879
6	3	882
6.3	6	888
10	1	889
14	4	893
16	1	894
25	1	895
39	3	898
56	2	900
100	2	902
160	2	904
200	1	905
230	6	911

Table 12: Estimated methane gas in air

Methane gas in air (%)	Count	Cumulative count
0.001	1	1
0.0012	1	2
0.0013	1	3
0.0018	1	4
0.0019	1	5
0.0023	2	7
0.0025	1	8
0.0031	1	9
0.0034	1	10
0.0037	3	13
0.0039	2	15
0.0045	11	26
0.0049	1	27
0.0057	1	28
0.0065	2	30
0.0073	2	32
0.0075	3	35
0.0083	1	36
0.0085	1	37
0.0086	11	48
0.0088	1	49
0.0098	3	52
0.011	4	56
0.012	6	62
0.013	3	65
0.015	2	67
0.016	3	70
0.017	6	76
0.018	1	77
0.021	3	80
0.022	2	82
0.023	11	93
0.026	6	99
0.027	1	100
0.028	3	103
0.031	2	105
0.036	1	106
0.037	1	107
0.04	1	108
0.048	2	110
0.052	1	111
0.059	1	112
0.06	1	113
0.082	81	194
0.091	1	195
0.1	2	197
0.12	61	258
0.15	1	259
0.18	84	343
0.27	132	475
0.38	1	476
0.39	41	517
0.63	18	535
0.67	175	710
0.69	31	741
0.81	1	742
0.95	54	796
1.1	4	800
1.2	48	848
1.3	23	871
2	8	879
3.7	3	882
3.8	6	888
5.9	1	889
8.1	4	893
9	1	894
14	1	895
21	3	898
29	2	900
48	1	901
49	1	902
73	2	904
91	1	905
100	6	911

Table 13: Estimated hydrogen gas in air

Hydrogen gas in air (%)	Count	Cumulative count
0.00042	1	1
0.00052	1	2
0.00056	1	3
0.00078	1	4
0.00082	1	5
0.001	2	7
0.0011	1	8
0.0013	1	9
0.0015	1	10
0.0016	3	13
0.0017	2	15
0.0019	11	26
0.0021	1	27
0.0025	1	28
0.0029	2	30
0.0032	2	32
0.0033	3	35
0.0037	1	36
0.0038	12	48
0.0039	1	49
0.0043	3	52
0.0047	1	53
0.0049	1	54
0.005	2	56
0.0052	2	58
0.0055	4	62
0.0057	3	65
0.0066	1	66
0.0067	1	67
0.007	2	69
0.0077	6	75
0.008	1	76
0.0093	1	77
0.0094	2	79
0.0097	2	81
0.011	11	92
0.012	10	102
0.014	2	104
0.015	1	105
0.016	1	106
0.017	1	107
0.018	1	108
0.022	2	110
0.024	1	111
0.027	2	113
0.042	1	114
0.049	2	116
0.057	1	117
0.068	1	118
0.077	81	199
0.11	84	283
0.12	60	343
0.13	65	408
0.16	67	475
0.33	41	516
0.36	175	691
0.38	19	710
0.45	31	741
0.59	54	795
0.83	1	796
1.1	4	800
1.3	48	848
1.4	1	849
1.6	22	871
2.4	8	879
4	6	885
4.6	3	888
6.2	1	889
8.6	4	893
9.7	1	894
15	1	895
22	3	898
32	2	900
54	2	902
82	2	904
100	7	911

Appendix 8 – Consequence screening assessment

The dispersion and consequence assessment parts of WP7 are used to take the data on leak sizes and frequencies, and to convert this into a set of parameters for use in the QRA. As development of the QRA was ongoing, a screening assessment of consequences was conducted, to allow an early assessment of what would happen if the gas leaks reported in the FCO survey were to occur in one consistent room type, rather than waiting until the end of the full QRA process. This appendix describes the process used for this screening.

By relating the rate of gas release to the maximum concentration developed at a high level in the room with the two gases, a screening relationship could be produced.

A method for segmenting the population of leaks by rate is based on the potential for consequences. It should be noted that the segmentation is illustrative only, as more detailed dispersion modelling and explosion consequence analysis was performed later using the leak data set developed in this part of the work.

- Between the higher MPLR and a leak rate that would give rise to an atmosphere of no more than 20% of the lower flammable limit of gas would represent one area where there would be negligible likelihood of adverse consequences from a leak, and would not prevent building entry and investigation by a gas operative.
- Between 20% and 100% of the lower flammable limit, the atmosphere developed as a consequence of a leak would still be non-flammable in general, but small pockets of flammable atmosphere may be present.
- Between 100% of the lower flammable limit and 8% gas in air (GIA), there is the potential for general ignition, but the flame speed in such a lean mixture for either natural gas or hydrogen limits the potential overpressure of an explosion and hence the consequences.
- Above 8% GIA, flame speeds become higher, and the potential for damage becomes significant. Atmospheres of either natural gas or hydrogen have the potential to cause major damage to property.
- For hydrogen only, an atmosphere containing over 15% hydrogen has the potential to give rise to somewhat higher damage to buildings.

Gas dispersion results from the Hy4Heat WP7 Lot 2 data [10] was used, selecting releases into a kitchen from low points to determine the maximum gas in air content as a function of energy release rates. As an initial screening assessment, a power law curve was fitted to the data to allow this estimation to be applied to the release data. Figure 12 shows this relationship.

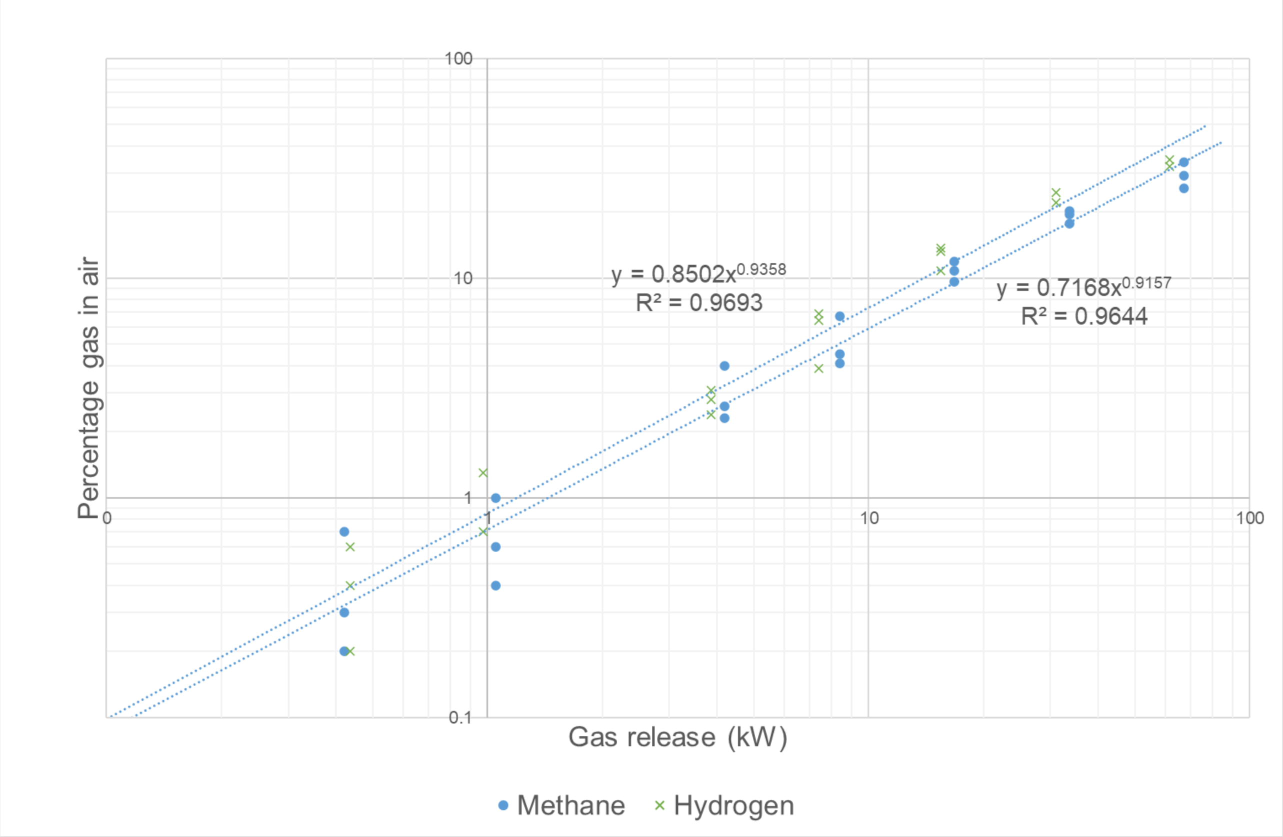


Figure 12: Illustrative relationship between gas release rate and peak GIA

As this is only used for screening purposes, the potential for the equation to predict concentrations in excess of 100% was not deemed to be an issue – any concentration greater than 8% is assumed to have potential for significantly damaging consequences, with hydrogen greater than 15% gas in air being particularly strong. These transition points fall within the range of points considered.

This relationship between gas release rate and percentage gas in air was applied to the natural gas and hydrogen leak rates inferred from the survey data, and used to calculate an approximate gas in air concentration for each release data points to allow the data to be shown in graphical form in Figure 13. Similarly, this is displayed with logarithmic x-axis due to the majority of leaks giving rise to low concentrations of gas in air.

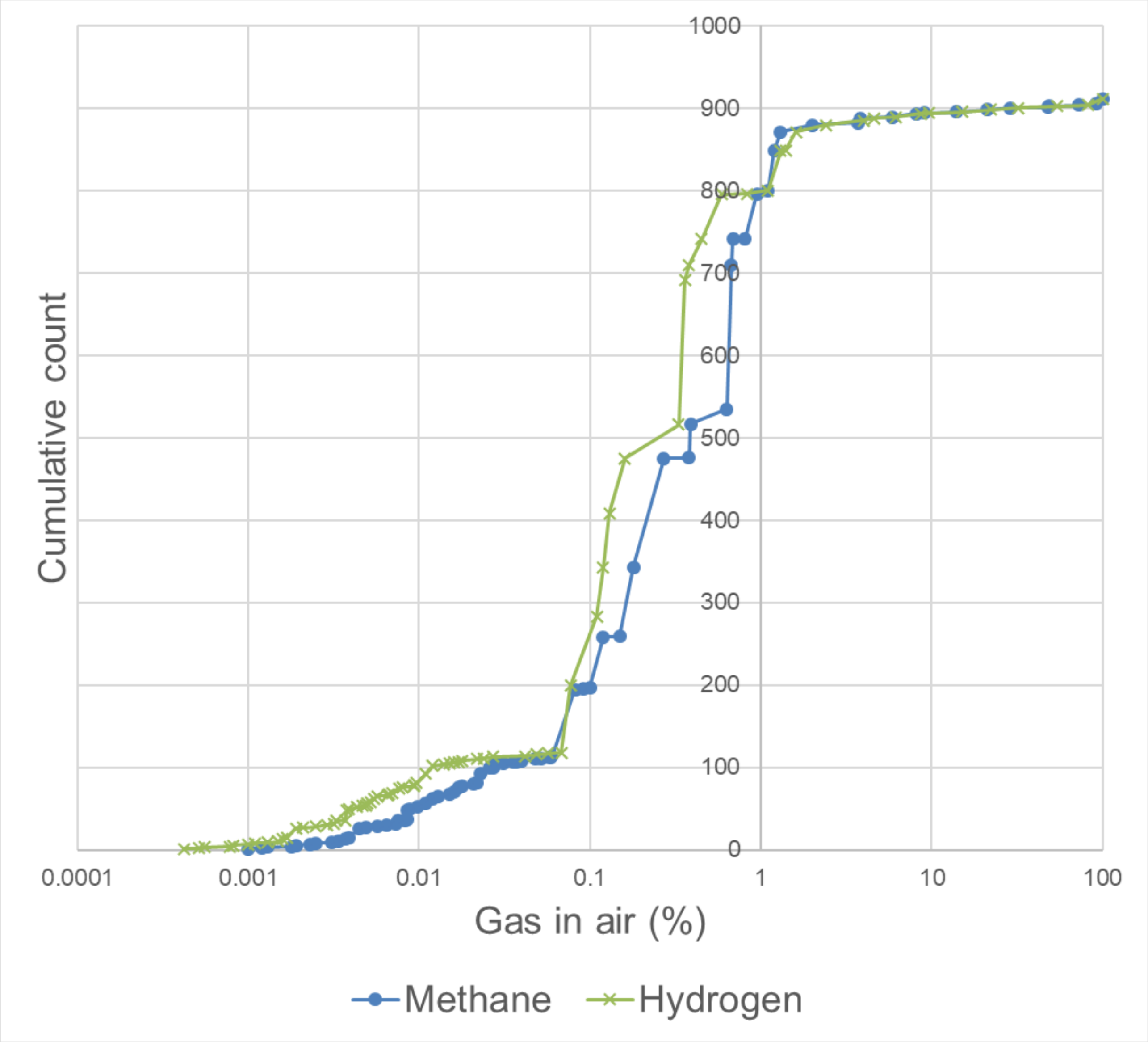
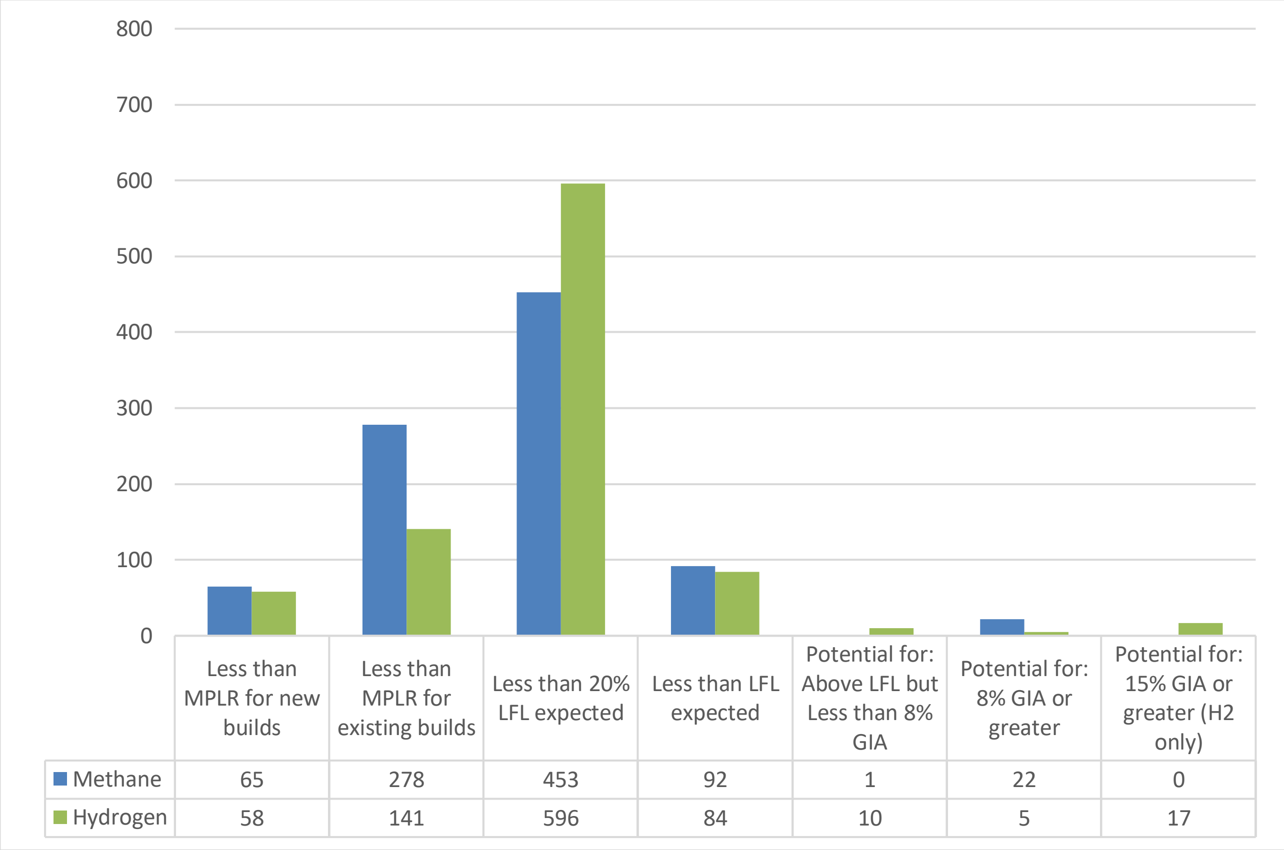


Figure 13: Cumulative counts of estimated gas in air values

It should be noted that Figure 13 illustrates the level of gas in air that might be found after an extended period of uncontrolled release. It is the case that some of the largest releases will be caused by human factors such as accidental damage to pipework during DIY work or a mini-digger driver in a garden. The presence of a person with the ability to respond in these cases will act as a layer of protection, increasing the likelihood that the release of gas will be stopped before fire or explosion could occur. This will be considered within the QRA rather than explored further here, as a change in likelihood should not be conflated with a change in potential consequence.

Categorisation of release types

Using the release categories described in at the start of this appendix to categorise the release rate and gas in air data allows a categorical histogram to be developed, as shown in Figure 14.



	Less than MPLR for new builds	Less than MPLR for existing builds	Less than 20% LFL expected	Less than LFL expected	Potential for: Above LFL but Less than 8% GIA	Potential for: 8% GIA or greater	Potential for: 15% GIA or greater (H2 only)
🟦 Methane	65	278	453	92	1	22	0
🟩 Hydrogen	58	141	596	84	10	5	17

Figure 14: Chart of gas release event counts for natural gas and hydrogen

This is only an informative chart rather than a definitive answer, but it allows the following observations to be made:

- A large minority of leaks reported would be below the maximum permissible leak rate on natural gas. Some of these leaks would be above the MPLR if hydrogen were to be conveyed.
- For the leaks that would not pass a tightness test with hydrogen when they would with methane, they would not fail to such an extent that a flammable atmosphere would be created.
- The median and modal sizes of leaks would give rise to atmospheres of below 20% of the lower flammable limit of either hydrogen or natural gas.
- There would be an increase of approximately one percentage point in the quantity of leaks that might be expected to give rise to a flammable atmosphere within the screening case.

Hy4Heat

www.Hy4Heat.info

@hy4heat